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POLISH MARITIME RESEARCH

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# POLISH MARITIME RESEARCH
## Special Issue 2006/S2


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# Editorial

POLISH MARITIME RESEARCH is a scientific journal of worldwide circulation. The journal appears as a quarterly four times a year. The first issue of it was published in September 1994. Its main aim is to present original, innovative scientific ideas and Research & Development achievements in the field of :

**Engineering**, **Computing & Technology**, **Mechanical Engineering**,

which could find applications in the broad domain of maritime economy. Hence there are published papers which concern methods of the designing, manufacturing and operating processes of such technical objects and devices as : ships, port equipment, ocean engineering units, underwater vehicles and equipment as well as harbour facilities, with accounting for marine environment protection.

The Editors of POLISH MARITIME RESEARCH make also efforts to present problems dealing with education of engineers and scientific and teaching personnel. As a rule, the basic papers are supplemented by information on conferences , important scientific events as well as cooperation in carrying out international scientific research projects.

# Scientific Board

# Coordinator's message

*The present special issue S2/2006 of the Polish Maritime Research includes articles selected from a rich output (257 thematic publications) of the consortium realising the Eureka E!3065 group European project entitled "A new generation of environment friendly inland & coastal ships for Polish east-west waterways". The project aimed at developing technical visions of new-generation inland ships, able to undertake regular navigation on the neglected inland waterways in Poland. The realised activities included studies of ecological threats, technical condition of the waterways, stream of cargo transported by ships across the inland area, various options of ship systems and hull characteristics, and, finally, working out a preliminary design of a relevant series of inland ship types meeting severe ecological requirements. A concept has been developed of a modern and luxurious two-module inland passenger liner, being the main subject of the present PMR issue, and its land harbour and hotel infrastructure. Moreover, a push train system making use of a concept of interchangeable functional modules (containers) mounted on a basic hull was the basis for designing, optionally, a standard-class passenger ship, a container ship, a car ferry, a car carrier, a hotel ship, a relevant pusher, and a traditional general cargo ship. The subjects relating to these ships will be discussed in the next issue S1/2007 of the Polish Maritime Research.*

**Project Coordinator: Krzysztof Rosochowicz, Prof.**

# Project Eureka E!3065

## *A new generation of environment friendly inland & coastal ships for Polish east-west waterways*

## INCOWATRANS

**Chief executor and coordinator of the project :**

## *Gdańsk University of Technology Faculty of Ocean Engineering and Ship Technology*

**Gdańsk 2006**

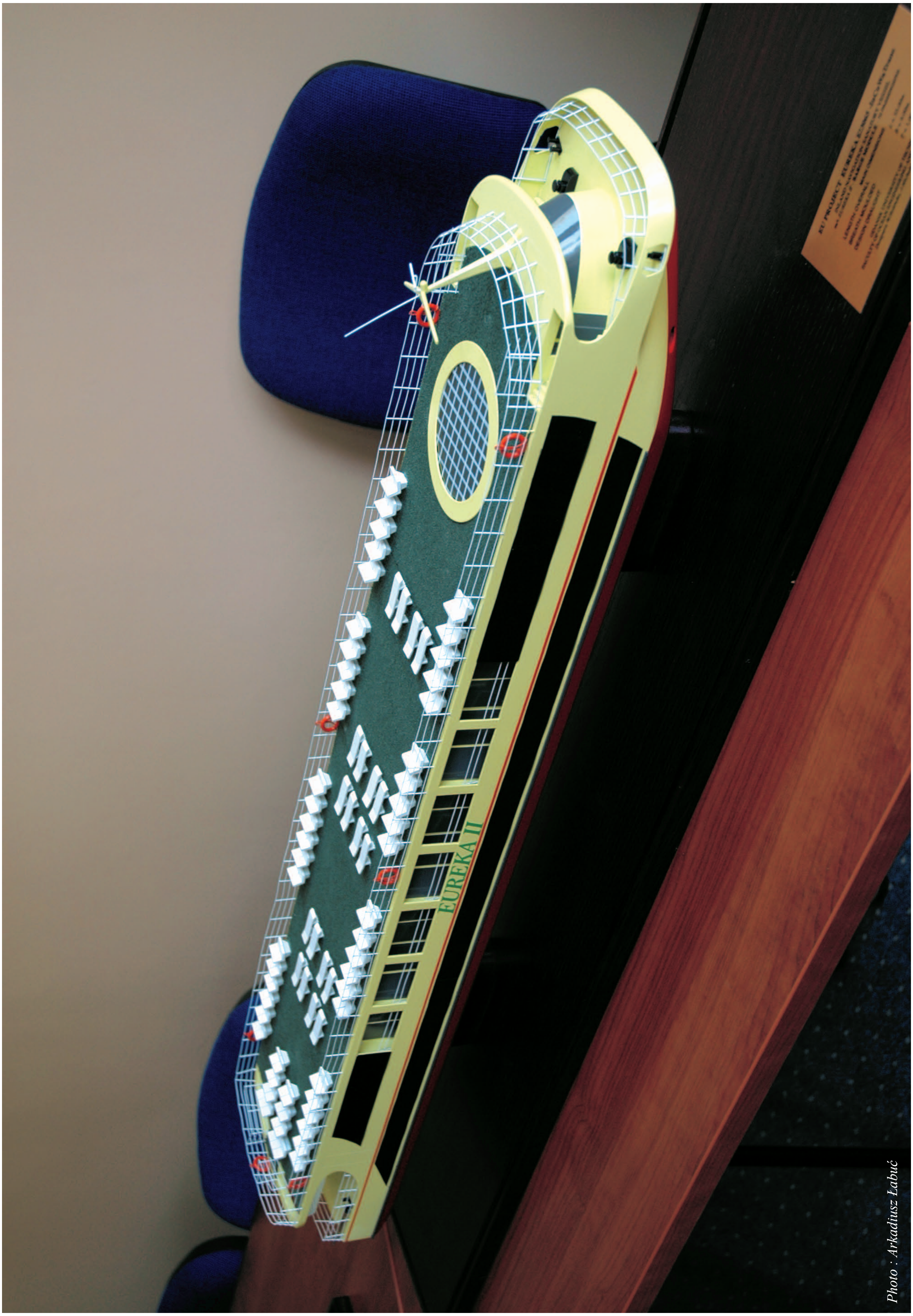

Photo : Arkadiusz Łabuć

# A design concept of ecological tourist – – passenger ship intended for Berlin-Królewiec (Kaliningrad) inland waterway service

**Waldemar Hołówko**[1],
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**Krzysztof Rosochowicz**[3], Prof.
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ABSTRACT

*This paper presents a design concept of a novel passenger segment ship intended for navigating on Berlin--Królewiec (Kaliningrad) inland waterway route, characteristic of application novel structural materials and engineering processes which make it possible to design structures in an innovative way and provide high operational merits for inland waterways ship. Conceptual, functional and technical assumptions for the designed ship as well as its service program was described. Exceptional features of the designed ship are : the general architectural concept which makes the ship free passing under small-clearance bridges and navigating in narrow and shallow waterways, possible, manufacturing technology of its hull structure made of „sandwich" panels as well as its combustion-electric engine (or combustion-hydraulic engine) propulsion system working on alternative ecological gas fuels.*

**Keywords** : ship designing, inland waterways ships, passenger ships.

## INTRODUCTION

European Union allocates significant funds for conducting active policy aimed both at development of shipping goods by using inland waterways and at their use for other transport services (tourism, passenger traffic). Growing road traffic flow, especially that of cars, has become tedious for public and noxious for the environment; it generates high costs of transport, ecological hazards as well as leads to traffic accidents. The above mentioned phenomena justify in a sufficient degree to undertake efforts and bear costs associated with searching for, elaborating and implementing alternative transport solutions including those aimed at directing a significant part of transport volume into sea shipping routes and inland waterways. Traffic capacity of the existing European highways is, in some spots, already close to their extreme limits, and the building of next ones becomes more and more problematic.

An intention of EU countries and international organizations dealing with water transport is to extend eastward the developed waterways systems of West Europe – including also Polish inland waterways – in such a way as to connect the EU system of inland waterways with sea ports and thus to get connections between :

- ✦ Baltic and North Sea ports and Mediterranean ones
- ✦ Baltic and North Sea ports and Black Sea ones
- ✦ inland ports of EU countries and the region of Gdańsk, Vistula and Kuronian Bay
- ✦ inland ports of EU countries and inland waterways of Wight Russia, Ukraine and Russia.

It is expected that further development of economy of EU extended by ten new countries since 1 May 2004, will be based on the development of Euro-regions by strengthening their competitive position. Hence it is necessary to prepare society to active taking part in socioeconomic processes orientated towards developing such human features as : enterprise, innovation, easy inter-personal communication, or skill in using informatics technology.

The regions of Noteć Primeaval Forests, Warmia, Mazury, Podlasie and Polesie, the rapids of Drawa, Wda and Brda river and old valleys of Vistula river represent unique nature merits, especially attractive for tourists from EU countries. Moreover on the territories are located unique historic monuments of world class such as sacred buildings, fortifications as well as medieval municipal complexes. For this reason the specified regions are predestined to serve as a tourism centre and in consequence to lead to livening up their economy and reducing unemployment by absorbing a workforce surplus by such sectors of services as gastronomy, hotels, shipping, yachting etc.

A contribution to realization of the above mentioned target is the concept of livening up the inland waterways tourist traffic realized by means of a fleet of safe high-standard passenger ships. This work is devoted to identification and formulation of functional and technical assumptions for designing the ship intended for realization of aims of the project.

## AIM OF REALIZATION OF THE PROJECT AND APPLICATION MODE OF THE SHIP

The design study of a novel ecological passenger ship elaborated in the frame of **Eureka InCoWaTranS E!3065 Program**[4] is aimed at making a proposal for development of tourism and passenger traffic along common inland waterways of Poland and other EU countries – in east – west direction. These are benefits possible to be obtained as a result of realization of the project in question :

- ❖ decreasing unemployment in northern regions of Poland, having poorly developed industrial infrastructure
- ❖ social activation of the regions crossed by the shipping route in question
- ❖ development of tourist services in the regions of unique nature merits

1. Architect of ship accommodations
2. Principal designer of the ship
3. Coordinator of the EU InCoWaTranS E!3065 project
4. Environment-friendly inland & coastal ships for Polish east-west waterways.

- integration and livening up cooperation of the border regions
- technological development of Polish shipyards and implementation of novel techniques to inland waterways transport by using environment-friendly ships
- revival of building – by Polish shipbuilding industry – the inland waterways ships having good export prospects to EU countries.

The building of inland waterways ships is the field of industrial activities in which Far East shipyards do not compete much as compared with the case of large sea-going ships, however a competition from the side of shipyards in EU countries should be taken into account. In the case of passenger ships intended for recreational service the following factors will decide on their success :

- Technical level of built ships
- Investment profitability
- Environment-friendly technical solutions
- High-standard aesthetic merits of ship accommodations and voyaging comfort
- Quality of organization and attractiveness of tourist-recreational programs.

## SERVICE PROGRAM OF THE SHIP

The presented concept of ship service program, which constitutes the basis for rational formulation of the design assumptions, both functional and technical, is a development of the concepts presented in [1].

It is assumed that the ship and accompanying tourist infrastructure will operate in summer season, i.e. from the beginning of May to the end of September, by offering :

- The trips, mainly addressed to EU tourist, on the route: Berlin-Bydgoszcz-Toruń-Malbork-Gdańsk-Elbląg-Królewiec (Kaliningrad); two kinds of such trips are provided for, namely Berlin-Królewiec-Berlin round trip and Królewiec--Berlin trip combined with coach transport to and from Królewiec.
- Fortnight tourist trips along inland waterways on board the new - generation high-standard ships, organized in cooperation of a group of professional tourist firms having at their disposal appropriate floating units and social living bases fitted with relevant tourist land-based infrastructure (hotels, harbours, coaches, forest clearings, mashroom picking areas, angling spots, water sport facilities, horse riding terrains etc); the trips will be connected with excursions to unique nature regions (Noteć Primaeval Forests, Warmia and Mazury, flood waters of Biebrza river etc) and visits to places of interest of historic, artistic and recreational merits.

Beyond summer season the ship in question is assumed to operate by organizing :

- The trips -mainly addressed to Polish tourists – along closed inland waterways routes with a departure point in e.g. Szczecin or Berlin – and orientated onto the regions of South-West Europe, attractive for tourists, and having a climate milder than in Poland; the routes should be selected on the basis of prior performed marketing studies and investigations.
- The cyclic fortnight periods spent on tourist trips in inland waters onboard the new-generation ships of high-standard living conditions, organized by a professional firm ensuring appropriate living conditions and relevant tourist infrastructure - leasing or reservation of hotel rooms, providing marinas or harbours, coaches etc, and programs of visiting the places of interest of historic, artistic and recreational merits.
- The extension of the ship's service is aimed at maximization of effectiveness of the funds invested in the project in question.

## DESCRIPTION OF THE TOURIST TRIP ROUTE

The data concerning the technical parameters of Berlin-Królewiec (Kaliningrad) trip route are presented in Tab.1.

## SHIP'S HULL CONFIGURATION

It was decided to choice the ship's hull configuration in the form of a push train consisted of one-, two-, or several segments. The solution has a number of operational advantages in view of the considered waterway with many small-size sluices, narrow canals, and the very rich tourist program. As compared with one-segment ship the advantages of the selected solution justify the made choice – as the push train consisted of the pusher fitted with social and recreational facilities and the hotel segment, makes it possible:

- to fully use traffic capacity of the considered waterway limited by dimensions of its sluices and meander radiuses because the segment push train can be much longer than the usual ship, therefore passenger shipping capacity of the push train can be much greater
- to reach a much greater flexibility in scheduling the trips.

Among significant drawbacks of the stiff-connected push trains their sensitivity to damaging action of waves can be numbered. However the considered route of the ship concerns mainly river waterways of a low state of waving. And, the coupling of segments will be realized by applying the novel devices which make it possible to change geometry of the train coupling in three degrees of freedom (yaw, pitch, heave).

## ARCHITECTURAL AND FUNCTIONAL CONCEPT OF THE DESIGN

Results of the performed analyses and the description of the assumptions for the accepted functional concept of the ship, are included in [1,5]. From the design studies has resulted the ship (object) of the following characteristic features.

- A segment passenger ship comprising innovative engineering solutions, fitted with cabins and intended for inland waterways shipping; characteristic of a high care paid for ecological merits during ship service, providing for high voyaging comfort and living standard as well as personal safety for passengers; intended for multi-day holiday-recreational trips on Berlin-Królewiec route; consisted of one propulsion segment (pusher) and one (or several) pushed segment(-s) (hotel barges)
- The propulsion segment equipped with developed social and dining facilities, can be also used independently as a daytime excursion ship which makes strolling trips in the time when the hotel segment stays in a stage tourist base harbour, if only its owner deems such variant of the ship's operation justified
- The pushed segment, without any own propulsion system, fulfills hotel and recreational functions
- Such configuration of the ship in question makes it possible to flexibly arrange design solutions of the pushed segment (or segments) by using the same hull as a basis – if a need justified by the market arises – for realization of some special functions e.g. by adding a swimming pool, mud or brine bath facilities, solarium etc.

***Tab. 1.** Itinerary of the trip on Berlin-Królewiec (Kaliningrad) inland waterways route.*

| Section of waterway | from [km] | to [km] | Length [km] | Passing depth | | Sluices | | | Bridges | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | SNW [m] | SW [m] | Number [-] | Length [m] | Breadth [m] | Breadth [m] | Clearence [m] |
| **Variant I** | | | | | | | | | | |
| **Berlin-Havel-Oder river** | 0 | 90 | 90 | - | - | - | - | - | - | - |
| **Oder river - Cedynia - - Warthe river** | 90 | 140 | 50 | 1.40 | 2.50 | - | - | - | - | 5.33 |
| **Variant II** | | | | | | | | | | |
| **Berlin - Spree - - Canal** | 0 | 104 | 104 | - | - | - | - | - | - | - |
| **Oder - Warthe - Przybrzeg** | 104 | 167 | 63 | 1.40 | 2.50 | - | - | - | - | - |
| | | | | | | | | | | |
| **Przybrzeg - Warthe - - Noteć river** | 167 | 235 | 68 | 1.30 | 2.00 | - | - | - | 14.00 | 5.15 |
| **Free - flowing part of Noteć river** | 235 | 334 | 99 | 1.20 | 2.00 | - | - | - | 10.00 | 4.14 |
| **Canalized part of Noteć river** | 334 | 472 | 138 | 1.40 | 1.60 | 14 | 57.40 | 9.60 | 11.50 | 4.09 |
| **Bydgoszcz Canal** | 472 | 497 | 25 | 1.40 | 1.60 | 6 | 57.40 | 9.60 | 11.70 | 4.04 |
| **Canalized part of Brda river** | 497 | 511 | 14 | 1.40 | 1.80 | 2 | 57.40 | 9.60 | 10.85 | 3.87 |
| **Vistula river - Bydgoszcz - Toruń** | 511 | 553 | 42 | 1.00 | 1.20 | - | - | - | - | 5.17 |
| **Vistula - Włocławek (option)** | | | (57) | | | | | | | |
| **Vistula - Toruń - - Bydgoszcz** | 553 | 595 | 42 | | | | | | | |
| **Vistula - Bydgoszcz - - Nogat** | 595 | 747 | 152 | 1.80 | 3.10 | - | - | - | - | - |
| **Vistula - Nogat - - Gdańsk (option)** | | | (42) | | | | | | | |
| **Nogat - Jagellonian Canal** | 747 | 794 | 47 | 2.70 | 3.50 | 4 | 56.00 | 9.60 | 9.60 | 5.25 |
| **Vistula Bay -Królewiec (Kaliningrad)** | 794 | 844 | 50 | 2.70 | 2.70 | | | | | |

**Acronyms**
**SW – mean water state**
**SNW – mean - low water state**

- ➡ The proposed configuration of the passenger ship makes it possible to flexibly arrange service schedules of the push train – depending on current needs of its owner and an expected economic situation on the tourist traffic market
- ➡ It is assumed that during recreational trip the passengers will be able to make use of several stage land bases prepared to providing for and arranging attractive cultural and recreational events, deliveries necessary for continuation of trips, as well as receiving from ship the wastes to be utilized. Additionally, the passengers will be given opportunity to spend the night in the land hotel bases.

## SHIP'S HULL STRUCTURE AND ITS MANUFACTURING TECHNOLOGY

It is assumed that the steel hull structure of the ship will be manufactured with the use of the *HiTech panel technology based on the assemblies built of laser-welded flat sandwich structural elements. From the preliminary estimations it results that this is the only concept to obtain a very light ship hull structure which makes it possible to fulfill the assumed design task, acceptable in the technical and economical sense.*

This results from the condition of simultaneous fulfillment of the following limitations dealing with :

- ➲ the maximum permissible service draught equal to 1.0 m
- ➲ the maximum permissible total height of the ship
- ➲ expected commercial effects (incomes depend on a number of places in passenger cabins on the ship and offered living comfort)
- ➲ the ensuring of ecologically safe operation of the ship.

If the classic structural solutions and traditional technology were applied the ship in question having two-tier configuration satisfying the above mentioned technical requirements, would be practically infeasible, which results from the required minimum height of the passenger accommodations, limited maximum permissible total height of the ship, as well as due to excessively high depth of stiffeners of typical deck and bottom structures.

The hull structure made of panels constitutes a more favourable solution both in the structural – technological sense and in the sense of quantity of hull mass and ship displacement.

## SHIP'S POWER PLANT AND PROPULSION SYSTEM

Within the frame of the accepted research assumptions for the project in question the following solution variants of ship's propulsion system were selected for design study analysis, namely :

1. typical combustion engine propulsion system
2. combustion-electric engine propulsion system
3. combustion-hydraulic engine propulsion system
4. turbine-hydraulic engine jet propulsion system
5. an option of magnetic propulsion has been analyzed in advance.

The usefulness analysis of the variant solutions was aimed at providing the knowledge necessary to select an optimum solution of propulsion system for the designed ship under the accepted assumptions and assessment criteria. As a result of the comparative analyses the alternatives of variants 2 and 3


***Fig. 1.** Architectural concept of the segment ship „EUREKA" – in its tourist – hotel functional version.*

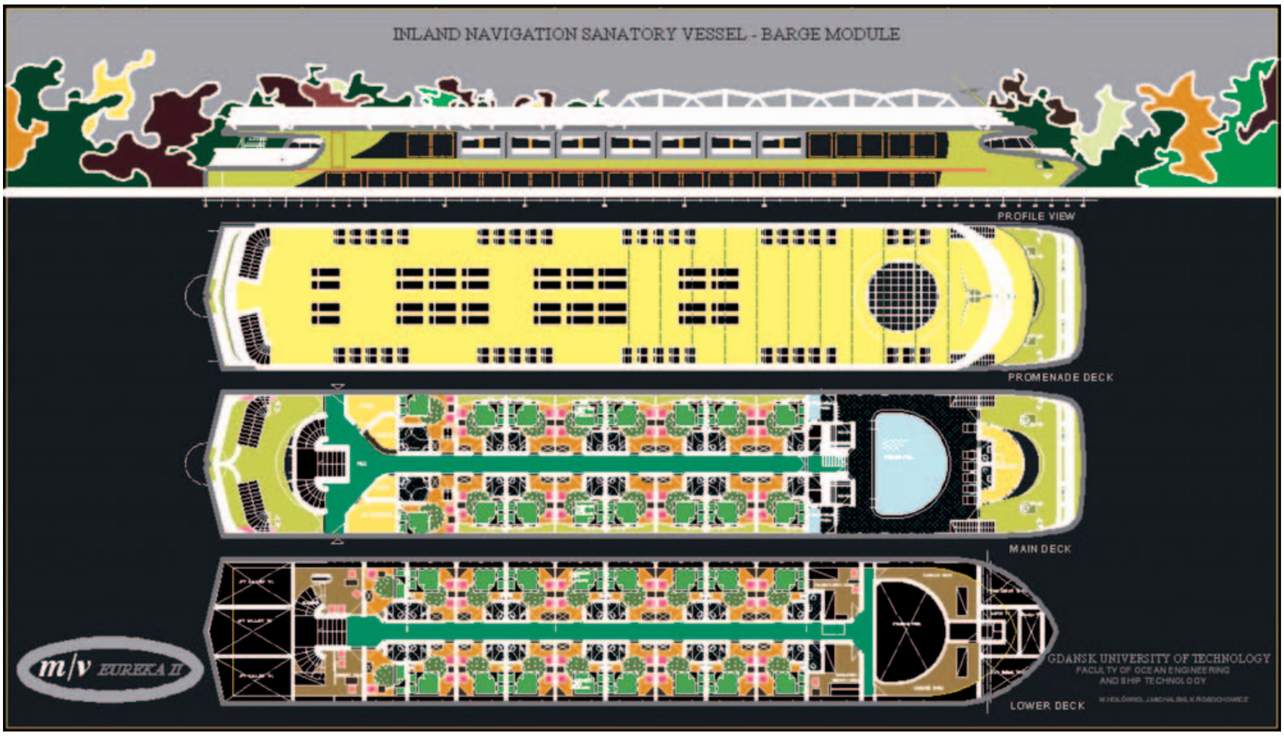


***Fig. 2.** Architectural concept of the segment barge of the ship „EUREKA II" – in its tourist – sanatorium functional version.*

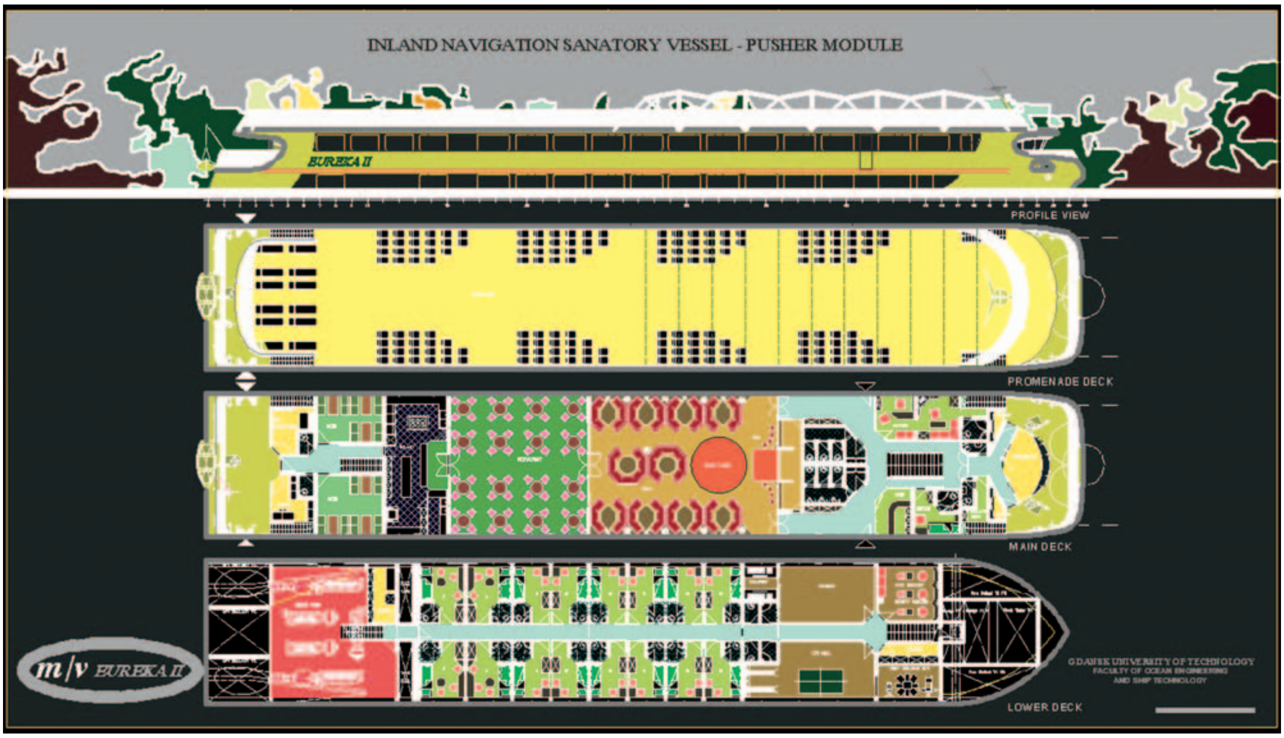


***Fig. 3.*** *Architectural concept of the pusher of the ship „EUREKA II" – in its tourist – sanatorium functional version.*

have been finally deemed the most promising. It is expected that the ecological aspect of the ship's operation will constitute an important element of usefulness measures applied to the selected variants of propulsion system.

In view of the small draught of the ship and necessity of ensuring good manoeuvrability qualities for the push train, it was decided to apply two fixed screw propellers ducted in rotatable Kort's nozzles and fitted with reversing devices or the propulsion system with two vertical-axis propellers of pod type. The selection of the fixed screw propellers was based on the service experience gained by Polish inland navigation ship owners [6], that is mainly associated with good reliability, low production cost and easiness of repair (many failures due to ship stranding) of such propellers.

In the bow part of the barge a thruster has to be installed. Within the frame of the considered design variants of the ship's propulsion system, preliminary analyses of feasibility, rationality and profitability of application of ecological combustion engines working on alternative fuels, i.e. bio-fuel, LPG or LNG, were made.

## SUMMARY

- The technical, functional and operational assumptions presented in this work concerning the passenger ship intended for making comfort tourist trips along attractive Polish inland waterways, ensure – to a potential tourist – an opportunity to commune with nature of unique worldwide merits. There are many premises that the project, if appropriately supported and inspired, may turn out a hit in the sense of investment, economy and politics
- The elaborated design study made it possible to identify possible drawbacks of the preliminarily taken decisions concerning the functional program of the ship's service, and it also helped in verifying the technical design assumptions for the ship; their further analysis planned to be carried out along with development of the research and design work, constitutes a subject of the further research realized within the scope of the project
- A fortnight round trip variant was presented. In another variant the ship's operator can offer one-way trips combined with coach transport of passengers. Final choice of a concept of operation of the ship and scheduling its trips will depend on demand for such services called on the tourist market of EU countries.

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# Current state of the waterway along the Warta and Noteć Rivers

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ABSTRACT

*In June 2004 took place an inspection trip aimed at assessing current state of the east-west waterway connecting the Odra and Wisła Rivers; during the trip a photographic documentation of the region was made as well. The below presented text contains also some conclusions resulting from the trip.*

**Keywords** : waterway, the Warta River, the Noteć River.

## GENERAL CHARACTERISTICS

The waterway of the Warta and Noteć rivers can be divided into three characteristic parts. The first of them contains the Lower Noteć from its estuary to the Warta at Santok up to Bydgoszcz Canal, then the Bydgoszcz Canal itself and a part of the Brda up to its estuary to the Wisła. The waterway goes partly along the freely flowing river and partly along the canalized river, it contains 22 chamber sluices of 9.6 m in breadth (including one of 9.1 m only), driven by hand or electric motors, and having the passage depth not less than 1.2 m.

The second part of the waterway contains the connection between the Lower Noteć and the Warta in the region of Konin – via the Upper Noteć Canal, the canalized Upper Noteć, the Gopło Lake and the Ślesin Canal. This part of the waterway contains 12 electrically driven chamber sluices of 9.6 m in breadth, located along the Ślesin Canal, and those hand-driven of 4.9 m in breadth, located in the Upper Noteć region. The passage depths of the particular sections vary from 1.8 m in the Gopło Lake, through 1.3 m in the Ślesin Canal to 0.8 m in the remaining sections.

The third part of the waterway contains the navigable part of the Warta, i.e. from the Ślesin Canal to the Warta estuary to the Odra nearby Kostrzyń. The waterway goes along the freely flowing river of passage depths as small as 0.5 m in some sections.

## WATERWAY FACILITIES

Currently all the sluices of the waterway in question and the weirs associated with them are serviceable and well maintained, however it mainly concerns the outer elements whose maintenance does not require any great financial outlays, whereas structural parts of some sluices have been found in a worse state. Families which operate particular sluices compete with each other in maintaining the area of their responsibility in the best appearance (Photo 1).

Much worse situation is with harbours and terminals as they are today practically unserviceable along the whole waterway. An exception is the well-maintained loading quay of the glassworks in Ujście, terminal at Santok upon the Lower Noteć, as well as the well- maintained and equipped terminal at Skwierzyn upon the Warta (Photo 2). Only a few harbour basins operate - such as that of the inland shipyard at Czarnków,

**Photo 1.** *(J. Kulczyk, R. Werszko) Sluice no. 2 – Łabiszyn at the Upper Noteć, Headquarter of Waterway Supervision Office. At the sluice outer harbour an illuminated bivouac site with a bonfire place, tap water source, electric supply terminal and WC can be seen .*

**Photo 2.** *(J. Kulczyk, R. Werszko) The terminal in Skwierzyn upon the Warta, fitted with a tap water source, electric supply terminal, a nearby located hotel with restaurant and car parking place. On the opposite side a municipal promenade .*

belonging to Bydgoszcz Shipping Company, or the winter stay for inland navigation barges at Krzyż. Many terminals are devastated, overgrown and deprived from mooring devices (Photo 3), and some of them should be presently deemed not existing at all. Harbour terrains in Poznań have been handed over for development of residential buildings, this way the city has been deprived from any possibility of receiving greater floating units. Moreover there is no real terminal equipped with any basic infrastructure.

***Photo 3.*** *(J. Kulczyk, R. Werszko) The devastated terminal in Oborniki upon the Warta .*

## OBSTACLES FOR NAVIGATION

Almost all navigational obstacles are associated with a low water depth state (Photo 4). Lack of water in rivers, especially in summer, is associated with the general hydrological situation in this part of Europe, which today has a permanent character. This leads to appearing very shallow places which limit the passage depth for an entire waterway section even to 0.5 m that actually makes cargo shipping impossible and leaves the waterway useful to tourist shipping only. A section particularly shallow and difficult for navigation is the navigable part of the Upper Warta – beginning from the Prosna estuary to its inlet to the Ślesin Canal.

***Photo 4.*** *(J. Kulczyk, R. Werszko) A shoal patch of about 1-1.2 m water depth and many erratic boulders resting on the river bed section of some kilometers in length and located close to Puszczykowo upon the Warta. A crew member is heaving the lead and showing its result to the ship master .*

## SHOAL PATCHES

All estuaries of rivers, drainage ditches and even small natural streams constitute places of difficulty in navigating because of drifting the sediments and building the shoal patches in the area of estuaries. For many years no dredging work has been carried out in such places.

Sewage discharge points constitute a separate problem. Sewage treatment and discharge systems are usually equipped with sedimentation tanks whose task is to reduce quantity of sediments brought into the river. They should be regularly cleaned. However as a rule they are not cleaned at all or from time to time only, especially in the case of less important or "forgotten" systems. In consequence, a superfluous quantity of sediments is brought into the river and a shoal patch appears in that point.

## REPAIR OF BRIDGES

A next difficulty is the way of carrying out repairs of bridges and other structures in a direct vicinity of the waterway, namely without taking into account shipping traffic needs. During the inspection trip a repair of the road bridge over the Upper Noteć Canal, on the Bydgoszcz - Poznań route, has been carried out. The erected scaffoldings significantly limited the clearance under the bridge, which made it necessary to disassemble the ship's signal devices and aerials protruding over the wheelhouse deck of the ship. In the case of only a little higher water level, to pass under the bridge would not be possible at all.

Also, drainage pipes ranging by more than 0.5 m below the bottom of the bridge span may endanger ship safety. Repair work on other bridges in that region is carried out in a similar way and also similarly dangerous drainage pipes are installed there (Photo 5).

***Photo 5.*** *(J. Kulczyk, R. Werszko) A repair of the road bridge over the Upper Noteć Canal. The changes being introduced during the repair work are expected rather to remove the existing obstacles for ship traffic than to cause more troubles .*

After-repair remains constitute an important problem. During the trip, almost under every bridge one finds rubble, often a piece of reinforced concrete with protruding steel rods, abandoned bank-strengthening concrete plates, or remnants of old bridgeheads. All the building remains significantly endanger ship traffic. It also happens that when a repair work of a road close to a bridge is conducted, things come to such a point that non - strengthened road shoulders are washed out due to rainfall and a large quantity of aggregate falls into a river or canal forming this way a dangerous local shoal patch.

## WASTES ON WATERWAY BED

Horrifying is the practice of throwing away various wastes into a canal or river. On their bed one can find very different things (car tires, refrigerators, baby cars, beds, buckets, vessels, sanitary ceramics) which landed there, but not in wastes storage places instead, due to a non-responsible activity of dwellers of villages and cities located nearby rivers and canals. The ecological awareness of a part of society is very low, transport of the wastes of a greater size to wastes storing places – costly and troublesome, and the fear for being caught in the act or finding guilty by police is practically absent – such precedences are not reported. Pollution of rivers and canals with various wastes is an identical phenomenon as an illegal dump of wastes, which lately becomes more and more common and troublesome.

The pollution events concern also industrial enterprises located nearby waterways. The wastes lingering on the bed of the Upper Noteć in the area of Inowrocław, which have the form of a section of electric energy cable insulation coating of several kilometers in length, and thrown away probably by „Soda Ciech" Chemical Works, Mątwy, constitute a great hazard for screw-propelled ships as the insulation coating could be wrapped around the screw propellers under action. According to available reports, almost every ship voyage along this part of waterway has been associated with such event.

## VEGETATION

Removing excessive vegetation out of waterway is a controversial issue. The most serious phenomenon occurring in water reservoirs is their accelerated eutrophication. It consists in enriching the water in reservoirs with nitrogen and phosphor compounds contained mainly in discharged sewage and fertilizing means applied to arable fields. It results in a more intensive growing process of plants, especially algae, and plankton, as well as in a disturbance of oxygen equilibrium mainly in demersal areas where descending dead organisms undergo decay. It may even lead to complete disappearance of oxygen in demersal layers of water in a reservoir and to start up oxygen-free processes associated with emission of hydrogen sulfide, methane and other noxious substances. Green plants contribute to favourable increase of oxygen content in water but their dead parts also to eutrophication.

From the point of view of ship traffic an excessive quantity of plants overgrowing the waterway constitutes an obstacle (Photo 6). It causes disintegration and devastation of bank walls and water structures, an increase of ship resistance and it makes ship manoeuvring more difficult. Water plants, if wound around screw propeller, lead also to propulsion efficiency dropping and ship engine overloading, and clogging up the water inlet to cooling system, that may result in a serious failure.

***Photo 6.*** *(J. Kulczyk, R. Werszko) The overgrown outer harbour of Sluice no. 4 at Frydrychowo upon the Upper Noteć Canal .*

In an extreme case, an excess of water plants may stop ship traffic at all. It also makes water economy running more difficult. In the case of intensively overgrown sections of rivers, opening the weirs does not lead to a fast and satisfying change of water level.

Another obstacle are the trees growing near the river banks, whose crowns sometimes are able to decrease breadth of waterway even by a half (Photo 7). Catching on tree branches generates a hazard for ship crews working on the deck; it may also cause a damage of protruding parts of the ship, e.g. signal devices or aerials. In consequence of scouring the trees growing at the river banks also their upsetting into the river may happen, that constitutes even a greater hazard – a failure to ship's hull, rudder or propeller in the case of running onto an immersed trunk invisible. The upset trees may also cause a blockage of waterway for some time until the obstacle is removed.

***Photo 7.*** *(J. Kulczyk, R. Werszko) The crowns of the trees growing just on the river bank limit the waterway breadth in many places. Such waterway sections are attractive for tourists, but dangerous for ship traffic .*

## INFRASTRUCTURE

Along the entire Warta–Noteć waterway any, even only basic, sanitary infrastructure is practically lacking. The necessary minimum thing is clean, maintained, accessible all the day through, toilets located close to mooring terminals (if they are substandard they will be not used at all), points for discharging the sewage from chemical toilets, and baskets for sacks with garbage from ships or yachts. Also, tap water points and freely accessible showers are needed.

## PROSPECTS OF USING THE WATERWAY

The lack of necessary actions to properly maintain the waterway is justified by insufficient funds. In any case their increasing should not be expected because of a slender use of the Warta – Noteć waterway for cargo shipping which has probably gone to the past at all. It results from low parameters of the waterway, first of all its insufficient passage depth in many sections, highly run-down or completely devastated cargo terminals in which any cargo handling is now not possible, as well as a lack of modern floating units profitable in service. In consequence, there is no organization interested in commercial use of the waterway, to say nothing of any investment in this range.

Nonetheless the Warta–Noteć waterway is characteristic of exceptional tourist merits. Unpolluted, almost wild nature in many areas, neighborhood of the Noteć Primeaval Forests, sites of birds and rare animals, e.g. beavers, unique landscapes, charming hand-operated sluices or historical monuments nearby located, rank the waterway as one of the unique in Europe. However in order to make it serviceable for tourist purposes the waterway should be fitted with an appropriate infrastructure, first of all sanitary one. Moreover, comprehensive publications –guide books for traveling along the waterway, concerning both its merits and obstacles possible to be met in particular its sections, and containing all practical information necessary for travelers, should be easily available.

# Waterway of the Middle Vistula (Wisła) and the Bug

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ABSTRACT

*In this paper was characterized the fragment of the east-west waterway from Płock to Terespol, composed of the section of the Vistula measured from 633rd kilometer (the backwater end of Włocławek Reservoir) to 520th km (Warsaw), Żerań Canal including a fragment of Zegrze Reservoir and the lower part of the Bug up to 282nd km (Terespol). Hydrological and geomorphologic conditions of both sections of the river--beds and the state of their regulation infrastructure were presented in the aspect of existing navigation conditions and causes of their limitations. It was stated that both the river-beds, i.e of the Vistula and the Bug over their analyzed sections, have not fulfilled the requirements determined by the waterway classification standards.*

**Keywords** : shipping, inland waterways

## GENERAL CHARACTERISTICS

The waterway of the Middle Vistula and the Bug is composed of the section of the Vistula from Płock (633rd kilometer at the backwater end of Włocławek Reservoir) to Warsaw (520th km), next Żerań Canal including a fragment of Zegrze Reservoir, and further – the Bug from its estuary (0th km) up to Terespol (282nd km). From Niemirów (224th km) to Terespol the Bug is a border river.

From hydro-morphologic point of view the sections of both rivers have a lowland character. However they differ to each other by a character of the upper part of river basin. The Bug has, in its basin, many marshes and old drainage areas filled with water, whereas most tributaries of the Vistula bring water from higher located terrains of low retention – uplands and mountains. From that result the differences in flow rates and variations of water level in the stream-ways of both the rivers (Tab. 1 and 2).

***Tab. 1.*** *Characteristic flow rates calculated for the period of 1961-1983 year, acc. [Report 2006] .*

| | | | | | For hydrological year of the 1961-1983 - year period [m³/s] | | | | | For shipping season of the 1961-1983 - year period [m³/s] | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | River | River gauge | km | Drainage area – km² | NNQ | SNQ | SSQ | SWQ | WWQ | $NNQ_{ż}$ | $SNQ_{ż}$ | $SSQ_{ż}$ | $SWQ_{ż}$ | $WWQ_{ż}$ |
| 1 | Bug | Włodawa | 378.3 | 14410 | 8 | 18 | 63 | 320 | 750 | 9 | 23 | 50 | 125 | 312 |
| 2 | Bug | Frankopol | 163.2 | 31336 | 21 | 43 | 134 | 546 | 1410 | 21 | 53 | 104 | 258 | 534 |
| 3 | Bug | Wyszków | 34.8 | 39119 | 19 | 55 | 178 | 777 | 2400 | 29 | 67 | 134 | 353 | 753 |
| 4 | Wisła | Warszawa | 513.3 | 84857 | 102 | 217 | 619 | 2755 | 5470 | 169 | 280 | 574 | 2156 | 5470 |
| 5 | Wisła | Kępa Polska | 606.5 | 168957 | 102 | 340 | 1014 | 3893 | 6730 | 249 | 426 | 877 | 261 | 6730 |

NNQ – the smallest flow rate recorded during an observation period
SNQ – mean flow rate calculated form the yearly lowest records during an observation period
SSQ – mean flow rate for an observation period
SWQ – mean flow rate calculated form the yearly highest records during an observation period
WWQ – the largest flow rate recorded during an observation period

The above given symbols but having the index „ż" stand for the respective values reduced (related) to the yearly navigation period.

***Tab. 2.*** *Water level variations acc. [IMGW 1997] .*

| No. | River | River gauge | Warning state (SO) | SSH state | State variation amplitude | Difference between SO and SSH | Difference between SSH and SNH |
|---|---|---|---|---|---|---|---|
| 1 | Bug | Włodawa | 250 | 163 | 4.4 | 1.0 | 0.7 |
| 2 | Bug | Frankopol | 250 | 154 | 4.9 | 1.0 | 0.8 |
| 3 | Bug | Wyszków | 400 | 262 | 5.1 | 1.4 | 0.9 |
| 4 | Wisła | Warszawa | 600 | 243 | 8.0 | 2.8 | 1.0 |
| 5 | Wisła | Kępa Polska | 420 | 268 | 5.4 | 1.5 | 1.0 |

SO – the water state established by the administration, exceedance of which triggers procedures of readiness for anti-flooding protection; it generally corresponds with bank-full stage.
SSH – mean state for an observation period
SNH – mean state calculated from the yearly lowest records during an observation period

## GEOMORPHOLOGY OF THE RIVER-BEDS

Between Dęblin and Włocławek the Vistula flows through the terrains belonging to Mazowsze Lowland. The Lowland's though is filled with Tertiary formations covered by boulder clays and glacial gravels as well as Pleistocene marginal-lake silts. The formations are highly disturbed. Alluvial formations of the today Vistula are not very thick hence on the river-bed almost non-washable strata may appear. In the work [Hydroprojekt 1982] the following regions of possible appearance of non-washable thresholds are specified : 515$^{th}$ km ÷ 519$^{th}$ km, 522$^{nd}$ km ÷ 523.5$^{th}$ km, 562$^{nd}$ km ÷ 567$^{th}$ km, 575$^{th}$ km ÷ 577$^{th}$ km, 583$^{rd}$ km ÷ 589$^{th}$ km, 595.5$^{th}$ km ÷ 598$^{th}$ km, 617$^{th}$ km ÷ 620.5$^{th}$ km, 622$^{nd}$ km ÷ 626.5$^{th}$ km. In Warsaw, in the region of the inlet to Żerań Canal the alluvial formations were completely washed out due to excessively large narrowing the high-water stream-way, dense regulation infrastructure as well as excessive sand mining for building industry purposes. At the mean-low water states paving stones protrude water level in the middle part of the stream-way.

From some research it results that over 300 years ago the Vistula river-bed down Warsaw was much more compact. Changes in developing the river basin made surface and ground retention decreasing. It led to an increased rubble flow from drainage area and starting the process of river-bed wild running which has been continued till today [Falkowski 1989, Monograph 1982]. In many places the Vistula flows around large islands on which farm buildings are located [Przewodnik 1967]. A part of the islands were cut off the main river-bed by means of embankments. The rest of farm buildings remaining within the embankments were moved outside them.

In the region of Warsaw from 501$^{st}$ km to 522$^{nd}$ km the Vistula is completely regulated on both banks. Whereas down the river up to Włocławek Reservoir the regulation infrastructure appears only in the region of bridges, as well as in order to limit bank erosion developing. It is generally one - bank strengthening or local one along short sections of both banks of the river, which often are substantially damaged.

Lack of funds for systematic overhauls, lasting 25 years, has led to devastation of bodies of longitudinal protecting groynes and almost complete destruction of most transverse repelling spurs, from which only small fragments remained. The buildings are not capable of stabilizing the main-stream position and improving navigation conditions, sometimes in reverse – their rests located in the main-stream constitute a serious hazard to shipping (Fig.1). Changes of the main stream-way position happen after every larger freshet as well as ice run-off.

***Fig. 1.** Remainder of regulation infrastructure in the main stream-way of the Vistula (Wisła) .*

**In the existing river-bed several characteristic situations can be distinguished** :

***1) The river-bed is divided by high islands into several side arms of similar widths***

In the period of occurrence of mean and high water flow rates one of the arms is dominating. It leads not only a substantial part of water flow but also prevailing amount of traction. At water states lower than mean energy of water is too small and the traction in the dominating arm rapidly drops and complex macro-folds appear to be obstacles for flowing water. The water flow then passes into one of the side arms often developed by means of a system of wing dams or transverse repelling spurs. Such situation exists e.g. in the region of Czerwińsk and Raków. Fast destruction of these buildings may then occur and on the bed sudden upheavals and deep scours may alternately appear, especially close to remainders of foundations of such buildings. Scours due to such obstacles can be compared with those created below bridge pier protections.

The remaining arms contain many chaotically spread sand outwashes of various heights. A part of them, protruding water-level, remains motionless, and other ones still but slowly change their planar location and affect local slopes of water-level.

***2) Between the islands there is a wide arm which maintains its dominating role in water flowing and rubble traction at water-level states below the mean***

Then in the central part of the river-bed systematic accumulation of tracted rubble starts to occur, gradually covering larger and larger part of the width of the bed's cross-section and shifting the flowing water together with a part of the rubble material towards the banks. Along with water-level sloping larger and larger areas of low sandy islands emerge and narrow and deep beds similar to "chutes" appear close to the banks. In some cases water inflow to a "chute" occurs laterally to the bank (Fig.2).

***Fig. 2.** Lateral transition of the stream-way towards the river bank .*

They appear near one or both banks, depending on local morphological conditions.

After passing-by the emerged sandy outwash the "chutes" gradually become wider and shallower and the stream-way comes back to the central zone of the river-bed. In such places no such sudden changes of the stream-way direction as those before the obstacle, are observed.

***3) The river-bed without high islands***

In the river-bed many macro-folds left by high waters and transformed during water-level sloping, occur. Two situations can happen : the first when the central zone of the river-bed becomes shallow and the "chutes" at the banks appear, and the other when – in reverse – the zones near the banks become shallow and the deeper portions appear in the central zone of the river-bed. The bed's morphology is generally similar to that in the situation with the dominating arm, described in 2).

***Fig. 3.** The edge of the macro-fold along the firm river-bed section of the Vistula (Wisła).*

Compensated water-level slopes of the Vistula vary insignificantly and amount to : from Warsaw down to the inlet of the Narew (551th km) – about 0.23 ‰, and further – about 0.19 ‰.

Geomorphology of the Bug valley is associated with the Middle-Poland glaciation and its further stages. In consequence, in the region of Mielnik and Niemirów, in the zone of uplifted chains of end moraines, appeared a fissure in which the huge bed-deposited layers of cobbles and boulders constitute the erosion boundary for subterranean river. The moraine cobble roof found also in other places, deposited just under the alluvial formations, constitutes the absolute boundary for subterranean erosion. In many places the alluvial formations were washed out and the moraine cobbles can be there found uncovered in the form of stone reefs and boulders. In the work [Report 2005] the following places of the kind are specified : 43$^{rd}$ km ÷45.5$^{th}$ km, Brańszczyk, Nakiel, Kamieńczyk, 67$^{th}$ km ÷68$^{th}$ km, 103$^{rd}$ km, 107$^{th}$ km, 110$^{th}$ km, 133$^{rd}$ km, 135$^{th}$ km ÷136$^{th}$ km, 145$^{th}$ km, 151$^{st}$ km, and 195$^{th}$ km.

Evolution of many sections of the Bug valley led to creation of the elements constraining the course of the river-bed and limiting free changes of its developing. These are the sections of the so called ripe constrained river (not winding its way despite many bends and curves). An example of such form is the fragment of the valley between Drohiczyn and Nur and that in the vicinity of Wólka Nadburzańska (surroundings of Siemiatycze) where the outcroppings of almost non-washable ground, i.e. moraine cobbles and rocky morass ore, appear a constraining factor. Another factor constraining development of the Bug river-bed are the sand dunes commonly found along the whole length of the middle and lower section of the river's valley.

Over its prevailing length the Bug shows the features of winding river. A degree of development of course of a river, including its particular bends, is conditioned by geological structure of its bed and geomorphology of the valley. From its winding character erosion of its banks result in many places. The erosion process lasts the whole year and specially intensifies in the time of spring water run-off. In such case position of the waterway may change each year as ice jamming often happen during ice drifting. The clogged water finds its outlet in the side arm making it deeper. This way a section of relatively deep river-bed of a limited width, is formed. Water-level slopes along the considered section of the Bug change insignificantly and range from 0.21 ‰ to 0.25 ‰. Only the initial section of the Bug, about 50 km long, from the side of the State border, has much smaller slope amounting to 0.15 ‰. The next so small water-level slope appears only at the inlet to Zegrze Reservoir.

The Bug is generally non-regulated. Only its sections from 9$^{th}$ km to 18$^{th}$ km and from 25$^{th}$ km to 35$^{th}$ km have been fully regulated. The regulating infrastructure along other fragments of the river-bed is aimed at stabilizing the banks near bridges, or fulfils the role of local bank protection, especially against intensive side erosion. However most of the buildings is devastated to a large extent.

## NAVIGATION CONDITIONS

In the decree of the Council of Ministers, dated 07.05.2002, the Vistula along the considered section has been classified to Class Ib, and the Bug – to Class Ia.

Dimensions of the waterway of Class Ib should be equal at least to :

- 20 m – width measured at the bottom of fully loaded floating object
- 1.6 m – transit water depth
- 200 m – radius of waterway bend axis.

The maximum main dimensions of floating objects amount to :

- length – 41 m
- breadth – 4.7 m
- draught – 1.4 m.

The data for the Vistula between Warszawa and Toruń, published in the 1950s [Tablice 1958] showed the transit water depths of 90 cm at the mean – low state lasting – together with the higher states - for about 80% of the navigation period, and of 110 cm at the mean state lasting – together with the higher states – for about 50 % of that period.

The data published in 1968 [Studia i materiały RNET 1968] showed the transit water depth of 1.0 m at the mean – low state for the Vistula between Warszawa and Toruń. In its stream-way appeared shoals of almost steady location, which required to be dredged. Between Czerwińsk (578$^{th}$ km) and Płock (631$^{st}$ km) nine shoals including the two decreasing water depth to 75 cm, were then found.

The partial regulating works carried out beneath the Narew outlet in the places difficult for navigation, made it possible to reach the water depth of 1 m at the mean-low state.

Bathometric measurements performed in 2004 revealed only three places of the water depth of 40 cm, a dozen or so meters long. Sections of 55 cm water depth were often found, their length did not however exceed 100 m. The shoal patches constituted fragments of the macro-folds on the surface of which intensive folding movement of traction material occurred despite a low water state. Surface of such bed is mild hence not leading to any failure to ship hull or its propelling devices. However it may be impossible for a ship of 1.4 m draught to pass over such long shoal patch, without any appropriate water depth margin at the yearly mean water state.

In Rakowo (596$^{th}$ km) the main river-bed in the period of low water states is not navigable. In 2005 in the period of water depths lower by about 15 – 20 cm than that yearly mean the smallest depth amounted to 45 cm. To sail this section over is possible only through the right-hand arm of the river, crossing over the damaged wing dams. The increased velocity of water in that river arm is an additional difficulty for navigation. The measured surface velocity amounted to over 1 m/s. The so distinct worsening of navigation conditions as compared with the state from before a few dozen of years, results from a large degree of devastation of regulation infrastructure. Along the considered section of the Vistula no problems resulting from the magnitude of bend radius and waterway width can be expected.

In the present state of the Vistula river-bed
it is hard to determine a radius of the waterway.

From approximate estimations
it can be assumed not smaller than 500 m.

Żerań Canal which connects the Vistula with Zegrze Reservoir, is 17.3 km long. Its depth amounts to 3.0 m at the normal backwater level in Zegrze Reservoir. Usual variations of water-level in the reservoir are equal to 0.5 m, its depth then drops to 2.5 m. The Canal is 25 m wide at the bottom. From the side of the Vistula it is closed by a sluice of the dimensions : 85 m length of the lock, 12 m serviceable width, and 3.0 m water depth at the upper threshold. The depth at the lower threshold of the sluice depends on water state in the Vistula [Materiały 2001].

Minimum dimensions of the waterway of the Class Ia
to which the Bug belongs, were determined as follows :

- its width measured at the bottom of fully loaded floating object – 15 m;
- its transit water depth – 1.2 m;
- bend axis radius of waterway– 100 m.

The maximum main dimensions
of floating objects amount to :

- length – 24 m
- breadth – 3.5 m
- draught – 1.0 m.

The data published in the 1950s [Tablice 1958] and in 1968 [Studia i materiały RNET 1968] showed the transit water depths in the range from 0.8 m to 1.0 m at the yearly mean water state. The measurements performed in 2005 at the water level state higher by about 40 cm than the yearly mean, showed, after correction, the decrease of the transit water depth to 0.5m – 0.6 m. Results of the investigations performed ten days later at the water states higher by only about 15 cm than the yearly mean, confirmed the above presented results. The most difficult place for sailing is the section of the river-bed in the vicinity of Granne ($144^{th}$ km ÷ $145^{th}$ km) in the place of the change (break) of the overall longitudinal rate of descent of the river on the outcropping of the almost non-washable grounds, located there.

The equalizing process of the river-bed during water state
dropping, probably would improve water depth conditions,
however a decrease of transit depth is obvious.

An important limitation for navigation on the Bug are curvature radiuses of the waterway. Taking into account the river bank curvatures one can expect the smallest radiuses to have about 100 m. On the bends of large curvatures the waterway width can be decreased – due to flow concentration – even to 15 ÷ 20 m (Fig.4). And, relatively favourable navigation conditions are observed along eroded banks. The stream –way is shifted towards the concave bank and only fallen-down trees can constitute an obstacle. In many cases the minimum width of the Bug waterway and its minimum radius can amount to a somewhat smaller values that those required by the rules.
Floating objects should then reduce its speed.

***Fig. 4.*** *A typical course of the Bug river- bed .*

A decisive limitation of navigation on the Bug waterway is its transit depth which – even at the yearly mean flow rate – is smaller than that required by the rules for Class Ia. Because of many stony reefs, traffic of ships at the minimum water depth
margins under the bottom equal to 20 cm,
can be very dangerous.

Though in the information materials [Informator 1961] the highest navigable water-level is given higher than the warning state, these authors have assumed that navigation will be continued only at the water-level contained within the river banks. Number of islands located in the main river-bed both of the Vistula and the Bug makes navigation at the higher water states
more hazardous (Fig.5).

***Fig. 5.*** *Mark signing the cape of the island on the Bug waterway .*

## SUMMARY AND CONCLUSIONS

- After over 50- year break in using the river-beds for shipping purposes, both the Vistula (Wisła) and the Bug lost their former, not very high values of waterway parameters as a result of devastation of their then regulation infrastructure, and uncontrolled processes of river-bed forming
- Many deposits of stones in the form of natural reefs on the beds of both the rivers and damaged regulation buildings constitute a significant obstacle and hazard to navigation
- A more detail marking of both the Vistula and the Bug waterways is necessary in the case of intensive – or at least regular – ship traffic on the considered waterways.

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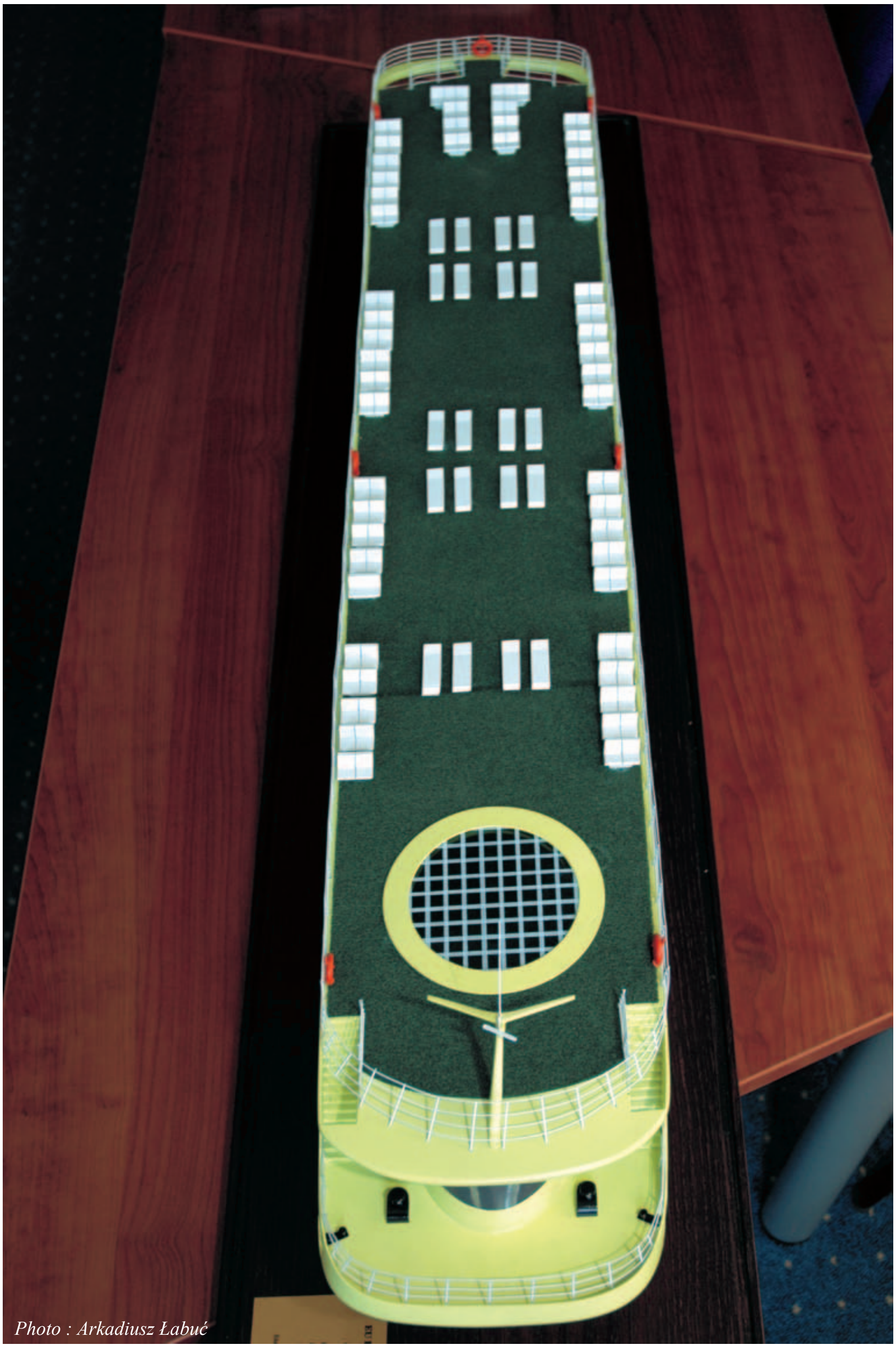

Photo : Arkadiusz Łabuć

# Ecological aspects of the river Bug waterway

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ABSTRACT

*The Bug valley from the State border, i.e. from Niemirów all the way to the Zegrze Reservoir is subjected - due to its unique natural and landscape merits –to different forms of nature preservation such as reserves, landscape parks, and has been included into the European system of preserved areas "Natura 2000". The natural resources can contribute to development of the region by intensification of tourism, on the other hand it can lead to a limitation of potential economical use of the Bug as a shipping waterway. This paper presents ecological and hydro-morphological conditions of the region and a proposal of intensification of tourist activities along the waterway, and variants of tourist servicing, which would not be in contradiction with the present forms of nature preservation applied to the Bug valley.*

**Keywords** : ecological tourism, Natura 2000.

## GEO-MORPHOLOGICAL CHARACTERISTICS OF THE BUG VALLEY

The form and geo-morphology of the Bug valley in its lower course between the end of the border section at Niemirów (207$^{th}$ km) and its inlet to Zegrze Reservoir were conditioned to a large extent by the Middle -Poland glaciation processes. The valley formed after glacier retreat, consisted of after-melting sections and the connecting erosion - built sections [Falkowski 2003]. The valley is built of diluvial sands covered in places by alluvial deposits. The valley bottom is occupied by a wide flooding terrace, and the sandy above-flooding terrace ascends 4- 8 m higher than the mean water-level of the river [Mierkiewicz, Sasim 2003].

Width of the valley gradually increases from several kilometers in the border section up to a dozen or so km at the inlet, except for the mentioned connecting sections which presently have a character of gorges, and constitute narrowing zones of the valley. The sections are characterized by greater slopes, and in the bed area appear formations of alluvial ground which build almost non-washable thresholds. In the region of Mielnik the valley crosses through the zone of Warta glaciation end moraines. The depth of valley incision into surrounding uplands reaches from 30 m to 60 m [Kondracki 2000].

The river-bed, though having many bends and curvatures, is only to some extent a winding bed due to limiting outcrops of almost non-washable formations, mainly residual cobbles and rocky morass ores.

Along its considered section the Bug is a lowland river having slopes from 0.19 ‰ to 0.10 ‰. Icing phenomena start usually from the beginning of December and last till 2$^{nd}$ decade of March.

## FORMS OF NATURE PRESERVATION IN THE BUG VALLEY

The basis of the policy of all European countries including Poland constitute : care of natural resources, preservation of nature merits being national resources, and economy management in compliance with the principles of balanced development. According to the Act on environment preservation (of 16 April 2004, Dz. U. 04.92.880) the aims of nature preservation are a.o. the following : the maintaining of ecological processes and stability of ecosystems, maintaining of biological variety, as well as the ensuring of continuous existence of species of plants, animals and fungi together with their sites. These aims are realized a.o. by taking into account the nature preservation demands in planning documents associated with site planning and development, as well as the introducing of various preservation forms to resources, formations and components of the nature.

Due to the unique natural and sightseeing merits of the Bug and its valley almost its entire considered section is subject to various forms of nature preservation (Fig.1). The areas most valuable from the point of view of natural merits and the least transformed ones were subjected to the reserve form of preservation. The reserves were established in order to preserve fragments of the forests along the Bug valley (Jegiel, Łęg Dębowy, Przekop), natural sites of plants including the protected species of stenothermal plants (Kózki, Skarpa Mołożewska, Szwajcaria Podlaska) as well as breeding standings and winter quarters of water fowl (Wydma Mołożewska).

The merits of the Bug valley which is only slightly transformed, with the river of winding bed, many islands, shoals, beautiful cliffs and old river beds, as well as the merits of the natural and cultural landscape of Podlasie region are subjected to the preservation within the frame of the landscape park "Podlaski Przełom Bugu" (Podlasie Gorge of the Bug), "Nadbużański Park Krajobrazowy" (Bug Landscape Park), as well as Nadbużański Obszar Chronionego Krajobrazu (Bug Area of Protected Landscape) (www.npk.pl, www.podlaskiprzelombugu.pl).

