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This journal is devoted to designing of diesel engines, gas turbines and ships' power transmission systems containing these engines and also machines and other appliances necessary to keep these engines in movement with special regard to their energetic and pro-ecological properties and also their durability, reliability, diagnostics and safety of their work and operation of diesel engines, gas turbines and also machines and other appliances necessary to keep these engines in movement with special regard to their energetic and pro-ecological properties, their durability, reliability, diagnostics and safety of their work, and, above all, rational (and optimal) control of the processes of their operation and specially rational service works (including control and diagnosing systems), analysing of properties and treatment of liquid fuels and lubricating oils, etc.

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THE MAINTENANCE OF THE SHIP TURBINES WITH THE APPLICATION OF THE KEY PERFORMANCE INDICATORS

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Abstract

The article presents the aspects of the application of the maintenance key performance indicators (KPI) in the management of the operation of the ship turbines on the floating vessels. There have been indicated the significant measurable technical, organisational and economic features of the management systems which determine the decisions related with the turbine maintenance in the good usability condition pursuant to the intended criteria. The indicators selection methods have been classified and reviewed. There has been made an attempt of the interpretation of some of their selected values. The reference has been made to the application of the indicators in the Computerised Maintenance Management Systems (CMMS) and the application of these systems in the control processes for the ships' power systems.

Key words: *Performance indicator, gas turbine, steam turbine, KPI, power system, floating vessel*

1. Introduction

The operation of the power systems of the floating vessels is nowadays a process subject to more and more specific monitoring. The contemporary supervision, measurement, recording and data acquisition/archiving systems, the faster and miniaturised computers and the universal and open software offer the appropriate conditions for that purpose. The data acquired become a valuable information resource, and their identification and analysis allows to rationalise the control of the operation process and improve the performance of the power systems [1].

The maintenance of the power systems on the floating vessels refers to the diversified activities aiming to maintain the functional usability of machinery, equipment and installations. The maintenance is a concept frequently encountered in the technical literature related to the operation theory and practice [1, 2, 3, 4, 5, 6, 7, 8, 9]. At times the concepts like operation maintenance or maintenance in operation are used as well. All these issues mostly refer to the behaviour of the

technical objects in the usable condition and readiness for use at the expected level and in due time. The maintenance comprises the activities both directly related with the technical object and the supporting activities, usually related with the object of operation indirectly through the activities within the management, information, logistics etc. The maintenance consists of the following activities [2, 3, 6]:

- technical service (repairs, overhauls, adjustments etc),
- logistic services/logistics of the spare parts and usable media,
- information acquisition on the objects of maintenance,
- the management of the knowledge and technical personnel,
- establishment and implementation of the periodical service procedures,
- diagnostics for the operation needs.

Maintenance is, next to the using, a key operation element, which in terms of the presently emphasised needs of the ships and other watercraft owners, requires precise monitoring for the purpose of the planning and the execution of the individual tasks in the satisfactorily efficient manner. The efficiency or in other words performance can be understood in different ways depending on the branch and conditions applicable for its evaluation. In the operation systems this is a property to satisfy the requirements in various terms: of reliability, economic, quality, capacity, power etc. [5]. The essence of the performance evaluation is the determination of the probability to maintain by the system of the nominal outputs during the use [4]. The performance of the operation systems is thus determined in the categories of the results achieved or expected [6] combining the applicable information groups from the selected areas of the operation and maintenance of the technical objects.

The lifecycle of the technical objects is divided into four stages which chronologically are as follows:

- stage I – the determination of the needs and designing,
- stage II – preparation for the operation, transportation, assembly, commissioning,
- stage III – the operation,
- stage IV – utilisation (post-operation use).

For the marine power plants at the stage of the ship design (I) there are determined the factors related with the implementation of the basic and auxiliary functions of the technical objects in the power systems:

- related to the mass and overall dimensions (unit mass and unit overall dimensions of the engines, machinery, equipment, installations and the entire engine rooms – of particular usability at the design stage,
- related to the technological aspects,
- related to the standardisation conditions,
- related to the unification qualities,
- related to the ergonomical features,
- related to the permissible vibration level in the engine room,
- related to the noise level,
- related to the microclimate conditions, i. e. temperature, relative humidity and air pollution.

At the stage of the implementation and operation (stages II and III) the need of information acquisition is manifested to enable the description of both the use and the maintenance of the individual elements of the power systems. Pursuant to the conducted measurements of the operation properties of the machinery and the equipment installed on watercraft, organisational and economical conditions, there are determined the significant information groups which are to be representative of the results, quality, capacity, and profitability of the operation activities which are carried out. Their presentation is done by use of the key performance indicators (KPI) which

presently form one of the basic tools of the rational operation management of the technical objects [7].

For the complex and varied technical systems such as marine power plants the performance indicators must be strictly defined and explicitly interpreted [13].

2. The Purpose of the Application of the Ship Turbine Maintenance Key Performance Indicators

The ship propulsion turbines, regardless whether their effective power is generated by means of steam (steam turbines) or combustion chamber exhaust gases (gas turbine), constitute an essential element of many systems of marine power plants. Despite the high reliability of ship turbines their performance in the main propulsion systems and the auxiliary power set-ups (eg production) is subject to more and more intensive monitoring. Additionally, nowadays, the contemporary conditioning in all micro-economical systems demand more precise cost control and optimisation of the operation systems aiming at the reduction of the expenses for the maintenance with the simultaneously kept reliability at the expected level.

The performance of the maintenance of the marine turbine power systems on floating vessels is a significant issue in terms of rationalisation of many aspects of human activities involving the use of marine transport, capacity and production units, marine oil rigs, FPSO and navy units [1, 2, 3].

The key performance indicators of the marine turbine maintenance describe the selected information groups in order to present the outputs of the examined power systems in the up-to-the-point manner and in the explicit way. The purpose of the application of the key performance indicators of the maintenance is:

- the obtainment of the current and historical values of the measures of the operation properties and their mutual relation, in order to compare the achieved values with the design values as well as with the values obtained in the course of observation of other operation systems and other technical objects,
- the diagnostics of the implemented maintenance activities,
- the implementation of the process of the continuous improvement through the search and elimination of any meaningful deviations from the assumed design figures,
- the monitoring of the changes and progress in the operation system,
- the motivating and accounting the technical and management personnel for the effects achieved.

The performance indicators discussed in this article refer to the examination and analysis of the power systems in terms of providing the desired information chiefly for the higher and middle management levels in charge of the proper maintenance in the technical, economical and organisational sense. However, there is an information group remaining so far beyond the analyses related with the key performance indicators, and at the same time significantly influencing the economical aspects. These are related with the power performance and their combination with the other indicators and the analysis of their effect on the operation management is the subject of the research conducted by the authors of this article [4, 5, 6, 13].

3. The Applied Maintenance Performance Indicators

The maintenance performance of the power systems of the floating vessels most frequently refers to:

- the quality of the implemented maintenance processes,
- the quality of the functioning of the machinery, equipment and installations,

- the organisation and effectiveness of the work of the technical personnel and
 - costs and profitability of the maintenance activities implemented.
- The key performance indicators of the maintenance have been formed in three categories [6]:
- economical indicators,
 - technical indicators,
 - organisational indicators.

In each group there have been separated the indicators on the general, intermediate and specific levels [6, 8]. Using the symbols applied in [6, 8, 9] the division of the indicators pre-defined in these materials is shown in the table 1.

Table 1. The structuring of the machinery maintenance performance indicators [6, 8, 9]

	Economical indicators	Technical indicators	Organisational indicators
Level 1 – general/owner’s (e.g. watercraft set)	E1, E2, E3, E4, E5, E6	T1, T2, T3, T4	O1, O2, O3, O4, O5, O6, O7, O8
Level 2 – intermediate (e.g. floating vessel power system)	E7, E8, E9, E10, E11, E12, E13, E14	T5, T6, T7, T8, T9, T10, T11, T12, T13, T14, T15, T16	O9, O10
Level 3 – specific (e.g. gas turbine)	E15, E16, E17, E18, E19, E20, E21, E22, E23, E24	T17, T18, T19, T20, T21	O11, O12, O13, O14, O15, O16, O17, O18, O19, O20, O21, O22, O23, O24, O25, O26

In the standards [8] there have been included the indicators recognised by the Technical Committee CEN/TC 319 “Maintenance” as the essential ones. However, this does not mean that the companies and institutions dealing with the operation of floating vessels [or watercraft in general] have any restrictions imposed upon. KPI are established and selected on the basis of the individual information needs in every operation system. Below there are presented the selected predefined in [8] and [6] key performance indicators of the maintenance of the turbine ship power plants with steam turbines and gas turbine engines.

Amongst the technical indicators one of the most often applied KPI is the availability A of a specified machine or the entire power system. This value corresponds to the readiness K used in Poland. There are distinguished technical availability A_T and the operational availability A_o .

$$[T1] A_t = T_{OT} / (T_{OT} + T_{DT.M}) \quad (1)$$

$$[T2] A_o = T_{UT.t} / t \quad (2)$$

where:

T_{OT} – total operation time

$T_{DT.M}$ – summarised downtime caused by maintenance activities

$T_{UT.t}$ – usability time in calendar time t

The indicators T1 and T2 allow to specify the reliability of the individual objects or the entire power system. Other technical indicator used to specify reliability is the mean time between failures (MTBF).

$$[T17] MTBF = T_{OT} / F \quad (3)$$

where:

F – number of failures

KPI applicable not only for the performance of the maintenance, but also object response to renewal/repair is the mean time to repair (MTTR).

$$[T21] MTTR = T_{DT.M} / F \quad (4)$$

One of the most frequently applied organisational indicator on floating vessels is the ratio of the planned tasks to the whole value of available manhours.

$$[O5] O_W = WO / WF \quad (5)$$

where:

WO – the planned sum of manhours of maintenance activities

WF – the available sum of manhours of operation maintenance activities

From the economical point of view the profitability indicator is often applied related to the costs of maintenance in the event of object or system replacement.

$$[E1] E_I = C_M / C_{Re} \quad (6)$$

where:

C_M – total maintenance cost

C_{Re} – total replacement cost

Or the maintenance cost indicator in relation to the operation or capacity parameter (e.g. in case of FPSO unit to one tonne of the oil product).

$$[E5] C_P = C_M / P \quad (7)$$

where:

P – production capacity

Also the performance of the warehousing/storage management is measured. An example of an indicator in this respect may be also the ratio of the total costs of the operation means/spare parts used in the activities of the maintenance of the stores value in a given period of time t.

$$[E12] E_{WT} = C_{Materials.t} / V_{Materials.t} \quad (8)$$

where:

C_{Materials.t} – the total cost of materials used for maintenance in operation during the period of time t

V_{Materials.t} – the average value of the materials stored to be used for maintenance in operation during the period of time t

4. The Maintenance Performance Indicators Selection Methods

The selection of the key performance indicators of the maintenance is most frequently done by use of the expert's method. It consists in the selection of the indicators from the entire operation range. This method takes its origin in the practices of project management and it is possible to use, if the following conditions are met:

- there is available personnel/workers who being aware of the functionality of the individual KPI are capable to decide in the general discussion which indicators in the specific part of the system operation would be applicable,
- in the group working over the selection there are persons from the different organisational levels (technical workers, lower management, upper management),
- if the performance indicators are used in parallel in the other parts of an enterprise (e.g. in relation to the floating vessels), then the definitions of the

individual components are made uniform and are known to the group of the experts working on the selection of the indicators for the power systems operation.

The experts' method is largely employed in the management of the operation of the floating vessels. The selection of the performance indicators by use of this method is strongly subject to the experience and knowledge of the specialist team members.

5. The Examples of the Key Performance Indicator Values in Turbine Maintenance

The adequately selected and presented KPI are likely to contain high information value. Owing to the proper interpretation the rational and reasonable operation decisions can be made, amongst others related with the repair planning, organisational changes, planning of purchase and spare parts deliveries etc.

By use of the Monte Carlo method the simulation examinations have been conducted for 30 ship turbines. The simulation of the mean time between critical failures [MTBF_c] has been conducted by the application of the value sampling from the normal distribution under the assumption that the mean value of failure intensity $\lambda_{sr} = 605.9$ is the same as the value quoted by OREDA-97 manual [12] for the selected group of turbine engines. For the demonstration of the deviations it has been assumed that the standard deviation is $S = 200$. The figure 1 presents the obtained MTBF_c values. The graph has also marked median M and the values: median +20% - $M_{+20\%}$ and median -20% - $M_{-20\%}$. It has been assumed that that the value $M_{-20\%}$ is the minimum expected value for this engine generation. Thus the range has been determined which for the examined generation group is recognised as the normal value range (values $M_{-20\%}$ and bigger).

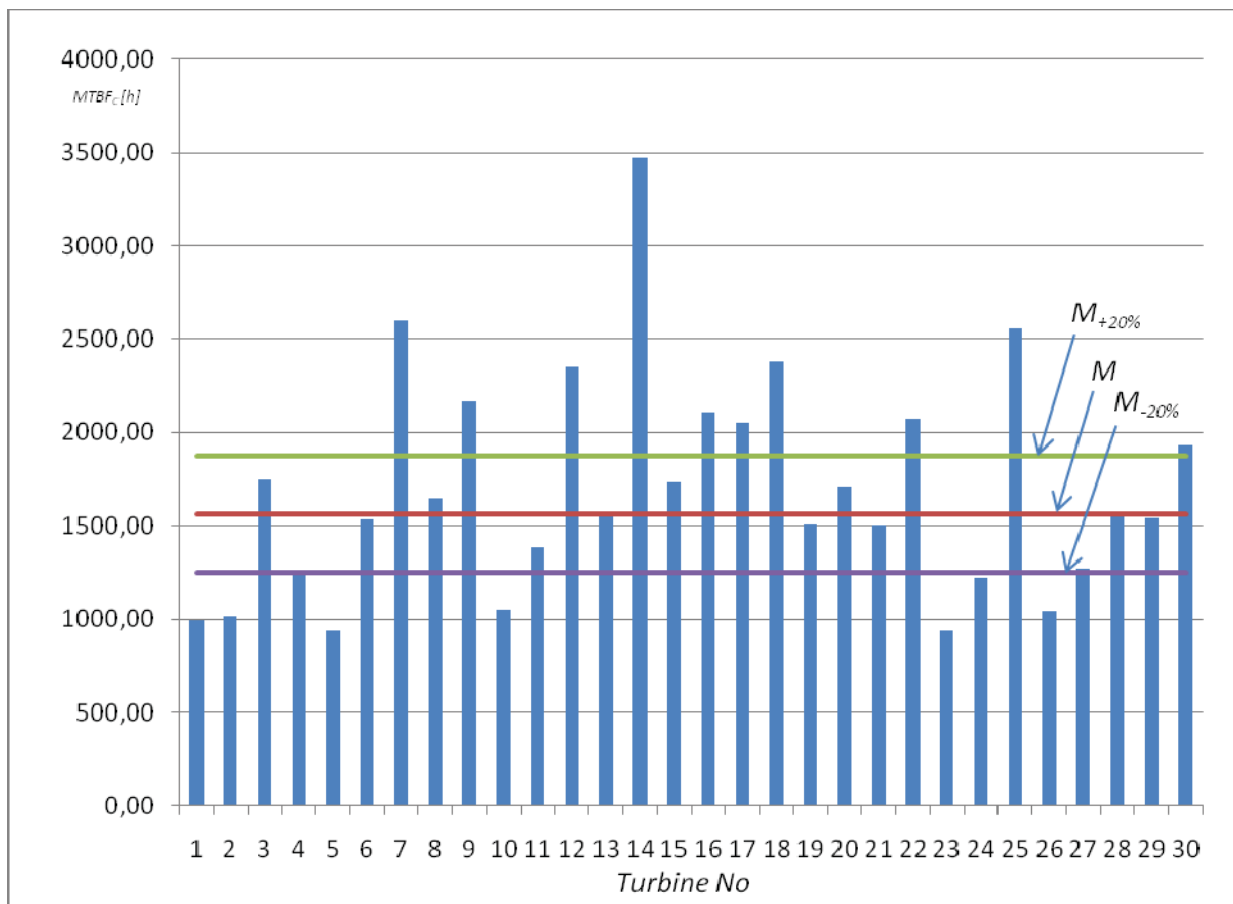


Fig 1. The values of the MTBF_c indicator for the generation of 30 marine turbine engines

On the basis of the analysis of the simulation results there has been obtained the set of the turbine engines below the expected (normal) values. So presented data may also be interpreted by the statement that the performance of maintenance (in terms of reliability) of turbines marked as 1, 2, 5, 10, 23, 24, 26 is unsatisfactory (below the expected values). However, analysis of only MTBF indicator is not sufficient to make significant organisational or technical decisions.

The figure 2 shows the obtained values of $MTBF_c$ together with the values of the mean time to repair of the critical failures $MTTR_c$ obtained by the application of similar simulation and the total annual maintenance costs in relation to the unit of generated power C_p .

The starting values for the MTTR simulation have been taken, similar as for MTBF, from the manual OREDA-97 [12], whereas the economical values have been taken from the data made available by the Northeast CHM Application Centre of the University of Massachusetts (USA). On the basis of the obtained values of the mean time between failures, mean time of repair $MTTR_c$ and the annual maintenance costs in relation to the unit of the power generated C_p as presented in the figure, the preliminary evaluation of the maintenance performance has been done. Engines marked with 2, 5, 10 and 24 whose mean time between failures amounts to less than the minimum expected value $M_{-20\%}$ and at the same time the mean time for critical failure repair and the total annual maintenance cost are relatively high. These engines are maintained much less effectively than the remaining ones from the examined generation.

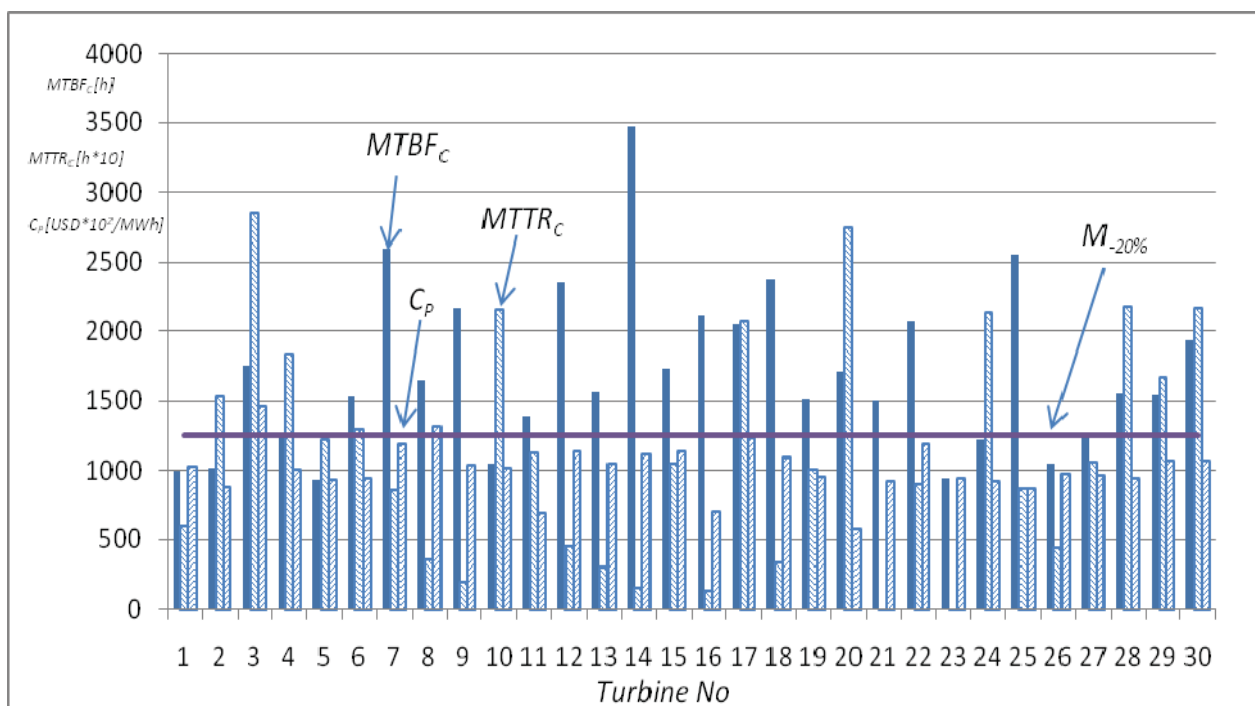


Fig 2. The values of the $MTBF_c$, $MTTR_c$ and C_p for the generation of 30 marine turbine engines

The improvement in the performance requires the implementation of specified organisational and operational activities, as well as some construction changes may be justified. The examples of the activities to improve the performance of the identified turbines could be:

- service procedure review and modernising,
- training for the crew operating/servicing the turbines,
- the implementation of additional procedures within the spare parts management,
- planning of general overhaul in the power systems where these turbines are installed,

- the implementation of extraordinary control procedures (inspections, diagnostics for the maintenance needs).

The selection of the activities to be taken aiming to improve the maintenance performance of the power systems depends on the components specified by the other indicators of this system and on the investment possibilities of the company or institution in charge of the operation. The rationalisation of the activities within maintenance is usually conducted on the basis of the leading criterion which may be for instance reliability or the total maintenance cost. It is of particular importance to establish the desired and alarm values of the individual indicators for the whole system as well as for its individual elements. The majority of the CMMS [Computerised Maintenance Management System] systems offered on the market makes possible the automation of the KPI value control. The notification of the alarm value being exceeded may be done by the message in the system, but also by e-mail to a person appointed to be in charge of the specific part of the power system. Automation of the notification process is usually related with the inclusion of the ship owner's office of a floating vessel into the group of alarm messages recipients.

6. Summary

The key performance indicators of the ship turbine maintenance formulated in the article are the appropriate set of values credibly evaluating the assessment and the correctness of the operational decisions made within maintenance. This thesis is applicable to the engines in ship's power systems in the technical scale as well as for obtainment of the information for the construction of the prediction models for the needs of the ship owner's logistics. The sources of the information presented by means of the key performance indicators may be historical data concerning the frequency and nature of the operational events as well as the data obtained by way of simulation examination adequate to the investigated maintenance process of the technical objects.

The research begun by the authors of this article within the evaluation of the applicability of the discussed key performance indicators consists the introduction to the further examinations of the construction of the model of maintenance evaluation of ship's power plants and other power systems. It is supposed to use not only the aforementioned information, but also other data, so far never analysed in connection with the key performance indicators.

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EXAMINATION OF CHANGES IN MICROSTRUCTURE OF TURBINE VANES WITH THE USE OF NON-DESTRUCTIVE METHODS

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Abstract

The processes associated with operation of traction, marine and avionic turbine engines entail occurrence of various defects affecting turbine components, in particular turbine vanes. The main reasons for defects and deterioration of gas turbine vanes include thermal fatigue and overheating of the vane material. This is why continuous monitoring of technical condition demonstrated by crucial engine components, such as turbine vanes, is a matter of great importance. The monitoring operations involve all the up-to-date diagnostic methods intended to detect and interpret possible hazards. The initial assessment is carried out with the use of visual inspection methods, but the major phase of investigations consists in metallographic examinations, which disables further operation of the vanes. Possible mistakes during the initial assessment of the engine condition result in huge costs due to unnecessary overhaul of the entire engine.

Therefore, there is a need to apply non-destructive test methods to the maximum possible extent with the aim to evaluate the overheating status of the gas turbine vanes on a current basis. This paper outlines the non-destructive test methods that are currently in use and that are based on analysis of surface images obtained from the examined parts within the visible bandwidth of electromagnetic waves as well as on surface analysis of examined items with the use of a ring-wedge detector. Particular attention is paid to opportunities that enable unbiased diagnostics of changes in the microscopic structure of vanes by means of the non-destructive thermographic method as well the X-ray computer tomography.

Keywords: *gas turbine, vane, diagnostics, non-destructive test methods*

1. Introduction

In applications for power engineering, traction, sea transport and aeronautics, gas turbines perform as a powering component for the entire structure. Its power determines performance of the driving unit and any increase of its efficiency reflects on growth of its power and drop of its unit fuel consumption and vice versa. At the same time the turbine, as it is subjected to huge thermal and mechanical loads (in particular, its vanes of the rotor rims), determines the overall reliability and durability of the entire structure where the turbine is built-in.

Turbine efficiency substantially depends on the temperature of the engine combustion gas upstream its inlet. The barrier to increase the temperature consists in troubles with materials, i.e. their resistance to creeping, thermal fatigue, sulphur corrosion at high temperatures as well as erosion. Currently, depending on applied materials and cooling intensity, the working temperature of turbine vanes, e.g. in avionic engines, is kept within the ranges [1]: 1120 - 1170 K (with no

dedicated cooling system), 1200 – 1300 K (dedicated cooling for vanes) or 1300 – 1500 K (application of intense cooling).

Further progress and perfecting of manufacturing technologies used for production of turbine vanes with the aim to increase the temperature of the combustion gas upstream the turbine was targeted to coating with heat resistant materials with good corrosion resistance at high temperatures, low thermal conductivity and high structural stability of alloys that are commonly referred to as super alloys [2].

Operation of gas turbines always entails various damages to their components. The analysis of own research works [3, 4, 5] as well as literature references [6, 7, 8, 9, 10] shows that most of defects is associated with incorrect operation (adjustment) of parts and subassemblies that collaborate with turbines, in particular the combustion chamber and the outlet jet in case of turbojet engines (Fig. 1). Only a very small number of defects that happen to turbine subassemblies arise as a result of material deficiencies, improper design or technological faults.

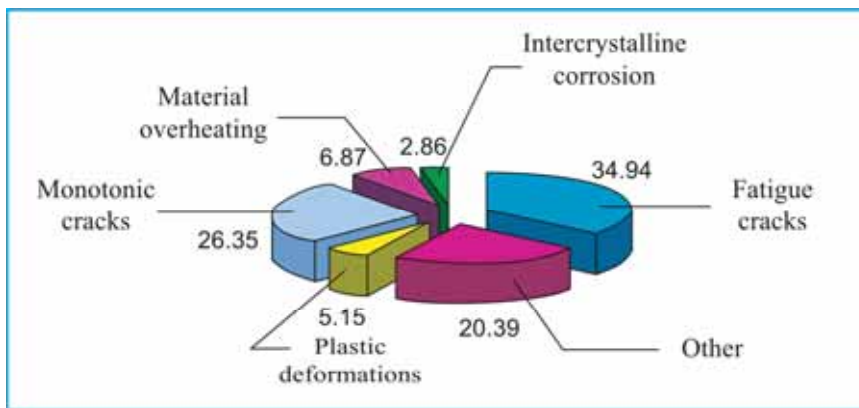


Fig. 1. Percentages of causes of damages to aircraft-engine turbines in service [3]



Fig. 2. Example forms of temperature defects demonstrated by vanes of the turbine rotor [6]

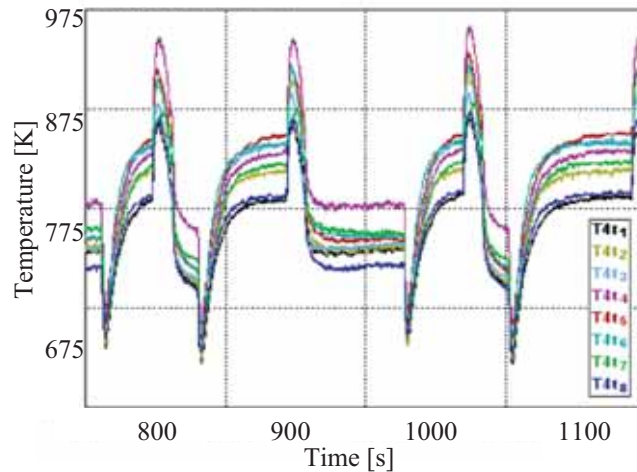


Fig. 3. Exemplary distribution of unevenness of the T4 temperature on the perimeter of the turbine in the function of time and rotation speed of an aircraft aerial engine, measured with help of thermoelements ($T4t_1 - T4t_8$) behind the turbine [11]

More frequently turbines suffer from adverse alterations to the material structure of vanes – overheating, thermal fatigue – caused by excessive temperature and exposure times as well as by aggressive composition of the combustion gas (Fig. 2). Overheating of the turbine vane material results from exceeding the permissible average temperature of combustion gas as well as due to non-uniform distribution of the thermal field along the turbine perimeter (Fig. 3). Non-uniform distribution of temperature downstream the turbine may happen due to improper atomizing of fuel due to carbon deposition on injection jets.

After exceeding the critical temperature the alloy subjects to overheating, which results in deterioration of its mechanical properties (Fig. 4). Overheating of the turbine vane material leads to malfunctioning of the gas turbine and sometimes even to accidents with disastrous consequences, which is particularly hazardous in aviation. Anyway, refining of the damaged turbine is always associated with a major overhaul and entails enormous expenses.

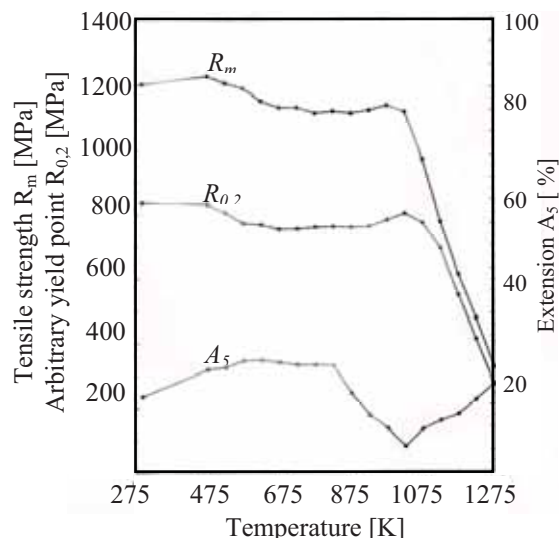


Fig. 4. Mechanical properties of EI-867 alloy in function of temperature [9]

The decision on the need to hand over the engine for a repair is always made by diagnostic staff after examination when, with the use of dedicated equipment, such as a videoscope, they are capable of assessing the condition of hard accessible components of the turbine. The appraisal is

made by comparison of current images recorded for surface of the component under test and the pattern images that present surfaces of operable and inoperable turbine vanes of the same type. Trustworthiness of the assessment depends on many factors, including competence and professional experience of the diagnostic staff, applied methodical approach, technical condition of the measuring instruments, external circumstances of experiments, etc. To a large extent, the final conclusion represents a subjective attitude of inspectors, which is associated with a risk of erroneous decisions. Mistakes in subjective findings committed by the diagnostic staff may cause that an overheated vane shall be accepted as a good one, or an operative vane shall fail the examination. Finding of diagnostic staff can be verified only by destructive techniques, when the examined vane undergoes analysis of its microstructure across a metallographic polished section. For that reason there is a need to develop and implement a non-destructive test method (computer aided) for the assessment of technical condition demonstrated by vanes of gas turbines during the turbine lifetime.

2. New methods of non-destructive examinations intended to assess the condition of gas turbine vanes

Some new methods for non-destructive examinations were developed over the recent years, including

1. analysis of images for surface of examined items acquired under white illumination – the RGB method,
2. detection of infrared irradiation emitted by the item under test – the thermographic method,
3. X-ray imaging – the method of X-ray computer tomography.

2.1. The RGB method

The RGB imaging consists in recording of three components that make up each colour (R- red, G – green and B – blue) and takes advantage of interrelationships between wave properties of light that correlate with physical and chemical properties of examined surfaces. These interrelationships decide about angular features of the incident and reflected light as well as absorption of individual wavelengths within the spectrum of electromagnetic irradiation [12]. Evaluation of vane condition is based on colour analysis for surface images and is interrelated with the material criteria (alterations of the item shape and increase in emission of the reinforcing phase γ'), i.e. deterioration in heat-resistance and high-temperature creep resistance after exceeding the combustion gas temperature that is specific for each material. Based on the nomograms that binds alteration of surface colours (either RGB colours or greyscale) and heating temperature of vanes one can assess how the alloy microstructure has been changed. The images are recorded with the use of a CCD matrix and analyzed by means of dedicated software that takes advantage of sophisticated algorithms for image processing and already developed patterns. Thus, qualitative assessment of the examined surface can be made. The foregoing method was applied to the assessment of gas turbine vanes made of the ŽS6-K alloy (Fig. 5).

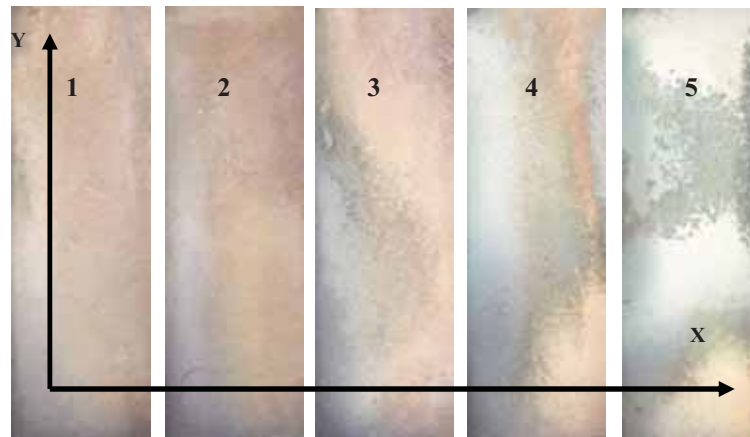


Fig. 5. Images for surfaces of gas turbine blades made of the ŽS6-K alloy, ordered according to the criterion of the increasing degree of the material overheating

Owing to m-files developed within the Matlab software environment it is possible to extract features of the recorded images for examined surfaces. These images are represented by histograms that combine distribution of intensities for individual components of colours and other parameters determined on the basis of the event matrix. Essential parameters of histograms, such as location of the maximum amplitude (chromaticity for RGB colours), averaged values for images (chromaticity values added up along rows of the matrix and divided by the number of rows) as well as the maximum amplitude value are calculated for the examined section of the vane image. Therefore, histograms contain quantitative information on overall brightness of images recorded for the items under test. Fig. 6 presents examples for translocation (bias) of the maximum amplitude for the image saturation associated with various degrees of deterioration demonstrated by vanes from Fig. 5.

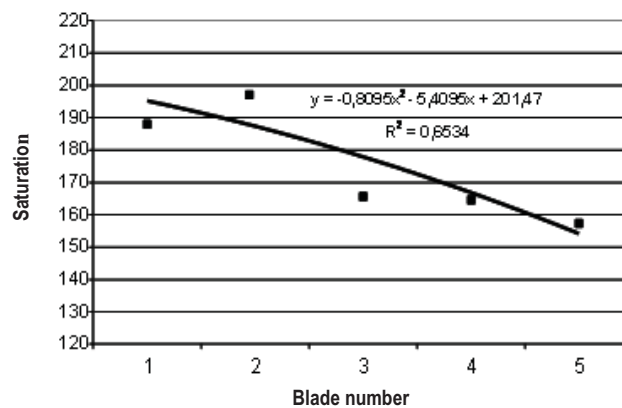


Fig. 6. Variations of the position value for the maximum amplitude of the image intensities for various technical conditions of blades from Fig. 5 (grey scale)

Analysis of images can be successfully carried out with the use of a use of a ring-wedge detector. The ring-wedge detector represents a ring-shaped model and is made up of two parts. The first part consists of concentrically disposed rings whilst the second part incorporates wedges with their common apex in the detector geometrical centre. Each of these areas represents a surface photo detector that converts the intensity of the incident light into an electric signal that is proportional to the intensity of that light.

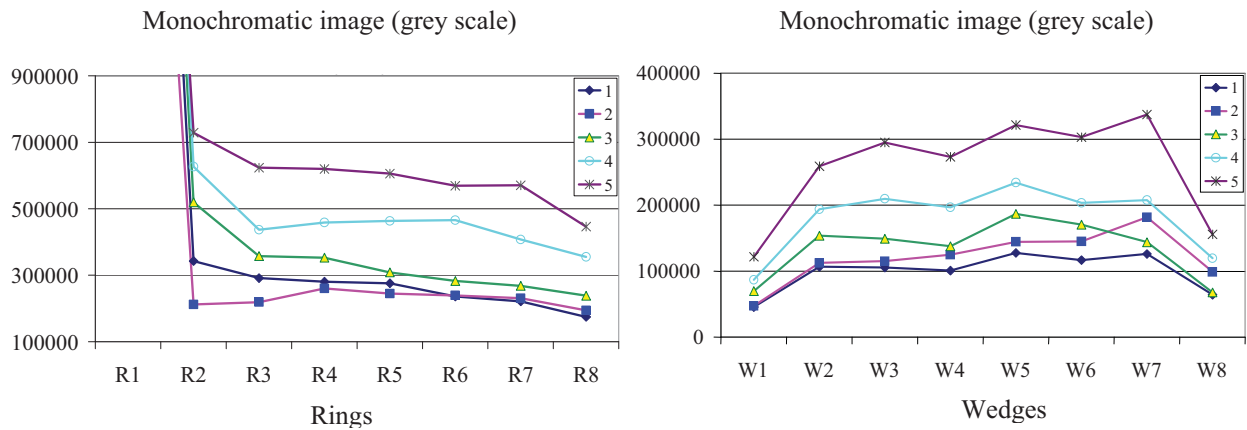


Fig. 7. Values of rings and wedges in the grey scale for individual deterioration degrees of wedges from Fig. 5

The computer generated hologram (CGH) has a shape that is analogical to the ring and wedge detector and is also made up of rings and wedges. Therefore CGH performs the role of an extractor that derives item features from images transformed to the frequency domain. Results from imaging and the analysis completed for surface of turbine vanes from Fig. 5 are shown in Fig. 7. Figures for wedges and rings for overheated vanes no. 4 and no. 5 clearly differ from the corresponding values for all the remaining items.