The Bug valley has been also included into the European system of preserved areas "Natura 2000" whose aim is to ensure permanent existence of European flora and fauna, preservation of valuable, endangered natural standings, as well as integration of nature preservation with human activity [Simonides 2003].

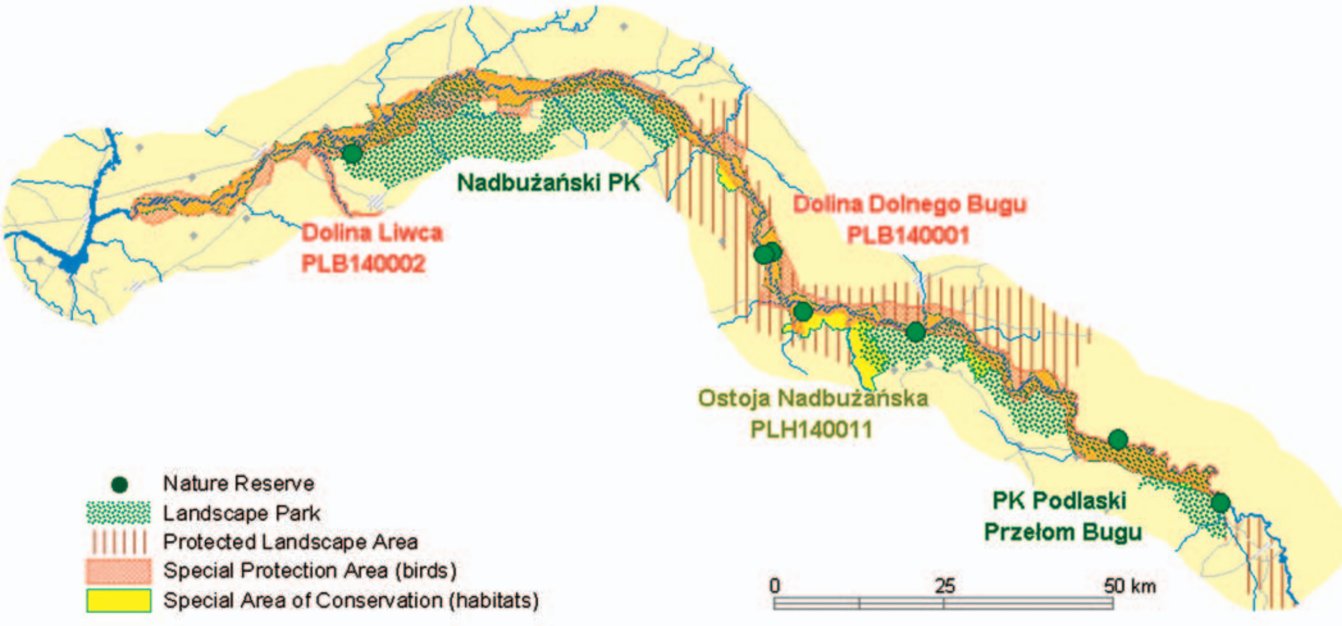


***Fig. 2.*** *Forms of nature preservation .*

The determined areas of the network "Natura 2000", i.e. the area of special protection of birds " The Lower Bug Valley – Dolina Dolnego Bugu" (The decree of the Environment Protection Ministry of 21 July 2004 concerning the areas of special protection of birds " Natura 2000" Dz.U. No. 229, item 2313) as well as the special area of protection of standings "Refugium upon the Bug - Ostoja Nadbużańska" (www.mos.gov.pl) cover almost the entire considered section of the Bug. The merits which decided on establishing such form of protection, are a.o. the following : the unimpaired valley and river-bed of the Bug with their sandy islands settled in different degree with the marshy forests, old river-beds of different stages of succession, swamp terrains and complexes of riverside forests.

The number of the already established protected areas as well as projects of new ones (www.podlaskiprzelombugu.pl) clearly demonstrate the recognition which the natural merits of the Bug and its valley received. Majority of the protected areas is closely associated with the river and its valley under relatively low anthropogenic influences. The high natural landscape merits make it possible to commune with the nature of a unique form, admiring its beauty and richness. Popularization of the merits of the region, tourist traffic development including the use of the Bug as the tourist waterway would certainly contribute to very desirable development of the region. However the preservation of the natural merits will require to be very careful in undertaking the activities which could disturb the present state and do a harm to the most precious values.

## THE PRESENT STATE OF THE WATERWAY

The natural character of the Bug with its many bends and old-river beds (Fig.2) and flooding terraces makes it possible to see a waterway of natural character and the river practically unchanged by human activity. In present an insignificant human interference has been limited to bank strengthening by means of faggot bands. In some sections still can be found old wing dams and stony bands which had to regulate the river stream-way but now not fulfilling their aim. The river washed out the not maintained infrastructure objects, a part of which became overgrown and turned into a wonderful place for fowl standings.

***Rys. 2.*** *Meandry i starorzecza rzeki Bug w okolicy Brańszczyka*

The Bug - from the inlet of the river Muchawiec (286$^{th}$ km) up to the inlet of the river Narew (0 km), i.e. over the section 224.2 km long - is the river of regional importance. It was classified as that of the Class Ia (acc. Dz.U. 77 dated 18 June 2002), which means that the minimum dimensions of the waterway have to satisfy the following criteria :

- ★ Width of the waterway (at the level of bottom of the ship under permissible load and at its full draught) – 15 m
- ★ Transit depth – 1.2 m
- ★ Bend axis radius of the waterway – 100 m.

At the beginning of shipping season, i.e. at the moment of opening the waterway, not all the above mentioned criteria are satisfied. For instance, the enouncement of the RZGW?,Warsaw, dated 28-04-2005, informed that the waterway on the Bug had to be opened on 6 May and the then waterway parameters were the following : 100 cm transit depth at 190 cm water-level measured on the river gauge at Włodawa, the waterway width of 25 m, the limiting value of the draught – 80 cm (whereas it should be of 100 cm acc. the classification of inland waterways – Dz.U. No. 77/2002, item 768).

During the shipping season navigation conditions worsen relatively fast. In the season 2005 the water-level indicated by the river gauge at Włodawa, dropped below 190 cm already in the beginning of June. Already on 11 July the waterway was closed due to excessively low water states (in the announcement of the RZGW, Warsaw, it was stated that along many sections of the river in question its water depth did not exceed 40 cm, which did not guarantee safe navigation).

The measurements of depth and width of the Bug waterway were carried out during three measuring campaigns in 2005: from 2 to 5 June, from 10 to 16 June and from 7 to 15 July at the water-level values in the range of the bank-full, bank-full/mean and mean/low states, respectively (Fig.3). The bathy-

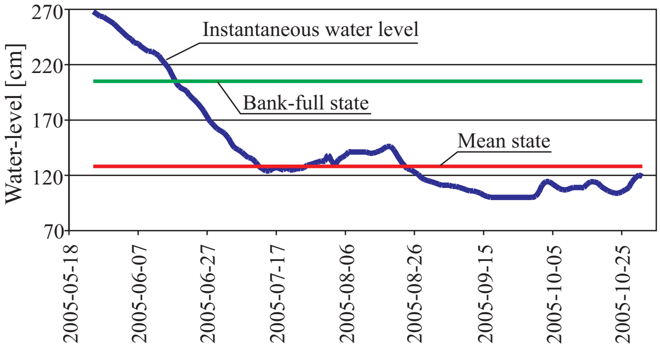


***Fig. 3.*** *Water-level state indicated by the river gauge at Włodawa .*

metric measurements were performed from a boat by means of an echo depth finder or measuring steel rod (at low states) and GPS receiver to localize measuring points. The continuous measurement of water depth (Fig.4) was performed along the cross-sections oblique relative to the river-bed axis. The last measuring campaign, at the low water state, made also it possible to find shallow waters, sandbanks, shoals, underwater dunes and islands emerging at low water states.

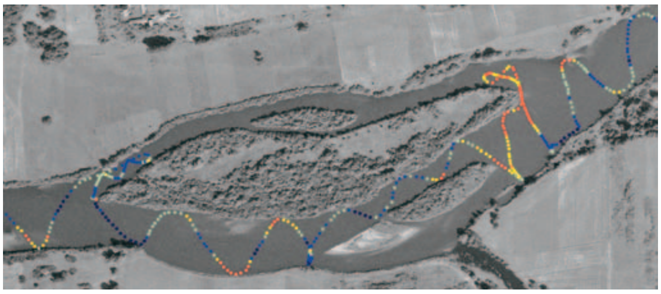

***Fig. 4.*** *An example of collected measurement results of the river-bed bathymetry (the used colours stand for water depth values obtained dring 3rd measuring campaign : red: < 50 cm, yellow : from 50 to 70 cm, green : from 70 to 100 cm, blue : > 100 cm) .*

The measurement results, after determination of local water depth values, were stored in a data base and superimposed onto calibrated maps and satellite photos of the river. Simple numerical procedures make it possible to receive information on current location of river-bed banks, their distances, parameters of bends, co-ordinates of river- bed axis, maximum depth contour lines etc.

The river waterway depth analysis was performed by using the spatial information system included in the ArcView software. To fix the waterway the water depth values measured during 1st and 2nd campaigns were reduced to the values corresponding to the water-level states recorded during the 3rd campaign. This made it possible to fix allowable shipping routes along the river and to determine the sections where the river is not navigable or where the obstacles in the form of boulders or sandbanks appear. Comparing the course of the river-bed represented on the maps and photos one can distinctly observe the changes which have occurred along with time (Fig.5).

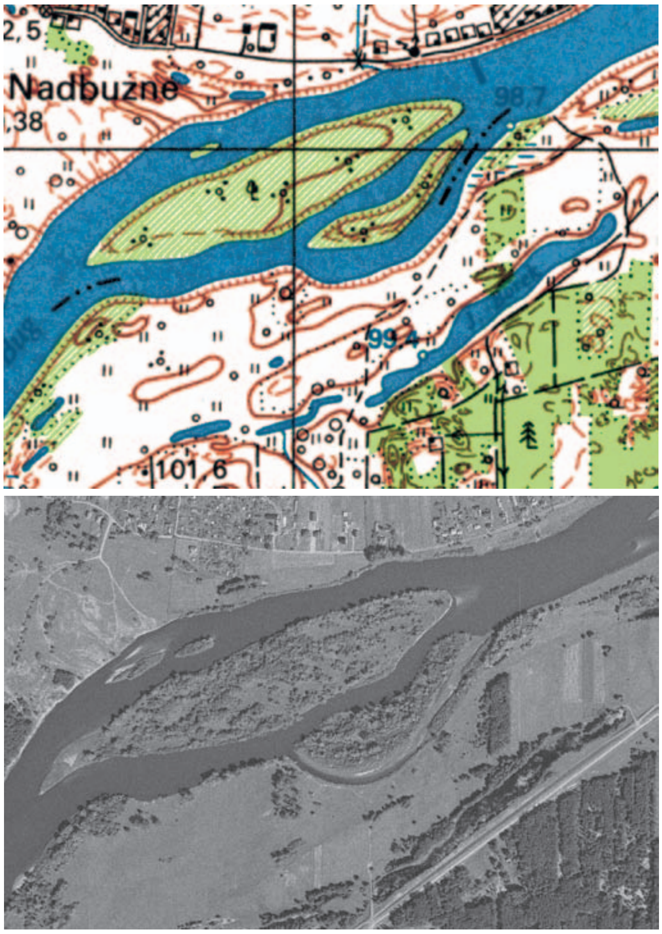


***Fig. 5.*** *An example of changes in the river-bed of the Bug (the overgrowing of the side arms around islands) .*

***Tab. 1.*** *Specification of non-navigable sections of the waterway of 70 cm water depth, and some proposals concerning its regulation*

| km | Location | Proposals of regulation work |
|---|---|---|
| 167.5 | Sarczewickie Błonia | Closing the water flow around islands |
| 144.5 | Granne | Forcing the water flow through left-side arm – closing the water flow behind the islands |
| 133 | Białobrzegi (inlet of the Nurzec, right-side bank) | Cutting the arm behind the island |
| 125.5 | Kamionka Nadbużna | Broads with islands in the river-bed – the narrowing of the bed by means of a longitudinal dam |
| 106-110 | Podgórze Gazdy – Rytele Olechny | Non-navigable section – no proposals for regulation not interfering into the natural environment |
| 89 | Zabocze/ Podkole | 1st – the narrowing of the river bed – right-side bank strengthening 2nd – the profiling of the bend by means of longitudinal dam |
| 43-55 | Nakieł-Szumin | Non-navigable section – no proposals for regulation not interfering into the natural environment |

For the assumed depth of the waterway of at least 100 cm, were specified 47 sections which have not complied with any of the selected criteria for water depth, and 7 such sections for the assumed depth of 70 cm. After performing the analysis on possible regulation of the river without any serious interference into the natural environment, two following non-navigable sections were specified :

- 1st - from the inlet of the Liwiec near the village Nakieł up to the village Szumin (about 12 km long)
- 2nd - between the village Rytele Olechny and Podgórze Gazdy (4 km long).

## PROSPECTS OF ECOLOGICAL TOURISM IN THE BUG VALLEY

From the point of view of economical development of the Bug valley and its region, seems to be interesting a concept of intensification of the use of the Bug waterway for developing ecological tourism. The concept should take into consideration the conditions of balanced development of tourism, in which the using and tourist development of the natural and cultural environment should be carried out in such a way as to ensure maintaining the balance of ecological systems and to prevent degradation of cultural merits of the region.

The high tourist merits of the Bug results from the fact that it is one of the last- in- Europe large rivers whose bed is practically unchanged by man, and its valley maintained almost in the natural state - with many bends, cut-off old river-beds, flooded meadows and swampy forests.

Worth stressing, that not only the Bug valley but also the whole region of Podlasie is rich in enclaves of almost intact nature (ecological lands), natural landscape complexes subjected to the various forms of preservation presented in Ch. 3 (peat lands, reed lands, field and forest water pools, clusters of trees and bushes, cliffs etc), which make the agro- tourist areas more interesting.

It is also important that there are many overlook points from which panoramic views can be observed (located mainly on cliffs of the Bug valley and tops of hills). Such especially exposed points, can be found on the high cliffs of the Bug valley close to the village Jegiel, Wiczogęby and Brzostowo. Especially attractive is the gorge of the Bug valley from the State border with White Russia to Wólka Zamkowa and Drohiczyn. Just in this region attractive relieves of terrain with large relative height differences can be observed.

The tourist attractiveness of the Bug region is associated with its cultural richness resulting from its violent history as well as from combining architectural relics with interesting landscapes. In contemporary tourism just such conglomerate of features, variety of tourist merits, and possible ways of versatile making use of them for tourist purposes, decides upon tourist attractiveness of a region and places.

Therefore opening a regular tourist tour along the Bug from the State border up to the Zegrze Reservoir would arouse a wide interest among tourists not only Polish but also from abroad.

In order to intensify tourist traffic, especially waterborne, is necessary to take care on complex development of the Bug and its surroundings by providing different forms of water tourist servicing, namely :

- Centres of tourist services with special taking into account water tourism
- Water tourist campsites and staying places for canoe trips
- Transfer points for tourists voyaging on passenger ships
- Development of the Bug valley and surrounding regions as regards the following forms of servicing : stays (in boarding-houses, rent rooms, agro-tourist objects), qualified and special tourist activities e.g. angling
- Complex development of towns and larger villages upon the Bug as regards the servicing of tourist stays, sightseeing tourism, vacation and holiday rest, as well as waterborne tramping
- Introduction of new agro-tourist objects over the entire region of the Bug respective to their co-operation within the network of the objects specially adjusted to servicing various forms of tourist activities (e.g. bases for waterborne, bicycle and horse riding tourism)
- Development of summer-resort building, outside landscape parks
- Introduction of a tourist information system in the Bug region.

As above mentioned, the navigation conditions of the Bug along the section from Niemirów up to Zegrze Reservoir, are varying. For tourist traffic organization, a crucial role play the limitations to passenger shipping over two non-navigable sections : that from the inlet of the river Liwiec to the village Szumin, and that from the village Rytele-Podgórze Gazdy up to Zgleczewo Szlacheckie. Taking into account the limitations one proposed to arrange a supplementary variant of passenger transport. Due to the present road network capable of ensuring effective coach transport, in the periods of low water states along the non-navigable sections, it is proposed to arrange the transfer points in the villages : Zuzela, Rostki-Piotrowice, Tuchlin as well as Kamieńczyk. Additionally, the transfer points can be used to broaden tourist service offer of the region and prepare proposals of associated tourist service products such as sporting and recreation, cultural and folklore events, nature observation e.g. nature and sightseeing tours, special trips.

Two variants of making use of the waterway depending on seasonal changes of water-level in the river, are proposed :

**Variant I** : representing the state of full navigability of the waterway from Niemirów up to Zegrze Reservoir which makes the waterway accessible for all kinds of floating units in the periods of bank-full water states of the river

**Variant II** : consisting in the split of the waterway into 5 sections, namely :

- three navigable sections : from Niemirów to Zuzela, from Rostki Piotrowice to Tuchlin, from Kamieńczyk to Zegrze Reservoir
- the two above specified non-navigable sections, under assumption that they are excluded from passenger shipping but accessible for waterborne touring by means of canoes, pontoons, rafts or similar floating gear not requiring a large water depth. In this variant land transport along the non--navigable sections could be organized by using coaches, chaises or bicycles.

Along the non-navigable section of the Bug between the village Zuzela and Rostki Piotrowice, south of the river, it is possible to organize various tourist activities. It could be even daylong landscape trips over the wide forest terrains located west of the commune village Ceranów, in the region of such villages as Wólka Rytelska, Noski, Radość, Krupy, Jakubiki and Garnek. There is also possible to organize qualified tourist trips (hikes, bicycle and horse rides) as well as various forms of nature observation and nature education tourism e.g. observation of forest fauna and photographing natural phenomena. The possibilities are associated with natural sights and curiosities of that terrain, to which e.g. the flora reserve "Biele" belongs. A supplementary item of the program can be making acquaintance with cultural merits of the region as well as taking part in folklore events.

In the case of navigation down the river the transfer points on the north side of the Bug at Tuchlin as well as in the village Kamieńczyk on its south side would make the main directions of tourist traffic, accessible : from Tuchlin westwards along the north side of the river via Wyszków, as well as from Tuchlin along the south side of the river to Kamieńczyk.

## SUMMARY

- To make use of the natural merits for development of the region one proposes to intensify tourist traffic and to perform a slight regulation of the river-bed of the Bug to an extent not contradicting the present forms of nature preservation applied in the river valley.

- To make use of the waterway two solution variants are proposed depending on seasonal changes of water-level states in the river.

- The first of them concerns the situation of full navigability of the waterway along its section from Niemirów to Zegrze Reservoir in the periods of bank-full water state in the river.

- In the second variant to divide the waterway into 5 sections is proposed, namely : three navigable sections from Niemirów to Zuzela, from Rostki Piotrowice to Tuchlin, from Kamieńczyk to Zegrze Reservoir, as well as two non-navigable sections along which tourist traffic can be realized by land with the use of coaches, chaises or bicycles.

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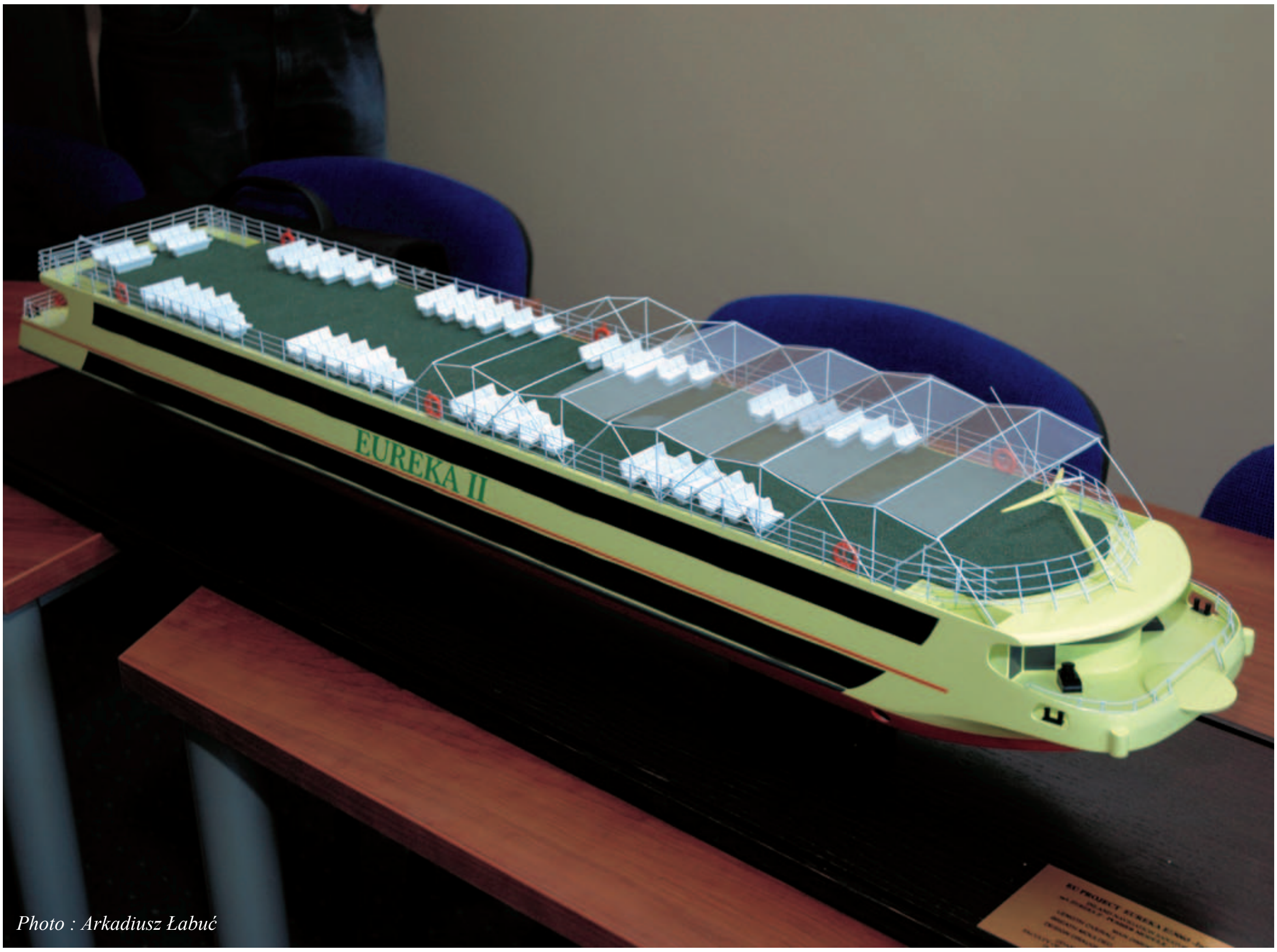


*Photo : Arkadiusz Łabuć*

# Influence of ship motion on waterway. Backward current velocity

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ABSTRACT

*In this work was presented an influence of bow form of inland waterways ship and waterway limitations on values of backward current velocity. The analysis was performed on the basis of results of calculations with the use of numerical modeling the flow around ship hull. The applied HPSDK computation system (a computer software developed by these authors) is based on using surface distribution of vorticity to analyze the velocity field and pressure distribution around ship hull. It was proved that the generated backward current velocity exceeded its permissible non-scouring values.*

**Keywords** : waterway, bow form, backward current.

## INTRODUCTION

Traffic of inland navigation ships constitutes one of the crucial factors deteriorating the waterways. And, the ships' operators often present their reservations about some parameters of waterways which do not make it possible to fully utilize capabilities of the inland waterways ships. Correct identification of the phenomena which take place during ship motion on a limited waterway can contribute to elimination or at least moderation of the mentioned problems.

During ship motion on a limited waterway many detrimental physical phenomena occur. These are :

- ★ increase of ship resistance
- ★ ship sagging
- ★ ship trimming.

The last two make the required clearance between the waterway bed and ship's bottom plating, decreasing. Simultaneously, ship's sagging and trimming generate an additional increase of ship's resistance. The detrimental influence of ship on waterway leads to limitations of ship's service draught and speed. They are as a rule imposed by the waterways administration. They are aimed at protecting the waterways against excessive degradation as well as at preventing ships against their stopping, failure of propulsion system and/or loss of floatation - due to taking contact with waterway bed. The waterways administration recommends to lower ship draught and/or speed, that adversely influences costs of transport on inland waterways.

Moving ship narrows transverse cross-section of canal, which leads to generation of an under-pressure and increase of velocity of water flow around hull ship, the so called backward current. Both the phenomena cause degradation of canal banks and bed. The influence is manifested by :

- backward current especially intensive at an asymmetrical position of ship relative to canal sides
- behind-the-propeller stream (race) which can generate erosion (scouring) of slope and bed of canal.

There is close connection between quantity of change of ship position and that of resulting under-pressure and backward current. An increase of water speed around ship makes water level lowering, that directly causes ship sagging. As ship's hull is not symmetrical with respect to the midship plane the backward speed varies along ship's length. It means that the water level lowering is not uniform over the whole ship length, that leads to ship trimming. The trim, as demonstrated also by model tests, does not significantly influence safety of ship traffic. Large trim values occur at speeds close to critical ones. Such speeds are reached neither by cargo nor passenger ships.

An additional factor of detrimental influence of ship motion on waterway is damaging action of generated waves on waterway bank protection. Extent of the influence is tightly associated with the share of wave resistance in ship total resistance to motion.

Results of the analysis of the influence of waterway limitations (its depth and width) on backward current velocity values, are presented below on the basis of the author's model of water flow around ship hull. Ship safe speeds are additionally dependent on geological structure of waterway bed.

## HPSDK COMPUTATIONAL SYSTEM

The HPSDK computational system is a computer software which has been developed for many years. Its beginnings date back to the end of the 1980s. It has been aimed mainly at elaboration of a mathematical model of hydrodynamic interactions occurring within propulsion system of inland navigation ship. On this basis, was elaborated a computer program package, which make it possible - in a numerical way - to determine such quantities as : nominal and effective wake factors (with taking into account hull interaction), propeller thrust, required torque to be delivered to propeller's cone, and propeller efficiency. Results of the calculations made it possible, if ship resistance curve is known, to elaborate prediction of ship propulsion characteristics for various values of ship service speed and waterway depth. In building the software, particular elements of ship propulsion system were assumed to be considered independently, and their mutual interactions to be taken into account in an iterative way. The choice of such approach was conditioned by available computer hardware. The elements of the propulsion system were : ship's hull, screw or ducted propeller. The limited waterway depth was associated with the data describing the form of underwater part of ship's hull. The computer software has been continuously subjected to development. In present it consists of three independent modules (Fig.1). In each of the branches are contained common segments, e.g. those intended for the calculating of propeller or nozzle-propeller unit. However main function of each of the modules is different.

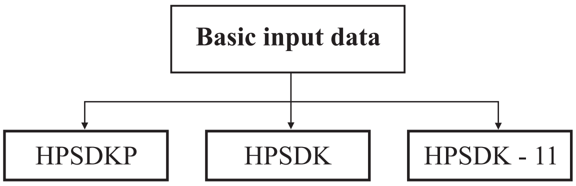


***Fig. 1.*** *Structure of HPSDK calculation system .*

The HPSDK module is basic one. Today, it makes it possible to calculate - apart from operational parameters of propeller, nominal and effective wake factors - pressure distribution on waterway bed, quantity of ship's sag and trim [5,13]. The calculations can be carried out for conditions of limited depth of waterway and trapezoidal or rectangular cross-section of canal. It is necessary to put in coordinates of points of the mesh which models the form of the whole ship (also a push train).

HPSDKP module makes it possible to analyze influence of half-nozzles and before-propeller nozzles on operational parameters of ship propulsion system [7]. Additionally, should be introduced data which describe geometry of those elements and their position respective to the central coordinate frame connected with the propeller plane and propeller shaft axis. In the calculations, ship stern form and limited water depth can be taken into consideration.

HPSDK-11 module is intended for the analyzing of interactions within propeller - rudder blades system [8]. As compared with the basic (HPSDK) module it takes into account an influence of rudder blades. It is necessary to put in data which describe geometry of the blades and their position respective to the propeller. The module is adjusted to analyze flow around either one blade or a blade system (of three blades in one propeller stream at most). It makes it possible to perform an analysis with taking into account only the influence of behind-the-propeller stream (screw propeller, ducted propeller) or also the influence of hull and waterway bed.

All the three modules have a common block which serves for introducing basic input data which concern :

- description ship's form
- screw propeller geometry
- propeller nozzle geometry (if ducted propeller is applied)
- remaining data : waterway limitations, ship service speed, propeller rotational speed, number of propellers, and a set of control data.

The nozzle and propeller geometry input data are directly taken from working documentation of the elements. Two editors serve to this end. Making use of a catalogue of propellers and standard nozzles described in dimensionless coordinates is possible. The mesh to model the hull itself is built separately by means of the SIATKA.EXE module. The basis for data preparation is hull body plan or body form described in AutoCAD environment [9,10].

Results of calculations of wake factor and pressure distribution on waterway bed have been verified on the basis of available model test results. A proper conformity of the results of the calculations with those from model tests has been achieved [5, 6, 13]. The HPSDK computational system was comprehensively verified by applying to elaboration of ship propulsion predictions for different service conditions. The calculations have been carried out during work upon the INBAT research project realized in the frame of 5$^{th}$ EU Outline Program. Their results have been verified on the basis of partial results of the model tests performed in Ship Hydrodynamics Centre, Ship Design and Research Centre, Gdańsk and in a research centre at Duisburg [3,4]. The pressure distribution on waterway bed due to ship motion is presented in the form of the dimensionless coefficient $c_p$ respective to the ship speed $V_S$. At a given value of the variability coefficient of pressure on the waterway bed, the local velocity $Vi$ in any point of the waterway bed is - according to Bernoulli equation – as follows :

$$V_i = V_S\sqrt{1 - c_{pi}} \qquad (1)$$

The velocity, when compared with the scouring one, can be used for the assessing of ship motion influence on waterway. The so obtained velocity determines local speed of backward current near waterway bed. The maximum value of the velocity is of a great importance from the point of view of the ship motion influence on waterway. This maximum occurs in the place where ship motion generates the largest under-pressure on waterway bed.

The HPSDK computational system makes it possible to calculate the pressure distribution in control points of the mesh modeling hull form. Making use of the relation (1), one can calculate [water flow ?] velocity in selected points of ship hull plating. Knowing its local values in ship hull control points one can calculate its mean value. The mean velocity is calculated as arithmetic one. The difference between the so determined velocity and assumed ship service speed gives the mean velocity of backward current.

The calculations in question were performed for model test conditions (in the model-scale $\alpha = 14$). The pressure distribution results are presented in the model-scale. The remaining results of the calculations (i.e. of backward current velocity) have been transformed to full-scale in compliance with the Froude modeling principle.

## BACKWARD CURRENT VELOCITY

In the subject-matter literature many methods of defining the backward current can be found [4, 11]. As a rule they appear together with those for calculating quantity of sagging. Their characteristic feature is that they do not take into consideration ship hull form. Here four characteristic bow forms were assumed to take into account the shapes typical for cargo ships operating on inland waterways. They are marked as follows : EIIb_89h, ELI_89, WALC_89 i B_89. The two first forms constitute a modified EUROPA II and ellipsoidal form, respectively. The two remaining forms : WALC_89 and B_89 were proposed by these authors. The forms were elaborated under the assumption that easiness of manufacturing process and getting large cubicoidal hold are the crucial criteria in their designing. The forms are presented in Fig.2. And in Fig.3 are presented changes of areas of bow frame lines. The bow form B_89 is of the largest fullness. Its additional feature is that it is consisted of the surfaces bent in one plane only.

In this work the [backward current ?] velocities are determined on the basis of the calculation results obtained from the HPSDK computational system.

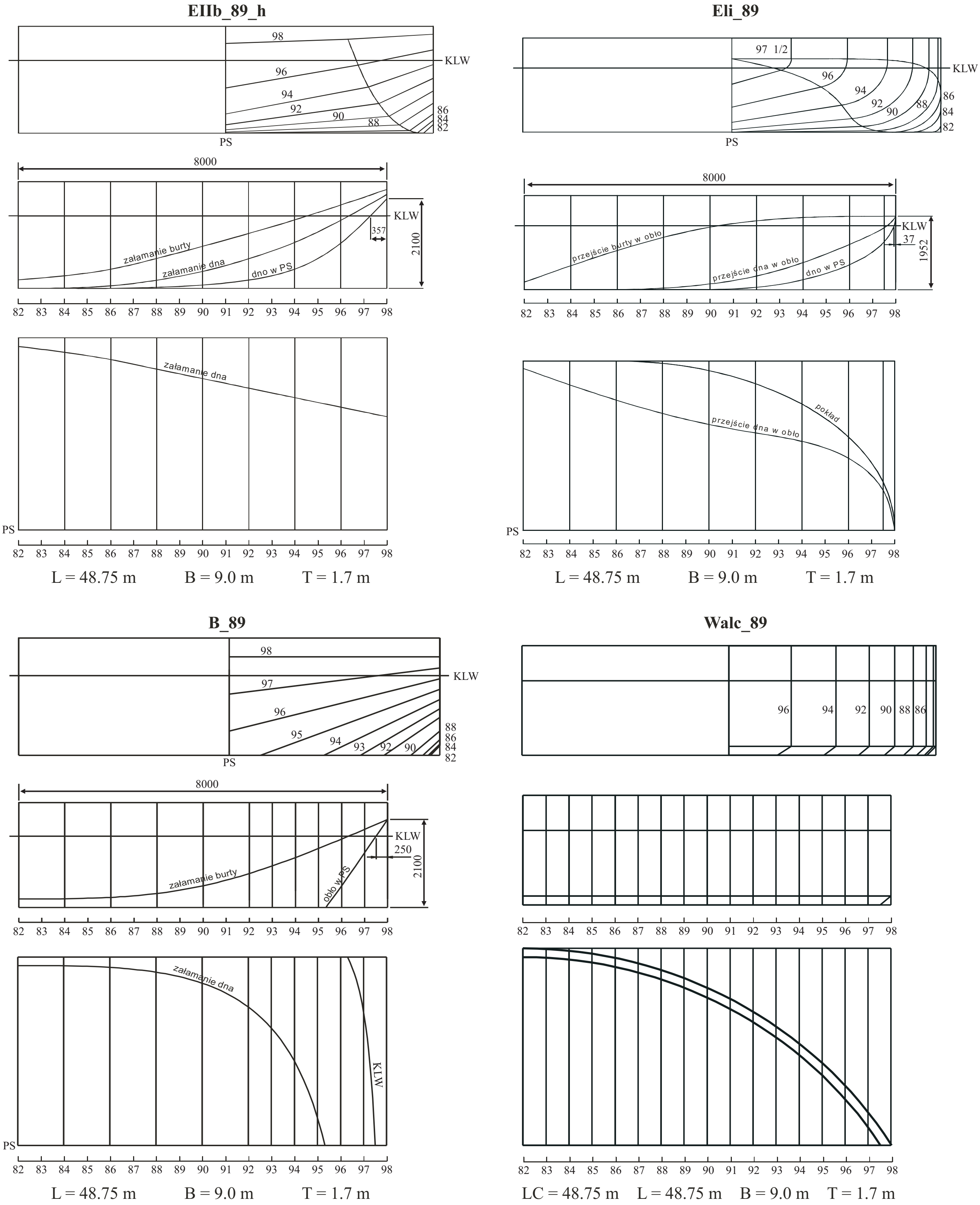


***Fig. 2.** Barge hull forms assumed for the analysis .*

By taking into account hydro-technical conditions of Polish waterways the calculations were carried out for a single-row, two-barge push train (without pusher). The following particulars of a single pushed barge were assumed :

**Overall length** : $L_C$ = 48.75 m ; Breadth B = 9 m ; Draught T = 1.7 m ; Bow length $L_E$ = 8 m.

The calculations were carried out for the limited water depth values as follows : h = 2, 2.5, 3, 4 and 5 m. Additionally, for some forms the calculations were carried out for the service conditions on Gliwice Canal which has the following particulars :

**Bottom width** : $b_o$ = 20 m ; **Side slope ratio** : 1 :3.

Values of water surface width depend on assumed water depth value taken for calculations. Three water depth values were assumed : 2, 2.5 and 3.4 m. The design depth of Gliwice Canal is equal to h = 3.5 m. To assess an influence of the Canal dimensions, additional calculations were performed for the trapezoidal cross-section of the Canal assuming its bottom width $b_o$ = 40 m, as well as for its rectangular cross-section of the width so chosen as to obtain the same cross-section area as in the case of the trapezoidal one.

Results of calculations of the maximum value of backward current velocity near waterway bed and its mean value are presented in the dimensionless form, i.e. the ratio of the velocity increment and ship service speed. The place of appearance of the maximum value of backward current velocity was determined on the basis of the calculated pressure distribution on waterway bed. Comparing the velocity value with the permissible one, preventing against scouring, one can assess whether ship motion is capable of disturbing the stability of waterway bed. The limit scouring velocity is the water velocity relative to waterway bed at which the loss of stability of waterway bed occurs (Tab. 1).

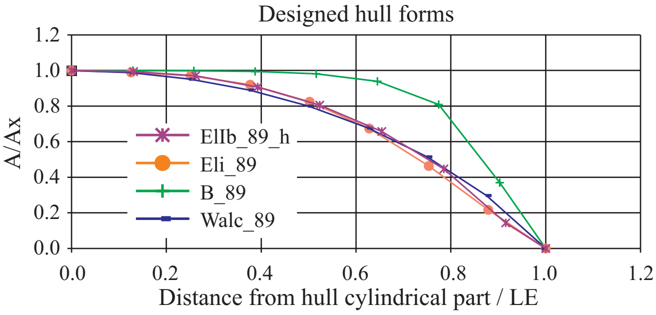


***Fig. 3.** Geometrical characteristics of the assumed barge bow forms .*

To take into account a kind of waterway is necessary when considering the backward current influence on waterway. Water velocity of the same value generates quantitatively different consequences for a canal, regulated and non-regulated river. Geological structure of waterway bed is an additional factor. On rivers where current velocity is present the influence depends on ship motion direction. If the natural phenomenon of rubble transportation occurs possible bed deformations may be leveled by the river rubble. Assessment of bed's stability consists, both in the case of river and canal, in comparing water velocities generated by ship motion with those permissible non-scouring for a given kind of bed soil. For cohesive soils it is recommended to assume the permissible velocities equal to 1,0 m/s. For loose soils this value amounts to 0,7 m/s.[1]. More accurate, but still rough values are shown in Tab. 1 [12].

***Tab. 1.** Rough values of limit scouring velocity .*

| Kind of bed material | Grain size [mm] | Limit velocity $V_d$[m/s] |
|---|---|---|
| Fine sand | 1-2 | 0.1-0.2 |
| Coarse sand | 2-7 | 0.2-0.3 |
| Fine gravel | 7-10 | 0.3-0.6 |
| Shingle | 10-20 | 0.6-0.7 |
| Small stones | 30 | 0.7-1.0 |
| Small cobbles | 100 | 1.5 |
| Large cobbles | 400 | 3.00 |
| Boulders | 700 | 4.00 |

In Fig.4 through 7 are presented example distributions of pressure exerted onto waterway bed in ship plane of symmetry. In very shallow water conditions (h/T = 1,17), a distinct influence of hull bow form can be observed. The B_89 form

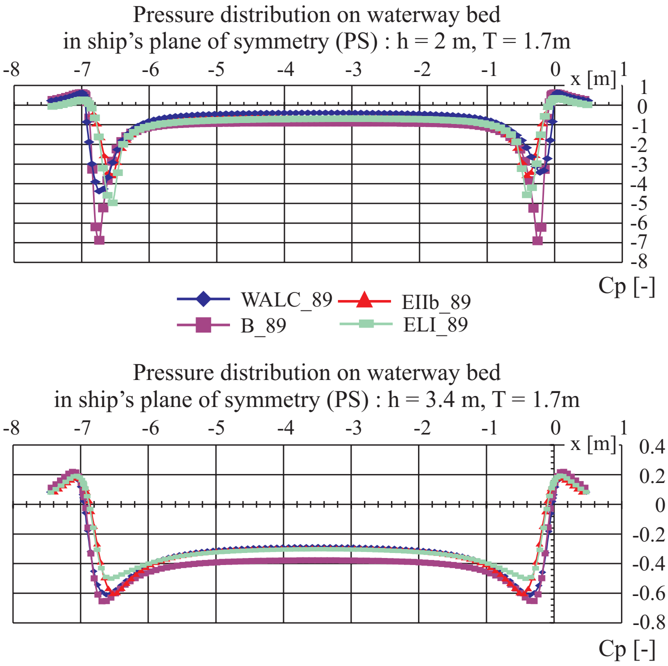


***Fig. 4.** Influence of hull form on pressure distribution on waterway bed .*

is the most unfavourable as regards quantity of the generated under-pressure on waterway bed. The form has the largest value of block coefficient of bow part of hull (Fig.3). As the water depth increases the influence of bow form distinctly decreases (Fig. 4 and 5).

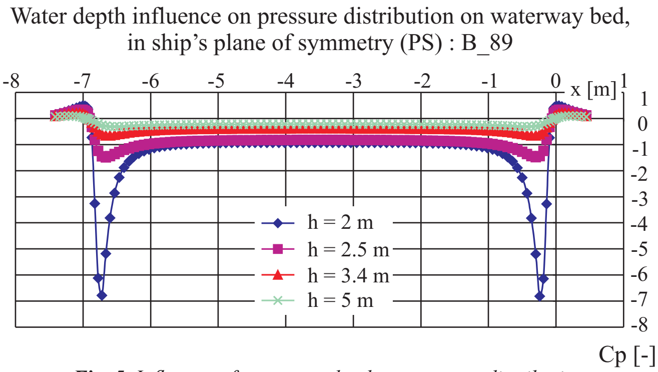


***Fig. 5.** Influence of waterway depth on pressure distribution on waterway bed .*

If a ship moves in a canal then - apart from different pressure distributions in bow and stern parts of hull- a distinct increase of under-pressure in midship area relative to the values which occur during ship motion in water of a limited depth only. Size of canal (at an assumed depth of it) in principle does not influence pressure distribution. However it can be stated that at an assumed cross-section area the rectangular canal is less favourable than that trapezoidal (Fig.6).

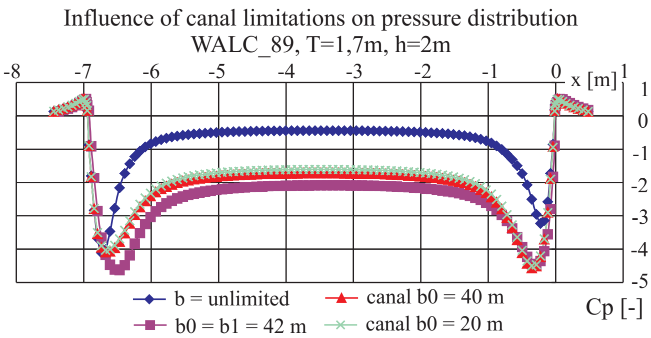


***Fig. 6.** Influence of canal limitations on pressure distribution on waterway bed, in ship's plane of symmetry .*

In Fig.7 the influence of bow part length on pressure distribution is presented for a elected bow form. The smallest under-pressure values were obtained for the shortest bow part ($L_E$ = 4 m). In the case of the remaining analyzed lengths ($L_E$ = 8 and 12 m) no significant differences have been observed.

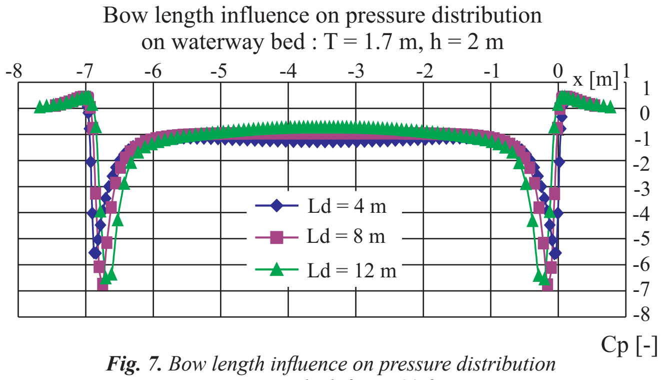


***Fig. 7.*** *Bow length influence on pressure distribution on waterway bed, for B_89 form .*

Fig. 8, 9, 10 and 11 presents the influence of waterway parameters and ship hull form on backward current velocity. Also, in each of the figures are presented mean values of backward current velocity as well as extreme ones determined on the basis of the maximum value of under-pressure on waterway bed. The differences can be observed especially in the case of small depths of waterway. For h/T = 1.176 the backward current velocity determined on the basis of mean velocity values, reaches from 8% to 15% of ship motion speed. The maximum backward current velocities near waterway bed, determined on the basis of pressure distribution, reach from 110% to 180% of ship motion speed. If to assume mean velocities to be a basis for analysis then the influence of hull form can be observed over the whole range of analyzed waterway depth values (Fig.8).

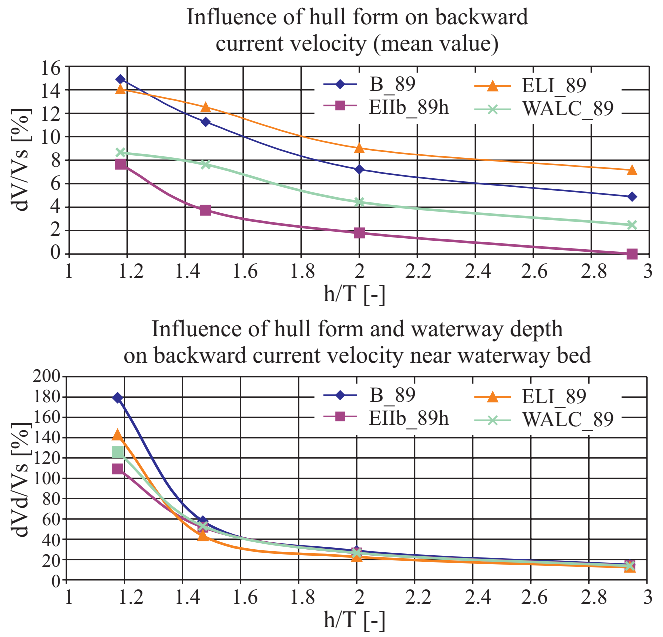


***Fig. 8.*** *Influence of hull form on backward current velocity .*

For water velocities near waterway bed the hull form influence is observed for the range of waterway depth from h/T = 1.176 to h/T = 2. Above the latter value the influence may be neglected. When taking into consideration the limit scouring velocities given in Tab. 1 it should be remembered that the scouring of waterway bed may occur if h/T < 2. In extreme conditions (for h/T = 1.176) the velocities near waterway bed significantly exceed their permissible values. E.g. already at ship motion speed of the order of 8 km/h (which is in principle the maximum available at that value of ship draught/water depth ratio), the backward current velocity can reach values from 2.44 m/s to 4 m/s which considerably exceed the limit ones shown in Tab.1. As results from Fig.8 for very shallow water conditions B_89 form is the least favourable, and EIIb_89 the most favourable. B_89 form is characteristic of the largest block coefficient of bow part and of a short undercut of bow in the plane of symmetry, as well as a large value of waterline entrance angle. An advantageous feature of the form in question is its simplicity and a large volume of bow part.

The bow length does not influence backward current velocity significantly. At the waterway depth h = 1.7m, (h/T = 1.176), the velocity near bed is contained in the range from 160% to 180% of ship motion speed (Fig.9). The obtained values correlate with the pressure distribution on waterway bed (Fig.7). This influence is not unambiguous. The problem should be analyzed in a greater detail. Waterway depth increasing makes backward current velocity decreasing, irrespective to bow part length. The same concerns also the backward current velocity determined by using mean velocity values. The calculation results presented in Fig.9, concern the B_89 form. In the case of the remaining forms in question similar changeability trends are observed.

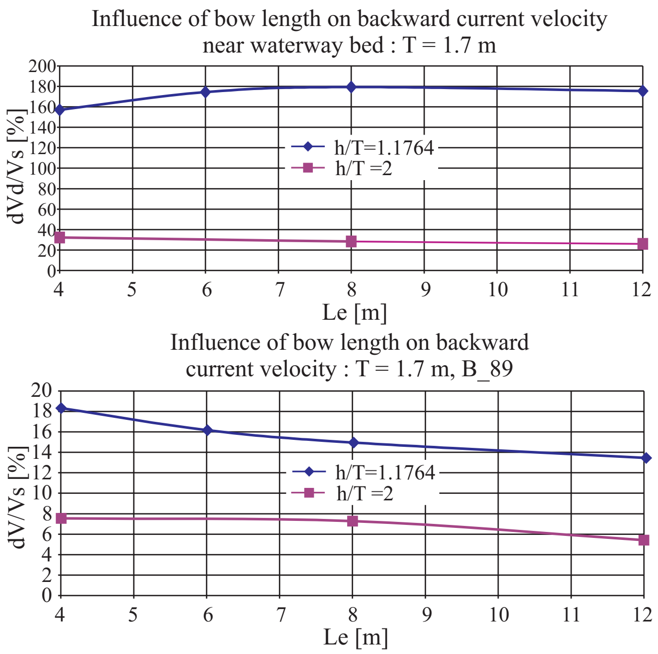


***Fig. 9.*** *Influence of bow length on backward current velocity, for B_89 form .*

In the case of ship motion in a canal, smaller values of backward current velocity are observed (at the same waterway depth). Its mean value for water of a limited depth only (in the whole range of analyzed depth values) is greater than that in the case of canal. A different character of changeability occurs in the case of the near-bed velocity. At the waterway depth h = 2.5 m no difference between the velocity in canal and shallow water is observed (Fig.10). The backward current velocity near waterway bed exceeds its permissible non-scouring values in a similar way as in the case of ship motion in shallow water. For the range of h/T ratio from 1.176 to 2, the velocity values varies within the range from 180% to about 30%.

In Fig.11 calculation results of backward current near waterway bed at canal slope, are presented. The results were obtained by using pressure distributions. Comparing the results with those presented in Fig.10 one can state that the velocities resulting from pressure distribution are of smaller values than those obtained on the basis of mean velocity values. Ship mo-

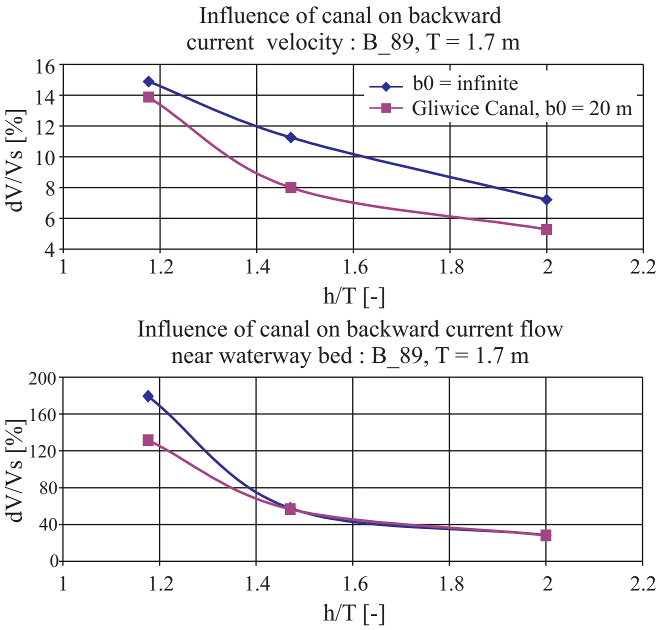


***Fig. 10.*** *Influence of canal on backward current velocity .*

tion influence on canal banks depends on bow form (WALC_89 bow form is more favourable than B_89 one). Also, a distinct influence of canal cross-section on backward current velocity near canal bank, appears. At the same water depth an increase of canal width leads to a significant decrease of backward current velocity. The backward current velocity itself is not a single cause of canal bank scouring. Some observations indicate that destructive action of ship motion on canal banks are mainly caused by waves generated by ship in motion.

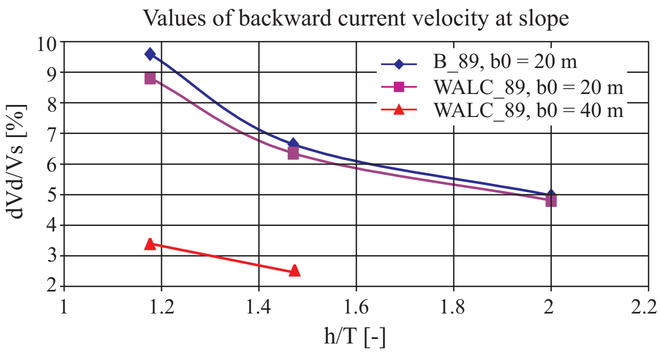


***Fig. 11.*** *Influence of canal cross-section on backward current velocity at canal slope .*

## FINAL CONCLUSIONS

It has been shown that the HPSDK computing system can be used in preliminary analysis of influence of ship form on quantity of backward current. The bow form itself significantly contributes to the influence of ship motion on waterway. The block coefficient of bow part of hull is of a fundamental influence on values of backward current velocity. The greater value of the coefficient the greater velocity of backward current. Out of two limitations of waterway (i.e. its depth and width) the waterway depth is of significant importance. The influence of waterway depth and ship motion speed on backward current velocity is unambiguous. The decreasing of the depth and increasing of the speed constitute important factors which make backward current velocity increasing. The backward current near waterway bed may exceed the permissible non- scouring velocity values. In view of natural rubble transportation in rivers the backward current does not affect the waterway itself detrimentally. The natural rubble transportation affecting river bed is deemed to cause more significant changes in the bed than the ship motion itself. The factors which deteriorate the waterway to a larger extent are : the behind-the- propeller stream and ship-generated waves [1]. The deteriorating action of the first of them is manifested especially during ship manoeuvers when screw propellers operate under large loads. In practice, the limit ship motion speeds are determined by quantity of ship sagging and ship resistance to motion on limited waterway.

## *Acknowledgements*

*This work has been carried out in the frame of realization of the EUREKA -E!3065 INCOWATRANS research project.*

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# Influence of ship–generated waves on waterway

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ABSTRACT

*Results are presented of calculations of ship – generated waves during its motion in canal. For the calculations FLUENT software was used. It was demonstrated that ship generates waves which, when approaching canal slopes, may constitute an important factor in deteriorating the banks, and that ship's wave resistance can be used as an assessment measure of influence of ship motion on waterway. The methods which are based on approximate formulae, are not reliable. The FLUENT software may be applied as a numerical towing tank.*

**Keywords** : waterway, ship–generated waves, numerical calculations

## INTRODUCTION

The wave system generated by ship in motion directly influences waterway banks. Analyzing the influence of the ship –generated waves on banks one should take into consideration the phenomenon of water level lowering which results from occurrence of backward current velocity. The two mutually interacting phenomena (i.e. ship–generated waves and water level lowering) produce alternately suction and impact pressure onto canal slope surface. The phenomena occur on the wetted zone of canal slope surface. Therefore the larger the zone the greater hazard of loss of stability of canal slope. A permissible ship speed in canal should be so determined as differences of water level in canal during ship motion not to exceed the slope strengthening zones. The differences can even reach the values of about 60 cm [1]. The deteriorating influence of ship waves on canal slope strengthened areas are observed especially where no maintenance work has been carried out. The photograph in Fig.1 shows the change of water level on Bydgoszcz Canal due to motion of an inspection ship. The observed failures of the canal slope are very distinct.

*Fig. 1. Difference of water level on canal slope due to ship motion .*

Energy of the wave system action can be identified with the share of ship wave resistance in total ship resistance to motion. The analysis of results of model tests of inland navigation ships, presented in [4], showed that the share was contained within the range from 30 to 70% of the total ship resistance. The upper limit concerns very shallow water conditions (h/T = 1.25), the lower one concerns h/T = 3. The analysis was performed with the use of the method of splitting the total resistance into two components : friction resistance of an equivalent flat plate, and residuary(form) resistance. In doing it, was applied a form factor which takes into account an influence of ship hull form on quantity of viscosity resistance.

In this work an analysis of the share of wave resistance in total resistance was conducted by using the FLUENT software. Also, results of calculations of water level profile on canal slope are presented. The results make it possible to assess wave height on canal slope. The calculations were performed for one selected form of pushed barge only.

## ASSUMPTIONS AND INPUT DATA FOR CALCULATIONS

The FLUENT software was verified by comparing the calculations of ship resistance and wave profile on ship side with model test results [4]. A suitable convergence of the calculation and model test results was obtained. An example comparison of the calculated ship-side wave profile and that obtained from model tests is presented in Fig.2.

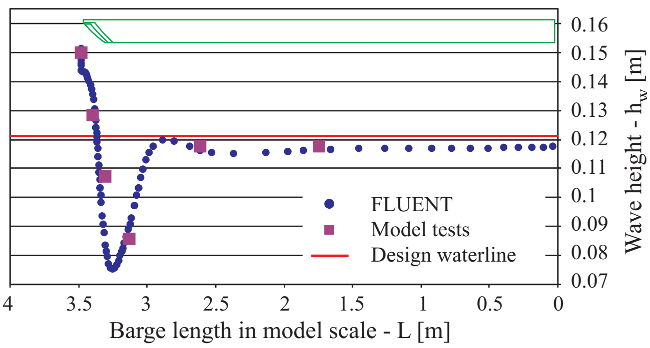



*Fig. 2. Wave profile on side of SFKO barge, h = 5.0 m; T = 1.7m; Vs = 14 km/h .*

The SFKO barge hull form was designed during realization of INBAT project financed within the frame of 5th EU Outline Program [3].

The calculations were performed for a two-barge one-row push-train (without pusher) satisfying hydro-technical conditions of Polish waterways. The following main particulars of a single pushed barge were assumed:

Total length : $L = 48.75$ m
Breadth : $B = 9.00$ m
Draught : $T = 1.70$ m
Bow length : $L_E = 8.00$ m.

The calculations were performed for sailing conditions in canal (limited width and depth). The following particulars of Gliwice Canal were taken into account :

Canal bed width $b_o = 20.00$ m
Canal slope ratio 1:3.

Water level width depends on water depth assumed for calculations. Two depth values were assumed : 2.0 and 3.4 m; hence the corresponding width values are : $b_1 = 32.0$ m and 40.4 m. The calculations were conducted in the model-scale $\alpha = 14$. To determine influence of limited waterway width the calculations were performed [also] for unlimited width conditions. The barge's hull form is presented in Fig.3.

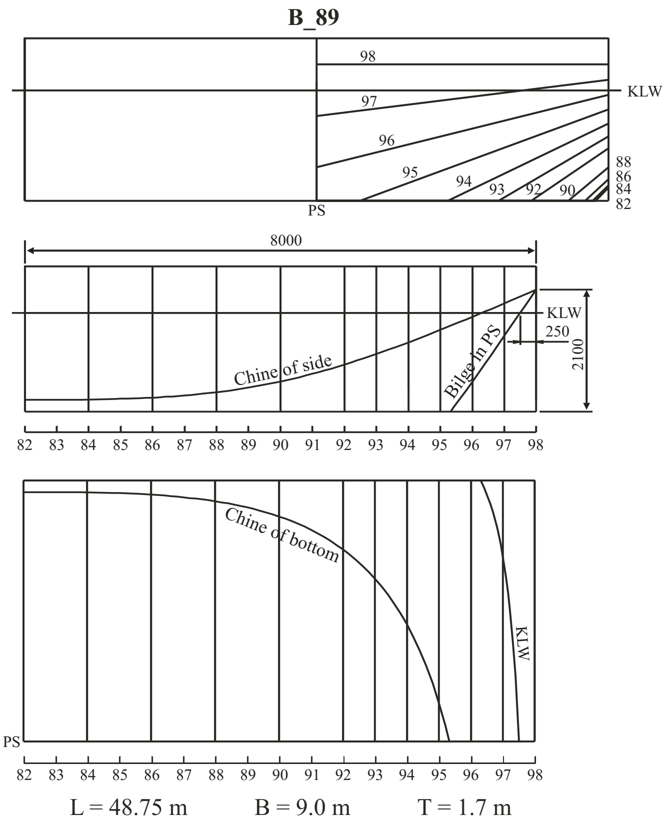



***Fig. 3.** Hull bow form of the considered pushed barge .*

The mesh for modelling the flow around the hull was built by means of GAMBIT program. It was based on the barge body lines generated by SIATKA program in **igs** format. On the so prepared hull form consisted of buttock and frame lines a 3D computation domain was imposed (water plane, basin's bed and slopes, plane of symmetry). The *hexa* elements were applied in order to precisely model water boundary layer with the use of relatively small number of mesh nodes. Since the calculations were carried out either with or without taking into account free water surface the computation domain containing basic flat water surface was prepared. Such approach has two important advantages : the basic water plane is smooth which means that mesh nodes belong to it, and the computation domain for water flow without taking into account free surface can be prepared very easily (it is sufficient to remove mesh containing volumes over the basic water surface). It makes it possible to calculate water flow around the hull both with and without taking into account free water surface, by using the identical mesh, which, in the case of comparing the results of calculations, eliminates errors resulting from building the numerical mesh. The calculations were carried out both under the assumption of unlimited width of waterway and canal conditions. For example, the mesh for calculations in canal conditions comprised about 250000 elements. In Fig.4 the computation mesh of hull bow part is presented.

The calculations were conducted for a reverse flow model, i.e. the ship was not in motion but the basin was moving together with the water inside. Due to such way of modelling, values of ship motion speed were set on basin's bed and sides, and on water surface. The RNG k - ε turbulence model of two equations was applied. 4% turbulence intensity was assumed. On all non-viscous partitions (ship hull, canal sides and bed), the mesh was so arranged as to maintain the parameter y+ which determines whether the first layer of mesh elements at a partition contains a laminar sub-layer of turbulent layer. This is Reynolds number relative to thickness of the laminar sub-layer. Value of the parameter should be contained within the range: $30 \leq y+ \leq 300$. The calculations of water flow around the hull with taking into account free water surface were conducted with the use the *Volume-Of -Fluid* multi-phase model (for non-mixing fluids, e.g. flows having free surface). The calculations were carried out with the time-step of 0.01s, and terminated when total resistance force value become stable.

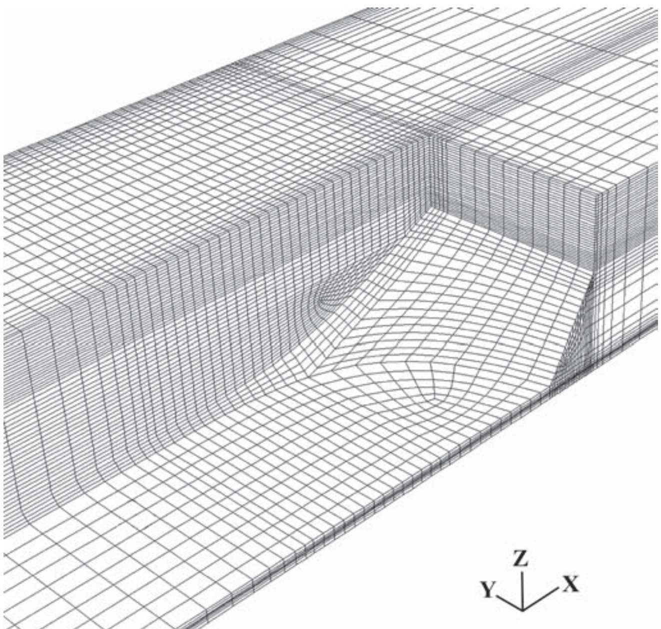



***Fig. 4.** The example computation mesh of B_89 hull bow form .*

In Tab. 1 the results of the resistance calculations for the assumed barge hull form are presented for normal and tangential resistance components, separately. They were carried out with taking into account influence of free water surface. Hence, the normal resistance constitutes a sum of pressure resistance and wave resistance. The tangential resistance can be identified with viscosity resistance. The calculation results are presented in model-scale. A significant share of the normal resistance component in the total resistance can be observed. The resistance component decisively influences resistance increase due to water depth decrease in canal. In the case of shallow water of unlimited width the water depth influence on quantity of the resistance component is much less important.

It results from that inland waterways ships operate at small Froude numbers.

*Tab. 1. Influence of waterway parameters on resistance of ship to motion. For B_89 hull form .*

| Waterway | | Canal | | Unlimited width | |
|---|---|---|---|---|---|
| Water depth h [m] | Ship speed V [m/s] | Viscosity resistance [N] | Normal resistance [N] | Viscosity resistance [N] | Normal resistance [N] |
| 0.1428 | 0.45 | 2.25 | 9.91 | 0.97 | 2.05 |
| | 0.6628 | 4.42 | 27.53 | 1.95 | 4.82 |
| 0.2428 | 0.6628 | 3.41 | 7.98 | 2.19 | 4.04 |

## PARAMETERS OF THE WAVE AT CANAL BANK

In the literature sources [1,2] some approximate methods for determining the wave height close to canal bank, can be found. The height is dependent on ship motion speed and dimensions of canal and ship. Gucma proposed the following formula for calculation of wave height close to canal slopes:

$$h_{Wmax} = CV^{3.5} \tag{1}$$

where :

$$C = 0.6\,e^{2.8\left(\frac{h}{b_r}\right)} k\,(0.1 t \cdot g \cdot h)^{-0.75}$$

$$t = \frac{(1-a)^2}{1-(1-a^2)}$$

$$a = 0.114\,\frac{b_r}{B} + 0.715 \quad \text{for : } b_r/B \geq 2.5$$

$$a = 1.0 \quad \text{for : } b_r/B < 2.5$$

$$b_r = \frac{b_0 + b_1}{2}$$

$$k = f(F/A_M)$$

- $A_M$ – midship section area [m$^2$]
- $b_0$ – canal width at bed [m]
- $b_1$ – canal width at water level [m]
- B – ship breadth[m]
- F – cross-section area of canal [m$^2$]
- g – gravity acceleration [m/s$^2$]
- h – water depth in canal [m].
- V – ship motion speed [m/s]

Basing on the data contained in [2], one can determine a value of the coefficient k from the formula :

$$k = 0.237\left(\frac{F}{A_M}\right)^{-0.9419} \tag{2}$$

Applying the formula (1) to the parameters of Gliwice Canal one obtains rather unreliable results. For the different water depths the constant C obtains its respective values as follows :

h = 2 m, C = 4.0967 ; h = 3.4 m, C = 0.52706

which yields unrealistic values of the wave height at canal slope.

In the source [1] the wave height at canal slope is dependent on ship length and canal water-level width only. In real conditions the wave height also depends on ship motion speed.

The example results of the calculations by using FLUENT software are presented in Fig.5 (for h = 2 m) and Fig. 6 (for h = 3.4m). In the case of shallow water canal the calculations were performed for two ship motion speed : V = 0.45 m/s equivalent to 0.38$V_{kr}$ , and V = 0.6628 m/s equivalent to 0.56 $V_{kr}$ . At the speed V = 0.6628 m/s a contact of the ship bottom with waterway bed is highly probable. For the canal depth h = 3.4 m the speed V = 0.6628 is equivalent to 0.43 $V_{kr}$. Basing on the calculation results of the wave profile on canal slope, shown in Fig.5 and 6. one determined maximum differences between wave crest and trough. It was assumed that values of the wave height $h_w$ were determined by the differences. On conversion to real-scale the values are as follows :

h = 2 m, V = 1.6837 m/s, $h_w$ = 0.4088 m (0.0392 m in model-scale)

V = 2.48 m/s, $h_w$ = 1.1634 m (0.0831 m in model-scale)

h = 3.4 m, V = 2.48 m/s, $h_w$ = 0.35 m (0.025 m in model-scale)

The above presented example results of the calculations indicate that the speed V = 2.48 m/s, for the ship of the draught T = 1.7 m, moving in the canal of the depth h = 2 m, is not permissible. At this speed the generated wave causes a change of water level on the slope. The difference of water levels exceeds the strengthened zone of canal slope. Energy of the ship-generated wave system is a measure of ship wave resistance. If viscosity influence and kinetic energy of motion of fluid particles are neglected the energy is proportional only to the square of wave amplitude :

$$E_c = \frac{\rho g}{2}\left(\frac{h_w}{2}\right)^2 \tag{3}$$

where :

- $E_c$ – wave system energy
- $h_w$ – wave height [m]
- ρ – fluid density [kg/m$^3$].

Under the assumption that across the whole width of water level the wave is of the same height as that on the canal slope, the wave resistance can be determined from the relationship :

$$R_W = E_c b_1 = \frac{\rho g}{2}\left(\frac{h_w}{2}\right)^2 b_1 \tag{4}$$

The wave resistance in model-scale – after taking into account the formula (4), as well as the heights of the wave systems generated by a ship moving in canal – amounts to :

For h = 0.1428 m, and V = 0.45 m/s : $\mathbf{R_w}$ = 2.3897 N

V = 0.6628 m/s : $\mathbf{R_w}$ = 8.4680 N

For h = 0.2428 m, and V = 0.6628 m/s : $\mathbf{R_w}$ = 2.2116 N.

Normal resistance can be determined under the assumption that the free water surface is not deformed. If to compare the so calculated resistance with the results of the calculations where the free water surface has been taken into account then the difference can be considered to be the wave resistance. At the known wave resistance, and making use of the formula (4), one can preliminarily calculate the approximate wave height in canal. For B_89 hull form, the normal resistance without taking into account free water surface in canal of the depth h = 0.1428 m (in model-scale) for the ship speed V = 0.45 m/s, amounts to $R_P$ = 7.46 N; and for the speed V = 0.6628 m/s – $R_P$ = 15.78 N. By taking into account the pressure resistance values contained in Tab. 1. the wave resistance amounts respectively to : 2.45 N for V = 0.45 m/s, and 11.75 N for the greater speed. The values are close to those obtained by using the formula (4), and this way the wave heights on the canal slope for the values of wave resistance, are known.

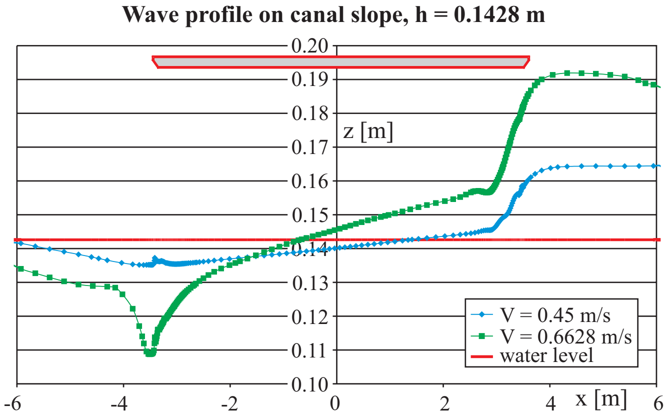



***Fig. 5.*** *Wave profile on canal slope.*
*Canal depth h = 0.1428 m. Model-scale applied .*

Additionally, in Fig.7 is presented the wave profile on ship side for canal and unlimited water width conditions. The profile is different than that on canal slope (Fig.4). An influence of limited canal width can be observed, especially in the bow region. During ship motion in canal a much higher bow wave is generated. In practice it may be manifested in the form of a greater value of trim by stern.

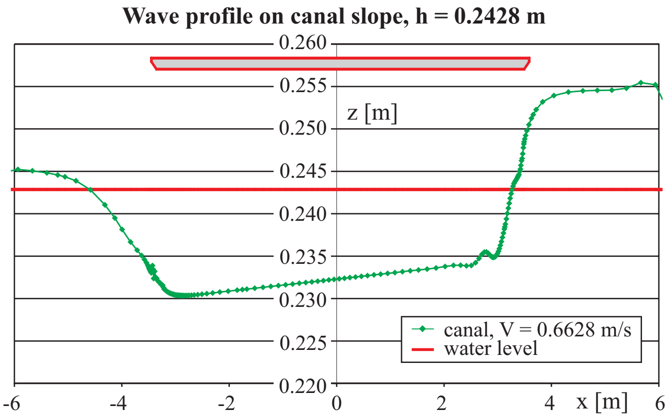
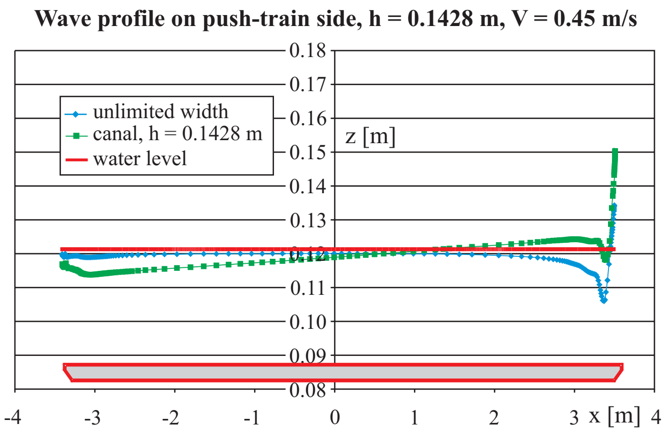



***Fig. 6.*** *Wave profile on canal slope. For h = 0.2428m. Model-scale applied .*
***Fig. 7.*** *Influence of canal on wave profile on ship side. Model-scale applied .*




## FINAL CONCLUSIONS

The FLUENT software can be used for analyzing and describing the phenomena which occur during ship motion on limited waterway. Calculation results of shape of free water surface show a suitable quantitative conformity with those from model tests, as well as with observations in real conditions. A disadvantage of application of the FLUENT software to calculations of ship motion with free water surface taken into account is a long calculating time. It was demonstrated that ship wave resistance may be useful in preliminary analysis of wave height on waterway slope. The ship-generated waves constitute the main factor which detrimentally affects stability of waterway banks. The ship-generated under-pressure occurring on waterway bed, the influence of behind-the-propeller stream (race) in normal service conditions are of a lower importance. Natural transportation of river bed rubble is deemed to cause larger changes in the bed than those due to ship motion itself.

***Acknowledgements***

*This work has been conducted in the frame of realization of the EUREKA -E!3065 INCOWATRANS research project.*

**NOMENCLATURE**

| | | |
|---|---|---|
| $A_M$ | – | midship section area [m$^2$] |
| B | – | ship breadth [m] |
| $b_0$ | – | canal width at its bed [m] |
| $b_1$ | – | canal width at water level [m] |
| $E_c$ | – | wave system energy |
| F | – | canal cross-section area [m$^2$] |
| g | – | gravity acceleration [m/s$^2$] |
| h | – | canal depth [m] |
| $h_w$ | – | wave height [m] |
| INBAT | – | Innovative barge trains for effective transport on shallow water |
| KLW | – | design waterline |
| PS | – | plane of symmetry |
| $R_P$ | – | normal resistance [N] |
| $R_W$ | – | wave resistance [N] |
| T | – | draught [m] |
| V | – | ship motion speed [m/s] |
| $V_{kr}$ | – | critical speed [m/s] |
| ρ | – | fluid density [kg/m$^3$] |

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# A probabilistic concept of assessment of amount of noxious substances contained in exhaust gas emitted from self-ignition engines

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ABSTRACT

*A probabilistic concept of toxicity assessment of exhaust gas emitted from self-ignition engines was presented. Without such assessment it is not possible to determine pro-ecological merits of various transport means driven by self-ignition engines, including inland waterways passenger ships. In the concept a model of starting-up process of self-ignition engines was taken into consideration. The model was presented in the form of a semi-Markovian process, discrete in states and continuous during service. The states of the process are : the cold engine state ($s_1$), warm engine state ($s_2$) and hot engine state ($s_3$). It made it possible to determine probabilities of the starting-up of engines from its particular states. For determination of mass of noxious substances contained in exhaust gas it is necessary to know the probabilities. Usefulness of the model in assessing amount of the noxious substances results from that during the starting-up of such engines many noxious substances are produced.*

**Keywords** : engine start-up, self-ignition engine, noxious substance

## INTRODUCTION

Presently, has been carried out research work on manufacturing the bio-degradable fuels having energy properties similar to those of fuel oils and being pro-ecological as much as possible, and which could be used to ship diesel engines instead of fuel oils. However before taking any decision on application of an alternative fuel to self-ignition engines it is necessary to perform a comparative analysis of combustion processes of fuels of the kind in such engines. It means that the following parameters of energy transformation in the engine should be considered {see Fig. 1. [13] } : overall efficiency of engine ($\eta_o$), heat emission coefficient ($w_c$), heat utilization coefficient ($w_{wc}$), heat generation coefficient (w), pressure increase rate ($\varphi_p$) etc, and content of such noxious substances in exhaust gas should be also analyzed, as : carbon monoxide (CO), hydrocarbons ($C_nH_m$), nitric oxides ($NO_x$), solid particles and sulfur compounds ($SiO_2$, $SiO_3$, $H_2SO_3$, $H_2SO_4$), aldehydes etc. Such analysis should show either that some alternative fuels make it possible to achieve better energy indices, or that they are more pro-ecological or even have both the merits. It can be based on laboratory tests. However no positive opinion on possible substitution of diesel oil for a given alternative fuel can be given without service tests of self-ignition engines. Only on the basis of such tests it can be unambiguously stated whether a given alternative fuel assessed fully applicable to diesel engines by means of laboratory tests will not cause a relatively greater wear of their main parts such as : injection system, piston-cylinder system and crankshaft bearings. Hence for the above mentioned analysis identification of combustion processes of diesel oil and alternative fuels in the aspects of energy, ecology and engine wear, is required.

In this work in the frame of such identification an original probabilistic method for assessing mass of possible noxious substances emitted from self-ignition engine has been proposed. In the method a model of starting-up the engine was taken into account. It was demonstrated that such model can be built in the form of semi-Markovian process. The presented proposal of assessment of toxicity of exhaust gases during start-up of the engine is important as environmental pollution by noxious substances is usually the highest just during engine start-ups.

## ENERGY AND PRO-ECOLOGICAL FEATURES OF COMBUSTION PROCESS IN SELF-IGNITION ENGINES

Combustion process in working volumes of self-ignition engines should ensure possibly the best energy indices as well as high engine reliability and durability and low environmental pollution [2, 9, 10, 13, 14]. Diesel engines for inland waterways passenger ships are fed with diesel oil. It would be advisable to use an alternative fuel having more pro-ecological merits, instead of diesel oil. Therefore the necessary knowledge of combustion processes of the above mentioned fuels should deal with transformation of chemical energy contained in the tested fuels (Fig. 1) into heat energy and next mechanical one, as well as its various effects. Moreover, application of an alternative fuel should not cause any faster wear of engines on which their reliability and durability as well as operational safety depend. In analyzing the run of combustion process in cylinders of self--ignition engines special attention should be paid to problems of emission of noxious substances the largest amount of which is produced during engine start-ups.

During operation of an arbitrary self-ignition engine the double transformation of energy occurs [2, 10, 13]. Such energy transformation is schematically presented in Fig.1.

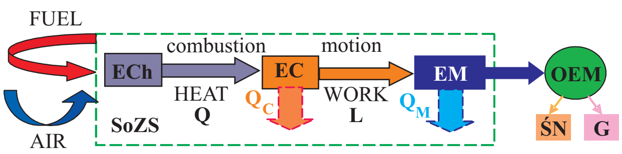


*Fig. 1. An example schematic diagram of energy transformation in self-ignition engine : **ECh** –chemical enegy; **EC** – heat energy; **EM** – mechanical energy; **SoZS** – self-ignition engine; $Q_c$ – thermal load; $Q_M$ – mechanical load, **OE** – energy consumer, **ŚN** – screw propeller, **G** – electric generator.*

Degree of perfection of energy transformation in self-ignition engines with taking into account the transferring of a part of transformed energy through its particular structural elements to surroundings, i.e the dissipated energy ($E_s$), is determined by using the overall efficiency of engine. The efficiency depends on losses occurring during work of engine, which are proportional to the dissipated energy ($E_s$). The energy constitutes the difference between the energy delivered to the engine ($E_d$) and the useful energy ($E_u$) produced by the engine in operation. The delivered energy ($E_d$) is chemical energy contained in the fuel injected to engine combustion chambers, and the useful energy ($E_u$) – mechanical energy delivered to energy consumers, e.g. screw propellers in the case of ship main engines (Fig.1). The investigations which have been done so far and concerned the run of combustion process in particular cylinders with taking into account not only fuel properties but also their working condition, made it possible to obtain a very high efficiency of self-ignition engines [2, 9, 10, 13, 14]. However not only the energy aspect is important. Important are also the contaminations contained in exhaust gases of the engines. Hence in shipboard conditions the combustion process cannot be assessed only on the basis of realization of pressure and temperature changes in cylinders (Fig.2) [9, 13, 14].

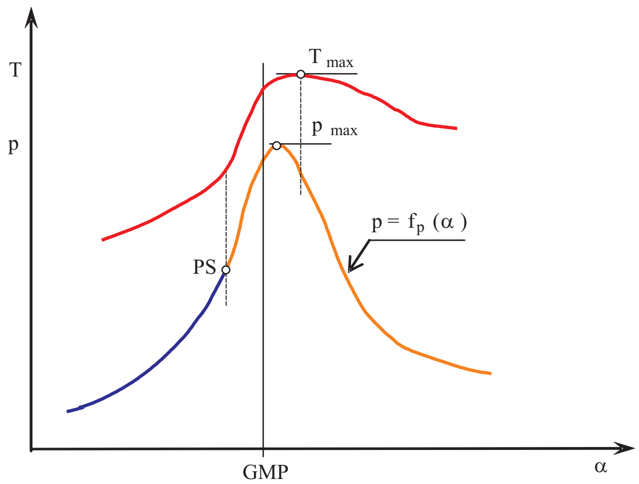


***Fig. 2.** Schematic diagram of run of pressure and temperature changes in cylinder of self-ignition engine : **p** – pressure, **T** – temperature, **α** – crankshaft rotation angle, $\boldsymbol{p_{max}}$ – maximum pressure, $\boldsymbol{T_{max}}$ – maximum temperature; **PS** – the beginning of fuel combustion in cylinder, **GMP** – upper dead centre of piston [16] .*

Among factors which significantly influence run of combustion process the following can be rated [9, 13, 14] :

a) physical and chemical properties of fuel, especially its chemical content, cetane number (LC), auto-ignition point ($T_{sz}$) and viscosity ($\nu$)
b) engine design features, especially type of its combustion chamber, compression ratio ($\varepsilon$),air temperature ($T_d$) and pressure ($p_d$) at the beginning of air inlet to cylinder
c) engine's main dimensions such as : the cylinder diameter (D) and piston stroke (S), piston material, injector type and run of process of fuel injection to combustion chamber
d) operational parameters of engine such as : torque load ($M_o$), rotational speed (n), injection pressure ($p_w$), combustion air factor ($\lambda$), ignition advance angle ($\alpha_{ww}$), cooling water temperature at inlet to engine ($T_{wd}$), amount of residual exhaust gases from the preceding cycle ($\gamma_r$).

The factors have impact on : ignition lag, quality of fuel spraying, velocity of conversion of fuel complex combustible particles into simpler ones such as : $H_2$, C, S and CO which can be oxidized, rate of pressure rise ($\varphi_p = dp/d\alpha$), temperature ($T_{ks}$) and pressure ($p_{ks}$) in the end of compression.

Correctness of run of combustion process can be assessed also by means of such parameters as [22] : heat emission coefficient ($w_c$), heat utilization coefficient ($w_w$), heat generation coefficient ($w_{wc}$), heat generation rate (w), the ratio of the maximum heat generation rate ($w_{max}$) and ignition-lag ($\tau_{zz}$).

From the heat generation characteristics it results that in order to ensure maximum transformation of the heat (Q) into the work (L) (see Fig. 1) it is necessary to form combustion process in such a way as to generate the largest amount of Q in the initial phase of combustion process, as close to GMP as possible (Fig.2). However it should be observed that then dynamic combustion indices grow. Therefore both combustion time and amount of the heat generated in the initial phase of combustion should be so selected as to obtain a compromise between heat utilization economy and mechanical load on engine crankshaft assembly system, as well as noise associated with its operation. Also, run of process of oxidation of combustible fuel components and formation of compounds noxious to the environment, should be taken into account. Primary products of oxidation resulting from chain reactions constitute peroxides and hydro-oxides which next undergo disintegration. The disintegration products enter into reaction with oxygen, which results in forming aldehydes, acides, water vapour, carbon monoxide (CO) (very noxious) and dioxide ($CO_2$), and is associated with heat educe. Carbon monoxide is also produced in such processes as [1] :

- low-temperature oxidation of hydrocarbons
- disintegration of RCHO aldehydes
- high-temperature dissociation of $CO_2$.

From research on fuel combustion processes it results that physical, but not chemical, factors have significant influence on emission amount of particular noxious components of exhaust gas, and that their emission is tightly mutually connected and the possible lowering of emission of one of them may cause increasing emission of another. Therefore all undertakings aimed at lowering content of noxious components in exhaust gas must result from a compromise to obtain minimum noxious effects of detrimental impact of the components to the environment.

From the literature sources [1, 5, 6, 15] it results that prevailing amount of noxious components in exhaust gas is produced during start-up of engine. Hence in order to predict amount of noxious compounds in exhaust gas a model of engine starting--up process should be elaborated with taking into account at least three engine states, namely : cold, warm and hot, in which such process is possible.

## SEMI-MARKOVIAN PROCESS OF SELF--IGNITION ENGINE STARTING-UP

The three distinguished thermal states of self-ignition engine, which can exist just before its starting-up, namely : the cold state ($s_1$), warm state ($s_2$), and hot state ($s_3$), can be taken as values of the stochastic process $\{U(t) : t \in T\}$, assumed to be the model of the real starting-up process of engine. According to [6, 4, 16] such model can be presented in the form of a semi-Markovian process having the set of states :

$$S = \{s_1, s_2, s_3\} \tag{1}$$

and the following interpretation of the states :

- the cold state $s_1$ which makes it possible to start up the engine in ambient conditions (in ship engine room) characteristic of a low temperature (T), not greater than 290 K as a rule
- the warm state $s_2$ which makes it possible to start up the engine in conditions of pre- heating the engine (T > 300

K), performed before its starting-up, and which was in the state $s_1$ before the pre-heating process is commenced

☆ the hot state $s_3$ which makes it possible to start up the engine in its working conditions which result from the necessity to stop it even under large load and then to start up it again.

The graph of states of the considered starting-up process, $\{U(t) : t \geq 0\}$, of self-ignition engines is shown in Fig.3.

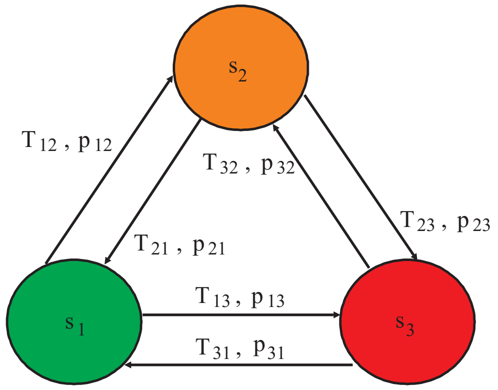


***Fig. 3.*** *The graph of states of starting-up process of an arbitrary diesel engine : **$s_1$** – cold state, **$s_2$** – warm state, **$s_3$** – hot state, **$p_{ij}$** – probabilities of transition of the process from the state $s_i$ to the state $s_j$ , **$T_{ij}$** – duration time of the state $s_i$ provided that the process passes to the state $s_j$ ; **i, j** = 1, 2, 3 .*

The triple-state process is of continuous realizations. It is semi-Markovian process [3, 4, 16] and – in the considered application – the simplest one out of those having practical importance.

Hence the set of the starting-up states of self-ignition engines, $S = \{s_1, s_2, s_3\}$, can be considered as the set of values of the stochastic process, $\{U(t) : t \in T\}$, of constant (uniform) intervals and realizations continuous on the right. The example realization of the process is presented in Fig. 4.

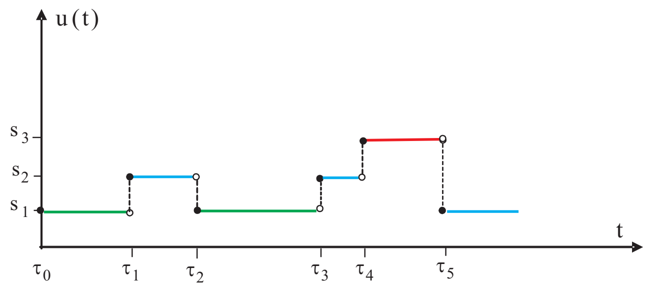


***Fig. 4.*** *An example of realization of the process, U(t) : t ∈ T}, of self-ignition engine : {U(t) : t ∈ T}–engine starting-up process, t–time of operation; **$s_1$** – state of full serviceability, **$s_2$** – state of partial serviceability, **$s_3$** – state of non-serviceability .*

The initial distribution of the considered process $\{U(t) : t \in T\}$ (see also Fig.3 and 4) is, for self-ignition engine, determined by the formula :

$$P_i = P\{U(0) = s_i\} = \begin{cases} 1 & \text{for } i = 1 \\ 0 & \text{for } i = 2, 3 \end{cases} \qquad (2)$$

and, the functional matrix of the process is as follows :

$$Q(t) = \begin{bmatrix} 0 & Q_{12}(t) & Q_{13}(t) \\ Q_{21}(t) & 0 & Q_{23}(t) \\ Q_{31}(t) & Q_{32}(t) & 0 \end{bmatrix} \qquad (3)$$

In the case of main engine of any ship it may be expected that its stays in ports would be long enough the engine to be cooled down up to the cold state after some time. Hence the repeated start-up of engine to continue the voyage will be performed from the state $s_1$. Moreover, the engine may be at idle running for a short time before starting-up. In consequence, the starting-up of engine may also commence from the state $s_2$. Also, the cases of the starting-up of main engines from the state $s_3$ cannot be omitted, that is usually associated with manoeuvres in ports or during moving through canals.

Hence for the presented process $\{U(t) : t \in T\}$, of the initial distribution (2) and functional matrix (3), one can determine the following limiting distribution [3, 4, 16] :

$$P_1 = \frac{\pi_1 E(T_1)}{H} \; ; \; P_2 = \frac{\pi_2 E(T_2)}{H} \; ; \; P_3 = \frac{\pi_3 E(T_3)}{H} \qquad (4)$$

and :

$$\pi_1 = \frac{p_{31} + p_{12}p_{32}}{2 + p_{12}p_{23}p_{31} + p_{13}p_{21}p_{32}}$$

$$\pi_2 = \frac{p_{32} + p_{12}p_{31}}{2 + p_{12}p_{23}p_{31} + p_{13}p_{21}p_{32}}$$

$$\pi_3 = \frac{1 - p_{12}p_{21}}{2 + p_{12}p_{23}p_{31} + p_{13}p_{21}p_{32}}$$

$$H = \pi_1 E(T_1) + \pi_2 E(T_2) + \pi_3 E(T_3)$$

where :

$P_1, P_2, P_3$ – probabilities of the event that self-ignition engine is started up from the states : $s_1, s_2, s_3$ , respectively

$\pi_j$ – limiting probability of the Markov chain which is inserted into the process $\{U(t) : t \in T\}$, and describes possible occurrence of the state $s_j$ , $j = 1, 2, 3$

$p_{ij}$ – probability of transition of the process $\{U(t):t \in T\}$ from the state $s_i$ to the state $s_j$

$E(T_j)$ – expected value of duration time of the state $s_j$ , ($j = 1, 2, 3$).

The presented starting-up states of any self-ignition engine are associated with relevant thermal states which represent those occurring in practice. Hence the proposed model may be used to determine mass of noxious substances contained in exhaust gas.

During starting-up the cold engine (state $s_1$) an increased emission of hydrocarbons ($C_nH_m$) and carbon monoxide (CO) occurs. Hence the starting-up of engine in a low temperature makes emission of carbon dioxide ($CO_2$) lower. However, emission of solid particles increases, but emission of nitric oxides ($NO_x$) decreases. It is due to a low temperature of fresh charge, that makes forming such compounds more difficult.

The reason of the situation are too low temperatures of surfaces of the elements which form combustion chamber, exhaust gas system and cooling system, [1, 7, 11, 12].

Too low temperature of cylinder walls causes intensive flame extinguishing (break of chain of chemical reactions). It leads to combustion quality worsening. As a result appears a greater amount of not fully combusted hydrocarbons in various forms, and a greater emission of CO and soot, in particular. The greater emission of soot results from a low temperature of engine cylinder interior, that is not conductive to burning-out the soot. According to [1] The absence of the soot burning-out phenomenon takes place in the case of lowering the temperature in the cylinder below 500 ÷ 600°C, which happens even if there is a sufficient amount of oxygen in it.

Too low temperature of exhaust gas system, like low temperature in cylinder volume, is not conductive to carbon dioxide ($CO_2$) forming. It results from the fact that combustion of carbon monoxide (CO) formed in low temperatures and carbon dioxide ($CO_2$) forming is possible only in the temperature more than 300°C [1].

Also, too low temperature of engine elements due to low temperatures of cooling water, makes full combustion developing more difficult. Moreover, low temperature of lubricating oil makes it much more viscid, that causes an increase of engine resistance to motion and thereby a loss of output power and increased fuel oil consumption. It results in an increased emission of noxious components of exhaust gas, especially CO, except of nitric oxides ($NO_x$).

During cold engine starting-up intensive wall effect occurs. It takes place when temperature of fuel-air mixture near the combustion chamber walls is too low to trigger correct combustion process, because of excessive loss of the heat transferred from the produced exhaust gas to the combustion chamber walls. As a result significant drop of temperature of fuel-air mixture in the boundary layer occurs, as much down as below its ignition temperature. According to the chain theory, the flame extinguishing results from decreased concentration of active particles of intermediate combustion products. Limiting value of the concentration, below which flame cannot be maintained, is function of pressure, temperature and content of combustible mixture in a given engine working volume.

## DETERMINATION OF MASS OF NOXIOUS SUBSTANCES DURING STARTING-UP PROCESS OF ENGINE

Analyzing research results on combustion process running (Fig. 2) one can state that during the process different conditions for forming the above mentioned noxious compounds occur in exhaust gas. Moreover, it is known that properties of fuel oil, including sulfur content in it, influence the exhaust gas toxicity [1, 8, 9, 14].

Sulfur content in diesel oil has significant impact on emission of noxious compounds, mainly solid particles, as it lowers engine life-time by accelerated wear of its elements being in contact with exhaust gas. During combusting sulfur compounds in engine working volume sulfur dioxide ($SiO_2$) and trioxide ($SiO_3$) is formed, which, in contact with water particles, produce sulfurous, ($H_2SO_3$), and sulfuric, ($H_2SO_4$), acid, respectively. A part of sulfur particles in the form of sulfur ions is absorbed by surface of solid particles and then discharged together with them to the environment.

Increase of cetane number (LC) of diesel oil makes content of carbon monoxide (CO) and hydrocarbons ($C_nH_m$) in exhaust gas, smaller. According to [26], the rise of cetane number, e.g from 40 to 50, decreases CO emission by 25% and $C_nH_m$ one - by 40%. Moreover, increase of the LC of diesel oil leads to a lower level of noise generated by engine : e.g. in the case of the diesel oil of LC = 48, engine noise level reaches 76 dB(A), and for LC = 60 – that of 73 dB(A).

Decrease of the diesel oil density (ρ) from 0, 845 [kg/dm$^3$] to 0, 825 [kg/dm$^3$] results in the drop of particulate matter emission by 5 ÷ 10% [16]. Such decrease of content of poly--cyclic aromatic hydrocarbons is favourable. For instance, by lowering the content of the hydrocarbons in diesel oil from 9% to 1% it is possible to reduce amount of particulate matter in exhaust gas by about 5% [16].

Toxicity of exhaust gas can be reduced also by introducing special additions which are able to lower content of noxious compounds in it. Nonetheless, mass of noxious substances which may be contained in exhaust gas, should be known in any case both before and after actions aimed at lowering their content.

Mass of emitted noxious substances can be determined by means of the following formula [1] :

$$e_k = \frac{v_{mix} \rho_k K_H c_k}{s} 10^{-6} \qquad (5)$$

where :

k = 1, 2,..., n – number (kind) of noxious substance

and :

- $e_k$ – mass of a polluting substance [g/km]
- $v_{mix}$ – volume of diluted exhaust gas in the normal conditions [dm$^3$/test]
- $\rho_k$ – density of polluting substance in the normal conditions [g/dm$^3$]
- $K_M$ – correction factor of humidity of mass of nitric oxides
- $c_k$ – concentration of a substance polluting the environment [ppm]
- s – distance covered by a ship during conducting the tests [km].

The emission $e_k$ (k = 1, 2,..., n) is different depending on whether the starting-up commences from the cold state ($s_1$), warm state ($s_2$), or hot state ($s_3$). During ship voyage of the length (s) when the test has to be conducted, many engine start--ups may be performed from its different states. The emission from the same engine will be also different as it depends also on technical state of equipment of its fuel system, and kind of fuel oil on which it works. Important are also ambient conditions in which the engine has to start up. Therefore it can be assumed that the mass of emitted noxious substances derived from the formula (5) constitutes realization of the emission which can be taken as the random variable $E_k$. Hence the mass of noxious substances can be expressed, by taking into account the relations (4) and (5), in the form of the expected value as follows :

$$E(E_k) = \frac{(p_{31} + p_{12}p_{32})E(T_1)}{M} e_{1k} + \frac{(p_{32} + p_{12}p_{31}E(T_2)}{M} e_{2k} + \frac{(1 - p_{12}p_{21})E(T_3)}{M} e_{3k} \qquad (6)$$

and :

$$M = E(T_1) + p_{12}E(T_2) + (1 - p_{12}p_{23})E(T_3)$$

where :

- $E(E_k)$ – expected value of the random variable $E_k$
- $e_k$ – mass of k-th substance polluting the environment, (k = 1, 2,..., n)
- $p_{ij}$ – probability of transition of the engine starting-up process $\{U(t) : t \in T\}$ from the state $s_i$ to the state $s_j$, $i \neq j$; i, j = 1, 2, 3
- $E(T_j)$ – expected value of duration time of the state $s_j$ (j = 1, 2, 3).

The formula (6) results from the fact that all relations given in the formula (4) which determines the probabilities $P_1$, $P_2$ and $P_3$, as well as the relation (5) were taken into account.

## FINAL REMARKS AND CONCLUSIONS

- The largest emission of noxious substances contained in exhaust gas occurs during the starting-up process of engines.
- Therefore it was proposed and demonstrated that to assess amount of emitted substances a semi-Markovian, triple-state model of engine starting-up process, i.e. that to which the three states : cold, ($s_1$), warm, ($s_2$), and hot, ($s_3$) are attributed, can be applied.
- Usefulness of the model for determining mass of the noxious substances emitted to the environment during engine starting-up was made evident. It was assumed that the masses of polluting substances, $e_k$, where k = 1, 2, ..., n {n–kind (number) of a given noxious substance}, possible to be determined, constitute realizations of the random variable $E_k$ which represents emitted mass of noxious substance of k-th kind.

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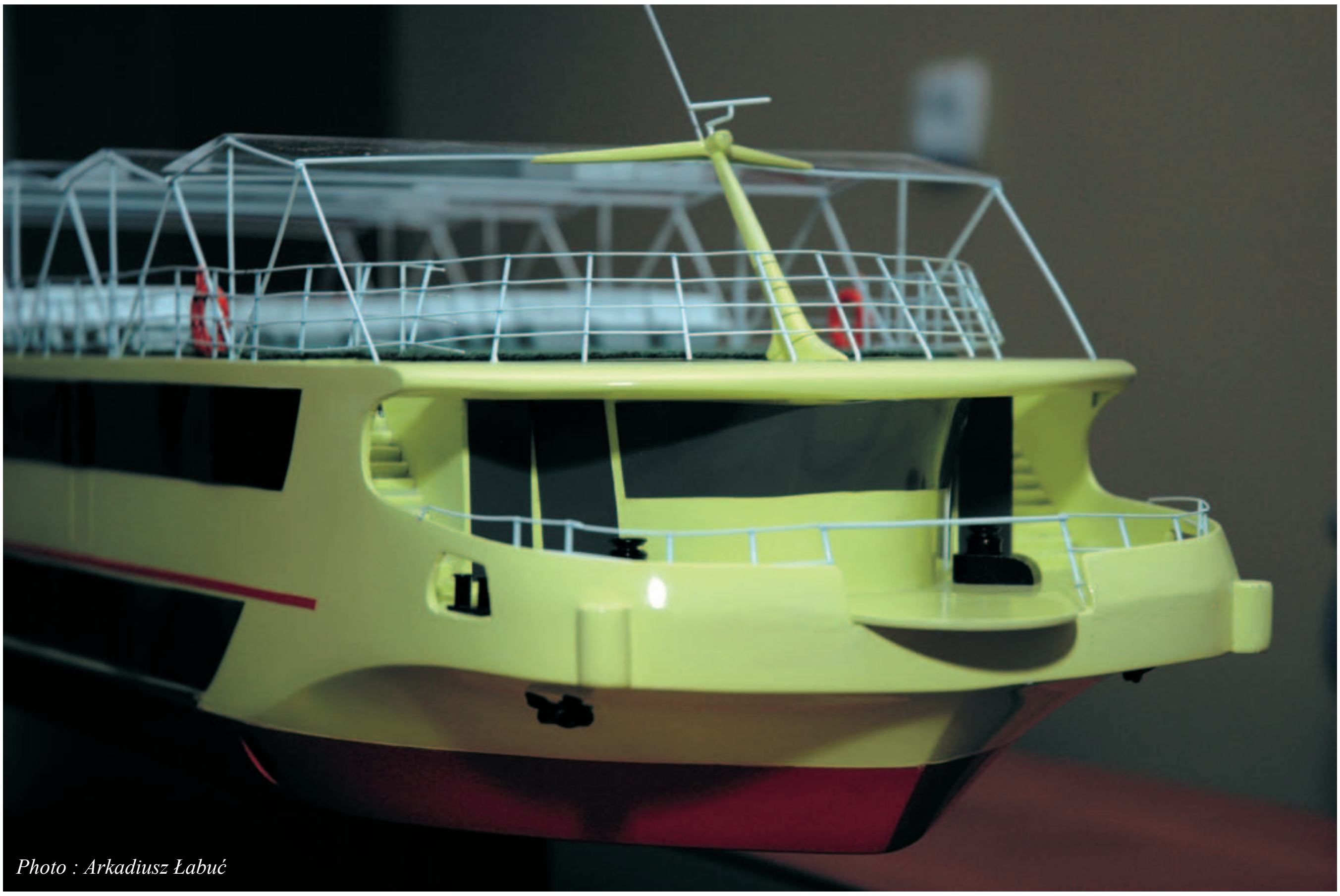

*Photo : Arkadiusz Łabuć*

# A model of occurrence of the situations endangering inland waterways passenger ships and the environment

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ABSTRACT

*In this paper a four-state semi-Markov model of occurrence of the situations endangering inland waterways passenger ships, is presented. The model was elaborated in the form of the semi - Markov process, values of which are kinds of the states interpreted as the following situations : normal, complicated, hazardous and emergency. An example of realization of the process of changing the situations possible to occur during trips of inland waterways passenger ships, is presented. Also, formulae are attached, which make it possible to determine probabilities of occurrence of the mentioned situations during ship trips. The formulae were interpreted as safety measures of operation of inland waterways ship. Possibility of performing statistical investigations which could provide data for determining the mentioned probabilities was also stated.*

**Keywords** : inland waterways ships, prediction of failure probability, availability indices of ship devices

## INTRODUCTION

During voyage of inland navigation ships and also during their stopovers in river ports, can happen various situations which, from the point of view of degree of their seriousness, can be divided into [6, 9, 12, 14] : normal, complicated, hazardous, emergency and disastrous.

Direct users of such ships (e.g. officers, engineers) as well as indirect ones (e.g. ship owner) tend ensuring the normal situation, i.e. that in which safe operation of the ship is possible. The safe operation of inland navigation ship is such an operation which does not cause a hazard to the ship and the environment. Such hazard can happen in the case of occurrence of an extensive failure (breakdown) of any of such its devices which influences significantly assurance of required safety (e.g. propulsion system, steering gear, sewage treatment plant etc). Failures of such devices can lead to loss of health (and also life) of a number of passengers and crew members as well as pollution of the environment.

Consideration of features of inland navigation passenger ships – from safety point of view – as well as psychical and physical predispositions of their crews, and also operation and maintenance conditions of their devices, makes it possible :

- ♦ to precisely describe a kind of situation in which a given ship operates
- ♦ to assess expected value of duration time of particular situations in which every device ensuring safe operation of a given ship, can be found
- ♦ to determine frequency of occurrence of the mentioned situations during a longer time of performing shipping tasks by a given ship.

As the situations in which inland navigation passenger ship can find itself, are random events and their duration time is a random variable, one can apply the theory of stochastic processes [3, 6, 8, 10, 11] (after some simplifications) for determining occurrence probabilities of the event of finding such ship in the particular situations.

Hence investigation of safety of the considered ships and their operational safety during their tourist trips requires to build a stochastic model of changes of the mentioned situations in which the ships can be found. Such model is necessary for determining probabilities of occurrence of particular situations during a longer time interval (theoretically when $t \to \infty$).

To prevent occurrence of unwanted situations (different from normal one) is possible in the case of taking appropriate decisions first of all by direct (and sometimes also indirect) users of ships of the kind. In order to take such decisions, is necessary not only to know values of occurrence probabilities of the mentioned situations, but also values of probabilities of finding the crucial devices of the ships (e.g. their propulsion systems or steering gears etc) in the particular technical states such as : full serviceability, partial serviceability, task unserviceability, full unserviceability [6, 7, 8, 14]. Below, the problem is considered of determination of probabilities of occurrence of the above mentioned situations, namely :
$s_0^*$ – normal, $s_1^*$ – complicated, $s_2^*$ – hazardous,
as well as $s_3^*$ – – emergency one.

## FORMULATION AND SOLUTION OF THE PROBLEM

Changes of particular situations in which traffic of inland navigation ships can be realized, in contrast to sea-going ones, may be considered in the form of the random process $\{Y(t): t \geq 0\}$, discrete within the states and continuous with time, of the four-element set of states $S^* = \{s_j^*; i = 0, 1,..., 3\}$, where t – realization time of the process, which practically represents trip duration time of a given inland navigation passenger ship [4, 5, 14].

In this case general interpretation of the states $s_j^* \in S^*$ (j = 0, 1,..., 3) is as follows :

- ✦ $s_0^*$ – normal situation
- ✦ $s_1^*$ – complicated situation
- ✦ $s_2^*$ – hazardous situation
- ✦ $s_3^*$ – emergency situation.

The disastrous situation $s_4^*$ which is considered in the case of sea-going ships, can be omitted when considering safety of inland navigation passenger ships. As sinkage of such ship is rather impossible because of very shallow waters in which such ship operates, as well as in view of ambient conditions which are much more mild than those at sea. However it can ground on a shoal and become an obstacle for navigation.

The distinguished states $s_j^* \in S^*$ (j = 0, 1,..., 3) occur at random instants and last within the time intervals $[\tau_0, \tau_1)$, $[\tau_1, \tau_2)$,..., $[\tau_n, \tau_{n+1})$, which are random variables.

In the normal situation ($s_0^*$) crews of inland navigation passenger ships (called further shortly :"ships") fulfil their duties in the conditions to which they are accustomed. Such conditions do not involve any excessive stress to the crews and do not push them to develop excessive physical and intellectual efforts.

The complicated situation ($s_1^*$) occurs when events making realization of a given task difficult, happen. In the case of passenger ships, among such events the following can be numbered a.o.: a failure of one of the main propulsion systems or all of them, i.e. a failure of the entire propulsion system of the ship. In such cases the ship crews are pushed to develop a short-term physical and intellectual effort to cope with tasks resulting from the necessity of removing causes of the occurred situation.

The hazardous situation ($s_2^*$) occurs when events making realization of a given task impossible, happen, for instance ship's arrival in time at a port, in line with expectations of tourists. Among such events the following can be numbered for instance: a failure of one of the main propulsion systems (or all of them) during worsening weather conditions (strengthening wind, or rainfall, increasing water depth and stream-way velocity of the river on which the ship sails), as well as a failure of steering gear, main electric switch board, underwater part of ship's hull, that leads to flooding its interior etc. In such cases to increase efforts of ship's crew to make the ship capable of safe sailing, is necessary.

The emergency situation ($s_3^*$) occurs when ship's crew cannot restore the technical state after occurrence of the mentioned failures, especially those of propulsion system and/or steering gear in conditions of worsening weather, strengthening wind etc, that makes anchoring the ship in the place of failure occurrence, necessary. Such state may endanger health and even life of the crew and perhaps also of some passengers especially those aged or having health problems.

In its initial phase, operation of every ship is usually realized in the normal situation determined by the following factors [1, 6, 7, 15] :

- the state of full serviceability of the object, especially of its propulsion system, steering gear and electric energy system
- the high level of psychical and physical predispositions of ship's crew members
- favourable ambient conditions in which the ship operates
- correct maintenance performed in advance, before commencing realization of a given task by the ship.

In the case of worsening the first of the three above mentioned factors and /or not performing the required maintenance (preventive or after-failure one) the ship (and also the considered process $\{Y(t): t \geq 0)$ undergoes transition from the state $s_0^*$ to the state $s_1^*$, which is equivalent to the change of the normal situation ($s_0^*$) in which the ship has been operated in given waters, into the complicated one ($s_1^*$) whose interpretation was highlighted in [14]. The change occurs with the probability $p_{01}$, after the time interval which is realization of the random variable $T_{01}$, representing the duration time of the situation (state) $s_0^*$ provided the next state will be the situation $s_1^*$. An appropriate action of the crew can certainly restore the situation $s_0^*$ that may occur with the probability $p_{10}$, after the time interval which is realization of the random variable $T_{10}$. In the case of worsening the mentioned factors it may happen that to come back to the situation (state) $s_0^*$ is not possible, that inevitably leads to the hazardous situation (state) $s_2^*$. It is equivalent to the transition of the investigated process $\{Y(t): t \geq 0\}$ from the state $s_1^*$ to the state $s_2^*$. Such change of the situation occurs with the probability $p_{12}$, after the time interval being the realization of the random variable $T_{12}$.

Crew's actions appropriate to the situation may lead back to the situation $s_0^*$, however only after recovery of the situation $s_1^*$. Otherwise the situation $s_3$ (emergency) may appear due to worsening the technical state of the ship and its operational conditions, with the probability $p_{23}$ and after the time interval being the realization of the random variable $T_{23}$ which represents duration time of the situation $s_2^*$ provided that the next will be the state $s_3^*$. From this situation it is possible sometimes to come back to the above mentioned situations, only as a result of crew's actions, but often it requires calling for help from the side of various rescue institutions.

Hence it can be stated that reasonable is to consider the process $\{Y(t): t \geq 0\}$ of the graph of changes of the states : $s_j^* \in S^*$j = 0, 1,..., 3), presented in Fig.1.

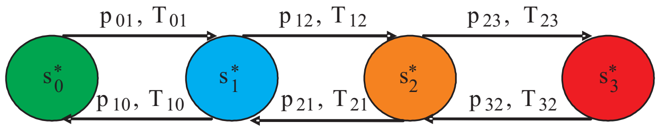


***Fig. 1.** Graph of state changes of the process $\{Y(t): t \geq 0\}$ .*

The above presented graph of changes of the states of the process $\{Y(t): t \geq 0\}$ is crucial for the proposed solution of the problem of determining probabilities of being the process in specified states, as it makes it possible to build the functional matrix necessary for determining the expressions for assessment of the mentioned probabilities. In the case of assuming another graph than that presented in Fig.1. other expressions for determining the probabilities will be obtained.

From the considerations it results that the appearance of the states $s_j^* \in S^*$ (j = 0, 1, 2, 3) depends on technical state of the main devices of ship especially its propulsion system, as well as on its ambient conditions of operation on a given waterway. Hence it is necessary to determine the set of technical states of the mentioned devices, knowledge of which could make it possible to avoid the most hazardous situations (and even emergency one) for the considered ships and the environment. The same conclusion concerns the set of technical states of the ships in question and their devices, which can appear during their tourist and recreation trips.

From the considerations presented in [5, 6, 10, 14, 15] it results that for determining the set of such states, is reasonable to assume the capability of fulfilling their tasks by the mentioned ships and their devices, to be the classification criterion of the states. In line with the criterion the following classes of the technical states (called further simply : states) can be distinguished :

- the full serviceability state $s_1$, which makes it possible to use ships and their devices in every conditions and load range, to which they have been adjusted during their designing and manufacturing
- the partial serviceability state $s_2$, which makes it possible to use ships and their devices in limited conditions and load range, lower than those to which they have been adjusted during their designing and manufacturing
- the serviceability state $s_3$, which does not make it possible to use ships and their devices in accordance with their mission

(because of their failed devices, e.g. propulsion system, performing of maintenance operation of the devices, during which ship operation is not possible, etc).

The specified states $s_i \in S$ (i = 1, 2, 3) of particular devices of the ships in question can be recognized by relevant diagnostic systems (SD) whose applicability depends on quality of the diagnosing system (SDG) as well as its capability of recognizing the mentioned states of the devices of every ship, considered as the diagnosed systems (SDN) [3, 6, 7].

An example of realization of the process $\{Y(t): t \geq 0\}$ is presented in Fig.2.

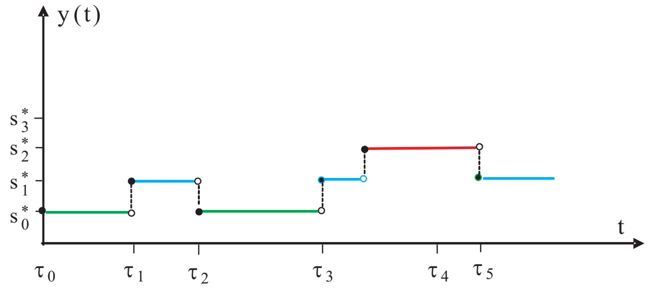


***Fig. 2.*** *An example of one-dimensional run of the process {Y(t): t ≥ 0} .*

Changes of the states belonging to the set $S^* = \{s_i^*; i = 0, 1,...,3\}$, during operation of every ship in question, can be considered as the process $\{Y(t): t \geq 0\}$ whose realizations are constant (uniform)within particular time intervals and continuous on the right [6, 11, 14]. Lengths of the intervals are the random variables $T_{ij}$ equivalent to duration time of the state $s_i^* \in S^*$ of the process in question provided that the next is the state $s_j^* \in S^*$, where : i , j = 0, 1,..., 4, and $i \neq j$. The variables are random, independent, having the finite expected values $E(T_{ij})$ and positively concentrated distributions. Moreover the process is characterized by that the duration time of the state $s_i^*$, occurred in the instant $\tau_n$ , as well as the state appeared in the instant $\tau_{n+1}$ do not depend stochastically on the previous states and their duration time intervals. Hence it can be assumed that future states (situations) depend first of all on the current situation. It means that the process $\{Y(t): t \geq 0\}$ can be considered as a semi-Markov process of the graph of state changes, presented in Fig. 1. In order to define the process its initial distribution $P_i$ as well as its functional matrix **Q(t)** should be determined in advance.

The initial distribution of the process $\{Y(t): t \geq 0\}$ is as follows :

$$P_i = P\{Y(0) = s_i^*\} = \begin{cases} 1 & \text{for } i = 0 \\ 0 & \text{for } i = 1, 2, \ldots, 3 \end{cases} \qquad (1)$$

In accordance with the graph presented in Fig.1 the functional matrix is of the following form :

$$\mathbf{Q(t)} = \begin{bmatrix} 0 & Q_{01}(t) & 0 & 0 \\ Q_{10}(t) & 0 & Q_{12}(t) & 0 \\ 0 & Q_{21}(t) & 0 & Q_{23}(t) \\ 0 & 0 & Q_{32}(t) & 0 \end{bmatrix} \qquad (2)$$

The elements of the matrix (2) are non-decreasing functions of the variable t, which represent the probabilities of transition of the process $\{Y(t): t \geq 0\}$ from the state $s_i^*$ to the state $s_j^*$ ($s_i^*, s_j^* \in S$ ; i , j = 0, 1,..., 3; $i \neq j$) during the time not greater than t, and which are described as follows [6, 11] :

$$Q_{ij}(t) = P\{Y(\tau_{n+1}) = s_j^* \quad \tau_{n+1} - \tau_n < t \mid Y(\tau_n) = s_i^*\} = p_{ij}F_{ij}(t) \qquad (3)$$

where :

$s_i^*, s_j^* \in S$(i , j = 0, 1,..., 3; $i \neq j$), and :

$p_{ij}$ – probability of one-step transition in uniform Markov chain inserted in the process $\{Y(t): t \geq 0\}$,

$F_{ij}(t)$ – cumulative distribution function of the random variable $T_{ij}$ representing duration time of the state $s_i^*$ of the process$\{Y(t): t \geq 0\}$ provided that the next is the state $s_j$.

The probability $p_{ij}$ is interpreted as follows :

$$p_{ij} = P\{Y(\tau_{n+1}) = s_j^* \mid Y(\tau_n) = s_i^*\} = \lim_{t \to \infty} Q_{ij}(t) \qquad (4)$$

In the situation, solving the so formulated problem consists in finding the limiting distribution of the process $\{Y(t): t \geq 0\}$, which has the following interpretation :

$$P_j = \lim_{t \to \infty} P\{Y(t) = s_j^*\} \quad ; \quad j = \overline{0{,}3}$$

The distribution can be determined by using the formula [11, 14] :

$$P_j = \frac{\pi_j E(T_j)}{\sum_{k=0}^{3} \pi_k E(T_k)} \quad ; \quad j = 0,\ 1,\ \ldots,\ 3 \qquad (5)$$

where :

$$\pi_j = \lim_{n \to \infty} \frac{1}{n} \sum_{k=1}^{n} P\{Y(\tau_n) = s_j \mid Y(0) = s_i\}, \text{ and :}$$

[$\pi_j$; j = 0, 1,..., 3] is the stationary distribution of the Markov chain $\{Y(\tau_n): n \in N\}$ inserted in the process $\{Y(t): t \geq 0\}$.

The distribution satisfies the set of equations (6) and (7) [11, 14] :

$$\sum_{i=0}^{3} \pi_i p_{ij} = \pi_j \quad ; \quad i, j = 0, 1, \ldots, 3 \qquad (6)$$

$$\sum_{i=0}^{3} \pi_i = 1 \qquad (7)$$

The matrix (2) is stochastic, hence the matrix of the transition probabilities $\mathbf{P} = [p_{ij}]$, i , j = 0, 1,..., 3 is as follows :

$$\mathbf{P} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ p_{10} & 0 & p_{12} & 0 \\ 0 & p_{21} & 0 & p_{23} \\ 0 & 0 & p_{32} & 0 \end{bmatrix} \qquad (8)$$

Therefore the equations (6) and (7) which characterize the limiting distribution $\pi_j$ , j = 1, 2, 3 of the Markov chain $\{Y(\pi_n$: n = 0, 1, 2,...} inserted in the process $\{Y(t): t \geq 0\}$ can be presented in the form of the set of equations [14] :

$$\left.\begin{aligned} [\pi_0, \pi_1, \pi_2, \pi_3] \begin{bmatrix} 0 & 1 & 0 & 0 \\ p_{10} & 0 & p_{12} & 0 \\ 0 & p_{21} & 0 & p_{23} \\ 0 & 0 & p_{32} & 0 \end{bmatrix} &= [\pi_0, \pi_1, \pi_2, \pi_3] \\ \pi_0 + \pi_1 + \pi_2 + \pi_3 &= 1 \end{aligned}\right\} \qquad (9)$$

By solving the set of equations (9) the following relationships are obtained according to the equation (5) :

$$P_0 = \frac{p_{10}p_{21}p_{32}E(T_0)}{M} \; ; \; P_1 = \frac{p_{21}p_{32}E(T_1)}{M}$$
$$P_2 = \frac{p_{12}p_{32}E(T_2)}{M} \; ; \; P_3 = \frac{p_{12}p_{23}E(T_3)}{M} \qquad (10)$$

and :

$$M = p_{10}p_{21}p_{32}E(T_0) + p_{21}p_{32}E(T_1) + $$
$$+ p_{12}p_{32}E(T_2) + p_{12}p_{23}E(T_3)$$

where :

$p_{ij}$ − transition probability of the process $\{Y(t): t \geq 0\}$ from the state $s_i^*$ to the state $s_j^*$ ($s_i^*, s_j^* \in S$; i, j = 0, 1,..., 3; i ≠ j)

$E(T_j)$ − expected value of the random variable $T_j$(j = 0, 1,..., 3) representing duration time of the state $s_j^* \in S$(j = 0, 1,..., 3) of the process $\{Y(t): t \geq 0\}$ regardless of the state to which the process comes.

The expected values $E(T_j)$ depend on the expected values $E(T_{ij})$ as well as on the probabilities $p_{ij}$, in the following way :

$$E(T_j) = E(T_i) = \sum_j p_{ij}E(T_{ij}) \; ; \; i, j = \overline{0,3} \; ; \; i \neq j \qquad (11)$$

The particular probabilities $P_j$(j = 0, 1,..., 3) have the following interpretation :

$$P_0 = \lim_{t\to\infty} P\{Y(t) = s_0^*\}$$
$$P_1 = \lim_{t\to\infty} P\{Y(t) = s_1^*\}$$
$$P_2 = \lim_{t\to\infty} P\{Y(t) = s_2^*\}$$
$$P_3 = \lim_{t\to\infty} P\{Y(t) = s_3^*\}$$

The probability $P_0$ can be considered to be a measure of safe trip of inland navigation ship including safe operation of its propulsion system, as well as any other energy system or device installed on the ship, hence also a measure of safety of passengers and crew members.

Also the probability $P_1$ can be considered as a measure of safe trip and safe operation of any energy system as well. Whereas the remaining probabilities ($P_2$ and $P_3$) can be taken as measures of unsafe trip of the ship in question, hence of unsafe operation of propulsion system of the ship and also any other energy system or device. The probabilities contain information on possible appearing a hazard and its growing beginning from the situation $s_2^*$, hazardous one. Hence the probability $P_B = P_0 + P_1$ can be taken as the safety measure of operation of inland navigation passenger ship and any device installed on it, on whose functioning safety of the ship and persons onboard, depends.

In order to obtain approximate values of the probabilities $P_j$(j = 0, 1,..., 3) to assess $p_{ij}$ and $E(T_j)$ is necessary.

The assessment of the probabilities $p_{ij}$ and expected values $E(T_j)$ is possible after obtaining the realization y(t) of the process $\{Y(t): t \geq 0\}$ within appropriately long time intervals of investigations, i.e. for $t \in [0, t_b]$, and $t_b >> 0$. Then can be determined the numbers $n_{ij}$(i,j = 0, 1,..,3; i ≠ j), which represent numbers of transitions from the state $s_i$ to the state $s_j$ within appropriately long time.

The following statistic appears to be the largest likelihood estimator of the transition probability $p_{ij}$ [11] :

$$\hat{P}_{ij} = \frac{N_{ij}}{\sum_j N_{ij}} \; ; \; i \neq j \; ; \; i, j = 0, 1, \ldots, 3 \qquad (12)$$

whose value : $\hat{p}_{ij} = \frac{n_{ij}}{\sum_j n_{ij}}$

constitutes the assessment of the unknown probability $p_{ij}$ of transition of the process $\{Y(t): t \geq 0\}$ from the state $s_i$ to the state $s_j$.

From the mentioned run y(t) also the realizations $t_j^{(m)}$, m = 1, 2,..., $n_{ij}$ of the random variables $T_j$ can be obtained. By applying the discrete approximation the estimation $E(T_j)$ in the form of the mean arithmetic value of the realizations $t_j^{(m)}$ can be easily obtained [2, 13, 15].

## COMMENTS AND CONCLUSIONS

Operational safety of inland navigation passenger ship, hence also its propulsion systems and other energy systems, depends on many factors. Among the most important the following can be numbered :

- ✰ technical state of propulsion system devices and other ship power plant equipment
- ✰ reliability and a degree of adjustment of diagnosing systems to recognizing crucial states of ship power plant devices
- ✰ ambient conditions during ship's voyage
- ✰ qualifications of ship's crew and its psychical and physical resistance to effects of destructive factors which may happen during ship's voyage
- ✰ availability (in particular readiness) of water, land and medical rescue units.

To maintain a satisfactory (required) operational safety level of energy systems, especially propulsion ones, of inland navigation passenger ships, hence the ships themselves, during the phase of their operation, is not possible without knowing a.o. :

- ❍ occurrence probabilities of the situations $s_j^* \in S^*$ (j = 0, 1,..., 3), especially those hazardous to ships in operation, i.e. $s_2^*$ and $s_3^*$
- ❍ occurrence probabilities of the states $s_i \in S$ (i = 1, 2, 3), first of all the states $s_2$ and $s_3$, i.e. those limiting possible loads onto the ship devices, especially those installed in ship power plant, to which they have been adjusted during their designing and manufacturing
- ❍ indices of readiness of ship's devices
- ❍ probabilities determining likelihood of diagnosis on the state of particular ship devices.

Applicability of the mentioned to determining a decision situation as regards ship operational safety, can be showed with the use of the statistical theory of operational decision-taking. To this end it is necessary to know likelihood of diagnosis on the technical state of devices of the considered ships, especially their energy and propulsion systems, steering gears and other ones significantly influencing safety of shipping on inland waterways.

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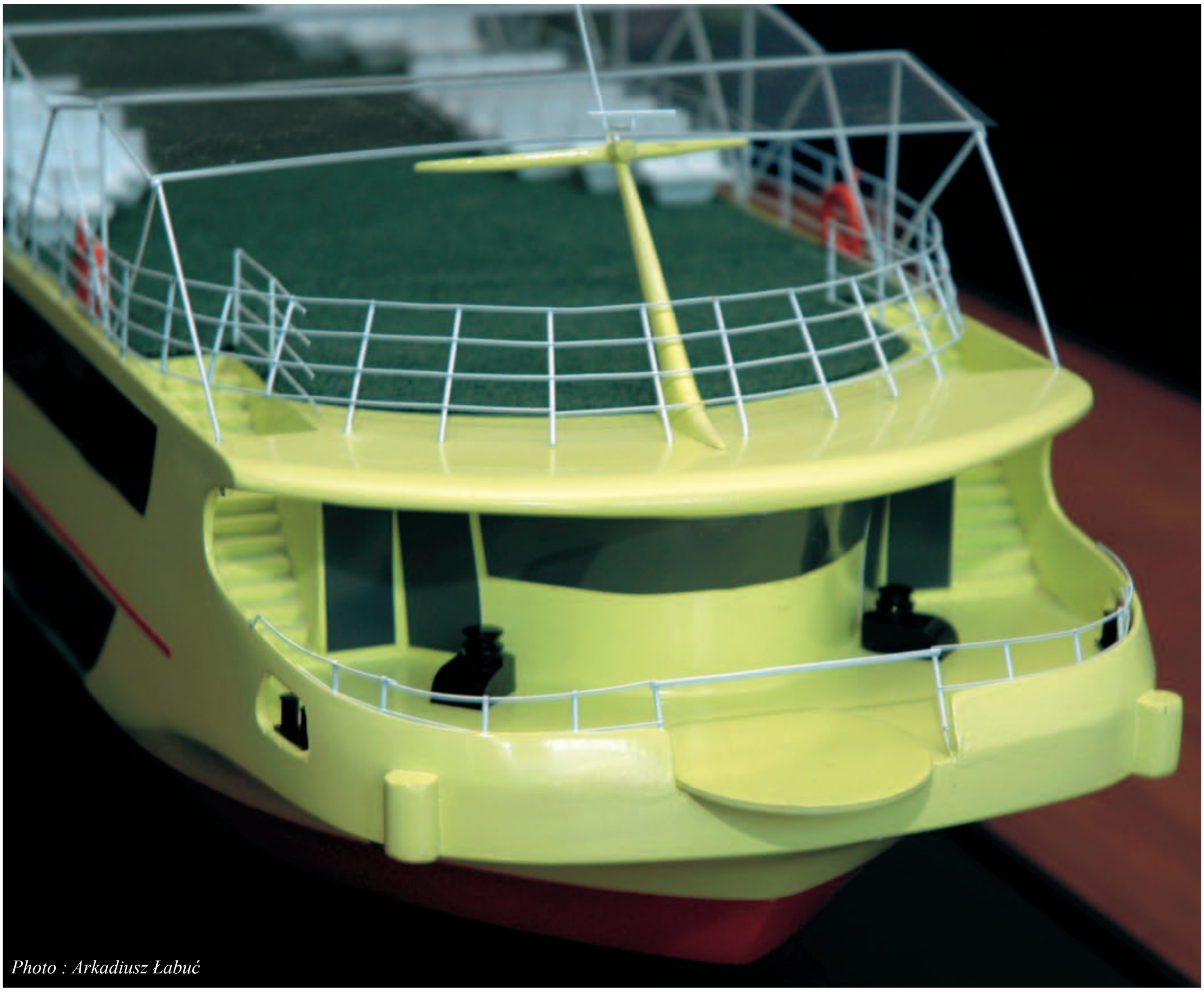

*Photo : Arkadiusz Łabuć*

# A method of predicting main propulsion power for inland waterways push trains

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ABSTRACT

*This paper presents a method of predicting effective power demand (brake horse power – B.H.P.) for propulsion of inland waterways push train, useful in the preliminary design stages. By using it, on the basis of known main particulars of a given push train, i.e. its length, breadth, draught and speed, a generalized Admiralty formula can be determined and then the pusher propulsion power can be preliminarily predicted by making use of the elaborated structure of the formula. Application of the method is illustrated on the example of a two-segment push train of inland waterways passenger ship designed in the frame of the Eureka INCOWATRANS E!3065 project.*

**Keywords** : inland waterways ships, ship design, brake horse power of push trains

## INTRODUCTION

Parametric methods used both for determining hull resistance and predicting propulsion power demand belong to the basic tools applied in ship design theory. Many parametric methods elaborated for and adjusted to sea-going ships are as a rule hardly applicable to designing inland waterways ships – because of :

- different values of ratios of hull main dimensions
- different ranges of Froude number design values
- significant influence of limited dimensions of navigation waters on hull resistance.