2.2. The thermographic method

The infrared thermographic method is based on detection of infrared irradiation and can be split into the passive and active options. The diagnosing of gas turbines with the use of the technique of passive thermography consists in recording images for distribution of temperatures at the turbine outlet (Fig. 8). When the turbine operates smoothly reference images (patterns) are recorded. Routine inspection during the lifetime period consists in the comparison of currently obtained thermographic images against patterns. Such an approach enables detection of even such defects (e.g. erosion of the entire turbine, damages to vanes, disturbed operation of the combustion chamber) that are poorly detectable with the use of other non-destructive techniques [10].

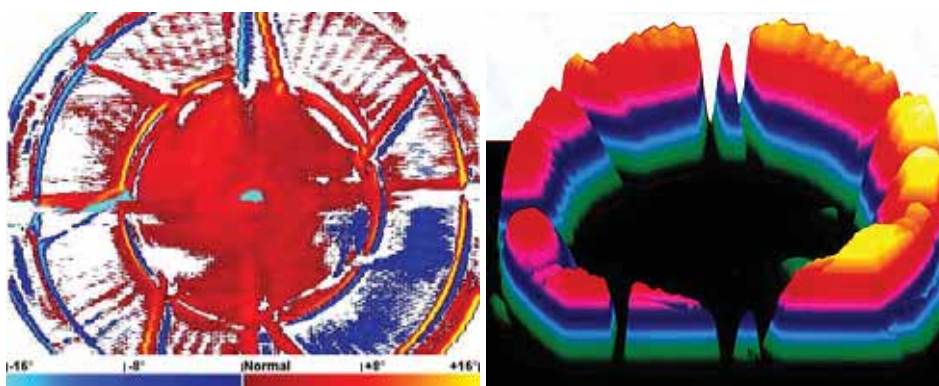


Fig. 8. Thermographic images for the stream of combustion gas that leaves the gas turbine of a helicopter engine [13]

Recent years have brought a development if research studies of ways to apply the method of active infrared thermography to detection of material defects. Essence of such investigations consists in analysis of thermal response to stimulation by means of an external thermal pulse. Depending on the stimulation technique some options of the active infrared thermography are distinguished, such as *pulsed thermography*, *lock-in thermography with modulated heating* and *pulsed phase thermography* [14].

Pulsed thermography consists in determination and analysis of temperature distribution on the examined surface during its cooling after preliminary uniform heating up by means of a thermal pulse (Fig. 8). For a one-dimension model and a homogenous material, the formula for variation of temperature during cooling of a surface preliminarily heated up with a short thermal pulse looks like as follows [16]:

$$T(t) - T(0) \sim Q\alpha^{-\frac{1}{2}} t^{-\frac{1}{2}}, \quad (1)$$

where:

Q - energy of the thermal pulse applied to a surface unit,

α - thermal diffusivity,

t - time when the surface is being cooled down,

T(0) - temperature at the selected location or on the area of already heated surface,

T(t) - temperature at any moment of the cooling down process.

When any material defects or alteration to its microstructure occur, they affect the heat diffusion velocity and make the foregoing relationship inapplicable.

Thermographic examinations employed samples of turbine vanes made of the Ei-867WD alloy. Samples were subject to heating within the temperature ranging from 1023 to 1423 K. Obtained results made it possible to find out that relationships between parameters associated with a thermal response of the material for examined vanes to a heat pulse was altered. Then, metallographic examinations were carried out to assess alterations in the microstructure of samples – chiefly alterations to the reinforcing phase γ' - Ni₃(Al,Ti). Results of those studies are demonstrated in Fig. 9 as a nomogram.

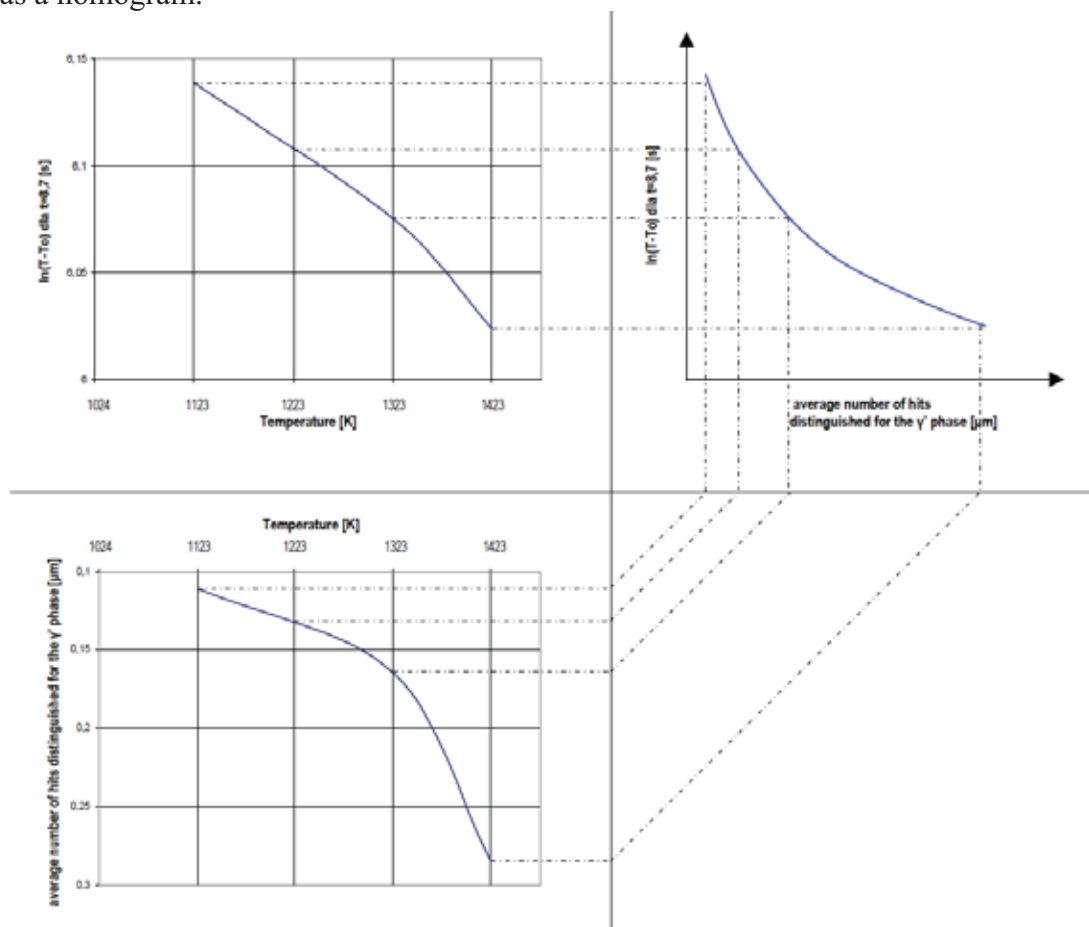


Fig. 9. The nomogram to assess microstructures of samples taken from a gas turbine made of the EI – 867 WD alloy plotted on the basis of the relationship between variation of the parameter $\ln(T-T_0)$ for the signal attributable to the thermographic method and variation in the number of hits for the γ' phase at various ageing temperatures [15]

The relationship between the thermal response of the sample material, represented as the value of $\ln(T-T_0)$ and the average number of hits for the γ' phase enables to assess the technical condition of the sample material. This relationship, in conjunction with the permissible alterations to the microstructure, serves as a basis to judge whether the sample material is suitable or not for further service. High temperature affects both the variations of the aluminium coating and the alterations to the structure of the γ' phase.

The investigated microstructure of the surface-adjacent layer reflects changes in the EI – 867 WD alloy and confirms overheating of the alloy structure after the vane samples had been heated at temperatures ranging from only 1223K (Fig. 10 and 11). When the material criterion is adopted, i.e. how the number of hits to the γ' phase has changed and it is the criterion that determines the applicability of vanes for further operation, one is able to determine a threshold limit for the vane lifetime. Results from metallographic tests confirm that the vane material loses its high-temperature creep resistance at the temperatures above 1223K due to clustering of fine-grained cubical particles of the γ' phase (Fig. 10), and formation of plates (Fig. 11).

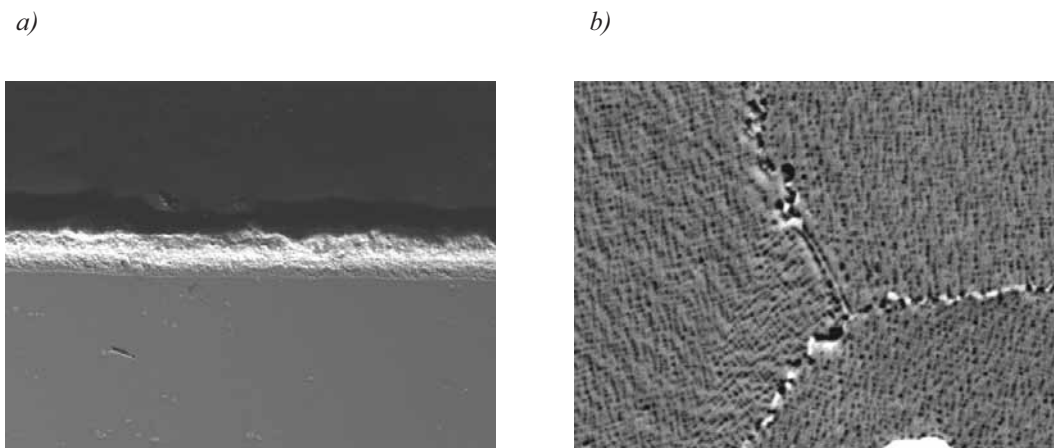


Fig. 10. The metallographic structure of a blade that has been aged at temperature of 1023K: a) coating (x450); b) the surface-beneath layer (x4500)

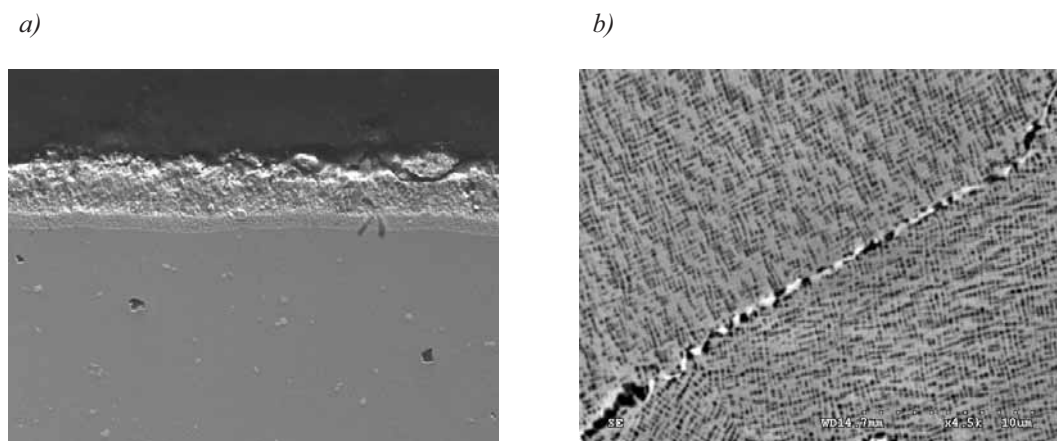


Fig. 11. The metallographic structure of a blade that has been aged at temperature of 1223K: a) coating (x450); b) the surface-beneath layer (x4500)

2.3. The method of X-ray computer tomography

Tomography is a collective name for diagnostic methods that are intended to obtain 3D images that present a cross-section of the examined item and thus a number of tomography techniques are known. For diagnostic purposes the method of Computed Tomography- CT is widely applied. It is the variation of X-ray tomography that makes it possible to obtain 3D images owing to X-raying of the object from various directions. The use of a tomograph (X-ray scanner) along with implemented computer software enables to produce tomographic images. The appliances use an X-ray tube as a source of irradiation

Detectors of X-rays that are applicable to the computer tomography chiefly include ionization chambers and scintillators. Data streams from such detectors conveys information on absorption or scattering of X-rays by individual components of the item under test. These data are stored in the computer memory and then subject to digital analysis in order to obtain greyscale images.

Nowadays the images are reproduced chiefly by means of the analytic methods. They offer the best results but they require really high computation performance. The method of 2D Fourier analysis uses the Fast Fourier Transformation (FFT) method to interpret the obtained absorption profiles. The FFT method is applied to each exposure and therefore the absorption coefficient can be determined for each voxel. The absorption coefficients are then converted to CT number, which are also referred to as Hounsfield Units (HU) [17].

$$1HU=K\frac{\mu_p - \mu_w}{\mu_w}, \quad (2)$$

where:

K - amplification coefficient for images (a characteristic parameter for each individual tomograph),

μ_p - absorption coefficient for each pixel,

μ_w - absorption coefficient for water (the reference value).

The CT numbers range from -1000 to +4000. Best results of diagnosing the condition demonstrated by vanes of gas turbines are obtained when the technique with a linear detector is applied. Results of CT examination can be used for measurements of geometrical parameters of vanes, for instance to measure the thickness of their internal walls with cooling channels or to examine structures of materials, to detect defects or to support the diagnostic process during repairs or overhauls. Images for scanned items can be presented with the use of colours (Fig. 12) and scaled to desired dimensions to determine shapes of internal walls (size and location of defects). Geometrical parameters of internal components can be also measured with a high accuracy to establish tolerances for their actual dimensions. In addition, spectrum of the CT signal can be used to analyse alterations to microstructure of the alloy (Fig. 13).

Thus, CT examination makes it possible to achieve a high accuracy in verification whether the examined items are manufactured with sufficient accuracy or not as well as to find out alterations in the alloy microstructure or to detect internal defects, e.g. fractures, clogging of cooling channels of vanes, etc.

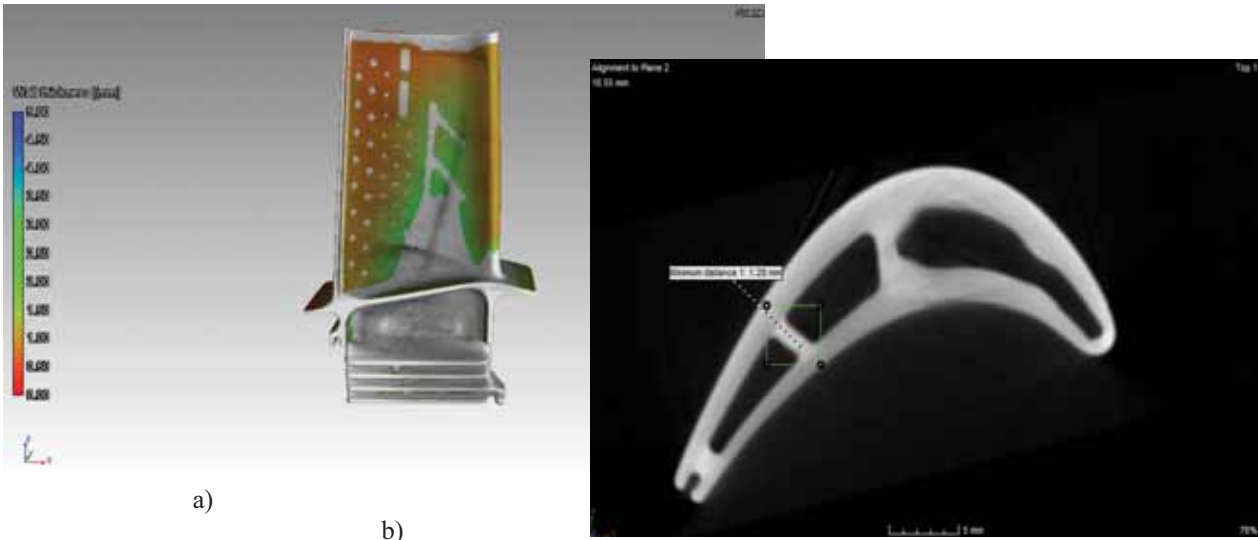


Fig. 12. Image for the gas turbine vane obtained by means of the tomograph from YXLON [17]:
 |a) determination of the profile thickness, b) example how to measure dimensions of internal walls.

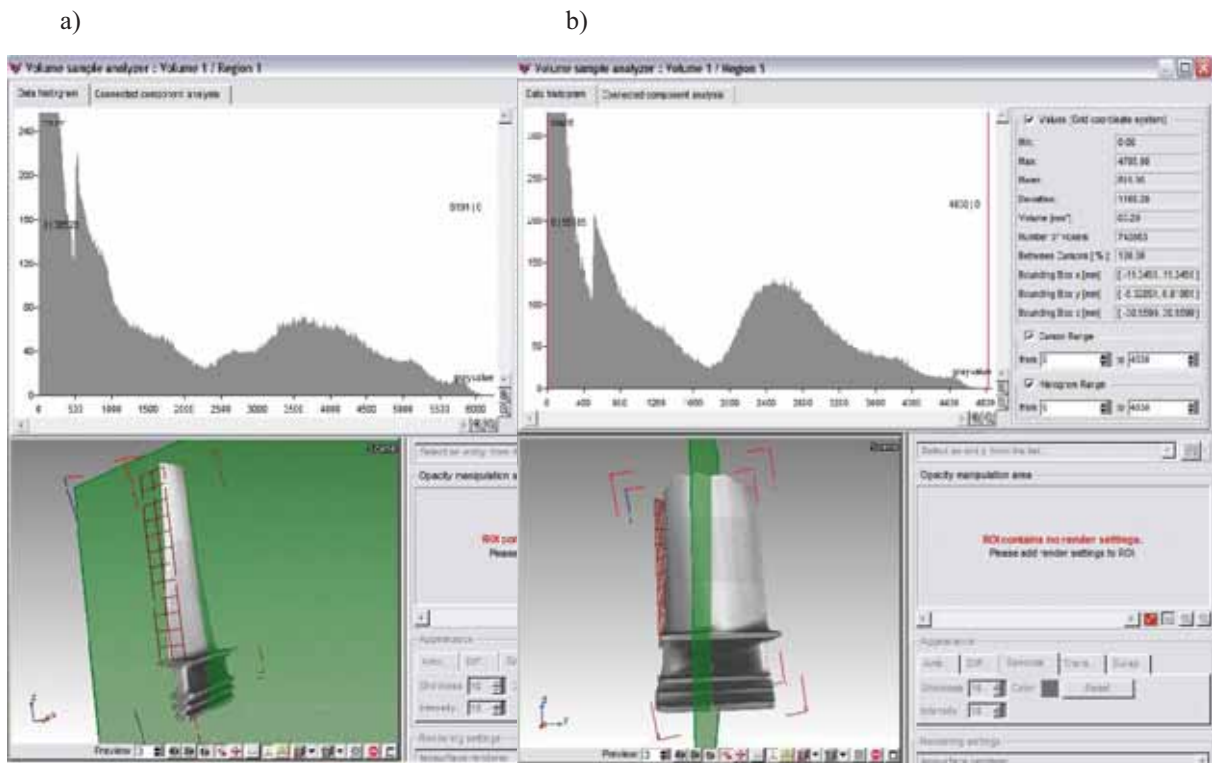


Fig. 13. Spectra for CT signals obtained by means of the tomograph from YXLON [17] for vanes made of the EI-867WD alloy with a) correct microstructure, b) overheated microstructure.

3. Conclusions

- The process associated with deterioration of gas turbine vanes starts from destruction of its protective coating. It subsequently leads to overheating of the base material that is demonstrated by detrimental alterations to their microstructure.
- The developed RGB method for digital processing of images recorded to surfaces of turbine vanes within the visible bandwidth enables to evaluate the technical condition of vanes, in particular evaluation of amendments to microstructure of vane materials.

- Analysis of images recorded for turbine vanes can be efficiently carried out with the use of a ring and wedge detector.
- The thermographic method offers investigation of interdependencies and interrelationships between signal parameters of thermal response from the vane material and alterations to the microstructure of vanes.
- The method of Computer Tomography enables quick and very accurate diagnostics of vane condition, i.e. measurement of geometrical dimensions, defects, structural faults and other irregularities.
- Application of NDT techniques presented in this paper shall substantially increase the probability that any alterations to technical condition of vanes shall easily detected as well as enable non-destructive evaluation of alterations to the material microstructure that has been unfeasible to date.

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PROPULSION RISK OF A SEAGOING SHIP PREDICTION BASED ON EXPERT OPINIONS

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Abstract

A prediction model of the ship propulsion risk is presented, i.e. a risk of the consequences of loss of the ship propulsion capability. This is an expert model based on opinions elicited by the ship power plant operators. The risk level depends, among other things, on the reliability state of the ship propulsion system components. This state is defined by operators in a linguistic form. The formal risk model parameters are determined by means of a neural network. The model may be useful in the ship operation decision processes.

Keywords: risk, propulsion, ship, expert, opinion

1. INTRODUCTION

The risk prediction model consists of a dangerous event (DE) module and the event consequence module. The DE connects the two modules - it initiates consequences of particular causes. In the case of propulsion risk (PR), the event DE is immediate loss of the propulsion capability by the ship, i.e. an immediate catastrophic failure (ICF) of its propulsion system (PS). The event may be caused by the PS element failures or operator errors.

It is assumed that the model parameter identification will be based on opinions of the ship power plant operators, hereinafter referred to as experts. The opinions will be formulated mainly in a linguistic form, supported to a minimum extent by numerical data.

The ship PS is well developed. In the example of a simple PS presented below, it consists of 11 subsystems (SS) and these of 92 sets of devices (SD) including several hundred devices (D) altogether. The PS sizes, the expert ability to express the opinions necessary to construct a PR model and the limited number of experts that the authors managed to involve in the study influenced the model form.

The problem of PR modeling and expert investigation methods used in this case were presented in publications [1,2,3,4,5,11].

2. PROPULSION RISK PREDICTION MODEL

The PR model form is determined by data that can be obtained from experts. It is assumed that they elicit:

- Annual numbers N of the system ICF type failures;
- System operating time share in the calendar time of the system observation by the expert $t^{(a)}\%$.

- Linguistic estimation of the share of number of PS fault tree (FT) cuts in the failure number N during a year.

- Linguistic estimation of chances or chance preferences of the occurrence of system ICF specific consequences, on the condition that the event itself occurs.

Those opinions are a basis for the construction of a system risk prediction model. The linguistic opinions are processed by means of pare comparison methods to obtain the numerical values of appropriate variables [6,11].

The following assumptions are made regarding the system risk model:

- The system may be only in the active use or stand-by use state. The system ICF type events may occur only in the active use state.

- The formal model of a PS ICF event stream is the Homogeneous Poisson Process (HPP). It is a renewal process model with negligible renewal duration time. This assumption is justified by the expert opinions, which indicate that catastrophic failures of some systems may occur quite frequently, even several times a year, but in general they cause only a relatively short break in normal system operation. Serious consequences with longer breaks in the system operation are less frequent. Also the exponential time between failures distribution, as in the case of HPP, is characteristic of the operation of many system classes, including the ship devices [10,13]. It is appropriate when defects of the modeled object and the operator errors are fully random, abrupt and no gradual, without wear and/or ageing-type defects. This corresponds with the situation where inspection and renewals are regularly carried out and prevent that type of defects.

- The HPP parameter is determined in a neural network from data elicited by experts. The network can be calibrated with real data obtained from the system (or a similar systems) operation.

- The operators can perform estimation of the PS components (devices (Ds)) reliability state and updating PR during ship operation, i.e. of the system ICF specific consequences, based on subjective estimations of the analysed system component condition.

For given ICF event a fault tree (FT) is constructed to determine the set of PS ICF type causes, where the top event is an ICF type PS failure and the basic events are the system minimum cut or cut failures. The notion of minimum cut is generally known. Cut is defined as a set of elements (devices) fulfilling a specific function which loss of that function results in a system ICF. In the case of minimum cut, failures of the same system elements may appear in more than one minimum cuts. Therefore, they are not disjoint events in the probabilistic sense. Besides, obtaining reliable expert opinions on the minimum cut failures is almost unrealistic. Also in the case of a PS ICF event cause decomposition to the minimum cut level the number of basic events in the FT increases considerably. - the cause decomposition is deeper. The more basic events it contains, the more data are needed to tune the neural network in a situation when the number of competent experts available is generally very limited. In the case of cuts (not minimum cuts), they can be arranged to form a complete set of events. Such events are serious failures in the ship operation process, very well remembered by the experts. Besides, there are generally fewer cuts than minimum cuts in the FTs.

Cuts have defined reliability structures (RS). If those structures and the number of cut failures within a given time interval are known, then the number of failures of particular devices in the cuts can be determined.

The scheme of a model in Fig. 1 illustrates the PR prediction within a period of time $t^{(p)}$. The system operator inputs estimated reliability states of the cut elements. The elements are devices (D) of the all system cuts. The estimates are made by choosing the value of the linguistic variable $L_V = \text{average annual number of ICF events from the set } \{\text{minimum, very small, small, medium, large, very large, critical}\}$ for the individual Ds. The operator may be supported in that process by a database.

Having the reliability states of the FT cut components Ds and the cut RS structures, average numbers N_{ik} of these cut ICF failures are determined by “operator algorithm”. The appropriate methods are presented in section 3 of this article. They are input to the neural network.

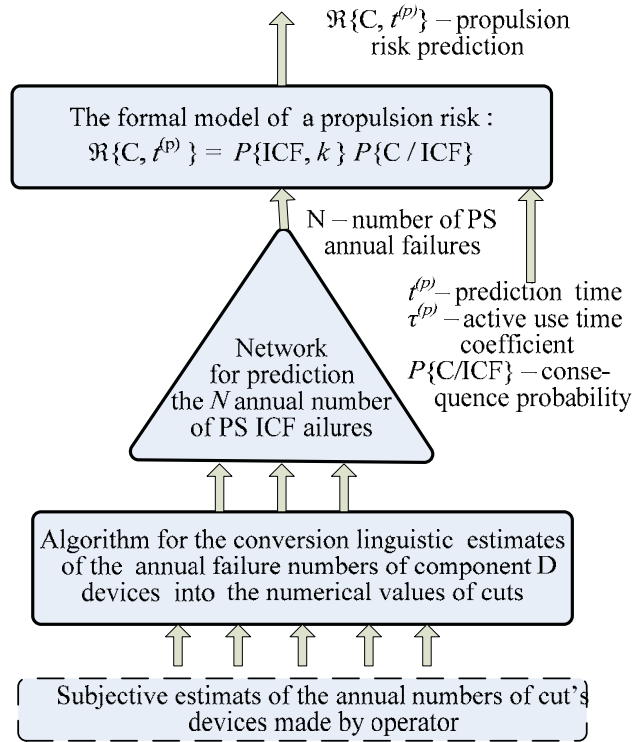


Fig.1. Scheme of propulsion risk prediction of a ship propulsion system

The neural network, performing generalized regression, determines the system ICF type failure annual number N in the numerical values. The network determines the respective value of an LV variable singleton membership function. Seven values of the LV were adopted. The network may be more or less complex depending on the number of cuts and the FT structure.

The neural network is built for a specific PS, according to its properties and size. Each cut at the FT lowest level implies an entry to the network. The network error decreases with the increasing amount of teaching data. We are interested in the number of teaching data which protects the error of calculus fulfilling some statistical standards. That depends on the number and appropriate choice of experts.

If there is disproportion between the number of entries to the neural network and the its teaching data lot size, then the network may be divided to smaller parts and a complex network may be built. In the example here below, the catastrophic failure (CF) connected with PS subsystems (SS) and CF connected with sets of devices (SD) are stood out. The sets of SSs CFs and SDs CFs form the complete sets of failures. The occurrence any of such CF leads to the ICF failure of the PS.

Inputs to the model are risk prediction calendar time $t^{(p)}$ [year], the modeled PS active use time coefficient $\tau^{(a)}$ and the conditional probability of the ICF event consequences. The prediction time is chosen as needed, in connection with the planned sea voyages.

The PS active use time coefficient:

$$\tau^{(a)} = (t^{(a)}/100) t^{(p)} \quad (1)$$

where $t^{(a)}$ % = propulsion system active use time as a share of prediction calendar time $t^{(p)}$ (approximately equal to the share of ship at sea time).

The value of $\tau^{(a)}$ coefficient is determined by operator from the earlier or own estimates. The probability of the system ICF event occurrence within the prediction time $t^{(p)}$ is determined by a size K vector:

$$P\{ICF_k, t^{(p)}\} = \left[\frac{(\lambda^{(a)} \tau^{(a)} t^{(p)})^k}{k!} e^{-\lambda^{(a)} \tau^{(a)} t^{(p)}} : k = 1, 2, \dots, K \right] \quad (2)$$

where $\lambda^{(a)} = N/\tau t$ [1/year] = intensity function (rate of occurrence of failures, ROCOF) related to the active use time, where N = number of the system ICFs within $t = 1$ year of observation, with the active use time coefficient τ determined by neural network; k = number of ICFs.

Vector (2) expresses the probability of occurrence of $k = 1, 2, \dots, K$ system ICFs within the prediction time $t^{(p)}$ interval.

Probability of occurrence of specific consequences on the condition of the analysed system ICF occurrence:

$$P\{C/ICF\} \quad (3)$$

where $C = C1 \cap C2$ = very serious casualty C1 or serious casualty C2 [8].

This probability value is input by the operator from earlier data obtained from expert investigations for a specific ship type, shipping line, ICF type and ship sailing region. The values may be introduced to the prediction program database.

The consequences C are so serious, that they may occur only once within the prediction time $t^{(p)}$, after any of the K analysed system ICFs. The risk of consequence occurrence after each ICF event is determined by vector whose elements for successive k -th ICFs are sums of probabilities of the products of preceding ICF events, non-occurrence of consequences C of those events and occurrence of the consequences of k -th failure:

$$\mathfrak{R}\{C, t_p\} = P\{C/ICF\} \sum_{k=1}^K P\{ICF_k\} (1 - P\{C/ICF\})^{k-1} \quad (4)$$

3. OPERATOR'S ALGORITHM

3.1. CUT MODELS

The algorithm allows processing of the subjective estimates of numbers of device D failures, creating FT cuts, into numerical values of the numbers of failures of those cuts. They are the neural network input data. The data are input to the model during the system operation, when devices change their reliability state. Additionally, the algorithm is meant to aid the operator in estimating the system reliability condition.

The numerical values of the numbers of failures in cuts are determined by computer program from the subjective linguistic estimates of the numbers of failures of component devices. The estimates are made by the system operators and based on their current knowledge of the device conditions. This is simple when cut is a single-element system, but may be difficult with the complex RS cuts. The algorithm aids the operator in the estimates. Specifically, it allows converting the linguistic values of D device CF events into corresponding numerical values of the

cuts. The data that may be used in this case are connected with cuts - the universe of discourse (*UD*) of linguistic variables *LV* of the cut numbers of failures for defined RSs. These numbers are determined from the expert investigations.

Cuts are sets of devices with specific RS - systems in the reliability sense. They may be single- or multi-element systems. They are distinguished in the model because they can cause subsystem CFs and in consequence a PS ICF failure. Annual numbers of the cut element (device) CFs change during the operation process due to time, external factors and the operational use.

The conversion problem is presented for the case when in the FT cuts of subsystems (CSS) are distinguished and in them cuts of sets of devices (CSD). The following CSD notation is adopted:

$$\text{CSD}_{ik} = \{e_{ikl}, l = 1, 2, \dots, L_{ik}\}, \quad (5)$$

where CSD_{ik} = *k*-th cut of *i*-th subsystem, $k=1,2,\dots,K$, $i = 1,2,\dots,I$; e_{ikl} = *l*-th element of *k*-th CSD, $l = 1,2,\dots,L$.

The CSD cut renewal process parameters, i.e. intensity functions λ (ROCOF), are determined from the expert investigations of the PS system. In this case, they are applied only to the ICFs causing the loss of CSD function. Annual numbers of failures *N*, whose functions are intensity functions λ , are determined. It may be assumed that the numbers elicited by experts are average values in their space of professional experience gained during multi-year seamanship. Then the asymptotic intensity function takes the form [9]:

$$\lambda^{(a)} \cong N/(\tau t) \quad (6)$$

where *N* = average number of the analysed system failures during the observation time *t*; τ = active use time coefficient; $t = 1$ year = calendar time that the estimate of the number of failures is related to.

We are interested in the dependence on the number of CSD cut ICFs to the number of such failures of the cut elements. It is determined from the formulas of the relation of systems, of specific reliability structures, failure rate to the failure rates of their components. It should be remembered that in the case of a HPP the times between failures have exponential distributions, whose parameter is the modeled object failure rate, in the analysed case equals to the process renewal intensity function λ . The formulas for the ship system CSD cut reliability structures are given below.

In the case of a single-element structure, the annual numbers of the cut failures and device failures are identical.

$$N_{ik} = N_{ikl}, \quad i \in \{1,2, \dots, I\}, \quad k \in \{1,2, \dots, K\}, \quad l = 1, \quad (7)$$

where N_{ik} = annual number of failures of *k*-th cut in *i*-th subsystem; N_{ikl} = annual number of failures of *l*-th device.

In a series RS, the number of system failures is a sum of the numbers of failures of its components.

$$N_{ik} = N_{ik1} + N_{ik2} + \dots + N_{ikl} + \dots + N_{ikL}. \quad (8)$$

A decisive role in that structure plays a "weak link", i.e. the device with the greatest annual number of failures. The CSD cut number of failures must then be greater than the weak link number of failures.

In a two-element parallel RS, we obtain from the average time between failures formula (8):

$$N_{Ik} = \frac{N_{ik1}^2 N_{ik2} + N_{ik1} N_{ik2}^2}{N_{ik1} N_{1k2} + N_{ik1}^2 N_{1k2}^2}. \quad (9)$$

If one element in that structure fails then it becomes a single element structure. Similar expressions can be easily derived for a three-element parallel structure.

In the structures with stand-by reserve, only part of the system elements are actively used, the other part is a reserve used when needed. The reserve is switched on by trigger or by the operator action. The trigger and the system functional part create the series reliability structure. When the trigger failure rate is treated as constant and only one of the two elements is actively used ($L = 2$), then:

$$N_{ik} = N_{ik}^p + \frac{N_{ik1} N_{ik2}}{N_{ik2} + N_{ik1}}, \quad (10)$$

where N_{ik}^p = annual number of trigger failures

In the case of a three-element structure ($L = 3$) with two stand-by elements, we obtain:

$$N_{ik} = N_{ik}^p + \frac{N_{ik1} N_{ik2} N_{ik3}}{N_{ik2} N_{ik3} + N_{ik1} N_{ik3} + N_{ik1} N_{ik2}}. \quad (11)$$

In the load-sharing structures, as the expert data on the number of failures in the case when entire cut load is taken over by one device are not available, a parallel RS can be adopted.

In operation, the CSD cut elements may become failure and cannot be operated. If in a two-element RS with stand-by reserve one element is non-operational then it becomes a single element structure. If in a three-element RS with stand-by reserve one element is non-operational then it becomes a two-element structure with one element in reserve. If in that structure two elements are non-operational then it becomes a single-element structure. Identical situation occurs in the case of element failures in the parallel RS systems.

3.2. FUZZY APPROACH TO THE CUT FAILURE NUMBER ESTIMATION

Our variables LV are estimates of the average linguistic annual numbers of CFs failures N_{ik} of cuts CSD_{ik} and N_{ikl} devices D_{ikl} , $i = 1, 2, \dots, J$, $k = 1, 2, \dots, K$, $l = 1, 2, \dots, L$. We define those variables and their linguistic term-sets $LT-S$. We assume seven-element sets of those values: *minimum, very small, small, medium, high, very high and critical*. We assume that these values represent the *reliability state* of appropriate objects [12].

From the expert investigations we obtain the universe of discourse values UD_{ik} of individual cuts. Each of those universes is divided into six equal intervals. We assume that the boundary values

$$N_{ik}^1, N_{ik}^2, \dots, N_{ik}^7 \quad (12)$$

of those intervals are singleton member functions of the corresponding linguistic variable values LV_{ik} [12].

The universe of discourse values UD_{ik} are the variability intervals of the numbers of failures of cuts CSD_{ik} appearing on the left hand sides of equations (7) – (11). In the case of a single element RS, parallel RS and with stand-by reserve composed of identical elements in terms of reliability, we can easily determine the minimum and maximum numbers of element failures

$$N_{ikl}^1, N_{ikl}^7 \quad (13)$$

and their universes of discourse UD_{ikl} and then the singleton seven-element member functions:

$$N_{ikl}^1, N_{ikl}^2, \dots, N_{ikl}^7. \quad (14)$$

If all the cut elements remain in the *minimum* state then the cut is also in the *minimum* state. If all the cut elements remain in the *critical* state then the cut is also in the *critical* state. The situation is more difficult when the cut elements are not identical in terms of reliability. Then expert opinion-based heuristic solutions must be applied.

4. CASE STUDY

The example pertains to the prediction of a seagoing ship propulsion risk. Determination of the probability of loss of ship propulsion capability and its consequences are difficult because of the lack of appropriate data. This applies in particular to the risk estimates connected with decisions made in the ship operation phase.

The object of investigation was a PS consisting of a low-speed piston combustion engine and a constant pitch propeller, installed in a container carrier operating on the Europe - North America line.

The FT of analysed PS ICF failure is shown in the Figure 2. For reasons of huge number of SDs the structure of a fuel oil subsystem is only described within the lowest FT level. The PS subsystems' SSs make the CSS cuts and their sets of devices SDs – the CSD cuts. In considered case the system FT consists of alternatives of those cuts. In general such FT structure doesn't have to appear in the case of that PS type.

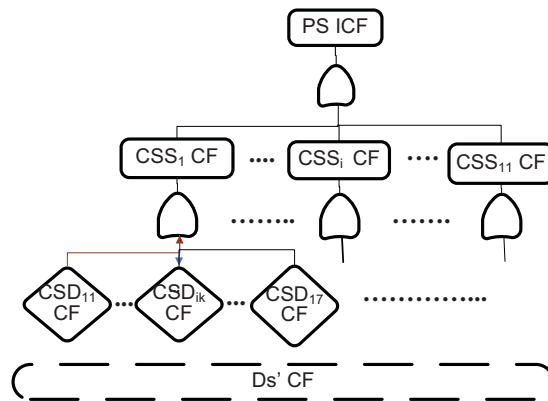


Fig. 2. Fault tree of a ship propulsion system ICF. Legend: PS – propulsion system; ICF – immediate catastrophic failure; CF – catastrophic failure.

CSS_i – subsystem cut, i=1 -fuel oil subsystem, 2 -sea water cooling subs.; 3 – low temperature fresh water cooling subs.; 4 – high temperature fresh water cooling subs.; 5 – startig air subs.; 6 – lubrication oil subs.; 7 – cylinder lubrication oil subs.; 8 - electrical subs.; 9 – main engine subs.; 10 – remote control subs.; 11 – propeller + shaft line subs.

CSD_{ik} – set of devices' cut; ik = 11 - fuel oil service tanks; 12 – f. o. supply pumps; 13 – f. o. circulating pumps; 14 – f. o. heaters; 15 -filters; 16 – viscosity control arrangement; 17 - piping's heating up steam arrangement.

The FT allows the building the neural network. The sets of input signals for the network are assigned.

Using the code [8], five categories of ICF consequences were distinguished, including *very serious casualty C1*, *serious casualty C2* and *three incident categories*. Consequences of the alternative of first two events were investigated ($C = C1 \cap C2$).

The consequences are connected with losses. They may involve people, artifacts and natural environment. They are expressed in physical and/or financial values. Detailed data on losses are difficult to obtain, particularly as regards rare events like the C1 and C2 type consequences. They

cannot be obtained from experts either, as most of them have never experienced that type of events. In such situation, the risk was related only to the type C consequences of an ICF event.

4.1. ACQUISITION AND PROCESSING OF EXPERT OPINIONS

The experts in the ICF event investigation were ship mechanical engineers with multi-year experience (50 persons). Special questionnaires were prepared for them, containing definition of the investigated object, SS and SD schemes, precisely formulated questions and tables for answers. The questions asked pertained to the number of ICF type events caused by equipment failures or human errors within one year and the share of time at sea in the ship operation time (PS observation time by expert). These were the only questions requiring numerical answers.

Other questions were of a linguistic character and pertained to the share of CF type failures of individual CSS in the annual number of the PS ICF type events and the share of CF failures of individual CSD in the annual numbers of CSS failures. In both presented cases the experts chose one of five values of the linguistic variables: *very great, great, medium, small, very small*. The elicited linguistic opinions were compared in pairs and then processed by the AHP method [6,11]. The obtained distribution of subsystem shares complies with the engineering knowledge. The greatest shares are due to the main engine and the electric power and fuel supply systems and the smallest - due to the propeller with shaft line.

The experts in the ICF event consequence field were ship mechanical engineers and navigation officers (37 persons). A similar questionnaire was prepared with questions about preferences of 5 possible consequences (*C1 - very serious casualty, C2 - serious casualty and 3 types of incidents*) of the ICF type event occurrence. The casualty types were defined in accordance with the code [8]. The experts could choose from the following preferences: *equivalence, weak preference, significant preference, strong preference, absolute preference, and inverse of these preferences* [6,11]. After processing of the so obtained data by the AHP method, a normalized vector of shares of the ICF type event consequences was obtained.

4.2. SOME RESULTS

The PR model was subjected to a broad range of tests. Some of the results are presented below. Figures 3 and 4 present the probability of the occurrence of defined numbers ICF type events of PS in dependence on the prediction time, when PS is in excellent and critical reliability states. The number of ICF events from 1 to 5 was adopted for each of those states. The probability was performed for the prediction time $t^{(p)} = 1, 3$ and 6 months. The diagrams 3 and 4 indicate that the occurrence of ICF events and their numbers are significantly greater when PS is in the critical state than in excellent state.

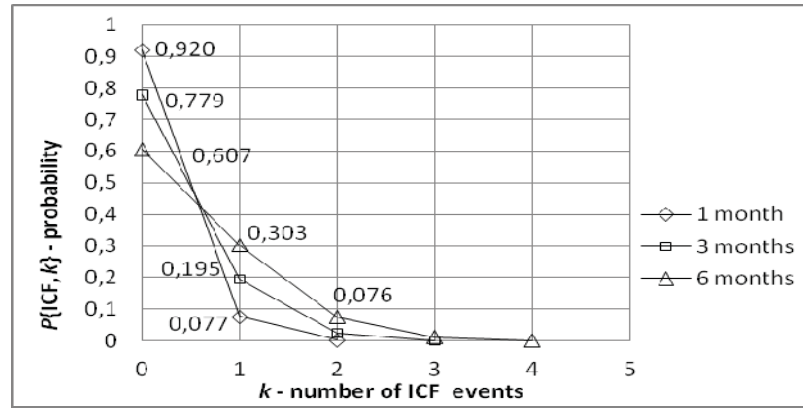


Figure.3. Probability of the ICF type events versus the numbers of those events for the selected times of risk prediction. PS reliability state is excellent.

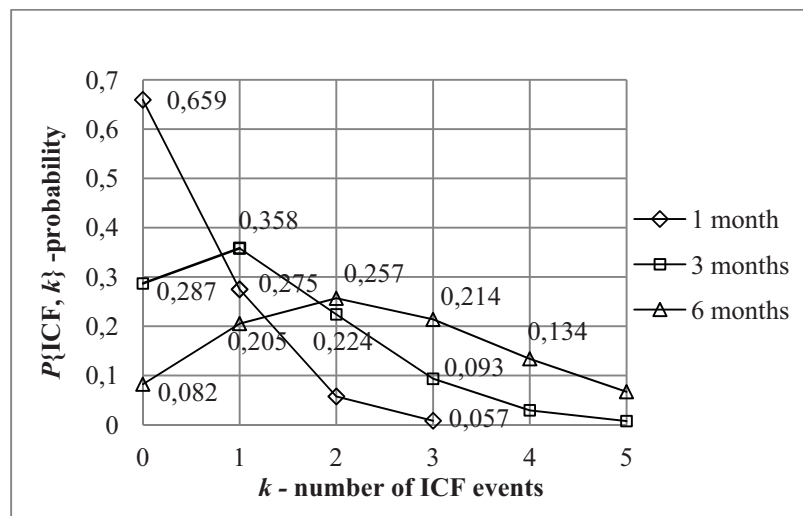


Fig. 4. Probability of the ICF type events versus the number of those events for the selected times of risk prediction. PS reliability state is critical.

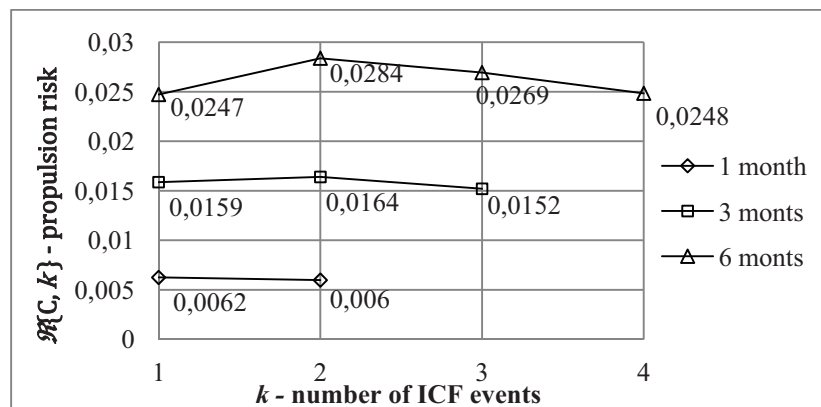


Fig. 5. Propulsion risk versus the numbers of ICF events for selected prediction times. PS reliability state is excellent.

Figures 5 and 6 presents the PR risk, i.e. the risk of type C consequences after occurrence of an ICF event, for the prediction times $t^{(p)} = 1, 3$ and 6 months, when PS is in the excellent and critical states. The diagrams show increased risk with deteriorating PS reliability.

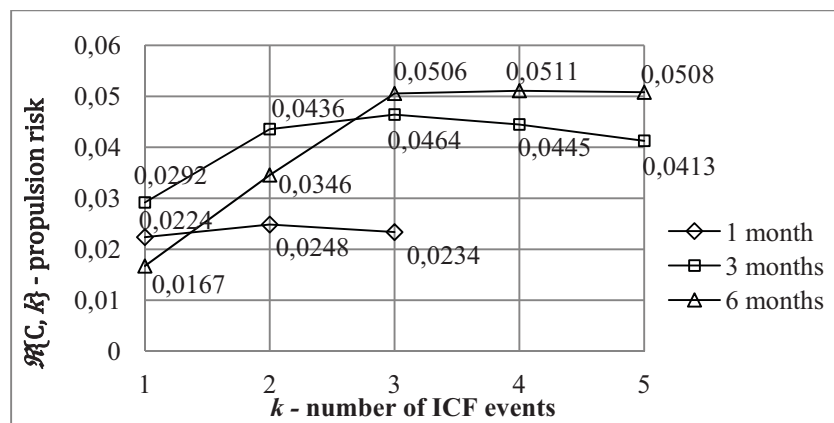


Fig. 6. Propulsion risk versus the numbers of the ICF events for selected times of prediction. PS reliability state is critical.

5. SUMMARY

A fuzzy-neural model of risk prediction has been developed, based on the knowledge acquired from experts. It is a model of homogeneous Poisson renewal process, where parameters are determined by means of a neural network. The model parameter estimation data were acquired from experts - the modeled system operators. Their opinions were elicited in a numerical form as regards the events observed by them many times and in a linguistic form in the cases where their knowledge might be less precise. The neural network was tuned with the elicited opinions. The network may be calibrated with data collected in the system operation process. In this way the Homogeneous Poisson Process can be adapted to real operating conditions - it becomes non-homogeneous in steps. The model allows prediction of the risk of dangerous events consequences, which may occur due to different systems.

In the expert investigations we have to rely on data obtained from experts and models are constructed from that data. The adequacy and type of obtained information depends on the form and adequacy of the data. The expert competence level must not be exceeded. In the case reported here, it might have happened in the estimates of occurrence of the ICF event consequences. In the authors' opinion, the competence level was not exceeded as the remaining data are concerned, as the choice of experts was careful.

The expert-elicited data have an impact on the level of adequacy of models used in the investigations - like data like model. A number of simplifying assumptions had to be made. Some of them are the following: two states of the use of modeled objects, failures possible only in the active use state, homogeneity of the Poisson renewal process, the cut notion, definition of the ICF event consequences etc.

Results of the propulsion risk estimates quoted in section 4 are not questionable as regards the order of magnitude of the numbers. Events from the subset of C consequences occur at present in about 2% of the ship population (20 ships out of 1000 in a year). This applies to ships above 500 GT. There are at present about 50 thousand such ships (7,13). The results are also adequate in terms of trends of changes in the investigated values, which are in compliance with the character of the respective processes.

It has to be taken into account that results of a subjective character may be (but not necessarily) subject to greater errors than those obtained in a real operating process. The adequacy of such investigations depends on the method applied, and particularly on the proper choice of experts, their motivation, as well as the type of questions asked. In the expert investigations the fuzzy methods are especially useful.

In the authors' opinion, the main difficulty in the neural network application for modeling is the necessity of having a considerable amount of input and output data for tuning the models. In the prospective investigations the data are generally in short supply. They may be gathered after some time in the operating process of the respective objects, but that may appear to be too late.

There is a chance of further developing and using the risk prediction program, developed under the project, aboard ships and not only for the propulsion systems. It could be coupled with the existing equipment renewal management or operating management programs.

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SHIP'S SAFETY HAZARDS DURING REPLACEMENT OF BALLASTS AT SEA

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Abstract

The sequential replacement of ballast water at sea during the ship voyage is commonly used on board the ships. However, the successive emptying and filling of ballast tanks causes the occurrence of hazards to ship's safety. The article presents hazards to ship's safety and the calculations have been performed of the most dangerous hazards in respect of ship operation, for the m/v „Orla” ship on calm water. The obtained service conditions of the ship during replacement of ballasts shall be the basis for calculating the ship's safety hazards on waves.

Key words: Ship ballasting, ship's safety hazards during replacement of ballasts, sequential method of ballast water replacement

1. Introduction

There occur such periods during ship operation and service in which water ballast is carried on board the ship. Such situations occur when the ship is sailing without any cargo, or if it is only partly loaded and the ballast taken on board is intended for improving or ensuring the ship's safety, mainly in respect of stability. In a situation when the ship is [to be] unloaded it takes on board the water ballast for safe voyage. In the port of destination, when the ship is loaded with a new cargo, the ballast taken on board earlier has to be removed. So as to avoid translocation of live organisms in ballast water from one point to another, the ballasts waters removed in harbour have to be cleaned / purified with physical or chemical methods. These methods are expensive and applied rather reluctantly, so what remains is the replacement of ballasts during the ship's voyage at sea, in areas specified by the relevant rules.

2. Replacement of ballasts at sea

There are three basic methods of replacing ballast waters:

- The sequential method in which ballast tanks are successively emptied and filled with sea water,
- The flow-trough method in which ballast tanks are filled with sea water, which in turn forces out the water previously taken into the tanks from these tanks,

- The dilution method, in which a ballast tank is filled from the top and at the same time water is pumped out of its bottom part so as to maintain the constant level in the ballast tank.

The first one of the methods described above is the most commonly used by the ships. It is the quickest and the least energy-consuming method of all and it does not need the use of additional technical solutions in the ballast system existing on board the ship. However, the successive emptying and filling of tanks results in periodical worsening of stability conditions and other characteristics of the ship, having an impact on its safety. In the sequential method particular operations make up the so called sequences (sequence of emptying and filling) on particular tanks. The sequential method is used when replacement of ballasts requires removal of rather big volumes of water at the moment of ship's voyage duration, followed by refilling of tanks with sea water from a given place of the ship's voyage. It is a new procedure, different from the ballasting technology applied at harbour, because at sea the probability of different hazards occurrence is much higher, especially during waves and wind effects acting on the ship.

The following procedure is applied when determining the sequences of emptying and filling of ballast tanks in the process of ballasts replacement. The ship's service characteristics are specified, such as: trim, draught, values of shearing forces and bending moments occurring in the hull. These calculations are carried out at the filling and emptying of the successive ballast tanks. Thus calculated values are compared with the critical values. Such calculations are repeated for subsequent tanks. The evaluation of safety conducted in such a way concerns only the ship service parameters as if it was on calm water without waves. In accordance with the Convention [5] the ballasts replacement sequence should be demonstrated at least for typical loading conditions derived from the approved Information on Stability. The description of the sequence of ballast waters replacement should be split into particular steps where each of them is summed up with the following information items:

- the water volume in each of the tanks,
- the pumps used,
- the approximate time of operation,
- the longitudinal strength of the hull, as the function of permissible values,
- the information on stability, taking into account free surface areas of liquid during the emptying or filling operations,
- the values of draughts at forward and after perpendiculars,
- other information items (ballast replacement location in geographic coordinates, etc.).

The sequence of ballast waters replacement may be different for different ships and for other loading conditions, one should be guided first of all by the ship's safety. Unballasting of tanks arranged along one ship's side shall be avoided (it involves the risk of the ship capsizing), as well as simultaneous emptying of neighbouring sections of tanks located in vicinity (high shearing forces and bending moments arise). Establishing the sequence of ballasts replacement occurs taking into account valid provisions of law and restrictions. The sequential method for a given ship is prepared in form of the Ballast Water Management Plan. This Plan is prepared individually for each ship and approved by a Classification Society.

During the ballast waters replacement the ship must be located at an appropriate distance from the shore and at a depth [draught] specified by relevant regulations. It is, respectively: 200 miles and 200 m [5].

3. Ship's safety hazards during replacement of ballasts

Depending on the ship size (number and size/capacity of ballast tanks) and also depending on delivery values of the pump used, the smaller-size ships need c.a. 24 hours for full replacement of

water in tanks and bigger-size ships (with a large amount of ballast) even up to more than 2 days. The obligatory duty of the ballast waters replacement causes that the replacement process must often take place during waves and wind effects acting on the ship. The ship has no option to wait for the end of severe weather conditions, and during the operation the weather conditions may get worse. Following the obligatorily imposed distance from the shore and the depth of the water area, where the replacement of ballast water can take place, the ballast replacement area may be very narrowed.

Hence one can assume that from the point of view of the ship's safety in terms of stability the process of ballast water replacement shall be rather hazardous; in addition, the intensification of hazards shall have growing tendency in unfavourable weather conditions.

The hazards arising during the ballast water replacements using sequential method in which ballast tanks are successively emptied and filled with sea water are presented in table 1.

Tab. 1. Kinds of hazards to ship's safety in selected methods of ballast water replacement [3], [6]

Item.	Kind of hazard to the ship	Flow-through method	Sequential method
1.	Reduction of stability of ships with ballast in cargo spaces	x	x
2.	Excessive bending moments and shearing forces in hull binding and lashing	-	x
3.	Excessive torsional stresses in the hull	x	x
4.	Damages of tank constructions	x	x
5.	Construction damages due to vacuum pressures in tanks during their emptying	x	x
6.	Construction damages due to excess pressures during their filling	x	x
7.	Stresses in constructions or troubles with maintaining stability at incorrect sequence of filling	x	x
8.	Construction damages of bottom bracings in forward part	-	x
9.	Loss of ship manoeuvrability and its ability to move	-	x
10.	Loss of visibility from the bridge due to big trims	-	x
11.	Overloading with stresses in cargo lashing and securing systems	-	x
12.	Difficulties in operating the equipment by the crew. Reduced efficiency of the whole operation, in particularly adverse weather conditions.	x	x
13.	Emergence of propeller	-	x
14.	Slamming	-	x
15.	Sloshing in ballast tanks	x	x
16.	Excessive heel of the ship	x	x
17.	Excessive increase of ship motions, especially roll motions	-	x

Kinds of hazards occurring during ballast water replacements at sea may be different for different types of ships which has been emphasized i.a. in [3].

Based on analyses included in various publications it is emphasized that the most important causes of the hazards occurrence are as follows:

- too long time of ballast replacement duration,
- wrong sequence tanks of emptying and filling of ballast tanks,
- unfavourable weather conditions (wind, high waves).

On the other hand, out of different hazards, the following ones are considered as the most dangerous in respect of the ship operational aspects:

- loss or considerable worsening of ship stability,
- increase of ship motions, especially roll motions,

- propeller emergence, at insufficient stern draught which causes worsening of propulsion characteristics and manoeuvrability,
- bow emergence which results in slamming occurrence and worsening of visibility from the navigating bridge (occurrence of the so called blind sector before the ship's bow).

For estimating the ship's safety during the operation of replacement of ballasts the following criteria or recommendations are applied:

- in case of ship stability – the criteria included in regulations of the Classification Societies or in provisions of IMO [4],
- for evaluating the visibility from the navigating bridge– The SOLAS Convention [2],
- minimum bow draught – DnV Rules [8],
- minimum stern draught – being of the value preventing the propeller emergence.

4. The ballast system of the m/v „Orla” ship

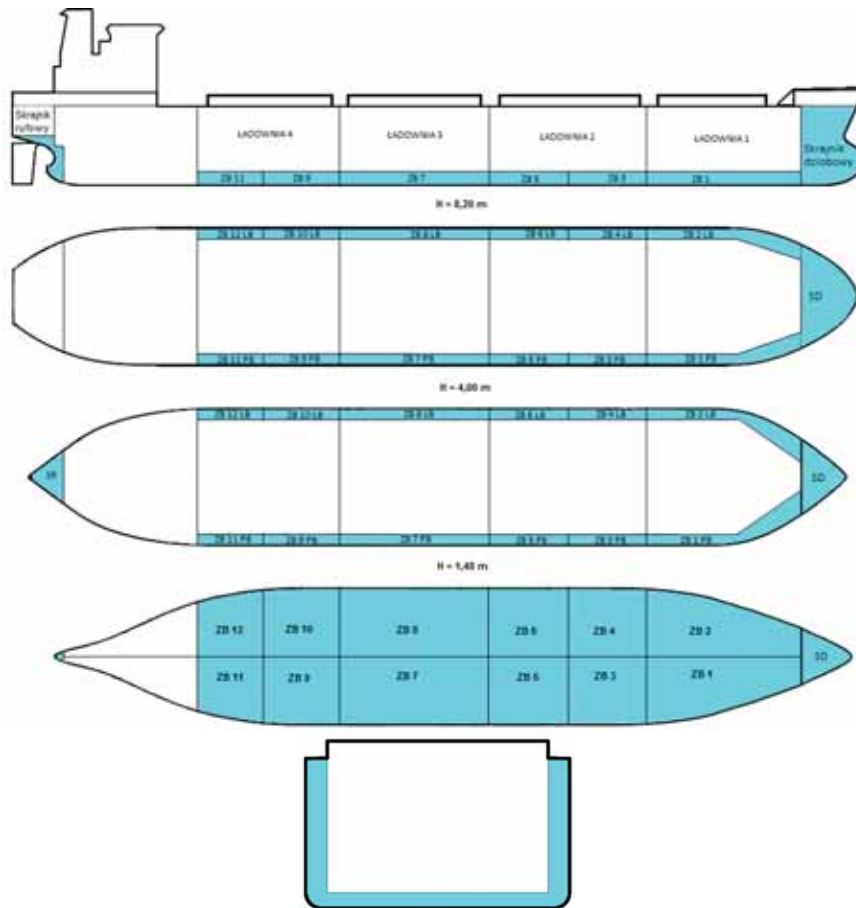
The calculation of the hazards to ship's safety during ballast water replacements have been performed for the m/v „Orla” ship, and the relevant parameters are presented in tables 2 and 3. In drg 1 the plan of placing the ballast tanks is presented and in table 4 - parameters of these tanks.

Tab. 2. Characteristics of the m/v „Orla” ship [1]

Name	-	Orla
Owner	-	PŻM [Polish Steamship Company]
Ship type	-	Universal bulk carrier
Rules (classifying authority)	-	PRS [Polish Register of Ships]
The ship service speed	V [kn]	7,08 (13,77 kn)
Length overall	L_{OA} [m]	149,4
Length between perpendiculars	L_{pp} [m]	138,0
Breadth	B [m]	23,11
Side height	H [m]	12,10
Draught to summer load waterline	T_s [m]	8,55
Displacement	D [T]	220150
Deadweight capacity	DWT [t]	17033

Tab. 3. Characteristics of the m/v „Orla” ship ballast system [1]

Total number of ballast tanks	14
Bottom tanks	14
Max. capacity of bottom tanks [m ³]	7650,7
Max. volume ballast water [m ³]	7650,7
Number of ballast pumps	2
Delivery of ballast pump [m ³ /h]	650
Max delivery of ballast pumps [m ³ /h]	1200
Time of ballast removal [h]	7,08
Time of ballast filling [h]	7,08



Drg. 1. Plan of the ballast tanks arrangement on board the m/v „Orla” ship

Tab. 4. Ballast tanks included in the ballast system of the m/v „Orla”ship [1]

Tank name	Number of frame [-]	Tank capacity V_z [m ³]	Water mass in tank M_z [t]	Coordinates of tank location			Moment of tank surface area MH_z [m ⁴]
				XG_z [m]	ZG_z [m]	YG_z [m]	
Forepeak	173-187	674	690,85	133,34	7,33	0	1618
Tank nr 1 PB	141-173	901	923,53	117,64	5,47	7,21	1728
Tank nr 2 LB	141-173	901	923,53	117,64	5,47	-7,21	1728
Tank nr 3 PB	126-141	422,4	432,96	98,38	4,32	8,63	1146
Tank nr 4 LB	126-141	422,4	432,96	98,38	4,32	-8,63	1146
Tank nr 5 PB	110-126	452,3	463,6	86,0	4,31	8,64	1240
Tank nr 6 LB	110-126	452,3	463,6	86,0	4,31	-8,64	1240
Tank nr 7 PB	78-110	838,4	855,26	67,69	4,11	8,49	2480
Tank Tank nr 8 LB	78-110	838,4	855,26	67,69	4,11	-8,49	2480
Tank nr 9 PB	63-78	418,6	429,06	48,04	4,35	8,61	1108
Tank nr 10 LB	63-78	418,6	429,06	48,04	4,35	-8,61	1108
Tank nr 11 PB	47-63	399,4	409,3	35,79	4,66	8,35	800
Tank ik nr 12 LB	47-63	399,4	409,3	35,79	4,66	-8,35	800
After-peak	8-19	110,7	113,46	4,14	6,88	0,4	435
Total	-	7650,7	7841,3	84,4	4,88	0,01	-

5. Impact of ballast replacement on the ship service parameters on calm water

Calculations of the ship's safety hazard occurring during replacement of ballasts were carried out for the sequence of emptying and filling of ballast tanks applied on board the ship – table 5.

Tab. 5. The sequence of emptying and filling of ballast tanks in the sequential method for the m/v „Orla”ship [7]

Replacement step	Operation name	Ballast weight [t]	Replaced ballast [t]	Replacement time [h]
0	Initial condition – ship in ballast	7841,9	0	0 ^h 0 ^m
1	Emptying, tanks nos: 7, 8, forepeak, after-peak	5318,8	2523,1	2 ^h 20 ^m
2	Filling, tanks nos: 7, 8, forepeak, after-peak	7941,9	0	2 ^h 10 ^m
3	Emptying, tanks nos: : 1, 2, 11, 12	5173,5	2668,4	2 ^h 30 ^m
4	Filling, tanks nos: 1, 2, 11, 12	7941,9	0	2 ^h 15 ^m
5	Emptying, tanks nos: 3 i 4	6976,9	865	0 ^h 50 ^m
6	Filling, tanks nos: 3 i 4	7941,9	0	0 ^h 45 ^m
7	Emptying, tanks nos: 5 i 6	6914,7	927,2	0 ^h 55 ^m
8	Filling, tanks nos: 5 i 6	7941,9	0	0 ^h 50 ^m
9	Emptying, tanks nos: 9 i 10	6983,7	858,2	0 ^h 50 ^m
10	Filling, tanks nos: 9 i 10	7941,9	0	0 ^h 45 ^m
				14^h10^m

The calculated ship service parameters during the emptying and filling of ballast tanks are presented in table 6 and in drgs 2 ÷ 6. In the drawings also the critical values are shown on the basis of which one can estimate in which stage (replacement step) specific hazards arise.

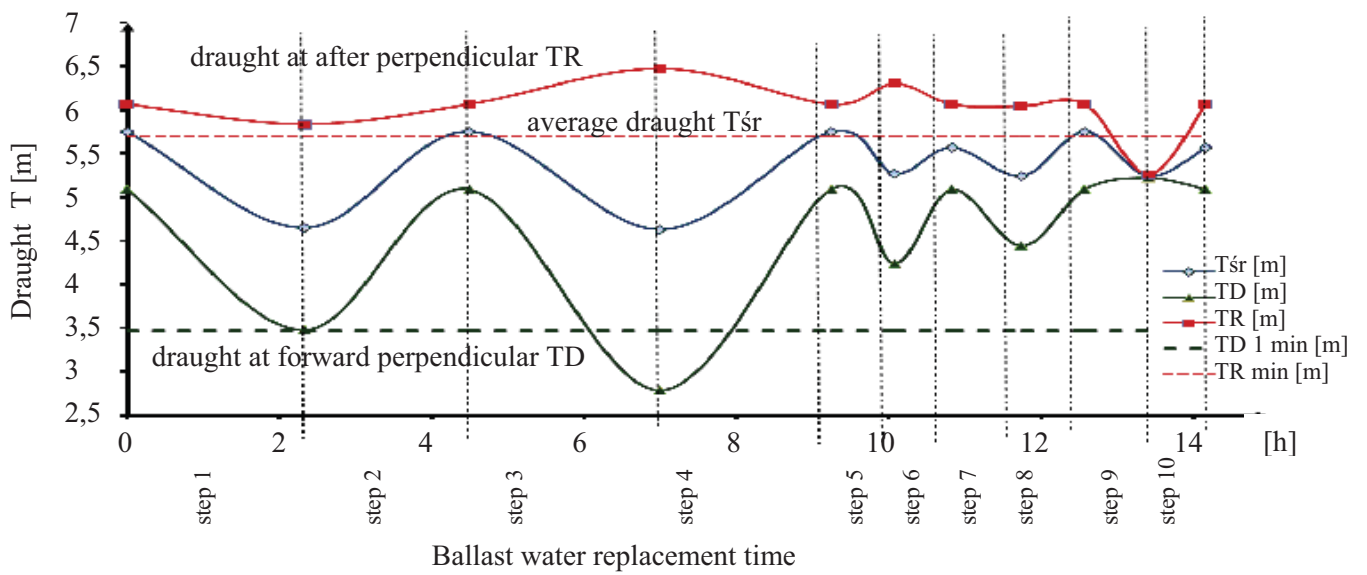
Tab. 6. The service and stability parameters of the m/v „Orla” ship during the emptying and filling of ballast tanks in particular replacement steps [7]

Step	D [T]	t [m]	T _S [m]	T _A [m]	T _F [m]	BM [%]	SF [%]	Propeller immersion draught [m] <456,7	Propeller draught [%]	GM [m]	KG [m]	KM [m]	GZ max [m]	GZ Range [°]	ΔGM [m]
0	13961,6	-0,96	5,57	6,06	5,09	70	27	147,39	106,7	3,77	6,49	10,32	2,86	> 60	0,06
1	11438,5	-2,35	4,65	5,83	3,48	79	28	187,78	102,2	4,32	6,8	11,19	2,85	> 60	0,07
2	13961,6	-0,96	5,57	6,06	5,09	70	27	147,39	106,7	3,77	6,49	10,32	2,86	> 60	0,06
3	11293,2	-3,68	4,63	6,47	2,79	50	27	222,15	113,0	4,39	6,79	11,29	2,87	> 60	0,07
4	13961,6	-0,96	5,57	6,06	5,09	70	27	147,39	106,7	3,77	6,49	10,32	2,86	> 60	0,06
5	13096,6	-2,07	5,27	6,30	4,24	70	30	172,35	110,6	3,86	6,64	10,55	2,81	> 60	0,06
6	13961,6	-0,96	5,57	6,06	5,09	70	27	147,39	106,7	3,77	6,49	10,32	2,86	> 60	0,06
7	13034,3	-1,61	5,24	6,04	4,44	79	28	163,53	106,1	3,86	6,65	10,57	2,91	> 60	0,06
8	13961,6	-0,96	5,57	6,06	5,09	70	27	147,39	106,7	3,77	6,49	10,32	2,86	> 60	0,06
9	13103,4	-0,04	5,24	5,26	5,22	76	33	163,60	92,9	3,86	6,63	10,55	2,81	> 60	0,06
10	13961,6	-0,96	5,57	6,06	5,09	70	27	147,39	106,7	3,77	6,49	10,32	2,86	> 60	0,06

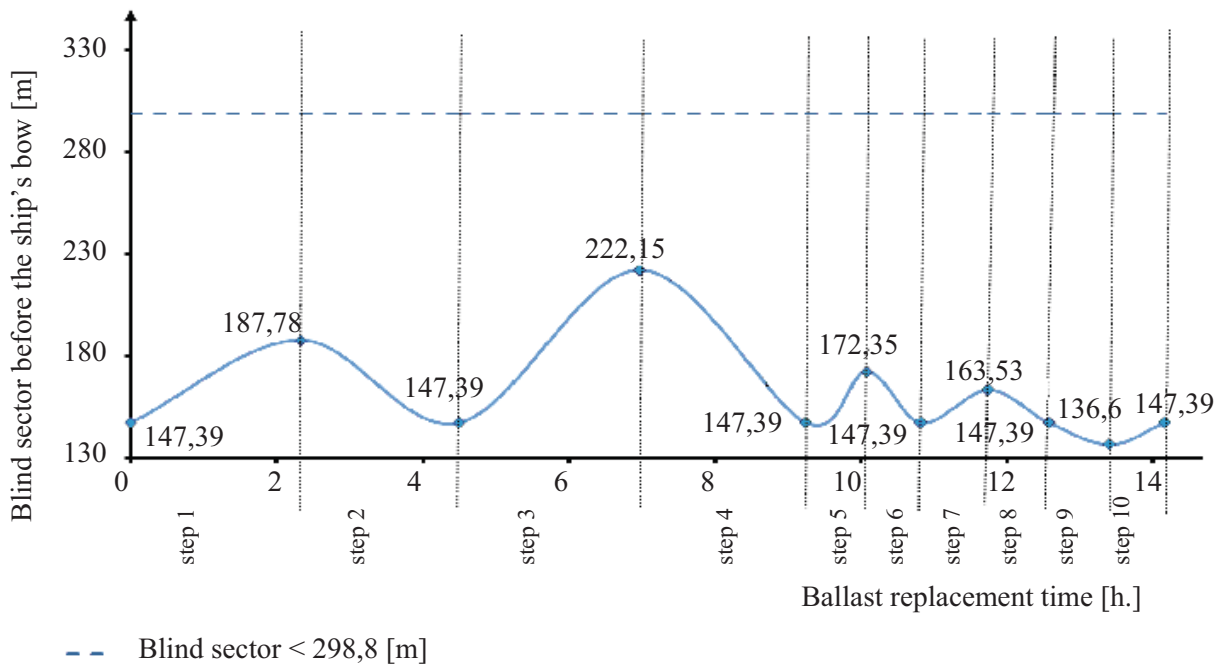
where:

- D – ship buoyancy,
- t – ship trim,
- T_S – average draught,
- T_A – draught at after perpendicular,
- T_F – draught at forward perpendicular,
- BM – value of bending moment in hull in % of maximum value,

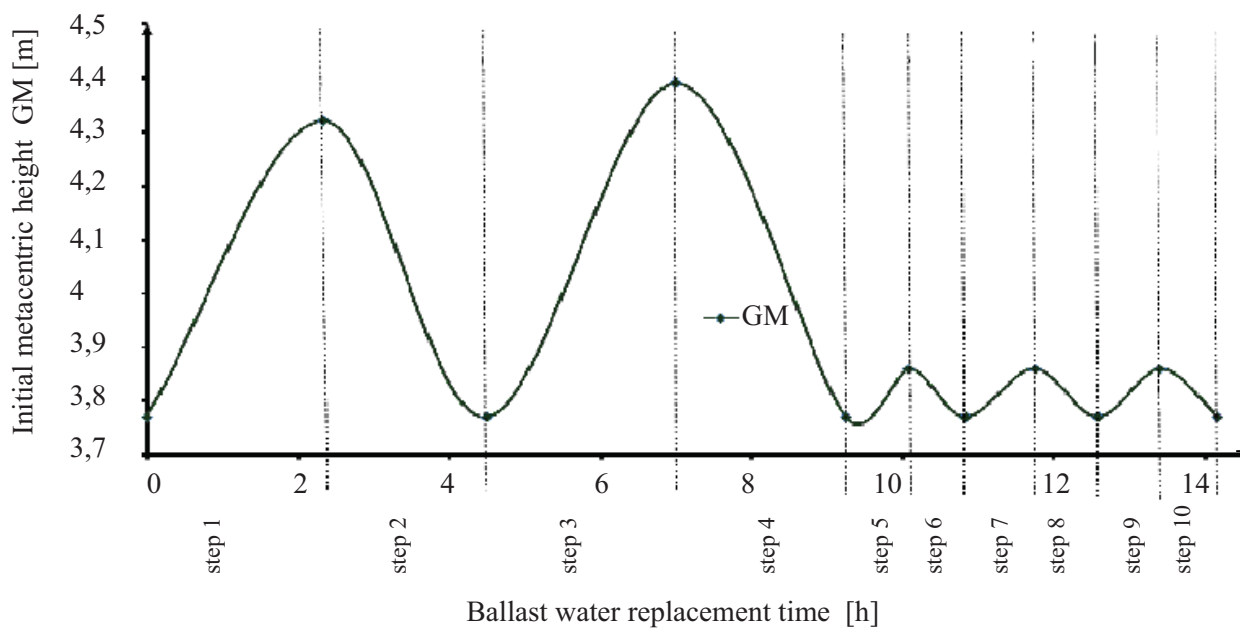
- SF – value of shearing force in hull in % of maximum value,
- GM – initial metacentric height,
- KG – rise of the centre of gravity of the ship,
- KM – rise of the metacentre,
- GZ – maximum value of righting arm,
- ΔGM – correction for free surface areas of liquid .