The subject-matter literature comprises a few methods for determining resistance of inland waterways ships, such as e.g. : that of Graff-Schlichting-Landweber [8], Karpov [8], Apuchtin [1,2], Baranov [3], or Wróblewska-Sirotina [4] – which are often useful in designing the ships of a small value of the draught T and large values of B/T (breadth/draught) ratio. More up-to-date proposals of such methods have been presented by Howe (given in [5]), Kulczyk [5] and Marchal [6]. However only several parametric methods strictly concern the predicting of brake horse power demand for push trains, as it is in the case of the Wróblewska's –Sirotina's method given by Pospielov [7].

The method of predicting the brake horse power demand for push trains, presented in this paper, was elaborated on the basis of an idea a little different from that used in the Wróblewska--Sirotina method where propulsion efficiency was determined separately on the basis of estimation of maximum permissible diameter of screw propeller and its load factor.

## STRUCTURE OF FORMULA FOR BRAKE HORSE POWER OF MAIN PROPULSION

The structure of the parametric formula expressing relation of the brake horse power $P_B$ demanded for inland waterways push train and quantities of its design parameters $\overline{x}$ which are identifiable already at early design stages, was assumed in the form constituting a generalization of the Admiralty formula :

$$P_B(\overline{x}) = \frac{D(\overline{x})^{\alpha} v^{\beta}}{A(\overline{x})} \qquad (1)$$

where :
D – push train displacement
v – its speed
$A(\overline{x})$ – effect function determined on the basis of statistical sample data of push trains of a considered type.

The original Admiralty formula elaborated in 19th century, was initially used for estimating the indicated power of steam machines used for ship main propulsion. The formula may be also applied to estimating brake horse propulsion power if only the factor A (called „Admiralty constant") is properly defined, as at low speeds of the then ships their hull resistance is mainly composed of friction resistance dependent on the ship speed v, hull wetted surface area Ω and friction resistance coefficient $c_f$ .

The hull wetted surface area can be expressed by using the Taylor's formula :

$$\Omega = c\sqrt{VL} = cV^{2/3}\left(\frac{L}{V^{1/3}}\right)^{1/2} = cV^{2/3}l^{1/2} \qquad (2)$$

where :
L – ship length
V – volumetric displacement of underwater part of ship hull
l – ship hull fineness ratio.

At small Froude numbers, hence at a negligible small wave resistance, the hull resistance R can be expressed as follows :

$$R(\overline{x}) = \frac{1}{2}c_f(\overline{x})\rho v^2\Omega(\overline{x}) =$$
$$= \left(\frac{1}{2}c_f(\overline{x})\frac{\rho}{\rho^{2/3}}cl(\overline{x})^{1/2}\right)(\rho V)^{2/3}v^2 = \frac{D(\overline{x})^{2/3}v^2}{a(\overline{x})} \qquad (3)$$

where :

ρ – water density
a – proportionality factor.

The dependence, to the power of two, of ship resistance on its speed results from neglecting the wave resistance component.

The classical form of the Admiralty formula for estimating the tow-rope horse power, commonly used in the case of sea-going ships, is obtained by using the expression for ship hull resistance (3) :

$$P_E = R(\overline{x})v = \frac{D(\overline{x})^{2/3}v^3}{a(\overline{x})} \quad (4)$$

For similar ships the factor :

$$a(\overline{x}) = \frac{1}{\left(\frac{1}{2}c_f(\overline{x})\rho^{1/3}cl(\overline{x})^{1/2}\right)} \quad (5)$$

is a weakly changeable function, that justifies its name – the „Admiralty constant".

The dependence of the effective propulsion power of inland waterways push trains on their dimensions and speed is more complicated since it additionally expresses, apart from resistance, such phenomena as :

- ✶ Effect of limited draught on permissible diameter of screw propeller and its efficiency
- ✶ Effect of small draught and large breadth of ship on values of wake and thrust deduction factors as well as rotative coefficient which expresses influence of distribution of water inflow velocity to propeller on its efficiency.

The data concerning parameters of existing push trains, derived from the subject-matter literature, were used as a statistical sample in elaborating the presented method.

As information concerning displacement values of the above mentioned ships was incomplete the following parameter (module) W was assumed instead :

$$W = LBT \quad (6)$$

The parameter W is strongly correlated with ship displacement, that results from low variability of hull block coefficients of push trains.

By applying the approximation method of least-squares of deviations were determined the values of the power exponents α, β of the formula (1), which provide the best approximation of the considered statistical sample. The approximation was achieved for the exponent values equal to :

$$\alpha = 3/5 \text{ and } \beta = 2 \quad (7)$$

The obtained result is different from the original Admiralty formula, which can be explained by small values of Froude numbers corresponding with low speed values of inland waterways push trains. Moreover in the relation (1) are contained the complex hydrodynamic interaction of hull, propeller and shores of water area – at a small draught of train, small depth of waterway and limited diameter of screw propeller.

## PARAMETRISATION OF ADMIRALTY FORMULA

The parametrisation of the quantity to be determined was performed by assuming that the factor $A(\overline{x})$ is a function of the selected design parameters $\overline{x} = (L, B, T, \ldots, v)$ of the train, i.e $A = A(\overline{x})$. Various forms of the function $A(\overline{x})$ were tested by using the prior assumed relation:

$$P_B = \frac{W^{3/5}v^2}{A(\overline{x})} \quad (8)$$

By examining the statistical sample of push trains such form of the function $A = A(\overline{x})$ was determined as to achieve approximated values of the brake horse power $P_B$ possibly close to the relevant values for the sample in question – in the sense of the assumed measures of approximation accuracy.

The best approximation was obtained – by applying the procedure of making research hypotheses about a form of the searched analytical relation, and next by performing their numerical verification – in the case when the weighting function $A(\overline{x})$ was of the following polynomial form :

$$A(\overline{x}) = c_1 + c_2L + c_3L^2 + c_4B + c_5B^2 + c_6T + c_7T^2 + c_8v + c_9v^2 \quad (9)$$

where :

- $v$ – train speed [km/h]
- L – train length [m]
- B – train breadth [m]
- T – train draught [m]
- $c_i$ – structural constants of the formula.

The parametric formulas (8) and (9) make the designer free from necessity of having at his disposal data on a standard push train, hence the formula can serve as a useful tool in the preliminary stage of ship design. The determined values of the structural constants in the formula (9) are contained in Tab.1.

***Tab. 1.*** *Values of the structural constants in the formula (9) .*

| Constants $\mathbf{c_i}$ | Value |
|---|---|
| $c_1$ | 0.138887366 |
| $c_2$ | 6.8508735E-005 |
| $c_3$ | -2.04243698E-007 |
| $c_4$ | -0.0246879704 |
| $c_5$ | 0.00163608016 |
| $c_6$ | -0.00530335023 |
| $c_7$ | -0.000538558047 |
| $c_8$ | -0.00228835285 |
| $c_9$ | 9.11419602E-005 |

The following measures were used to assess accuracy of the approximation :

⇨ $\Delta P_B$ – relative error of approximation
⇨ E – relative percentage error of approximation
⇨ $E_S$ – global average percentage error of approximation.

The obtained values of the approximation accuracy measures are presented in Tab.2. In Tab.2, Col. 2 contains the real values of brake horse power, Col. 3 – the brake horse power values determined by using the presented method, and in the last column are given the values of the factor $A(\overline{x})$ determined for the statistical sample elements.

## EXAMPLE OF APPLICATION OF THE PROPOSED METHOD

The presented method was applied to predict brake horse power demand for the push train of hotel-passenger ship intended to operate in inland shallow waterways between Berlin and Królewiec (Koenigsberg), designed in the frame of the Eureka INCOWATRANS E!3065 project. The predictions were made for various draughts of the train operating in deep waters.

The main parameters of the push train in question :

- pusher length L = 55.0 m
- length of pusher and barge together L = 110.0 m
- breadth of pusher and barge B = 9.0 m
- draught of pusher and barge T – varying, equal to : 0.8 m; 1.0 m and 1.2 m.

*Tab. 2. Assessment of approximation accuracy of the method for determining brake horse power of push trains .*

| No | $P_B$ [kW] | $P_B(\overline{x})$ [kW] | $\Delta P_B$ [kW] | E [%] | $E_S$ [%] | $A(\overline{x})$[-] |
|---|---|---|---|---|---|---|
| 1 | 102 | 84.2 | 17.8 | 17.4 | 1.0 | 2.199073 |
| 2 | 132 | 149.2 | -17.3 | 13.1 | 1.8 | 2.988848 |
| 3 | 176 | 171.1 | 4.9 | 2.7 | 1.9 | 2.576852 |
| 4 | 236 | 239.5 | -3.5 | 1.5 | 2.0 | 2.562530 |
| 5 | 294 | 280.1 | 13.9 | 4.7 | 2.3 | 2.440841 |
| 6 | 294 | 271.2 | 22.8 | 7.7 | 2.7 | 2.394053 |
| 7 | 144 | 187.3 | -43.3 | 30.1 | 4.5 | 3.463092 |
| 8 | 588 | 581.4 | 6.6 | 1.1 | 4.6 | 3.056463 |
| 9 | 588 | 629.3 | -41.3 | 7.0 | 5.0 | 3.266292 |
| 10 | 566 | 558.9 | 7.1 | 1.2 | 5.1 | 1.527448 |
| 11 | 294 | 311.6 | -17.6 | 6.0 | 5.4 | 2.514442 |
| 12 | 368 | 353.2 | 14.7 | 4.0 | 5.7 | 2.641990 |
| 13 | 294 | 291.4 | 2.5 | 0.8 | 5.7 | 2.774303 |
| 14 | 147 | 146.7 | 0.3 | 0.2 | 5.7 | 1.646277 |
| 15 | 1382 | 1410.7 | -28.7 | 2.0 | 5.9 | 1.663954 |
| 16 | 2120 | 2047.3 | 72.7 | 3.4 | 6.1 | 2.514117 |
| 17 | 808 | 794.2 | 13.7 | 1.7 | 6.2 | 2.231999 |

Results of the elaborated predictions are presented in Fig.1, where the brake horse power demanded either for the push train consisted of pusher and barge or the pusher alone, versus speed are given in the form of diagrams for different train draughts, as follows :

- *L110 T08 curve* : for the train at its draught T = 0.8 m
- *L110 T10 curve* : for the train at its draught T = 1.0 m
- *L110 T12 curve* : for the train at its draught T = 1.2 m
- *L55 T08 curve* : for the pusher alone at its draught T = 0.8 m
- *L55 T10 curve* : for the pusher alone at its draught T = 1.0 m
- *L55 T12 curve* : for the pusher alone at its draught T = 1.2 m

**Brake horse-power preliminary prognosis of INCOWATRANS push train type passenger ship**

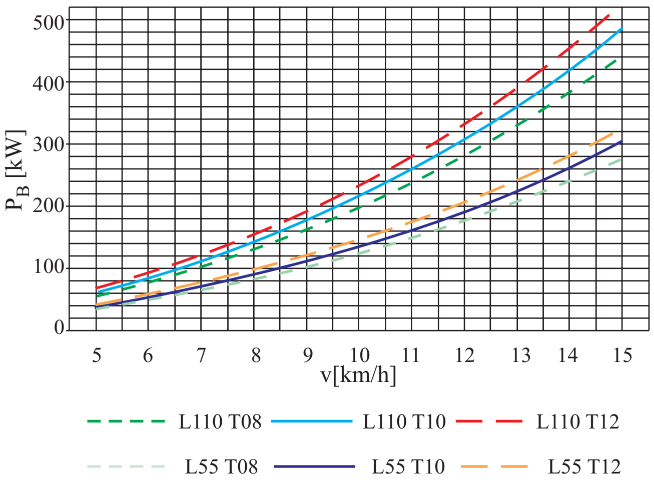


***Fig. 1.** Preliminary design predictions of the brake horse power demanded for push trains versus train speed .*

The method was preliminarily verified by making comparisons of the results obtained for the push train *Eureka* at the design draught T = 1.0 m, designed in the frame of the INCOWATRANS project, with those obtained by using the method of Zwonkow [8] as well as that of Leningrad Design Office [8], which consisted in approximate estimations of ship propulsion efficiency, that made it possible to determine approximate curves of brake horse power demand. The calculations were performed for the pusher alone as well as the pusher-barge train. The obtained results of the calculations are presented in Fig.2 in the form of the diagrams where :

- *Zwon55 curve* shows the BHP demanded for the pusher alone, achieved by applying the Zwonkow method
- *Lenin55 curve* shows the BHP demanded for the pusher alone, achieved by applying the Leningrad Design Office method
- *JM55 curve* shows the BHP demanded for the pusher alone, achieved by applying the presented method
- *Zwon110 curve* shows the BHP demanded for the pusher-barge train, achieved by using the Zwonkow method
- *Lenin110 curve* shows the BHP demanded for the pusher-barge train, achieved by using the Leningrad Design Office method
- *JM110 curve* shows the BHP demanded for the pusher-barge train, achieved by applying the presented method.

**Pusher brake horse-power prognosis confrontation (deep water L = 55 m and L = 110 m)**

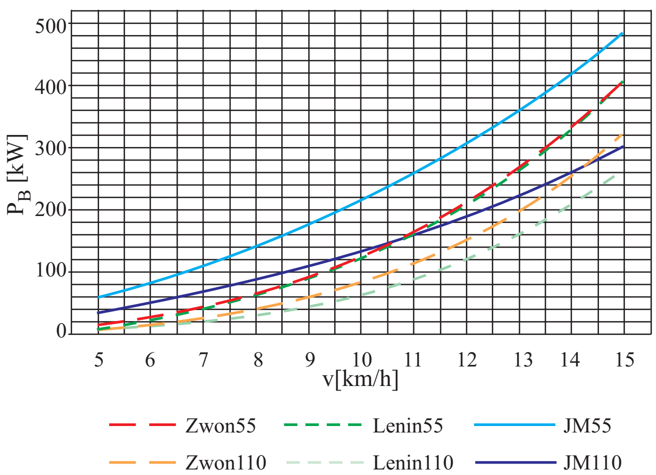


***Fig. 2.** Comparison of the brake horse power demand for the pusher and push train, calculated by using various methods .*

From an analysis of the achieved results it can be concluded that in the case of the pusher alone the proposed method provides results only slightly different from those obtained by means of the remaining method. Whereas in the case of the pusher-barge train the brake horse power calculated by using the presented method is greater than that obtained from the comparative methods. The comparative tests which have been made so far, indicate the method to be correct. To perform a more thorough verification it would be necessary to carry out the tests based on a more ample comparative material, namely data on push trains of various ratios of main dimensions and various Froude numbers.

The following electric energy consumers, apart from the propulsion system, are provided on the designed ship :

- air-conditioning systems for ship accommodations
- drive systems of thrusters
- drive systems of steering gear
- drive systems of shipboard devices
- drive systems of auxiliary devices of ship power plant
- ship lighting system
- other electric appliances.

It was preliminarily estimated by using an index method that the demanded electric power for the designed ship amounts to about 200 kW. The demanded power for the ship's electric devices is only slightly smaller that that for its propulsion system, that speaks for application, to the ship in question, of the combustion-electric propulsion system consisted of several combustion-electric generating sets and electric motors. Such system makes it possible to obtain a high flexibility in using the installed power output at full load imposed onto particular generating sets working then at their maximum efficiency. Moreover such solution makes it possible – in emergency situations, e.g. in order to refloat the ship after its stranding – to use an electric power surplus for temporary supporting the main propulsion system.

## RECAPITULATION AND CONCLUSIONS

- The elaborated method makes it possible to determine the generalized Admiralty formula, which enables – together with the formula for determining the brake horse power (BHP) – to predict in an approximate way the BHP demanded for main propulsion system of the pusher – on the basis of the assumed main parameters of the push train, namely : its length, breadth, draught and speed. The elaborated formula differs in its structure from that of the original Admiralty formula, which is supposed to result mainly from small values of Froude numbers characteristic for push trains
- From the test investigations it results that in the case of the pusher alone the obtained BHP values only slightly differ from those achieved by applying the remaining methods. However in the case of the pusher-barge train within the whole investigated speed range the BHP values are greater than those obtained by using the other methods
- The determined simple analytical relations model the brake horse power which expresses the complex hydrodynamic interactions of ship hull, propeller and shores of water area, characterized by limited hull draught, small depth of waterway as well as limited permissible diameter of screw propeller.

### NOMENCLATURE

$a(\overline{x})$ – effect function of push train parameters
$A(\overline{x})$ – approximating function of „ Admiralty constant”
B – push train breadth
BHP – brake horse power
c – proporcionality constant
$c_f$ – friction resistance coefficient
$c_i$ – structural constants of a formula
D – push train displacement
E – relative percentage error of approximation
$E_S$ – global average percentage error of approximation
l – push train fineness coefficient
L – push train length
$P_B$ – brake horse power of push train
$P_E$ – tow rope power of push train
R – hull resistance
T – push train draught
v – push train speed
V – volumetric displacement of push train underwater part
W – module of push train dimensions
$\overline{x}$ – vector of push train parameters

$\alpha, \beta$ – constant power exponents
$\rho$ – water density
$\Omega$ – wetted surface area of push train
$\Delta P_B$ – absolute error of approximation.

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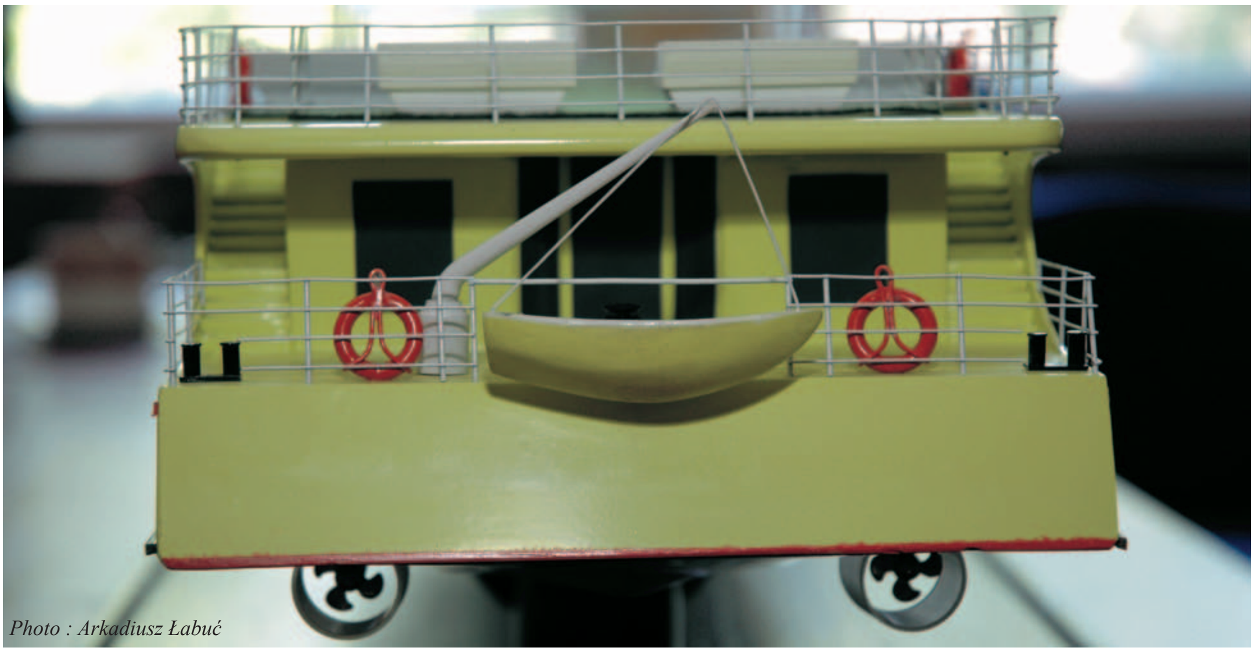
*Photo : Arkadiusz Łabuć*

# Economical analysis of selected variants of power plant for inland waterways passenger ship intended for operating on Berlin - Kaliningrad route

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ABSTRACT

*This paper contains an economical analysis of three selected variants of power plant for inland waterways passenger ship intended for operating on Berlin-Kaliningrad route. Purchase cost of elements of the ship's energy system and fuel consumption cost were assumed as the assessment criterion for the analyzed variants of the ship's power plant. The economical indices : Average Annual Cost (AAC) and Net Present Value (NPV) were taken into consideration.*

**Keywords** : Inland waterways passenger ship, ship power plant, ship propulsion systems

## INTRODUCTION

Choice of the most favourable solution of power plant of inland waterways passenger ship is a complex issue, like in the case of sea-going passenger ships. Number of possible power plant variants which satisfy ship's technical requirements is large as a rule. In selecting appropriate technical solutions of the whole ship [7], its power plant [1] or only its propulsion system [8] various economical criteria are often and often used. The indices such as : Average Annual Cost (AAC) and Net Present Value (NPV) are most often applied.

This paper presents economical analysis of three design variants of power plant of an inland waterways passenger ship intended for operating in inland waters of Germany, Poland and Russia, mainly on Berlin-Kaliningrad route.

## CHARACTERISTICS OF THE CONSIDERED PASSENGER SHIP

The passenger ship in question is designed as a two-segment unit consisted of a pusher and barge. Such system is conditioned by characteristics of the waterway on Berlin-Kaliningrad route. Along the route are located 24 locks of the dimensions which make it possible to accommodate ships not longer than 55 m and not broader than 9 m [11].

In the initial design phases the following preliminary design assumptions were adopted [9,10] :

- The main service route of the ship : Berlin–Kostrzyń––Bydgoszcz–(Toruń)–Malbork–Elbląg–Zalew Wiślany––Kaliningrad
- Two-segment ship consisted of a pusher (i.e. the propulsion and energy supply segment on which, apart from the power plant, also crew and recreation accommodations, restaurant and coffee-bar will be located) and a barge (i.e. the passenger segment containing Lux-class cabins)
- Tourist voyage cycle : 14 days
- Number of passengers and crew members: 80 – 100 persons
- Ship's speed: 15 km/h (in deep waters)
- Main dimensions of the segments :

| | |
|---|---|
| Overall length | $L_c$ = 55.00 m |
| Length b.p. | $L_{pp}$ = 54.00 m (pusher) |
| | $L_{pp}$ = 53.30 m (barge) |
| Breadth | B = 9.00 m |
| Design draught | T = 1.00 m |
| Length of the push-train | L = 110.00 m |

- Propulsion system of two nozzle - ducted fixed-pitch propellers (optionally : two azimuthing nozzle - ducted fixed-pitch propellers)
- An air-conditioning system for passenger accommodations and a high-level equipment of gastronomy compartments (restaurant, coffee bar etc) is provided to ensure a high-level comfort on the ship.

It was assumed that the ship's service is seasonal, namely for about 6 – 7 months yearly. Voyages of the whole push-train on Berlin-Kaliningrad route is the main service task of the ship. Another possible mode of operation is connected with day-long trips of the pusher alone and the use of the barge as a floating hotel lying along a quay.

## DEMAND OF ENERGY FOR SHIP MAIN PROPULSION AND AUXILIARY CONSUMERS

Solution of main propulsion system and output power of main engines of inland waterways passenger ship is associated with a waterway on which it has to operate, its size and speed. Speed of a designed ship will be highly dependent on its route. According to [11] the maximum speed values of the ship in question will be as follows :

- 15 km/h - in deep waters (control-delivery trials)
- 10 km/h - in shallow and extremely shallow waters
- 6.5 km/h - in canals and canalized rivers.

In the initial design phases it was assumed that for the designed ship the system with two fixed and ducted propellers (or optionally that of two azimuthing fixed and ducted propellers) will be the best solution of propulsion system. During preliminary calculations [6,7] the following quantities were determined : the power at the propeller cone equal to 2×150 kW, and the nominal rotational speed of the propellers equal to 600 rpm.

The electric power demand for auxiliary purposes was determined in the publications [2,6] whose results are presented in Tab.1.

*Tab.1. Mean electric power demand in three basic service states of the ship [kW]*

| Ship's configuration | Moving | Manoeuvres | Staying in port |
|---|---|---|---|
| Pusher + barge | 145 – 165*) | 160 – 200*) | 110 – 140**) |
| Pusher | 85 – 100 | 100 – 120 | 55 – 75**) |
| Barge | - | - | 50 – 70**) |

*) – work of the thruster is taken into account
**) – with passengers on board

On the basis of Tab.1 one can determined the total rated power of the electric power plant (operating for auxiliary purposes). The total power amounts to about 250÷300 kW at the assumed diversity factor value of 0.7÷0.8.

## POWER PLANT VARIANTS AND ASSESSMENT OF PURCHASE COSTS

Out of a few feasible design variants of power plant for the passenger ship in question three most probable systems characterized by the highest efficiency were selected for comparative analysis [5,6], namely :

- the power plant with two main combustion engines driving two fixed propellers through reversing-reduction gears (one engine drives one propeller); the electric power plant is consisted of 2 or 3 electric generating sets
- the power plant with four main combustion engines driving two propellers trough two reversing-reduction gears (two engines drives one propeller); the electric power plant is consisted of 2 or 3 electric generating sets
- the combustion electric power plant consisted of 2 or 3 main electric generating sets and 2 or 3 smaller auxiliary electric generating sets, two propellers driven by two identical drive systems consisted of one AC (alternate current) electric motor of controlled speed (by using a frequency converter) and /or a reduction gear (depending on which kind of electric motor is applied), each.

In the case of two systems with combustion-engine drive of propellers, size of the main propulsion engines was determined in the following way. For the assumed power at the cone of the propellers (2×150 kW) the rated output power of the installed combustion engines depends on the power transmission system efficiency as well as on the service load factor assumed at given propeller design parameters [2,5]. Preliminarily assuming the shaft-line efficiency $\eta_{lw} = 0.98$ and the reversing-reduction gear efficiency $\eta_{prz} = 0.96 – 0.97$ one can obtain the power transmission system efficiency of the value from 0.94 to 0.95, counted between the coupling of engine (-s) and the cone of propeller.

In design practice the service load factor of the main propulsion combustion engine serves as a basis for determining nominal parameters of the engine. Full service power value of the engine, assumed for ship propulsion, is lower than that rated (contractual). A problem is associated with expected changes in propeller characteristics (propeller curve) during ship service, against its course in the conditions determined by the design assumptions. For sea-going cargo ships the statistically obtained value of the service load factor of main propulsion combustion engines is contained within the interval of 85÷90% $N_{SG}^{nom}$ (rated power of main engine). It is known that for service conditions on North Atlantic the design load factors of main combustion engines are sometimes assumed on the level of 75÷80% $N_{SG}^{nom}$ [2,6].

For inland waterways passenger ship even a lower value of load factor of its main propulsion combustion engines should be assumed for the reason of the specific waterway's features such as a low depth, changeable midstream and many meanders, in presence of which highly variable operational conditions occur, making the characteristics of the fixed-propeller propulsion system changing, that impacts engine load in a very unfavourable way. It leads to decreasing engine's service rotational speed with all negative consequences resulting from worsening the supercharging process. Moreover in the case of ship's grounding the large power margin of its main propulsion engines makes the ship's refloating easier.

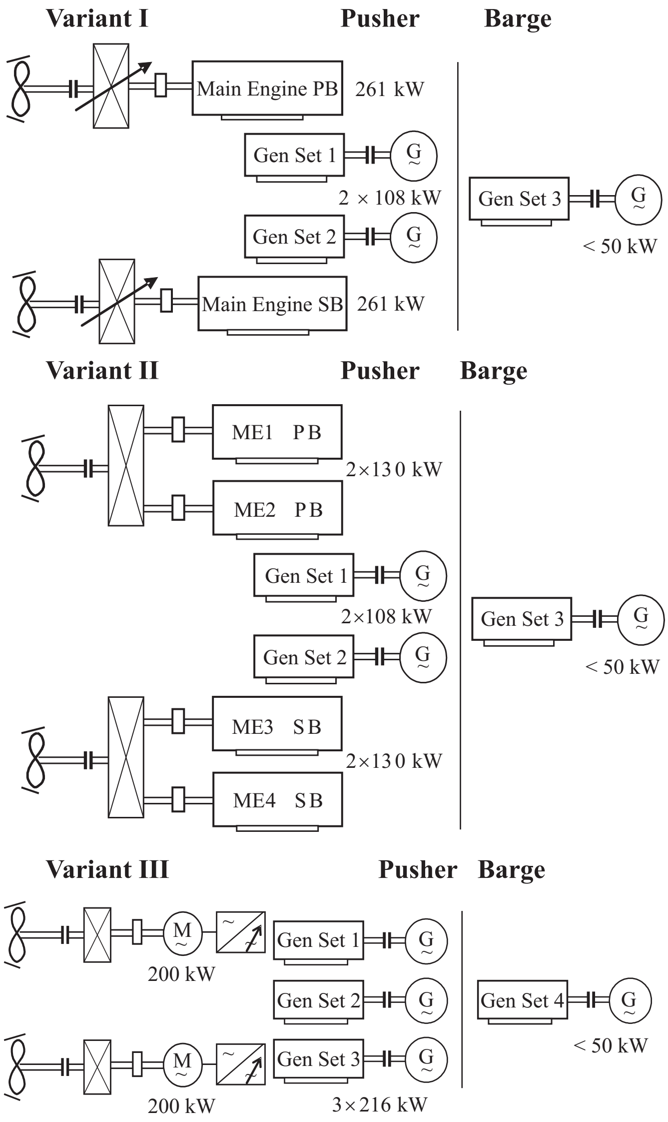


***Fig.1.** Schematic diagram of three selected design variants of power plant for the designed passenger ship. **ME** – main engine, **PB** – port board, **SB** - starboard .*

On the basis of the performed analysis of operational conditions of the main combustion engines driving fixed propellers installed on the designed passenger ship [2,6] it seems reasonable to assume the load factor of the main engines equal to about 70% $N_{SG}^{nom}$. Hence for the assumed power at the cone of propellers of 2×(150÷170) kW two combustion engines of the rated power of about (230÷270) kW each, or four combustion engines of the power of about (115÷135) kW each, should be chosen.

In the case of the combustion-electric propulsion system, values of the output power of electric motors can be smaller for the reason of more favourable working characteristics of the motors at decreased rotational speeds. According to [2], the output power of the main drive electric motors should amount to about 190 ÷ 210 kW.

As the main and auxiliary engines for the ship in question Caterpillar and Volvo Penta combustion engines were selected. The choice was preceded by the analysis presented in [2,3].

For the comparative analysis the engines of only one producer were taken into account as the prices of main engines and electric generating sets of similar power, offered by both the preferred firms (i.e. Caterpillar and Volvo Penta), are close to each other, as well as also their specific fuel oil consumption characteristics are very similar. Final choice of a producer may be done in a further design stage after possible contact with ship owner. For the purposes of this analysis Volvo Penta combustion engines were assumed. In the case of the combustion-electric power plant electric motors and frequency converters should be taken into account additionally. To this end, EMIT electric motors and Danfoss frequency converters [2,3] were finally selected. The following variants of power plant were assumed (Fig.1) :

- **Variant I** : two D9MH Volvo Penta main combustion engines of 261 kW output power driving propellers through reversing – reduction gears (of 1:3 reduction ratio), two larger, D7AT Volvo Penta, electric generating sets of 108 kW output power, as well as one smaller electric generating set of less than 50 kW output power (installed on the barge)
- **Variant II** : four D7A TA Volvo Penta main combustion engines of 130 kW output power each, driving two propellers through reversing – reduction gears, two larger, D7A T Volvo Penta, electric generating sets of 108 kW output power, as well as one smaller electric generating set of less than 50 kW output power ( installed on the barge)
- **Variant III** : three D9MG Volvo Penta main electric generating sets of 216 kW output power each, as well as one smaller electric generating set of less than 50 kW output power (installed on the barge), two Sg 355 S2 EMIT electric motors (of n = 1450 rpm) with VLT Danfoss frequency converters, driving propellers through reduction gears of 1:2,42 reduction ratio.

In Tab.2 are presented purchase costs of the elements of three design variants of power plant for the passenger ship in question. Only purchase costs of main engines, electric generating sets and elements of power transmission system of main energy consumers, were taken into account. The data were achieved from the offers submitted by the producers of the elements of energy supply – propulsion system.

## FUEL OIL CONSUMPTION COSTS

In accordance with the adopted assumptions, the designed inland waterways passenger ship will operate mainly on Berlin-Kaliningrad route (in the configuration “pusher+barge”), and also autonomous day-long excursion trips of the pusher alone will be carried out [6].

Time structure of the particular service states of the ship on the route Berlin-Kaliningrad, based on the assumption that one tourist voyage cycle will last 14 days (about 330 h), and determined in [5], is presented in the table below :

| Service state | Duration time | |
|---|---|---|
| | Hours | % |
| Sailing in shallow waters | 75 - 85 | 23 - 26 |
| Sailing along canals | 55 - 65 | 17 - 20 |
| Manoeuvres, locking operations | 30 | 9 |
| Stays in ports | 150 - 170 | 45 - 52 |
| Total | 330 | 100 |

For the day-long trip, 9 h duration time (including 6 h for cruising and 3 h for port staying) was assumed [5].

In [5] were predicted load characteristics of main engines and electric generating sets during the voyage on Berlin-Kaliningrad route as well as during the day-long trip. The relevant results are given in Tab.3.

***Tab. 3.*** *Predicted load distribution parameters of the main and auxiliary engines installed on the designed ship .*

| Variants of power plant | Voyage on Berlin-Kaliningrad route | | | | Day-long trip | | | |
|---|---|---|---|---|---|---|---|---|
| | $N^{av}_{ME}$ | $\sigma_{ME}$ | $N^{av}_{GS}$ | $\sigma_{GS}$ | $N^{av}_{ME}$ | $\sigma_{ME}$ | $N^{av}_{GS}$ | $\sigma_{GS}$ |
| I | 174.8 | 73.4 | 129.7 | 36.9 | 110.0 | 41.4 | 88.2 | 22.8 |
| II | 174.8 | 73.4 | 129.7 | 36.9 | 110.0 | 41.4 | 88.2 | 22.8 |
| III | - | - | 235.9 | 130.9 | - | - | 163.1 | 89.5 |

$N^{av}_{ME}$ – mean load of main engine
$\sigma_{ME}$ – standard deviation of load distribution of main engine
$N^{av}_{GS}$ – mean load of main electric generating sets
$\sigma_{GS}$ – standard deviation of load distribution of main electric generating sets

In calculating fuel oil amount consumed by the ship’s power plant (in various variants) the use was made of :

- ★ the predicted load distributions for main and auxiliary engines, presented in Tab.3
- ★ the fuel oil consumption characteristics in function of engine load fact (producer catalogue data [12])
- ★ the calculation method given in [4].

***Tab. 2.*** *Comparison of purchase costs of elements of three variants of power plant for the considered passenger ship .*

| Elements of Energy System | Power plant design variants | | | | | |
|---|---|---|---|---|---|---|
| | Variant I | | Variant II | | Variant III | |
| | Specification | Price (×1000 Euro) | Specification | Price (×1000 Euro) | Specification | Price (×1000 Euro) |
| **Main engines, elastic couplings, reversing-reduction gears** | 2×261 kW | 142 | 4×130 kW | 190 | - | - |
| **Main electric generating sets** | - | - | - | - | 3×216 kW | 231 |
| **Auxiliary electric generating sets** | 2×108 kW<br>1×50 kW | 109 | 2×108 kW<br>1×50 kW | 109 | 1×50 kW | 26 |
| **Electric drive of propellers: electric motors, reduction gears, frequency converters** | - | - | - | - | 2×200 kW | 63 |
| **Total cost** | | 251 | | 299 | | 320 |

In Tab. 4 the fuel oil consumption for one ship's voyage on the route Berlin – Kaliningrad (in the configuration „pusher + barge") and for one day-long trip (of the pusher alone) are presented. In calculating the values of fuel oil consumed by electric generating sets it was assumed that a successive set would be switched on when 85% load level is exceeded by the currently operating set (-s) [5].

***Tab. 4.** Fuel oil consumption values determined for three variants of the power plant for the considered passenger ship, [kg] .*

| Design variants of power plant | Fuel oil consumption Berlin – Kaliningrad voyage | | | Fuel oil consumption Day-long trip | | |
|---|---|---|---|---|---|---|
| | ME | EGS | Σ | ME | EGS | Σ |
| I | 7085 | 9295 | 16380 | 168 | 171 | 339 |
| II | 7020 | 9095 | 16115 | 165 | 176 | 341 |
| III | | | 15740*) | | | 300*) |

ME – main engine
EGS – electric generating sets
*) – total fuel oil consumption by all electric generating sets

It was assumed that both main engines and electric generating sets will work on the Marine Gas Oil (MGO). Prices of diesel oils of all kinds have dramatically increased lately. For two last years they increased 2.5 times, e.g. in December 2003 purchase cost of 1 t of MGO amounted to 280 $ but it was already within 620 ÷ 670 $/t interval in September 2005. On 10 November 2005 1 t of MGO costed 574 ÷ 575 $/t (489 ÷ 490 Euro/t) in Gdańsk port [6]. Fear is felt that in the nearest years fuel oil prices will be further increasing. According to some analysts, during the nearest years the rise of prices even by 100 % may be expected.

For the calculations three prices of the MGO were assumed and on this basis the fuel oil consumption costs to be incurred during one voyage on Berlin – Kaliningrad route as well as during one day-long trip (about 9 h), were calculated. The relevant results are given in Tab.5.

***Tab. 5.** Fuel oil consumption costs to be incurred during one voyage on Berlin – Kaliningrad route as well as during one day-long trip, [Euro] .*

| Design variants of power plant | **Assumed price** | | | | | |
|---|---|---|---|---|---|---|
| | **500 Euro/t** | | **750 Euro/t** | | **1000 Euro/t** | |
| | Berlin-Kali-ningrad voyage | Day-long trip | Berlin-Kali-ningrad voyage | Day-long trip | Berlin-Kali-ningrad voyage | Day-long trip |
| I | 8190 | 169,5 | 12285 | 254 | 16380 | 339 |
| II | 8057.5 | 170,5 | 12086 | 256 | 16115 | 341 |
| III | 7870 | 150 | 11805 | 225 | 15740 | 300 |

## ECONOMICAL COMPARISON OF DESIGN VARIANTS OF POWER PLANT

The comparative analysis of the power plant design variants was performed with the use of the **AAC** (Average Annual Cost) and **NPV** (Net Present Value) economical indices.

The AAC index takes into account purchase costs of main engines, electric generating sets and other elements of the energy system (gears, couplings, electric motors of main consumers, frequency converters etc) as well as costs of operation for its assumed duration time. Only fuel oil cost (which amounts to about 80 % of total costs of power plant operation) was taken into consideration because of a relatively low share of cost of lubricating oils, spare parts and repair work in the total operational costs.

The Average Annual Cost (AAC) expressed in [$10^6$ Euro/year] is determined by the following formulae :

$$AAC = \frac{PW}{X} = \frac{I}{X} + K \quad [10^6 \text{ Euro/year}] \qquad (1)$$

$$X = \begin{cases} q \times \dfrac{q^L - 1}{L^{q-1}} & \text{for } q \neq 1 \\ & \text{for } q = 1 \end{cases} \quad [\text{years}] \qquad (2)$$

$$q = \frac{1+s}{1+r} \qquad (3)$$

where :

r – rate of profit (discount rate)
s – rate of fuel cost increase
PW – value of total costs currently incurred
I – purchase cost of main engines, electric generating sets and other elements of energy system
K – annual purchase cost of fuel oil
L – years.

The most favourable solution is that having the smallest value of AAC index·

Presently, the NPV index is very often applied in comparing various solutions of propulsion system or entire energy system of a ship. In this case the differences in total outlays for an alternative solution and for basic one, are analyzed. Usually, out of those analyzed, the less expensive solution is assumed basic one.

The NPV index is determined by the formula :

$$NPV = \Delta K \times X - \Delta I \qquad (4)$$

where :

ΔI – difference between purchase cost of a given variant of energy system and that of the least expensive variant assumed basic one
ΔK – difference between yearly fuel oil cost for the energy system variant assumed basic one and that for a given energy system variant.

One calculated values of the economical indices **AAC** and **NPV** making use of the data given in Tab.2 and 5 as well as the formulae (1),(2),(3) and (4).

As the ship has to operate for 6 ÷7 months per year, hence 10 voyages of the ship (pusher + barge) on Berlin – Kaliningrad route and 30 day-long trips (pusher alone) can be assumed.

The calculation results of AAC and NPV index values for the compared design variants of the passenger ship's power plant are presented in Tab. 6 and Fig. 2, 3 and 4.

For the calculations included in Tab.6 the constant value **r** = 5 % and ship's service time of 10 years were assumed, however values of the fuel cost increase rate were assumed changeable.

***Tab. 6.** Economical indices AAC and NPV for three design variants of power plant of the considered passenger ship, and the assumed 10-year service time, [$10^3$ Euro] .*

| Economical indices \ Design variant | | I | II | III |
|---|---|---|---|---|
| **AAC** | s = 5 % | 112.1 | 117.5 | 115.2 |
| | s = 15 % | 95.0 | 95.9 | 93.5 |
| | s = 25 % | 91.5 | 91.4 | 84.7 |
| **NPV** | s = 5 % | 0 | -54.05 | -31.15 |
| | s = 15 % | 0 | -26.6 | 48.9 |
| | s = 25 % | 0 | 4.8 | 140.7 |

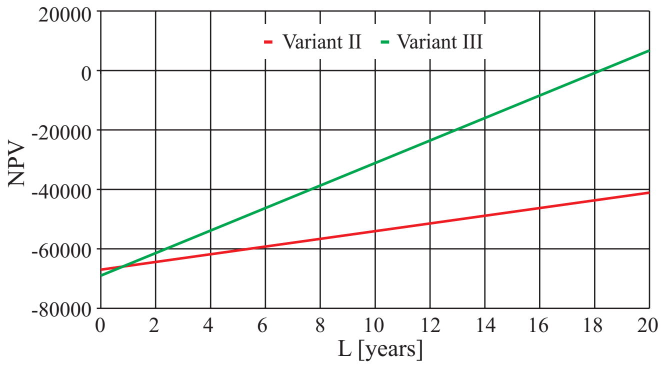


***Fig. 2.*** *NPV index in function of ship service time L (for s = 5%) .*

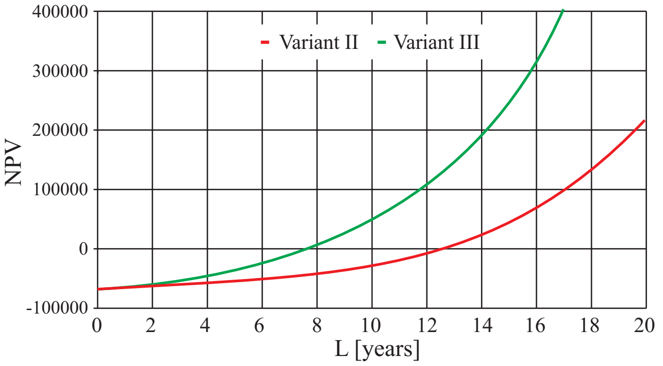


***Fig. 3.*** *NPV index in function of ship service time L (for s = 15%) .*

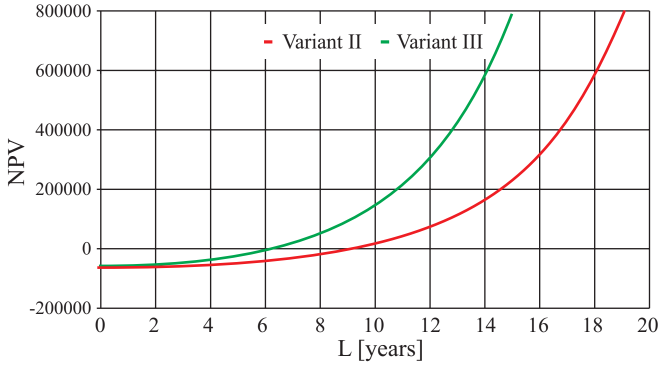


***Fig. 4.*** *NPV index in function of ship service time L (for s = 25%) .*

It should be observed that assumed values of **r** and **s** and current fuel oil price can seriously influence values of the economical indices in question. For the fuel oil price of about 500 Euro/t and the fuel price increase rate of **s** = 5%, variant I is the best solution. The increased investment outlays in the case of variant III would be returned as late as after 19 years, and those of variant II after more than 20 years. The situation will change when fuel price increasing is faster. And, at the fuel price increase rate **s** = 15%, return of the increased investment outlays for variant III would be realized after 8 years and for variant II after 13 years of service. At the higher rate of fuel price increase (**s** = 25%) the return of the increased investment outlays for variant III would be effected after 6 years, and for variant II after 10 years of service.

It can be also observed that at a stable but moderate increase of fuel price, variant I will be really the best solution. However, if the prices increase like in the last years then it will be rational to take variant III into considerations.

## SUMMARY

- The performed economical analysis of selected variants of power plant for the designed inland waterways passenger ship showed that the most economical variant is the power plant consisted of two main combustion engines driving two fixed propellers through reversing-reduction gear (one engine drives one propeller) and two electric generating sets (i.e. variant I).
- The conclusion may be changed in the following situations:
  - ⇨ sudden increase of fuel oil costs in the nearest years
  - ⇨ all-the-year-round operation of the ship over the rivers of entire Europe.

In such case the return time of investment outlays associated with application of variant III (i.e. combustion–electric power plant) will be shorter and probably acceptable for the ship owner.

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# Two design concepts of power plant for an inland waterways passenger ship intended for operating on BERLIN – KALININGRAD route

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ABSTRACT

*This paper presents two most probable design solutions of power plant for a two-segment passenger ship intended for operating on inland waterways of Poland, Germany and Russia. Preliminary designs of the main power plant to be installed on the pusher are presented, as well as requirements for the auxiliary power plant to be placed on the barge are outlined.*

**Keywords** : Inland waterways passenger ship, ship power plant, ship propulsion systems

## INTRODUCTION

The passenger ship intended for operating on inland waterways of Poland, Germany and Russia is designed as a two-segment unit consisted of a pusher and barge. Such system is conditioned by characteristics of the waterway on Berlin-Kaliningrad route. Along the route are located 24 locks of the dimensions which make it possible to accommodate ships not longer than 55 m and not broader than 9 m [7].

With taking into account the assumptions concerning equipment and mode of operation of the ship the variant consisting in the idea of the main power plant to be installed on the pusher and the auxiliary power plant to be installed on the barge, was adopted.

The main power plant is intended for providing energy for ship propulsion as well as supplying all electric energy consumers (both on the pusher and barge) in all states of the ship's operation. In preliminary design phases it was assumed that the best solution of the ship's propulsion system would be a two-propeller system with two fixed screw propellers ducted in nozzles [6]. Among possible propeller driving systems the mechanical one with two high-speed diesel engines operating through reversing-reduction gears seems to be most economical [3,4]. An alternative solution is the diesel – electric drive.

The auxiliary power plant installed on the barge is first of all intended for providing energy to drive an auxiliary propeller located on the bow of the barge as well as for supplying electric energy consumers on the barge during locking operations when the two segments are disconnected.

Caterpillar and Volvo Penta engines are recommended as the main and auxiliary engines. The choice of the firms was preceded by the relevant analysis presented in [1,2].

In the preliminary design phase the Volvo Penta engines and electric generating sets were assumed [5]. Final selection of a producer of engines can be done during further design phase after consulting the ship owner. In the case of the diesel electric power plant, electric motors and frequency converters are additionally included into the main propulsion system. It was decided to apply EMIT electric motors and Danfoss converters [2,5].

## POWER PLANT WITH MECHANICAL (DIESEL ENGINE) DRIVING SYSTEM OF SCREW PROPELLERS

Choice of a main propulsion system and electric plant is the crucial part of the preliminary design of the power plant. For the power plant with diesel-engine driving system of screw propellers the following elements of it were selected on the basis of the performed analysis [3,4] :

- ★ Two D9MH Volvo – Penta main diesel engines developing 261 kW each at the rotational speed of 1800 rpm
- ★ Two MG5114DC-E Twin Disc reversing-reduction gears installed directly on flywheel casings of main engines and fitted with thrust bearings. Gear reduction ratio equal to 3,2:1
- ★ Two D7A T/UCM274F Volvo – Penta electric generating sets of 108 kW output power each, 3×415 V voltage and 50 Hz frequency.

On the pusher the engine room of 8 m in length (between 4th and 12th abscissa), 8.5 m in breadth and 2.5 m in height,was provided [6,8]. However it should be added that due to the applied form of the stern the ship's hull bottom in the region of the engine room has not a rectangular shape of 68 $m^2$ area, but it has a trapezoid-like shape of the area of only about 50 $m^2$. The propeller shaft-line spacing has to be 6 m.

In order to satisfy the requirement concerning the propeller shaft-line spacing of 6m the main propulsion engines together with the reversing-reduction gears must be shifted fore. The coupling flange of the gear will be then located between 8$^{th}$ and 9$^{th}$ abscissa. The main engines should be placed on their foundations in such a way as to get the axes of output shafts of the reversing-reduction gears located at the height of 0.5 m above the ship's bottom. The propulsion shaft-line axes should be parallel to the base plane and plane of symmetry of the ship.

The electric generating sets will be located closer to the stern, symmetrically on both sides of the ship's plane of symmetry. Auxiliary devices of the power plant will be arranged in two regions of the power plant : between the electric generating sets and between the main propulsion engines. In both the cases the arrangement of the engines and devices will be such as to ensure possible passage from their control and operation posts to escape routes.

All diesel engines (main and auxiliary) will be fresh-water cooled. Heat will be absorbed by outboard water within water-water coolers. Each of the engines will be fitted with the fresh-water and outboard-water circulating pumps driven by engines. Water coolers with thermostatic valves and expansion tanks will be also suspended on the engines.

An outboard-water pump driven by a separate electric motor will be installed to absorb heat from other devices (oil coolers of reversing-reduction gears, cooling medium condenser of air--conditioning control unit, reefer store cooler, possible cooling system of bearings etc).

The outboard-water main will be situated along 11$^{th}$ abscissa. Water intake will be arranged from two sea-inlet valves shifted to each other by one frame spacing.

Every diesel engine will be fitted with one lubricating oil circulating pump driven from the engine, double oil filter and oil cooler (cooled with outboard water) [10]. Lubricating oil purification process in centrifugal separators is not taken into account.

Waste oil will be pumped from engine oil sumps to waste oil tank by means of an oil transport pump. A fresh-oil storage tank will be also included in the system. To transport the oil inside the ship as well as to discharge the waste oil out of the ship, an oil transport pump driven by a separate electric motor will be installed (possible application of hand –operated pump is also taken into account because of low flow rates and sporadic use of the pump).

The reversing-reduction gears are equipped with a circulating pump, filter and oil cooler cooled with outboard water.

Every Volvo – Penta diesel engine will be fitted with a fuel supply pump driven from the engine. The fuel supply pumps will suck in the fuel directly from the storage tanks (placed just behind the engine room bulkhead).

As the application of Marine Gas Oil (MGO) is assumed no centrifugal separators are provided for fuel oil. An electrically-driven fuel transport pump is provided to pump fuel oil to and from the tanks (i.e. the storage tanks on the pusher and barge as well as overflow tank) and to discharge the fuel oil out of the ship if necessary.

Every diesel engine will have its separate exhaust gas duct leading outside the ship. Outlet of exhaust gases through the ship's stern is proposed. The gas exhausts will be so situated as not to allow to suck in the gas from an operating engine to those not operating at all or operating only under low load.

In all the exhaust gas ducts of diesel engine, 35 dBA silencers fitted with spark catchers and an appropriate number of thermal expansion compensators will be installed. The exhaust gas ducts will be appropriately insulated.

Start-up of all diesel engines will be electric one with the use of 24 V voltage supplied from an accumulator battery. The main engines will be equipped with alternators driven from the engines, serving to charge the battery with 60 A current.

In the engine room, apart from the devices of auxiliary systems of diesel engines, will be also installed other devices being elements of other systems: fresh-water (potable and sanitary), sewage discharge, bilge, ballast and fire extinguishing one.

It is proposed to equip the ship with a common fresh- water system intended simultaneously for the purposes of drinking, washing and washing-out fecal matter. The fresh-water storage tanks will be supplemented with fresh water from land every second day. Separate systems will be installed on the pusher and barge. The water supply system on the pusher will include : two fresh-water hydrophore pumps (one to stand by), hydrophore tank, circulating pump for hot sanitary water (for washing), sanitary-water electric heater, fresh-water storage tanks, filters and fresh-water disinfection devices (optionally).

It is proposed to equip the ship with a common sewage discharge system for „black" and „grey" sanitary water simultaneously. It would be a collecting system. Sewage and waste sanitary water will be discharged to tanks and there stored, and next pumped out to land. The sewage discharge system on the pusher will include : a sewage discharge pump and sewage collecting tanks (built-in the hull).

For the bilge system is proposed the solution without any retention tanks, with one bilge pump (self-sucking-in rotary pump driven by electric motor); the ballast pump (of the same characteristics as the bilge one) will serve as a stand-by pump. Bilge water is assumed to be discharged during stays in ports.

Besides, it was assumed to fit the power plant with an air compressor (of 8 bar pressure) for auxiliary purposes. It is electrically driven and built together with 110 dm$^3$ pressurized air tank as one unit. And, the following devices were preliminarily selected: ballast pump, fire pump, compressor in air conditioning control unit as well as the so-called "power pack" intended for supplying hydraulic motors installed on the pusher.

The arrangement plan of the devices in the engine room is presented in Fig.1.

Tab. 1 contains the preliminary specification of the power plant equipment. Numbers shown in Fig.1 correspond with those given in Tab.1.

***Tab.1.*** *Preliminary specification of the devices for the power plant with mechanical (diesel engine) drive of screw propellers .*

| No. | Name of device | Number of pieces | Characteristics |
|---|---|---|---|
| 1 | Main diesel engine | 2 | Volvo Penta D9MH<br>N = 261 kW<br>n = 1800 rpm |
| 2 | Reversing-reduction gear | 2 | MG5114DC-E<br>N = 261 kW<br>i = 3.2:1 |
| 3 | Electric generating set | 2 | Volvo Penta<br>D7A T/UCM274F<br>N = 108 kW<br>n = 1500 rpm |
| 4 | Main engine silencer | 2 | To be delivered by the engine's producer |
| 5 | Auxiliary engine silencer | 2 | To be delivered by the engine's producer |
| 6 | Fuel oil transport pump | 1 | Q = 2 m$^3$/h ; p = 2 bar |
| 7 | Lubricating oil transport pump | 1 | Q = 20 dm$^3$/min<br>p = 2 bar |
| 8 | Outboard-water pump | 1 | |
| 9 | Fire pump | 1 | Q = 40 m$^3$/h ; p = 6 bar |
| 10 | Ballast pump | 1 | Q = 35 m$^3$/h<br>p = 2.5 bar |
| 11 | Bilge pump | 1 | Q = 35 m$^3$/h<br>p = 2.5 bar |
| 12 | Auxiliary compressor | 1 | Q = 20 m$^3$/h ; p = 8 bar |
| 13 | Compressor in air-conditioning control unit | 1 | |
| 14 | Fecal matter pump | 1 | Q = 36 m$^3$/h ; p = 1.5 bar |
| 15 | Potable and sanitary water pump | 2 | Q = 2 m$^3$/h ; p = 5 bar |

| | | | |
|---|---|---|---|
| 16 | Hydrophore tank | 1 | V = 500 dm$^3$ |
| 17 | Hot water circulating pump | 1 | Q = 1.5 m$^3$/h ; p = 2 bar |
| 18 | Water electric heater | 1 | Q = 20 kW |
| 19 | Power pack | 1 | N = 25 kW |
| 20 | Main electric switchboard | 1 | |

## DIESEL-ELECTRIC POWER PLANT

An alternative variant of the power plant in question is the diesel-electric design solution. The main propulsion system and electric power plant consist of the following elements :

- Three D9MG/HCM434C Volvo – Penta main electric generating sets. Each of 216 kW output power and the electric parameters : 3×415 V, 50 Hz
- Two Sg 355 s2 EMIT main drive electric motors of 200 kW output power each at 1450rpm rotational speed
- Two VLT Danfoss frequency converters
- Two NF 3 Renk-Tacke reduction gears of 2.5:1 reduction ratio.

The main drive electric motors together with the reduction gears will be shifted fore like in the case of the first solution of the power plant. The coupling flange of the gear should be located between 8th and 9th abscissa. The main drive electric motors should be placed on their foundations in such a way as to get the axes of output shafts of the reversing-reduction gears located at the height of 0.5 m above the ship's bottom. The axes of propulsion shaft-lines will be parallel to the base plane and symmetry plane of the ship [5].

Three main electric generating sets will be placed closer to the stern, symmetrically on both sides of the ship's plane of symmetry. Auxiliary devices of the power plant will be arranged between the propulsion systems containing electric motors. The minimum value of gangways between engines and devices should be not smaller than 600 mm [9].

In the case of the solution in question a greater concentration of machines and devices within the ship's engine room, hence a lower comfort level for operators of the power plant, is obtained. From the comparison of mass values of both the power plants (Tab.2) it reveals that the first variant is also a better solution as the diesel-electric power plant would be heavier by about 5 t [4].

***Tab. 2.*** *Mass of the main elements of two design variants of the ship's propulsion and energy supply systems [kg] .*

| | Variant I | Variant II |
|---|---|---|
| Main diesel engines together with elastic couplings and reversing-reduction gears | 4000 | - |
| Electric generating sets | 3000 | 7800 |
| Main drive electric motors with gears and frequency converters | - | 4100 |
| **Total** | **7000** | **11900** |

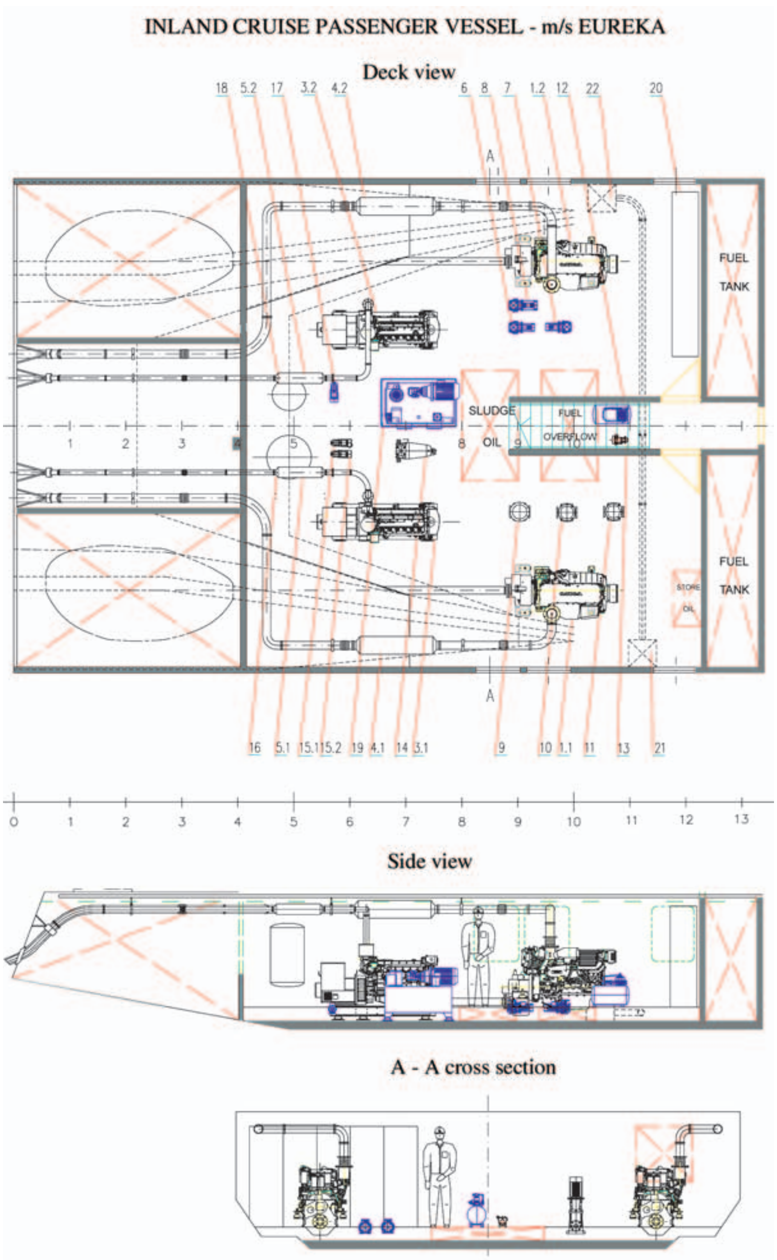


***Fig.1.*** *General arrangement plan of the power plant with mechanical (diesel engine) drive of screw propellers .*

On all diesel engines, as in the case of the first solution, the pumps for fresh water, outboard water, lubricating oil and fuel oil supplying will be suspended (to be driven by the engines). The engines will be also fitted with fresh-water and lubricating oil coolers, oil and fuel filters, and surge tanks. The reduction gears will be equipped with an oil circulating pump, filter and oil cooler. Any centrifugal separating process of oil and fuel is not assumed, hence into the set of the auxiliary systems for diesel engines and propulsion system elements, which not will be delivered together with the engines or gears, will be included only the following: outboard-water pump, fuel oil transport pump and lubricating oil transport pump, like in the first variant of the power plant. Similarly, the outlet of exhaust gases from diesel engines will be also arranged through the ship's stern. However, as the main electric generating sets will be placed within the engine room it is proposed to place only their silencers outside the engine room. (see Fig.2).

The remaining auxiliary devices will be installed within the engine room, like in the case of the first solution, however in a different arrangement. The arrangement plan of all machines and devices within the engine room is presented in Fig.2. The preliminary specification of the devices of the diesel-electric power plant is given in Tab.3. The numbers shown in Fig.2 correspond with those given in Tab.3.