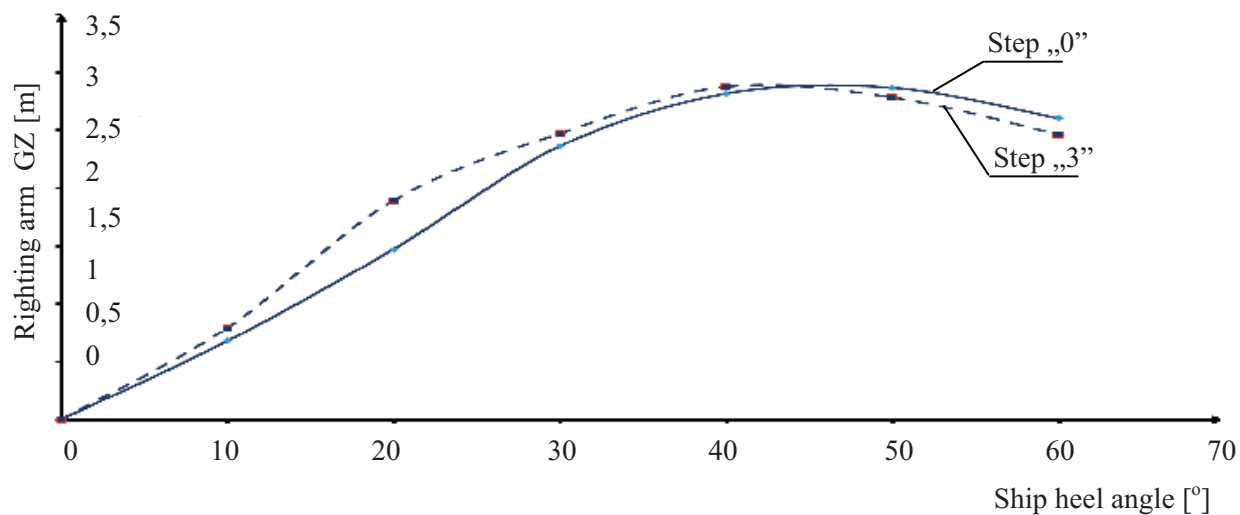
Drž. 2. Change of the *m/v „Orla”* ship draughts during the ballast water replacements



Drž. 3. Change of the blind sector before the *m/v „Orla”* ship bow during the ballast water replacement



Drž. 4. Change of the initial metacentric height of the m/v „Orla” ship during the ballast water replacements



Drž. 5. Curve of righting moment lever of the m/v „Orla” ship for selected stages of the ballast water replacements



Drž. 6. Diagram of maximum values of the shearing forces and bending moments in the ship hull initial during the ballast water replacements – the m/v „Orla” ship

6. Evaluation of the ship’s safety during replacement of ballasts on calm water

On the basis of the obtained calculation results it was found out that:

- the bow and stern draught is minimum, it is exceeded in the middle and final stages of ballast replacement, which during the ship navigation on waves shall result in slamming and the propeller emergence,
- the initial transverse metacentric height is very high,
- the range of curves of statical stability is very good.

General conclusions

The Plan of Ballast Replacement prepared and used on board the ship does not guarantee full safety even on calm water.

As regards the ship’s safety in respect of stability it does not occur on calm water. For the ship the emptying of the ballast tanks does not cause worsening of the curves of statical stability or reduction of the initial metacentric height – it is quite the other way round, during the emptying of the ballast tanks the initial metacentric height rises. However, the initial metacentric height being too high is not a good solution, either, because on waves the ship has low [small] period of motions – it becomes too “rigid”.

The performed analysis of changes in selected ship service parameters has proved that replacement of ballasts on calm water is a difficult procedure being hazardous to the ship. The level of ship’s safety gets changed with the change of the service parameters values in relation to criterial values.

In the next article there shall be conducted the ship safety analysis during ballast replacement at waves and wind effects acting on the ship.

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INFLUENCE OF WEATHER CONDITIONS ON THE SHIP'S SAFETY DURING REPLACEMENT OF BALLAST WATER

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Abstract

The sequential method of ballast water replacement at sea during the ship voyage is commonly used on board the ships. However, the successive emptying and filling of ballast tanks causes the occurrence of hazards to ship's safety. The article presents the calculation results of ship roll motions, pitch motions, slamming and emergence of propeller during ballast replacement at different sea states. It has been shown at which stages of ballast replacement specific hazards arise and how they could be avoided or minimized, especially under severe weather conditions.

Key words: *ship ballasting, ship's safety during replacement of ballasts, sequential method*

1. Introduction

The article [2] presents the calculation results of the m/v „Orla”ship service parameters when applying the sequential method of the replacement of ballasts during the ship's voyage at sea. For certain steps of emptying and filling of ballast tanks on calm water the service parameters values were higher than critical values and this fact already constituted a hazard to safety of the ship. In this article certain sea-keeping abilities of the ship shall be presented which are of major significance during replacement of ballasts, mainly for these cases in which hazard to ship safety occurred already on calm water.

2. Ship's sea-keeping abilities during replacement of ballasts

For estimating the ship's safety on waves during the operation of replacement of ballasts the following sea-keeping abilities were chosen which may constitute a hazard to safety of the ship [4]:

- rolling,
- pitching,
- slamming,
- emergence of propeller,

2.1. Ship motions on waves

Using the commonly applied linear theory of ship motions [3], within the scope of which, on regular waves described by equation:

$$\zeta(t) = \zeta_A \cos(kx - \omega t), \quad (1)$$

ship motions on these waves are given in the following form:

$$u = u_A \cos(-\omega_E t + \varepsilon_u), \quad (2)$$

where:

ζ_A – amplitude of regular wave,

k – wave number,

$$k = \frac{\omega^2}{g} \quad (3)$$

ω – frequency of regular wave,

u_A – frequency transfer functions of ship motions „ u ”, (for $u = 4$ - rolling Φ , $u = 5$ - pitching θ , respectively),

ω_E – frequency of encounter of ship motions,

$$\omega_E = \omega - kV \cos \beta_w \quad (4)$$

V – ship speed,

β_w – wave direction related to ship ($\beta_w = 0^\circ$ following sea [waves] from the aft, $\beta_w = 90^\circ$ beam sea [lateral wave], $\beta_w = 180^\circ$ head sea).

ε_u – angle of phase displacement between wave and ship motion.

The random motions of the ship on the irregular waves can be simply determined on the basis of knowledge about frequency transfer functions of ship motions on regular waves and about function of the random wave energy spectral density. The variance of ship motions is then equal to:

$$D_{uu}(\beta_w, V) = \int_0^\infty [Y_{u\zeta}(\omega_E / \beta_w, V)]^2 S_{\zeta\zeta}(\omega_E) d\omega_E, \quad (5)$$

where:

D_{uu} – variance of motions u ,

$Y_{u\zeta}$ – frequency transfer functions of ship motions u on regular waves,

$S_{\zeta\zeta}(\omega_E)$ – function of the random wave energy spectral density, the value of which depends mainly on the significant wave height H_S and on period T_1 ,

The root of a variance D_{uu} is a mean square deviation of ship motions on irregular waves, on the basis of which statistical value of random motions can be calculated, having the assumed probability of exceeding, e.g.:

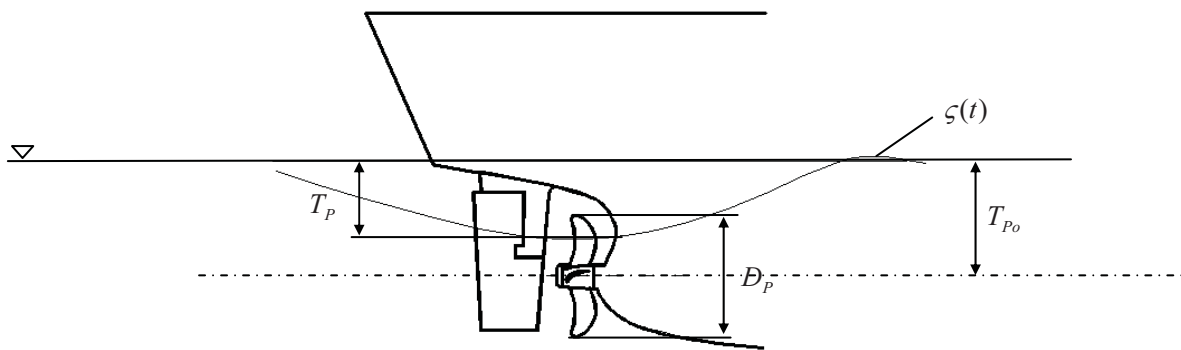
$$\bar{u}_{A1/3} = 2,0\sqrt{D_{uu}}, \quad (6)$$

$u_{A1/3}$ – significant amplitude of ship motions u (mean value of motion amplitude u out of 1/3 highest values of motions).

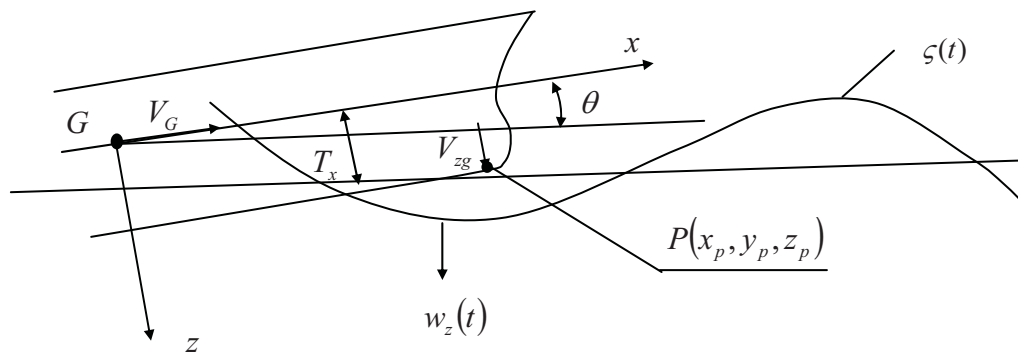
Other aforementioned phenomena, arising during ship navigation on waves, can be made conditional on ship motions.

2.2. Ship relative motions on waves

During ship motions on waves, its movement can be determined, related to wavy water surface. The occurring relative movement has a decisive influence on such phenomena like the emergence of propeller (drg. 1) or slamming (drg. 2, in case of slamming, what is also important is the relative vertical speed of the ship in area in which the probability of slamming occurrence is calculated).



Drg. 1. Influence of relative movement of the ship on emergence of propeller



Drg. 2. Bow emergence and relative velocity of bow submergence in wavy water (slamming)

The vertical relative displacement of the ship resulting from the ship motions and from shape of wavy surface is equal to:

$$R_{ZP} = Z_G + y_P \Phi - x_P \Theta - \zeta(t), \quad (7)$$

where:

$\zeta(t)$ is the wave profile described by equation (1),
 Z_G – ship heaving.

The vertical component of relative velocity of bow submergence in water (drg. 2) is equal to:

$$V_{RZP} = \dot{Z}_G + y_P \dot{\Phi} - x_P \dot{\Theta} - V \Theta - w_z(t), \quad (8)$$

where:

$\dot{Z}_G, \dot{\Phi}, \dot{\Theta}$ – speeds of ship motions heaving, roll motions and pitching,
 $w_z(t)$ – is the vertical component of water particle velocity in the wave motion,
 x_P, y_P – coordinates of point, for which relative movement or relative velocity is calculated, (in this case it will be respectively the point lying on the propeller blade – drg. 1, or on the bottom in the bow area – drg. 2).

Considering the fact that emergence of propeller or slamming are not continuous phenomena and they occur only in certain [specific] situations, for these phenomena probability is calculated when:

- the relative motion exceeds the depth of the propeller T_p point position (for the emergence of propeller, drg. 2),
- the relative motion exceeds the bow draught T_x and at the same time the relative velocity of bow submergence in water V_{RZP} , drg. 1, shall exceed the critical velocity $V_{kr} = 0,093\sqrt{gL}$ (for slamming).

For the phenomena listed hereinabove their number and probability of their occurrence are as follows:

– for the emergence of propeller:

$$N_{ZP} = \frac{3600 \cdot p_{ZP}}{T_u}, \quad (9)$$

where:

N_{ZP} – number of bow emergences within an hour,
 \bar{T}_u – mean period of motions,
 p_{ZP} – probability of the emergence of propeller:

$$p_{ZP} = \exp\left(-\frac{H_{Ezp}^2}{2c_u D_{ZP}}\right), \quad (10)$$

- D_{ZP} – variance of relative water motions at the ship's side, in the propeller area,
- c_u – correction factor considering inaccuracy of linear model of ship motions on real wave, [6],
- H_{EzP} – effective propeller immersion draught, including height of wave produced by ship movement with speed V ,

– for slamming:

$$N_{SL} = \frac{3600 \cdot p_{SL}}{T_u}, \quad (11)$$

where:

- N_{SL} – number of bow emergences within an hour,
- p_{SL} – probability of bow emergence and critical velocity exceeding,

$$p_{SL} = \exp\left(-\frac{T_{EXSL}^2}{2c_u D_{SLW}} - \frac{V_{KRSL}^2}{2c_u D_{SLP}}\right), \quad (12)$$

- T_{EXSL} – effective ship draught in area for which probability of bow emergence is calculated, including height of wave produced by ship movement with speed V ,
- D_{SLW} – variance of bow relative motions,
- V_{KRSL} – critical velocity of bow submergence in water, for which probability of deck wetness is calculated,
- D_{SLP} – variance of bow relative velocity.

2.3. Criteria of ship seakeeping ability estimation

On the basis of many-years' observations and experience, permissible values of ship motions and of accompanying phenomena have been specified; when these are exceeded, it may endanger safety of the ship, of the crew or of the equipment working on the ship, thus resulting in limitation of transport mission. Level of permissible values depends also on ship type and size. Specification of criteria, proposed by different researchers for selected seakeeping abilities is included in [5], [6].

For estimating the ship's safety during the operation of replacement of ballasts in waves conditions the following criterial values are assumed:

- for ship roll motions – $\Phi_{A1/3} = 12^\circ$
- for pitch motions – $\theta_{A1/3} = 3^\circ$
- for slamming – $N_{SL} = 20,3$ times/hour
- for the emergence of propeller – $N_{ZP} = 250$ times/hour

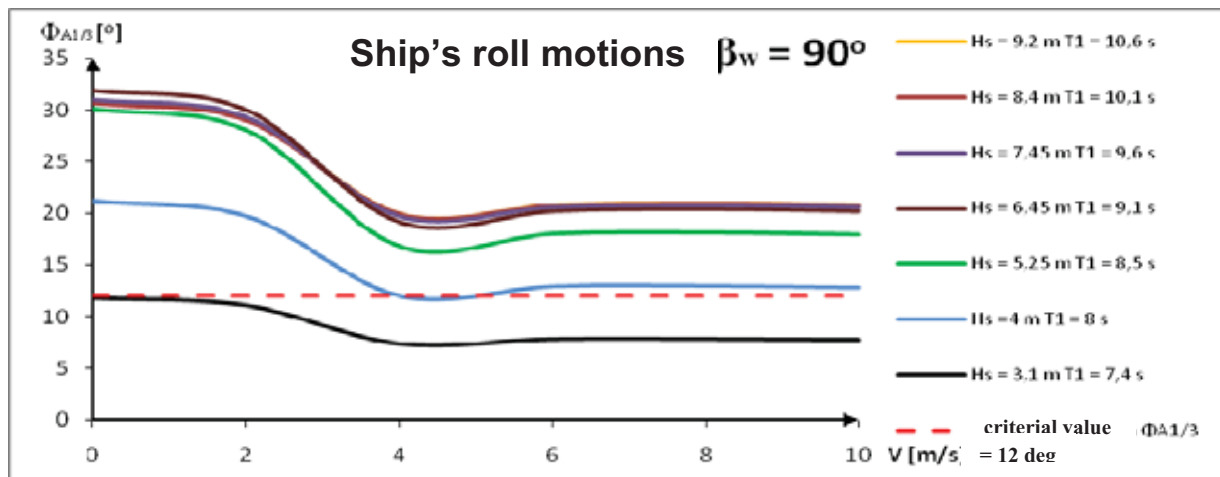
When investigating the influence of the ship's speed and ship's course related to [direction of] waves, the additional intermediate criteria were assumed:

- for ship roll motions – $(\Phi_{A1/3})_1 = 10^\circ$ i $(\Phi_{A1/3})_2 = 12^\circ$
- for pitch motions – $(\theta_{A1/3})_1 = 2^\circ$ i $(\theta_{A1/3})_2 = 3^\circ$

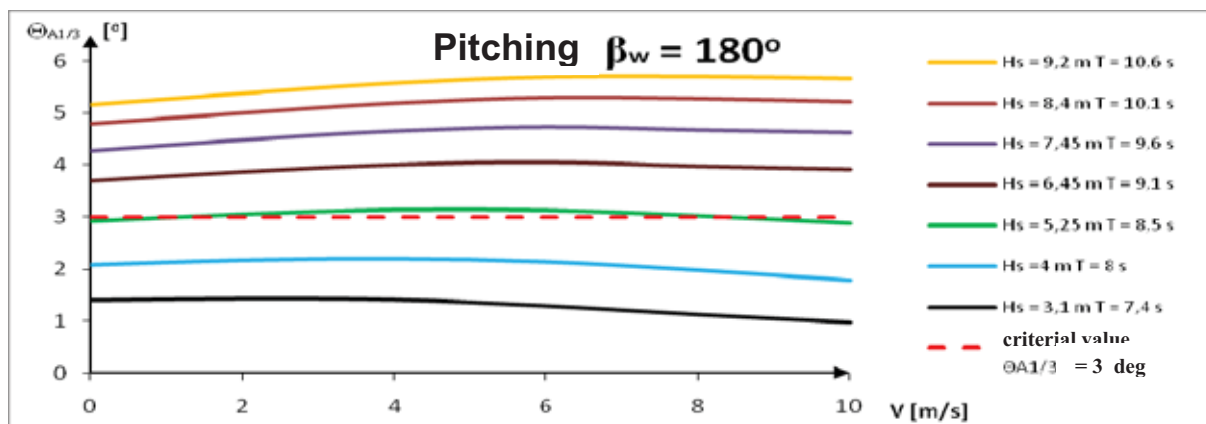
- for slamming – $(N_{SL})_1 = 15$ times/hour and $(N_{SL})_2 = 20,3$ times/hour
- for the emergence of propeller – $(N_{ZP})_1 = 200$ times/hour and $(N_{ZP})_2 = 250$ times/hour

3. Results of calculations of the selected ship’s sea-keeping abilities during replacement of ballasts at sea

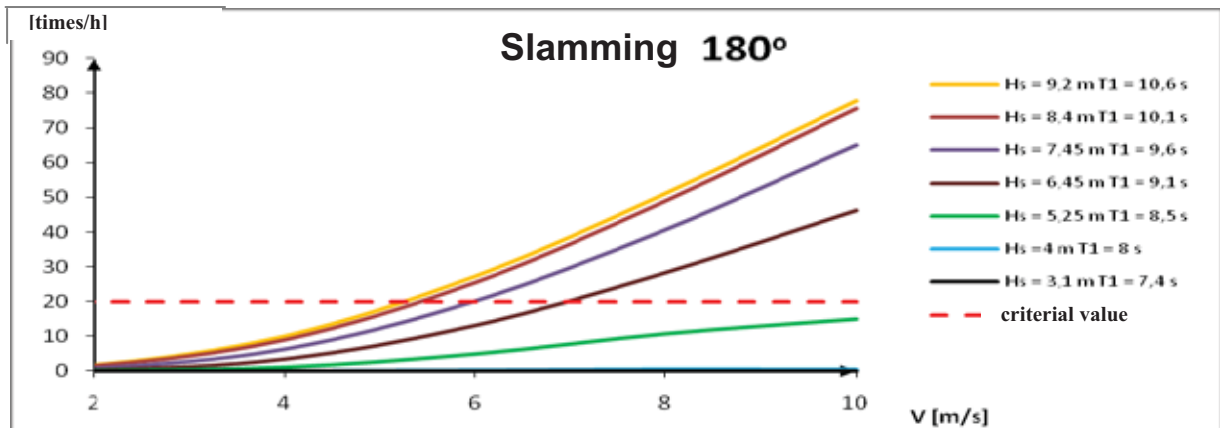
Calculations of the aforementioned seakeeping abilities have been performed for different sea states, specified by the significant wave height H_s and period T_1 (values of these parameters have been assumed for navigation line (ocean route) passing through the Northern Atlantic), for particular steps of ballast replacement, and at the same time for each step the calculations have been performed for a different state [percentage] of the ballast tank filling from 100% (full tank) to 0% (empty tank) every 25%. The exemplary calculation results for selected steps of ballast replacement are presented in drg 3 ÷ 6 (full set of calculations is included in [1]).



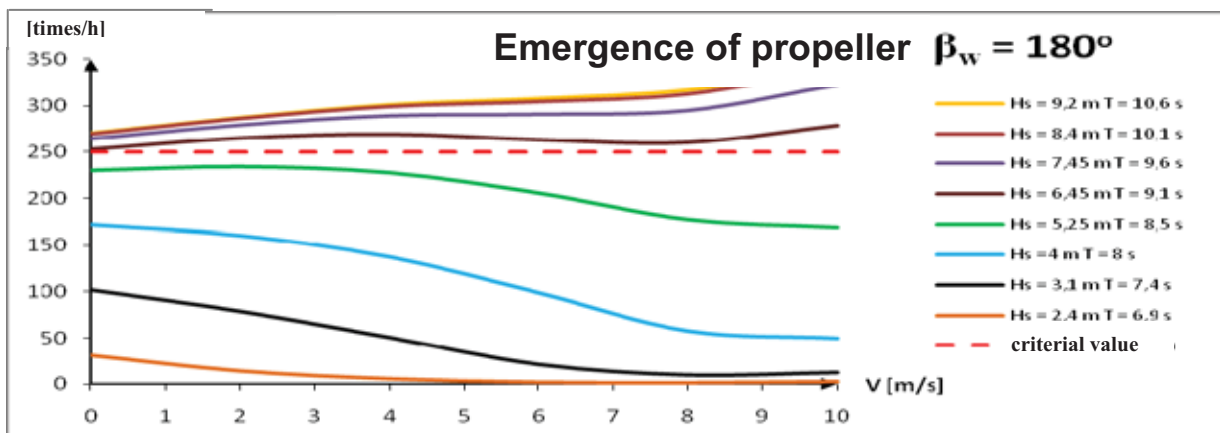
Drg. 3. Influence of sea state on significant value of ship’s roll motions. Step “1” – state [percentage] of tank/tanks filling 50%



Drg. 4. Influence of sea state on significant value of ship’s pitch motions. Step “1” – state [percentage] of tank/tanks filling 50%

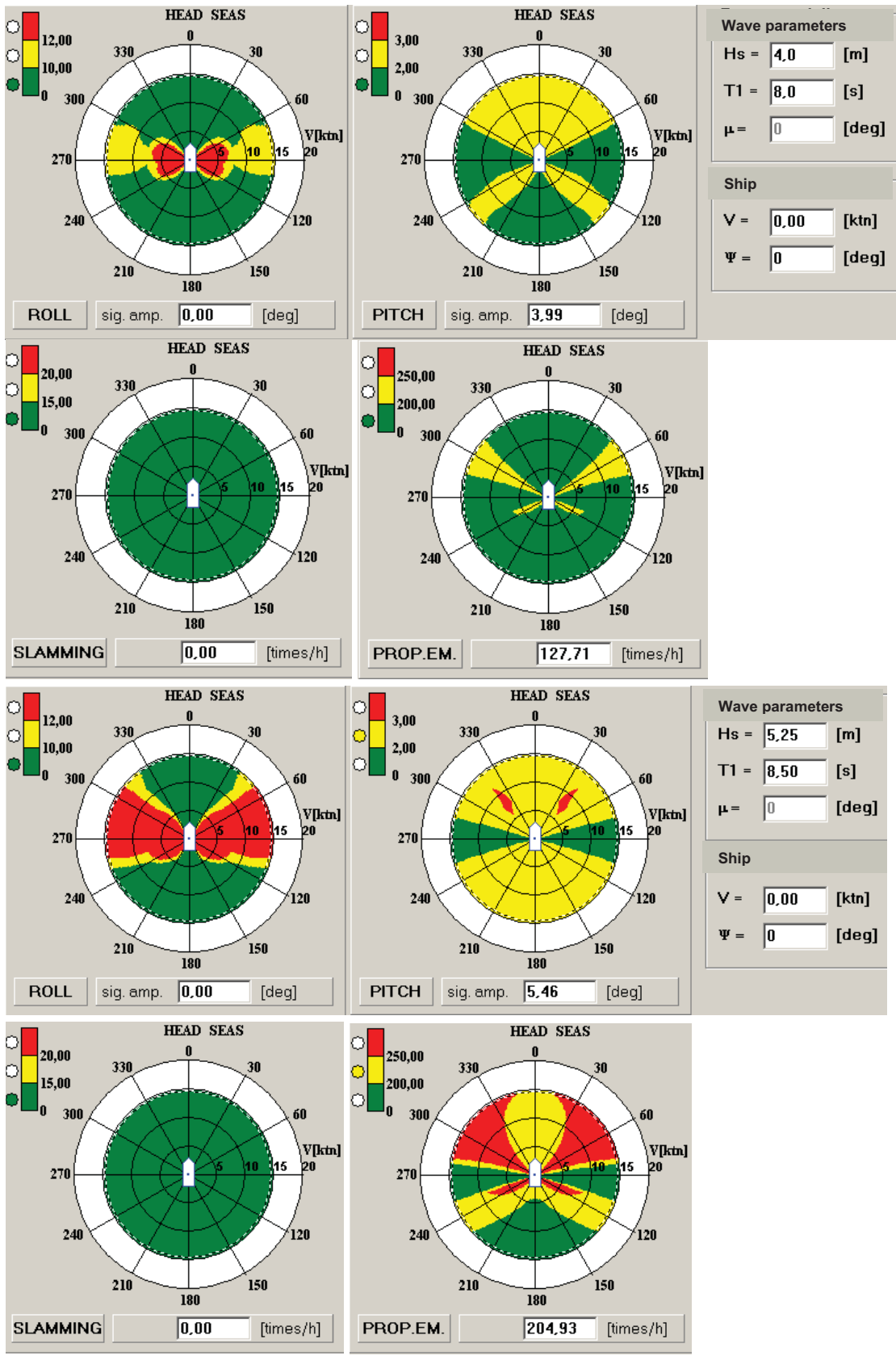


Drg. 5. Influence of sea state on frequency of slamming occurrence. Step "1" – state [percentage] of tank/tanks filling 50%



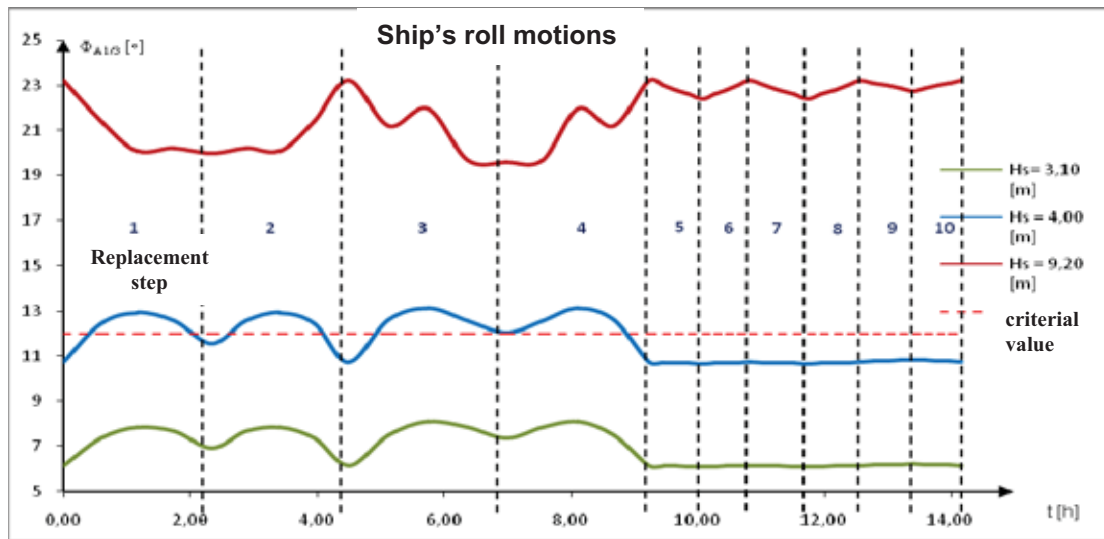
Drg. 6. Influence of sea state on frequency of emergence of propeller. Step "1" – state [percentage] of tank/tanks filling 50%

Drawing 7 presents the influence of the ship's speed and ship's course related to direction of waves on selected seakeeping abilities for different sea states. The following states are presented in this drawing: safe ballast replacement (green colour), warning (yellow colour) and hazard (upper/maximum criterion exceeded – red colour). This drawing shows that at severe weather conditions, in order to limit the hazard state at ballast replacement, the ship's course related to wave direction can be reduced and/or changed.

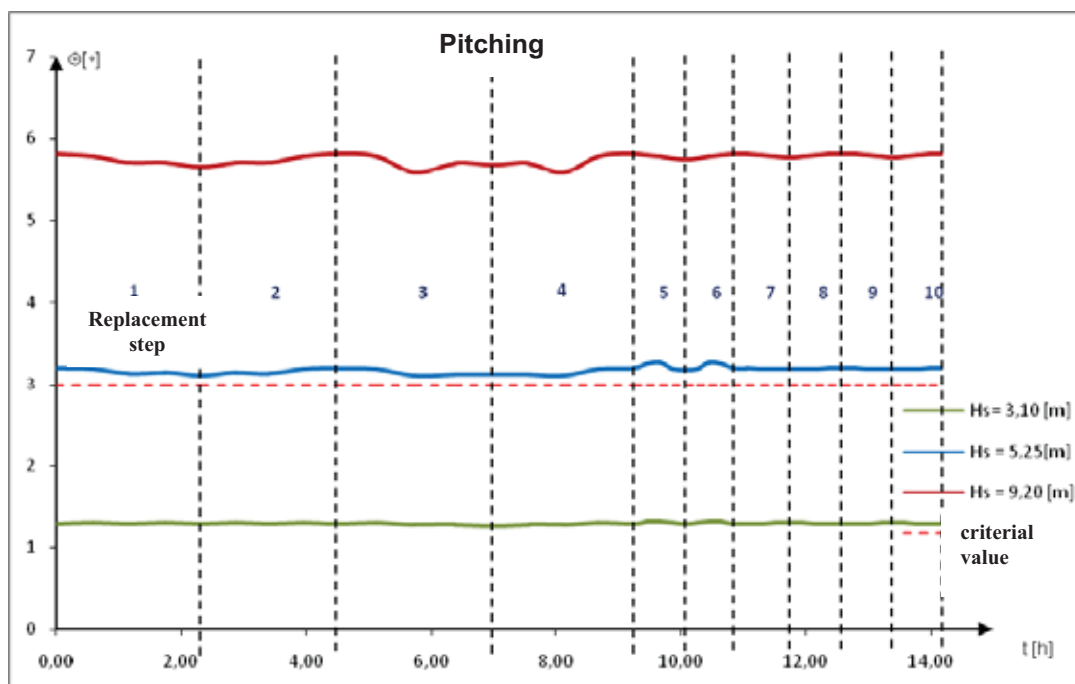


Drg. 7. The influence of the ship's speed and ship's course related to direction of waves on selected seakeeping abilities. Step "1" – state [percentage] of tank/tanks filling 50%

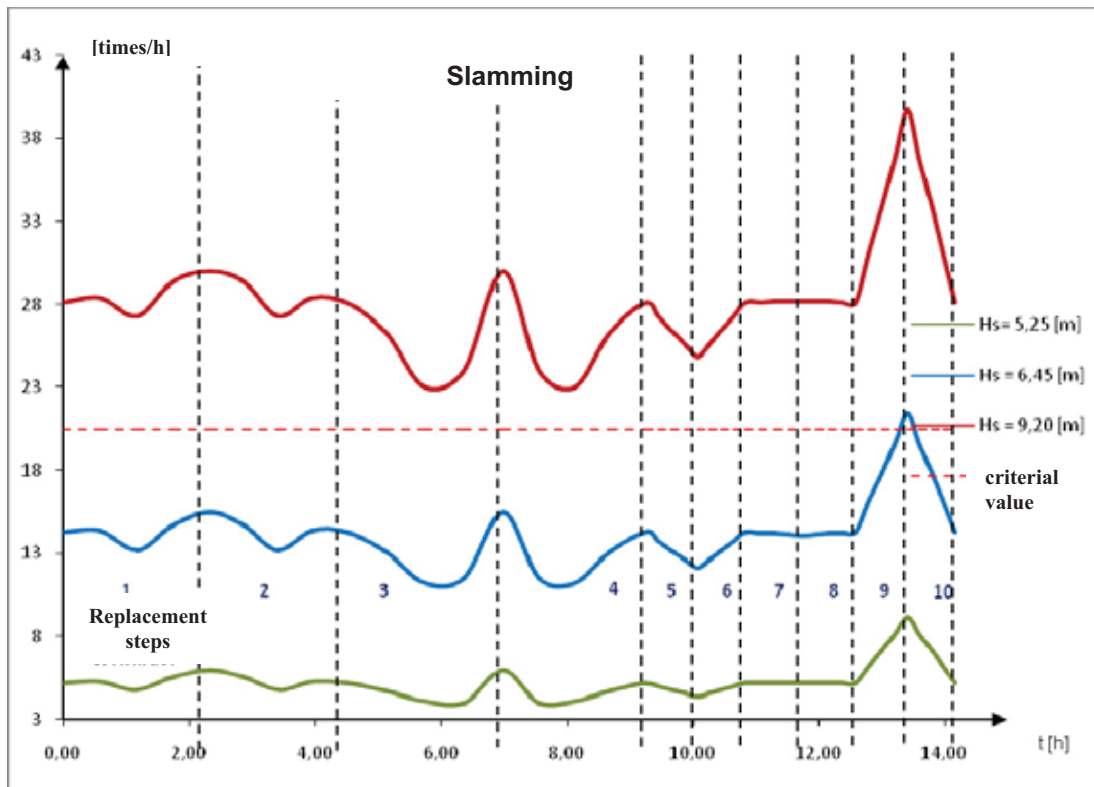
The calculated values of seakeeping abilities for the whole process of ballast replacement are presented in drgs 8 ÷ 11, for different sea states and ship service speeds.