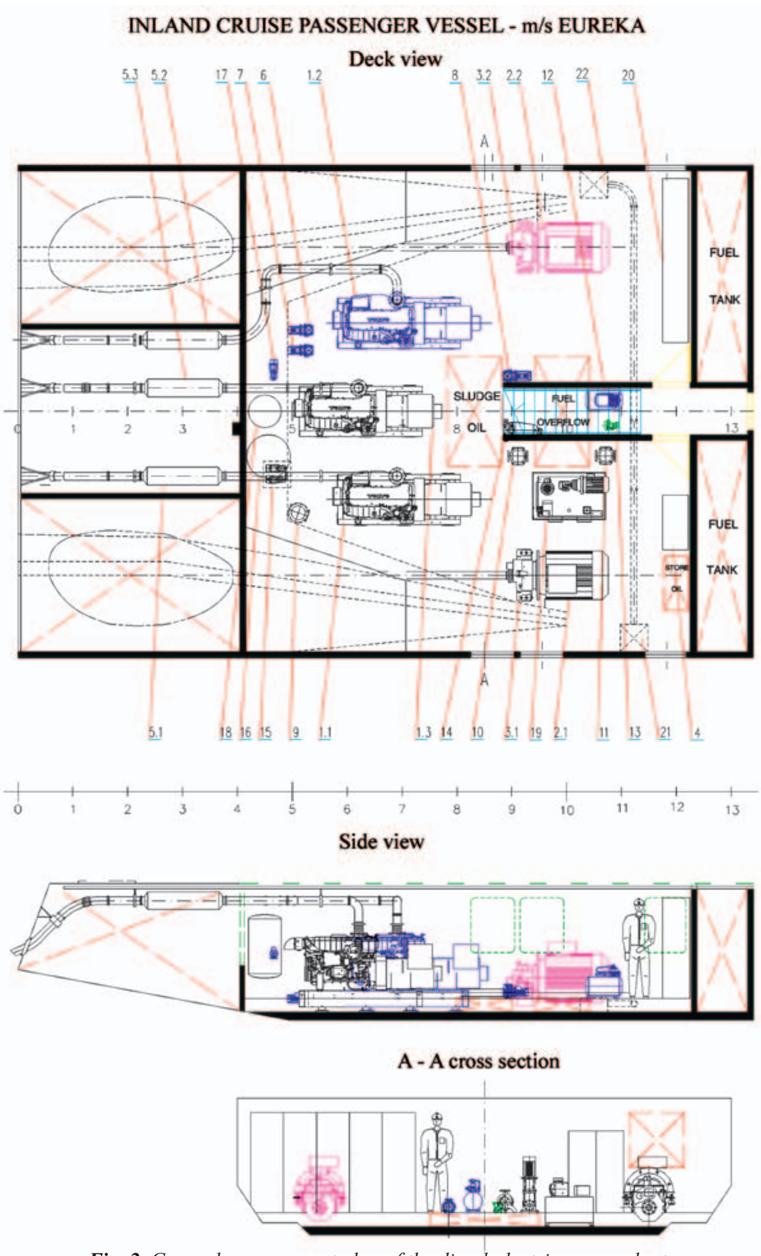


***Fig. 2.** General arrangement plan of the diesel-electric power plant .*

## ENGINE ROOM ON THE BARGE

A small electric generating set of about 40 – 50 kW output power will be the main device installed in the barge's engine room. Its task will be to satisfy electric energy demand in the following situations:

- ⇨ During disjoining the pusher and barge when the ship starts its locking process. The electric generating set would then cover electric energy demand of the barge. The demand would be associated a.o. with operation of a small propeller installed on the bow of the barge and intended for moving the barge out of the lock, lighting as well as with operation of the devices then necessary
- ⇨ During the maximum demand for electric energy, then the electric generating set on the barge would work in parallel with the electric generating sets installed on the pusher
- ⇨ During lying the barge along quay and its functioning as a hotel, in the case of lack of energy supply from land.

The electric generating set would be fitted with all auxiliary devices necessary for its operation (the devices suspended on the engine and driven by it will be the following : water pumps, oil pump and fuel pump). The barge should be provided with one fuel storage tank at least. Its capacity should be not greater than 100 dm$^3$ (or 2×50 dm$^3$). Unfortunately, discharging the exhaust gases is possible only through one of the barge sides. The exhaust gas duct will be fitted with a 35 dBA silencer and a spark catcher. The (L×B×H) dimensions of the electric generating set will be approximately equal to1400×800×1200 mm, and its mass to 600 – 800 kg (mean unit mass of 14 kg/kW).

The remaining devices which should be installed in the engine room of the barge are the following : outboard-water pump, sewage discharge pump, two pumps for potable and sanitary water, hydrophore tank, hot water circulating pump, water electric heater, fire pump, ballast pump, compressor in air-conditioning central unit, power pack, electric switchboard [5].

***Tab.3.** Preliminary specification of the devices for the diesel-electric power plant .*

| No. | Name of device | Number of pieces | Characteristics |
|---|---|---|---|
| 1 | Mian electric generating set | 3 | Volvo Penta D9MG/HCM434C<br>N = 216 kW n = 1500 rpm |
| 2 | Main drive electric motor | 2 | EMIT Sg 355 s2<br>N = 200 kW ; n = 1450 rpm |
| 3 | Reduction gear | 2 | NF 3<br>N = 200 kW ; i = 2.5:1 |
| 4 | Frequency converter | 2 | Danfoss VLT 6000 |
| 5 | Engine silencer | 3 | To be delivered by the engine's producer |
| 6 | Fuel-oil transport pump | 1 | Q = 2 m$^3$/h ; p = 2 bar |
| 7 | Lubricating-oil transport pump | 1 | Q = 20 dm$^3$/min ; p = 2 bar |
| 8 | Outboard-water pump | 1 | |
| 9 | Fire pump | 1 | Q = 40 m$^3$/h ; p = 6 bar |
| 10 | Ballast pump | 1 | Q = 35 m$^3$/h ; p = 2.5 bar |
| 11 | Bilge pump | 1 | Q = 35 m$^3$/h ; p = 2.5 bar |
| 12 | Auxiliary compressor | 1 | Q = 20 m$^3$/h p = 8 bar |
| 13 | Compressor in air-conditioning control unit | 1 | |
| 14 | Fecal matter pump | 1 | Q = 36 m$^3$/h ; p = 1.5 bar |
| 15 | Potable and sanitary water pump | 2 | Q = 2 m$^3$/h p = 5 bar |

| | | | |
|---|---|---|---|
| 16 | Hydrophore tank | 1 | V = 500 dm$^3$ |
| 17 | Hot-water circulating pump | 1 | Q = 1,5 m$^3$/h ; p = 2 bar |
| 18 | Water electric heater | 1 | Q = 20 kW |
| 19 | Power pack | 1 | N = 25 kW |
| 20 | Main electric switchboard | 1 | |

In order to satisfy the requirements for proper maintenance of devices as well as for necessary width of gangways the minimum area of the engine room on the barge should be equal to about 25-30 m$^2$ [5].

## FINAL REMARKS

- Out of the two presented variants of the power plant for inland waterways passenger ship the best solution seems to be the power plant with mechanical (diesel engine) drive of screw propellers. Firstly, such solution is the most economical [3,4], secondly, it is also better as regards mass and dimensions of the power plant.
- The diesel-electric power plant is an alternative solution which may appear more favourable in the case of yearlong operation of the ship on European waterways and a sudden rise of fuel prices in the years to come.

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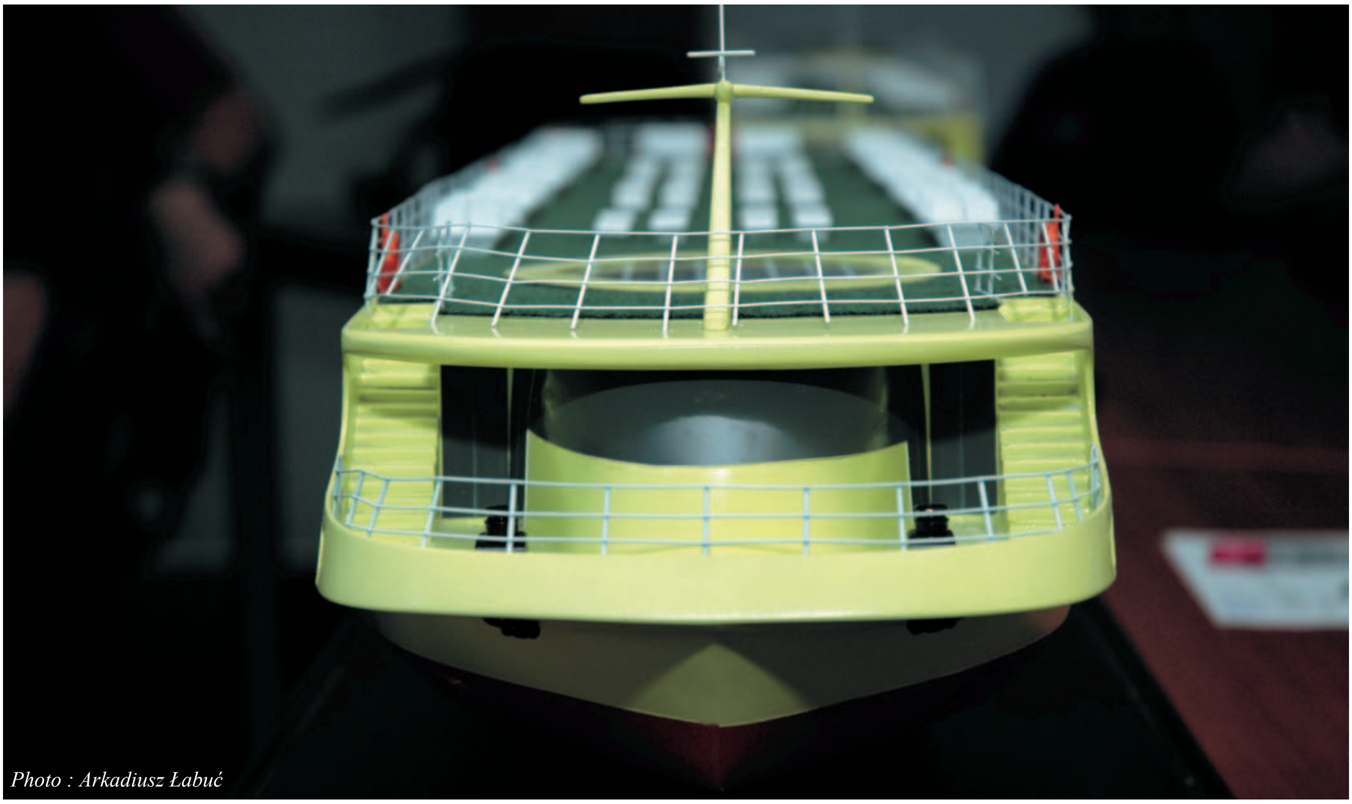
*Photo : Arkadiusz Łabuć*

# A design concept of main propulsion system with hydrostatic transmission gear for inland waterways ship

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ABSTRACT

*This analysis is aimed at presentation of a design concept of ship's main propulsion system and determination of its total efficiency. To realize the task it is necessary to have a look at description of energy losses and efficiency of hydrostatic transmission gear, with taking into account its possible simplification. Image of mutual interaction of losses generated in all elements of hydraulic system appears very complex. In this paper energy balance of main propulsion system with hydrostatic transmission gear intended for a segment ship for inland waterways and coastal service, was analyzed under assumption of necessary simplifications.*

**Keywords :** inland ships, hydrostatic propulsion system

## INTRODUCTION

Selection of a ship's propulsion system should be preceded by an analysis which takes into account a.o. : types of today applied solutions, possibility of fulfillment of its demanded tasks, efficiency, initial and operational costs. Out of many analyzed propulsion systems applicable to ship operating in shallow inland waters, a system based on a hydrostatic transmission gear and fixed screw propeller ducted in a rotatable Kort nozzle, was selected to be designed. The system is consisted of a high-speed diesel engine which drives a variable delivery oil pump feeding hydraulic motor (-s) which directly or through a reduction gear drives a fixed screw propeller.

It should be mentioned that as compared with the hydraulic system the traditional propulsion system with fixed screw propeller has, apart from its higher simplicity and reliability, many important drawbacks such as : the necessity of application of a reversible reduction gear, a lower efficiency in distinctly varying operational conditions, as well as a lower possibility of ship speed control and power plant automation.

Hydraulic drives are widely used on contemporary merchant and naval ships. They serve for driving steering gears, windlasses, mooring, trawling and hoisting winches, closing devices of hatch covers, watertight and fire protecting doors, for driving ship-rolling fin stabilizers as well as fixed propellers of ship thrusters and low –power main propulsion systems.

Hydraulic drives are today applied not only to the mechanisms of to-and-fro-motion but wider and wider also to the rotary mechanisms. The reason is much smaller weight and inertia moment of hydraulic motor as compared with those of electric motor of the same output power.

Below are presented : schematic diagram, drive concept and energy balance of the main propulsion system with hydrostatic transmission gear intended for a segment ship provided for inland waterways and coastal service.

## SCHEMATIC DIAGRAM OF SHIP'S MAIN PROPULSION SYSTEM

The schematic diagram of ship's main propulsion system with hydrostatic transmission gear is presented in Fig.1. It is supplemented with the drives of inclination mechanisms of Kort nozzles which fulfill function of rudders in the case in question.

The main propulsion system is composed of two independent sub-systems. Each of them is equipped with a high-speed diesel engine which directly drives a set of pumps as well as – through a reduction gear – an electric generating set, that makes operating with constant rotational speed necessary. The main pump of the system is of variable delivery and it feeds - in closed circulation - hydraulic motors of constant absorbing capacity. By changing geometrical working volume of the pump it is possible not only to change steplessly its capacity from 0 to $Q_{max}$ , but also to reverse oil pumping direction, hence to control direction and rotational speed of the motors fed by the pump and of the screw propeller driven by the motors.

Closed-circulation drives usually have smaller dimensions as compared with open- circulation ones, and they operate more stable as during operation air does not get inside the main. Hence they are suitable for operating in automatically controlled systems.

Closed -circulation systems are as a rule applied where load changes its sense at changed direction of rotation, e.g. in the case of ship screw propeller. As in the closed- circulation systems the suction and pumping pipes interchange their functions they cannot be connected with open oil tanks, hence heat transfer conditions in them are worse than in open-circulation systems, hence it is as a rule necessary to apply oil coolers.

A main drawback of closed - circulation systems is the fast heating of circulating oil, which requires the generated heat to be absorbed to make long -lasting work under full load

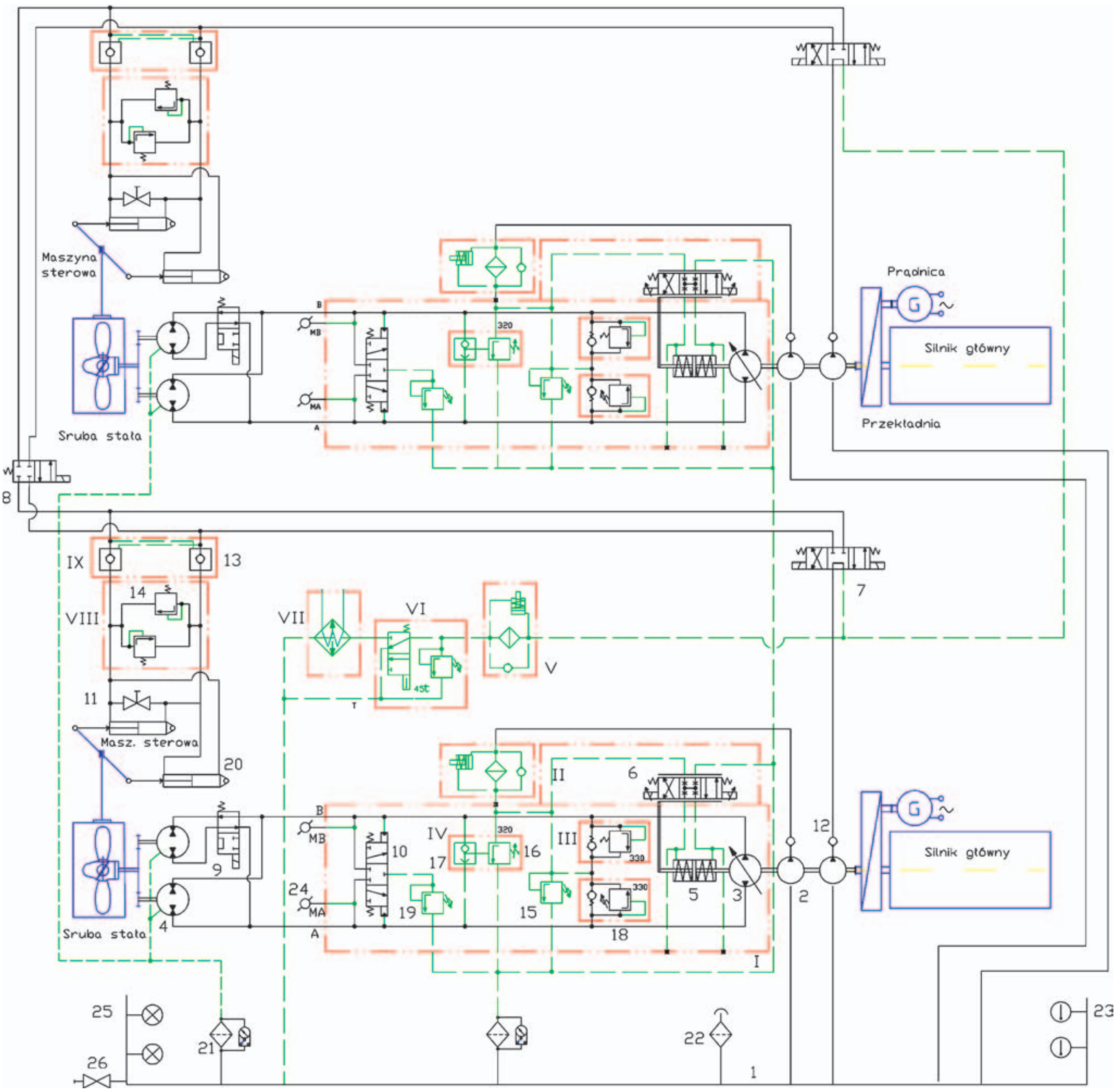


*Fig. 1. Schematic diagram of ship main propulsion system and its control [1] .*

impossible. Generally it is accomplished by means of continuous replacing a part of the heated oil taken from the main circulation by cleaned cool oil from the auxiliary reconditioning circulation.

Each of the main engines drives one electric generating set and three pumps (no. 3, 2 and 2a) including two of variable delivery. In the main hydraulic system are installed : the pump no. 3 of variable delivery per revolution and variable pumping direction, two reversible motors no. 4 of constant absorbing capacity, the scavenging pump no. 2a, the main pump safety valves no. 18 and the valves, no. 15 and 16, of the scavenging filling-up pump, the check valves connected in series with the valves no. 18, as well as the filter no. 21.

Depending on pumping direction of oil either through the pipe A or B, clockwise or anti-clockwise direction of revolution of the motors no. 4 is obtained. It depends on pumping direction which of the safety valves no. 18 can be active.

The system of check valves ensures that the refreshing oil always is delivered to the low-pressure branch of the main circulation. In the low-pressure part some over-pressure usually equal to 0.5÷1.5 MPa, is maintained. The pressure prevents the suction piping from airing and cavitation as well as improves filling conditions of the working chambers of the pump no. 3. Hence a greater rotational speed of pump shaft can be used as compared with that in open-circulation systems.

The scavenging pump no. 2a pumps oil through the filter and check valves into the main. It ensures the reconditioning of oil in the main circulation system and the simultaneous supplementing of oil losses resulting from non-tightness of the pump no. 3, motors no.4 and fittings.

The overflow valve no. 15 is set-up at the opening pressure a little higher than that at the valve no. 19, hence the fresh oil is delivered through one of the blocks no. 18 to currently low--pressure branch of the main circulation. Whereas the valve no. 16, in cooperation with the distributor no. 6, limits capacity of the main pump in the case of a pressure increase in the pumping branch of the main propulsion hydraulic system.

The motors no. 4 drive – through the reduction gear – the fixed screw propeller ducted by the rotatable Kort nozzle having this way function of rudder. Stepless control of speed and direction of propeller rotation is accomplished by changing the capacity and pumping direction of the pump no. 3. To this end serves the hydraulic servo-mechanism of the pump, consisted of the setting cylinder no. 5 and the electro-magnetically controlled proportional distributor no. 6. Hence choice of direction of movement either forward or astern can be made by means of the latter distributing valve electrically and remotely controlled from cabin.

To ensure oil exchanging and cooling in the circulation, the so-called block of scavenging valves is used. The heated and contaminated oil is discharged to the tank by means of the distributor no. 10 and overflow valve no. 19. Change of pumping direction of the pump no. 3 (and direction of rotation of the motors no. 4) triggers automatically switch-over of the distributor no. 10 in such a way as to make oil exchange occurring always within the low-pressure branch of the circulation. Therefore the fresh oil cooled in cooler VII comes into circulation.

The pump no. 2 pumps oil – through the distributor no. 7 – – to the cylinders no. 20 of the Kort nozzle inclination system. The system is secured by two safety valves no. 14. They connect to each other both pipes of the cylinders in the case of exceeding the permissible force applied to the cylinders. In the central position of the distributor no. 7 the inflowing oil is directed through the unit of filter V and cooler VII, in the case when the oil were heated over 45°C.

Advantages of the closed-circulation system are the following :

- the possible changing of motion direction of consumer by means of the pump and
- the possible braking of drive by means of the pump and main motor.

Arrangement of basic units of the system

The ship's propulsion system is presented in Fig. 2, 3 and 4.

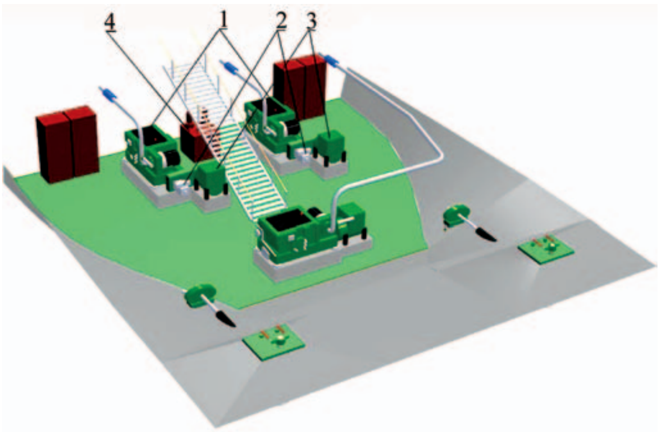


***Fig. 2.** Aft view on the ship and its devices arranged in ship power plant .*

The main engines used to drive the pumps of the hydraulic system as well as the electric generating sets are IVECO CURSOR 300 Common Rail direct injection diesel engines (no.1 in Fig. 2). The engines develop 220kW (300 KM) output power at 2000 rpm speed.

The main engines serve for direct driving the Rexroth A4VSG 180 main hydraulic pumps (no. 2 in Fig. 2). They are multi-plunger (axial) pumps of inclining disk, which can operate at the nominal pressure up to 400 bar and maximum rotational speed equal to 2400 rpm, in closed circulation. The pump is integrated with the auxiliary pump of the scavenging circulation and control system.

Additionally, in the system the belt transmission (no.7 in Fig. 4) to drive Leroy Somer 42.2 VL8 electric generating set (no. 3) and the additional pump delivering oil to the hydraulic nozzle-rotation control system (no. 5 in Fig. 3), are provided for.

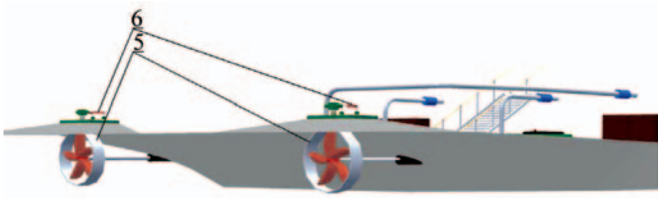


***Fig. 3.** Aft view on the ship fitted with the propulsion system in question .*

The belt transmission (no. 7 in Fig. 4) is designed on the basis of Gates QuadPower II toothed vee-belts. Such construction eliminates practically entirely sliding the vee-belt wheels, which would be not acceptable because of the function of driving the electric generator, realized with its help.

The IVECO GE8210M22 electric generating set (no. 8 in Fig.4) was proposed to be used as an additional electric energy source. The diesel engine driving the electric generator is of direct injection (effected by BOSCH pump of P type). The generator is provided for operation both during ship sailing and staying (i.e. when its main engines are stopped).

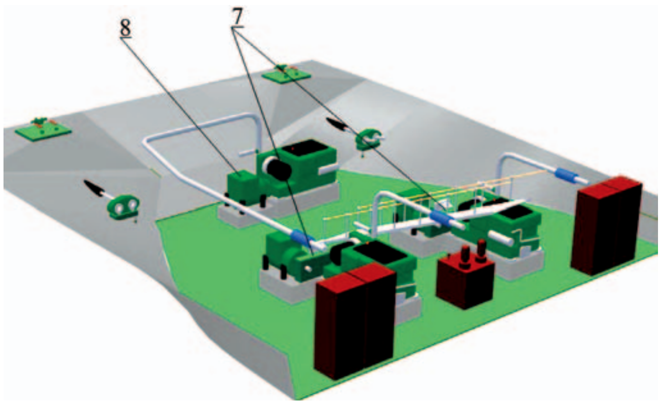


***Fig. 4.** Fore view on the ship : schematic image of the devices arranged in ship power plant .*

Each of the fixed screw propellers of the ship is driven through the cylindrical gear (to decrease its mass and increase reliability) by two Rexroth A2FM 80 hydraulic motors (of multi-plunger (axial) construction, inclining cylinder block and constant absorbing capacity per revolution). The motors can operate under pressure up to 400 bar and 5000 rpm speed. The rotatable nozzle (no. 5 in Fig.3) is inclined by means of hydraulic cylinders.

The oil tank (no.4 in Fig.2) is located under stairs.

## ENERGY EFFICIENCY OF HYDROSTATIC SYSTEM

One of the crucial features characterizing the hydrostatic system is its energy efficiency defined as the ratio of the output power obtained from the engine (-s) and the power delivered to the pump shaft. Apart from economical and energy consequences, drop of the efficiency results also in an increase of oil temperature and associated change of its viscosity, which influences the system's operational characteristics. Hence sometimes it can constitute the factor which decides on possibility of application of such system in a given case.

In many cases energy losses are mutually connected, e.g. mechanical friction in gaps is usually associated with leakages and both the phenomena mutually interact. Therefore unambiguous separation of particular parameters from each other and determination of their impact on run of the phenomena, e.g. in a working pump, often meet serious difficulties. The general principle that the total efficiency is the product of partial efficiencies, being in force in mechanics, in hydraulics, should be considered as a simplification due to occurrence of various interactions and feedbacks difficult for investigation and complicating the principle. Under necessary simplifications, was analyzed energy balance of the main propulsion system with hydrostatic transmission gear, intended for a segment ship for inland waterways and coastal service.

## ANALYSIS OF ENERGY LOSSES AND EFFICIENCY OF SHIP MAIN PROPULSION SYSTEM WITH HYDROSTATIC TRANSMISSION GEAR

Structure of hydraulic system greatly impacts its efficiency. Its influence is usually considered under assumption of an ideal pump and motor and that real energy losses occurring in the pump and motor will result in a further proportional decrease of total efficiency of the system.

However, image of mutual interaction of losses in all elements of the hydraulic system appears much more complicated. Instantaneous energy efficiency of pump, for instance, results, apart from other factors, first of all from an applied structure of hydraulic motor control system.

The closed-circulation systems find wide practical application, and in their work it is necessary to supplement oil leakage occurring in the main propulsion system of propeller as well as to exchange heated oil circulating in the system.

Calculations of hydrostatic transmission gear and selection of its elements for a given drive are difficult because of many possibilities of such selection. Input data for calculations of the hydrostatic gear are the following :

- the maximum rotational speed of ship's propeller, $n_{2max}$ = = 12.5 rps [750 rpm]
- the pump shaft rotational speed $n_1$ = 33.3 rps [2000 rpm]
- the propeller shaft power $N_1$ = 150 kW
- the maximum pressure in the system, $p_1$ = 27 MPa.

In elements of hydraulic system occur the losses which functionally depend a.o. on working liquid viscosity, as well as the energy losses which do not practically depend on viscosity.

In order to simplify the problem of viscosity influence on energy performance of the hydraulic system, the kinematic viscosity $\nu_n$ = 35 $mm^2s^{-1}$ was chosen as the reference level recommended by producers from the point of view of the functioning of hydraulic elements produced by them.

From the schematic diagram presented in Fig. 1. it results that in the hydrostatic propulsion system of the ship the transmission gear controlled by changing geometrical working volume of the pump which cooperates with two motors of a constant absorbing capacity, is applied.

As above mentioned, in the hydrostatic gear the controllable plunger axial pump with inclining cylinder block, operating in the closed -circulation system with possible change of oil pumping direction, is applied. This is Rexroth A4VSG 180 pump of 180 $cm^3$ displacement volume. The demanded theoretical capacity of the pump, $Q_{Pt}$ , is equal to 0.00594 $m^3/s$ [356.4 $dm^3/min$]. Whereas from the characteristics of the real capacity of the pump, $Q_P$ , in function of working pressure (catalogue data) it results that the real capacity is equal to 0.00558 $m^3/s$ [335 $dm^3/min$] at the pressure p = 27 MPa, and from the pump characteristics at 27 MPa pressure – the displacement efficiency of the pump, $\eta_{Pv}$ , equals 0.91. Hence the power $P_{ep}$ delivered by the pump amounts to 165.7 kW.

Then two hydraulic motors, also produced by Rexroth, were selected for each of the two propulsion systems of the ship. These are A2FM 80 motors of 365 Nm torque at 27 MPa working pressure. The minimum rotational speed $n_{min}$ at which shaft rotational speed is still maintained, amounts to 0.8 rps [50 rpm]. For the selected high-speed motor, high efficiency can be obtained at the speed within the range of 10 ÷ 56 rps [600÷ ÷ 3400 rpm]. The total efficiency $\eta_s$ read from the efficiency characteristics of the motor operating with the rotational speed of 35 rps [2100 rpm] at 27 MPa working pressure, is equal to 0.94.

Hence the power $P_M$ of one hydraulic motor obtained from calculations is equal to 76 kW.

The ship screw propeller was assumed to rotate with the rotational speed of 12.5 rps [750 rpm, therefore application of a mechanical reduction gear is necessary. Of course, the propulsion efficiency would be then lowered by the mechanical gear efficiency $\eta_{prz}$ which can be assumed equal to 0.97.

The total propulsion efficiency of the ship, η, being the product of the total efficiencies of the pump, motor and mechanical gear, is equal to 0.82.

After preliminary determination of sizes of consumers and approximate arrangement of hydraulic elements on the ship it was possible to select diameters of piping and nominal diameters of valves and fittings. Usually, the principle of selecting uniform nominal diameters of piping, valves and other devices for one pipeline, is used. The selection of nominal diameter of piping and control elements is very important as the diameter decides on flow losses hence also on the whole device efficiency. If the nominal diameter is too small the flow losses are high and the whole system efficiency – low. A too large nominal diameter would not provide any significant increase of the system efficiency and simultaneously would lead not only to increased cost of the installation but also to difficulties in arranging particular devices on the ship. Hence to reach a reasonable compromise is necessary.

By assuming the liquid velocity $v_t$ equal to 4 m/s in the pumping pipeline the nominal diameter $D_t$ = 40 mm was selected for it. As the closed circulation is taken into account the return pipeline diameter is selected equal to that of pumping one.

If TOTAL Azola 46 oil (of 873.3 $kg/m^3$density in 20°C) is chosen and the limit design temperature range from -10°C to +60°C is assumed, then to determine oil viscosity in the limit temperatures is possible, namely : $\nu_{-10}$ = 400 cSt and $\nu_{60}$ = 20 cSt, respectively. Then the efficiency which can be obtained by the system at the viscosity of 35 $mm^2s^{-1,}$ amounts to 0.82.

## SUMMARY

- An applied speed control structure of hydraulic motor (-s) is the crucial factor which decides on an instantaneous value of energy efficiency of pump or whole hydrostatic drive. The known descriptions of energy losses in pump serve mainly to explain complexity of the phenomena which occur during operation of displacement machines. They have a simplified form as to grasp all factors deciding on the losses is not possible. Simultaneously, the form does not allow to describe global image of relationships of particular kinds of losses and working parameters of the system.

- To obtain description of hydraulic system's efficiency in function of load and speed of motor it is necessary, in the displacement machines, to separate mechanical losses from pressure ones which depend in different ways on pressure level and flow rate of working medium. The system's efficiency model which takes into account influence of working medium viscosity, makes it necessary to apply such description of displacement losses, in which proportions of the main elements of the losses, i.e. layered leakages and turbulent ones are taken into consideration [5].

- The efficiency of the described hydraulic propulsion and control system for the inland waterways passenger ship operating under full load, will be equal to 0.82. However under lower load the total system's efficiency will be lower. Hence a power surplus of the diesel engine driving the pump can be taken over by the generator.
- On the basis of the elaboration [2] were considered successive concepts of ship propulsion systems, e.g. that fitted with azimuthing propeller. The considered concepts of hydraulic propulsion system of the ship did not influence energy balance of the system significantly.

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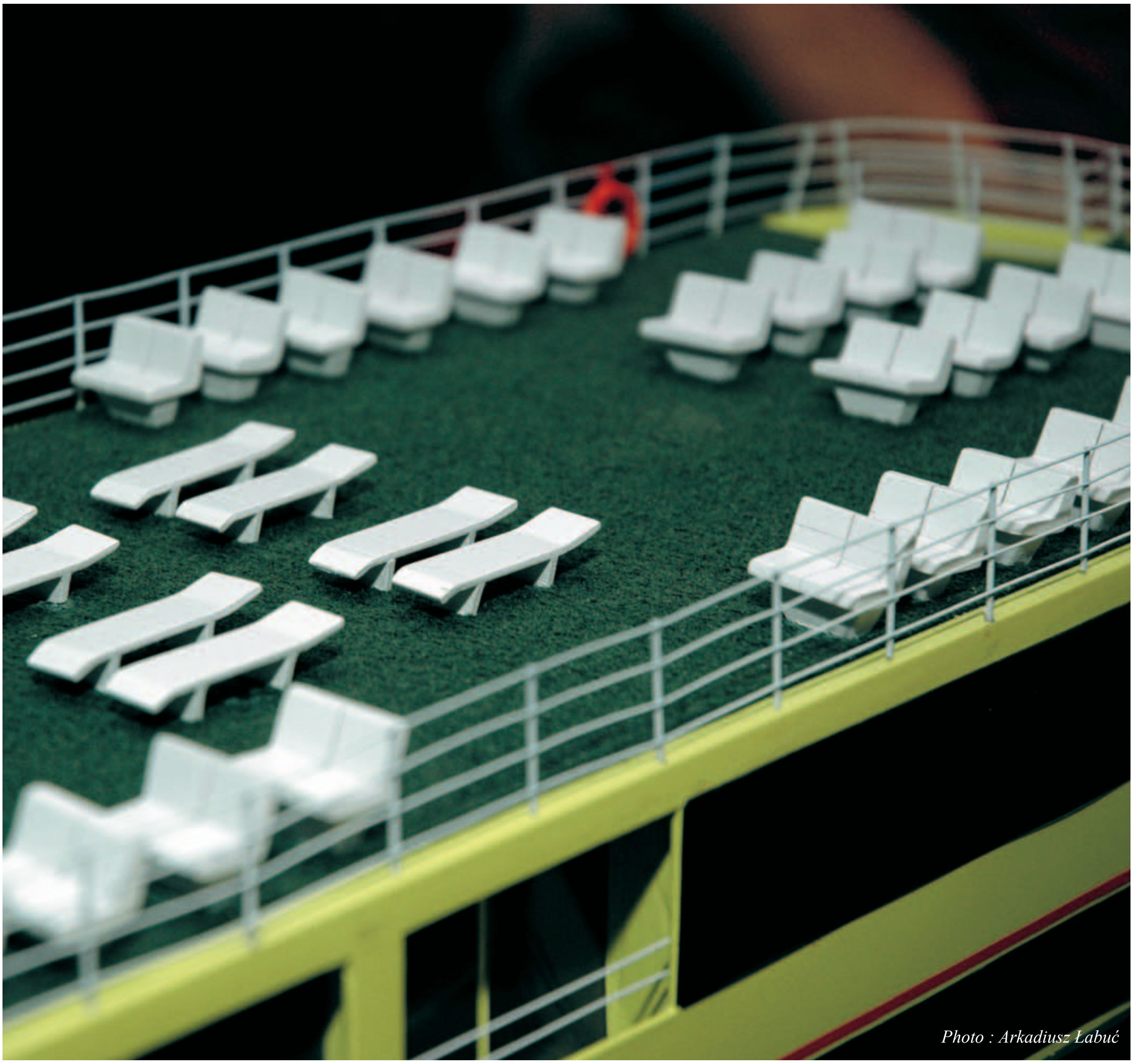

Photo : Arkadiusz Łabuć

# Design concepts of propulsion and steering system for hotel unit of two-segment inland waterways ship

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ABSTRACT

*This paper presents design assumptions and two conceptual design solutions of the propulsion and steering system for the hotel barge constituting a part of two-segment inland and coastal navigation ship. Both presented solutions are based on application of a small-power bow thruster with fixed propeller placed in a rotatable nozzle. In one of the solutions the propeller is driven by a hydraulic motor and in the other – by an electric motor. In both solutions the thruster's column rotating is driven by a hydraulic cylinder.*

**Keywords** : shipboard devices, hydraulic drives, electric drives

## INTRODUCTION

The designed two-segment inland waterways ship consisted of a pusher and hotel barge is intended for coastal and inland navigation on the route Berlin – Toruń – Kaliningrad.

A few design concepts of the propulsion and steering system for the ship were elaborated, including diesel-electric and diesel-hydraulic one, with application of two azimuthing propellers (rotatable thrusters).

Also, a design concept was prepared of an articulated joint connecting barge and pusher in a way which makes it possible to control pivoting both the segments against each other.

Both the above mentioned driving systems ensure relevant navigating and manoeuvring capabilities of the pusher and the entire push-train on the route. However still remains a troublesome problem of passing the train through many locks whose dimensions do not allow for accommodation of the whole train in them. Hence it is necessary to pass the pusher and barge separately. If the passing of the pusher which has its own propulsion system and good manoeuvrability would not constitute any problem, to ensure the safe and effective passing of the barge may be very troublesome if it is not equipped with suitable devices for realization of the operation.

The design conditions and assumptions as well as two concepts of solving the problem are presented below.

## DESIGN ASSUMPTIONS AND OUTLINE OF GENERAL DESIGN CONCEPT

To ensure passing the hotel segment through locks, to fit it with appropriate equipment was assumed to make it possible to realize the operation; such equipment will be characterized by the following features :

- ✪ ensuring high independence of the unit during locking operation
- ✪ providing good manoeuvrability of the unit and easiness of steering
- ✪ non-lowering voyage comfort, to a noticeable extent for passengers
- ✪ possibly low emission of vibrations, noise and polluting agents such as e.g. exhaust gas, during work of the devices
- ✪ versatility of the devices to make it possible to use them also to other operations or cooperation with other equipment
- ✪ possibly small dimensions
- ✪ relatively low cost.

Many possible solutions of the above stated problem were considered, a.o. the following systems :

- ➢ a thruster fitted with suitably formed ducts and two controllable flap valves intended for changing water jet appropriately
- ➢ a typical bow thruster and hoisting winches, e,g, mooring ones, which, after fastening the lines to quay bollards, would make it possible, in co-operation with the bow thruster, to move the barge during its entry to and exit out the lock
- ➢ a system of a few hoisting winches combined with the necessity of fastening the lines to both quays, that entails the need of appropriate outfitting the quays and makes the entire operation very complicated and troublesome
- ➢ a lowerable propulsion system consisted of a combustion engine, reduction gear and fixed screw propeller on a rotatable column
- ➢ a rotatable bow thruster with fixed screw propeller ducted in a suitably formed nozzle and driven directly by a hydraulic motor placed in an underwater pod
- ➢ a similar rotatable bow thruster but driven - through an intersecting axis toothed gear - by an electric motor vertically mounted in the barge hull; rotational speed of the motor has to be controlled by a frequency converter.

The above enumerated design concepts were subjected to a preliminary analysis consisting in defining the most important features of each of them in order to select the most favourable and focus further designing process on them. As a result it was concluded that the first of the design solutions, though improves manoeuvrability of the whole push train, makes the underwater part of the hull much more complicated and requires to install movable units, that increases hull resistance to motion and risk of failure, moreover it does not ensure an appropriately high manoeuvrability of the barge during passing through locks.

The second solution (point b) is much simpler but it lowers independence of the barge and makes locking operations longer and more complicated.

The third solution (point c) is the simplest out of all above enumerated, but it introduces many complications and lengthens the locking operations, moreover it requires suitable mooring bollards to be installed on both canal banks near the lock.

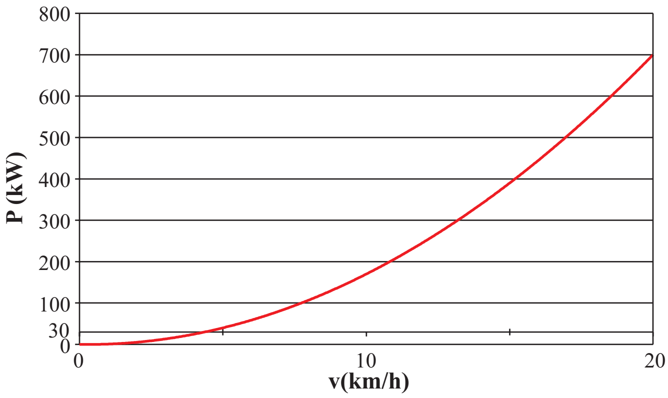
Moreover, it does not improve manoeuvrability of the whole push train during regular operation.

The application of the propulsion unit (point d) to be lowered to water during passing through locks requires to shape appropriately the hull form and to ensure a required area, also on the deck of the barge. It should be also taken into account that such device and its control unit will be more complex and noise emitting during work. It may be also difficult to find a producer for such device of demanded power. It should be added that to use such unit to improve manoeuvrability of the push train during its regular operation is rather not viable because of noisy work of combustion engine and necessity of securing the propeller against failure resulting from catching on waterway bed.

Two last solutions (point e and f), where the use of rotatable bow thruster is proposed, can be considered as the most favourable out of the above enumerated ones. The rotatable thruster located on the bow ensures relatively good manoeuvrability of the barge, moreover, during ship's regular sailing especially in rough conditions it may be periodically used both for improving steering capabilities of the push train, by working as the thruster, and supporting the main propulsion system of the pusher.

As the solution based on the rotatable bow thruster was chosen for further considerations it is necessary to determine its power demand.

Also, it is necessary to take into account not only the need of bringing the barge slowly in and out the lock, but also of fulfilling the supporting function of the rotatable thruster in ship steering during voyage, as well as the function of a reserve energy source for hotel devices. To ease the task, was prepared the relationship between the power demand of the propeller and the barge speed, based on results of model tests, as presented in Diag.1.




***Diag. 1.*** *The relationship between the power demand of the propeller and speed of the barge, for the barge draught of 1m .*

After a broader analysis of both the above mentioned model tests and the propulsion-steering system of the ship as well as other technical and operational conditions it was assumed that the effective power of the propeller should be contained in the range of 20 ÷ 30 kW. For the so determined power the progressive speed of the barge may even reach the value of 3 ÷ 4 km/h.

The two design solutions of the propulsion system of the barge, based on application of the rotatable bow thruster, but differing to each other by a kind and power of propeller driving motor, are presented below.

## THE PROPULSION SYSTEM WITH THE ROTATABLE BOW THRUSTER DRIVEN BY HYDRAULIC MOTOR

In Fig. 1 the arrangement of main components of the barge propulsion and steering system in the version with the rotatable bow thruster driven by a hydraulic motor is shown in an simplified axonometric form.

From the figure it results that the system in question requires a relatively small area, of about 2,5 m in length, only; in spite of that free access to particular devices is still maintained. The motor compartment has to be ventilated. The process will be realized by an ignition-proof exhaust fan.

During designing the system the principle of using catalogue devices or units of recognized producers was complied with, wherever it could be possible.

***Tab.1.*** *Specification of the devices and their mass .*

| No. | Name | Mass [kg] |
|---|---|---|
| 1 | GE 8065M12 IVECO electric generating set | 1075 |
| 2 | CELMA electric motor of 45 kW rated power and 50 rps rotational speed | 335 |
| 3 | A2FO4 REXROTH hydraulic pump of 50 rps rated rotational speed and 18 MPa working pressure | 13.5 |
| 4 | VETUS hydraulic tank, fully equipped | 100 |
| 5 | Rotatable bow thruster : screw propeller and pod with hydraulic motor installed inside, being a unit of VETUS thruster | ?? |
| 6 | Mechanism of rotation | ?? |
| | **Total mass** | **1523.5** |

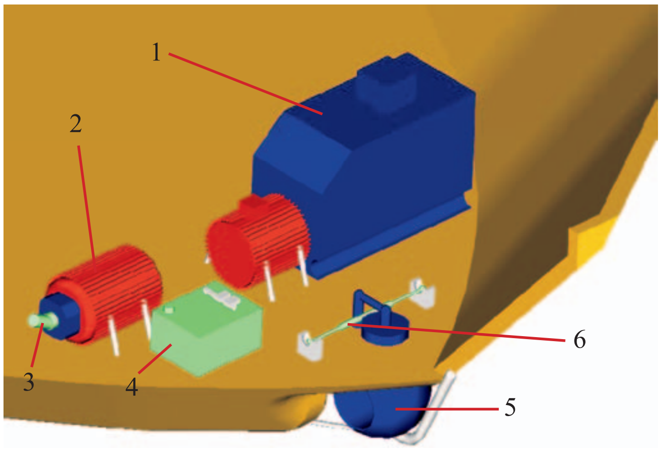



***Fig. 1.*** *The proposed arrangement of main components of the barge propulsion and steering system : **1** – electric generating set; **2** – electric motor; **3** – hydraulic pump; **4** – oil tank; **5** – rotatable bow thruster; **6** – rotating mechanism of bow thruster's column.*

The rated power of the electric generating set (1) was determined with a large surplus with a view to make main hotel devices located on the barge working possible during operation of the rotatable bow thruster. Dimensions of the generating set allow to place it under the deck, near the rotatable bow thruster, that is very advantageous. The medium-speed electric generating set was chosen with a view to noise level moderating. Its estimated noisiness amounts to about 65 dBa. It may be supposed that when an appropriate acoustic insulation is installed in the bow part of the power plant the generated noise will be not troublesome for passengers. To additionally decrease noise emission by the generating set, an exhaust gas system fitted with water injection could be applied. An additional advantage of such solution is an effective limitation of unpleasant smell emission.

The rated power of the electric motor (2) driving the oil pump was chosen as large as to ensure oil supply not only to the hydraulic motor of the propeller but also to the rotating mechanism of the column of the rotatable bow thruster. In this case the high-speed motor of somewhat smaller weight and gabarites was chosen. It should be added that an alternative solution with a little less noisy medium-speed motor is also provided for. The selected oil pump (3) is of a constant capacity, which highly simplifies the hydraulic system but somewhat limits possibility to continuously control working parameters of fed consumers. In the case when higher requirements from the side of ship owner would have to be complied with or supplying also other consumers from the system in question would be required, a multi-section pump or that of variable capacity can be applied.

To drive the screw propeller, was applied a special – directly coupled with it –hydraulic motor of small transverse dimensions, adjusted to be installed inside a pod for small-power thrusters, e.g. those produced by Vetus firm. In order to minimize hull resistance the outer surface of propeller nozzle is given the form of a sphere with pole parts cut at some parallel. In the position indicated in Fig.1 the propeller fulfils the function of a typical thruster. It should be stressed that the screw propellers used for thrusters are so shaped as to generate the same value of thrust in each of the opposite directions when direction of rotation is changed, that makes it possible to restrict the demanded rotation angle to 180° in the case of their application to the rotatable bow thrusters.

In the hydraulic system the oil tank with necessary equipment and valve block has to be applied. To assess its dimensions and mass one of the tanks offered by Vetus firm was chosen, depending on size of the system. The tanks are ribbed to ensure more effective heat transfer, that - in the case of short-lasting, short-term work of consumers - may eliminate necessity of applying an oil cooler, or reduce its dimensions.

The proposed rotating mechanism of the rotatable bow thruster's column is relatively simple and easy for realization. It will be driven by a two-piston-rod slidable cylinder to which a toothed bar is fixed. The bar will co-operate with a toothed wheel mounted on the rotatable bow thruster's column. To obtain low noisiness of that gear and to eliminate necessity of its lubrication, the toothed wheel will be made of a plastic material of good strength properties and a relatively low friction coefficient, such as. tarnamid.

The rotation angle of the column is limited to 180$^{o}$, i.e. 90 $^{o}$ both a-port and starboard. The mechanism in question ensures to reach any arbitrary direction of water jet within the whole round-angle range because the hydraulic drive of the propeller makes it possible to change direction of rotation of the propeller.

The rotatable bow thruster's column is supported by rolling bearings seated in the casing fixed to the hull in a relatively flexible way. As a result, a small inclination of the column casing against the hull is possible when significant load on the nozzle and propeller is exerted. To eliminate any excessive bending moment applied to the column, an additional slide bearing placed under the nozzle, along the column rotation axis, is used. The bearing's sleeve is seated in a special cage protecting the rotatable bow thruster against catching on waterway bed. The proposed form of the bow part of the ship hull and the above mentioned cage is shown in Fig.2 (side view) and 3 (view from below). The hull form allows for free operation of the rotatable bow thruster as a bow thruster but only within the

***Fig. 2.*** *Side view of the hull. The propulsion unit with the screw propeller of 400 mm diameter .*

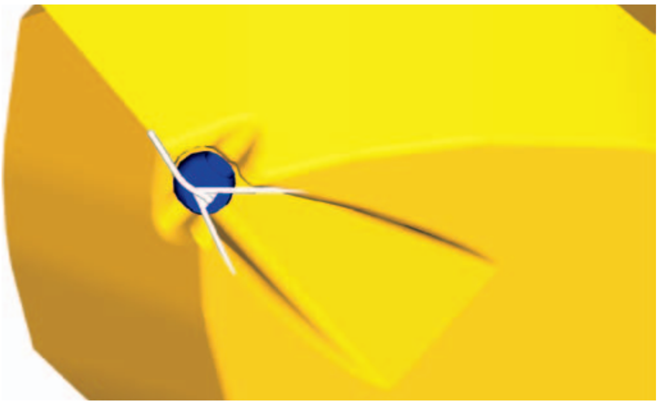


***Fig. 3.*** *Isometric view from below. The propulsion unit with the screw propeller of 400 mm diameter .*

range of column rotation angle from 30$^{o}$ to 45$^{o}$ any effective action of water jet is not possible, that should not be of a great importance in the considered application.

## THE PROPULSION SYSTEM WITH THE ROTATABLE BOW THRUSTER DRIVEN BY ELECTRIC MOTOR

The barge propulsion and steering system with the rotatable bow thruster driven by electric motor was designed for somewhat smaller power than that given in the preceding chapter, in order to show a broader range of possible design solutions.

The arrangement of the main components of the system in question is shown in a simplified axonometric form in Fig.4.

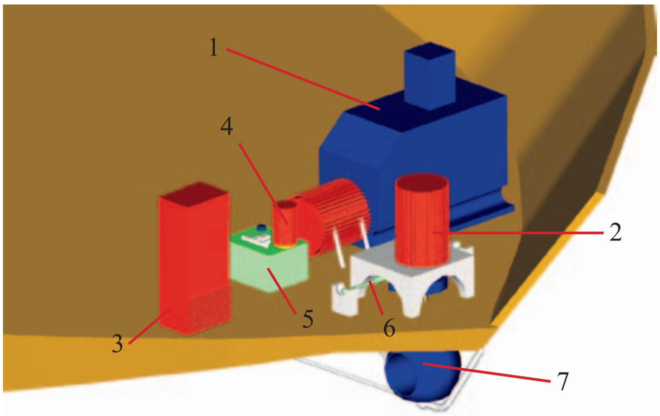



***Fig. 4.*** *The proposed arrangement of the main components of the barge propulsion and steering system :* ***1*** *– electric generating set;* ***2*** *– electric motor driving propeller;* ***3*** *– frequency converter;* ***4*** *– electric motor driving oil pump;* ***5*** *– oil tank;* ***6*** *– rotating mechanism of bow thruster's column.;* ***7*** *– rotatable bow thruster (screw propeller ducted in rotatable nozzle) .*

The presented system (Fig. 4) is compact; it covers only 2,3 m in length and ensures easy access to all components. The motor's compartment is also ventilated in this case.

Like in the preceding solution also in this case the principle of applying catalogue devices or units of recognized producers was complied with, wherever it was possible.

The chosen components of the system are a little smaller and lighter than those in the preceding solution, despite a relatively large unit, the frequency converter, was added.

The propeller driving electric motor (2) is supplied from the frequency converter (3), that makes propeller rotational speed, thus thrust force, continuous changing possible.

The hydraulically driven rotating mechanism was applied to the column of rotatable bow thruster. Such decision was made after analysis of the solutions where an electric motor and either worm gear or planetary gear had to be applied; the solutions appeared more complex, larger and heavier. An additional

*Tab. 2. Specification of the devices and their mass .*

| No. | Name | Mass [kg] |
|---|---|---|
| 1 | GE 8045M08 IVECO electric generating set | 860 |
| 2 | INDUKTA electric motor of 22kW power and 25 rps rotational speed class | 175 |
| 3 | VLT 5032 DANFOSS frequency converter in IP 54 casing | 41 |
| 4 | Sh 80-2A BESEL electric motor of 0,75W ? and 45,7 rps rotational speed class | 7.8 |
| 5 | Oil tank | 55 |
| 6 | Mechanism of rotation | |
| 7 | Rotatable bow thruster : screw propeller fitted with intersecting axis toothed gear installed inside the pod, being a unit of VETUS thruster | ?? |
| **Total mass** | | **1138.8** |

argument speaking for the hydraulic drive is the possible application of the hydraulic system to driving shipboard devices, e.g. mooring-anchoring winch. It should be added that during the regular sailing of both joined ship's segments the hydraulic system will not operate even if the rotatable bow thruster is used only as a typical bow thruster.

The relatively small dimensions of the nozzle of the rotatable bow thruster make it possible to shape much more simply the bow part of the hull, that can be observed in Fig.5 and 6. The hull form is simpler in manufacturing and ensures to make effective use of water jet in the whole range of possible angular positions of the column of the rotatable bow thruster.

***Fig. 5.** Side view of the hull. The propulsion unit* ***with the screw propeller of 300 mm diameter .***

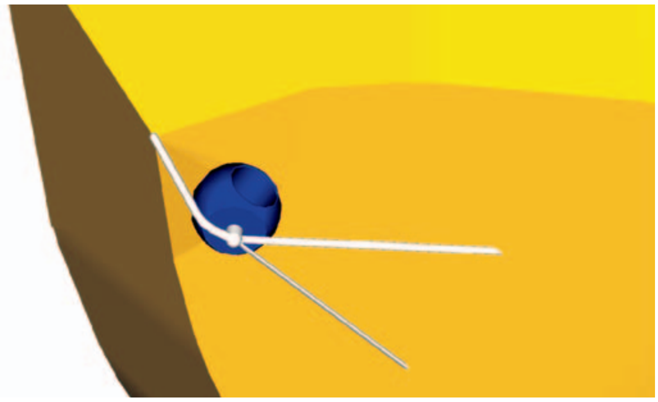


***Fig. 6.** Isometric view from below. The propulsion unit with the screw propeller of 300 mm diameter .*

## CONCLUSIONS

- Both the described design solutions based on the rotatable bow thruster, in spite of the differences in ways of realizing propulsion and steering functions, do not differ much to each other in gabarites, however the solution with the electrically driven propeller demands a smaller power. Though this solution occupies somewhat greater area, total mass of both systems is comparable
- The estimated efficiency of the system with the electrically driven propeller will be greater by a few percent than that of the system with the hydraulically driven propeller even if to take into account that the first system additionally contains the intersecting axis toothed gear and frequency converter. Both the additional units are of so high efficiency (abt. 98%) that the fact of their use does not change superiority of general efficiency of the first system. It should be stressed that the efficiency criterion is rather not decisive in selecting an optimum solution of the systems in question because of their rather small power values and small differences in total efficiency as well as an short-term and short-lasting character of work of such systems.
- A more important criterion is level of emission of noise, vibrations and pollution agents as well as reliability and simplicity of operation and maintenance of a system. Also from this point of view the system with the electrically driven propeller seems to be a little more favourable. The location of the power plant in a small compartment in the bow part of the barge makes it possible to lower noise level by applying a soundproof insulation to walls of the compartment. This is important as in its neighbourhood passenger cabins may be situated.
- In the case of staying the barge in an undeveloped site the electric generating set installed on the barge may serve as a reserve electric energy source to supply hotel equipment as well as shipboard devices such as : mooring - anchoring winches, collapsible aerial mast, various lifts and covers.
- One of the most important advantages of the system with the hydraulically driven propeller is providing, for the drive transmitting elements, a good protection against overload which may happen in the case of an increased resistance of the ship propeller to motion, or even its entire locking, due to entangling in nets, ropes or other garbage elements; this way risk of a serious failure of the rotatable bow thrusters may be greatly lowered.
- In the opinion of the authors the above presented design concepts constitute a good basis for selecting the most favourable solution of the propulsion and steering system for the barge, to be elaborated in the preliminary design phase.

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# Waterjet propulsion of small-draught inland waterways ships

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ABSTRACT

*This paper presents some aspects of ship waterjet propulsion. Advantages and limitations of its applicability are discussed. Also, possible use of waterjet propeller to move a small-draught inland waterways ship, is considered .*

**Keywords** : ship propulsion, hydromechanics

## GENERAL CHARACTERISTICS OF SHIP WATERJET PROPULSION

Waterjet propulsion of ship is based on application of 3rd principle of Newton's dynamics : „If two bodies mutually interact, their interaction forces are equal to each other and pointing in opposite directions". In the waterjet propulsion a crucial role is played by a pump. Located nearby ship's stern, it takes in water through a recess in ship's bottom. From outlet of the pump the water is directed under high pressure to a nozzle placed in the ship's stern. The force pushing out the water from the stern is equal – as to its value – to the force moving the ship in the opposite direction. As to rotate the nozzle is possible practically by an arbitrary angle the same ship propulsion force can be obtained at any arbitrary position of the nozzle. The ship propulsion force depends on water flow rate at the nozzle outlet.

The pump is driven – through the shaft – by a diesel engine (in most applications which have been realized so far) or a gas turbine. The waterjet propulsion may even be of a higher energy efficiency as compared with that of the conventional propulsion (screw propeller), however only in the case if the nozzle, pump and driving engine are properly selected.

The steering of waterjet-propelled ship (change of direction of its motion) is effected by an appropriate change of outlet nozzle position. Astern motion is ensured by application of a deflector with the use of which the change of sense of ship propulsion force can be obtained. In general, the waterjet propulsion is considered favourable at the ship speed exceeding 25 knots. However, a correctly designed waterjet propulsion may be competitive against conventional one also at much smaller speeds. The waterjet propulsion extends its application to the recreation ships and sea-going coastal ships of special use. As compared with conventional one the waterjet propulsion has many advantages which are discussed below.

## EXAMPLES OF WATERJET PROPULSION APPLICATIONS MADE SO FAR

Attempts to apply waterjet propulsion to ships have appeared as early as in the ancient ages.* However the Hamilton's low-power waterjets (1954) intended for propulsion of fast river boats can be considered as the first developed construction.**

Nowadays many firms build waterjets of a wide range output: from a few hundred kW to a few dozen MW.

Rolls-Royce company, a leader of modern waterjet constructions, offers complete propulsion systems for very fast ferry ships, cargo vessels, warships, cruise ships and yachts. Up to now about 1400 assemblies of the output from 22.000 kW to 70.800 kW have been built. And, a ship propulsion system of 250 MW output is under development

Due to the advantages of waterjet propulsion, its application range has become wider and wider. The most important of them are : good manoeuvrability of ship, environmental safety, comfort for passengers. Out of the ship waterjet propulsion applications made so far the following are worth mentioning :

- ✰ In the navy – it serves for propelling the patrol crafts, torpedo boats, destroyers, frigates and cruisers, first of all in USA, but also in France, Italy, Norway, Australia, Spain, Thailand, Canada, Japan, Republic of South Africa and Germany
- ✰ In the passenger fleet – it serves for propelling small inland waterways ships, fast yachts, recreation ships, including fishing ones
- ✰ In the merchant fleet – it has so far had rather narrow application, first of all for propelling fast ferries.

## ADVANTAGES OF WATERJET PROPULSION

The waterjet propulsion – as far as its application to recreation passenger ships is concerned – shows many important advantages.

### *Safety*

In contrast to the screw propeller drive the waterjet propulsion is not endangered by floating solid fragments, ropes or fishing nets. In particular, the waterjet propulsion **correctly fulfils** its role in shallow waters (like in the considered case of its application to an inland waterways ship). Also, persons remaining in water : swimmers, water skiers, divers etc are not exposed to hazards from the side of such device. Any overload of main engine is excluded as its power demand maintains constant regardless of developed ship speed.

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* Archimedes axial water pump (287-212 AChN), Leonardo da Vinci pump (1452-1519), Toogwood's & Hayese's patent (1661), Beniamin Franklin's pulsators (1706-1790).

** So-called „First Hamiltonians".

### Manoeuvrability

Even at a low speed of motion the waterjet- propelled ships maintain excellent maneouvrability due to possible setting an arbitrary spatial position of the outlet nozzle. Thrust force of an arbitrary value and arbitrary direction can be applied to ship . It is especially useful on narrow waterways (like in the considered case). In no circumstances any help from the side of any other floating unit is necessary. Even in rough weather conditions (strong wind, high waves) ship motion control is possible.

### Energy efficiency

The waterjet propulsion correctly adjusted to the driving engine and ship hull, makes engine work at optimum settings possible, i.e. when the specific fuel oil consumption is the lowest. It concerns all its operational phases : moving, starting, stopping and standing-by. Moreover, maintenance cost of such installation are low; it means that operational costs of such propulsion system are low.

### Travelling comfort of passengers

As compared with the screw propeller drive the waterjet propulsion ensures lower noise and vibration level on board of ship. In particular, no cavitation noise from the side of screw propeller is emitted . Screw propellers being of a lower rotational speed than that of rotating elements of waterjet propulsion system, are more bothersome. Pumps are placed in properly insulated casings.

### Refloating the grounded ship

Motion of an inland waterways ship in shallow waters is considered. In the case of grounding the waterjet-propelled ship is able to refloat without any help but only by using its reverse propulsion which can develop a high thrust value.

On standing-by ship or during manoeuvres waterjet thrust reaches its maximum value expressed by the formula :

$$F_{u_{max}} = m \cdot (w_2 - u)_{u=0} = m \cdot w_2 \quad (1)$$

where :

m – water mass flow rate of waterjet [kg/s]
$w_2$ – out- of- the- nozzle flow velocity
u – ship speed.

In the rated working point of waterjet the following relation is satisfied :

$$w_{2_{nom}} = \frac{u_{nom}}{\left(\frac{u}{w_2}\right)_{nom}} \quad (2)$$

where :

$$\left(\frac{u}{w_2}\right)_{nom} \cong 0.8 \div 0.85$$

hence :

$$\frac{F_{u_{max}}}{F_{u_{nom}}} \sim \frac{1}{1 - \left(\frac{u}{w_2}\right)_{nom}} \cong 5 \div 7 \quad (3)$$

It means that on the standing-by ship a propulsion force several times greater than that nominal can be achieved. It is a greatly favourable feature of such propulsion system as in the case of ship grounding it enables to cause an effective motion of ship hull, unavailable by means of any other propulsion system.

### Impact on the environment

The waterjet propelled ships generate much lower waterborne disturbances (noise) as compared with the screw-propelled ones. It is specially important for the water natural environment because of much lower hazard to flora and fauna.

At a properly designed inlet to diffuser (based on model test results) can be obtained laminar inflow, lack of flow separation and turbulence (Fig.1). This way only small losses at inlet to diffuser are produced. The following relation is fulfilled with a good accuracy :

$$w_1 \cong u \quad (4)$$

where :

u – ship speed
$w_1$ – water velocity at inlet to diffuser.

Furthermore the vertical component velocity of the water flowing into the diffuser (Fig. 1) :

$$w_H = w_1 \cdot \sin\alpha = u\,tg\alpha \quad (5)$$

decides on the force imposed on the waterway bed (scouring force); in the case of shallow water it is of a very small value and amounts to about 5÷10% of the water inflow velocity $w_1$. Therefore it can be stated that erosion impact of waterjet propeller on the bed of shallow water is not greater than that of conventional screw propellers.

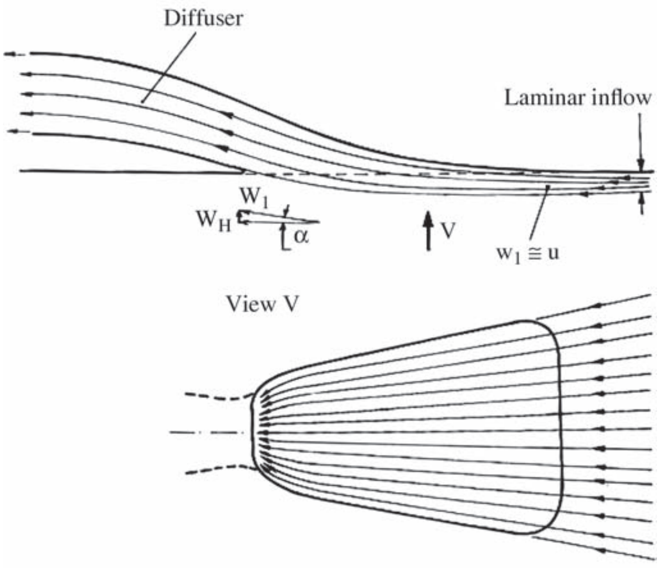


***Fig. 1.*** *Laminar water flow into diffuser .*

### Simplicity of construction

The waterjet propeller is characterized by a high simplicity of construction. It consists of a flow passage (diffuser and confusor), rotary pump (diagonal, helicoidal or impeller one) and a deflector which makes flow reversing and ship rotating possible.