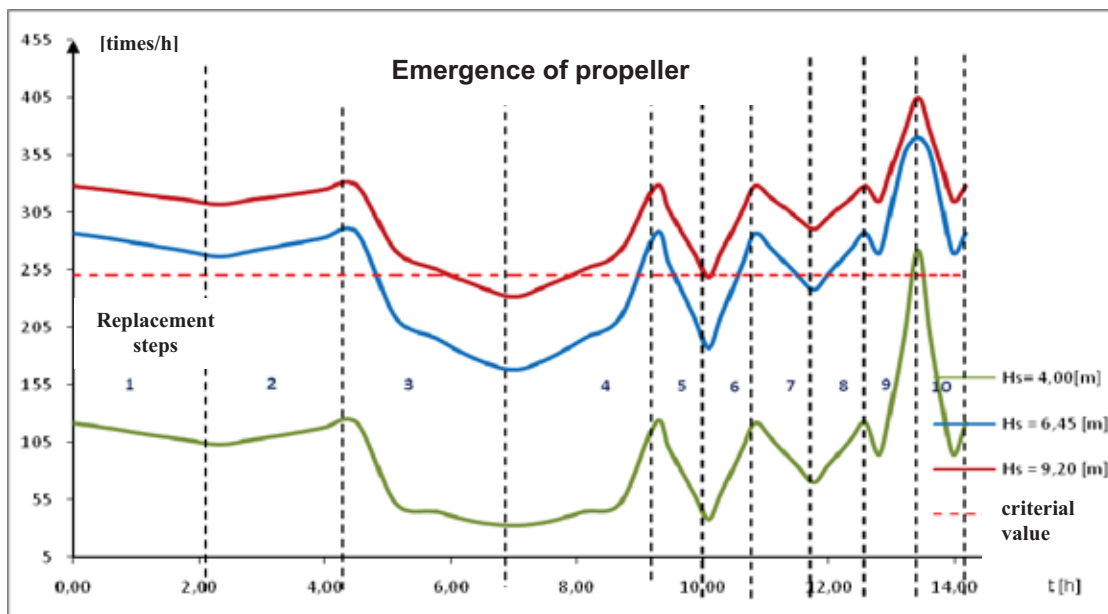
Drq. 8. The ship's roll motions on waves ($\beta_w = 90^\circ$) during the ballast water replacement on the m/v „Orla” ship



Drq. 9. The ship's pitch motions on waves ($\beta_w = 180^\circ$) during the ballast water replacement on the m/v „Orla” ship



Drg. 10. Slamming ($\beta_w = 180^\circ$) during the ballast water replacement on the m/v „Orla” ship



Drg. 11. The propeller emergences on waves ($\beta_w = 180^\circ$) during the ballast water replacement on the m/v „Orla” ship

4. Conclusions from the conducted tests and investigations

The obtained results in form of changes of the values of the investigated seakeeping abilities and possible exceeding of critical values for particular steps of ballast replacement fully comply with results of analyses for calm water [2]. With the increase of sea state (wave height) the critical values are exceeded more and more frequently. So it is possible to determine the maximum weather conditions in which the operation of ballast replacement can be carried out safely. Another option is the instantaneous reduction of the ship speed and/or the change of the ship course for the stage (step) of the ballast replacement for which the exceeding of critical values occurred. It is also possible to change the sequence of emptying and filling of ballast tanks so as to minimize the hazard arising at a given sea state (such situations were investigated in [1])

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INFLUENCE OF MESH MORPHOLOGY NEAR THE NOTCH ON PRECISION OF SCF DETERMINATION

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Abstract

The researches considered the problem of mesh forming for numerical analyses of notched elements. Stress concentration factor K_t was assumed as the characteristic value determined during the calculations. The calculations were performed for flat bars with opposite U-shaped notches and for round bars with V-shaped notches. Both analysed the notches generally assumed as shallow notch $K_t \approx 1.7$ and sharp notch $K_t \approx 2.8$. Two-dimensional FEM linear elastic analyses were performed in the ANSYS software environment. For the purpose of the analyses, free and mapped meshes for coarse geometry and mapped meshes for modified geometry with one and two subareas were assumed. It has been revealed that precision of numerical calculations for stress concentration factor depends on morphology of the mesh located near the notch. It has been revealed that free mesh enables to obtain a satisfying precision of the calculations. Introduction of division in formed geometry of the notch for sub-areas followed by their division according to the standard did not improve precision.

Keywords: notch, local approach, stress concentration factor, finite element mesh

1. Introduction

The procedure of determination of fatigue life for mesh elements with a notch assumes, in the first stage, estimation of damage level, assuming strain, stress or the value corresponding to the energy in the notch as a parameter. Damage level estimation can be performed locally and non-locally. The local approach determines damage at one point. In most cases, the stress on the notch root is the parameter. Its value is usually determined according to net nominal stress taking into account the stress concentration factor K_t . The non-local approach assumes that the selected parameter is determined in some sort of area near the notch root [3].

The simplicity of the description as well as wide experimental verification of the local approach in fatigue calculations of notched elements make the approach commonly used. Among the group of formulas representing the manner of description, the highest respect [8] was gained by Neuber theory (1) and strain energy density theory (2):

$$\frac{\sigma^2}{E} + \sigma \left(\frac{\sigma}{K'} \right)^{1/n'} = \frac{(K_t S)^2}{E}, \quad (1)$$

$$\frac{\sigma^2}{E} + 2 \frac{1}{1+n'} \sigma \left(\frac{\sigma}{K'} \right)^{1/n'} = \frac{(K_t S)^2}{E}, \quad (2)$$

where:

σ - local stresses in the notch,

S – net nominal stresses,

E, n', K' – material parameters .

Experimental verification of the Neuber theory indicates a conservative character of the results gained with the use of the theory [1]. Juxtaposition of the researches results and calculations based on strain energy density theory indicates that the theory might underestimate stress values on the notch root [4]. In order to eliminate the above mentioned limitations, various modifications of notation are proposed (1) and (2). Example of this approach is introduction of power density of stresses parameter [4] on the member of an equation describing local stresses, maintaining unchanged form of unit based on nominal stresses. Other method, to decrease conservatism of Neuber theory, is modification of its notation on the site of nominal stresses via use of the notch factor K_f in it. The factor includes minor plastic changes in the notch also occurring when nominal stresses S are much lower than yield strength S_y [9]. The approach, in most cases, does not result in elimination of factor K_t from calculations. Apart from comfortable cases when the value of the factor K_f was determined directly during researches, its value is usually set indirectly depending on Peterson [7] or Neuber [8] theories based on K_t .

Having the above in mind, a major importance of stress concentration factor K_t for fatigue calculations of elements with notch performed on the local approach basis is revealed. Determination of the value of stress concentration factor K_t for various notch geometries and load types is performed via experiment and calculations with the use of analytic and numerical methods [1]. For the purposes of calculations, for stress concentration factor K_t regarding various types and sizes of notches, they were made as diagrams or described as simplified dependences [7]. Assumed, due to their ease in calculation, simplifications result that the value of K_t factor might involve even 10% error [5]. It provides a significant influence on the precision of the entire fatigue calculations as K_t factor occurs in second power in notations (1), (2) and derivatives.

Some sort of solution to the problem of precision is provided by determination of K_t factor value based on approximate dependencies [5]. Limitations of the approach results from significant complexity of notations depended on the type or sizes of notches, moreover, due to the fact that it indicates various precision for individual methods of notch load [6]. The use of numerical methods not bearing such limitations, for engineering calculations as well as for scientific researches, seems to be a natural solution. Even though, based on FEM commercial software introduces more efficient algorithms for mesh generation and much stronger solvers, control over precision of calculations dependent on discretization error still seems to be an essential issue. First of all, the error depends on the size and morphology of the notch and the size and finite element order. Basic features of mesh morphology is its density near the notch and its rarefaction away from the notch. Such structure of the notch enables to control the size of computer resources need for analyses and to control the time for calculations. Other essential feature of mesh morphology is the shape of finite elements located very near to the notch root and its influence on precision of determining of stresses on the notch roots. Presence of triangle and irregular elements in the area, created via automatic division of notch geometry, might lower precision of calculations.

2. Calculations and its conditions

The researches considered the problem of mesh forming for numerical analyses of elements with notch. Researches were performed in plane strain state for, assumed according to the work [2], round bars with V-shaped notches (fig. 1a) and in plane stress state for flat bars with opposite

U-shaped notches (fig. 1b). Both analysed the notch generally assumed as shallow notch $K_t \approx 1.7$ and sharp notch $K_t \approx 2$. Geometrical dimensions of both bars geometry presented on fig. 1 presented in the table 1.

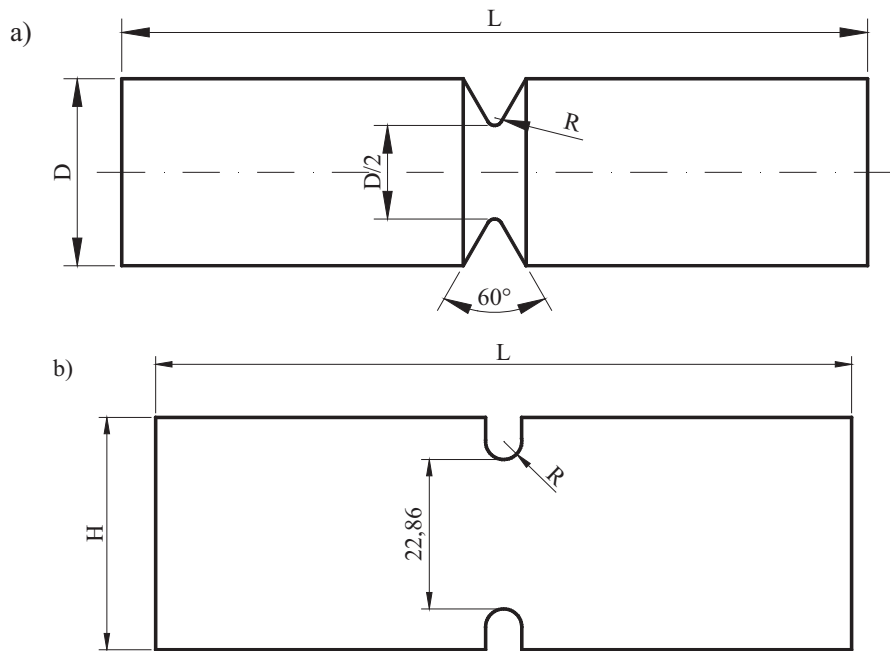


Fig. 1. Bar samples for analyses; a) round bar with V-shaped notches, b) flat bar with opposite U-shaped notches.

Due to significant length of the round bar, on the stage of preliminary calculations, speculations considering what length of the bar could be omitted during analyses has been made. The analyses enabled to reduce the model and quickening of calculations without any loss of precision. A characteristic, transverse dimension of the bar has been assumed as a reference length: D diameter for round bar or height H for the flat bar (Fig. 1).

Tab. 1. Nominal dimensions of analysed bars

	V-shaped notch			U-shaped notch		
	L [mm]	D [mm]	R [mm]	L [mm]	H [mm]	R [mm]
shallow notch, $K_t \approx 1.7$	107.95	12.7	0.529	78	41.12	9.128
sharp notch, $K_t \approx 2.8$	107.95	12.7	1.588	78	35.56	2.778

FEM linear elastic analyses were made in the environment of ANSYS software. They were of two-dimensional character, what in the case of round bars lead to analysis of axisymmetric issue. The analyses used tetragonal finite elements with the second order shape function. Due to dual symmetry of both, geometrical shape and boundary conditions, the analysis assumed the quarter of the bar sample. Rejection of the part of the bar sample located on the second side of the longitudinal surface and transverse axis or symmetry surface which depended on bar sample geometry, has been adequately taken into account properly defining symmetric boundary conditions on the division edges.

Changes in precision of calculations depended on the length of the bar normalised with transverse characteristic dimension presented on Fig. 2. Arrangement of calculation error depended mainly on bar length and whether analyses were performed in plane stress state or plane strain state. It only slightly depended on stress concentration factor. In plane strain state (for round bars) it was four times lower than in flat stress state (for round bars). In both cases, the error value decreased practically to zero when the length being formed exceeded twice the value of transverse

characteristic dimension of the bar. On the above grounds, for the analyses of the round bar, according to designations on Fig. 2, the total length $L=25.4\text{mm}$ was used and for the flat bar with shallow notch $L=78\text{mm}$, and with sharp notch $L=71.2\text{mm}$.

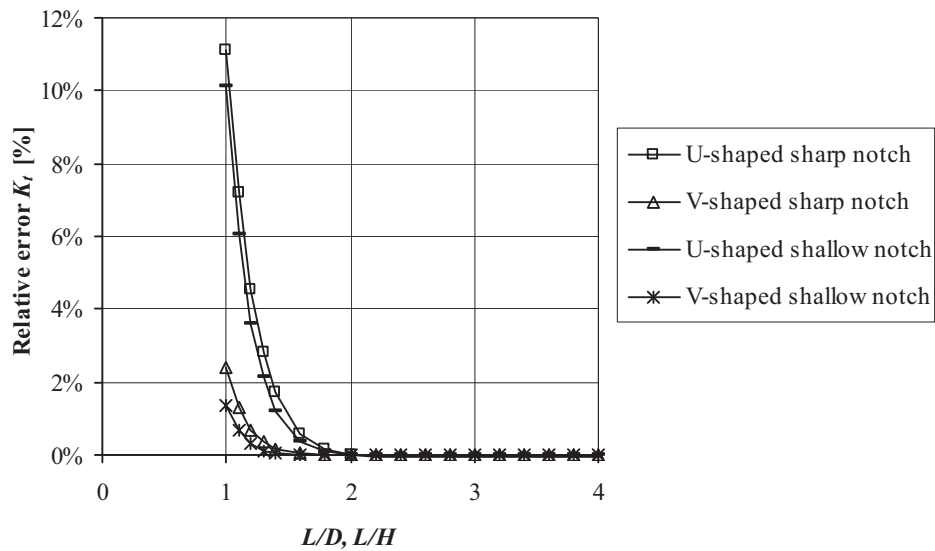
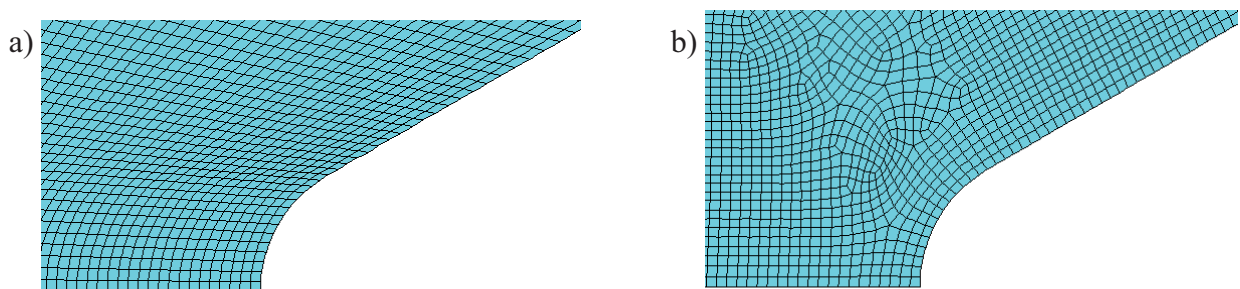


Fig. 2. Change of calculation precision K_t depended on the length L of the bar.

Taking into consideration the guidelines of the analysis of which results are presented on fig. 2 and the assumption to perform calculations for the quarter of the bar, calculation length of $L_o=L/2$ has been assumed as characteristic dimension for that length. For the analyses of the round bar calculation length of $L_o=12.74\text{mm}$ was used and for flat bar with shallow notch $L_o=39\text{mm}$; with sharp notch $L_o=35.6\text{mm}$.

3. Calculations

Calculations have been performed for sharp notches $K_t \approx 2.8$ as for both types of bars and with the use meshes formed through four methods. Examples of creations of such meshes for V-shaped notch with the angle of $\beta=60^\circ$ are presented for the coarse geometry on Fig. 3a and b, and for geometry with sub-areas indicated near notch on Fig. 3c and d.



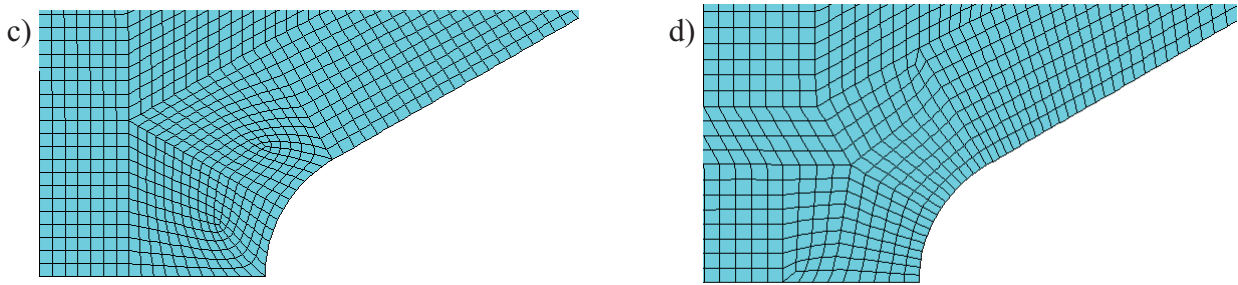


Fig. 3. Meshes for analyses differentiated with respect to the way of forming: a) mapped mesh, b) free mesh, c) mapped mesh with one sub-area, d) mapped mesh with two sub-areas.

Meshes for analyses were created of finite elements with second order shape function, tetragonal 8-node and triangular 6-node. Mapped mesh Fig. 3a has been assumed as a reference. Due to specific character of its creation, degeneration of the shape of the finite element comes along with decrease of the notch angle. For the 0° of the notch angle it is impossible to create mesh with the use of the mapped method. The above mentioned limitations do not concern free mesh (Fig. 3b). The method enables to create regular elements on the edges of the areas describing the notch but in some distance from the notch, the algorithm of automatic division generates elements of disunified size and shape. In order to employ the advantages of the mapped method for meshes creation and to avoid its limitation, a division on sub-area of formed geometry near the notch was proposed. Two versions of such solution have been agreed. The first includes one sub-area (Fig. 3c) in the way that its side comprise arch described via notch root radius. The second version includes two sub-areas (Fig. 3d) so each comprises half on the arch described via notch root radius.

4. Results

Calculation results for coarse geometry are presented on Fig. 4, and Fig. 5 for modified. Calculations were performed for various sizes of finite elements. Along with the decrease of size of the elements, the number of node increased which illustrates in increase of DOF for the problem. Stresses determined during the analyses were calculated into values of stress concentration factor K_t .

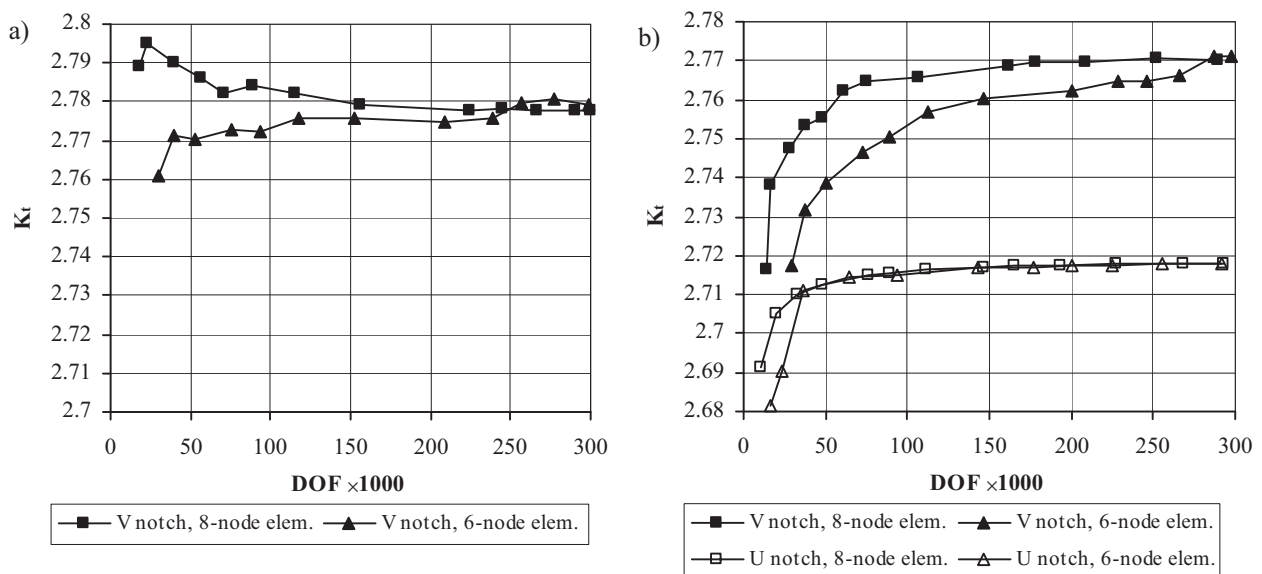


Fig. 4. Result of analyses for: a) mapped meshes, b) free meshes

Results analyses for coarse geometry (Fig. 4b) indicates that the number of nodes in finite element influences more on the precision in plane strain state than in plane stress state. In plane stress state both types of elements allow to obtain a satisfying precision even at approx. 100k DOF. For V-shaped sharp notches mapped meshes enabled to obtain $Kt=2.78$ at approx. 150k DOF, for free meshes a slightly lower value has been obtained $Kt=2.77$ at 170k DOF. Introduction of sub-areas near the notch resulted in decreased precision. In case of one sub-area, the result of Kt below 2.76 at 250k DOF has been obtained. For two sub-areas, the value of Kt approached 2.77 but only at approx. 300k DOF has been obtained.

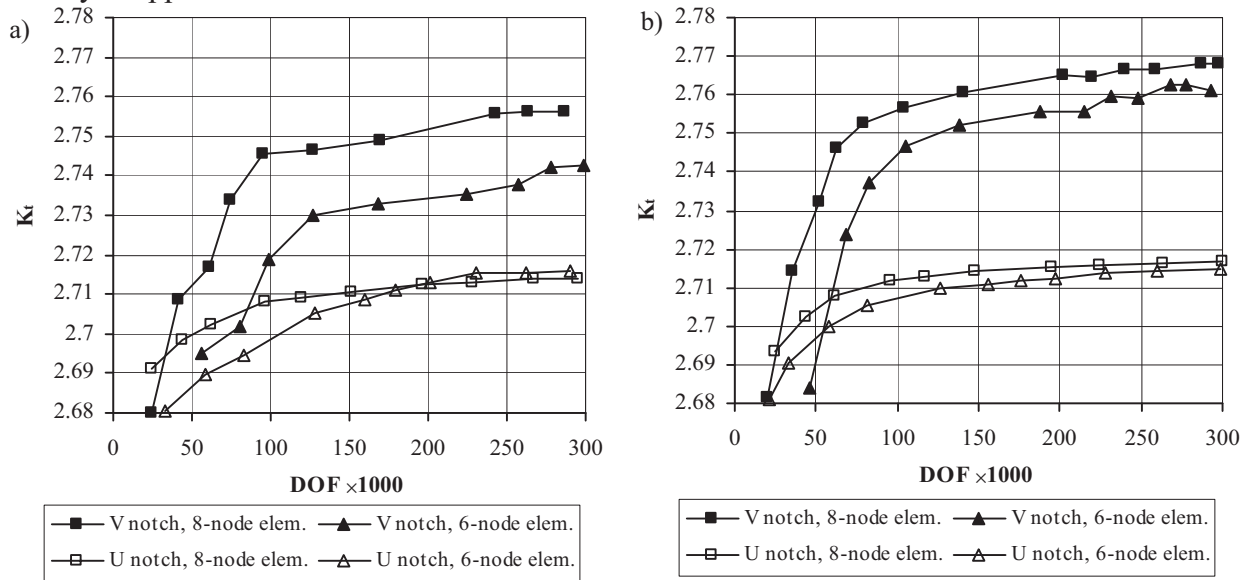


Fig. 5. Result of analyses for mapped meshes: a) with one sub-area; b) with two sub-areas

5. Conclusions

The precision of numerical calculations of stress concentration factor depends on the morphology of mesh near the notch. Mapped mesh enables to obtain the highest level of precision. Slightly lower level, but with the higher number of DOF, can be obtained with the use of free mesh. Introduction of notch geometry division on sub-areas followed by mapped meshing did not improve the precision of calculations. 8-node elements allow to obtain higher precision of stress concentration factor with lower number of DOF. The result of the work enable to indicate not only the optimal structure of mesh but also to indicate the size of finite element allowing to obtain high precision of calculations with controlled number of DOF.

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SOME ADJUSTMENT AND EXPLOITATION PROBLEMS OF THE CONTROLLABLE PITCH PROPELLER PNEUMATIC AND HYDRAULIC CONTROL SYSTEMS

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Abstract

The paper presents selected problems of the controllable pitch propeller (CPP) pneumatic and hydraulic control systems. For this aim a description of the collision of the rescue fire ship with the trestle of the fuel pier in the North Port in Gdańsk was used. Activities undertaken by author, included analysis and an experiment conducted by a commission, permitted to explain the reasons of the event. It is expected that presented description of the works and their results will be a useful knowledge material for designers and users of the control systems.

1. Introduction

Few years ago in the North Port in Gdansk the rescue fire ship during last stage berthing operation suddenly started to move rapidly ahead with grooving speed and in short time struck the trestle of the fuel pier in the North Port in Gdańsk. According to the captain and the crew relations after setting control lever of the CP Propeller in “astern” position in wheelhouse for final stopping of the ship, the pitch automatically was setting in “full ahead” position. It resulted in rapid grow of the main engine load and ship speed. Because attempts of the CPP pitch changing did not succeed and the vessel quickly moved close to the pier, captain pressed “switch off” button of the main engine, ordered to throw an anchor and left the wheelhouse. A moment later superstructure of the ship struck the concrete trestle. Fortunately, because of a better elasticity of the superstructure than the bow part of the ship hull, the dynamic force of a collision was reduced and damages of the ship equipment as well as the trestle infrastructure were smaller. Fortunately, there were no fatal victims, but not serious injuries only. Also, there were no dangerous damages to main ship systems such as fuel, ballast or bilge systems. Similarly, on the trestle only fresh water pipeline was damaged, which lay along the fuel pipe line but on side close to edge of the trestle.

After towing away the ship and mooring her at safe part of the wharf a detailed inspection of the propulsion system was carried out, especially controllable pitch propeller. Some investigation actions which were done with the aim to clarify the reasons of the event, are presented in the following parts of the paper.

2. Description of the analysed controllable pitch propeller control system

Controllable pitch propeller, which is applied on the ship has a diameter of 2,1m and is

driven by the middle – speed diesel engine through a reduction gear. The CPP control system is a pneumatic – hydraulic type. The remote control from the wheelhouse and from the engine control room is pneumatic and local direct control is hydraulic. Simplified drawing of the propulsion system with a scheme of the hydraulic part of the CPP control system is presented on fig. 1.

The controllable pitch propeller 1 is mounted on the flange of the propeller shaft 2, which is located on journal bearing at the stern tube. The propeller shaft has a coaxial hole with a control rod inside it. One end of the control rod is connected with a pivot mechanism of the blades located in the propeller hull and second end is fixed to a piston of the hydraulic cylinder 4. The hydraulic cylinder is simultaneously a section of the main shaft and is connected with the flange clutch of the propeller shaft at one end with an output shaft of the gear 5 at the second end. An oil distribution box is coaxial attached to a fore wall of the gear. In the oil distribution box there are: a directional control valve, a feedback mechanism and a transmitter of a real pitch indicator 22. On a side wall of the oil distribution box there is an installed lever 8 of the manual control of the propeller pitch. The lever is connected to a pneumatic servomotor 7 through pneumatic connector (look item 5 on fig. 3).

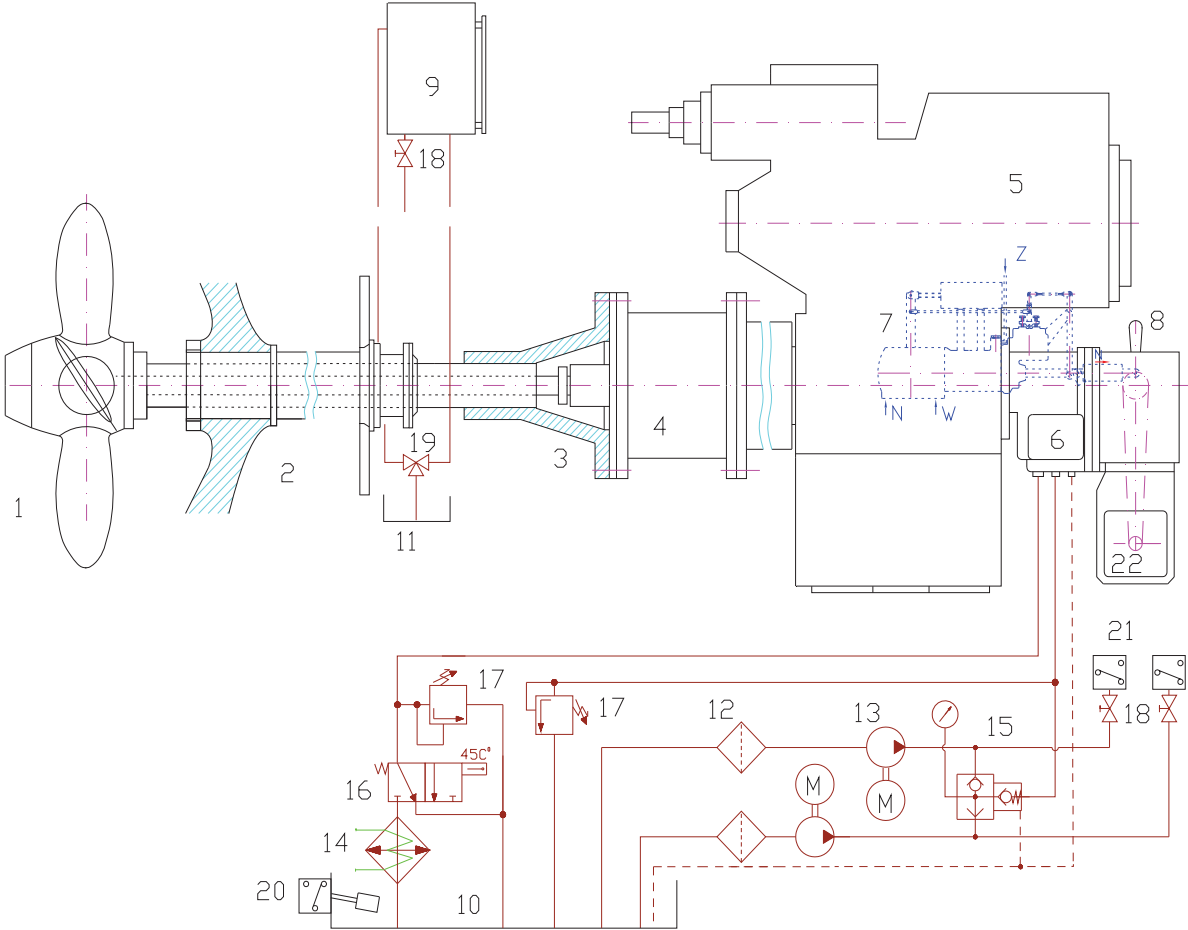


Fig. 1. Simplified drawing of the propulsion system with a scheme of the hydraulic part of the CPP control system

A hydraulic oil supply unit consists of a main tank 10 and two identical interchangeably worked subsystems. Each of these subsystems contains: suction filter 12, screw pump 13 driven by asynchronous electric motor, shut-off valve 18 and pressure relay 21. Both

subsystems are connected through a logical valve 15 and a check valve with a main line supplying oil to the directional control valve located in the oil distribution box which is presented more clearly on fig. 2. In case of significant pressure drop in the main oil conduit the second pump automatically starts to work simultaneously with varying signal. Oil returning from the directional control valve flows through thermostatic directional valve 16 to the water-oil cooler 14 or directly to the tank 10 depending on the oil temperature. Pressure relief valves 17 protected the main and return oil lines from excessive increase of pressure. In case of oil level drop to lower acceptable value a relay 22 turns on varying signal.

At the hydraulic oil system of the controllable pitch propeller there is also an additional stern tube oil lubrication unit. The unit consists of two oil tanks: gravitational tank 9 and discharge tank 11, three-way cock 19, shut-off valve 18 and tubes. Oil flows from the gravitational tank through the three-way cock into the stern tub bearings and the propeller hub. The tank 9 is located at a height of 3 - 4 m over the the sea level with the aim of obtain an oil pressure value inside the hull higher than a hydrostatic pressure of the sea water outside. During inspections or repairs the oil from the gravitational system is drained into the discharge tank 11. Possible oil losses in this system are resupplied with use of additional oil line with check valve (not shown on fig. 1) connected to the main line supplying oil to the directional control valve. The shut-off valve 18 located under the gravitational tank 9 enables periodic inspection leaktighness of the system by draining a small quantity of oil from the bottom of the tank and checking if there is no water or other pollutants.

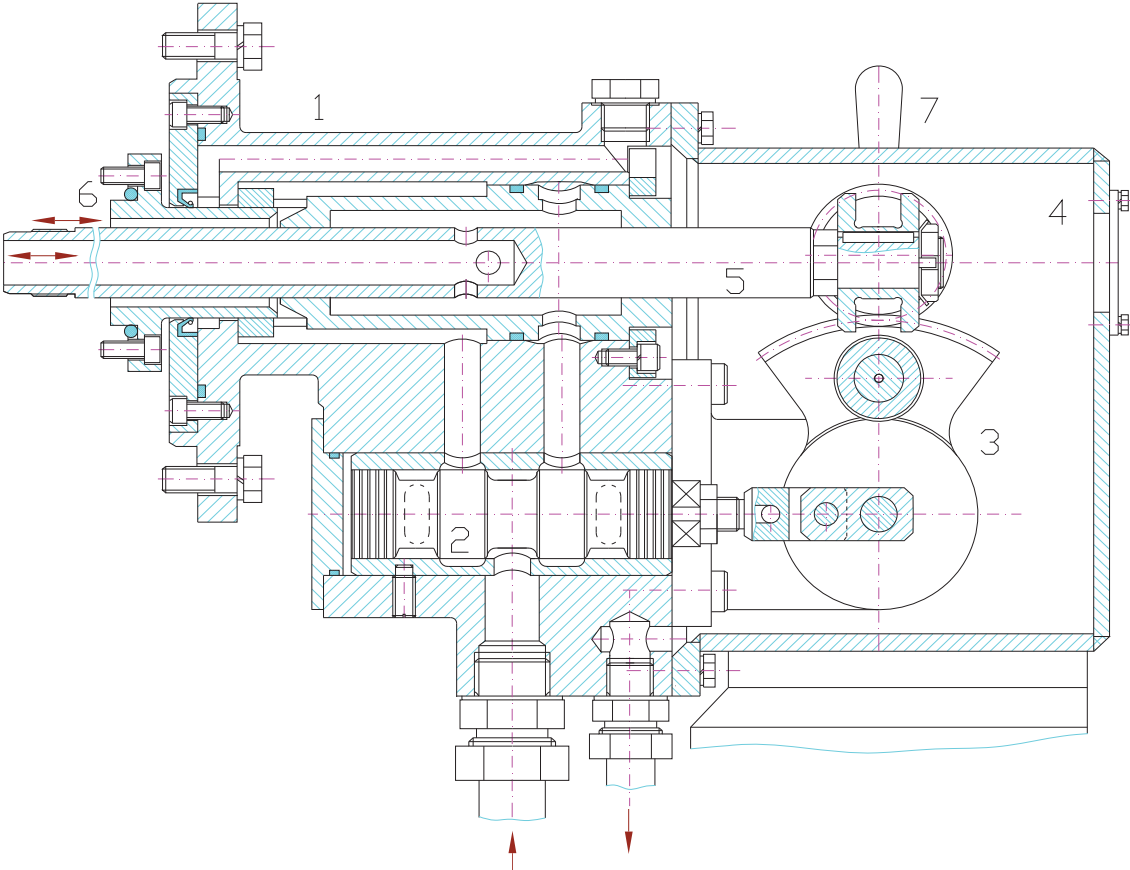


Fig. 2. Simplified drawing of the oil distribution box with visible directional control valve and the feedback mechanism

The oil distribution box is presented on fig. 2. A flange of a body 1 of the box is fixed to a front wall of a gear box (item 5 on fig. 1). The directional control valve 2 is in a lower part

of the body. The valve 2 is underlap version (in a central position oil flow from the supply to return line). Such kind of the valve 2 enables significant lightening of the pump during keeping up adjusted pitch of the propeller, especially in “full ahead” position. It should be mentioned that in the typical modern CP propellers the maximum loads of a servomotor, therefore also the highest oil pressure, appears during changing pitch of the propeller from “astern” to “ahead” direction when it passes the “0” position. Considering that the ship usually sails more than 95% of the time with the pitch adjusted to “full ahead or close to it, the pump works with the forcing oil pressure only a little higher than it is needed in the servomotor. It increases survivability and reliability of the pump as well as effectiveness of whole propulsion system.

Adjustment of the propeller pitch is realized by turning the lever 7. It can be done by using the pneumatic cylinder ((item 7 on fig. 1) and the pneumatic connector – in case of remote control or directly by hand. In both cases a steering signal from the lever 7 is carried through a unit 3 of shafts, wheels and levers to a control spoon of the directional control valve 2, causing its displacement. Displacement of the control spoon to the right causes the oil flow from the main supply line to the right outflow and next to an interior of the control rod 5, which passes through a coaxial hole of the output shaft of the gear. The aft end of the rod is connected to the piston of the servomotor (item 4 on fig. 1), so the oil flows into an aft chamber of the servomotor. Simultaneously the oil from the fore chamber flows out through a space outside the rod but inside the outer shaft and fixed to it sleeve 6 and next through a left channel to the directional control valve. From the valve the oil flows through channels drawing broken line to the return line (visible only on fig.1).

On the fore end of the rod there is fixed a sliding ring with a circumferential groove, in which is located a shoe attached in a revolving way to one of the feed back unit (3) lever. Displacement of the servomotor piston and the rod and sliding ring connected to it causes movement of the feed back unit elements and as a result displacement of the control spoon of the directional control valve in opposite direction then the piston. The movement lasts till a moment when a real value of the propeller pitch achieve an adjusted value in assumed accuracy.