Such propellers are produced as complete units by such firms as Hamilton Waterjet, Castoldijet, Ka-Me-Wa, Lips, Graupner etc.

To drive the waterjet propeller rotary pump a diesel engine or gas turbine is used. In Fig. 2 the ship fitted with the waterjet propeller of Ka-Me-Wa, driven by the Rolls-Royce gas turbine, is presented.

Owing to the above mentioned advantages the waterjet propulsion constitutes an alternative for the screw propeller drive in some, but not all, applications. It may only supplement but not substitute the crew propeller drive. As usually the proper way is to choose one of the two kinds of ship propulsion system by selecting that suitable for a given ship's type and function.

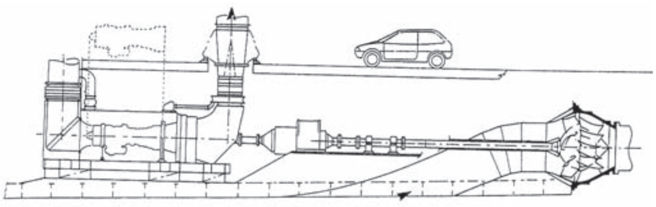

***Fig. 2.*** *The waterjet propeller driven by the gas turbine*

## LIMITATIONS IN APPLICATION OF WATERJET PROPELLER

An important design problem of waterjet propeller is strong dependence of the nozzle outlet area $A_2$ on the ship speed u.

$$A_2=\left(\frac{N_u}{\frac{1-\bar{u}}{\bar{u}^2}\cdot\rho_w\cdot z}\right)\cdot\frac{1}{u^3} \tag{6}$$

where :

$N_u$ – propulsion power

$\bar{u}=\frac{u}{w_2}$ – velocity index

$\rho_w$ – water density

z – number of outlet nozzles.

At given values of $N_u$ and $\bar{u}$ the decreasing of the velocity u by 10% makes the outlet nozzle area $A_2$ increasing by 37%; at 20% decrease of u the outlet nozzle area increases almost twofold, and the velocity decrease by 30% results in the outlet nozzle area $A_2$ almost three times greater.

Taking into consideration the relationship :

$$N_u = \alpha\cdot u^3 \tag{7}$$

where :

α – coefficient of ship resistance power, one can obtain the following area of a single nozzle :

$$A_2=\left(\frac{1}{\frac{1-\bar{u}}{\bar{u}^2}\cdot\rho_w\cdot z}\right)\cdot\alpha \tag{8}$$

The ship resistance power coefficient α is defined as a function of the ship mass displacement $D_w$ (expressed in tons) and the Admiralty coefficient $C_0$ :

$$\alpha\left[\frac{kW}{m^3/s^3}\right]\cong 5.40\,\frac{\sqrt[3]{D_w^2}}{C_0}\left[\frac{KM}{knot^3}\right] \tag{9}$$

In Fig.3 the $A_2$ - α relationship is presented for the selected values of the velocity index $\bar{u}$ = 0.6; 0.7; 0.8 and 0.9, and the assumed number of outlet nozzles z = 2.

And, as shown in Fig. 4 the smaller ship speed the greater hydraulic losses. The coefficient of total hydraulic losses has been defined as follows [10] :

$$\sum_{i=1}^{h}\zeta_i = 2\,\frac{N_L+N_H}{mu^2} \tag{10}$$

where :

$N_L$ – power of hydraulic losses in flow passage of waterjet propeller

$N_H$ – power of elevating the water stream which flows out of the nozzle, up to the level H (H is the height of nozzle axis over the water level).

Hence it can be stated that the waterjet propeller is well adjusted to propelling fast ships.

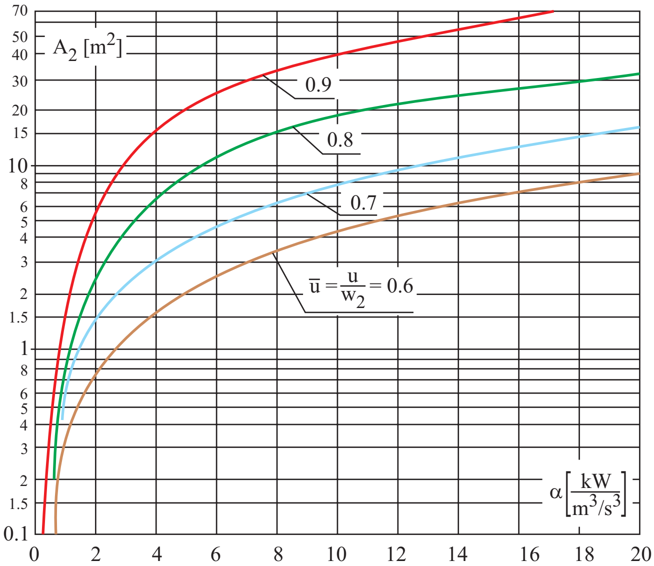


***Fig. 3.*** *The outlet area of two-nozzle waterjet propeller, $A_2$ , in function of the ship resistance power coefficient α and the velocity index $\bar{u}$ .*

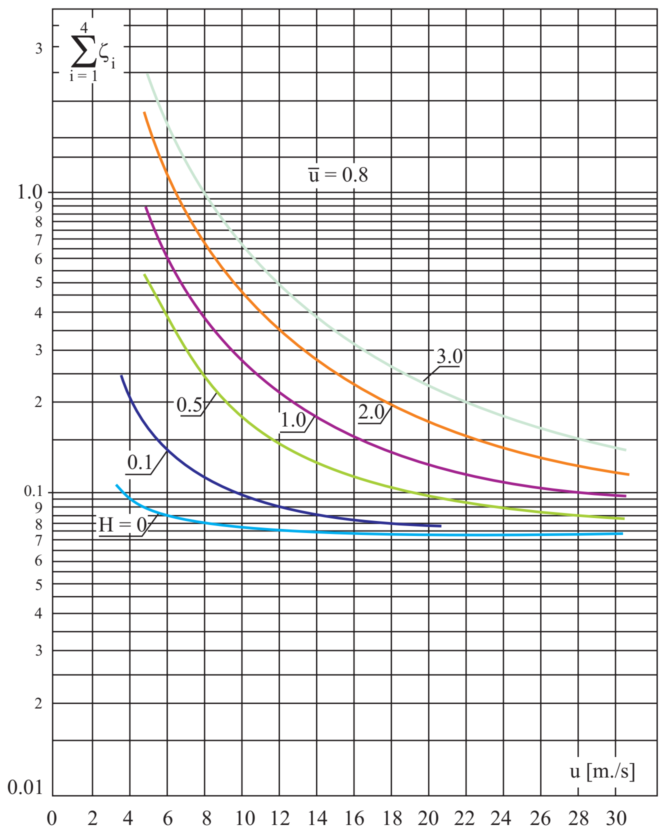


***Fig. 4.*** *Diagram of total energy losses in flow passage of waterjet propeller .*

## SPECIFIC REQUIREMENTS FOR WATERJET PROPULSION OF SMALL-DRAUGHT INLAND WATERWAYS SHIPS

The propulsion system of the two-segment recreation passenger ship intended for inland waterways service, is here considered. Such application requires to take into account a few specific conditions. The following belong to them :

- ❖ limited width of waterway (limited width of locks)
- ❖ limited depth of waterway (a small draught of ship is demanded)
- ❖ possible events of ship grounding on shallows
- ❖ environmental protection requirements
- ❖ ensuring a necessary travelling comfort for passengers
- ❖ limited ship speed.

Possible application of waterjet propulsion should be analyzed with taking into account a.o. the above mentioned aspects :

- ➲ As far as the aspect of limited waterway width is concerned, the waterjet propulsion makes it possible to precisely control ship motion at an arbitrary speed. Ship steering at a very low speed („zero speed") facilitates berthing the ship as well as keeping it stopped short. The waterjet propulsion ensures also precise steering the ship during its moving astern.
- ➲ In the waterjet propulsion there are no elements protruding below the hull bottom . This way, ship sailing in very shallow waters is possible. Water-outlet area and ship's bottom surface are matched up. Nozzle's outlet can be located over water level. The more shallow water the lower efficiency of ship screw propeller. It does not concern the waterjet propeller.
- ➲ If waterjet-propelled ship grounds its refloating is facilitated by two circumstances : firstly, such ships usually have no elements protruding below hull bottom surface, secondly, waterjet propulsion ensures large value of thrust in moving astern. It is also important that in those conditions to cause a failure to waterjet propeller by carried - away sand and gravel is much less probable as compared with the case of screw propeller.
- ➲ Waterjet- propelled ships are much less hazardous to the environment than screw-propelled ones. It concerns possible mechanical failures of living organisms (fauna and flora), as well as waterborne noise.
- ➲ Passengers onboard waterjet- propelled ship enjoy a higher travelling comfort as compared with that on screw-propelled ship. As thrust force is directly transferred from waterjet propeller to hull, without help of any shafting and screw propellers the engine and pump can be seated on an elastic foundation, that reduces hull vibrations generated by propulsion system. There are neither hull vibrations due to transmission shafting and screw propellers nor cavitation noise effected from the side of screw propellers. In waterjet propulsion system, engine shaft's rotational speed is much greater than that in screw propeller drive system. Moreover the whole propulsion system is secured by a tight casing to lower effects of noise emitted to environment.
- ➲ As assessed, the waterjet propulsion system is most efficient at ship's operational speed in the range from 20 to 40 knots. And, at a given ship speed the screw-propeller drive system is a little more efficient than the waterjet propulsion. However the difference is balanced by a little higher ship hull efficiency (due to a lower hull resistance to motion), resulting from lack of screw propellers, shafts, rudders and shaft brackets located outside the hull. As a matter of fact the influence of the above mentioned elements on hull resistance to motion decreases along with ship speed decreasing.

Application of waterjet propulsion to large fast floating units is wider and wider. And, to decrease ship resistance to motion special hull forms are applied such as : catamarans, slender hulls (of a large L/B ratio) fitted with side sponsons to improve ship's stability. Worth mentioning, the waterjet propulsion makes it possible to fully make use of driving power at any ship speed value, a very small too.

## SPECIFIC FEATURES OF SHIP WATERJET PROPULSION

- ⇨ Application of high-speed diesel engine or gas turbine as a waterjet driving motor requires a transmission gear to be installed between the engine and pump.
- ⇨ Choice of a waterjet propeller depends a.o. on ship's hull form, on one side, and on the other side, in designing the ship hull form the specificity of such kind of propulsion should be taken into account.
- ⇨ In selecting the waterjet propulsion an important role is played by the ratio of propulsion power to weight of power plant.
- ⇨ A driving engine and propeller itself should be so selected for a given ship speed as to eliminate phenomenon of cavitation.
- ⇨ As ship propulsion thrust force does not affect the driving engine (through shafting and transmission gear) the shaftline can be inclined by a small angle to make alignment of shaft and waterjet propeller, easier. The maximum values of shaft slope angle depend on shaft's rotational speed and are equal from about 3° at 5000 rpm to about 8° at 2000 rpm.
- ⇨ The underwater exhaust gas pipe has not to be located before the water inlet to propeller so as to avoid gas sucking -in to the pump, which could result in lowering the propulsion thrust force. It should be placed aft the water inlet.
- ⇨ The fuel oil tank should be placed in longitudinal position close to ship's centre of gravity so as to avoid ship's trim disturbing as a result of fuel consumption or refuelling operations.
- ⇨ The driving engine and electric generator (if a shaft generator is provided for) should be placed close to ship's centre of gravity. For this reason they should be installed, if possible, on guides to facilitate ship balance correction after trials.
- ⇨ In ship design calculations an additional weight of the water contained in the propeller should be taken into account. Application of gas turbine to waterjet propulsion for small--draught inland waterways ship

The output power of waterjet propellers is contained in the range of 75 ÷ 900 kW. Like in the ship screw- propeller propulsion, also in the waterjet propulsion the application of high-speed diesel engines prevails. Gas turbines are also used however their share is lower.

Gas turbines – in a simple arrangement – are of a lower thermodynamic efficiency as compared with that of piston engines (in some cases regeneration is applied to improve the efficiency of gas turbines). Whereas it seems that other features of gas turbine could prevail in the considered application of waterjet propulsion to the passenger inland waterways ship in question.

In the above mentioned application the following features of gas turbine should be considered favourable :

- ➢ low sulphur content in exhaust gas (exhaust gas cleaning devices - unnecessary)
- ➢ low level of bending and torsional vibrations and noise (passenger cabins can be located close to propeller)
- ➢ low cost of maintenance, overhauls and lubricating oil
- ➢ high serviceability (high reliability, and possible fast repair or replacement of engine)
- ➢ small dimensions.

The features predestine gas turbine for propelling the passenger inland waterways ship in question. Therefore in the preliminary concept of waterjet propulsion system for the ship a gas turbine was chosen to drive the pump, an element of the waterjet propeller.

## SUGGESTIONS AS TO POSSIBLE APPLICATION OF WATERJET PROPELLER TO MOVE THE PASSENGER SHIP INTENDED FOR BERLIN – KALININGRAD ROUTE

- ★ a waterjet propeller, selected out of the units available on the market (produced e.g. by Castoldijet or Hamilton Waterjet), should be adjusted to the assumed nominal velocity u = 4,166… m/s, by matching - up its nozzle outlet area to the required $A_2$ value and output power
- ★ if to apply – instead of the proposed gas turbine – a diesel engine, to obtain total efficiency more than two times greater will be possible. Similarly, if to assume that the centre of outlet nozzle is not placed over water level, i.e. H = 0, the total efficiency will increase by ~13%
- ★ in Fig.5 and 6, on the basis of Casteldijet's offer drawings, are presented the gas- turbine-driven propulsion devices arranged in ship's engine room.

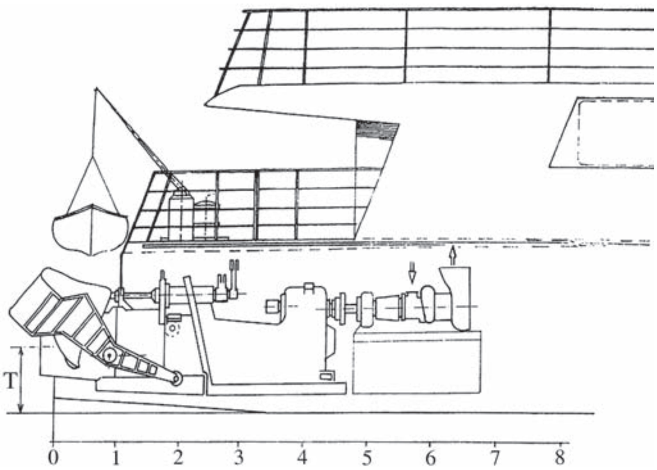


***Fig. 5.*** *Arrangement of the waterjet propeller in ship' engine room – side view .*

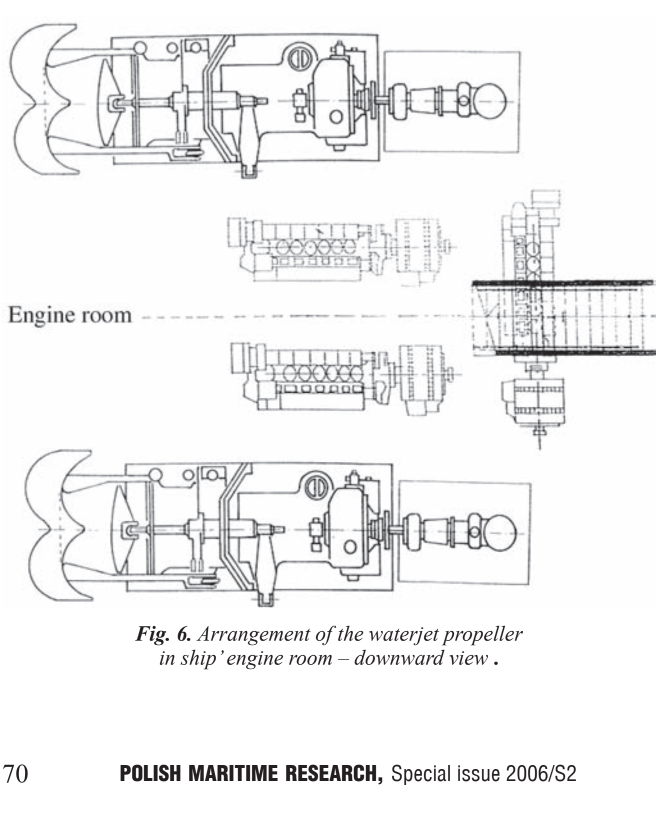


***Fig. 6.*** *Arrangement of the waterjet propeller in ship' engine room – downward view* **.**

## FINAL REMARKS

Summing up, the following aspects of the ship waterjet propulsion system are worth attention paying :

- ❍ The waterjet propulsion system is of important advantages as compared with the conventional screw - propeller propulsion system :
  - Lack of any movable elements behind the hull
  - Much lower hull-propeller interaction resulting in the hull efficiency increase by 13 ÷ 19%
  - Favourable energy indices at partial load
  - Lower torsional vibrations
  - Easy execution of turns and astern moving
  - Possible elimination of need of blade rudder (which results in lowering hull resistance to motion).
- ❍ Losses in flow passage are inversely proportional to $u^2$ and monotonically increasing along with the ship speed u increasing (Fig.4). The losses depend only slightly on the velocity index $\overline{u}$. Moreover they depend on smoothness of flow passage, hence its high smoothness should be ensured.
- ❍ Large dimensions of flow passage constitute an important design problem of waterjet propulsion. The circular cross--section area of its outlet, $A_2$, is proportional according to some expression as follows :

$$A_2 \sim \alpha \left( \frac{\overline{u}^2}{1-\overline{u}} \right)$$

where :

$\alpha$ – acc. (15) – coefficient of hull resistance to motion

$\frac{1-\overline{u}^2}{\overline{u}}$ – the expression proportionally associated with the efficiency : i.e. the greater the assumed efficiency the greater the required dimensions of outlet nozzle (and flow passage).

- ❍ Reliable performance of waterjet propeller is ensured by :
  - protection of its pump and flow passage against hard solid fragments,
  - better control of turning and astern moving,
  - modernization of load - carrying bearing installed inside the pump, e.g. by applying a bearing fitted with water--lubricated ceramic sleeves.

The small-draught inland waterways ship in question has to operate with a low speed. It affects its propulsion efficiency. The ship is slender - hence its flow passage dimensions are restricted, which as a result limits waterjet propulsion efficiency.

**NOMENCLATURE**

$A_2$ – cross-section area of outlet nozzle [$m^2$]
$F_u$ – thrust force [N]
m – rate of water mass flow through propeller [kg/s]
u – ship speed [m/s]
$w_1$, $w_2$, $w_H$ – water velocity of inflow to diffuser, outflow from confusor, and vertical component of velocity of water inflow to propeller, respectively [m/s]
$\overline{u}$ – propeller velocity index [–]
$\alpha$ – coefficient of ship hull resistance power [$kW/(m/s)^3$]
$\rho_w$ – water density [$kg/m^3$]
$\zeta_i$ – dimensionless coefficient of hydraulic losses and those for water stream elevation [–].

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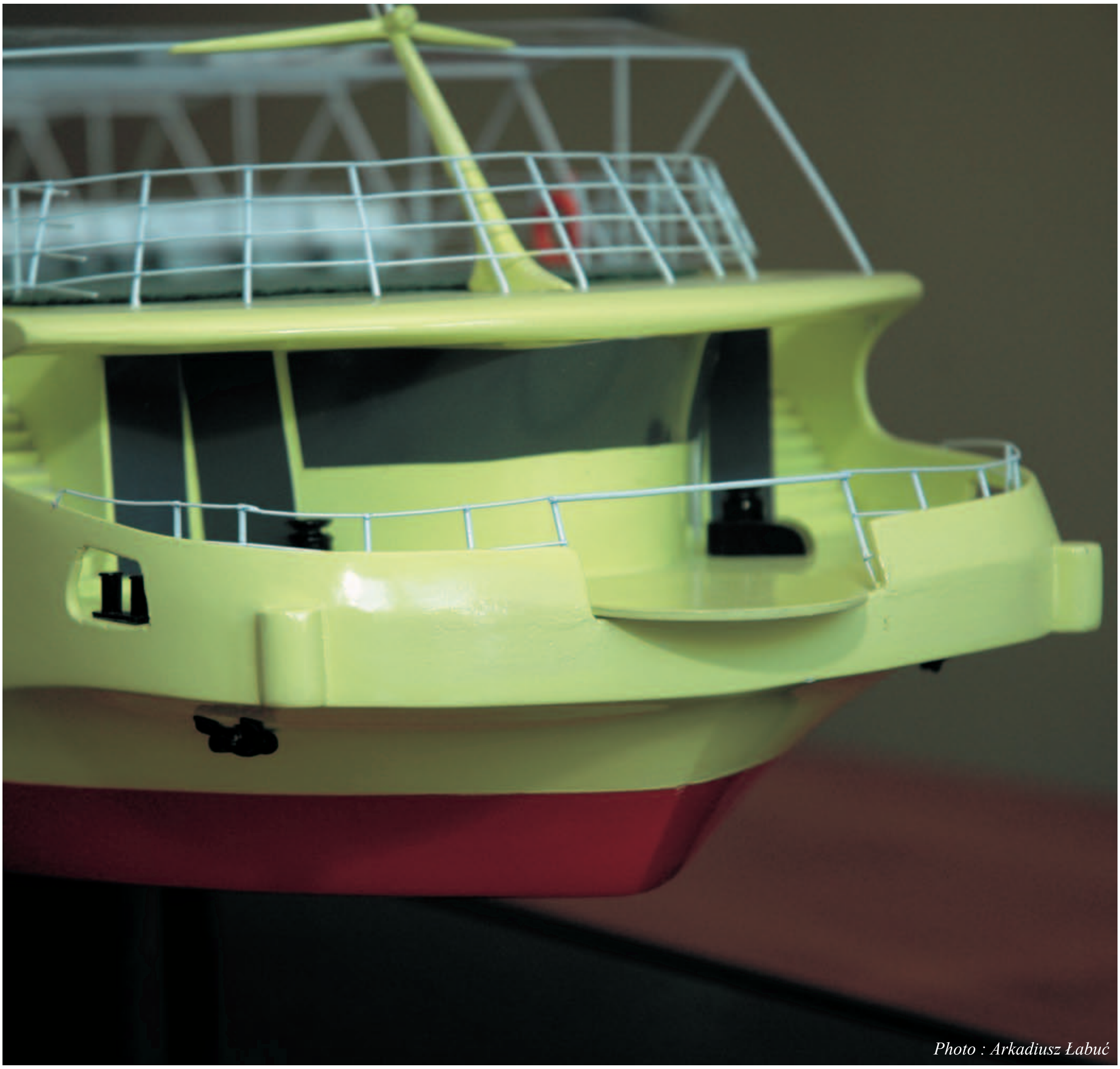

*Photo : Arkadiusz Łabuć*

# Anchoring and mooring equipment for a two-segment inland waterways ship

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ABSTRACT

*This paper presents a review and analysis of anchoring and mooring equipment for contemporary inland waterways ships. Also, a design proposal of such equipment for a two-segment passenger ship as well as a list of selected components of the equipment and plan of their arrangement on the ship's deck, is presented.*

**Keywords** : inland waterways ships, shipboard equipment, anchoring and mooring equipment

## INTRODUCTION

Anchoring and mooring equipment of inland waterways ships is one of the crucial elements of shipboard equipment of such ships. As opposed to anchoring equipment of sea-going ships where ship is fitted as a rule with two bow anchors, inland waterways ships should be equipped – in compliance with PRS rule requirements [3] – with four anchoring units : two on the bow and two on the stern.

In this paper is presented comparative analysis of the anchoring and mooring equipment for two-segment passenger inland waterways ship, selected on the basis of PRS rules and compared with the equipment applied on contemporary inland waterways ships operating on Polish waterways. The analysis was elaborated on the basis of photographs taken by these authors, as well as relevant information available by internet. On the basis of the analysis, new solutions of anchoring and mooring equipment were elaborated and proposed for the ship in question designed by the team of Faculty of Ocean Engineering and Ship Technology, Gdańsk University of Technology.

The main design parameters of the two-segment ship composed of a pusher and hotel barge, are as follows :

- ★ length of each segment — L = 56 m
- ★ breadth — B = 9 m
- ★ draught — T = 1 m
- ★ mass displacement: for T = 1 m — $D_{1.0}$ = 440 t; for T = 1.2 m — $D_{1.2}$ = 530 t
- ★ effective output power for ship propulsion — P = 300 kW
- ★ contract speed of the entire push-train — v = 15 km/h

## ANCHORING AND MOORING EQUIPMENT SELECTED ON THE BASIS OF PRS RULES

### *Outline of design assumptions*

In selecting the anchoring and mooring equipment for the push-train composed of the barge (hotel segment) and the pusher (propulsion segment) one should proceed in the same way as in the case of the classical barge-pusher train. In such case according to the rules it is required to locate anchoring equipment on the bow of the barge as well as on the stern of the pusher. Then, for the two units joined together only one Equipment Number is calculated and on its basis main data concerning the anchoring and mooring equipment are determined.

However, it should be taken into account that for the hotel segment also such service periods are provided for when it lies along quay and the pusher (also fitted with tourist equipment) sets out on an independent tourist trip. Hence it is necessary to fit the pusher with anchoring and mooring equipment also on the bow. Its elements should be selected on the basis of Equipment Number calculated for the pusher only. As a result, their gabarites and weight will be accordingly smaller than those determined for the entire push-train.

### *Equipment Number*

Calculation of the Equipment Number was preformed on the basis of the above formulated assumptions and in compliance with the "Rules for the classification and construction of inland waterways ships" of Polish Register of Shipping [3], which yielded the following values :

$N_{az}$ = 1155 m$^2$ – for two joined segments of ship (push-train)
$N_{ap}$ = 770 m$^2$ – for the pusher alone.

### *Selection of anchoring and mooring equipment*

For the above given values of Equipment Number, below are presented the main parameters of anchoring and mooring equipment for both ship segments, determined on the basis of the PRS Rules, (detail calculations and description of particular elements of the equipment can be found in [2]).

**The pusher**
***Anchoring equipment** :*
*Bow :*

- ❖ 2 anchors of 325 kg mass each
- ❖ chain diameter – 15 mm (steel grade 2)
- ❖ anchor chain length – 65 m (two pieces)
- ❖ anchor windlass (capstan) towing force ~7 kN (steel grade 2)

*Stern* :

- 2 anchors of 432 kg mass each
- chain diameter – 16 mm (steel grade 2)
- anchor chain length – 42 m (two pieces)
- anchor windlass (capstan) towing force ~8.5 kN (steel grade 2)

*Mooring equipment* :

- number of ropes – 2
- length of one rope – 99 m
- breaking strength – 184.8 kN (wire ropes); 230.5 kN (synthetic fibre ropes)
- rope selection – material: PP (polipropylene), breaking strength: 264.97 kN, diameter: 44 mm, mass: 0.88 kg/m, producer : Lanex
- bollards (2 fore and 2 aft) of the following parameters : D – 132 mm, L – 444 mm
- hawse-pipes and fairleads – 2 fore and 2 aft
- mooring winches (capstans): aft : mooring heads of anchor windlasses [towing force ~8.5 kN (steel grade 2)], fore : mooring heads of anchor windlasses [towing force ~7 kN (steel grade 2)].

**The barge**

***Anchoring equipment*** :

*Bow* :

- 2 bow anchors of 450 kg mass each
- chain diameter – 17,5 mm (steel grade 2)
- anchor chain length – 65 m (two pieces)
- anchor windlass (capstan) towing force ~9,6 kN (steel grade 2)

*Mooring equipment* :

- number of ropes – 2
- length of one rope – 99 m
- breaking strength – 184.8 kN (wire ropes); 230.5 kN (sythetic fibre ropes)
- rope selection – material: PP (polipropylene), breaking strength: 264.97 kN, diameter: 44 mm, mass: 0.88 kg/m, producer : Lanex
- bollards (2 fore and 2 aft) of the following parameters: D – 135 mm, L – 450 mm
- hawse-pipes and fairleads – 2 fore and 2 aft
- mooring winches (capstans): fore : mooring heads of anchor windlasses [towing force ~11.5 kN (steel grade 1); ~9.6 kN (steel grade 2)], aft : one additional mooring capstan of ~3 kN towing force.

## ANALYSIS OF ANCHORING AND MOORING EQUIPMENT INSTALLED ON SIMILAR CONTEMPORARY SHIPS

The analysis of anchoring equipment of similar contemporary ships was performed on the basis of available data concerning inland waterways ships sailing mainly on European waterways, including the modern tourist ship „Frederic Chopin" which has lately made trips along the Lower Vistula.

The example photographs of partly visible elements of the anchoring and mooring equipment, and of their arrangement on the deck are shown in Fig. 1, 2 and 3.

As a result of the performed analysis of the equipment in question a few important regularities have been stated, namely :

1. All the analyzed ships are fitted with patent anchors of higher holding power.
2. All of them are equipped with only one anchor aft.
3. The anchoring and mooring devices applied on them constitute winches with horizontal rotation axis of working elements, i.e. rope drums and heads as well as chain wheels.
4. In the bow part of ships anchor chains are used whereas in their stern part such role is fulfilled by wire ropes.
5. Mooring bollards in the bow part of ships are usually arranged in a triple mode, and placed along ship's side just near its edge.


***Fig.1.*** *Anchoring and mooring equipment arranged in the bow and stern part of the tourist ship „Frederic Chopin" .*

**Comments**

**Ad. 1.** The application of patent anchors of higher holding power on inland waterways ships is fully justified. As a rule the ships are rather small and their owners tend to make full use of their capacity and deadweight. As compared with Hall's anchors commonly applied on sea-going ships, the patent anchors of higher holding power make it possible to reduce anchor mass down to 75% of the anchor mass given in the relevant PRS rules for sea-going ships, maintaining the same holding power at least. Application of the anchor with higher holding power is as a rule associated with the use of higher strength anchor chains, and – owing to this – of smaller diameter and mass, which makes it possible to lower size and mass of anchor windlasses as well as other units of anchoring equipment. It is specially important in the case of small passenger ships intended for sailing in shallow waters.

**Ad. 2.** The application of only one anchor aft, but having a higher holding power, results mainly from a limited deck area in that part of ship. The aft deck, usually having relatively small area, must accommodate also other elements of shipboard equipment, such as e.g. life saving appliances which require an appropriate free space to ensure safe evacuation. For this reason one presently tends to replace two „sets" of anchoring and mooring equipment with one, but more versatile and modular. It brings additional measurable advantages resulting from a smaller weight of that part of ship which is as a rule heavily loaded by ship's power plant located under the deck.

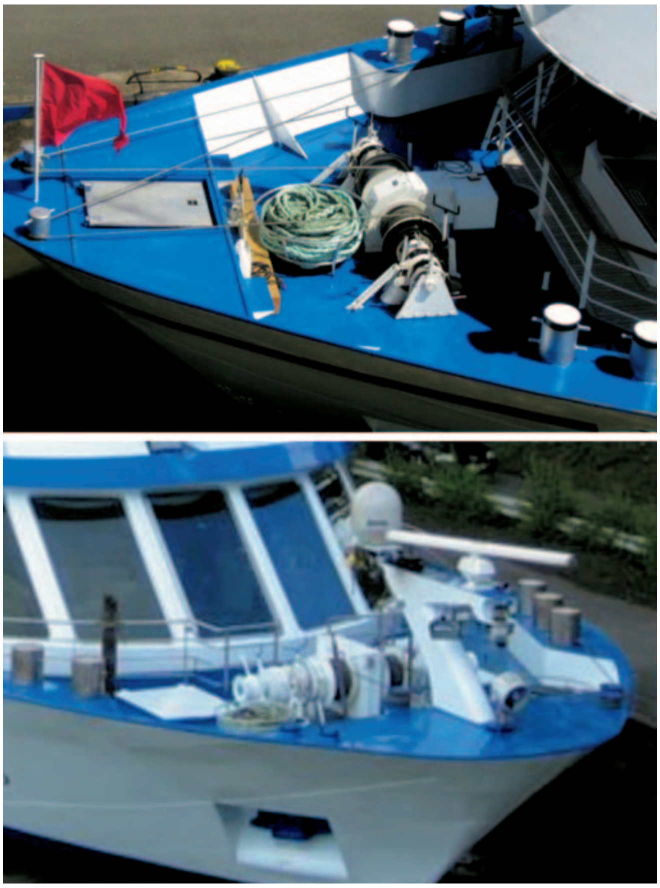

***Fig.2.*** *The anchoring and mooring equipment arranged in the bow part of the ship .*

**Ad. 3.** According to the above given comments, the winches, as opposed to capstans, are more versatile machines which can realize more functions. The winch can be consisted of three mooring-anchoring units simultaneously: rope drum, mooring head and chain wheel. If the anchoring-mooring winches are appropriately located on the deck all necessary operations can be performed and some deck area, mass and cost of the device can be simultaneously saved.

**Ad. 4.** Space in the bow part of ship is as a rule less valuable for equipment arranging, hence there is no problem with location of small chain lockers. The fact and advantageous features of the chain tension members make application of anchor chains on the bow, justified. To arrange an appropriate space in the stern part of ship, either on or under the deck, is usually very difficult as just there ship's power plant is located, and various cable and pipe lines or ballast tanks are placed. For this reason, application of a wire rope with only short section of chain near the anchor, instead of anchor chain, is more advantageous, as the rope can be stored on the winch drum and the winch having modular structure does not require any additional space under the deck, as opposed to capstans.

**Ad. 5.** Bow decks are usually open ones hence especially on passenger ships it is important to arrange particular elements of mooring equipment in a way as favourable as possible. The location of bollards just near the ship side makes it possible to eliminate either hawse-pipes or fairleads and this way to extend free area of that part of the deck.


***Fig.3.*** *Examples of the anchoring and mooring equipment arranged in the stern part of various inland waterways ships .*

## PROPOSED ANCHORING AND MOORING EQUIPMENT

To elaborate the design of anchoring and mooring equipment for the pusher-barge train it is necessary to take into account not only the requirements of classification societies but also development trends and novel technical solutions. In the authors' opinion as the PRS rules for inland waterways ships, still being in force, were published in the 1980s, they should be considered applicable in a rather not obligatory way so as not to constrain progress in developing the equipment in question.

The above presented example solutions of the equipment in question applied on the new ships operating in European waters show that other classification societies have already approved the mentioned development trends. With taking this into account, the following design proposal of anchoring and mooring equipment for the designed ship, are presented below :

**The pusher**

***Anchoring equipment** :*

*Bow :*

- 2 higher holding power anchors of 245 kg mass each
- chain diameter – 11 mm (steel grade 2)
- anchor chain length – 65 m (two pieces)
- anchor windlass towing force ~4 kN (steel grade 2)

*Stern* :

- 1 higher holding force anchor of ~500 kg mass
- wire rope (instead of a chain) of 116 kN breaking strength
- anchor rope length – 55 m (plus 1 m of chain section)
- anchor windlass towing force ~7 kN

*Mooring equipment* :

- number of ropes – 2
- length of one rope – 99 m
- breaking strength – 184.8 kN (wire ropes); 230.5 kN (synthetic fibre ropes)
- rope selection – material: PP (polipropylene), breaking strength: 264.97 kN, diameter: 44 mm, mass: 0.88 kg/m, producer : Lanex
- bollards (2 fore and 2 aft) of the following parameters: fore : D – 300 mm, L – 590 mm (with guide roll), aft : D – 135 mm, L – 450 mm
- hawse-pipes and fairleads – 2 aft
- mooring winches (capstans): aft : mooring heads of anchor windlasses [towing force ~7 kN (steel grade 2)], fore : mooring heads of anchor windlasses [towing force ~ 4 kN (steel grade 2)].

**The barge**

***Anchoring equipment** :*

*Bow :*

- 2 higher holding power anchors of 340 kg mass each
- chain diameter – 15 mm (steel grade 2)
- anchor chain length – 65 m (2 pieces)
- anchor windlass towing force ~7 kN (steel grade 2)

*Mooring equipment* :

- number of ropes – 2
- length of one rope – 99 m
- breaking strength – 184.8 kN (wire ropes); 230.5 kN (sythetic fibre ropes)
- rope selection – material: PP (polipropylene), breaking strength: 264.97 kN, diameter: 44 mm, mass: 0.88 kg/m, producer : Lanex
- bollards (2 fore and 2 aft) of the following parameters: fore :D – 300 mm, L – 590 mm (with guide roll), aft : D – 135 mm, L – 450 mm
- hawse-pipes and fairleads – 2 aft
- mooring winches (capstans): fore : mooring heads of anchor windlasses (towing force ~7 kN (steel grade 1); aft : one additional mooring capstan of ~3 kN towing force.

The proposed anchoring and mooring equipment for the pusher is shown in Fig.4. On the bow, in parallel to the ship's axis of symmetry, is located the twin bollard (a guide roll is fixed on one of them, which allows the mooring rope to go onto winch perpendicularly) as well as the anchoring-mooring winch. The winch is fitted with the mooring drum which serves also for rope storage, chain wheel, as well as mooring head. The winch obliquely is situated to the ship's axis of symmetry. The same set of the equipment is provided for on the other side of the ship.

The winch on the stern is also an anchoring-mooring winch in which, instead of chain wheel, the drum is fitted to reel the anchor rope on (instead of a chain). Additionally, the winch is fitted with the mooring head. The mooring rope is directed onto the head by means of the fairleads and guide roll. Along course of the mooring rope two mooring bollards are placed just near the ship sides, situated perpendicularly to the ship's axis of symmetry.

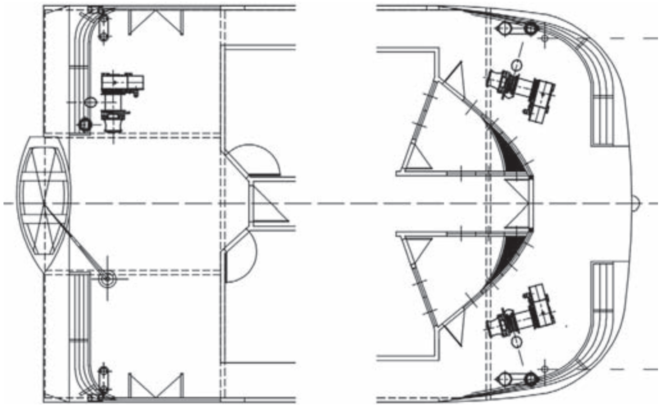

***Fig.4.** Example arrangement of the anchoring and mooring equipment on the pusher .*

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# A concept of pusher - barge coupling device of two-segment ship for inland waterways and coastal service

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ABSTRACT

*This paper presents design assumptions and a constructional concept of the device for coupling the pusher and hotel barge of two-segment inland waterways and coastal ship. The presented device makes it possible to reach either stiff connection or mutually controlled inclination of both segments against each other, which greatly improves the ship's manoeuvrability and thus safety of navigation especially on narrow and meandering waterways.*

**Keywords** : ship devices, hydraulic drive and control

## INTRODUCTION

The concept of two-segment passenger ship split into a propulsion unit and hotel unit has many advantages. It makes it possible to design a much larger push-train adjusted to sailing along a given river-bed, as compared with a single hull of similar dimensions.

Another important advantage of it is an improvement of manoeuvrability and this way increase of safety of navigation especially through narrow river-beds, available due to possible mutual inclination of coupled segments of the ship. Despite the mentioned advantages of such solution its practical application is to a large extent limited because of lack of a suitable device for coupling both the ship segments. One of the concepts for solving the problem is presented below.

## DESIGN ASSUMPTIONS

Approaching to elaborate the drive and control of the coupling device for segments of inland waterways push-train, the authors have based on the following design assumptions :

1. For the device hydrostatic drive has been selected,
2. The hydrostatic drive of both units of the device, namely : that of main coupling cylinders and that of bolt-removing cylinders, should be independent on each other. It results from that both units have to be permanently fastened to different segments.
3. Both hydraulic units are independent on other ship devices. The assumption may be changed in the course of elaboration of technical design of both segments when detail information on kinds and location of other devices is available. In the phase of conceptual design to assume that it is not possible to supply them from hydraulic systems of other devices, is more safe.
4. Elements applied to the system should be typical and manufactured by recognized producers so as to ensure their high reliability in service, easiness of purchase and replacement at a moderate cost.
5. Starting the device should be effected in the state of no load applied to it or in such a way as to avoid sudden loads exerted on the ship energy network.
6. Control of operation of both units of the device should be carried out from the ship control centre.
7. The demanded angle of mutual lateral inclination of the segments, $\alpha$, amounts to about 12°
8. The possible mutual angular displacement in the vertical plane, of the coupled segments, $\beta$, amounts to ± 3°
9. The possible mutual linear displacement in the coupling of both hulls amounts to $\Delta h = \pm 25$ mm
10. Local hand control, especially fast uncoupling the push-train segments in situation of emergency, should be ensured.

## DESCRIPTION OF THE SOLUTION

The arrangement of elements of the device is shown in Fig.1 on the background of the ship segments, and additionally in Fig.2 in the axonometric projection.

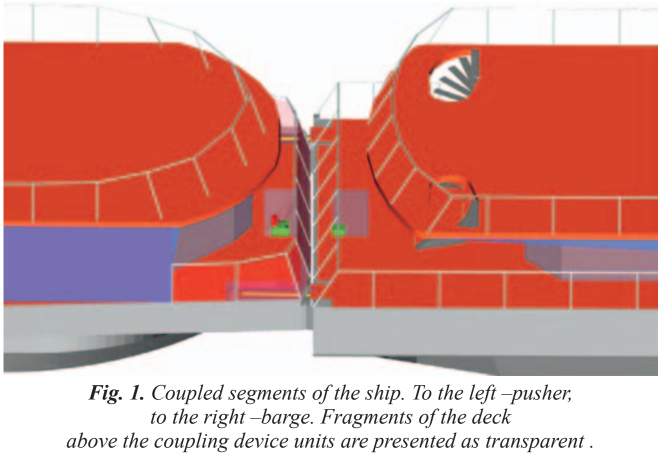

***Fig. 1.*** *Coupled segments of the ship. To the left –pusher, to the right –barge. Fragments of the deck above the coupling device units are presented as transparent .*

The device is composed of two pairs of typical hydraulic cylinders of single piston-rod. Two larger coupling cylinders are placed horizontally in the bow part of the ship about 7.4 m apart. They serve for keeping both push-train segments in a strictly determined position to each other. The cylinders as such are fastened to the pusher hull in a way which makes certain angular displacements in both planes, i.e., horizontal and vertical, possible. In a similar way are fastened the piston-rod eyes to the hull of the pushed segment, i.e. the hotel barge.

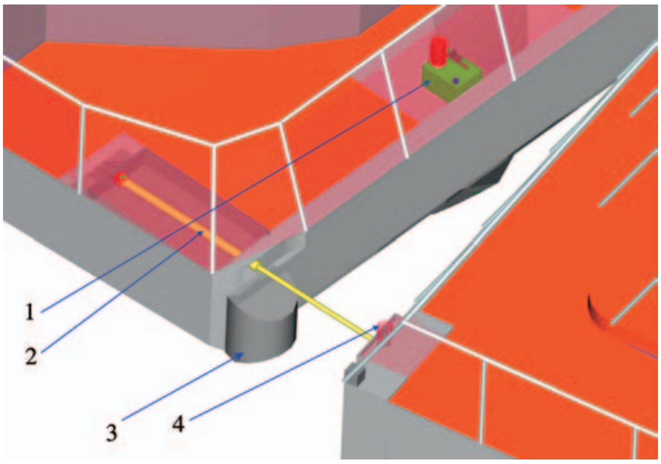


*__Fig. 2.__ A view over the segments which are parted by the angle of 12 deg. Notation: __1__ – hydraulic supply unit of main cylinders, __2__ – hydraulic coupling cylinder, __3__ – fender, __4__ – cylinder for removing the bolt form the piston-rod eye of the coupling cylinder (see Fig. 3). Fragments of the deck above the coupling device units are presented as transparent .*

To limit values of mutual displacements of both the hulls in the place of their coupling, suitably shaped body lines of the hulls in that region were proposed. The convex cylindrical fender of the pusher enters the similarly formed socket of the barge, which can be clearly observed in Fig.2.

However it should be mentioned that the above proposed hull form is presented only as an alternative out of many other possible. In this case an important thing is to prevent the device (cylinders) against large random transverse loads due to e.g. very rough weather conditions. During normal service when the push-train segments are situated along common axis both the coupling cylinders can be hydraulically cut-off and serve only as permanent connecting rods which this way link both the ship segments almost rigidly. By this time the hydraulic supply system can be switched off, or in the case of application of a hydraulic accumulator – be on standby.

The inclination manoeuvre of the segments requires only oil to be delivered to only one of the cylinders. Due to location of the cylinder eye in the cylindrical „fender" axis the length of the non-operating cylinder remains unchanged during execution of the manoeuvre.

The hydraulic supply system of the coupling cylinders will be equipped with overflow (safety) valves which have to be so adjusted as to protect the cylinders against overloading, especially resulting from axial compression, and this way to avoid a danger of their buckling. The way in which the coupling cylinders and the bolt - removing ones are fastened, is more precisely shown in Fig.3. Each of the bolt -removing

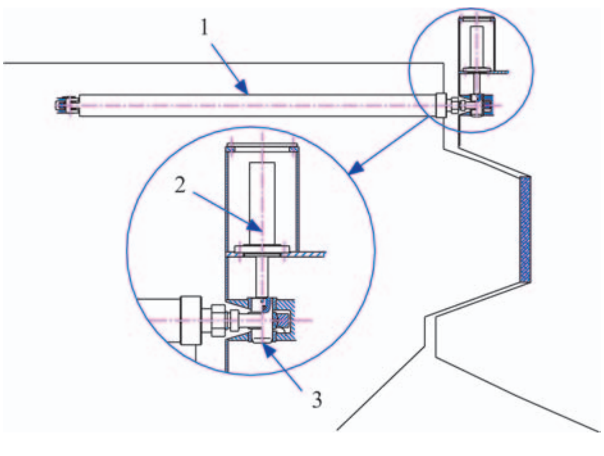


*__Fig. 3.__ The coupling unit of the ship segments. Notation: __1__ – coupling cylinder, __2__ – bolt-removing cylinder, __3__ – removable bolt of piston-rod eye .*

cylinders is placed in a cylindrical casing on the deck of the pushed segment directly over the point of the fastening of the coupling cylinder eye. The bolt-removing cylinders are of a flange type. The piston –rod of each of the cylinders is rigidly connected with the bolt 3 of the main cylinder's eye. The bolt led in special sleeves can be axially shifted within the range which makes it possible to disconnect the main cylinder eye completely. Hence, if disconnection the push-train segments is necessary it is sufficient to set the distributor in such a way as to make oil flowing under pressure to the auxiliary cylinders, that will bring about the bolts shifting out of the eyes of the coupling cylinders.

As the discussed auxiliary cylinders have to be installed on the pushed segment, their hydraulic supply unit should be also placed on that segment, but its starting and control operations should be also executed from the pusher, if possible. To this end, application of a relatively simple hydraulic unit with small hydraulic accumulator and electrically controlled distributor, is provided for.

## DESCRIPTION OF THE DRIVE AND CONTROL OF THE DEVICE

Concepts of the hydraulic drive and control of both above mentioned units of the coupling device, elaborated on the basis of preliminary calculations, are presented below.

### *The unit of the coupling cylinders*

The schematic diagram of the unit of hydraulic drive and control of coupling cylinders is presented in Fig.4.

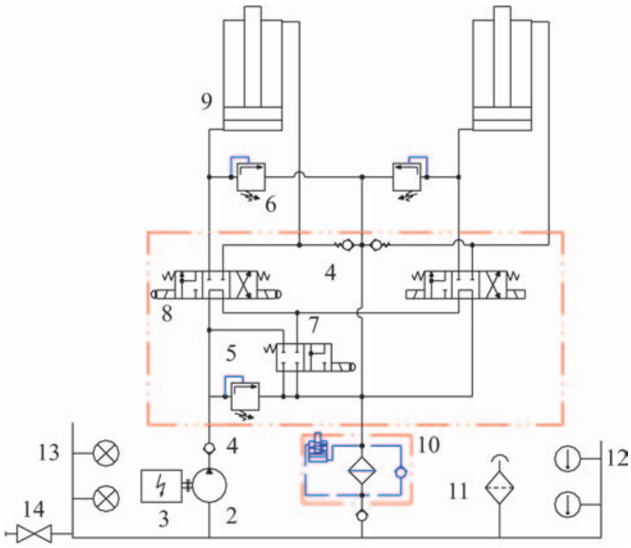


*__Fig. 4.__ Schematic diagram of the unit of hydraulic drive and control of the main coupling cylinders of the coupling device*

The unit is equipped with the oil tank (1). The constant capacity pump (2) driven by the asynchronous electric squirrel--cage motor (3) sucks in oil from the tank and pumps it through the check valve (4) to the pipe connected with the overflow valve (5), the four-path two-position distributor (6) as well as the four-path three-position distributor (7).

The overflow valve (5) serves as a safety valve, i.e. it prevents the unit from an excessive increase of pressure. The distributor (7) makes it possible to connect the supply channels of both distributors (8) with the outflow pipe, that is desirable during the coupling and uncoupling operations of both segments, as discussed further.

The distributors (8) serve to control operations of the coupling cylinders (9) by directing working oil flow to appropriate chambers of the cylinders. In the central position the distributor cuts off hydraulically both chambers of the cylinder and simultaneously connects the supply channel with the outflow pipe. This is favourable as it makes it possible to maintain the set position of the cylinder's piston and this way the mutual angular position of the coupled push-train segments, simultaneously unloading the pump, as well as to start up the motor and pump without loading. Switching-over any of the distributors (8) to the right results in connection of both chambers of the cylinder cooperating with it, to oil supply, and makes the cylinder's piston-rod moving out. It results from different working areas of the piston on both its sides. Switching-over the distributor to the left connects the piston-rod chamber of the cylinder to oil supply, and the piston-rod -free chamber - to the outflow, that makes the piston –rod moving into the cylinder. Velocities of both the mentioned movements would be approximately the same. The expected working loads of the cylinders would not be identical in both directions. Compressive loads would be greater. It should be mentioned that the selection of the cylinders was based on the buckling strength condition which made to apply somewhat greater diameters of piston-rod and cylinder necessary, as well as resulted in working pressure lowering. These factors made the application of such distributors as those of the kind (8), reasonable.

The pipes which deliver oil to the piston-rod- free chambers of the cylinders are connected with the overflow valves (6) which have to prevent the cylinders from excessive loading which could happen in the event of catching the pushed segment on an obstacle when the piston-rod of the cylinder is pull-out at the central position of the distributor (8). In this case, a sudden rise of loading and resulting increase of oil pressure would force the considered valve to open and the piston –rod to pull--in reducing this way the risk of its buckling and mitigating dynamic loads on the device and ship. In order to prevent - during the described situation - arising the under-pressure and cavitation phenomena in the cylinder piston-rod chamber, in the oil pipes leading to the chambers are installed check valves which make it possible to deliver oil from the outflow pipe to the mentioned chambers.

At the end of the outflow pipe are installed the check valve and the oil filter (10) equipped with a by-pass valve and indicator of contamination level of the filter.

The oil tank is fitted with the inflow filter (11), temperature gauge (12), low and high oil level indicators (13) as well as the drain valve (14).

When uncoupling the ship segments has to be urgently executed it is necessary first to switch over the distributor (7) to the left and both the distributors (8) to the right. It will make both the chambers of the main cylinders to be connected with the outflow pipe, and this way the cylinders to be unloaded, which will help in fast pulling out the bolts by means of their cylinders located on the hotel segment.

## *The unit of the bolt-removing cylinders*

The drive and control unit of the bolt-removing cylinders is shown in Fig.5. In the unit is installed the small oil tank (1) and two pumps, one of which, (2), is driven by the asynchronous squirrel - cage motor (4), and the other, (3), - by hand. Both the pumps are connected with the pump main through the cut--off valves (5). With the pump main the following equipment elements are connected :

- the overflow valve (6) which serves as safety valve
- the small gas-hydraulic accumulator (10)
- the pressure control (11), which controls switching-on and - off the motor (4), the pump (2), depending on a value of oil pressure in the accumulator
- the pressure gauge (14)
- the two-path two-position distributor (7), which is usually closed and ensures tight cutting the accumulator off the remaining part of the system.

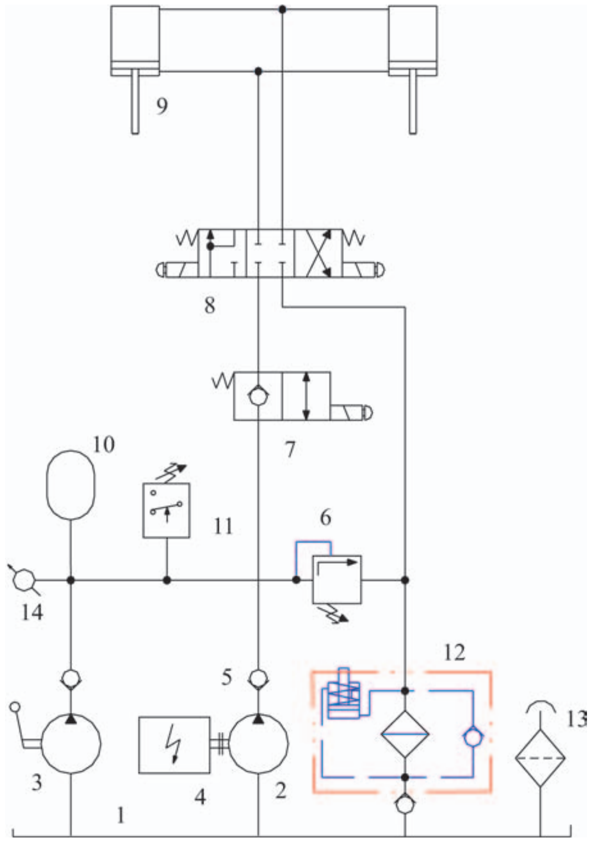


***Fig. 5.*** *Schematic hydraulic diagram of the drive and control system of the bolt- removing cylinders of the coupling device .*

The switching-over of the distributor (7) to the left realizes connection of the accumulator with the four-path three-position distributor (8) intended for the operational controlling of the bolt-removing cylinders (9). Shifting the slider of the distributor (8) to the left makes the piston-rod chambers of the cylinders to be connected with oil supply, and the piston-rod-free chambers – with the outflow, and the piston-rods pulling out, which is associated with the removing of the bolts out of the eyes of the main cylinders and the uncoupling of the push-train segments. Shifting the slider of the distributor (8) to the right connects both the chambers of the cylinders with oil supply and forces the outside movement of the piston-rods, which is associated with the inserting of the bolts into the eyes of the main cylinders and the coupling of both the push-train segments.

In the outflow pipe the oil filter (12) and the cut-off valve (5) is installed. The oil tank is fitted with the inflow filter (13).

The bolt-removing cylinders applied in the system and the way of their supplying require a very small amount of oil for realization of their task. For that reason the oil pump and its driving motor can be of a small power. The gas-hydraulic accumulator applied in the system makes it possible to lower power and size of the pumping set and to store suitable amount of energy necessary for switching –over the cylinders several times. The hand-operated pump makes it possible to charge the accumulator within a short time and to switch over the cylinders also when electric energy is not delivered.

## CONCLUSIONS

- The presented concept of the coupling device of the push-train segments of the inland waterways and coastal ship, elaborated as a result of the analysis of many alternative solutions, has been deemed optimal.
- It makes it possible to realize the demanded tasks, being relatively simple and based on application of typical and relatively inexpensive elements. Hence its initial, maintenance and operational costs will be low.
- Another its favourable feature is that when the ship sails with uninclined segments the cylinder piston-rods are entirely pull into the cylinders thus the working surface of the piston-rods is prevented from exposure to atmosphere and contamination agents and the whole pusher-barge train becomes more stiff and capable of transferring greater loads.
- It should be mentioned that for the reason of visualizing the concept a few necessary changes were introduced to the upper part of the pusher for which the device in question was designed.
- The solutions presented in Fig. 6 and 7 should be considered as alternatives out of many other possible.
- The presented driving systems of both units are favourable from the point of view of their service, and more energy-saving, as compared with other devices of the kind. The set of the coupling cylinders operates only during manoeuvres of mutual inclination of ship segments, and is put in operation without any loading. During remaining service time the pump is switched off and both chambers of the cylinders are hydraulically cut-off, maintaining their set position.
- The set of bolt-removing cylinders practically remains all the time free of switch-over operations, being on standby, and only supplementing from time to time oil losses to the accumulator. By an appropriately programmed sequence of switch-over operations of the distributors in such a way as to first connect both chambers of the cylinders with the outflow and only next to supply the bolt-removing cylinders in order to uncouple or couple the ship segments, this operation becomes much easier and safer.
- In the case when the ship is equipped also with other hydraulic devices a simplification of the systems by using common tanks and pumps may be possible.

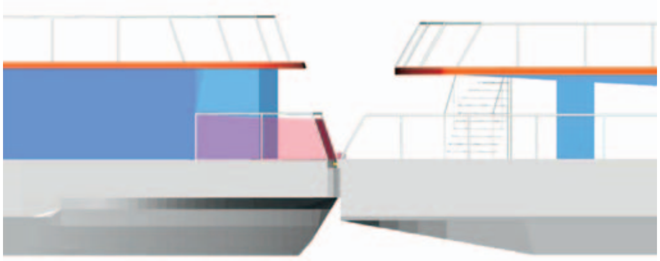

***Fig. 6.*** *Side view over the coupled ship segments .*

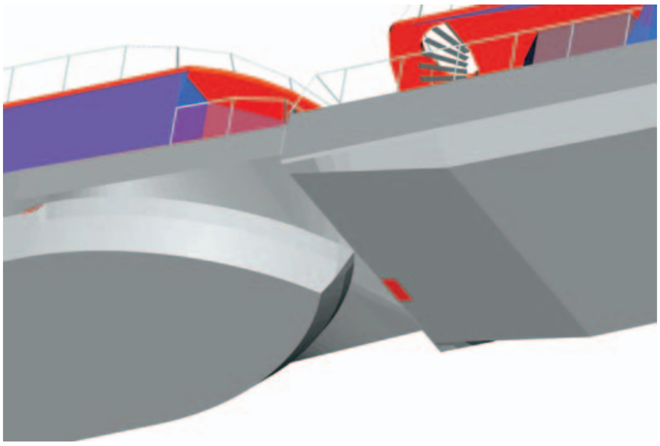

***Fig. 7.*** *View from below over the coupled ship segments .*

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*Photo : Arkadiusz Łabuć*

# A method for predicting propeller-hull interaction, applicable to preliminary design of inland waterways ships

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ABSTRACT

*This paper presents a proposal of a parametric method for predicting the characteristics of wake fraction, $w(\bar{x})$, and thrust deduction, $t(\bar{x})$, of ship hull of the draught close to waterway depth. The method makes it possible to take into account an influence of low waterway depth in preliminary selecting propulsion system parameters of ships intended for operating in shallow waters, e.g. of inland waterways ships. The mathematical model of the problem was determined with taking into account the aspect of coding easiness of calculation algorithm to be applied to computer software useful in computer aided design. Application of the method was demonstrated with the use of the example characteristics of the passenger ship intended for operating in shallow waters on Berlin-Kaliningrad route, whose design was elaborated in the frame of the EU Eureka INCOWATRANS E!3065 project.*

**Keywords** : design of inland waterways ships, selection of propulsion system parameters, characteristics of propeller – hull interaction.

## AIM AND SCOPE OF THE WORK

In the classical problems of ship design theory, mutual interaction of ship hull and a propeller operating close to ship stern, is expressed by characteristics of the wake fraction w and the thrust deduction t, dependent on the vector of ship parameters $\bar{x} = (x_1, x_2, x_3, \ldots)$, such as hull main dimensions, its form coefficients etc. The relations found in literature sources, used to practically determine the characteristics $w(\bar{x})$ and $t(\bar{x})$, are given in the form of diagrams or non-structural formulae based on approximation of large number of data obtained from experimental model tests. In the problems of ship theory it is assumed that for a given ship hull, values of w and t functions are constant; for this reason in the subject-matter literature the characteristics are usually called "interaction coefficients (factors)". In the problems of ship design theory, w and t should be considered as functions of the arguments $\bar{x} = (x_1, x_2, x_3, \ldots)$, i.e. as the hull influence characteristics.

In the case of sea-going ships operating in practically unlimited waters, the reliable characteristics $w(\bar{x})$and $t(\bar{x})$ can be achieved by using the known methods, e.g. that of Holtrop and Mennen [1] or that of Harvald [2].

If the characteristics $w(\bar{x})$ and $t(\bar{x})$ are additionally made dependent on waterway's parameters and ship speed then generalized characteristics useful for the designing of propulsion systems of ships intended for operating in shallow waters, can be obtained. Lack of such generalized methods is a shortage in engineering knowledge and an obstacle in defining correct methods for selecting propulsion system parameters of inland navigation ships. The necessity of overcoming the drawbacks, resulting from practical design needs, has constituted an inspiration to undertake the investigations in question.

The characteristics $w(\bar{x})$ and $t(\bar{x})$represent total energy balance which takes place in the water flow around hull – they result from the phenomena associated with boundary layer forming, wave system generating as well as influence of water area limits on flow velocity field [2, 3, 4].

Empirical investigations concerning the influence of water area limitations, i.e. its depth and width, on hydrodynamic characteristics of hull-propeller interaction, meet difficulties both of conceptual and measuring nature since an influence of particular factors is difficult to be identified and generalized, moreover physical quantities to be determined in such experiments are hardly measurable. Hence the scarce subject-matter literature provides not many experimental results though such knowledge is crucial for engineering applications. To have at one's disposal the generalized characteristics is necessary for determining correct, especially optimum, values of propulsion system parameters of the ship adjusted to operation in restricted waters. Correct choice of propulsion system greatly influences service and economic merits of designed ship - hence it may have a great impact onto ship owner's investment decisions.

In order to elaborate a computer method for optimum selection of propulsion system parameters of the ship intended for operating in shallow waters it is necessary to have at one's disposal a set of parametric mathematical models, namely :

- the hull resistance characteristics $R(\bar{x})$ – taking into account that the resistance depends also on the considered waterway's depth and width, as given in [5]
- the characteristics of wake fraction, $w(\bar{x})$, and thrust deduction, $t(\bar{x})$, including their dependence also on waterway depth and width (to be presented)
- the hydrodynamic characteristics, $K_T(\bar{x})$, $K_Q(\bar{x})$, of propellers, within a broad spectrum of their geometrical parameters.

In this paper is proposed a method for determining parametric mathematical models of the wake fraction, $w(\bar{x})$and thrust deduction, $t(\bar{x})$, including influence of ship speed and waterway depth. The mathematical models determined by means of the proposed method are unique, being a cognitive achievement and contributing to development of ship design theory. Usefulness of the method is demonstrated by the presented example of its application to the determining of the characteristics $w(\bar{x})$ and $t(\bar{x})$of the ship designed within the frame of the Eureka E!3065 INCOWATRANS project.

The planned application of the method concerns its use for optimization of propulsion system parameters for inland navigation ships intended for operating on shallow waterways.