The remote pneumatic control system of the controllable pitch propeller is presented in a simplified way on fig. 3. A setting lever 1, together with pressure signal relays 2 (for “ahead”) and 3 (for “astern”) are located in the wheeling room. After deflection of the lever 1 from a central position pressure signals from the relays run through a connecting valve 6 to the pneumatic servomotor 4. In result, a piston rod displaces and together with it moves also joined with it pneumatic connector 5, which causes deflection of the local control lever (item 8 on fig. 1). The pneumatic connector 5 serves as an elastic element, which characteristic depends on the supply air pressure. The connecting valve 6 together with a hydraulic – pneumatic transmitter 7 and main engine regulator 12 constitute automatic control system. The main aim of the system is protection of the main engine from overload by reduction of the propeller pitch value.

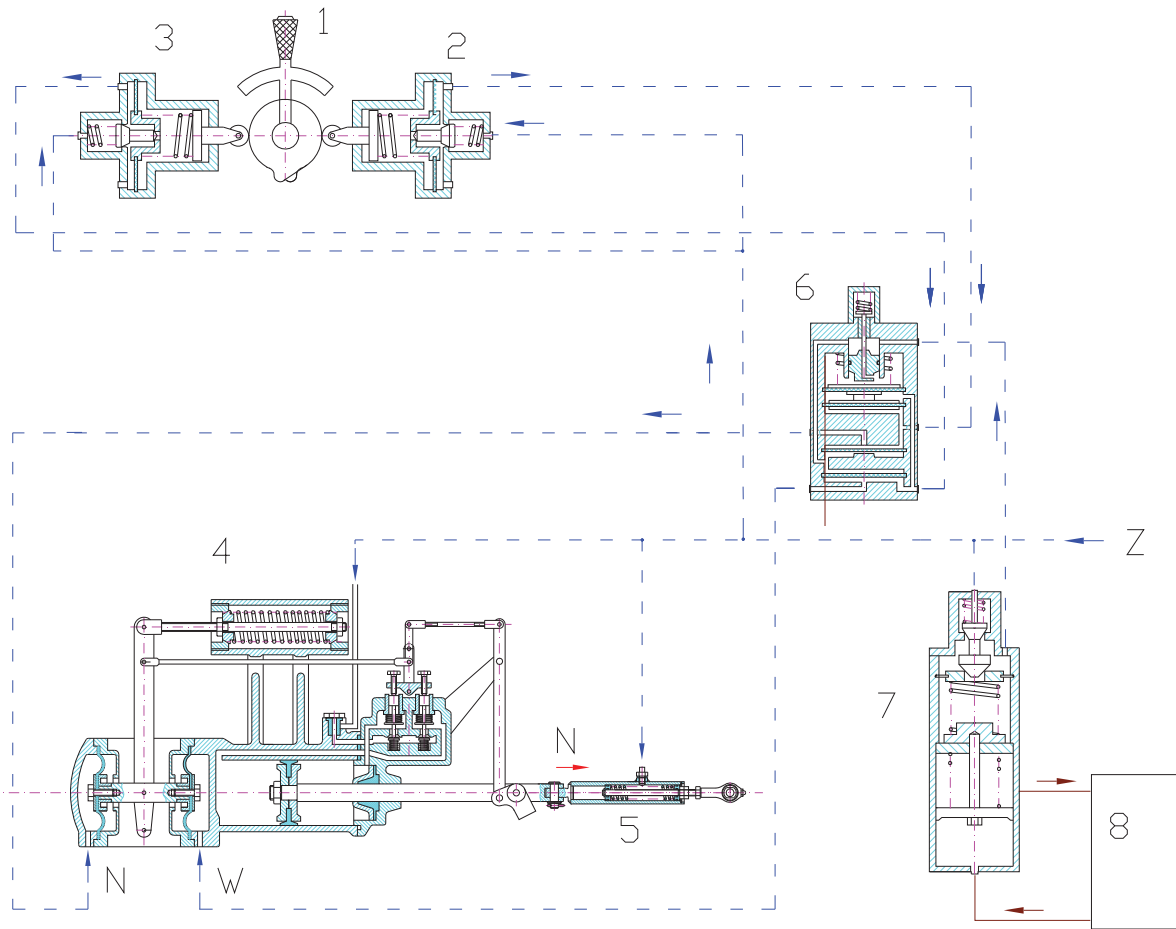


Fig. 3. A simplified drawing of the remote pneumatic control system of the controllable pitch propeller. Letter nomenclature: N – „ahead” direction, W – „astern” direction, Z – air supply.

The pneumatic servomotor is presented more clearly on fig. 4. The pneumatic pressure control signals run to intakes N and W of a double membrane cylinder 1, which a rod is connected by articulated joint with a lever 2. The lever 2 is connected in the same way with a body of the cylinder 1 at the lower end and with connectors 3 and 5 at the upper end. Movement of the rod causes a deflection of the lever 2 and displacement of the connectors 3 and 5. The connector 3 is attached to the pneumatic servomotor body through elastic preloaded element 4, what enables to cumulate the energy of the control signal for its bigger value. A right end of the connector 5 is joined with the lever 6 what causes its deflection relate to its axis of articulated joint with connecting link 7, and also deflection of a tri-armed lever 9, which controls action of a double valve 10. A lower chamber of a valve body is common for both valves and is connected with air supply pipe Z through an air filter 13. Two upper separate chambers of the valve body are individually connected with fore and back chambers of the main pneumatic cylinder 11. Deflection of the tri-armed lever 9 causes throttling air flow in one valve and simultaneously reliving in second. It resulted in diversifying of the pressure values on both sides of a pneumatic cylinder piston and its movement. The movement of the piston together with a piston rod 12 and connected with it a lower end of a lever 8 will last till a moment when an upper end of the lever 8 moving in opposite direction together with the connected link 7 and an upper end of the lever 6 cause returning movement of the lever 9 to a central position. Then the pressure in both chambers

will be equal and the piston will stop at a position adequate to an adjusted value of the propeller pitch.

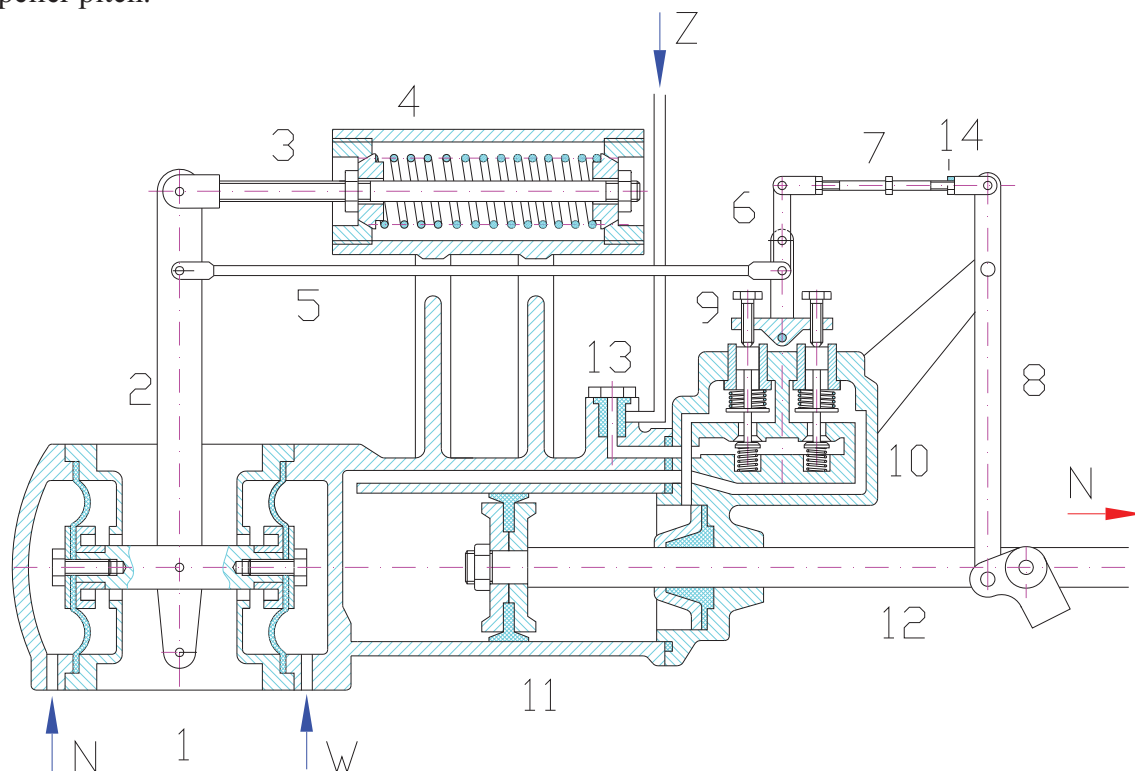


Fig. 4. A simplified drawing of the pneumatic servomotor of the controllable pitch propeller remote control system. Letter nomenclature: N – „ahead” direction, W – „astern” direction, Z – air supply.

3. Investing conduct of the collision’s cause

Two hours after collision during the engine room machinery inspection the ship’s engineer spotted the broken connecting link (item 7 on fig. 4). A break intersection was at a fore face plain of a left lock-nut, which is shown on fig. 5. No other damages were found.

Outside the air pipes connecting control desk in the wheel house with the engine room lying on interior side of a front wall of the ship superstructure were bended, similarly as the wall, but not broken. All following investigation works were conducted with knowledge and in presence of the author of the paper.

In the beginning, the testimony of the captain and the ship crew concerning collision circumstances and a technical documentation of the CP propeller were analysed. Next in the CP propeller producer presence tested the CPP hydraulic control system. The main engine was switched off. During this test different values of the propeller pitch in a full range were set, with the local control lever (item 8 on fig.1). Simultaneously a diver kept underwater observation and checked correctness of this test results. The system worked correctly and nothing wrong was noticed.

The remote pneumatic control system without broken connecting link was also tested. Even by very light finger pushing on the upper end of the lever 6 (on fig.4) the piston rod 12 moved in one or another direction according to direction of finger pushing. In full range of control it worked correctly. During this test I have noticed one characteristic feature of the pneumatic servomotor. It was that from each set position of the piston rod after stopping pushing on lever 6, it automatically moved to “full ahead” position.

After one more analysis of the control system I have decided to conduct next test but of the completed system with mounted new connecting link, which basic significant dimensions

would be exactly the same as in the damaged one. Conformity of two most significant dimensions, namely a distance between outer surfaces of both pins of connecting link and distance between the pin and face surface of the connecting link screw, which are shown on fig. 5, was checked in front of the commission.

The tests were conducted in a presence of the representatives of all interested sides. At the beginning a correctness of the CPP hydraulic control system operation was checked with the use of the local setting lever. The propeller pitch was several times changed in a full range from one to second extreme positions, until relief valve opening. During this test the system worked correctly.

The following tests were conducted with using the remote pneumatic control system and checking conformity of the set values with real values of the propeller pitch during a few full cycles of the pitch changing. Also this time the system worked correctly. In this situation I have decided to repeat last test changing gradually, step by step the propeller pitch and each time observing and touching the connecting link 7, gently pressing it by finger. In almost all steps the pressing connector displaced slightly crosswise in a clearance range, but just in positions “full ahead” and close to it the connector tensed and stiffened. Precise observation of this connection unit revealed a reason of this stiffness. Just in mentioned above position close to „full ahead”, a face surface of the connector link screw rested against the lever 6 in such way, as is shown on fig. 5. Because of it, a bending moment in the screw was generated. This additional bending moment load was undoubtedly many times bigger than a nominal axial force load.

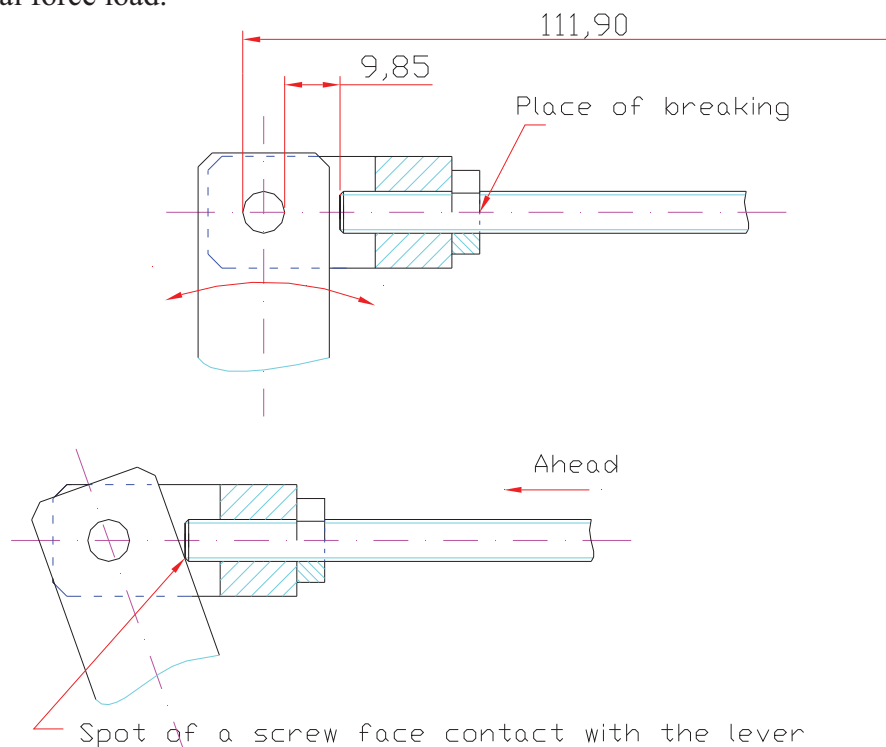


Fig. 5. An articulated joint of the connecting link with the lever in “zero” and “full ahead” positions with shown two dimensions checked in front of the commission

A test of the system reaction on a rapid disconnection of the connecting link 7 and lever 6 was conducted by pulling off the pin connecting both these elements, which simulated a break of the connecting link. The simulation was done for both extreme and a few intermediate pitch settings. Every time at a moment of disconnection of the system caused a change of the propeller pitch to “full ahead” position.

Apart from described works a metallographic examination of a broken screw surface was conducted at the Faculty of Ocean Engineering and Ship Technology of Gdansk University of Technology Laboratory. The results of the examination shown that the connecting link breaking was caused by material fatigue under influence of changing bending moment loads in a long period of time.

Photographs of the screw fatigue fracture with marked zones of conducting fatigue damages are presented on fig. 6. A fatigue crack was a result of acting in the first area a parallel but displaced in comparison with a screw axe force in long period of time, what generated a bending moment. This kind of load caused sequential “opening” and “closing the fatigue crack which propagated in the zone”2” direction. With the passage of time the crack was slowly increasing and after reaching the zone “2” the increase was successively faster because of a more significant decreasing of a loaded cross-section area and growing value of stresses. When the crack reached zone “3” about 60% of a screw cross-section area was lost and stresses excided strength of the material what caused final breaking

4. Final remarks

The above presented analytical works and inspections as well as the CPP control system tests and a metallographic examination of the fatigue fracture enabled to find a real reason of the collision. It was an incorrect adjustment of the feedback elements connection in the pneumatic servomotor unit. More precisely speaking the screw of the connecting link 7 was too deep screwed in the lug at the side of lever 6 (fig. 4 and fig. 5). Because of it, every time in the “full ahead” propeller pitch position the screw face contact with the lever occurred. It caused an additional load of the bending moment on both these elements. The moment was acting at a vertical surface of their movement. The effects of such loads were most unfortunate for this screw, because its cross-section area was the smallest and the thread was a significant notch. It should be marked that during the nominal work the load of the screw, that is – axial force being very small, about 1 N, the generated stresses could not cause such damage. But the additional periodic bending moment loads were multiply bigger and generated much higher stresses. Value of these stresses was lower than static strength so did not caused short term breaking, but repeating continuously in long period of time led to fatigue breaking. Mechanism of this kind of damage was explained in the metallographic examination of a broken screw surface report [1].

It is worth mention that there is conformity of the damage area propagation direction with the bending moment acting surface, what is noticeable on fig.6

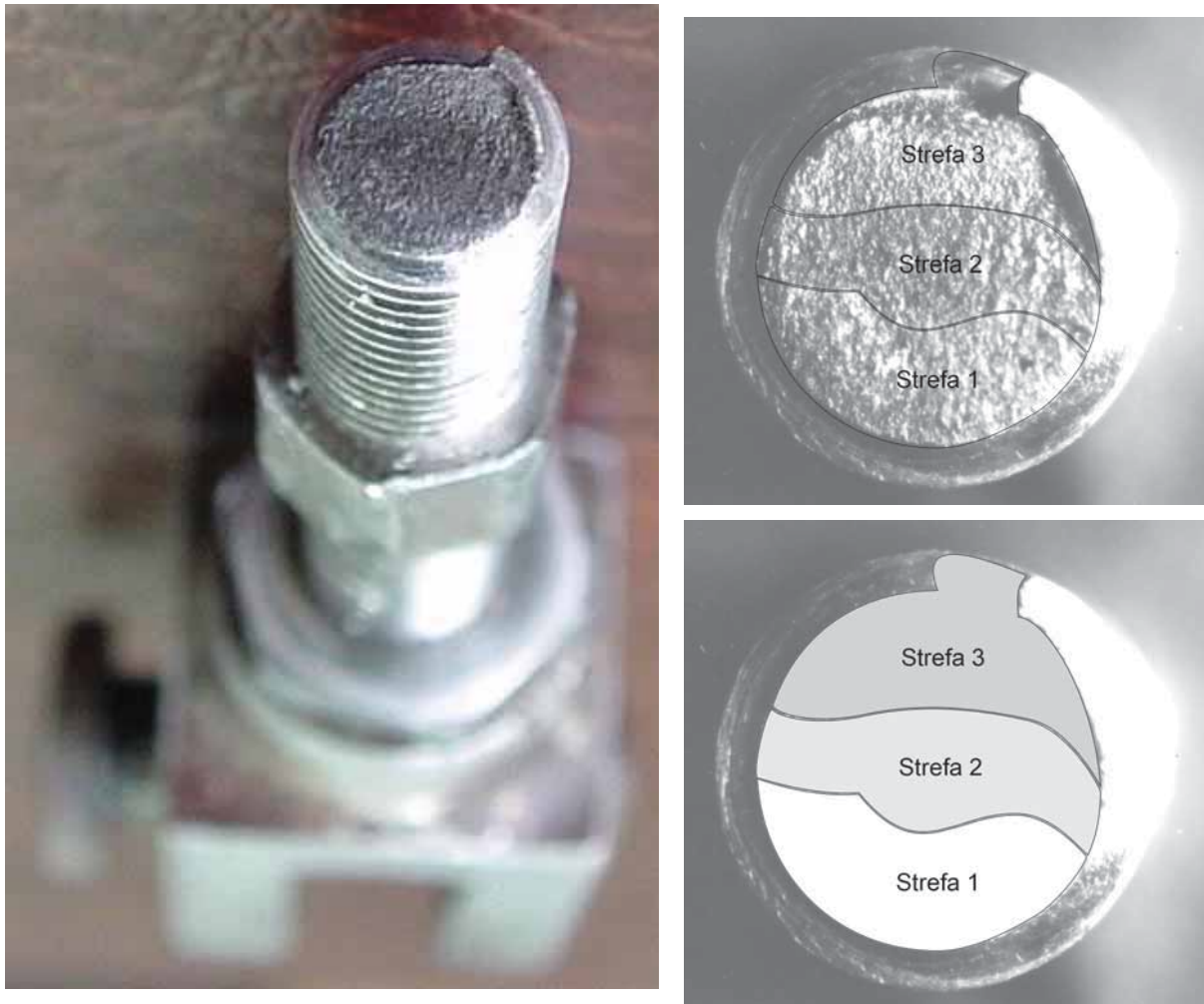


Fig. 3. A view of the fatigue fracture with marked zones of conducted fatigue damage

Apart from an explanation of the reason of the connecting link breaking it is worth to wonder when and in what circumstances the incorrect system regulation took place. Analysis of the technical period inspection report of the CPP control system, which was written a half of year before the collision, has shown that the length of the connecting link did not change and event did not disconnect this element. Only the correctness and precision of the CPP control system work in a full range of its operation was checked, especially in zero position. Because the system worked correctly and sufficiently accurately, which was confirmed during an investigation tests with the new connecting link, the service crew did not see a need to do a detailed inspection which could be done after dismantling the system elements. Probably the previous inspections were conducted in similar way, which explains such long period of the exploitation time, and propagation of the fatigue damage.

Essentials feature of the presented CPP remote control system was its incorrect adjustment contradictory to a rule widely accepted in engineering that damage of any control system or supply unit element should cause stoppage of the device or switching over on the most safe operation conditions. In this case a break of the connecting link should have caused a setting change rather to “full astern” than “full ahead”. It should be marked that modern CP propellers are made with a blade geometry designed in such a way to generate on its surface hydrodynamic forces and moments automatically causing the turning of the blade, from each actual pitch to “full astern” position. It is advantageous from two reasons. Firstly, in case of any failure the hydraulic control system and oil pressure drop the propeller pitch

automatically changes to “full astern” position, which causes decrease of the ship velocity. It enables to switch off the main engine at the proper moment and to stop the ship. Secondly, a constant direction of external load assures system operation with a slightly one-direction tensioned elements, which eliminates an influence of the any clearance and increases accuracy of the CPP control system.

I hope that presented description of the control system and analysis of the collision reasons might be a useful knowledge material, especially for designer and users of the control systems

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CONCEPTION OF DIAGNOSING SELF-IGNITION ENGINES FED WITH BIOFUELS IN OPERATION CONDITIONS

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Summary

The article deals with the question of diagnosing the high power self ignition (SI) engines fed with pro-ecologic fuels in an aspect of appearing operation problems. There has been presented the specific of action and techno-operation profile of the combustion engine foreseen as an investigations object. The preliminary conception of diagnostic investigations of the engine 7L35MC type produced in H. Cegielski - Poznan S.A. factory on MAN DIESEL A/S license has been demonstrated. The investigative problem and the main aims of undertaken diagnostic research have been formulated. Within this conception there has been taken into account an action model of the considered engine at an application of its diagnosing and controlling application. There has been also considered the proposal of investigation and diagnostic inference enabling an elaboration of the appropriate diagnosis about the engine technical state. Additionally, a way of the research organization as well as the specification of measuring equipment of the proposed diagnosing system diagnosing has been discussed.

1. Introduction

The results of preliminary investigations conducted by the authors as well as different publications [1,10,11,14,18,21,22] containing the research results concerning bio-fuels usefulnesses to feed SI engines lead to conclusion that the further continued investigations should be mainly directed into issues, as follows:

- qualification of the engine's energetic properties by assignment of such parameters (the coefficients) of its action like: maximum combustion pressure in cylinders (p_{max}), the indicated pressure (p_i), exhaust temperature (T_s),
- diagnostics application for identification of the engine's working spaces technical state, especially cylinders' bearing surfaces, pistons' heads, fuel injectors as well as cylinders' heads from the side of a combustion chamber.

We propose an application of diagnosing systems during engines' technical state evaluation, as follows: (fig. 8, 10, 11): a digital register and analyzer of vibration "SVAN 956", digital indicator of the cylinder pressure "the LEMAG the PREMETS" as well as the measuring videoendoskop "XLG3".

The scientific research aimed to evaluate a method of the energetic features estimation of self ignition engines feed with the palm oil as well as procedures of the identification of their technical state. Proposals in this regard have been introduced in point 3.

2. Profile of the research object

The worldwide crisis of shipbuilding industry in Poland extorted the necessity to search for the new sale markets by many country (and not only) manufacturers of marine machines and devices. The far performed changes of the production profile have been often necessary. A major polish producer of marine engines H. Cegielski - Poznan S.A. did not unfortunately avoid this problem. The factory specializes in production of licensed Wartsila as well as MAN the DIESEL A/S engines. Experiences gathered during a realization of the signed's contract along with Greece, on delivery several stationary energetic systems driven by low-speed two-stroke engines made it possible to take over the next order, from behind shipbuilding industry, this time for Germany. The contract signed-up in 2008 includes a delivery of the complete unit of a electric supply powering in the refinery PBB GmbH located in Brake [20]. A two-stroke low-speed engine of 7L35MC-S type produced on the license of MAN DIESEL A/S, adapted to feed with commercial biofuel - raw palm oil has been applied in he propulsion line of the electric power station. This is the first in the world the ecological electric power station, and gathered operation experiences will surely help to improve the propulsion engine's construction. It will also enable an application of different ecological fuels e.g. rapeseed oil, methylic spirit and even the animal tallow in the immediate future. Physical-chemistry properties of the applied biofuel has imposed a necessity of the engine's construction structure modification (elements of the engine's fuel feed system were adapted to have a contact with the fuel of a high acidic number equals 13-16 mgKOH / g), as well as the constructional form.

Currently the engine works on a crude palm oil at the parameters as follows:

Free fatty acids		max	7 %
Impurities		max	0.5 %
Water		max	0.5 %
Ignitron temperature		min	200 °C
Phosphorus		max	100 mg/kg
Acid number		max	14 mg KOH/g
Net calorific value		min	36 000 kJ/kg
Cetane number		min	36
Density		max	930 kg/m ³
Fluidity temperature			18 °C
Resistance to oxidation	100 °C	min	8 std.
Viscosity	50 °C	max	32 mm ² /s
Viscosity	70 °C	max	20 mm ² /s

Sulfur	max	10 mg/kg
Ash	max	0.01 %

The engine's fuel system has been feed with the fuel come from chicken fat during starting the tested engine. This fuel also showed its usefulness to feed such kinds of diesel engines.

The MAN B&W engine of 7L35MC-S type is a 7-cylinder, low-speed, crosshead, two-stroke, high charged engine in a row configuration - fig. 1. A nominal engine's power of the piston stroke - 1050 mm and cylinder diameter - 350 mm equals 4520 kW, at the crankshaft rotational speed - $214,3 \text{ min}^{-1}$ and supercharged pressure - 0,27 MPa. The specific fuel consumption, within the load range burden 80-90% P_{nom} , does not exceed 179 g/kWh. It gives the general engine's efficiency about $\eta_o=54,7 \%$ taking into consideration that the net calorific value of the applied biofuel equals $W_d = 36770 \text{ kJ/kg}$. Figure 2 i 3 demonstrate the schematic diagram of the port-valve scavenging in the engine's cylinder system. The engine represents a propulsion unit for the alternating current generator of LEZ, St. Petersburg 4/5750 kW/kVA, 50Hz /11000kV type. The engine's basic parameters are introduced on the load profile - fig. 4.

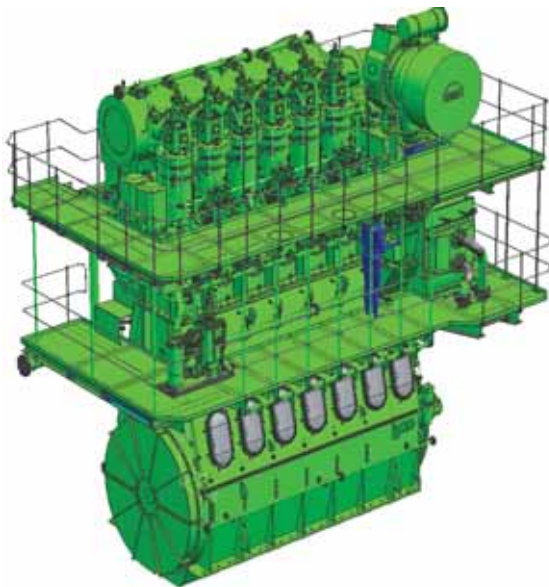


Fig. 1. General view of the 7L35MC-S engine

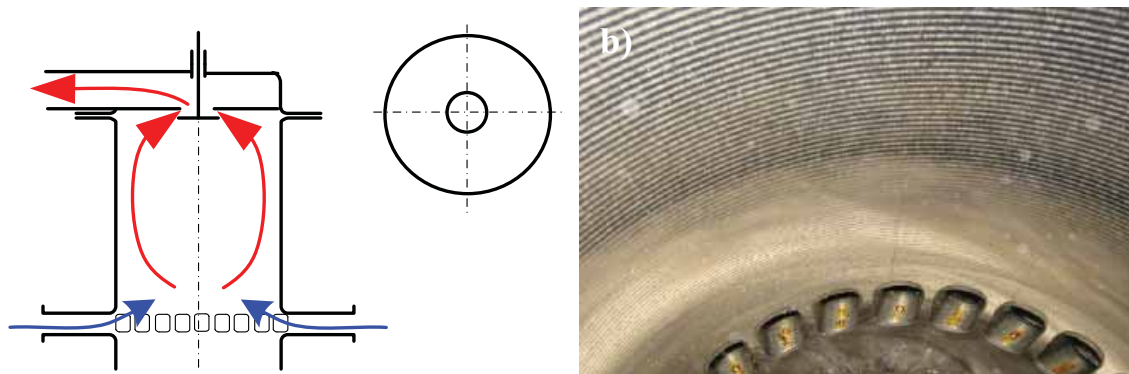


Fig. 2. Port-valve timing system of the 7L35MC-S engine a) flow diagram of the working medium, b) inlet (admission) ports.



Fig. 3. Exhaust outlet of the port-valve timing system of the 7L35MC-S engine
 a) exhaust valve stem, b) exhaust valve fungus in the low plate of the cylinder head.

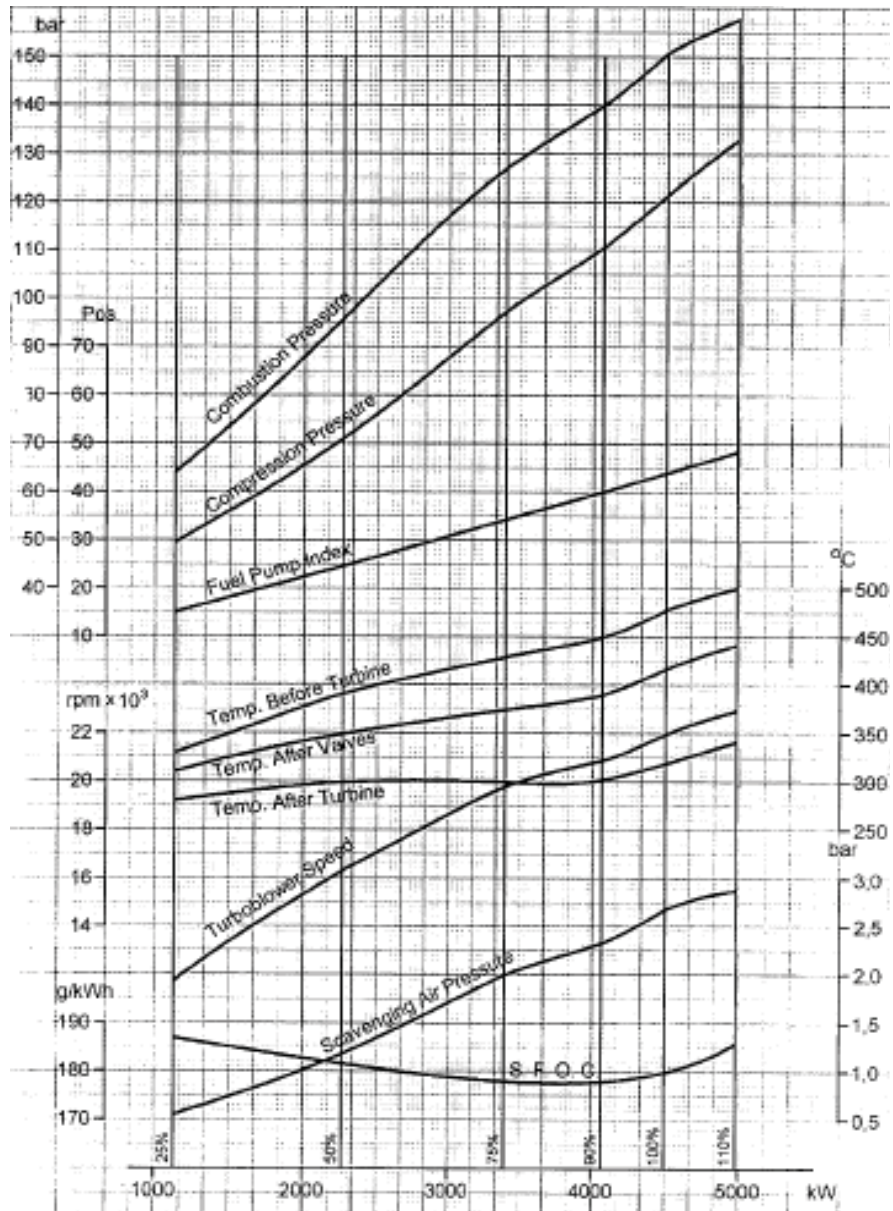


Fig. 4. Load profile of the 7L35MC-S engine

Basic technical parameters which characterize the whole energetic installation:

- Electric power: 4,5 MW;
- Thermal power in a steam and hot water: 3.5 MW;
- Efficiency of the electric energy production: 48%;
- The general efficiency of the electric and thermal energy production: 87%;

The introduced installation is characterised with the highest standard in a range of the environment protection fulfilling the EU requirements within the scope of the Best Accessible Techniques so called BAT (Best Available Technology) - which marks:

- Obtainment of the minimum efficiency of the electric power production with delivered chemical energy in a liquid, in the range of 40 - 45 %;
- Obtainment the associated efficiency (the cogenerative) of the electric power and warmth production (in the form of low-pressure steam from the warmth delivered to the waste-heat boiler as well as in the form of hot water from the warmth delivered to heat exchangers of the cooling cycles HT and LT), in the range of 75-90 %;
- Limitation of dustiness to the level of 20 mg/m³, by means of the electrofilter application;
- Limitation of SO₂ emission, by means of the low-sulphur fuel application;
- Limitation of NO_x emission, by means of the SCR system application;
- Limitation of CO and hydrocarbons emission, by means of OxyCat system application;
- Limitation to minimum of the water dirt, by means of an application of the closed cooling systems of oil and water medias as well as restrictive fulfilling the German norms within this range.

The Competitive Committee of XIII International Energetic Market ENEX 2010 rewarded the project with medal for the innovation and applied technical solutions in an acknowledgement of the innovation of the applied solutions in Brake electric power station.

The operation parameters of the power station as well as the positive opinion of the German customer caused the interest of different investors in this solution. At present HCP realizes the next contract on an equipment delivery of two electric power stations at the power of 13 MW (the engine plus generator and TCS) on English market. The engines will be fed with the rapeseed oil. The electric power stations have to be ready before the next Olympiad (the location on the suburbs of London, in Beckton and Southall).

There is also considered the electric power station building at the power of 32 MW for Ireland - animal fat will be the fuel here, and also building the identical electric power station, how there is in Brake, in Poznan on HCP terrains.

The engine of Brake electric power station overworked about 3500 hours till January 2010. The engine has been twice subjected a technical state evaluation (after 1868 and 3462 overwork hours) since the statement-receiving tests carried out in 24 March 2009.

It is worth pointing out the HCP signed the service contract with German customer in Brake assuring the maintenance of the system's proficiency and its disposability by the period of two years. There is expected that the contract realization will permit on gathering additional experiences and help in selection of optimum solutions in the next projects.

3. Conception and diagram of the research performance

A control of an operation process of any SI combustion engine requires, among other things, controlling both its technical states and energetic states during operation. Moreover, the energetic states controlling may be worked out only during the engine's action (running). In case of a SI engine, the controlling process consists in well ordered impact on the engine's

constructional structure parameters, controlling devices and the direct user (the controlling system), according to principles, programmes and algorithms accepted by the decision-maker. They should be adapted to the executed tasks, of which undertaking requires the regard of limitations (H), criteria function (F) as well as the results of diagnosing in the form of diagnoses (D), or diagnoses and also the prognoses (P), or diagnoses and also the possible origins (genesis G), or the full diagnoses (it means together diagnoses, prognoses and origins), generated by the diagnosing system (SDG). Such a situation is pictured in form of diagram introduced in fig. 5 [6]. The above mentioned task $Z = \langle D_Z, W_R, t \rangle$ could be interpreted as the correct action consisting in production of the required power in engine's cylinders - in general - the engine's functioning (D_Z), in definite operation conditions (W_R) and in the settled time (t). The controlling process should assure a rational engine's action, which consists in the proper energy transforming in the form of warmth and work. Consequently, the engine's overall efficiency does not deviate considerably from the optimum value of the overall efficiency that could be possible to obtain for the considered engines' types. Moreover, a technically dry friction does not occur within the engines' most significant tribologic systems. The only mitigated solid friction is acceptable. A rational action of this engines does not lead to premature damages of its elements (pistons, piston rings, main and crank bearings etc.), causing the unserviceable states, especially characterised with extensive disturbances of constructional structure, so called the breakdowns.

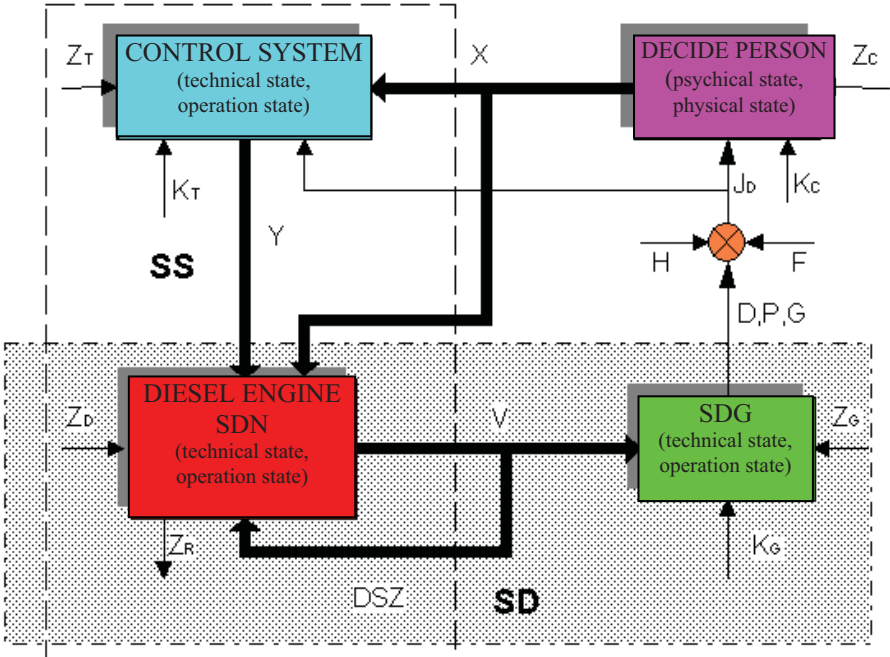


Fig. 5. Simplified model of combustion engine operation with regards to diagnosing and controlling in time of operation [6]: D - diagnosis, DSZ - destructive feedback, F - criterion function, G - genesis, H - operational limitation, J_D - decision information, K_C - disturbances while making operational decisions, K_D - disturbances of the system being under diagnosis (SDN) and simultaneously under control (ST), K_G - disturbances of diagnosing system (SDG), K_T - disturbances of controlling system, P - forecast, SD - diagnostic system (SDN and SDG), SS - control system, V - vector of initial processes, X - vector of decision, Y - vector of control, Z_C - power supply of a decision maker, Z_D - supplied power, Z_G - power supply of a diagnosing system, Z_R - lost power, Z_T - power supply of a controlling system.

The result of foregoing considerations is that the credibility of diagnosis should be taken into account during undertaking operation decisions [2,6,7]. In case of a determined fact that

the diagnosing system (the *SDG*) has been in full operation readiness (in the full serviceable state and acted without fail) during diagnostic investigations and diagnosis elaboration about the engine's technical a diagnosis pertinence should be taking into account [2,6]. The additional result is that the rational regard of the diagnostics within the control process of combustion engines requires the accomplishment of a diagnostic identification of the individual engines, in which the information enabling the construction of suitable diagnostic models of these engines should be worked out. This task requires also a diagnostic process identification aiming an obtainment of the information defining a specific of this process. The information got has the essential meaning, because the course of this process influences on the diagnosis' credibility, indeed (alternatively on the pertinence) about the technical state of individual combustion engines. The process can be viewed variously, but it goes without saying that the process is created by the realizations, as follows: always:

- diagnostic investigation,
- diagnostic inference.

In general, a diagnostic inference is usually created by the inferences: signal, measuring, symptomatic, structural and operational [2]. A schematic diagram of such an inference is introduced in fig. 6.

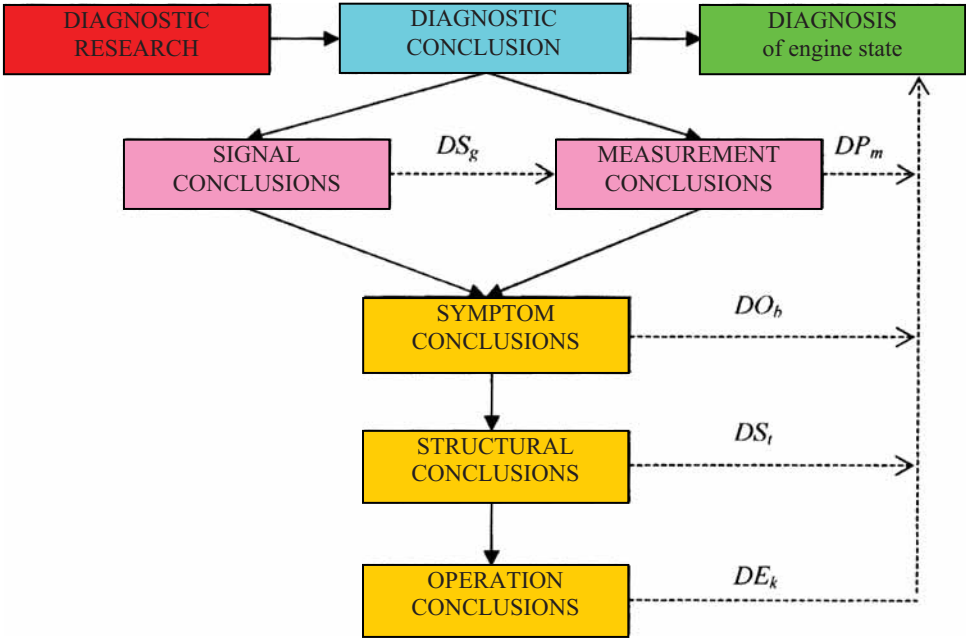


Fig. 6. Diagram of diagnostic inference enabling elaboration of a diagnosis about technical state of an engine (*SDN*) and simultaneously about making operational decision: engine of „full ability”, „partial ability” or „disability” for employment in compliance with its destination: DS_g - signal diagnosis, DP_m - measurement diagnosis, DO_b - symptom diagnosis, DS_i - structure diagnosis, DE_k - operation diagnosis.

As far as the introduced diagnosing conception is concerned the diagnosing process has go the values (states), which represent a diagnostic investigation and specified kinds of the inference, and the time of these kinds duration reflects realizations of these states. Therefore, this is the process of the following class: discreet in states and continuous in time. From the research which have been carried out so far results that this process can be recognized as the semimarc one [7,8,9].

The mistakes made within every kind of mentioned above inferences can accumulate. Moreover, the more states *SDN* are contained in a diagnostic task the greater mistakes are. The more exact diagnosis is necessary (it means a diagnosis at the larger credibility) the

mistakes meaning is greater. These facts cause, that only three states class *SDN* are considered: full fitness, partial (incomplete) fitness and unfitness.

4. Research apparatus

4.1. General description of the research apparatus

Permanent modernizing and enlarging the possibility of the measurement-diagnostic systems applied within the energetic system driven with combustion piston engines enables widening functions of the control system of control including, except standard measurement of the operation parameters, also the functions of measurement and registration:

- pressure in an engine's cylinders,
- vibration generated by the chosen points of an engine's constructional structure (the head, turbocompressor's frame),
- vision of internal spaces.

Schematic diagram of the designed diagnosing system, taking into account the constructional form of 7L35MC-S engine as well as the accessible investigative apparatus, is introduced in figure 7.

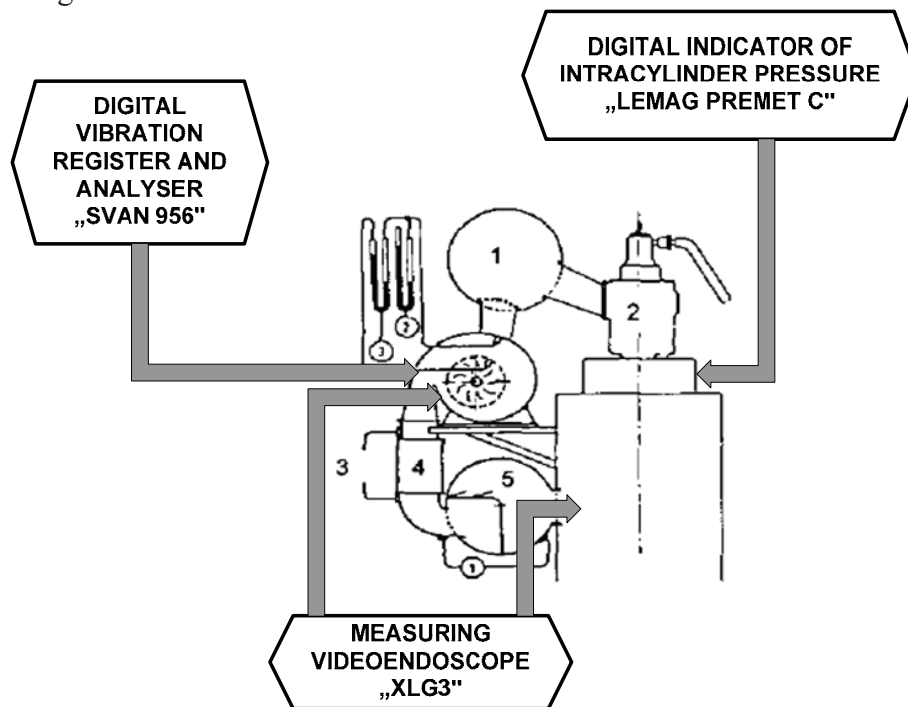


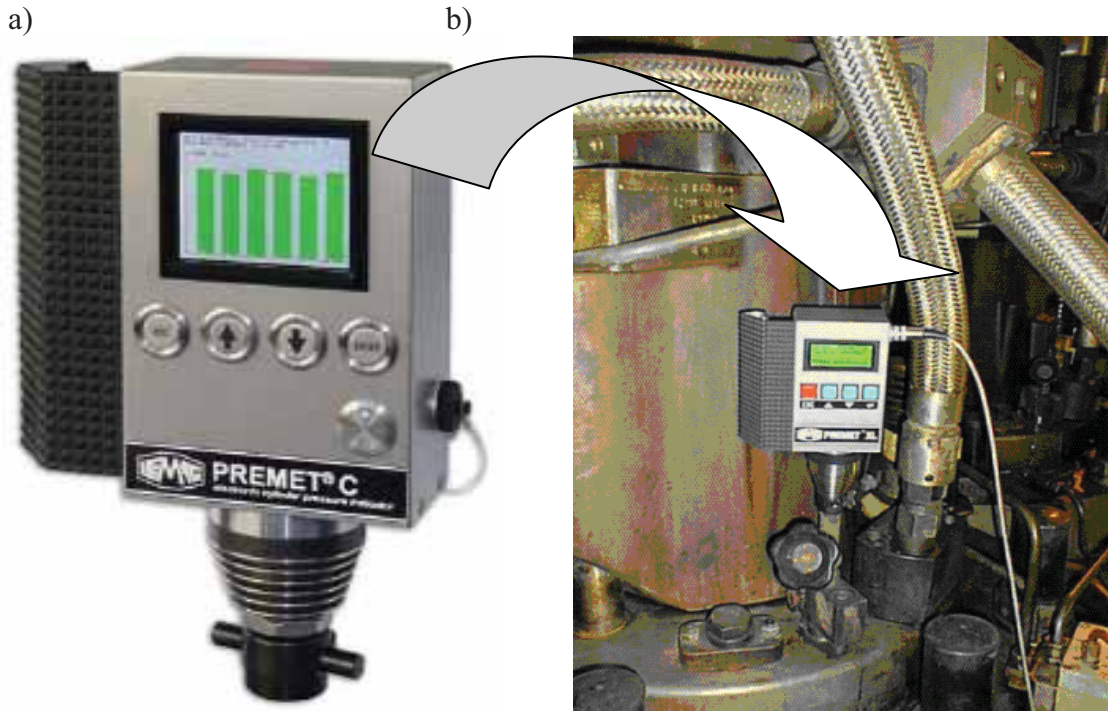
Fig. 7. Schematic diagram of 7L35MC-S engine along with diagnosing system's elements
 1 – exhaust-storage cell, 2 – outlet valve, 3 – turbocompressor, 4 – scavenging air cooler, 5 – scavenging air-storage cell.

4.2. Digital indicator of the pressure in engine's cylinders

A selective indicating the engine's cylinders during a steady running on representative and settled ranges of the engine's load represents the basis of a realization of the parametric diagnostic investigations. Developed indicator diagrams are created by means of the specialist electronic indicator "LEMAG PREMET C" (fig. 8). The diagrams represent the courses of pressure alterations in the engine's cylinders in terms of an angular position of the crankshaft. Moreover, a crankshaft's angular position on the indicator diagram is related to the piston's

IDC (inner dead centre) - fig. 9a. Such diagrams are then overlaid each other, averaged and compared in terms of a load's inequality of the engine's individual cylinders - fig. 9b. It has got relocation on the spectrum of torsion vibration of the engine's output shaft deciding about the lifespan of elements transmitting a torque to the power receiver. If the cylinders' pressure measurements were associated with the vibration measurements generated from the engine's head during hittings the co-operating constructional elements of valve timing and fuel apparatus the more precise and deeper formulation about the engine's governing state would be possible.

The results of cylinders' indicating will be also used in a trends analysis to evaluate alterations of the engine's technical state in different stages of the usage process and to elaborate rational operation decisions.



*Fig. 8. Digital indicator of the engine's intracylinder pressure „LEMAG PREMETS C” [23]
a) complete indicator along with adapter, piezoelectric Kistler sensor (0-25,0 MPa) and projector LCD, b) the way of indicator installing on the RTA48TB engine.*

On the basis of simultaneous measurements of pressures in cylinders, crankshaft rotational speed and vibration generated from cylindrical heads there is possible determination of the engine working spaces' diagnostic parameters, as follows:

- maximum compression and combustion pressure,
- average indicating pressure of individual cylinders,
- indicating power of individual cylinders as well as the whole engine,
- intensity of pressure growth in cylinders $dp/d\alpha$,
- angles of the injector's opening and closing,
- angles of an occurrence of the fuel self-ignition in a cylinder,
- angles of cylinder valves' opening and closing.

a)

b)

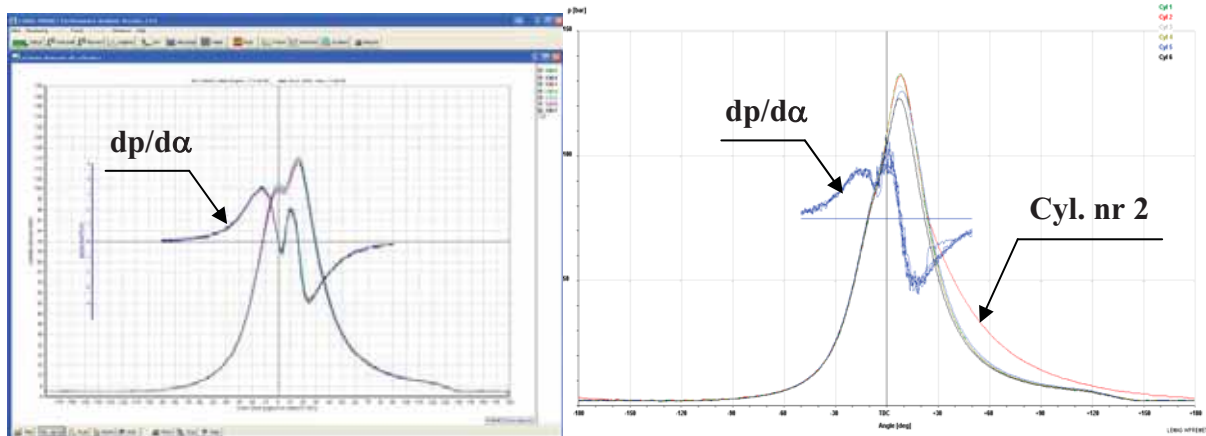


Fig. 9. View of the computer screen after starting-up an analyzing program of the indicator
 a) analysis of the intensity of pressure growth in cylinders, b) overlaid indicator diagrams – fuel afterburning during expansion process worked out in cylinder number 2 (disturbances within the atomization process, leakage of the injector sprayer).

A convenient menu of the analysing indicator programme enables working out the functions, as follows:

- display of a course of the cylinder heads vibration's envelope on a background of the intracylinder pressure course in terms of the crankshaft rotation angle,
- quick presentation of all the measured and computed parameters' values in the form of tables as well as developed graphs and bar graphs, and also the comparison of their values to the average values for the engine,
- comparison of the indicator diagrams of any cylinders of a studied engine, as well as the gathered data of different engines of the same type.

There is possible to carry out the analysis of the engine's technical state on the basis of assigned diagnostic parameters, as follows::

- assessment of the engine cylinders' tightness,
- assessment of the load equability of individual engine cylinders,
- assessment of the control quality of the injection unit,
- assessment of the performance of the whole engine,
- assessment of the engine's and propulsion system's mechanical losses,
- forecasting the time of the engine's correct running,
- precise readjustment of the engine to the work on partial loads, which leads to limitation of fuel consumption even by 30%.

4.3. Digital vibration register and analyzer

A fatigue strength of the material of constructional structure's elements stands for one of the parameters which has got the most essential impact on a combustion engine's lifespan. A multiple alterations of mechanical and thermal loads during an engine's work might cause serial springy and plastic deformations of the constructional elements. They represent the reason of a formation of variable internal tensions, until the fatigue cracks occur (high - and low-cycle fatigue). A vibration resulting from the stability loss of the engine's mechanical unit stands for the most frequent reason of fatigue cracks of a combustion piston engine. With regard to a special construction's complexity of the combustion piston engine, as a fluid-flow machine at the periodic action, there is possible appearing the resonance phenomenon of all the vibration's forms: torsion, longitudinal and transverse. The huge variety and

changeability of the occurred extortions (and disturbances), at a lack of sufficient information about the frequencies of proper (own) vibration of constructional parts causes the opinion that the state of an operational vibration diagnostics of combustion piston engines is still discontent, because only few engine's components are susceptible on this method of a technical state's evaluation. Nevertheless, many scientists dealing with a diagnostics of combustion piston engines of a large power (particularly marine diesel engines) undertake trials to make a spectral analysis of all the vibration's forms for the technical state's evaluation of chosen constructional elements of the engine. It would concern, among others, cylinder liners - longitudinal and transverse vibration [19], fuel injectors and working spaces - a crankshaft's torsion vibration [3,4,5,17], cylindrical valves (clearances) - the transverse vibration of a head [15], turbocompressors (bearing and blading system) - longitudinal and transverse vibration of the rotor [16].

On the basis of so far reached results, there can be concluded that in case of the considered 7L35MC-S engine the measurement and spectral-correlational analysis of the vibration signal generated with a turbocompressor running represents the most promising method of a complex evaluation of its technical state. An attractiveness of the spectral analysis confirms its common applying in diagnostics of whirling machines. It induces the measuring devices' manufacturers to construct the more and more perfect vibration's registers and analyzers which give a possibility of the following trends of values' alterations of the spectrum parameters in different characteristic frequency bands, for the well-known and recognizable states of operation unfitness [24].

It is foreseen, that in the first stage of diagnostic investigations of the 7L35MC engine's turbocompressor a single-channel digital vibration measuring instrument SVAN 956 type equipped with the function of frequency analysis (FFT function - Fast Fourier Transform function) of spectrum amplitudes of the recorded vibration signal will be applied- fig. 10.



Fig. 10. Digital vibration register and analyser „SVAN 956” [24]
1 – piezoelectric sensor of vibration’s acceleration, 2 – laser tachometer probe.

It is equipped with DYTRAN piezoelectric acceleration sensor 3185D type. A magnetic connection of the sensor makes it possible a quick exchange of the measurement place which has got the very essential meaning in case of variable and limited conditions of the measurement's realization. Three independent measuring profiles applied in the analyzer

permit selecting three filter sets and time-constants for the simultaneous measurement of vibration's acceleration, velocity and displacement within the frequency range from 0,5 kHz to 20 kHz (limited with a transfer band of the applied transducer). Thanks to the large power of a signal processor the simultaneous narrow-band analysis FFT, the simultaneous frequency analyses within the octave- and tercial-bands as well as the simultaneous analysis of vibration envelope are possible during the measurement realization. The analyzer's capacious memory (32 MB) enables recording a time history of the measurement within unsteady processes (turbocompressor rotor's acceleration and deceleration) for an observation of the level alterations and frequency spectrum during measurements: root-mean-square value (RMS), peak value (PEAK), peak to peak value (PEAK-PEAK), maximum root-mean-square value (MAX). There is also accessible the register's version equipped with a function of whirling machine balancing, which requires the rotational speed measurement (laser tachometer probe - from 1 to 99999 min⁻¹) with a simultaneous vibration measurement.

4.4. Measuring videoendoscope

A visual examination o internal space of marine diesel engines with the use o edoscopies is currently the basic method of technical diagnosis. The surface structure of the construction material is seen as if through a magnifying glass during the examination which enables detections, identification and quantitative assessment of the malfunctions and material defects, eventually leading to the quick assessment of the level of deterioration and fouling of the constructional elements while the engine is excluded from the motion. They do not usually generate observable alterations of the diagnostic parameters' values. Depending on the method of observation and image processing o a surface under examination we can distinguish a classic optical endoscopy utilizing rigid (lens based) boroscopes and flexible fiber glass fiberscopes and dynamically developing digital endoscopy utilizing highly sophisticated videoendoscopes fitted with high resolution micro cameras – fig. 11.

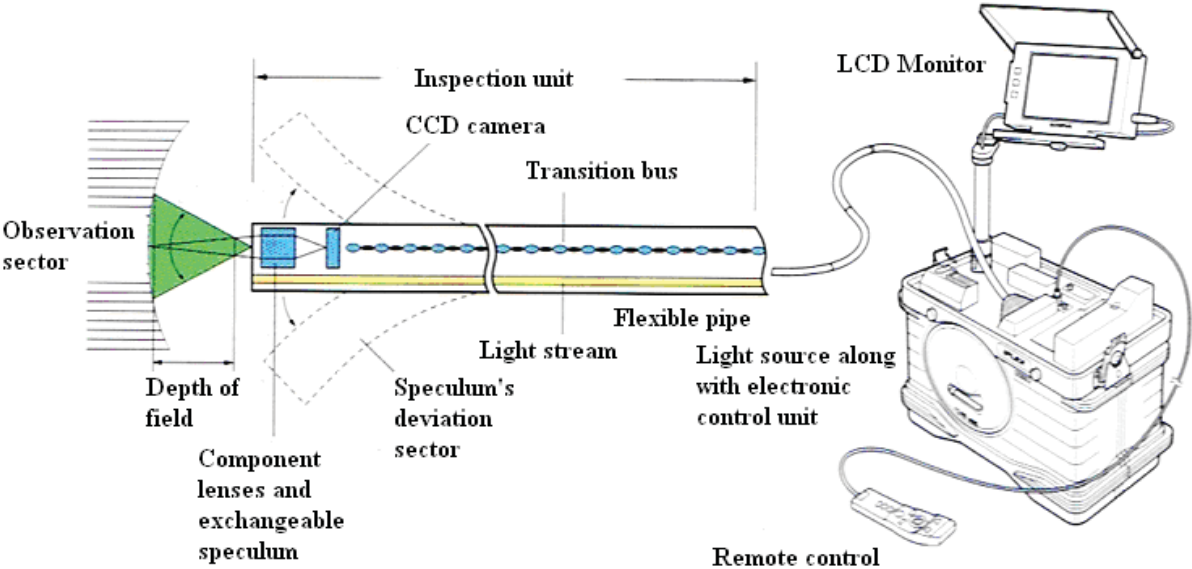


Fig. 11. Schematic diagram of a videoendoscope [25]

A CCD camera processes optical image into an electronic one which is digitally transmitted via a bus into a color LCD unit. This solution generates new diagnostic

possibilities such as the ability of qualitative assessment of the surface deterioration (the possibility to measure the detected structural changes – defects, discolorations, contrast etc.). Because producers of marine machines and devices give permissible values of the surface defects of the most vulnerable construction elements the precise assessment of the real dimensions of the defect represents a key diagnostic issue.

Another important advantage is the high resolution of the image reaching several hundred thousand pixels which ensures sharpness even under poor illumination – fig.12. A digital recording of the image as videoinformation in e.g. JPEG can be transmitted on long distances (cellular networks, the internet). This allows a multilateral didactic (training an exchange of experience) or specialized consultation aiding the process of diagnostic reasoning.

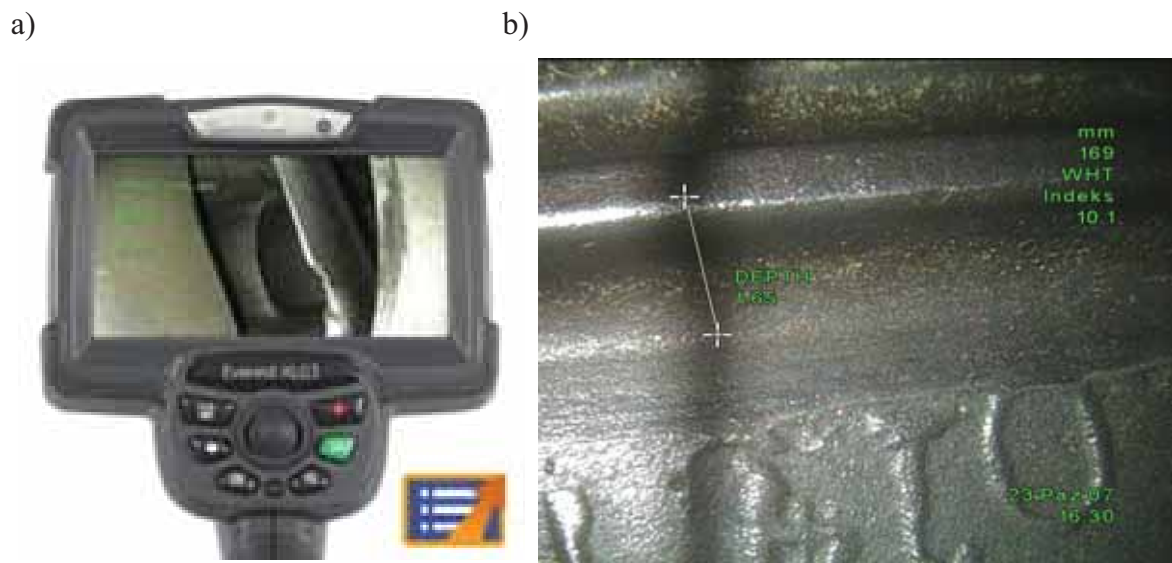


Fig. 12. Digital recording of the image by means of measuring videoendoscope XLG3 [12,25]
 a) panoramic LCD projector, b) depth's measurement of the concave surface profile with the „Shadow” method.

5. Summary. Final remarks and conclusions

Biofuels application at the defined physical-chemistry proprieties requires the adaptation of the engines' constructional structure to the biofuels which have to feed them. There has been affirmed the relationship between the applied biofuel and constructional structure of the engine, representing the investigation, which is fed with this fuel.

A two-stroke, low-speed engine of 7L35MC type produced on licence of MAN DIESEL A/S Company, adapted to biofuelling with a raw palm oil has been undertaken as an investigation object.

There is a possibility of widening the measuring offer of universally applied control system by means of, except standard measurements of operation parameters also, functions of the measurement and registration:

- pressure in the engine's cylinders,
- vibration generated by the selected points of the engine's constructional structure (cylinder head, turbocompressor frame),
- image of the engine's internal spaces.

The measuring possibilities of the specialist electronic indicator "LEMAG PREMETS" (fig. 8) have been characterized. It is designed and foreseen to create a developed indicator diagrams which represent courses of the pressure alterations in the engine's cylinders in terms

of crankshaft angular position. Moreover, the crankshaft angular position on a developed indicator diagrams is related to the piston's IDC.

There has been also paid an attention within the proposed investigations on usefulness of a multi-channel vibration meter "SVAN 956" type, equipped with the function of frequency analysis (FFT function) of the spectrum amplitudes of the recorded vibration signal (fig. 10). The vibrometer is additionally equipped with a piezoelectric acceleration sensor DYTRAN 3185D type.

One of the most up-to-dated videoendoscope, namely a measuring videoendoscope "XLG3" type, foreseen to diagnostic investigations has been presented. This kind of endoscope is equipped with miniature digital camera CCD, at high resolution (fig. 11), which processes an optical image into an electronic one. Its digital record is transformed by the sonde (broadcasting rail) on the LCD colorful monitor.

An application of the above mentioned diagnostic devices is necessary with regard to need to obtain the credible information concerning not only energetic aspects and potential contamination of a natural environment with toxic substances, but also aspects within the range of wear and tear process of the engine fed with biofuels and the same its reliability and durability.

It results from the gathered information about MAN Diesel 7L35MC-S engine wearing (affects its reliability and durability), that a technical diagnostics has to be necessarily applied. It should be expected, that diagnosing systems like mentioned: digital vibration register and analyzer "SVAN 956", digital indicator of the pressure in engine's cylinders "LEMAG PREMETS C" as well as the measuring videoendoscope "XLG3" applied together with classic diagnosing systems which provide contemporary self ignition engines represent interesting possibilities to incorporate information about technical shape of biofuelled engines.

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SIMPLIFIED RESEARCH TESTS OF TOXIC COMPOUNDS EMISSION'S FROM MARINE DIESEL ENGINES

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Abstract

Valid at present standards and measuring regulations of toxic compounds in exhaust gases oblige the manufacturers and exploiters of marine Diesel engines to use of a suitable tests and measuring procedures. In case of marine piston engines the fulfilment of required standards in engine bed test at manufacturer does not make any problem, however such tests on board of ship may be difficult or sometimes impossible to execute. The additional problem is a requirement of repetition of exhaust gas toxicity in definite time period. It the proposal of study of universal profile marine Diesel engines in article was contained as well as two - and three-phases research test of toxic compounds in exhaust gas of engine installed in an engine room.

Keywords: *Marine Diesel engine, exhaust gas, emission, research test, at-site measurement*

1. Introduction

In having on aim the qualification of coefficients investigations and the standard is in force the characteristics of toxic compounds of marine Diesel engines ISO 8178 standard and connected with him prescriptions the IMO (for example " Technical Code").

Standard consists of 9 parts [1-9], that mentioned parts the exact researches conditions, their course, measuring apparatus as well as research report were described. As a validity research parameter, the coefficient f_a , fulfilling following condition was introduced:

$$0.98 \leq f_a \leq 1.02, \quad (1)$$

The parameter f_a was counted according to the following examples:

- combustion-ignition engines not supercharged and charged mechanically:

$$f_a = \left(\frac{99}{p_s} \right) \times \left(\frac{T_s}{298} \right)^{0.7}, \quad (2)$$

- combustion-ignition turbo-compressor engines charged with or without air cooling :

$$f_a = \left(\frac{99}{p_s}\right)^{0,7} \times \left(\frac{T_a}{298}\right)^{1,5}, \quad (3)$$

where: T_a - the absolute temperature of air incoming to the engine [K],
 p_s - the atmospheric dry air-pressure [kPa].

The formulas 2 and 3 are identical to regulations of the ECE (*Economic Commission for Europe*), EEC (*European Economic Community*) and EPA (*Environment Protection Agency*) relating the exhaust gas emission.

The base for exhaust gas emission is uncorrected effective power. The all installed on engine auxiliaries, indispensable only for running of ship's power station as: the compressor supporting of steering arrangement, the compressor of air-conditioning arrangement, pumps of hydraulic steering, should be disassembled to the tests. Losses on auxiliaries should not exceed 5% of maximum measured power.

The accuracy of gauges should assure the not exceeding of deviations introduced in ISO 8178-1 [1] for measurements executed on test post and in ISO 8178-2 [2] for measurements executed in place of installation.

The total error of measurement, including sensibility on interferential effect different gases, should not exceed of $\pm 5\%$ read value or $\pm 3,5\%$ of the full range of scale, and the lower of these values should be taken. For concentration lower than 100 ppm, the measurement error should not exceed of $\pm 4\%$. The measurements in a place of installation comparing with measurements on test post are less exact and precise because of environmental influences and running conditions. The repeatability and accuracy also depends (for example) on, volumetric concentration (ppm), mass concentration ($\mu\text{g}/\text{m}^3$) or specific emission ($\text{g}/(\text{kW}\cdot\text{h})$).

The engine's load setting for each of test should be calculated according to formula:

$$S = \left[(P_m + P_{\text{AUX}}) \frac{L}{100} \right] - P_{\text{AUX}}, \quad (4)$$

where: S - the setting of engine's break [kW],

P_m - maximum measured or declared power at the test engine speed under test conditions [kW],

P_{AUX} - declared total power absorbed by auxiliaries fitted for the test [kW],

L - percent torque related to the maximum torque for the test engine speed.

The measurements and estimation of gas exhaust emission should be executed using of suitable research cycle, proper for given use, accordingly to requirements ISO 8178-4 [4]. For researches of marine piston combustion engines the tests E2, E3, D2, C1 should be executed (table 1 and 2).

Tab. 1. The main engines' researches cycles with no time limitation - E2 the (running with constant rotational speed), E3 (running according to the screw characteristic) and the generators with variable load D2 (according to ISO 8178) [4]

	E2				E3				D2				
Engine speed [%]	100	100	100	100	100	91	80	63	100	100	100	100	100
Load [%]	100	75	50	25	100	75	50	25	100	75	50	25	10
Weighting factor	0,2	0,5	0,15	0,15	0,2	0,5	0,15	0,15	0,05	0,25	0,3	0,3	0,1

Tab. 2. Engines' researches cycles working at variable rotational speed and changeable load - cycle C1 (according to ISO 8178-4) [4]

C1								
Engine speed [%]	Rated Power				Intermediate			Idle
Load [%]	100	75	50	10	100	75	50	0
Weighting factor	0,15	0,15	0,15	0,1	0,1	0,1	0,1	0,15

Part 2 of the standard ISO 8178 can be used for investigations guided in a place of engines' installation. However, if during researches in a place of installation it is not possible to keep exact working conditions as on the test post, the emission values may not be identical to values obtained on test post [2]. Moreover, the standard determines that the running of engine accordingly with researches cycles - as in ISO8178-4 - is not always possible in each case, yet the realization of researches should be the closest according to procedures of ISO 8178part 4.

Basing on above mentioned records and researches over characteristics of exhaust gas toxicity of marine engines, the short test of toxicity for mean speed engine working according to screw characteristic has been undertaken.

2. Proposal of two and three-phases research test

During such researches over marine engine of Sulzer type 6AL 20/24 installed on test post at the Naval Academy in Gdynia [10] on the NO_x concentration speed characteristic it was observed some points, permitting on qualification the maximum and minimum values of NO_x concentrations without necessity the realization of whole E3 test accordingly to ISO 8178-4 (Fig. 1). These points are equivalent to the idle of engine and load of 25% P_n.

It is necessary to aid, that the E3 test does not foresee the researches of the no-load engine, which is result of normal working conditions. However, in a case of ships like, the fishing ships, tugs or battleships, such working state is quite often and can exceed 8% of all running time of the engine [11, 12].

In a case of researches on board, it can turn out to difficult or even the impossible to perform of whole test according with standard (as floating with power rating engine load depending on the weather) what induced the authors to study of test of two and three-phases based on requirements of E3 test, but possible and easier to realization in any conditions of engine exploitation.

The two-phase research test of NO_x emission of engines working according to screw characteristic covers the point of the minimum NO_x concentration related to the engines' idle and the point of maximum NO_x concentration related to the load of 25% P_n (Fig. 2).