## INTRODUCTION

The propeller thrust horsepower $N_T$ is as a rule greater than the towrope hull horsepower $N_h$, which is conditioned by the wake and thrust deduction interaction between propeller and hull's stern part. Propeller which operates near the hull and waterway bed, moves relative to water with the advance speed $v_p$, smaller than the ship speed v. The difference of the speeds :

$$\Delta v = v - v_p \tag{1}$$

determines the wake velocity, whereas the ratio :

$$w = \frac{\Delta v}{v} \tag{2}$$

defines the wake characteristics,
and the advance speed is then expressed as follows :

$$v_p = v(1 - w) \tag{3}$$

The wake speed depends both on the velocity field within the flow considered potential, and the boundary layer distribution on hull surface. The wake characteristics can be approximately expressed in the form of the sum of components as follows :

$$w = w_v + w_p \tag{4}$$

where :

$w_v$ – stands for the viscosity component
$w_p$ – the potential component which can be determined by means of theoretical methods of ideal fluid hydromechanics.
Hence for geometrically similar hulls the wake fraction is a function both the Froude number Fn and the Reynolds number Rn :

$$w_p = f(Fn) \;\; ; \;\; w_v = f(Rn) \;\rightarrow\; w = f(Fn, Rn) \tag{5}$$

Magnitude of the wake fraction depends on hull form – mainly on its fullness and slenderness. A large fullness and small slenderness make flow –around – stern velocity to drop significantly. At a small fullness and large slenderness the potential wake speed may be near zero, and in some circumstances – even of a negative value. In unlimited waters such case can happen when the behind-the-stern propeller finds itself in trough of ship-generated wave. The viscosity component depends on the boundary layer distribution over hull surface, which increases in function of square root of ship length up to the point of flow separation dependent on a form of stern part of ship's hull.

Propeller's work modifies the nominal pressure field in the stern region since an increase of water velocity resulting from the propeller work makes dynamic pressure dropping which generates the effect of thrust deduction increasing ship pressure resistance. The increase of flow velocity makes tangential stresses increasing in the stern part of hull, which results in viscosity resistance increasing. Hence the resistance of the propeller-driven ship is greater than that of the ship towed by an external force.

For a ship in uniform motion the thrust force $T_p$ generated by its propeller is to be greater than the propulsion force $T_N$ balancing the towed – ship resistance R :

$$T_p - \Delta T = T_N = R \tag{6}$$

where :

$\Delta T$ – increase of resistance due to decreased pressure in the stern region, resulting from propeller work.

By the ratio :

$$t = \frac{\Delta T}{T_p} \tag{7}$$

the thrust deduction fraction characteristics is defined [6, 7].

Selection of ship propulsion system parameters is performed under assumption that the state of kinematic equilibrium which occurs at the equality of forces, is achieved :

$$T_p = \frac{R}{1 - t} \tag{8}$$

The fraction t depends also on the Froude number and Reynolds number.
Reducing the problem to an ideal, one can express the thrust deduction fraction as the sum of components as follows :

$$t(Fn, Rn) = t_p(Fn) + t_v(Rn) \tag{9}$$

The propeller thrust power $N_T$ is the product of the thrust force and the propeller speed respective to water :

$$N_T = T_p \cdot v_p \tag{10}$$

In the subject-matter literature the ratio of the hull towrope horsepower $N_h$ and the propeller thrust power $N_T$, marked $\xi_k$, is called – the hull efficiency, or more correctly – the hull interaction factor :

$$\frac{N_h}{N_T} = \xi_k = \frac{1 - t}{1 - w} \tag{11}$$

The hull interaction factor does not comply with the definition of efficiency since the $w(\bar{x})$expresses a return of a part of the energy earlier delivered by propulsion system to the water surrounding the hull, and $t(\bar{x})$ - a loss of the power resulting from the suction effect exerted by propeller onto hull. When the quantity $w(\bar{x})$ is greater than the quantity $t(\bar{x})$, then $\xi_k$ is greater than 1, that can be obtained in the case when the hull stern form is designed correctly.

The conventional character of the hull interaction factor is usually distinguished by attributing to it the symbol ξ instead of η traditionally standing for efficiency.

## CONCEPT OF THE METHOD AND ITS ASSUMPTIONS

Basin [7] – on the ground of his own experiments as well as some literature data – presented the diagrams of $w(\bar{x})$ and $t(\bar{x})$characteristics for inland navigation ships of typical hull form, making the following quantities variable :

- the ratio h/T > 1, i.e. that of the water depth h and the ship draught T
- the Froude number related to the water depth $F_h \frac{v}{\sqrt{g_z \cdot h}}$
- location of the hull buoyancy centre.

The diagrams presented in [7] concern only that hull whose parameters were assumed the same as of the parent hull form. However the diagrams are rather not useful for elaborating computer calculation algorithms – in contrast to relevant mathematical models. Moreover, in order to elaborate a design method it is necessary to generalize the diagrams [7] in such a way as to cover the hulls of extrapolated parameters. Further considerations are focused on realization of the postulates.

To this end, were prepared the tables of discrete values taken from the diagrams [7], which next served as the basis for determination of approximate analytical relationships.

The analytical relationships to be determined, should be so chosen as to correctly approximate the set of discrete values of the characteristics $\{w_i(\bar{x})\}$ and $\{t(\bar{x})\}$ for various hull form parameters $\bar{k}$, Froude numbers $F_h$, and ratios h/T. The following analytical relationships were postulated :

$$w(\bar{x}) = w\left(F_h, \frac{h}{T}, \bar{k}\right) \tag{12}$$

$$t(\bar{x}) = t\left(F_h, \frac{h}{T}, \bar{k}\right) \tag{13}$$

To make further description of the formulae easier the following notations were applied : $F_h$ = p and h/T = g.

A hypothetical structure of mathematical models of the determined characteristics was *a priori* assumed in the form of the product of functions having identical structure, and being the combinations of elementary analytical functions as follows :

$$w(p, g, \bar{k}) = F(p, g) \cdot r(\bar{k}) \tag{14}$$

$$t(p, g, \bar{k}) = F(p, g) \cdot s(\bar{k}) \tag{15}$$

The functions dependent on full form parameters, $r(\bar{k})$ and $s(\bar{k})$, deal with the characteristics concerning deep water conditions - for the designed hull and parent hull, respectively, and the function f(p, g) has to take into account the influence of ship speed and waterway depth.

## SELECTION OF STRUCTURE OF MATHEMATICAL MODELS

Within the frame of the established structure of approximating models, different combinations of elementary analytical functions were tested by determining numerical values of approximation accuracy measures, and on this basis the most appropriate model was chosen. Both in the case of the wake fraction and thrust deduction characteristics the best approximation, at h/T = const and $H_h$ = var, was achieved by applying the rational function which makes it possible to obtain a required number of inflection points :

$$f(p, g_j = \text{const}) = \frac{\sum_{i=0}^{3} c_i \cdot p^i}{\sum_{i=4}^{7} c_i \cdot p^i} = \frac{c_{0,j} + c_{1,j} \cdot p^1 + c_{2,j} \cdot p^2 + c_{3,j} \cdot p^3}{c_{4,j} + c_{5,j} \cdot p^1 + c_{6,j} \cdot p^2 + c_{7,j} \cdot p^3} \tag{16}$$

The constants $c_{i,j}$ appearing in the formula (16) in the case of the characteristics $w(\bar{x})$, are presented in Tab.1, and the constants dealing with the characteristics $t(\bar{x})$ – in Tab.2.

***Tab. 1.*** *Values of the coefficients $c_{i,j}$ for determination of the characteristics $w(\bar{x})$ .*

| Coefficients $c_{i,j}$ in $f(p, g_1)$ | | Coefficients $c_{i,j}$ in $f(p, g_2)$ | | Coefficients $c_{i,j}$ in $f(p, g_3)$ | |
|---|---|---|---|---|---|
| $C_{0,1}$ | 3.75903 | $C_{0,2}$ | -0.79985 | $C_{0,3}$ | 0.30069 |
| $C_{1,1}$ | -13.42912 | $C_{1,2}$ | 3.63016 | $C_{1,3}$ | -0.51936 |
| $C_{2,1}$ | 16.01725 | $C_{2,2}$ | -5.02485 | $C_{2,3}$ | 0.29658 |
| $C_{3,1}$ | -6.38144 | $C_{3,2}$ | 2.18602 | $C_{3,3}$ | 0.0 |
| $C_{4,1}$ | 21.09661 | $C_{4,2}$ | -8.77254 | $C_{4,3}$ | 2.32048 |
| $C_{5,1}$ | -74.00941 | $C_{5,2}$ | 40.91477 | $C_{5,3}$ | -4.86127 |
| $C_{6,1}$ | 86.11529 | $C_{6,2}$ | -60.43182 | $C_{6,3}$ | 3.14136 |
| $C_{7,1}$ | -33.20242 | $C_{7,2}$ | 28.81875 | $C_{7,3}$ | 0.0 |

***Tab. 2.*** *Values of the coefficients $c_{i,j}$ for determination of the characteristics $t(\bar{x})$ .*

| Coefficients $c_{i,j}$ in $f(p, g_1)$ | | Coefficients $c_{i,j}$ in $f(p, g_2)$ | | Coefficients $c_{i,j}$ in $f(p, g_3)$ | |
|---|---|---|---|---|---|
| $C_{0,1}$ | 4.94207 | $C_{0,2}$ | -0.06528 | $C_{0,3}$ | 0.24071 |
| $C_{1,1}$ | -6.49645 | $C_{1,2}$ | 0.42923 | $C_{1,3}$ | -0.54335 |
| $C_{2,1}$ | -6.58369 | $C_{2,2}$ | -0.73321 | $C_{2,3}$ | 0.34214 |
| $C_{3,1}$ | 8.77740 | $C_{3,2}$ | 0.37536 | $C_{3,3}$ | 0.0 |
| $C_{4,1}$ | 33.52143 | $C_{4,2}$ | -0.51611 | $C_{4,3}$ | 3.41621 |
| $C_{5,1}$ | -44.26194 | $C_{5,2}$ | 3.60430 | $C_{5,3}$ | -7.35229 |
| $C_{6,1}$ | -45.02972 | $C_{6,2}$ | -6.30664 | $C_{6,3}$ | 4.13618 |
| $C_{7,1}$ | 60.08500 | $C_{7,2}$ | 3.27293 | $C_{7,3}$ | 0.0 |

The constants were determined by applying the approximation method consisting in minimization of sum of squares of deviations over discrete set.

For the case of h/T = var and $F_h$ = const a sufficient approximation accuracy was obtained by applying the Lagrange polynomial $L_i$ having constant interpolation nodes as follows: h/T = $g_1$ = 2.0 ; h/T = $g_2$ = 4.0 and h/T = $g_3$ = 8.0, which cover the range of dimensionless waterway depth in question. As a result, the following structure of the formula was obtained:

$$F(p,g) = \sum_{i=1}^{3}[L_i(g) \cdot f(p, g_i)] = \frac{(g-g_2)\cdot(g-g_3)}{(g_1-g_2)\cdot(g_1-g_3)} \cdot f(p,g_1) + \frac{(g-g_1)\cdot(g-g_3)}{(g_2-g_1)\cdot(g_2-g_3)} \cdot f(p,g_2) + \frac{(g-g_1)\cdot(g-g_2)}{(g_3-g_1)\cdot(g_3-g_2)} \cdot f(p,g_3) \tag{17}$$

In the method in question the influence of buoyancy centre location was not taken into account both due to a weak correlation with the determined characteristics and necessity of adjusting the method to be capable of identifying the ship in the preliminary design phase.

## METHOD FOR DETERMINING GENERALIZED CHARACTERISTICS

The diagrams given in [7] concern the hull of the following parameters $\bar{k}_p = (L_p, B_p, T_p, CB_p, CM_p)$ = (80.0 m, 8.89 m, 1.25 m, 0.587, 0.981), which is considered as that of the parent form. At small $F_h$ numbers the shallow water influence is low and the characteristics $w(\bar{x})$ and $t(\bar{x})$ are almost constant hence they can be determined with the use of the formulae valid for deep water. Hence the method of Holtrop and Mennen [1] was applied to determining $w_m$ and $t_m$ values both for the parent hull and designed one, respectively, which consequently served for determining the correction functions $r(\bar{k})$ and $s(\bar{k})$**,** namely :

$$r(\bar{k}) = \frac{w_m(\bar{k}_d)}{w_m(\bar{k}_p)} \tag{18}$$

$$s(\bar{k}) = \frac{t_m(\bar{k}_d)}{t_m(\bar{k}_p)} \tag{19}$$

where :

$w_m(\bar{k}_d)$ – deals with the designed hull and deep water
$w_m(\bar{k}_p)$ – the parent hull and deep water.

In the case of deep water the characteristics $w(\bar{x})$ and $t(\bar{x})$ are monotonous respective to the hull parameters $\bar{k}$, hence the characteristics described by the formulae (17) and corrected by the functions $r(\bar{k})$ and $s(\bar{k})$ in compliance with the formulae (14) and (15), model in an approximate way (extrapolate) the generalized characteristics $w(p, g, \bar{k})$ and $t(p, g, \bar{k})$, therefore they may serve for determining the characteristics of designed ship of variable parameters both of hull form, water depth and ship speed ; as they are expressed *explicite* by parametric mathematical models they satisfy the demand put to genuine parametric methods applicable to preliminary design of ships.

The generalized relationships can be next used for determining the generalized characteristics of propeller-hull interaction in shallow water, in compliance with the following formula :

$$\frac{N_h}{N_T} = \xi_k(p, g, \bar{k}) = \frac{1 - t(p, g, \bar{k})}{1 - w(p, g, \bar{k})} \tag{20}$$

The elaborated proposal of the method may be applicable to preliminary determining the parameters of propulsion system of ships intended for operating in shallow waters, e.g. in designing inland waterways ships.

In Fig.1 are graphically presented the characteristics of wake fraction, and in Fig.2 – those of thrust deduction, determined for the ship designed for the shallow waterway on Berlin–Kaliningrad route (the example concerns twin-propeller ship).

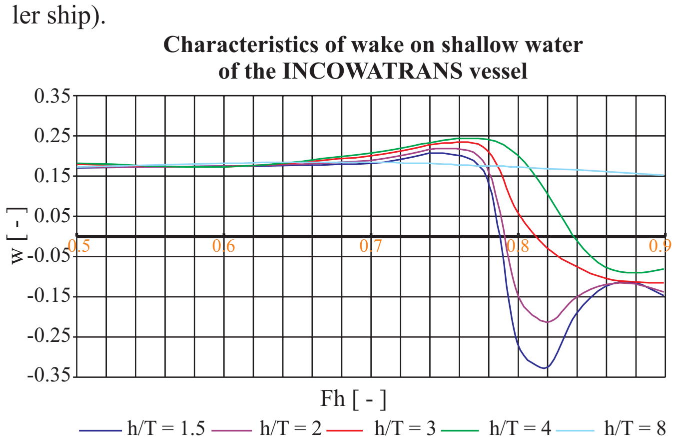


***Fig. 1.** A graphic representation of the mathematical models of the wake fraction characteristics $w(\bar{x})$ for the INCOWATRANS ship .*

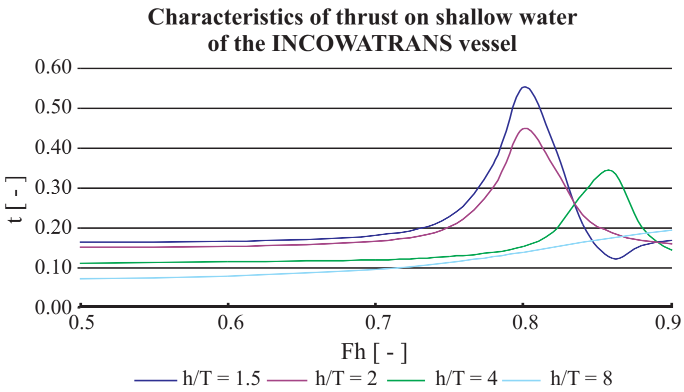


***Fig. 2.** A graphic representation of the mathematical models of the thrust deduction characteristics $t(\bar{x})$ for the INCOWATRANS ship .*

## SUMMARY

- The presented method can be used for determining the propeller-hull interaction characteristics in the case of designing a ship intended for operating in shallow waters of the depth only somewhat greater than ship's draught. The applied generalization makes it possible to approximately determine w and t characteristics in the cases not covered by the diagrams given in [7].
- Analysis of the presented models makes it possible to offer the following comments :
  - when the Froude number related to water depth decreases then the w function tends to the value corresponding with that for deep water (Fig.1)
  - when the Froude number exceeds the value of 0.7 then w value decreases
  - when the Froude number exceeds the value of 0.8 then, at a sufficiently large water depth, w value decreases only a little (bold line in Fig. 1)
  - when Froude number value is greater than $F_h = 0.75$ then the t characteristics increase up to their extreme value and next, in the case of shallow water, decrease (Fig.2).
- Recapitulating, when the value $F_h = 0.75$ is exceeded, then the smaller the water depth, the greater the drop of values of the hull interaction characteristics, which results in a drop of propulsion system efficiency.
- The determined models of the generalized characteristics $w(p, g, \bar{k})$ and $t(p, g, \bar{k})$ have been implemented in the computer algorithm under development, intended for the determining of optimum parameters of propulsion system for inland navigation ships.
- The presented conclusions are in compliance with the present empirical knowledge, however the presented quantitative assessment has been only possible on the basis of the elaborated mathematical models.
- Computer implementation of the presented method was used in design work concerning optimization of propulsion system parameters for the tourist passenger ship intended for operating on the inland waterway route between Berlin and Królewiec, designed within the frame of Eureka E!3065 INCOWATRANS project.
- The method can also find use in preliminary designing the propulsion systems for inland navigation ships intended for sailing on shallow rivers, canals and lakes, or for coastal ships and naval landing crafts.

## NOMENCLATURE

$g$ – dimensionless waterway depth
$g_z$ – gravity acceleration
$h$ – waterway depth
$\bar{k}$ – vector of hull form parameters
$\bar{k}_p$ – vector of parent hull form parameters
$\bar{k}_d$ – vector of designed hull form parameters
$p$ – Froude number related to water depth
$t$ – thrust deduction characteristics
$t_m$ – thrust deduction characteristics for deep water
$v$ – ship speed
$v_p$ – velocity of water inflow to propeller
$w$ – wake fraction characteristics
$w_m$ – wake fraction characteristics for deep water
$\bar{x}$ – vector of ship parameters
$B_p$ – parent ship breadth
$C_{Bp}$ – parent ship hull block coefficient
$C_{Mp}$ – parent ship hull midship-section coefficient
$F_h$ – Froude number related to water depth
$N_h$ – towrope horsepower
$N_T$ – propeller thrust power
$R$ – ship hull resistance
$T$ – ship draught
$T_N$ – propelling force
$T_p$ – parent ship draught

$T_P$ – propeller thrust

$\eta$ – propeller efficiency

$\xi_k$ – propeller –hull interaction characteristics.

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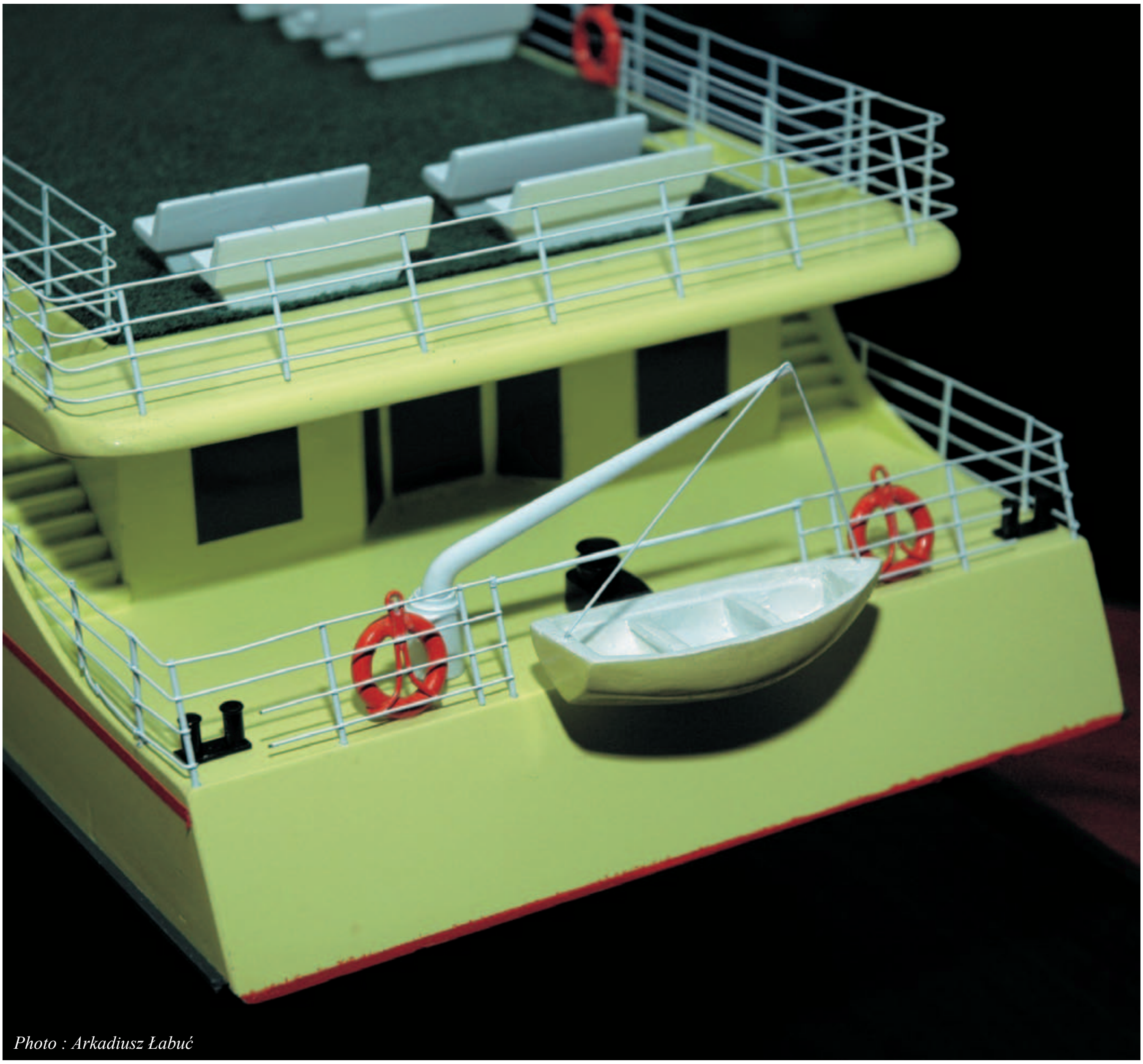

*Photo : Arkadiusz Łabuć*

# Application of steel sandwich panels to hull structure of two-segment inland navigation passenger ship

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ABSTRACT

*This paper presents a concept of hull structure of novel environment-friendly inland navigation and coastal ships for Polish east-west waterways. In compliance with its assumptions the inland navigation passenger ship is designed in the form of two mutually connected segments : a propulsion segment which contains gastronomy and entertainment infrastructure and crew accommodations and an articulated hotel segment. In this paper attention is focused on solutions of the hotel segment of an innovative structure mainly consisted of steel polyurethane-filled sandwich panels. Similar structural solution is intended for the propulsion segment.*

**Keywords** : inland navigation passenger ship, sandwich panels, sandwich structures.

## DESIGN ASSUMPTIONS AND PRELIMINARY DESIGN WORK

The maximum draught of the designed ship was assumed not greater than 1 m because of local limitations of the transit depth of the waterway – to the value of 1.2 m – on the planned route from Berlin via Kostrzyń, Nakło, Bydgoszcz, Toruń, Elbląg to Królewiec, moreover the ship has to be capable of instantaneous increasing its draught over 1 m in order to be able to pass under some bridges in view of a limited water clearance under them. In particular the first condition made it necessary to design the structure of significantly smaller weight than that of classical one, and simultaneously guaranteeing strength features and stiffness conditions comparable with those of the classical structure of the kind. It was decided that it will be feasible if steel laser-welded sandwich panel plating is applied to the hull structure; such panels consist of two external plates and the system of parallel webs and foam filling placed between the plates. Such plate structure made it possible to lower structural weight even by 30%, at maintained high stiffness and increased resistance to local punching. In Fig.1 a fragment of sandwich plate structure is shown. Such structures were planned to be used to the structural elements characterized by distinct flatness and lack of a great number of openings. In the case of the designed ship it concerns bottom and deck structures within the middle body of ship hull, usually very long in inland waterways ships. The bow and stern part structures were assumed to be designed in the traditional form**.** Similarly, the ship side structures, due to many window openings (Fig. 2), had to remain in a traditional form because of a low gain of weight possible to be obtained by using sandwich panels.

The design work was started from elaboration of an effective way of structural modelling for the calculation by means of Finite Element Method (FEM), of structures built of sandwich panels.

Before performing FEM calculations of large fragments of the structure it was necessary to determine such way of modelling as to assure reasonable time of calculations and use of disk space.

Application of solid elements to modelling of a single panel seemed to be natural and providing satisfactory results close to experimental ones. However in many cases such approach

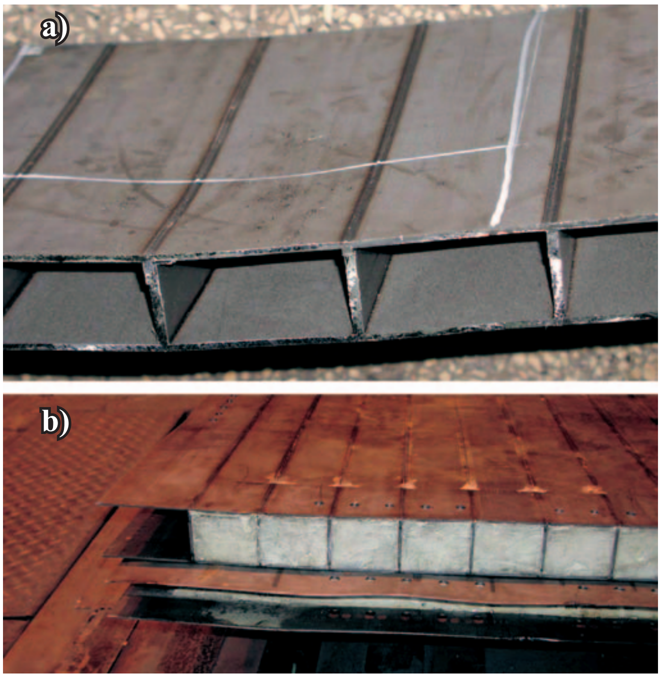


***Fig. 1.*** *An example of sandwich panel plate structure of the following scantlings : – outer plate thickness : 6 mm; – inner plate thickness : 4 mm; – web depth (distance between the plates) : 40 mm; – web thickness : 6 mm;*
***a)*** *sandwich structure free of filling*
***b)*** *sandwich structure with polyurethane filling .*

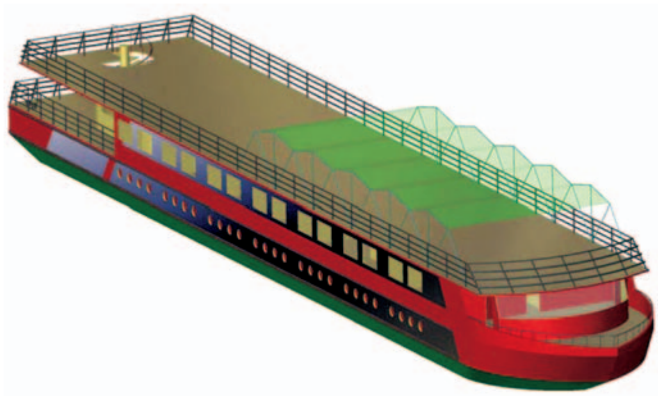

***Fig. 2.*** *Image of the hotel segment hull .*

would make it impossible to conduct calculations of more complex structures than a single panel, because of required vast calculation time and computer memory and disc space. An alternative appeared to be the application of shell layer elements combined with beam ones, that made it possible to effectively simplify the structural model and shorten time of calculations.

To build an equivalent shell model of sandwich panel was aimed at, having the features equivalent to those of a solid model, to a degree which could make it possible to build 3D model and conduct FEM calculations of a large fragment of the segment's hull structure, rationally. It was necessary to so select characteristics of the used elements as to obtain sufficiently accurate approximation of displacement and stress distributions yielded by the solid model (reference) and shell-beam one (equivalent) under a given load.

All calibrating calculations were performed by using ANSYS software. Illustrative comparison of the displacement distributions achieved from one of the tasks aimed at calibrating element characteristics, is presented in Fig.3 and 4.

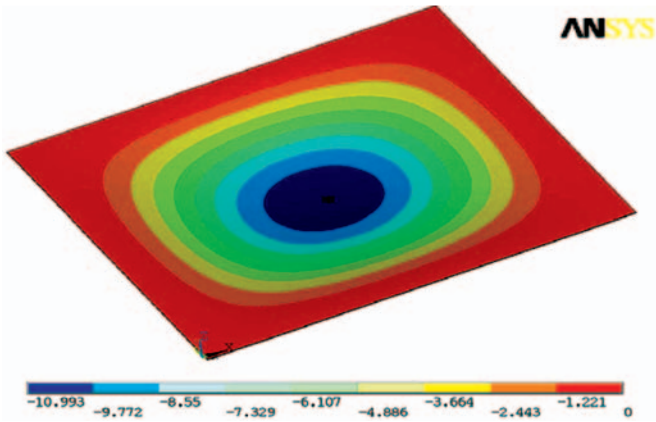


*Fig. 3. The vertical displacements UZ – obtained from the solid model (reference) .*

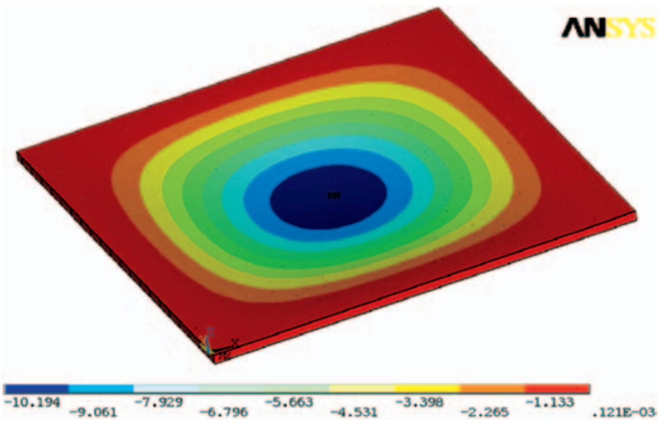


*Fig. 4. The vertical displacements UZ – obtained from the shell-beam model (equivalent) .*

Next, was prepared and then realized a concept of preliminary strength calculations of the hotel segment's structure and the propulsion segment's (pusher) structure consisted to a large extent of steel sandwich panels with polyurethane filling.

Certain number of variants of the structural arrangement were considered. On the basis of the previously gained experience, the decision was taken as to the selection of the final form of hull structure of the two-segment passenger ship. The selected hull structure form of the considered barge and pusher served as a basis for subsequent design work on ship power plant, ship systems and equipment, as well as for further improvements of the structure itself. In the elaborated solution was utilized the initial concept of the structural arrangement consisting in using sandwich polyurethane-filled panels for prevailing part of the hull structure though in the earlier concepts their application to bulkheads and some parts of side plating was not taken into account for manufacturing and functional reasons. Bottom, deck and side structures of the hotel segment's hull were divided into three zones : stern, midship and bow one. Below, the particular zones of the hull structure are described in order to provide an overall idea of its arrangement.

### *Bottom structure*

The bottom midship zone has to be built of sandwich polyurethane-filled panels having webs parallel to the ship's longitudinal axis. The panels are mutually connected with the use of rectangular pipe profiles intended also for strengthening the bottom structure. The profiles are located both in longitudinal and transverse directions respective to ship axis. The stern and bow zones of the bottom have to be built as classical single-shell structures.

### *Deck structure*

The midship zone of deck structure has to be constructed of sandwich polyurethane-filled panels longitudinally stiffened and mutually connected with the use of rectangular pipe profiles directed longitudinally and transversely. The stern and bow zones of the deck structure have to be built in the form of classical single-shell structures. The deck plating is transversely stiffened. The stiffeners are supported by a deck girder or longitudinal bulkhead. In the extreme part of ship's bow the deck is longitudinally stiffened by plate girders.

### *Structure of ship sides and transom*

In the midship zone up to the height of 1000 mm over the base plane (PP), the ship side structure has to be built of sandwich polyurethane-filled panels having longitudinal webs. The panels are mutually connected by means of the rectangular pipe profiles in the same way as in the case of the bottom and deck structures. The side and bottom panels are connected to each other with the use of a flat bar to which they are welded with tee-fillet joint. The side panels are closed from the top by bulb profiles.

Above the height of 1000 mm over the base plane, as well as in the stern and bow zones, the sides have to be built in the form of classical single-shell structures vertically stiffened. In the same way the transom structure has to be made.

### *Structure of longitudinal and transverse bulkheads*

Both the longitudinal and transverse bulkheads are designed as vertically stiffened single – shell structures. Ends of their stiffeners (webs) have to be welded to rectangular pipe profiles in the case when a given bulkhead is placed in the region where sandwich panels are used, or the web ends have to be fixed by brackets when a given bulkhead is connected with a single-shell structure. The typical midship section of the barge hull is shown in Fig.5.

**Cross-section 25050 mm distant from AP**

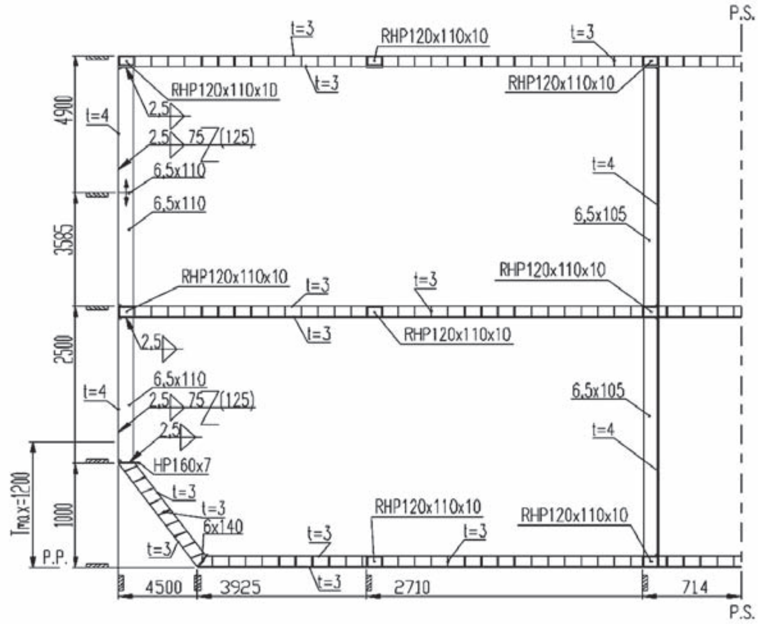


*Fig. 5. The typical midship section of the barge hull,*
*where : **t** – side plating thickness, **RHP** – rectangular pipe profile .*

## *Structural calculations*

In order to determine stresses occurring in sandwich panels preliminary structural strength calculations were performed by using the Finite Element Method (FEM).

The analysis was conducted on two levels :

- zone level (the structural models cover the length of a whole living cabin and two halves of neighbouring cabins)
- local level with the aim of determining stresses which occur in the panel joints (detail models of selected joints).

The 3D models, calculations and visual presentation of their results were elaborated with the use of the ANSYS software. In Fig. 6 and 7 geometrical features of the models are presented. As regards local strength of the classical hull structures (plating and stiffeners) the authors based on the requirements of the *Rules for the classification and construction of inland waterways ships,* Part II (Hull) of Polish Register of Ships (PRS), published in 2004.

The estimated stresses resulting from FEM analysis of the zone and local structural models, reach their maximum values which do not exceed permissible levels. Also, the total normal stresses due to overall bending, determined on the basis of the PRS rules, as well as the stresses in X- direction, determined from FEM calculation, do not exceed permissible ones.

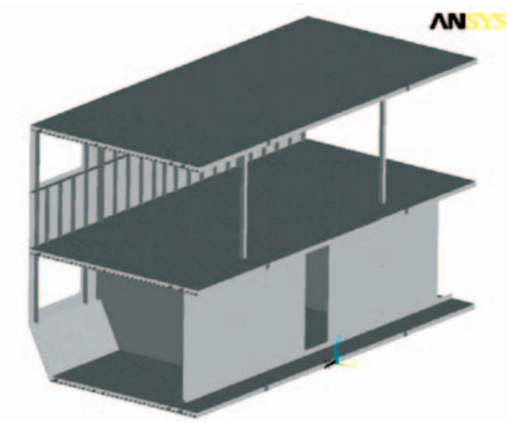


***Fig. 6.** Zone model geometry .*

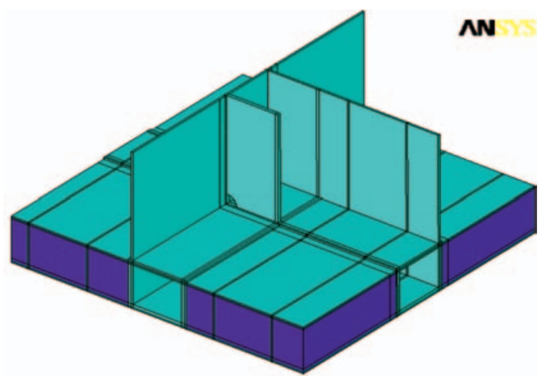


***Fig. 7.** Geometry of a selected structural joint .*

## RECAPITULATION

- Basing on the so far performed work one can state that the concept of building articulated inland waterways ship whose main part consists of sandwich polyurethane-filled panels, is feasible and fulfils the assumptions for preliminary design stage, both as regards ship mass and maximum gabarites of hull structural elements, assuring sufficient easiness and comfort of moving and staying on board the ship for passengers and crew members.

- This work bore fruits consisting in gaining experience in the area of designing relatively „risky" and innovative structural solutions, as well as of modelling and computing the structures consisted of sandwich panels.

- However one should be aware of that this is still the preliminary stage of the design, which contains several simplifications and not yet solved problems such as e.g. strength assessment criteria for sandwich panel structures, based on FEM calculations.

- During the next stages of ship design a more detailed strength analysis of sandwich panels and their joints will be necessary.


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# Concept of barge hull structure made of extruded aluminium panels

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ABSTRACT

*A design of the hotel barge of 52 m overall length and 9 m breadth , intended for inland waterway shipping on the route from Berlin to Kaliningrad, is presented. Hull of the barge is characterized by a unique structure consisted of densely stiffened aluminium panels of 4.5 mm plate thickness and 70 mm depth of stiffeners, supported by transverse walls or girders. The stiffeners of the panels are longitudinally directed. Also, are described problems associated with assurance of adequate strength and stiffness of such structure, resulting from a limited maximum depth of the barge.*

**Keywords** : inland waterways ships, ship hull strength, structures composed of aluminium panels.

## INTRODUCTION – PUSH TRAIN CONCEPT

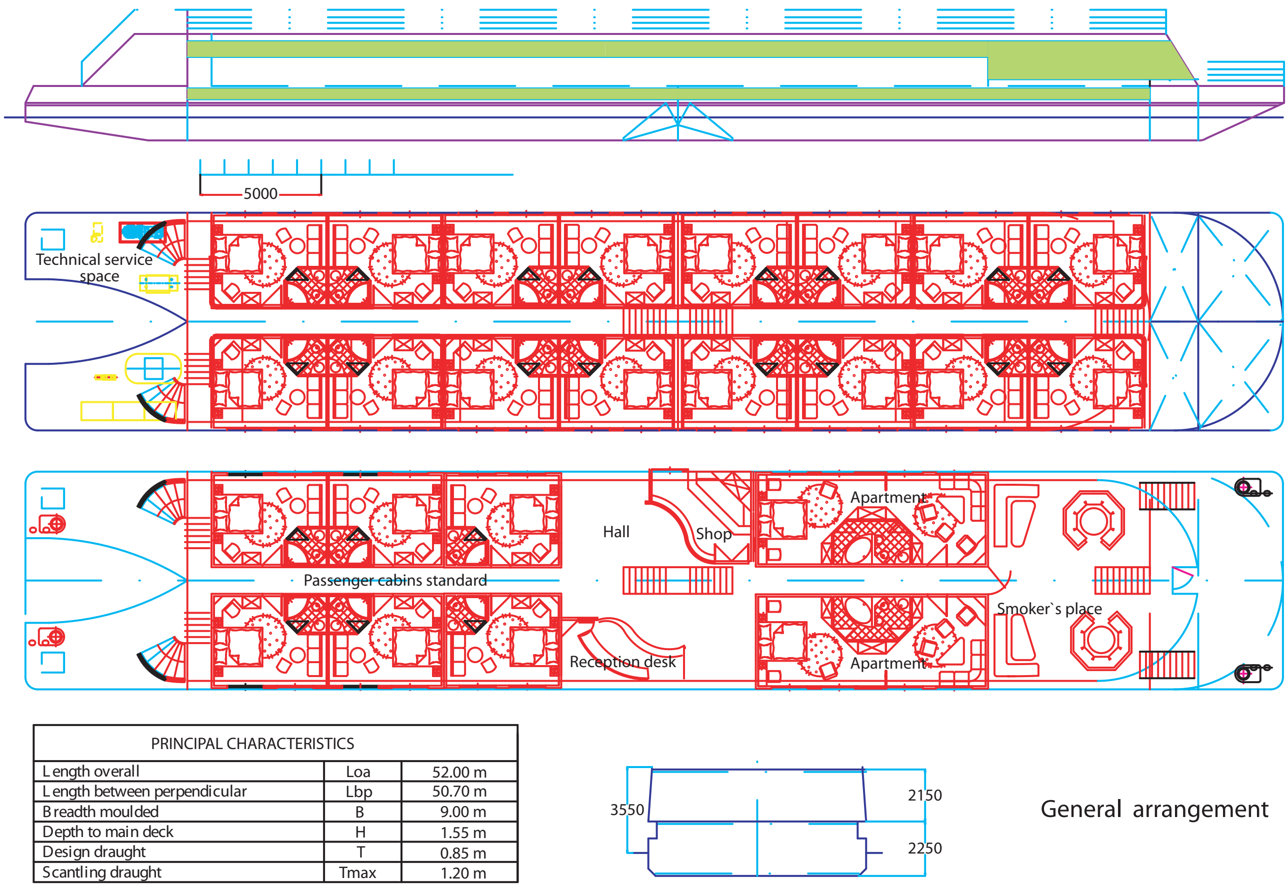
The push train shown in Fig. 1. is intended for operating on Berlin – Kaliningrad route. The train is composed of a hotel barge, restaurant barge and pusher. The lack of any protrusions on the upper decks characterizes the barges. The decks fitted only with folding bulwark rails serve as sun bath decks.

Such arrangement of the barges results from their limited depth associated with gabarites of bridges across the rivers and canals along the planned shipping route.

A unique construction of stern parts of the barges was proposed. The recesses provided there, are adjusted to the bow part of the pusher. As a result, an easily operated and strong connection between the two units is obtained.

The maximum depth limitation of the barges creates certain problems associated with assurance of appropriate strength of barge hull structure.

The problems are discussed in detail in Ch.3. And, in Ch.2 is described a unique structure of barge hulls composed of extruded aluminium panels.




| PRINCIPAL CHARACTERISTICS | | |
|---|---|---|
| Length overall | Loa | 52.00 m |
| Length between perpendicular | Lbp | 50.70 m |
| Breadth moulded | B | 9.00 m |
| Depth to main deck | H | 1.55 m |
| Design draught | T | 0.85 m |
| Scantling draught | Tmax | 1.20 m |

***Fig.1.** General arrangement of the push train .*

## BARGE HULL STRUCTURE

The limitations described in Ch.1 make that the sun bath deck (superstructure deck) cannot be located higher than 4.4 m above the base plane.

Therefore it was proposed that the barge accommodations should have the following gross height (i.e. that determined without taking into account plate stiffening system or girders which make the net height even smaller) :

- from the base plane to the main deck : 2.25 m
- from the main deck to the sun bath deck : 2.15 m.

The so small gross heights of accommodations make it necessary to apply a specific structural arrangement in order to obtain the minimum permissible net height of living and servicing accommodations. Hence it was decided to use the unique structural arrangement composed of the extruded panels made of 6082 aluminium alloy (acc. OIN) having the tensile strength $R_m$ = 290 MPa. The cross-section of the panels is shown in Fig. 2.

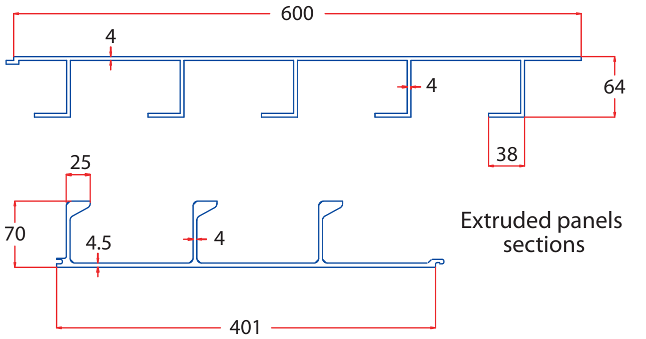



***Fig. 2.*** *The extruded panels to be applied .*

Such panels are densely stiffened. At 70 mm depth, they ensure relatively high bending strength of the stiffeners as well as local bending strength of the plates of 4.5 mm thickness. This way it is possible to eliminate transverse frames from the space below the main deck, which would support the panels, as the panels, longitudinally stiffened, can be supported directly by the transverse walls which are also intended to be made from extruded aluminium panels of stiffeners directed vertically.

The walls are placed with spacing not greater than 4.5 m, which results from the barge space subdivision because on the lower tier of each of the barges is designed a row of passenger cabins (hotel barge), crew cabins or various servicing accommodations (restaurant barge). The panels are so strong that at the barge draught T = 0.85 m they can transfer the load resulting from water pressure over so large span as that (i.e. up to 4.5 m).

The midship section of the barge hull composed of the stiffened panels is shown in Fig.3.

The specific construction of the joint of the stiffened panels and transverse walls is presented in Fig.4.

In the corridor between cabins the panels are to be supported by transverse girders just in the planes of transverse walls.

Short spans of the girders allow for making them of aluminium profiles of a relatively low depth. As a result, a sufficient net height of the corridor is obtained.

On higher tiers of both barges (under sun bath deck), relatively large accommodations are located, where the distance between transverse walls exceeds 4.5 m substantially, and in consequence the girders supporting both the deck and side panels cannot be avoided. In order to obtain a sufficiently large net height of the accommodations it is necessary to apply such joints between the panels and transverse girders as shown in Fig.5. It is also necessary to provide additional support of the transverse girders by means of pillars, to reduce the girder depth as much as possible. The pillars are placed just at the transverse walls separating the cabins.

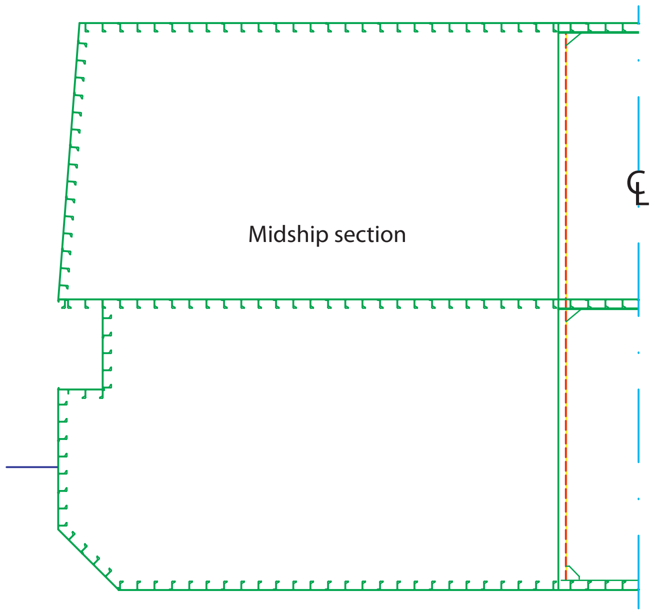



***Fig. 3.*** *Midship section of the barge hull .*

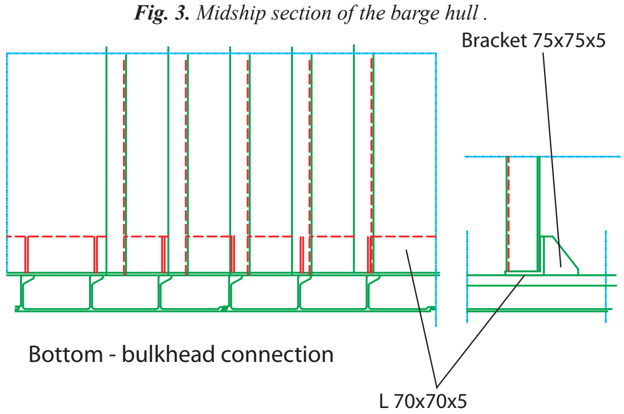



***Fig. 4.*** *The joint between the stiffened panels and transverse walls .*

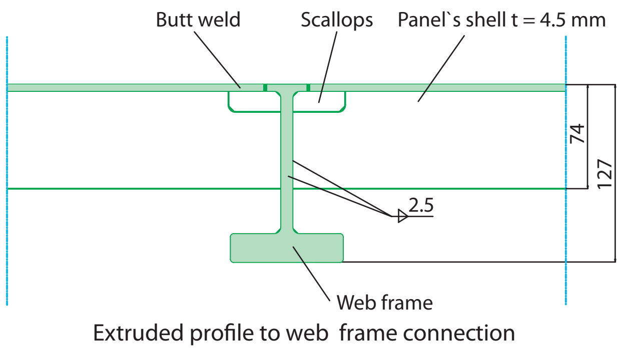



***Fig. 5.*** *The joint between the panels and transverse girders .*

## STRENGTH OF BARGE HULLS

The above described barge hull structures composed of extruded aluminium panels greatly differ from equivalent classical steel structures. Hence specific strength problems arise.

The assumed large span of the panels (up to 4.5 m) results in a high level of stresses due to local bending of stiffeners of the panels supported by transverse walls or girders.

At the pressure acting on the barge bottom, p = 12.0 kPa (resulting from the draught T = 0.85 m and wave load), and the span l = 4.5 m, the bending stresses are equal to :

$$\sigma = \frac{psl^2}{12W} = 165\ [MPa]$$

where :

p, l – as given above,
s = 0.133 m – spacing of stiffeners (see Fig. 20)
W = 16.28 $cm^3$ – strength modulus of stiffener with plate strip of effective width.

The σ value is relatively large, not exceeding however the permissible one acc. [1], where the following is assumed :

$$\sigma_{dop} = 0.8\ \sigma_y = 200\ MPa$$

($\sigma_y$ = 250 MPa – proof strength of the aluminium alloy).

Another consequence of the relatively large span l are also the relatively large deflections of the panels. At the pressure p = 12.0 kPa the maximum deflection amounts to about 37 mm (at the Young modulus of the aluminum alloy, E = 70 000 MPa).

A relatively massive structure of the panels results in that there are no problems with the assuring of sufficient strength to the barges under overall bending.

It was assessed that the maximum stresses σ resulting from the minimum bending moment [1] applied to the barge hull :

$$M_{min} = 0.07\ BHL^2 = 2510\ kNm$$

where :

B – barge breadth (9.0 m)
H – barge depth (1.55 m)
L – barge length (50.7 m)

enlarged by the wave bending moment $M_w$ = 851 kNm (for the navigation zone „3" of the wave height up to 0.6 m, acc. [1]), are equal to σ = 9.0 MPa only (in the barge bottom plate, assuming that the superstructure deck is the strength one).

The so small value of compressive stresses are not imminent as regards the buckling either of panel stiffeners in compression or their plating.

The Euler stresses for the stiffeners of bending mode of instability at the span l = 4.5m, are equal to about 24 MPa.

The Euler stresses for the stiffeners of torsional mode of instability and those for panel plate buckling are many times greater than the above given stresses for stiffeners of bending mode of instability.

During designing the barge hull structures, emerged a serious problem dealing with assuring a sufficient bending stiffness to the deck transverse girders. It was revealed that the deck transverse girders, though they satisfy the strength requirements of the Rules [1] at their span of 4.5 m and the calculation pressure p = 4.5 kPa for passenger decks, have their bending stiffness smaller than the critical one. Thus they do not prevent the decks against overall buckling. In order to obtain their stiffness greater than the critical it was necessary to apply pillars to support the transverse girders in the spacing not exceeding ¼ B (where B – barge breadth).

## FINAL REMARKS

- Limitation of the overall depth of the barges forced to apply a specific construction to their hulls. To this end, the extruded aluminium panels of stiffeners directed along the ship axis, were used. The panels were supported by walls or transverse girders placed relatively sparsely – even as much as about 4.5 m apart.
- On the upper tier of the barges where spacious accommodations were designed it was necessary to apply many pillars in order to ensure sufficient structural strength and stability of the transverse girders of the superstructure deck. The pillars -without a doubt – affect negatively functionality of the accommodations.
- The expected deflections of the bottom panels between transverse walls reach significant values (up to 37 mm). Hence some difficulties may appear in using the accommodations of the first tier of the barges.

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*Photo : Arkadiusz Łabuć*

# Selected problems of technological preparation of production of a two-segment passenger inland waterways ship of a combined structure

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ABSTRACT

*This paper presents some aspects of technical preparation of production of inland waterways ship of combined structure contained partly: classical structures (bow and stern part) and sandwich panel structure. Due to prototype character of inland waterways ship structure it was decided to define a new subdivision of shipbuilding process into phases and create new classification principles if constructional and technological documentations.*

**Keywords** : sandwich panels, documentations, phases of production, subdivision, structure

## INTRODUCTION

Main tasks of technical preparation of production of a given product contain elaboration of constructional documentation respective of a given design stage (Preliminary design – PW, Technical design – PT, Working design – PR) (in the frame of constructional preparation of production), and technological documentation (in the frame of technological preparation of production). In the case of ship production the elaboration of constructional and technological documentation is based on the constructional and technological subdivision of sea-going ships covered by the Branch standard ZN- 80/101088 [1] as well as the principles of numbering and nomenclature covered by the Branch standard ZN – 80/101089 : Design & construction documentation of sea-going ships [5].

Approaching to elaboration of the assumptions for the outline technology of production of the inland waterways ship which is designed in the confines of the INCOWATRANS project, one has met several problems resulting from distinctness and novelty of the ship in question. The inland waterways ship is a floating unit composed of two autonomous parts : a pusher and hotel barge. Construction of each of the mentioned parts is combined one, i.e. composed partly of classical structure (bow and stern part) and partly of sandwich panel structure. The panel structure greatly differs from the traditional structure as far as design principles are concerned. As the analyzed inland waterways ship constitutes a floating unit of prototype character for Polish shipbuilding industry, elaboration of the following documents has been deemed justified :

a) a new subdivision of shipbuilding process into phases (in the frame of technological preparation of production)
b) classification principles of constructional and technological documentation (in the frame of constructional preparation of production)
c) proposals of modification of the typical work places used in shipyards in order to adjust them for the purposes of machining and prefabrication of panel structures
d) assumptions for elaboration of a model workmanship standard for the hull structure consisted of panel elements and transition regions, i.e. connections between panel structure and classical single-plating structure.

This paper presents the assumptions for the outline technology of production of the inland waterways ship, in particular with development of the topics contained in the points a) and b).

In the summary, also other, more detailed, problems associated with the outline technology of production, which go beyond the scope of this paper, are sketched.

## ASSUMPTIONS FOR THE OUTLINE TECHNOLOGY OF PRODUCTION

The outline technology of production of ship is one of the crucial documents prepared in the frame of the plan of preparation and commencement of production of prototype ship, which determines main technological and organizational information necessary for realization of ship production process. The document contains as a rule the following information dealing with :

- construction and function (purpose) of a ship : general data (type of ship, ship owner, function, engine room position, ambient conditions etc), technical data (main dimensions, speed, kinds of materials, ship class and institution supervising construction of ship)
- site and methods of building the ship (subdivision of ship building process into phases), basic deadlines of building process (the so- called "mile stones" of building schedule, associated with subdivision of ship building process into phases)
- technological remarks (concerning subdivision into sections and blocks, prefabrication, general concepts of building particular fragments of ship hull, subdivision into outfitting regions etc)
- list of associated documents (in particular list of technological instructions being in force)
- the workmanship standard for hull structure.

As above mentioned, the building process of the ship in question is of a prototype and innovative character.

Its novelty consists in wide application of steel sandwich panels. Hull structure of the ship is combined and non-uniform. Its bow and stern parts are traditional (i.e. of a single, transversally-supported plating and traditionally manufactured).

The midship part of cylindrical form, constituting about 65% of ship's length, is designed as a panel structure whose design process and production methods differ substantially from those of traditional construction.

Hence, the necessity results of elaboration of a new subdivision of ship production process into phases and classification principles of constructional and technological documentation in the frame of the outline technology of production of the inland waterways ship.

As far as the subdivision of ship production process into phases is concerned the following reasoning was applied :

- irrespective of a building place of an inland waterways ship, its production process will be carried out with taking into account the subdivision of the hull into the fragments of conventional structure and those of panel structure
- building method of the ship's hull fragments of panel structure will be realized differently depending on a kind of applied sandwich panels :
  - Rough steel sandwich panels, i.e. those subjected to initial machining process in a shipyard which builds the ship
  - CAD steel sandwich panels, i.e. those delivered to the shipyard after machining by their manufacturer in accordance with CAD documentation prepared by and received from the constructional – technological team.

The notions : rough panels and CAD panels have been introduced for the purposes of the INCOWATRANS project; they have not been so far used in the subject-matter literature, where such panels are not distinguished depending on a degree of their prefabrication by manufacturer. The classification principles of constructional and technological documentation were elaborated on the basis of the existing, widely known subdivision established in the Branch standard ZN-80/101088 [1], by adjusting it to the needs of building of a prototype ship. A novelty is the proposal of changing the principles of numbering Classes, Groups and Subgroups as well as the adjustment of items constituting content of particular groups and subgroups to the needs resulting from the specificity of the combined panel – conventional hull structure of the inland waterways ship. The proposed changes of numbering principles should not be considered final ones. They have to serve for putting in order the documentation necessary for building the prototype ship as well as implementing and making use of informatics techniques in the area of documentation management. In the case if a shipyard commences production of similar ships in series it will be necessary to critically review the proposals and possibly to adjust them to the shipyard's possibilities; it especially concerns outfitting phases resulting from application of panels. The proposed classification principles of documentation may be considered as a model reference, which may be justified by the fact that none of the Polish shipyards is today prepared and experienced in building the ships consisted of steel sandwich panels.

## CHARACTERISTICS OF STEEL SANDWICH PANELS

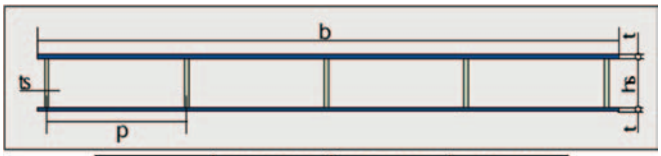
One of the main assumptions for production process of the ship in question is that the sandwich panels - irrespective of their initial state (either rough or CAD machined) - are delivered to the shipyard building the ship in the form of ready product, which means that the shipyard does not manufacture such panels.

The application of sandwich panels to the building of ship results in that :

- Range of technological operations realized by the shipyard will depend on a state in which the panels would be delivered
- Certain technological operations will be common for both rough and CAD panels, whereas some of them will be characteristic for rough panels only.

### *Characteristics of rough panels*

The rough panels are such sandwich panels which are subjected to initial machining in the shipyard which builds the ship, and they are delivered in accordance with standard gabarites, filling material or without it. Example gabarites of the panels are shown in Fig. 1, [2].




| | von / *from* | bis / *to* | Standard |
|---|---|---|---|
| Breite / *width* | 500 mm | 3000 mm | |
| Länge / *length* | 1000 mm | 10000 mm | |
| t | 2 mm | 10 mm | 2.5 mm |
| p | | | 120 mm |
| hs | 40 mm | 100 mm | 40 mm |
| ts | 3 mm | | 4 mm |

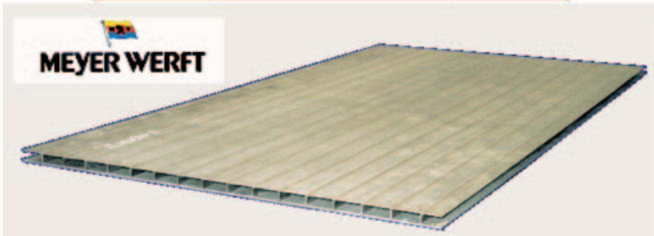



***Fig. 1.*** *Example rough panels .*

The range of technological operations applicable to rough panels is the following : delivery control according to a technological instruction, storage, transport (of panels and fragments of the structure made of panels, including inter-operational transport), precise cutting, edge preparation to welding, cutting the openings and passages, straightening (locally around cut and to-be-framed openings, free edges in the area of welded joints), welding the panels, assembling and outfitting acc. Phase 08 (Prefabrication of sections, outfitting with : passages and fixtures, seatings, installations), painting and preserving (including the filling of internal space between panel plates, quality control and final acceptance.

### *Characteristics of CAD panels*

The CAD steel sandwich panels are such panels delivered to the shipyard, which are fully machined by the panel manufacturer basing on the achieved CAD documentation prepared by the design - constructional- technological team. Such panels contain some outfit elements, fastening sockets or machinery seatings. An example CAD panel is shown in Fig.2.

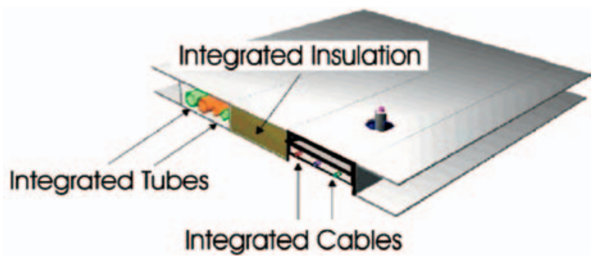



***Fig. 2.*** *Example CAD panel equipped with some outfit elements [3] .*

As far as CAD panels are concerned the range of technological operations is similar to that for rough panels – and differences deal with : application of margins and technological allowances (certain edges of CAD panels may be prepared ready-to-welding), outfitting acc. Phase 8 dependent on a degree of outfit work made by manufacturer, range of painting and preservation of panel inter-plating volumes.

## *Subdivision of production process of inland waterways ship into phases*

Building cycle of a ship arising in a shipyard is split into building periods which determine duration time of particular phases of production process, called also the building phases. The usual subdivision of ship building process into phases of : machining, prefabrication, assembling and tests (trials) [4] is rough one, which finds practical application only in the preliminary design of technological processes of ship production. Every shipyard realizing ship building processes applies practically different phase subdivisions of production process, dependent on its own technological and organizational level, and depending on a degree of minuteness of detail of production process scheduling. The below proposed subdivision of building process of inland waterways ship into phases (Tab.1) is modeled on the phase subdivision which is in practical use of shipyards. It does not mean that the proposed subdivision is the only one. A shipyard which would be ready to undertake building the inland waterways ship may itself apply another phase subdivision of building process according to its own experience and needs. The below given presentation of the proposal of subdivision of building process of inland waterways into phases is aimed at emphasizing the distinctness of building process of panel structure as compared with that of conventional ship structure. The distinctness concerns first of all the building phases beginning from launching and deals with differentiating the tasks specified in the outline scope of work, and with events ending a given phase. The subdivision of building process of inland waterways ship into phases is shown in Tab.1.

***Tab. 1.*** *Subdivision of building process of inland waterways ship into phases*

| No. of phase | Conventional part ➔ see the next page | | | |
|---|---|---|---|---|
| | Phase name | Unit subdivision | Outline range of work | Events |
| 10 | Preparation of documentation | Concept of constructional and technological subdivision of ship into panel-built part and conventional part. | Catalogue of constructional units (joints connecting panels and conventional structures) | Elaboration of documentation together with selection of units |
| | | | CAD project | |
| 09 | Hull structure machining | Machining groups | Plate initial machining, cutting, initial prefabrication | End of hull machining |
| 08 | Prefabrication and outfitting of sections | Hull sections | Prefabrication of hull sections and outfitting with passages and fixtures, seatings, installations | End of prefabrication |
| 07 | Assembling and outfitting of blocks | Hull blocks | Assembling of blocks, equipment, passages and fixtures, seatings, mechanisms, outfit modules | Readiness of blocks for butting to panel part |
| 06 | Hull assembling and outfitting prior to launching | Outfitting aft and fore regions | Butting and connecting with panel part, joining of installations, preservation prior to launching | Launching |
| 05 | Outfitting | Outfitting region: fore + aft + panel part | Mechanisms, devices and installations | End of hull work Readiness to leak proof tests |
| 04 | Outfitting to water and gas leak proof tests | Outfitting region: bow + stern+ panel part | Installations, outfit fixtures, sockets, fixtures for ceiling and insulation | |
| | Tests of compartments and systems | Task regions | Plans and specifications of leak proof tests | End of leak proof tests |
| 03 | Final outfitting | Outfitting regions | Small welding operations, insulation, boarding, floor finishing, electric equipment, furniture | Readiness to trials |
| | | Task regions | Painting, fixing spare parts and inventory elements, connecting of electric devices to network | |
| 02 | Trials | Task regions | According to program of trials | |
| 01 | Finishing work | Task regions | Recommendations from trials. Final outfitting and painting | |
| 00 | Hoisting a flag | | | Delivery of ship |

***Tab. 1.*** *Page ….← Subdivision of building process of inland waterways ship into phases .*

| Panel part – „rough” | | | | | Panel part – CAD | | | |
|---|---|---|---|---|---|---|---|---|
| **No. of phase** | **Phase name** | **Unit subdivision** | **Outline range of work** | **Events** | **Phase name** | **Unit subdivision** | **Outline range of work** | **Events** |
| **10** | Preparation of documentation | Concept of constructional and technological subdivision of ship into panel-built part and conventional part. | Catalogue of constructional units (joints connecting panels)<br>CAD project | Elaboration of documentation including selection of units | Preparation of documentation | Concept of constructional and technological subdivision of ship into panel built and conventional part. | Catalogue of constructional units (joints connecting panels)<br>CAD project | Elaboration of documentation including selection of units |
| **09** | Machining of rough panels | Machining groups | Initial machining of plates, cutting, initial prefabrication | End of e. g. machining of hull parts | Machiningof panels for assembling and welding | Panels | Cleaning, accurate cutting, cutting of e.g. openings | End of machnining of panels |
| **08** | Prefabrication and outfitting of sections | 2D panel sections | Prefabrication of sections and outfitting with: passages and fixtures, seatings, installations | End of prefabrication | Prefabrication and outfitting of panels | 2D panel sections | Joining of panels into flat sections. Assembling of passages, fixtures etc. | End of prefabrication |
| **07** | Assembling and outfitting of blocks | 3D panel blocks | Assembling of blocks, and equipment, passages and fixtures, seatings, mechanisms, outfit modules | Readiness of blocks to butting with panel part | Joining of flat sections into blocks | 3D panel blocks | Joining of "D sections into blocks. Assembling of passages, fixtures etc., seatings and installations. | Readiness of blocks to butting |

## CLASSIFICATION OF CONSTRUCTIONAL AND TECHNOLOGICAL DOCUMENTATION AND ITS PRINCIPLES

Topical subdivision of constructional and technological problems into classes, groups and subgroups constitutes the subject of classification concerning the building of inland waterways ship.

The following principles of indexing (numbering) the documentation were assumed :

- ✪ Class – two-digit numbers – from 00 to 10
- ✪ Group – Class number + one digit – from 00 to 10 + (0 to 9)
- ✪ Subgroup – Class number + Group number + one digit – from 00 to 10 + (0 to 9) + (0 to 9)
- ✪ After Subgroup number, the symbol „ – ” or „ / ” has to be included.

If necessity of further subdividing arises subsequent subdivision layers have to be numbered with two digits and separated by the symbols put after subgroup number. Application of successive layers is associated with a degree of minuteness of detail of documents. It should be aimed at attaching information (number of document) on mutually related documents, non-depending on their hierarchy in structure.

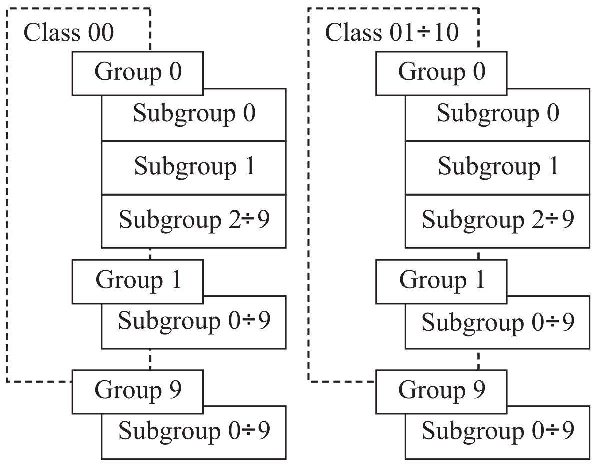



***Fig. 3.*** *Numbering principles of subdivision into classes, groups and subgroups .*

In Tab.2 the subdivision into classes and groups is presented. The most important changes after the modification are as

***Tab.2.*** *Constructional and technological classes and groups of inland waterways ship .*

| Class 00 Theoretical documentation | Class 01 Hull | Class 02 Deck equipment | Class 03 Accommodation outfit | Class 04 Engine room (ER) | Class 05 Piping | Class 06 Electrical equipment and automation | Class 07 Special arrangements | Class 08 Other elements | Class 09 Inventory and spare parts | Class 10 Technological subdivision |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 General group | 0 General group | 0 General group | 0 General group | 0 General group | 0 General group | 0 General group | 0 General group | 0 General group | 0 General group | 0 General group |
| 1 Hull form, spatial layout | 1 Bottom structures | 1 Steering and manoeuvring equipment | 1 Insulation and boarding of living, sanitary and service accommodations and corridors | 1 Shafting | 1 ER piping | 1 Power installations and switching devices | 1 | 1 | 1 Standard inventory elements | 1 Lofting |
| 2 Hydrodynamics and model tests | 2 Bulkheads and partitions | 2 Loading equipment | 2 Insulation and boarding within ER | 2 Main propulsion | 2 Bilge, ballast and fuel piping | 2 Lighting installations | 2 | 2 | 2 Standard spare parts | 2 Positioning and shifting the ship |
| 3 Masses and their centres | 3 Side structures | 3 Anchoring, mooring and towing equipment | 3 Coverings of floors and walls | 3 Exhaust gas piping | 3 Hull piping | 3 Signalling installation | 3 | 3 | 3 Additional inventory elements | 3 Scaffolding communication and transport |
| 4 Hydrostatics and stability | 4 Decks | 4 Floating life-saving, rescue and working appliances | 4 Doors, windows and sleeves connecting the ship segments | 4 Electric generating sets | 4 Driving installations for devices outside ER | 4 Telecommunication installations | 4 Refrigerating devices | 4 | 4 Additional spare parts | 4 Electrical installations |
| 5 Strength, vibrations and noise | 5 Stern structures | 5 Outer communication devices | 5 Equipment of living, sanitary and service accommodations | 5 Mechanisms and devices | 5 Fire - extinguishing installations | 5 Radio-communication and navigation installations | 5 | 5 | 5 Positioning and arranging of inventory elements | 5 Gas & water installations |
| 6 Application of materials | 6 Bow structures | 6 Hold closing equipment | 6 Equipment of compartments for refrigerated and non-refrigerated provisions | 6 Compartments | 6 Ventilation and air-conditioning installations | 6 Installations of other devices | 6 | 6 | 6 Positioning and arranging of spare parts | 6 Heating and ventilating |
| 7 Constructional and technological agreements | 7 Superstructures and deck houses | 7 Closing equipment of openings together with companionways | 7 Equipment of general stores and workshops beyond ER | 7 | 7 Central heating and sanitary installations | 7 Automation | 7 Pump room | 7 | 7 | 7 Conservation and preservation of ship during building |
| 8 Trials and tests of ships | 8 Various hull elements | 8 Various deck equipment | 8 | 8 Floors and gratings in ER | 8 Potable water | 8 Cableways, arrangement and fixing of devices | 8 | 8 | 8 | 8 Tests, trials and overhauls |
| 9 Calculations and economical analysis, contracts | 9 Hull passages, fixtures etc | 9 Coverings of outer decks | 9 Protecting coatings | 9 Lifting equipment, steering and various elements | 9 Other pipings and installations | 9 Cables and wires | 9 Manoeuvring and stabilizing devices | 9 | 9 | 9 Technological documentation non-involving costs |

follows : the renumbering of the technological Class-00 into Class-10; the non-filled positions of groups and subgroups of the classes in which they appear constitute a reserve for additional subdivisions. Details of the subdivision together with the blank for particular problem's executors can be found in [6].

## GENERAL COMMENTS

The above presented problems do not exhaust the entire scope of the topics of the outline production technology of inland waterways ship and the associated technological documentation. The following items should be developed in detail :

- selection of building site and methods
- determination of detail subdivision of panel part of ship hull into sections and blocks in a chosen shipyard (depending on its technological conditions and kind of applied panels)
- determination of a range of machining and prefabrication of panels
- determination of an assembling method of whole panel block
- technological guidelines for preparation of panel structure to preservation and filling
- elaboration of comprehensive technological instructions such as : plan of measurement reference bases and plan of surplus values and allowances, determination of a scope of special instrumentation, outline hull manufacturing tolerances
- catalogue of standard structural joints
- catalogue of ship equipment - with taking into account EU directives, requirements of ship owner and TK, as well as technological level of a chosen shipyard.

Moreover, each of the above mentioned problems should be assigned a relevant document such as : instruction, plan, list (documents of acceptance, protocols, certificates etc.). The numbering of the documents should be in compliance with the classification principles of constructional and technological documentation. They will be elaborated as separate tasks realized within the frame of the project in question.

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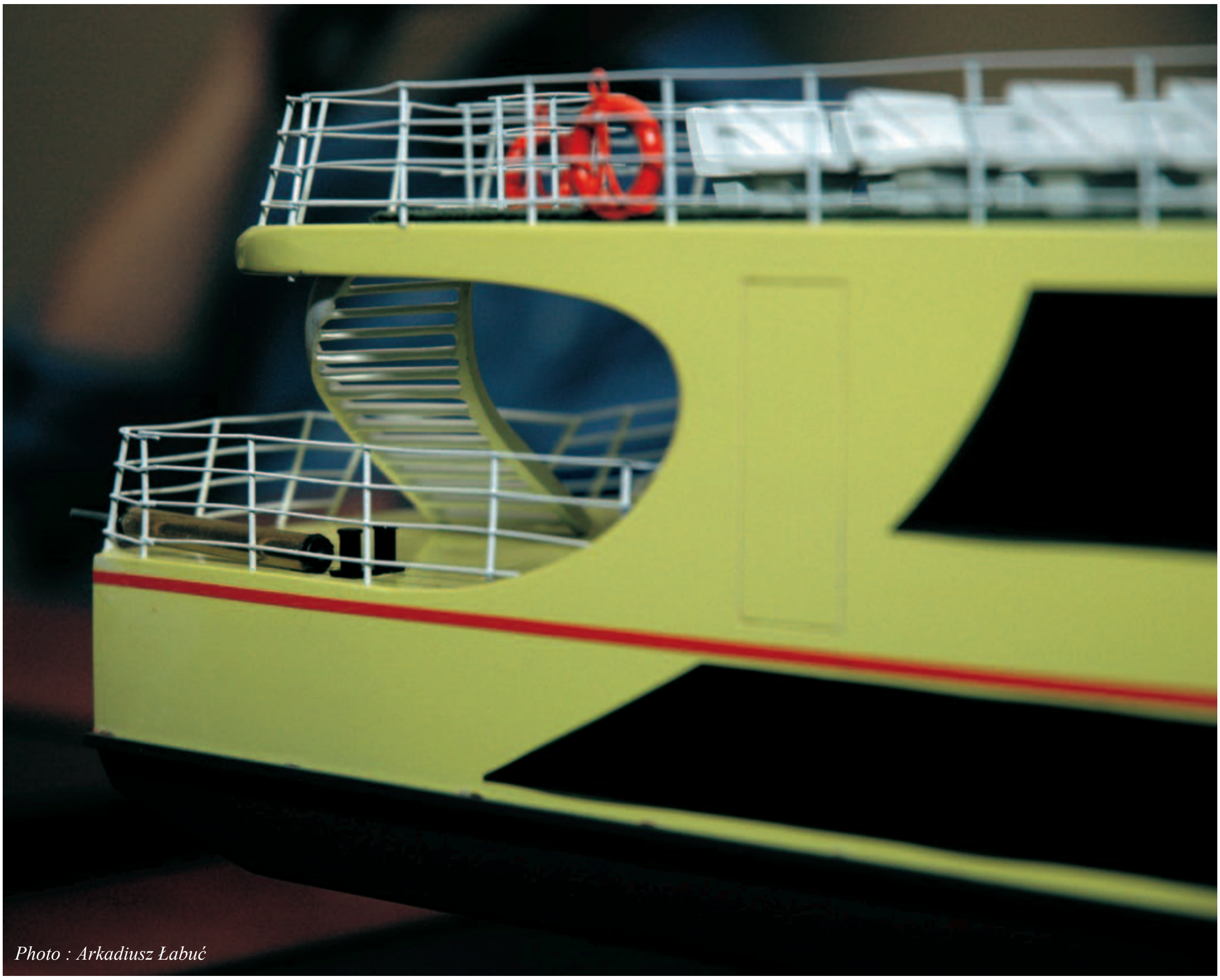

*Photo : Arkadiusz Łabuć*

# Design concept of a modular stage-stop-over terminal for inland waterways passenger transport on East-West routes

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ABSTRACT

*Key position of the Vistula in the ecological system of Poland potentially makes it possible to form an "ecological corridor" of this country, connected with the natural macro-system of Europe. The possible use of the Middle Vistula and its meridional connection with Kaliningrad region as well as Belarus and Ukraine territories concerns the rivers : Warthe, Notec Vistula, Narew and Bug Realization of functional connections between neighbouring territories will stimulate development of their economy and culture and make it possible to demonstrate their natural merits. Ecological and economical aspects of transport based on inland waterways make it necessary to formulate criteria for architectural objects to be created on waterfront areas (with taking into consideration of social, historical and location contexts, local conditions and architectural traditions).*

**Keywords** : waterfront, riverfront, inland waterways, stage-stop-over passenger terminal, Vistula, Notec, Warthe, Toruń, Elbląg, Wintering Harbour, Bazaar Island

## INTRODUCTION

Key position of the Vistula in the ecological system of Poland potentially makes it possible to form an "ecological corridor" of this country, connected with the natural macro--system of Europe. It results not only from the environmental state of the Vistula and a prevailing part of its basin but also from ecological priorities of European policy. Ecologization of the Vistula by fundamental improvement of its environment state will also valorize its cultural merits formed by the towns and historical objects located along the axis of the river and being a part of European cultural heritage [1].

The unique natural and cultural merits can form a permanent basis for developing domestic and international tourism and possibility of creating one of the more attractive tourist routes of Europe [1], that results from the fact that the above presented functions of the Vistula form a non-conflict - generating, complementary and mutually supporting complex of nature, society and economy.

And, even at the turn of 18[th] and 19[th] century the role of the Vistula weakened due to a lack of continuity in investing and modernizing technical state of its transport potential (partitions of Poland and division of the river into three parts subjected to foreign powers) it is still an European territory having waterway problems.

Its attractiveness consists in the possibility of being a meridional connection between the Vistula and Danube and a waterborne connection between the Baltic Sea and Black Sea, as well as in parallel use of the Middle Vistula for connecting the West-European waterways system with East-European one (the Pripet, the Dnieper) (Fig.1.)


*Fig. 1. Schematic diagram of the proposed East-West waterway shown on the background of the principal waterways of Europe .*

Use of the potential waterways network depends on appearance of demands for passenger traffic and goods shipping, as well as on relation of investment cost of such undertaking, including cost of opening the passage through the run-wild waterways especially those along the Bug and through the Vistula Bay. The enumerated factors are not so effective as to justify that huge investment undertaking. However it does not exclude to use the connections for tourist passenger traffic based on exceptional attractiveness of the rivers and their surroundings, as well as on elaboration of a new generation of inland waterways and coastal ships well adjusted to real conditions of the route and friendly to the environment, which is the subject of investigations carried out within the frame of the Eureka Incowatrans E!3065 project. The presented design concept of stage-stop-over terminal (Research project W,A,1/2004 and 2/2005) is one of the links of multi-directional research and design activity realized within that frame.

## MAJOR PREMISES FOR SELECTION OF STOP-OVER SITES

The possible use of the Middle Vistula and its meridional connection with Kaliningrad region as well as Belarus and Ukraine territories concerns the rivers : Warthe, Notec Vistula, Narew and Bug.

Realization of functional connections between neighbouring territories will stimulate development of their economy and culture (Bydgoszcz, Toruń, Włocławek, Warszawa, as well as Kwidzyn, Malbork and Elblag) and make it possible to demonstrate natural merits of such areas as : the National Park of Warthe Estuary, Notec and Bydgoszcz primeval forests, Kampinos National Park, Bug-valley Landscape Park, White Primeval Forests as well as historical attractions of Biskupin, Licheń and Ciechocinek, sites of ancient fortifications etc.

Ecological and economical aspects of transport based on inland waterways make it necessary to formulate criteria for architectural objects to be created on waterfront areas (with taking into consideration of social, historical and location contexts, local conditions and architectural traditions). Such approach requires also all "for and contra" arguments resulting from the new approach to problems of forming the waterfront space, to be analyzed. As water-courses are linear objects many aspects should be analyzed by analogy to land transport systems.

Waterfronts of the urbanized areas develop usually as derivatives of development of port and transport infrastructure having origins in the times of industrial revolution.

Appearance of a new architectural quality on the riverfront areas, in the form of back–up facilities supporting water transport makes it possible to create a link between river and land, and nature and man.

A partial target of the Eureka Incowatrans project in the area of architectural tasks has been to present a concept of a hotel & recreation complex of modular structure, which would be an important element of tourist traffic infrastructure both in antropogenic space of a high degree of transformation and the environment's space.

The object in question should have such structural arrangement as to make it possible to obtain an arbitrary configuration of elements, depending on functional demands and ground conditions, as well as to ensure its high architectural standard. The functioning of the complex should be realized with the use of environment-friendly technical solutions such as renewable energy sources, usage of rain water for the "grey-water" system etc. The so-designed architectural object would fulfill the role of a back-up facility for a floating unit having passenger shipping function, designed within the design & construction part of the project, e.g. in the form of segment passenger ship.

Trips of passenger ships consist of a few stages with stop--over in some points of the route, selected with taking into consideration the following criteria :

★ stop-over frequency required by technological factors : to take fuel, discharge various operational substances for their utilization outside the terminal, as well as to carry out minor overhauls and repairs of floating units
★ degree of attractiveness of a given location for potential tourists
★ possible use of existing or planned port infrastructure
★ interest and engagement of local authorities in building such stop-over terminals and their back-up facilities with a view of creating new workplaces for local population.

Hence in the project's scope
have appeared the following design items [2] :

❋ technological solutions for ensuring possibility of ship mooring and also supplying it with operational materials, as well as mooring a local transportation ship (passenger river boat)
❋ a hotel part which, apart from lodging services, should provide : boarding, organizing common entertainment events etc
❋ sport & recreation program – realized both in the terminal's accommodations and the open air (including a swimming pool with appropriate infrastructure)
❋ tourist attractions such as one-hour coach excursions for sightseeing a given region; trips by a river boat or pusher of the designed ship (lasting 10 hours in total at the most, directed to places of interest of a given region, available by water transport means).

## DESIGN CONCEPT OF A MODEL MODULAR STAGE-STOP-OVER TERMINAL

In choosing a place for location of the stage-stop-over terminal has been taken into account possible use of existing port infrastructure and attractiveness of the terrains surrounding the considered inland waterways system from the point of view of their use for purposes of inland water tourism not only in the scale of this country.

Hence, preliminary investigations in that area took into account two locations : in the surrounding of Toruń and that of Elbląg.

The choice of Toruń has been told by its location in the north part of Polish inland waterways which, going from Berlin through the Oder, Warthe, Notec and Vistula, leads northward to Gdansk, and further via Vistula Bay and Elbląg, to Kaliningrad.

Its suitable railway and road connections in north-south and east-west direction as well as the existing port basin (Timber Port) provide a chance for shipped cargo to be reloaded onto multi-modal transport means in the surrounding of Toruń and to be sent in the direction of Belarus and Ukraine.

Moreover, in this town there is a suitable post-industrial basin which temporarily serves as a wintering harbour for river vessels.

The choice of Toruń as a model of using inland waterways for domestic and foreign water tourism purposes and the place of about 340 cultural heritage monuments is consistent with the intentions of its local authorities.

According to the description of development projects of the Vistula's embankments, possible modernization and erection of new tourist infrastructure objects to increase tourist attractiveness of the town and neighbouring waterfront terrains would make it possible to create an additional area which could constitute a "green heart" of the town whose *"attractiveness will systematically grow by developing there functions resulting from monitoring the increasing needs of its inhabitants…the idea of creation of such open recreation centre in which cycle tracks, walking paths, resting places adjusted to handicapped person needs, water tourism harbours, water sport areas etc, will be located."*

Basing on the local study on directions of the site planning of the town of Toruń, as well as on development its pro-ecological transport systems, the authors have selected the site for location of the stage- stop-over terminal, placed in the terrain neigbouring the so-called Wintering Harbour (Fig.2).


***Fig. 2.*** *Functional ideograph of site planning for the area of Wintering Harbour in Toruń .*

It is the site having suitable connections with main directions of road transport, not very far distant from the Old Town - the main attraction of Toruń, located in the direct neighbourhood of the existing port infrastructure used for wintering the barges, which may be used for mooring the segment hotel ship to overhaul it and for receipt of any operational substances to utilize them outside the terminal.

The choice of the site would make
the designed ships possible :

- to moor along the existing quay of the Vistula bank, to disembark a part of passengers for a short stop-over and lodge them at the designed terminal
- to depart with the remaining passengers onboard, making use of their cabins during the stop-over, and to arrive at the Wintering Harbour, to moor in the direct vicinity of the recreation & hotel terminal taking over boarding functions for 2-3 days necessary for developing a tourist program.

Owing to the selected location both groups of tourists : that lodged on land and that onboard the ship would have oportunity to make use of the back-up facilities of the terminal, being apart by only a short walk from the Old Town and the hotel currently under modernization, based on the former Navy High School's buildings, which could be an alternative land-based lodging place for passengers.

The choice of such location was told, apart from the fact of favourable location of the Wintering Harbour and a short distance from the Old Town area, also by an attractive view on the reserve Kępa Bazarowa (Bazaar Island) as well as on the remnants of the 15$^{th}$ century King's Castle (Zamek Dybowski).

If at the Little Vistula estuary on the Bazaar Island to erect a small harbour is provided it will be possible to extend the tourist offer by sightseeing this place.

To this end, a project of refurbishment and activation of the Castle remnants (agreed with Municipal Conservator of historical objects) has been provided for, with a view to locate there a museum with a boarding back-up and exclusive hotel apartments as well as with a viewpoint toward the Old Town, an interesting old residential area and relic fishery houses.

Maintaining the natural character of the Bazaar Island one has provided for to mark out walking paths along the island side, which would lead - beginning from the Dybowski Zamek through a footbridge over the Little Vistula - to an existing viewpoint.

Modernization of the viewpoint by giving a new structural form to it, would make it possible to demonstrate wide panoramic view of the Old Town, and the planned erection of the river harbour would provide a waterborne connection with the left-hand side part of the town with the Philadelphia Boulevard, simultaneously being an alternative to the bridge connection, and the connection of the Podgórze area with the City (an extension of the road along the view axis up to the railway sites).

In Fig. 3 and 4 are presented the elaborated model modular hotel objects of the stage-stop-over terminal, having light-

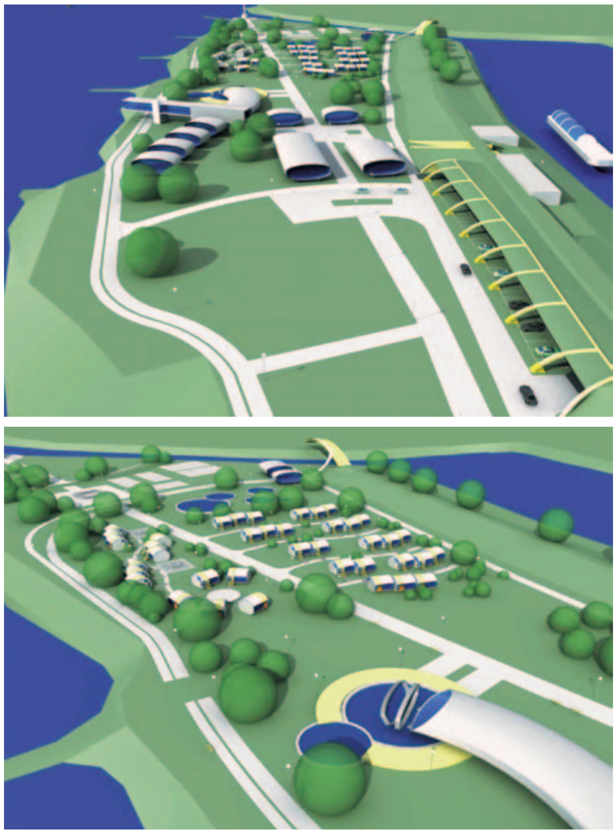

***Fig. 3, 4.*** *Visualization of the model option of the modular terminal located in the area of the Wintering Harbour in Toruń (authors : Felski B., Ptaszyński M.) .*

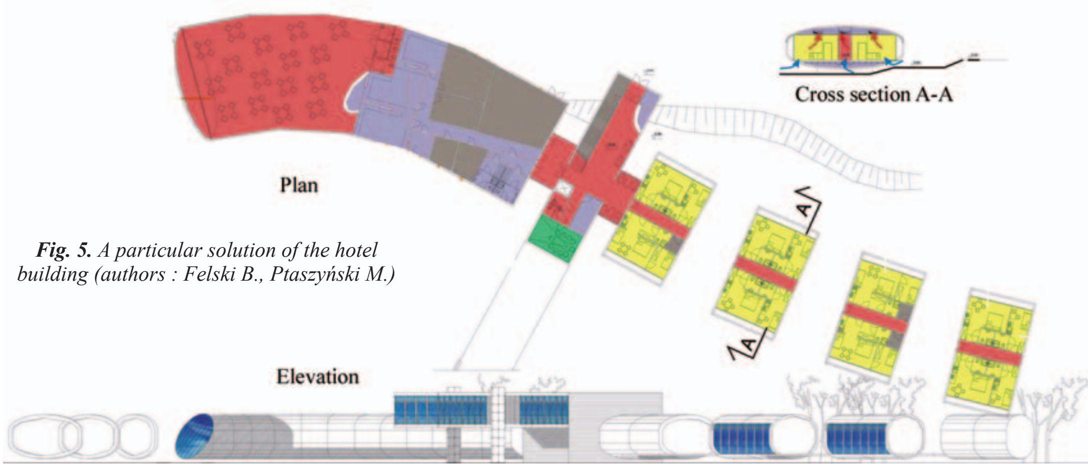


***Fig. 5.*** *A particular solution of the hotel building (authors : Felski B., Ptaszyński M.)*

-weight structure and ensuring possibility to be composed in many variants, arbitrary situations and spatial forms and to be located at arbitrary sites; they are so designed as to be independent of local ground conditions hence it is possible to place them over the ground level (Fig.6), this way risk of failure at a high river stage would be excluded.

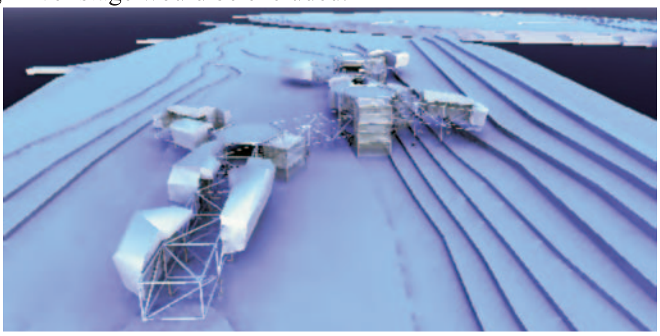

***Fig. 6, 7.*** *A variant solution of the modular stage-step-over terminal (concept draft by Szumilas A.)*

Elaboration of the identical analysis of possible location of a stage-step-over terminal for the designed inland waterways ship, with regard to the Vistula Bay area, made it possible to select the town of Elbląg as a successive centre which - like Toruń – fulfils requirements for possible use of the existing port infrastructure (Fig.7) as well as attractiveness of the town itself in the aspect of being a tourist product (Fig.8).

*Fig. 8. The historical architecture substance of the Elbląg city, considered as a potential tourist product*

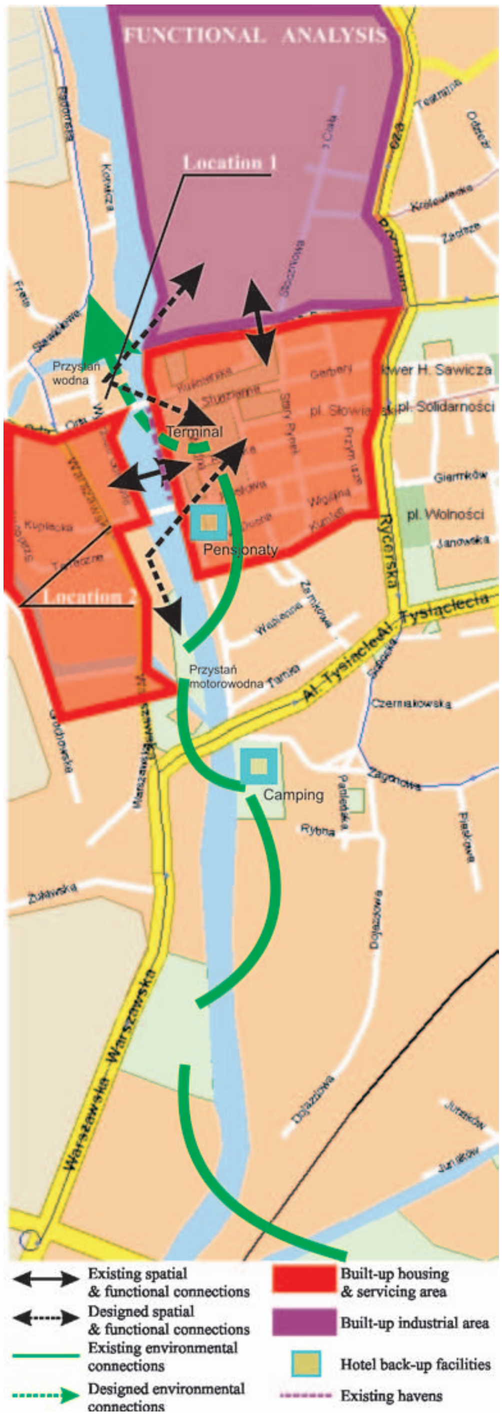


***Fig. 7.*** *The areas selected as potential locations of the stage step-over terminal in Elbląg*

In the area of the town developed on the basis of the river Elbląg two potential locations have been chosen in direct vicinity of the town centre, on the left-hand side of the water-course. Because of the specificity of the Elbląg tourism centre both the locations have been analyzed on the basis of a less extended set of additional functions as compared with that for Toruń. Such decision is justified by the following factors :

- intermediate or final character of the terminal;
- lack of crossing the water-course corridor by other inland runs;
- a relatively small area for potential use;
- partly existing infrastructure : inland harbour, hotel back-up in the town.

## FINAL CONCLUSIONS

The above described locations, in spite of different contexts of local architecture and specific conditions resulting from the proposed set of functions, are associated with the common priorities such as :

- The need of activation of the areas which – after economical transformation – became degraded (the chaotically developed areas of low-standard buildings, neighbouring with port & industrial terrains). Low esthetic merits lowering the municipal space quality, detrimentally influence local development of the areas in question.
- Use of the potential of the areas in question resulting from their short distance from the city considered as a centre-creating and culture-creating factor, as well as of the river as an element which makes tourist development to be a possible way for local population activation. An additional advantage of the discussed locations is accessibility to their underground infrastructure, that makes investment cost lowering possible and this way their attractiveness increasing - from the point of view of potential investors.
- Creation of the modern architecture of high esthetic merits, with the extensive use of the technical solutions which enable to design the objects to function on the basis of renewable energy sources, biodegradable materials and a low energy outlay during their production. The proposed foundation of the buildings over ground level makes it possible to prevent biologically active areas from degradation and to make the buildings independent of specific ground conditions which result from the vicinity of water environment.

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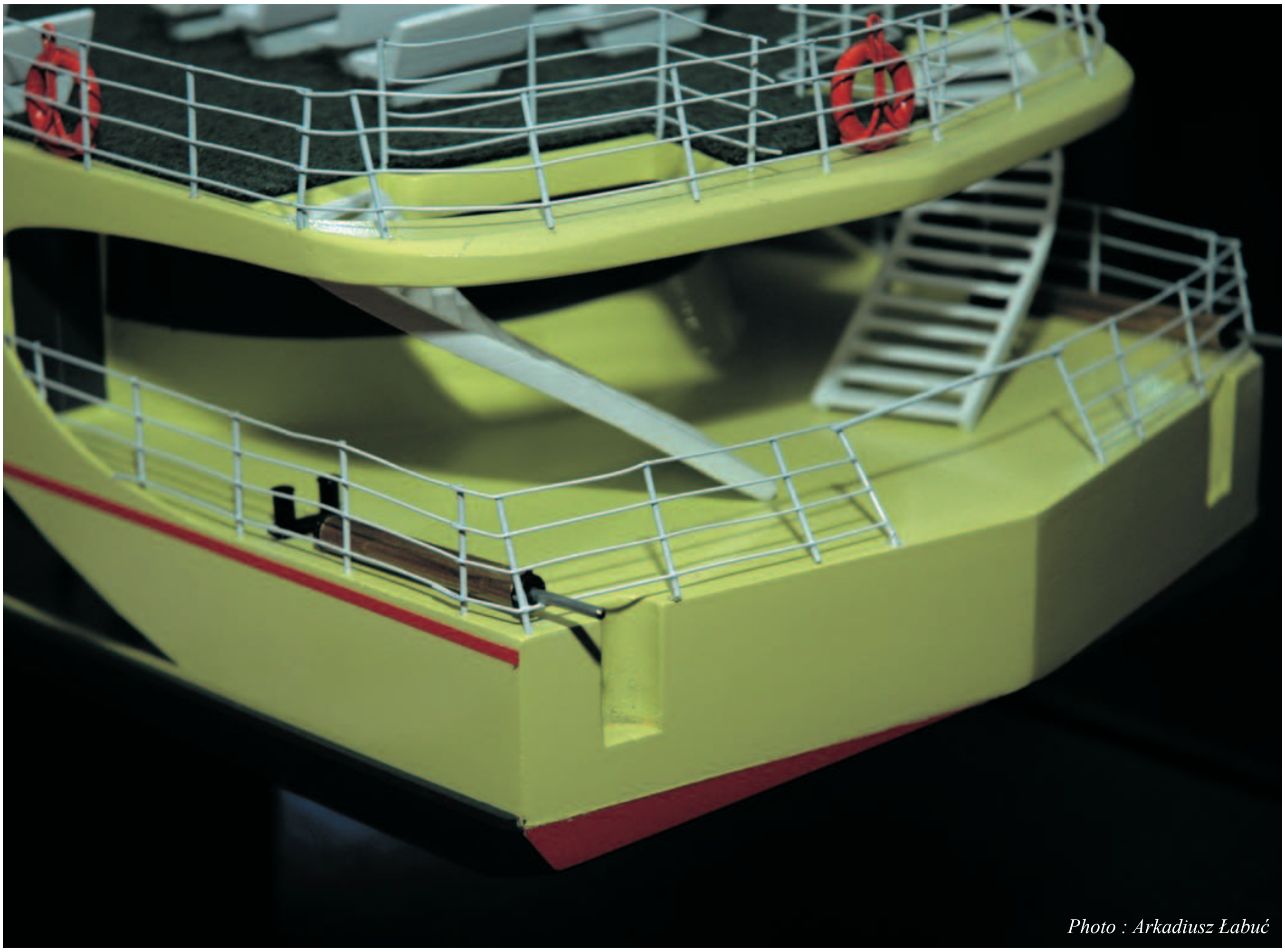

*Photo : Arkadiusz Łabuć*

# Geographic Information System (GIS) tools for aiding development of inland waterways fleet

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ABSTRACT

*The information aiding of planning and operation of inland waterways fleet covers many items among which problems associated with analysis of existing waterways are especially important. Such analyses concern mainly their navigability features (from the point of view of elaboration of design assumptions for floating units) as well as planning land-waterborne transport links. Range of input data for the analyses is very broad hence they can be next used for managing the waterways. This paper presents a concept of forming the GIS data model for the purposes of INCOWATRANS project with taking into consideration the existing data and their possible usage by the administration of waterways and their other users.*

**Keywords** : polish waterways, inland shiping, proposal of navigating system

## INTRODUCTION

Data bases elaborated for the purposes of INCOWATRANS project are mainly aimed at providing tools and data for spatial analyses covering course and bathymetry of waterways, leading to generation of correct design assumptions for inland waterways fleet. However a preliminary analysis already shows that the structure and content of such data base is so broad that its limitation solely to that aim would be a loss of time and money. The data necessary for realization of the main aim can be successfully applied also to other tasks provided they could fulfill certain requirements. To this end were defined potential additional tasks of such base, its users and resulting requirements first of all concerning its structure which should be made ready for additional data input in the future without their modification and excessive increase of labour outlay for elaboration of the data model itself.

To comply with existing standards is also important in order to make it possible to integrate the data base in question with already existing systems.

## DESIGN ASSUMPTIONS FOR THE DATA BASE

The expanded GIS data base can contain many additional functions going beyond analysis of navigability features of waterways shared and maintained by many users simultaneously. The most potentially interested in using such tool can be the following :

- ship owners (operators) – (their land staff and ship crews)
- producers (constructors) – (building and repair companies engaged in building waterway infrastructure)
- supervisors (state and local administration, ship classification institutions, insurance companies, engineering supervision)
- scientific research and didactic institutions
- other commercial and non-commercial users (tourist agencies, forwarding agents etc).

The most important functions of the base desirable from the point of view of the potential users cover the following :

- Inventory control functions
  - Inventory control and aiding the management of waterways infrastructure resources
  - Inventory control of waterways land-surroundings
  - Aiding the financial analyses and rationalization of infrastructure maintenance costs
- Analytical functions
  - Running the spatial analyses associated with ship traffic – – mainly concerning navigability of waterways and resulting requirements for floating units
  - Running the spatial analyses aimed at planning the inland navigation maintenance and development as well as its infrastructure (e.g. disclosing "bottlenecks" and planning modernization)
  - Running the network analyses aimed at optimization of land-waterborne transport.
- Interface functions
  - Integration of existing distributed data
  - Accessing the existing data in internet in a coherent way, with taking into account priorities and access rights of particular users
  - Ensuring a uniform mechanism of access to all necessary data for all interested in waterways usage (including non-GIS data, e.g. technical documentation of hydro-engineering facilities or floating units)
- Navigation functions
  - Improving safety of navigation on waterways by real – – time monitoring current navigation situation to avoid collisions and to support environment protection and emergency management
  - Tracking positions of ships and planning their navigation
  - Accessing information on navigability state resulting from water level state.

From the so defined functions of the base technical requirements also result for the entire system which should definitely ensure :

- Effective data collecting which guarantees access to coherent and updated information.
- Comprehensive analysis of collected data on the basis of which it would be possible to generate knowledge useful for their users.
- Information turn automation which covers a.o. :

- Control of access of particular users to information and permissions to put the data into the base
- Control of data modification and validation level of modification (what to modify itself a user is authorized, about what he is to inform other users, for what and from whom he is to get acceptance)
- Control of propagation of messages on modifications (who should be informed about modification and in which way)

♦ Processing the data of different kinds, covering :
- CAD technical documentation (technical drawings and 3D models)
- GIS documentation (of waterways infrastructure)
- Text documentation (procedures, protocols etc)
- Multi-medial documentation (graphic, audio, film, measurement data files etc)
- Database files (catalogues of products, material properties etc)

## ARCHITECTURE OF THE DATA BASE

Two kinds of problems associated with fleet and waterways management, which require different informatics tools to be used, can be distinguished as follows :

☆ Problems associated with object's structure – the domain of Product Lifetime Management (PLM) data bases
☆ Problems associated with dispersion of geographic objects – the domain of Geographic Information Systems (GIS).

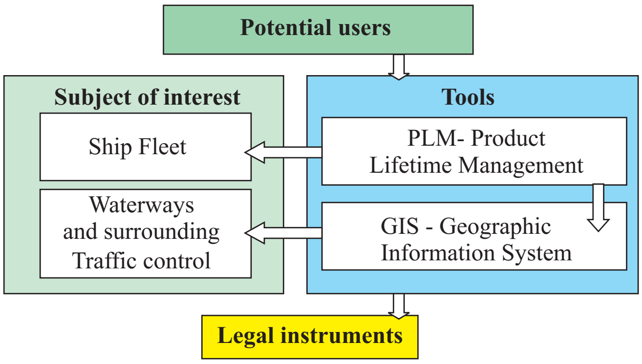


***Fig. 1.*** *Structure of issues covered by data base .*

The data base for INCOWATRANS project connects both approaches by means of integration of GIS and PLM tools into one coherent system ensuring user access to all data in a way which best corresponds with their character.

The next important issue, the first element of data base structure is a mode of access to data. In order to ensure up-to-date information the distributed structure was chosen. It is characterized by uniform access to data on logic level though their physical location may be different, and by avoiding redundancy of data.

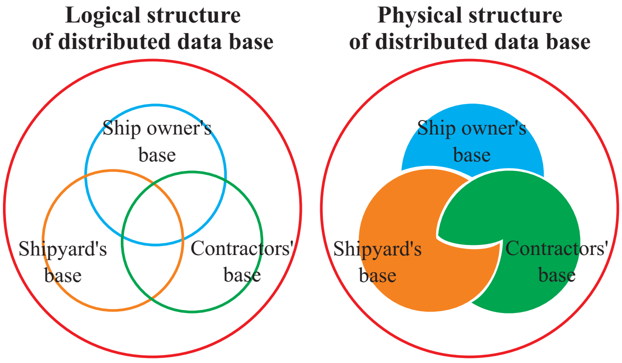


***Fig. 2.*** *Structure of distributed data base .*

## GIS DATA

From the very beginning it was assumed that the base in question will be built on the official data accessible in official data bases and enabled for research purposes at no charge or preferential conditions. Hence selection of data is crucial for GIS model structure. Models and data quality of a few bases were preliminarily analyzed and as a result the base of Map of Hydrographic Division of Poland (MPHP) and the base of General Geographic Data (BDO) were selected as those potentially most useful.

## MODEL ANALYSIS

Model analysis of the selected data bases is aimed at answering the question whether they are conceptually coherent and may be used to build an integrated GIS covering shipping problems and which elements of both the bases may and should be used to this end.

The MPHP base contains the data on surface waters in Poland, having the accuracy equivalent to a map in 1 : 50 000 scale. Such accuracy of data makes their using for navigation purposes possible. Next, their structure enables to conduct network analyses (all water-courses have defined axes and nodes in junctions). A drawback of the MPHP data is the lack of attributes determining navigability of water-courses.

The BDO base was elaborated with the accuracy corresponding with a map in 1:250 000 scale. Hence it is less precise, however apart from layers describing waters it contains several layers of the so called "background" which describes land surrounding waterways. Additionally, the water-courses have defined attributes describing their navigability however in the way not complying with the Act on Inland Navigation. In Tab.1. the most important criteria of the model in question and BDO and MPHP bases are compared.

***Tab. 1.*** *Comparison of content of BDO and MPHP base .*

| Content | INCOWATRANS base | MPHP base | BDO base |
|---|---|---|---|
| Waterways | Yes | Yes | Yes |
| Water-course network | Yes | Yes | Yes |
| Land - water - course network | Yes | No | Yes |
| Navigability | Yes | No | Yes |
| Compatibility with UZS | Yes | No | Yes |
| Roads | Yes | No | Yes |
| Railways | Yes | No | Yes |
| Ports | Yes | No | Yes |
| Hydro-engineering objects | Yes | No | Partial |
| Navigation obstacles | Yes | No | Partial |
| Compatibility with TBD | Partial | No | Partial |
| Compatibility with RDW | Partial | No | No |
| Scale | 1 : 50 000 | 1 : 50 000 | 1 : 250 000 |
| Coordinate frame | WGS84 | WGS84 | WGS84 |

The optimum solution seems to be connection of the MPHP layers describing water-courses and reservoirs and the BDO "background" layers. For such data integration speaks the fact that both the bases were elaborated with the use of the same frame of geographic coordinates, namely WGS84.

## ANALYSIS OF DATA QUALITY

Assessment of data quality is usually very important for estimation of labour consumption for their implementation, and it covers several aspects :

- Correctness of geometrical and attribute data
- Completeness of geometrical and attribute data
- Topological coherence of water network and land-water network within a given data base as well as at the points of contact of the bases to be integrated.

To ensure an efficient and reliable assessment a few procedures and techniques of quality control were applied. Some of them were of organizational character, another were based on available informatics tools. The most important are the following :

- Automated control realized by means of the tools available within GIS software (e.g. coherence control of topological network)
- Automated analysis of data base content (e.g. searching for nonsense quantities : odd values, exceeding limits, control whether all attributes are determined, whether appropriate error codes are introduced for those not determined etc)
- Manual control of the GIS on the basis of spot check of well documented areas (e.g. basins of ports of Gdańsk and Szczecin)
- A part of metadata attributes was shifted from the level of class description to that of records (e.g. date of input, date of approval, putting-in person). Due to this a better control over quality of input/ modified data was achieved.

Correctness assessment of geometrical data was performed only for water-courses and reservoirs. It consisted in simultaneous displaying the hydrological layers of BDO and MPHP bases and their visual comparison. The observed differences resulted from the different scales of the bases and consisted in simplification of shoreline on BDO layers against that on MPHP layers, which seem unimportant however. The maximum shifts of characteristics points did not exceed 10 m. As in both the cases the data were introduced independently the mutual coherence of water-courses and shorelines demonstrate that the data stored in both bases are correct.

Assessment of completeness of the data covers only those connected with water-course navigability. The assessment was performed by means of :

- Comparison of content of the data bases with maps of Gdańsk area (the lack of about 20 landing stages and 10 other hydro-engineering objects was stated)
- Analysis of data base content as regards filling base records with all attributes (the common lack of many important attributes, e.g. name of port/landing stage is observed only for a few biggest port facilities, also an error code description is lacking in the case of a lacking value of attribute)
- Analysis of base structure completeness and possibility of its supplementing by means of existing data. The lack of objects of the type "MOST" in the BDO base may be given as an example. Such objects can be indicated by pointing out sections of roads and railways having the attribute "PRZEBIEG" of the value "PO MOŚCIE".
- Analysis of completeness of definitions of particular classes of objects against demands of the elaborated model and possibility of their extending. As an example the height above water level for bridges and electric transmission lines crossing water-courses, and current speed for selected river sections can be given. Many lacks were here revealed and their detail description is contained in the report on the modified data model.

In the case of the topological coherence control the following was assessed :

- Topological coherence of water-course networks within MPHP and BDO bases.
- Topological coherence of water-course network and land-water-course nodes and land junction network within BDO base (in MPHP base there is no land objects).
- Topological coherence of water-course network of MPHP base as well as land- water-course nodes and land junction network within BDO base.

The topological coherence was investigated by means of relevant tools contained in GIS GeoMedia system. Sporadic lacks were revealed in junctions between water-courses covered by MPHP base (Fig.3) as well as lacks of junctions of the type of water-course/port, port/road as well as port/railway,which can be deemed typical for BDO base (Fig.4). Therefore without any further control was assumed the lack of coherence between the water-course network of MPHP base and the land network of BDO base. Additionally, to include sea ports into network analyses some artificial sections of sea waterways to connect the ports with inland waterways network, should be added.

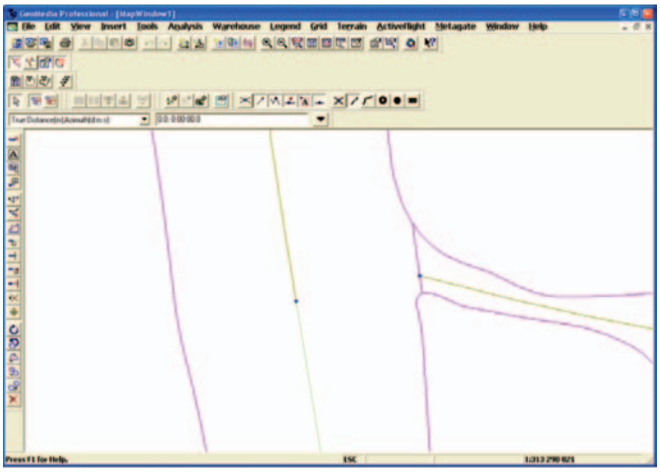

*Fig. 3. An example of lack of junction between water-courses represented in MPHP base .*

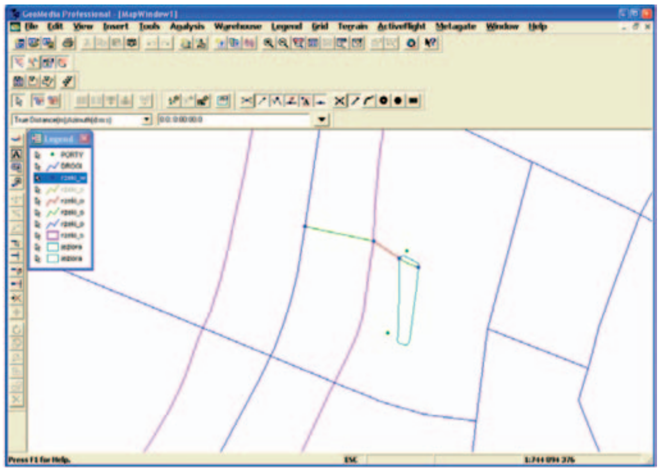

*Fig. 4. An example of lack of coherence between water-course network and road network represented in BDO base .*

## DESCRIPTION OF GIS MODEL

For elaborating the GIS data model were established several principles and guidelines resulting from provisions of Polish legal acts {Act on Inland Navigation (UŻŚ), Topographic Data Base (TBD)} and European ones {General Outline Water

Directive (RDW)} as well as from structures of the existing data bases whose data have to be used in building INCOWATRANS data base.

The most important are the following :

- ★ All types of objects of the same functional features (i.e. those described by the same attributes) are located in one class but other layers. For instance the class "Pipeline" covers the layers : "Water pipeline", Gas pipeline", "Oil pipeline".
- ★ A part of attributes resulting from location of an object on a map is duplicated within the base structure. It results from possible inaccuracies or ambiguities e.g. in which way should be territorial membership of an object located on the border of two administrative regions qualified ?
- ★ Water-courses are divided into sections of constant features. Additional division points are assumed in the points where nodes are located even if the water-courses in question do not there change their properties.
- ★ As use is mainly made of existing data (MPHP, BDO) and easy integration of the elaborated base is aimed at, only new classes of objects are defined (not included in MPHP and BDO) or the definitions of existing classes are extended by navigability features (without any changes of the existing ones even at the expense of redundancy of some attributes).

Model class hierarchy can be defined on the basis of a kind of geometrical representation of objects (Fig.5) or their functions. The presented scheme of the model contains only the classes introduced to be used solely in shipping model, and not defined in the MPHP.

## DESCRIPTION OF PLM MODEL

PLM base serves for effective collection of data on infrastructure objects of waterways (and ships) in the way which is not possible in GI- systems which impose some limitations on the depth of hierarchy of classes and types of objects (limited to simple 2D geometrical objects). In PLM system an arbitrary object structure of an arbitrary depth of class nesting in model hierarchy can be modeled. In the current stage of implementation of the system the PLM structure limited only to floating units was elaborated. It results from the classification of ships adopted by most ship classification institutions, shipyards and authors of CAD software for shipbuilding industry.

Important is that in the same way the data base for ships and that for hydro-engineering objects can be built.

In Fig. 6. the hierarchy of PLM model classes is presented. It can contain an arbitrary number of nested levels of subsystem and subpart classes. The main ship systems cover the following :

✦ Hull ✦ Piping ✦ Cabling
✦ HVAC ✦ Machinery ✦ Equipment.

The example structure of one of the systems (Hull) shown in Fig.4, contains several subsystems :

⅄ Geometry ⅄ Structure ⅄ Material.

## SUMMARY

- ❍ The structure of GIS model coherent with description of features of navigable inland waterways was presented together with the premises laid down during its elaboration. All efforts were made to achieve the elaborated structure complying with formal and practical standards being in force in the domain of GIS modelling, especially in water economy.
- ❍ The range of elaborations which have been so far worked out within the frame of building the GIS base intended for INCOWATRANS project, contains main conceptual investigations associated with the elaboration of the data model and its implementation. They contain the following items :
  - ⌘ Control of inventory and analysis of legal acts with a view to building GIS model.
  - ⌘ Elaboration of the preliminary GIS data model covering various functions of the model such as :
    - ⅄ analytical
    - ⅄ inventory
    - ⅄ interface
    - ⅄ navigation.
  - ⌘ Acquisition of the existing data (BDO, MPHP).
  - ⌘ Conversion of the data into an editable form which makes their extension by means the available GIS tools (GeoMedia 5.1) possible, as well as split of the data which makes their handling easier and processing within the network also possible.
  - ⌘ Consultations of the data base design assumptions with its potential users (Water Economy Office inWarszawa, RZGW in Gdańsk, Institute of Meteorology and Water Economy (IMGW), CODGiK, Port of Szczecin).
  - ⌘ Test implementation of the model and conformity tests of software, data and the assumed model of usage of the data base (the distributed data base model).

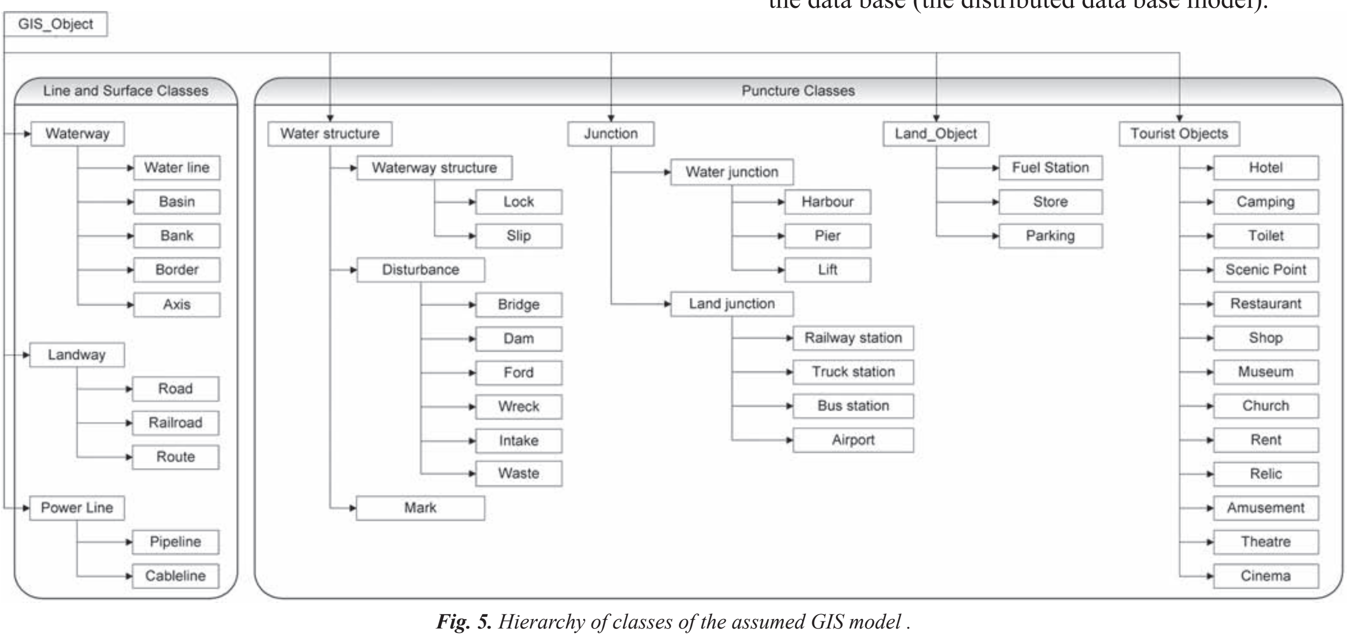


***Fig. 5.*** *Hierarchy of classes of the assumed GIS model .*

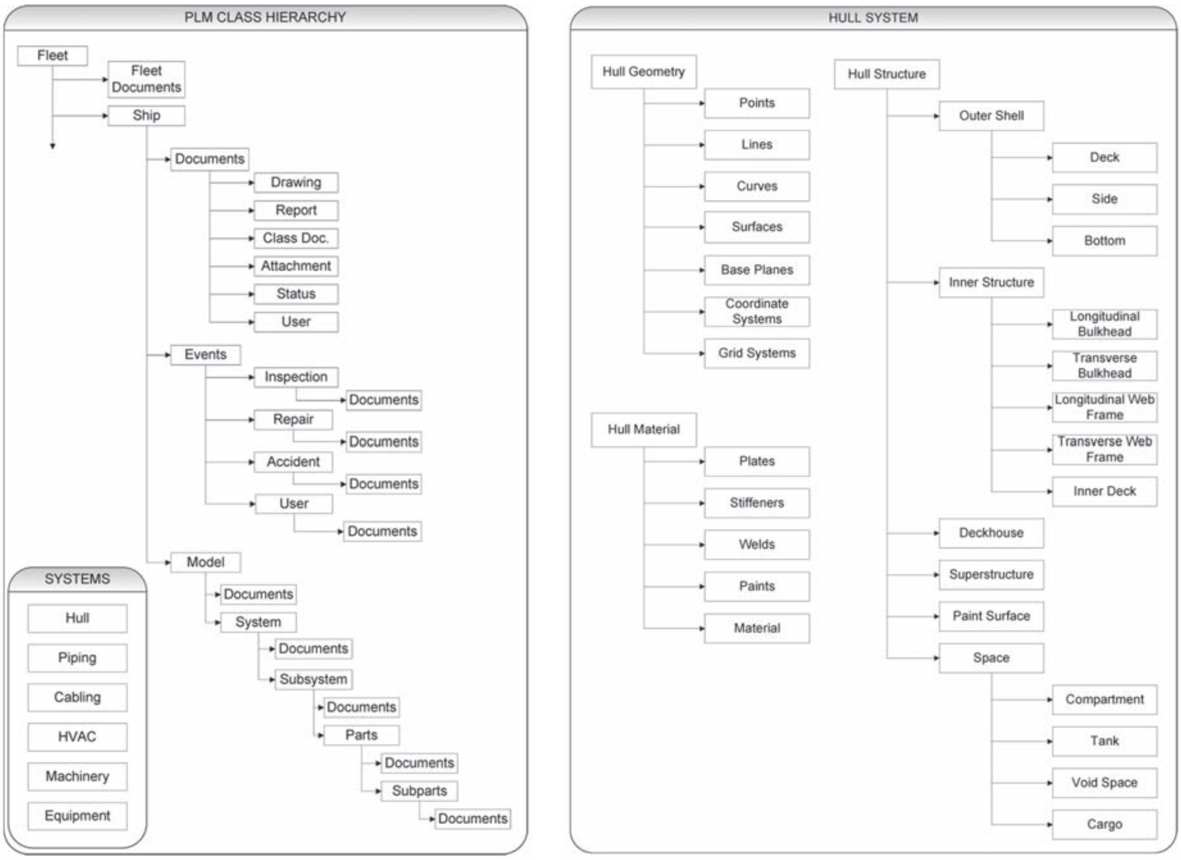


*Fig. 6. Hierarchy of classes of PLM system model for ships. Hierarchy of classes of HULL system .*

- Amendment of the design assumptions and the model on the basis of the two preceding points so as :
  - to make use - at the possible greatest extent - of the existing data of the MPHP and BDO,
  - to maintain the present structure of data, which – after removal of introduced extensions - will facilitate integration of the new data and corrected ones taken from the BDO and MPHP,
- Elaboration of an application program for automatic acquisition of data on water-level indications from IMGW internet portal, as well as elaboration of a simple interpolation model of water levels at particular sections of rivers.
- Digitalization of selected documents of water objects to implement PLM base and test the interface function of GIS base.
- Elaboration of “taken from nature” documentation for selected sections and objects,
- Elaboration of inventory control of the internet data sources together with their storage in a local server.

Full implementation of the model in question necessitates to realize several additional tasks as follows :

- Harmonization of the data stored in the BDO and MPHP in the range of roads and water- engineering objects (e. g. shifting the ports up to the water-course nodes, extending the roads up to the ports etc)
- Comprehensive verification and correction of the BDO and MPHP data in order :
  - to remove errors from BDO in the range of attributes and location of water -engineering objects
  - to add several water - engineering objects on the basis of maps and aerial and satellite photographs.
- Acquisition of shipping and bathymetric data and their addition to the bases.
- Elaboration and implementation of procedures for data input and update (e.g. by means of reporting errors by users via internet).
- Solution of formal and legal problems associated with making available to third parties the data acquired for the project’s purposes.

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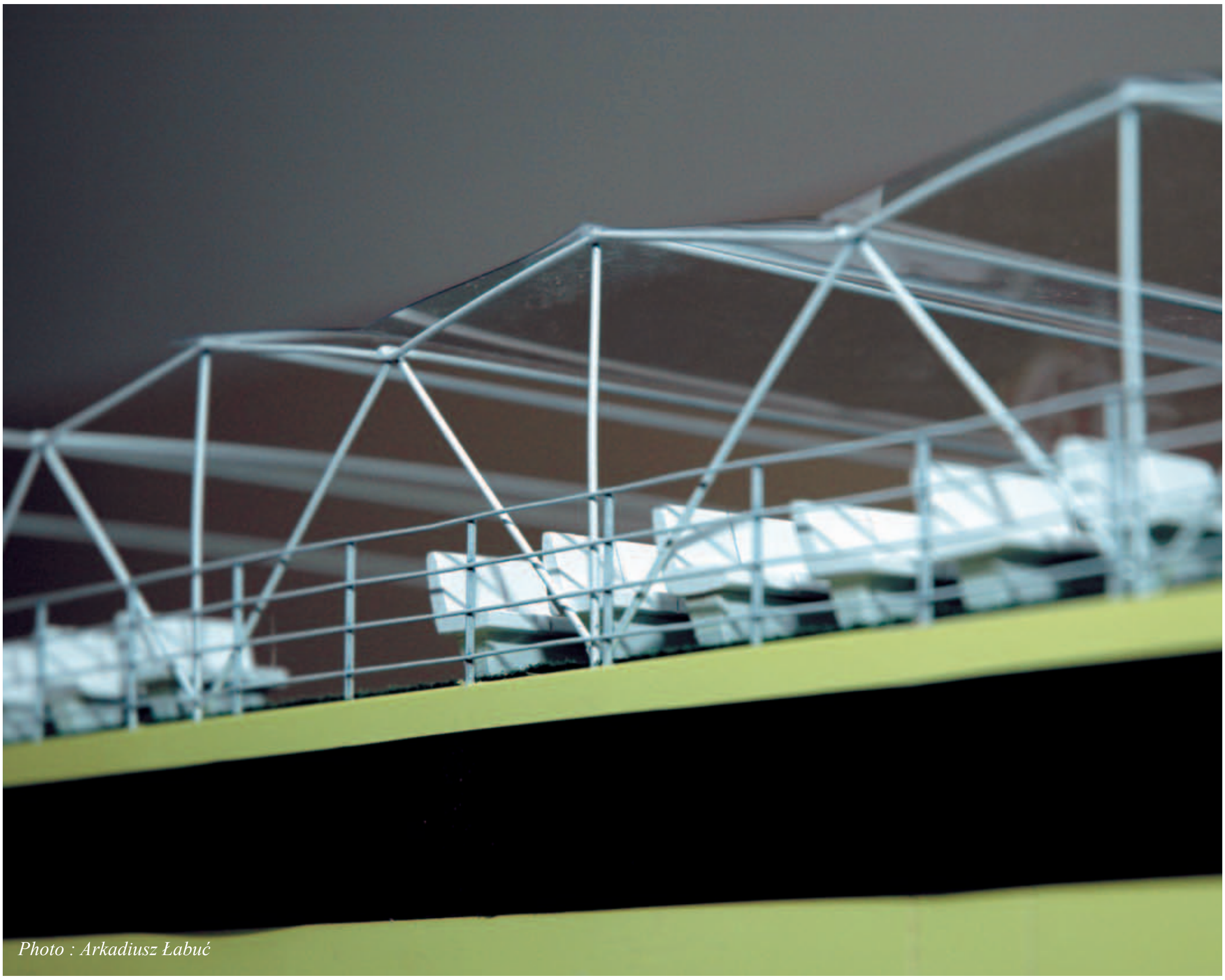

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