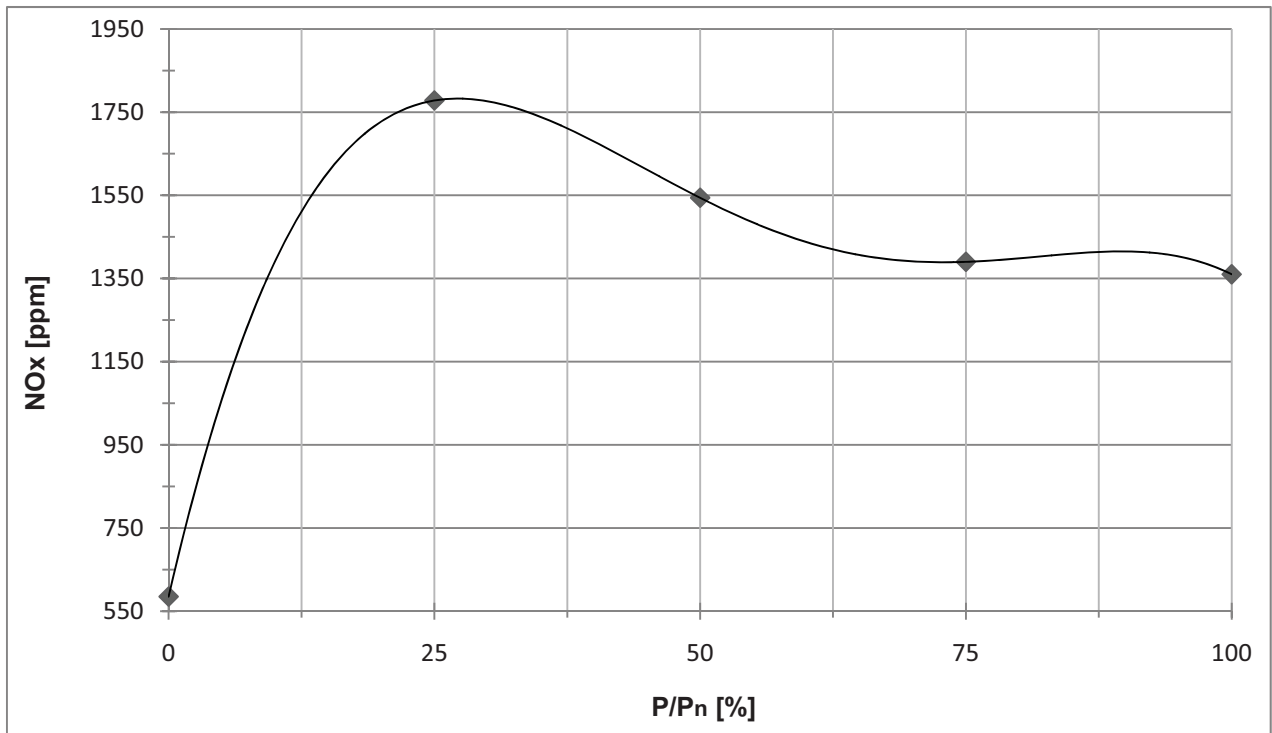


Fig 1. The characteristic of NOx concentration changes as a function of engine 6AL20 / 24 load according to the test E3 of ISO8178-4

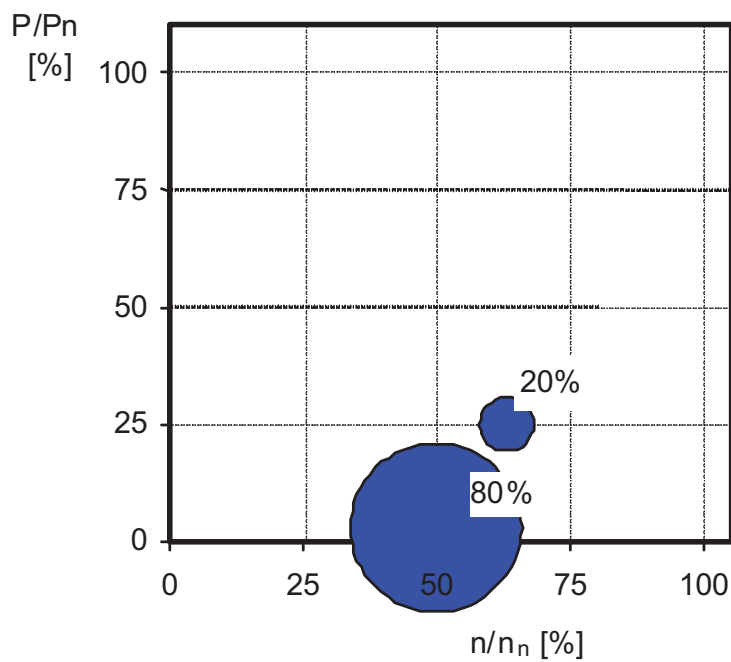


Fig 2. Two-phase research test of exhaust gas toxicity of marine engine working according to the screw characteristic

In aim receipt of three-phase test, the point of 50 % engines' load P_n for which NO_x concentrations are close to other points of E3 test was added (Fig. 3).

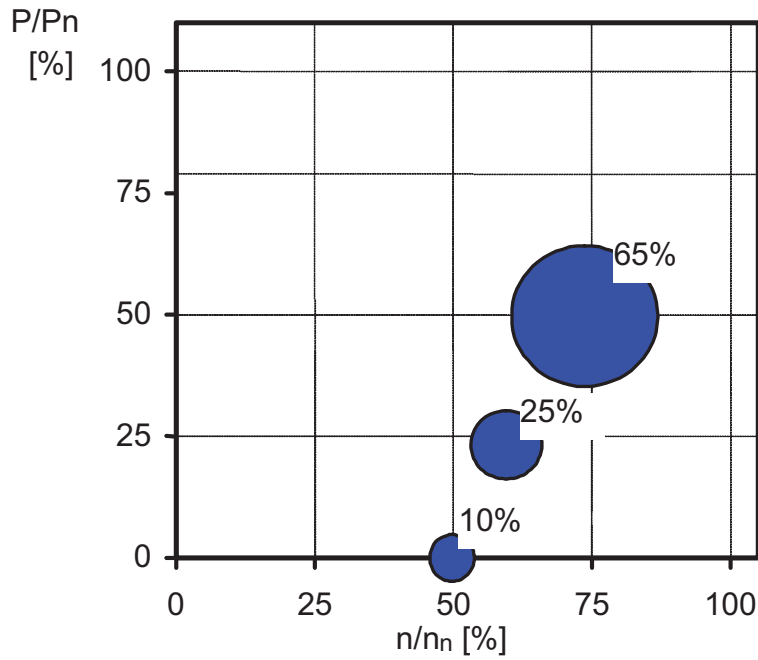


Fig 3. Three-phase exhaust gas toxicity of marine engine working according to screw characteristic

In order to the proposed tests permitted on realization of researches adequate to full E3 test it was necessary to determine proper parameters of running test (test phase weight coefficients – W_f) as well as to modify the equation describing the NO_x specific emission of the studied engine.

The specific emission coefficient of exhaust gas components Gas_{in} [g / (kW·h)] is expressed by formula:

$$Gas_{in} = \frac{\sum_{i=1}^{i=n} B_{si} \cdot W_f}{\sum_{i=1}^{i=n} P_{ei} \cdot W_f}, \quad (5)$$

where: W_f - weighting factor,

P_{ei} - the effective power of the engine [kW],

B_{si} - the mass emission intensity [kg /h] or [g /h].

In a case of shortened two-phase test the formula (5) is as:

$$Gas_2 = \frac{[(B_{s0}/3) \times 0,8 + (B_{s25}/2) \times 0,2]}{P_{e0} \times 0,8 + P_{e25} \times 0,2}, \quad (6)$$

where: B_{s0} and P_{e0} - the NO_x emission intensity values and the effective power for idle,

B_{s25} and P_{e25} - the NO_x emission intensity values and the effective power for 0,25 P_n .

and for the proposed three-phase test:

$$Gas_3 = \frac{[(B_{s0}/3) \times 0,1 + (B_{s25}/2) \times 0,25 + B_{s50} \times 0,65]}{P_{e0} \times 0,1 + P_{e25} \times 0,25 + P_{e50} \times 0,65}, \quad (7)$$

where: B_{s0} and P_{e0} – NO_x emission intensity values and the effective power for idle,
 B_{s25} and P_{e25} - NO_x emission intensity values and the effective power for $0,25 P_n$,
 B_{s50} and P_{e50} - NO_x emission intensity values and the effective power for $0,5 P_n$.

3. Verification of exactitude of proposed tests

In the aim of the proposed tests exactitude verification, for NO_x emission estimation, the two Sulzer diesel engines were tested:

- six- cylinder type 6AL20/24 of $P_n = 432 \text{ kW}$ and $n = 720 \text{ min}^{-1}$,
- sixteen-cylinder 16ASV25 / 30 of $P_n = 3600 \text{ kW}$ and $n = 1000 \text{ min}^{-1}$.

The results that research were introduced on drawings 4 and 5.

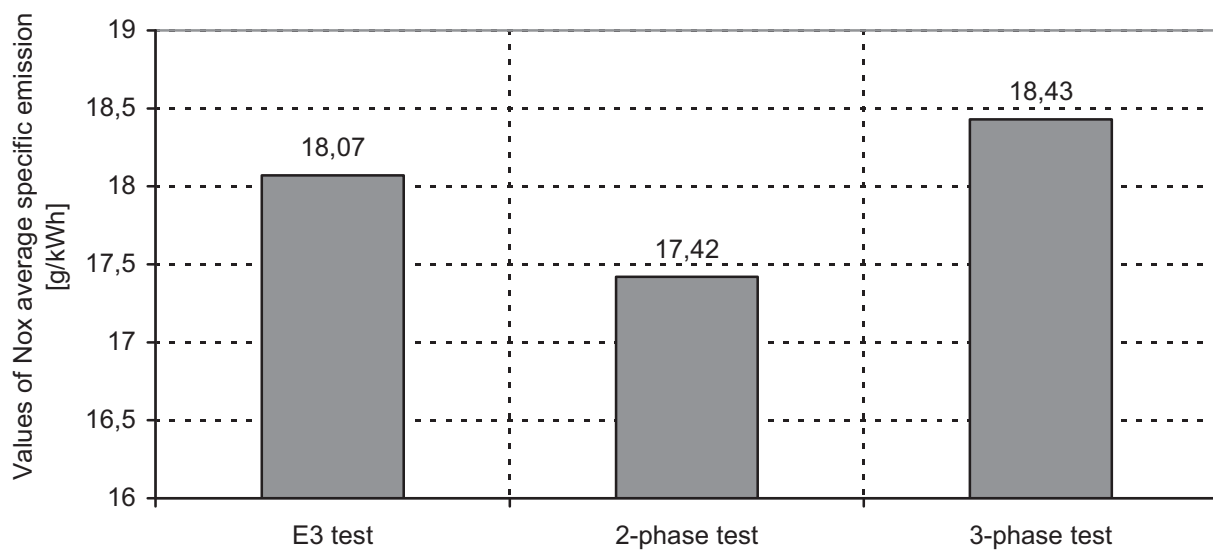


Fig.4. The comparison of NO_x average values specific emission determined using the E3 test according to ISO 8178-4 and two and three-phase test for engine of the Sulzer 6AL20/24 type

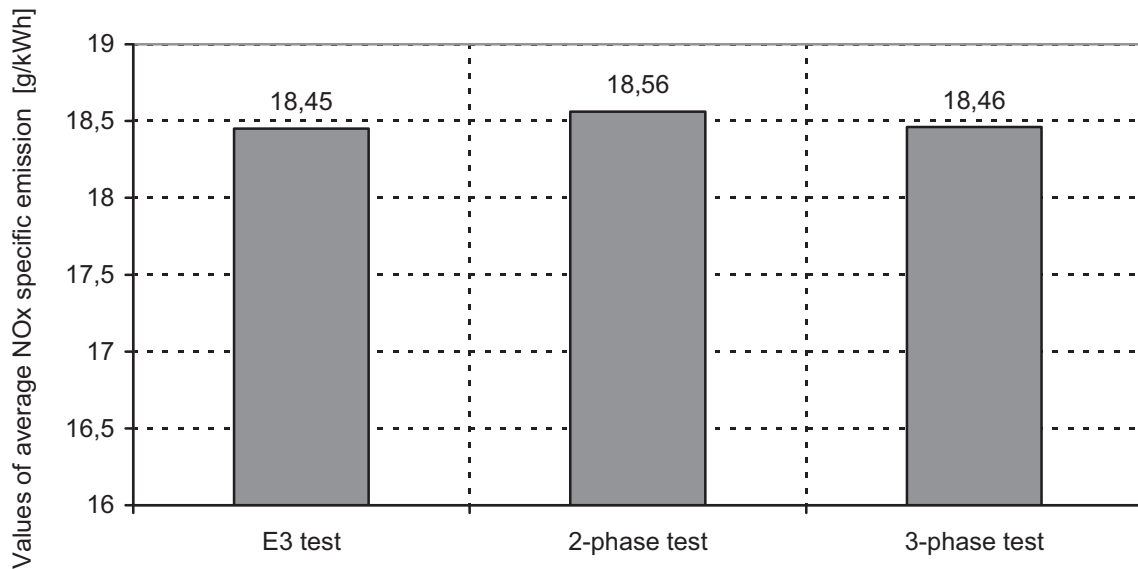


Fig.5. The comparison of NO_x average values specific emission determined using the E3 test according to ISO 8178 – 4 and the and two and three phase test for the engine of Sulzer 16ASV25 / 30 typ.

In the case of Sulzer 6AL20/24 type engine the difference between NO_x average specific emission determined by E3 test, according to ISO 8178-4 and adequately:

- shortened two - phase test was 3, 6 %;
- shortened three - phase test was 1, 9 %;

Differences between average specific emission fulfil the requirements of ISO 8178 standard with regard on the exactitude and repeatability of measurements results in place of installation (table 2), which allows $\pm 9\%$ error for measurement of exhaust gas components.

For Sulzer 16ASV25/30 type engine the results of measurements proved the considerable similarity of tests, because the difference between the average NO_x emission value determined by E3 test according to the ISO 8178-4 and proposed adequately:

- two-phase test was 0, 1 %;
- three-phase test was 0, 01%;

Summary

Basing on conducted researches it was confirmed the possibility of applying of the simplified and sufficiently effectives tests of NO_x emission for marine mean speed combustion engines working according to screw characteristic. In the case of low speed engines the research verification should be made, in order to determine usefulness of proposed tests and equations to determine the average NO_x emission value.

The accuracy of measurement grows up along with the quantity of test phases so the two and three-phases tests could be applied first of all to follow-up control tests of engines (as periodical, required by regulations or ship-owners) and for certification, if realization of the full test would be impossible.

The further researches over tests of research of toxic compounds in exhaust gas can permit on preparation of the universal test for all kinds of main power marine engines regardless of load during exploitation

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AN ATTEMPT OF A PRELIMINARY ASSESSMENT OF THE SERVICEABILITY ASSURANCE PROCESS ON THE BASIS OF STATISTICAL ANALYSIS OF A CHAIN OF DAMAGES

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Abstract

The investigation object in this paper is a real system of an urban transport bus operation and maintenance in a large urban agglomeration. The investigated system belongs to the class of operational systems with a goal oriented behaviour. The paper presents the results of the investigations concerning damages to the buses of an urban transport system. Based on the analysis of the statistical data regarding the damages to the elementary bus subsystems some feature has been found, and namely that certain sequences of the damage chain occur with excessive frequency. The damage chain is considered to be a random sequence whose elements are the codes of the successively damaged bus subsystems. The analysis of the damage chain may be one of the elements to evaluate the maintenance subsystem within complex operation and maintenance systems of technical objects.

Keywords: *chain of damages, transition probability matrix, operation and maintenance process*

1. Introduction

The essential source of information allowing to obtain objective results of quantitative analysis of bus damages are statistical data during the operation and maintenance investigation performed.

In scope of the operation and maintenance investigation performed a matrix of probabilities of “transitions between damages” of the selected bus subsystems was set. The term of “transition between damages” may be illustrated by the following sequence of the bus operation and maintenance events and processes: a damage to the subsystem denoted with the code U_i , $i \in N$ - renewal - usage – a damage to the subsystem denoted with the code U_j , $j \in N$. If at the moment t , $t \in R$ the subsystem denoted with the code U_i was damaged, and at the moment $(t + \tau)$, $t, \tau \in R$ the subsystem U_j was damaged and at the same time at the time interval $(t, t + \tau)$ there was no damage to the bus, then such a sequence of events is called “transition between damages” – transition from a damage to the subsystem U_i to a damage to the subsystem U_j [12].

On the basis of the analysis of the statistical data concerning damages to the elementary bus subsystems a certain property (regularity) was found, and namely that some sequences of a chain of damages (two-element sequences were analysed) occur much more frequently than others. This regularity occurs particularly distinctly for the damages of the same type (of a subsystem). It was found that a probability of occurrence of so called “repeated damage” to a bus subsystem (e.g. a

damage to the steering system - renewal – usage - damage to the steering system) is much more frequent (sometimes by two times) than statistical frequency of its damages.

The analysis of a chain of damages may be the ground to assess efficiency of the maintenance subsystem staff.

2. Investigation object

The investigation object in this paper is a real system of an urban transport bus operation and maintenance in a large urban agglomeration. The investigated system belongs to the class of operational systems with a goal oriented behaviour. Controlling the processes being performed in that system enables to achieve the planned goals. It is a complex system operating within a specific environment. For the needs of this work the system complexity is understood as a feature of a system consisting of many subsystems, which in turn may be considered as complex systems. Assurance of serviceability state for the means of transport being used is executed by the maintenance subsystem.

Four subsets of vehicles belonging to a set of vehicles being used in the investigation object were investigated. A vehicle subset is determined by the vehicle make and type. The individual subsets represent respectively the following vehicle types: Ikarus 280.70 (subset 1 P1), Jelcz 181 MB (P2), Volvo B10 LA (P3), Volvo B10 MA (P4). The vehicles were selected in such a way to have vehicles with similar usable potential in the individual subsets. It was assumed that from the point of view of the analysed feature for the investigation purposes the vehicles belonging to the specific subset constitute a set of homogenous objects. The investigation period covered two years. Each group of the vehicles consisted of 15 buses. All the investigated busses performed transport tasks on daily basis for the full period of two years. The investigations of the selected buses being operated and maintained in the investigation object were performed by means of a passive experiment. Observation of the process was performed under normal bus usage conditions, it means during passenger transportation according to the timetable of the buses selected for the investigations.

A bus as a complex technical object consisting of the elements forming distinguishable systems, assemblies and subassemblies, according to the rigors of the system method were treated as a technical system and were divided into subsystems.

Eleven main bus systems were distinguished at the first division level.

The following bus systems were distinguished:

- UK - steering system
- UZ - suspension system
- UE - electric installation
- UW - body
- UN - drive system
- UJ - wheels and steering system
- UO - feed system
- UC - cooling system
- UP - pneumatic system
- US - engine
- UH - braking system

In order to simplify description, the following denotations were used hereafter: The UK system is denoted with the code U_1 , while the remaining systems respectively with U_i , $i=2,3...11$.

3. Chain of damages

A chain of damages is understood as a random sequence, the elements of which are the codes of consecutively damaged subsystems of a technical object TO. However, if at the moment t , $t \in \mathbb{R}$ there was the m -th damage to the TO, and the damaged subsystem is a system (an element) denoted with the code U_i , $i \in \mathbb{N}$ and at the moment $(t + \tau)$, $t, \tau \in \mathbb{R}$ there was a damage to the subsystem U_j , $j \in \mathbb{N}$ and at the same time in the time interval $(t, t + \tau)$ there was not damage to the TO, then such a sequence of events is called a one step transition between damages – transition from a damage to the subsystem U_i to a damage to the subsystem U_j . From the above statement it results that at the moment $(t + \tau)$ a damage to the subsystem U_j is $(m+1)$ -th damage to the TO.

By using the following denotations:

- U_i - code of the damaged elementary subsystem of the TO, $i = 1, 2, \dots, k$,
- k - number of the elementary subsystems distinguished,
- $p_i = P(U_i)$ - probability of occurrence of such an event that if there was a damage to a bus, then the damaged subsystem of the TO is the subsystem denoted with the code U_i ,
- $p_{ij} = P(U_j/U_i)$ - probability that the damaged subsystem of the TO is the subsystem denoted with the code U_j provided that the formerly damaged subsystem was the subsystem U_i , $i, j = 1, 2, \dots, k$,
- $m = 1, \dots, n$ - consecutive number of the damage, $n \in \mathbb{N}$,

it is possible to build a random process (chain) $X(m) = U_j$, where $m = 1, 2, \dots, n$, $j = 1, 2, \dots, k$, with a finite set of states $U = \{U_1, U_2, \dots, U_k\}$.

Probability of transition of the chain $X(m)$ from the state U_i to the state U_j in the n -th step is presented by the following relation:

$$p_{ij}^{(n)} = P(X_n = U_j / X_{n-1} = U_i). \quad (1)$$

It was assumed that the transition probabilities $p_{ij}^{(n)}$ do not depend on the number of the step n (the index (n) is omitted in the record hereafter).

The following relation was adopted as an estimator of the transition probability p_{ij} :

$$\hat{p}_{ij} = n_{ij}/n_i, \quad i, j = 1, 2, \dots, k, \quad (2)$$

where:

n_{ij} - number of such m , $1 \leq m \leq n$, that $X_m = U_i$, $X_{m+1} = U_j$ (number of the process transitions from the state U_i to the state U_j ,

$$n_i = \sum_{j=1}^k n_{ij}.$$

All the chain transition probabilities $X(m)$ may be formulated together in the form of the matrix P as follows:

$$P = [p_{ij}] = \begin{bmatrix} p_{11} & p_{12} & \dots & p_{1k} \\ p_{21} & p_{22} & \dots & p_{2k} \\ \dots & \dots & \dots & \dots \\ p_{k1} & p_{k2} & \dots & p_{kk} \end{bmatrix} \quad i, j = 1, 2, \dots, k. \quad (3)$$

The probabilities occurring in the individual lines of the matrix P meet the following condition:

$$\sum_j p_{ij}=1, p_{ij} \geq 0. \quad (4)$$

4. Selected investigation results

On the basis of the investigation results the elements of the matrix P (3) were assessed by applying the relation (2) for the chain of damages with the number of the states $k=11$. The matrix P of probabilities of state changes of the chain of damages is called the matrix of transitions between damages.

Because the analysed properties of the determined matrices for the particular subsets of the investigated vehicles are similar and in order to present more clearly the investigation results, the further part of the document presents the investigation results for a set of all the investigated vehicles.

The assessed values of the elements of the matrix $P = [p_{ij}]$ of transitions between damages are presented by the following relation:

$$P=[p_{ij}] = \begin{bmatrix} 0,28 & 0,02 & 0,24 & 0,14 & 0,02 & 0,03 & 0,02 & 0,07 & 0,14 & 0,05 & 0,05 \\ 0,02 & 0,25 & 0,25 & 0,14 & 0,01 & 0,04 & 0,04 & 0,08 & 0,17 & 0,03 & 0,03 \\ 0,02 & 0,03 & 0,43 & 0,22 & 0,02 & 0,03 & 0,03 & 0,08 & 0,10 & 0,05 & 0,05 \\ 0,02 & 0,03 & 0,34 & 0,32 & 0,01 & 0,04 & 0,03 & 0,08 & 0,09 & 0,05 & 0,05 \\ 0,02 & 0,03 & 0,28 & 0,17 & 0,25 & 0,01 & 0,03 & 0,05 & 0,07 & 0,10 & 0,04 \\ 0,02 & 0,03 & 0,35 & 0,20 & 0,02 & 0,12 & 0,04 & 0,07 & 0,10 & 0,05 & 0,06 \\ 0,04 & 0,02 & 0,21 & 0,17 & 0,02 & 0,05 & 0,25 & 0,08 & 0,10 & 0,07 & 0,04 \\ 0,02 & 0,02 & 0,31 & 0,17 & 0,02 & 0,03 & 0,03 & 0,25 & 0,10 & 0,07 & 0,04 \\ 0,02 & 0,05 & 0,25 & 0,16 & 0,02 & 0,04 & 0,03 & 0,08 & 0,31 & 0,04 & 0,06 \\ 0,02 & 0,01 & 0,25 & 0,16 & 0,01 & 0,03 & 0,03 & 0,11 & 0,07 & 0,33 & 0,04 \\ 0,01 & 0,03 & 0,27 & 0,19 & 0,01 & 0,03 & 0,02 & 0,06 & 0,11 & 0,05 & 0,27 \end{bmatrix}, \quad (5)$$

where:

$i, j = 1, 2, \dots, 11$.

On the basis of the analysis of the obtained results a significant difference between values of probabilities of transitions between damages p_{ij} and the values of unconditional probabilities p_i of occurrence of the damages to the distinguished systems was found. It refers to all the subsets of the investigated buses. The largest differences occur for the elements of the matrix P lying on its main diagonal. The values of those elements of matrix (p_{ii}) are distinctly higher than the values of the unconditional probabilities p_i and than the values of other elements of the specific matrix column ($p_{ii} > p_{ij}$, for $i \neq j$). The P matrix elements lying on the main diagonal represent assessments of probability of "reoccurrence" of a damage to the same bus system.

Tab. 1. Quotient of the conditional p_{ii} and unconditional p_i probability

i	p_{ii}/p_i
1	15,39
2	8,03
3	1,27
4	1,47

5	17,14
6	3,56
7	8,69
8	2,70
9	2,57
10	5,06
11	4,63

In scope of performance of the investigations a simulation of a chain of damages was carried out. The moments of damages to the subsystems of the TO were simulated. It was assumed that the damages to the subsystems of the TO are independent, and the times between the damages to the distinguished subsystems are exponential. Different values of the distribution parameters between damages to the particular subsystems were assumed. The resultant chain of damages was obtained by ranking the codes of damages according the moment of the damage occurrence. The matrix of probabilities of transitions between the states of the generated chain of damages was set. The determined values of the quotients p_{ii}/p_i oscillated around 1. Only with a small number of the state changes (with a smaller number of the state entries than 200) that quotient deviated by more than 5% from the value of 1.

The observed regularity, such that a damage to the subsystem U_i has influence on a repeated damage to that system is called the reoccurrence of damages [2], [12].

The quotient of the conditional p_{ii} and unconditional p_i probability, that is $MP_i = p_{ii}/p_i$ was adopted as a measure of reoccurrence of damages.

The values of the quotients p_{ii}/p_i determined for the analysed bus systems are gathered in the Table 1.

5. Summary

It seems that the analysis of a chain of damages may be one of the elements to assess a maintenance subsystem in complex operation and maintenance systems of technical objects. The damage reoccurrence index, determined on the basis of a chain of damages, being a quotient of the conditional p_{ii} and unconditional p_i probability of a damage to an object may constitute a premise to take actions aimed at increasing the efficiency of the repairs performed in a maintenance subsystem.

It should be mentioned that on the basis of the value of the reoccurrence index MP_i the assessments concerning the maintenance subsystem should be formulated carefully. The determined values of that index may be burdened with a significant error in case of a small number of transitions between damages and for small values of probabilities p_i .

On the basis of the analysis of the performance of the investigation object it may be stated that the possible reasons for the damage reoccurrence phenomenon are: limited scope of performing post-repair diagnosis, no reliable diagnostic information on the actual bus state, no reliable diagnostic information concerning the past states of a bus.

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SELECTED ASPECTS OF DETERMINING THE RELIABILITY OF THE PUMP SUBSYSTEMS WITH REDUNDANCY, USED IN MAIN ENGINE AUXILIARY SYSTEMS

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Abstract

The rules of classification societies require the use of redundancy in the systems essential for the safety of the ship. Duplication of pumps in the main engine auxiliary systems like cooling water system, lubricating oil system, fuel oil system is a good example here. Therefore, in the author's opinion, some attention should be paid to this issue. Two important questions arise here. Does duplication of pumps in marine systems make sense? What impact does the use of redundancy on the reliability of the system? To answer these questions, it is necessary to adequately assess the reliability of subsystems with redundancy. But it is not so simple. The first problem is gathering the reliability data. The second problem is the so-called human factor. The third problem, widely discussed in this article, is to adopt the appropriate reliability model.

Key words: redundancy, reliability model, pumping systems.

1. The idea of redundancy

In technical systems redundancy means the duplication of critical elements of a system. The idea of redundancy is to increase reliability of the whole system. In case of failure of one component, the second (redundant) component takes over its function. In complex systems, the best results are achieved through the duplication of the most unreliable elements, as shown in Fig.1. Duplication of item 2 with the lowest reliability gives the highest reliability of the system.

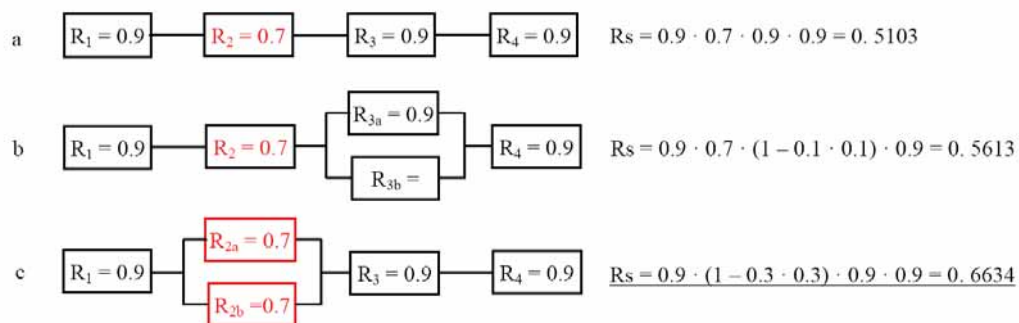


Fig. 1. The idea of redundancy in complex systems; a) system without redundancy, b) system with redundancy of item 3 with high reliability level c) system with redundancy of item 2 with low reliability level, R_i - reliability of the item "i", R_s - reliability of the whole system

2. Redundancy in main engine auxiliary systems

Reliability of the main engine is extremely important for ship's safety. But the proper operation of the main engine depends on the reliable operation of its auxiliary systems (cooling water system, lubricating oil system, fuel oil system). That's why the Ship Classification Societies like: Lloyd Register of Shipping, Det Norske Veritas, Germanischer Lloyd, American Bureau of Shipping, Polish Register of Shipping etc. require redundancy in the most important systems on ships. One of them is the fuel oil system. As we can see in Fig .2. the pumps and the filters are doubled.

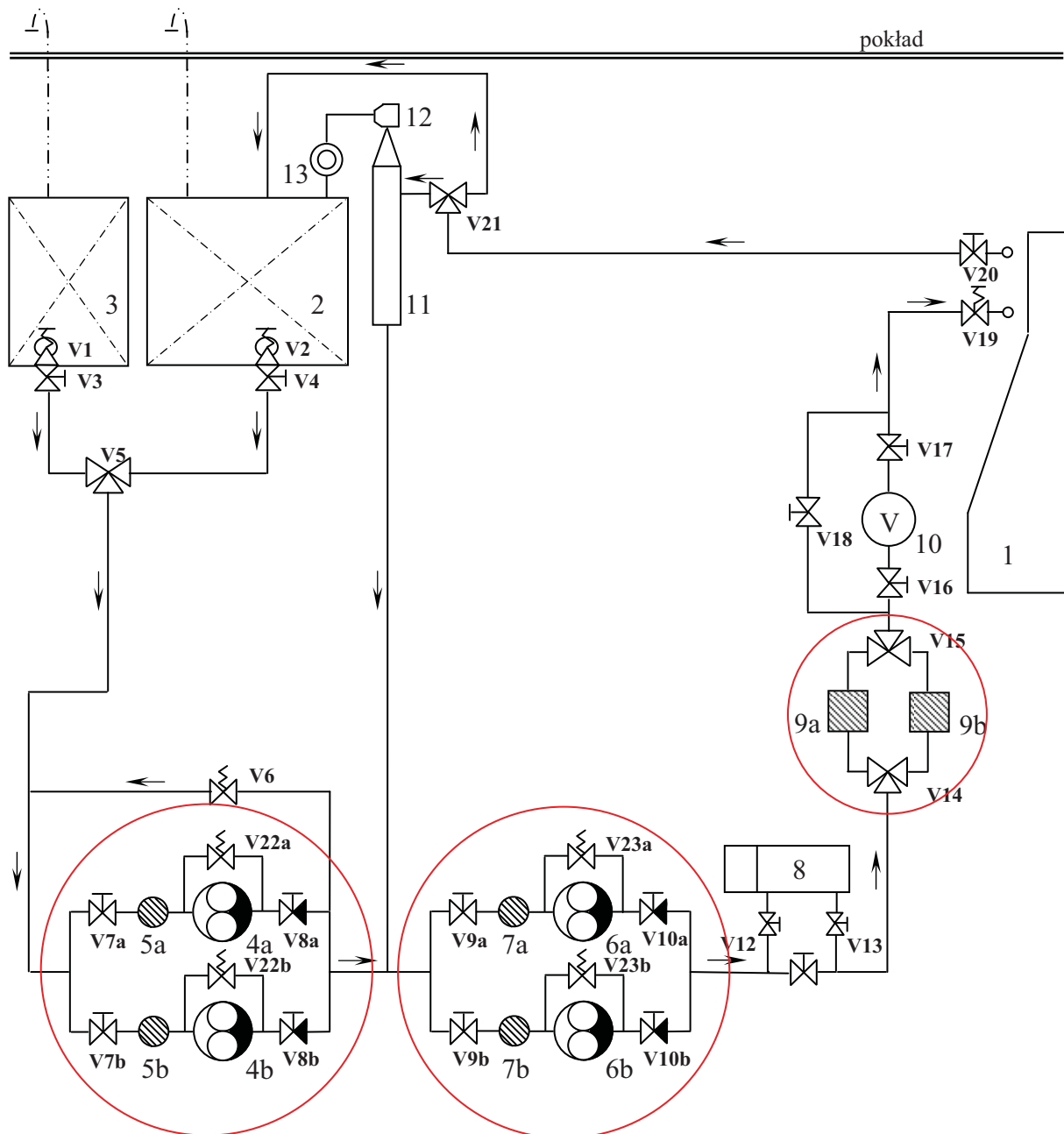


Fig. 2. Fuel oil system for the MAN MC – type diesel engine [1];

1 – main engine; 2 – HFO service tank; 3 – MDO service tank; 4a, 4b – fuel oil supply pumps; 5a, 5b – filters; 6a, 6b – fuel oil circulating pumps; 7a, 7b – filters; 8 – fuel oil pre-heater; 9a, 9b – fuel oil duplex filter; 10 – Viscometer; 11 – venting box, 12 – automatic de-aerating valve, 13 – sight glass, V – valves

3. Does duplication of pumps make sense?

As it has been stated in the second paragraph of the article - ship classification societies require, inter alia, redundancy of pumps in main engine auxiliary systems. For example, the requirements of Polish Register of Shipping are as follows [2]: “Sea-water cooling system of one main engine shall be provided with two pumps, one of which shall be a stand-by pump...”; “In machinery installations where one main engine is fitted at least two lubricating oil pumps of equal capacity shall be provided...”; At least two power-driven pumps shall be provided for fuel transfer...”.

Why the pumps? To answer the question we have to look at reliability indicators of components of cooling water system, lubricating oil system and fuel oil system. Those components are mostly: vessels, pumps, filters, heat exchangers, valves, pipe straight sections, control systems. A good source of reliability data is OREDA [3]. The objective of the handbook is to collect reliability data from offshore drilling and production operations. Unfortunately it is very hard to find such a data for the ship installation. So, the only possible solution for now is to use a set of data from OREDA. The reliability data collected in OREDA has a form of the failure rate λ given by the formula:

$$\lambda = \frac{n}{\tau} [h^{-1}]; \quad (1)$$

where:

n [-] - number of failures,

τ [h] - aggregated time in service [h].

According to OREDA [3] the sum of critical failure rates of selected components are, respectively:

Pumps:	$\lambda = 106.03 \cdot 10^{-6} h^{-1}$,
Vessels:	$\lambda = 17.46 \cdot 10^{-6} h^{-1}$,
Valves:	$\lambda = 12.39 \cdot 10^{-6} h^{-1}$,
Heat exchangers:	$\lambda = 6.03 \cdot 10^{-6} h^{-1}$.

The critical failure means a failure which causes immediate and complete loss of a system’s capability of providing its function.

The above presented set of data clearly shows, that pumps are characterized by the highest failure rate. Therefore, they are the most unreliable elements of the systems under consideration. So according to the rule, that the best results are achieved through the duplication of the most unreliable elements, we can say that duplication of pumps makes sense.

4. Reliability model of redundant subsystems with pumps

The second problem, what impact the use of redundancy does on the reliability of the system - still remains open. To solve this problem, it is necessary to build an adequate reliability model. The essence of redundancy is to create a parallel reliability structure in place of a serial structure. Using a simple example with cooling water pumps let’s consider, whether the subsystems with duplicated pumps create purely parallel reliability structure, as it has been shown in Fig. 3.

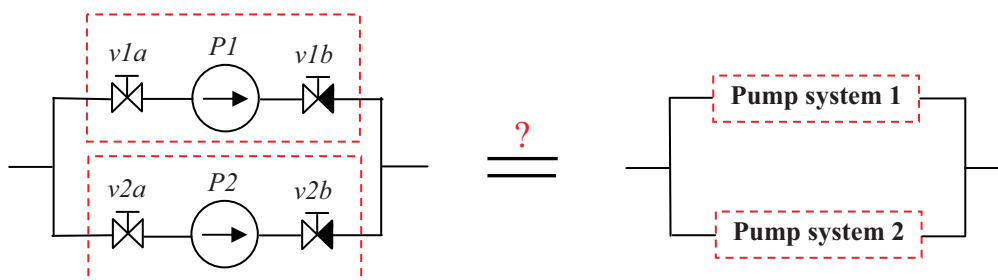


Fig. 3. Parallel reliability structure of pump subsystem

At the first glance the answer is yes. Such approach can be found in books [4, 5]. But in real systems, in the opinion of the author, the problem is more complicated. First of all, not only pump is duplicated. Shut – off valves are duplicated too. Their task is to cut off the flow through the pump unfit. But some failures of those valves have an impact on the work of both pumps. To explain this, we have to review possible failure modes of valves. In Tab.1. there are given critical failure modes of valves based on the OREDA handbook [3].

Tab. 1. Critical failure modes of valves [3]

Critical failure mode	Failure rate
delayed operation	$\lambda = 0.16 \cdot 10^{-6} \text{ h}^{-1}$
external leakage to environment	$\lambda = 0.76 \cdot 10^{-6} \text{ h}^{-1}$
fail to close (actuator failure)	$\lambda = 2.90 \cdot 10^{-6} \text{ h}^{-1}$
fail to open (actuator failure)	$\lambda = 1.96 \cdot 10^{-6} \text{ h}^{-1}$
internal leakage (non return valve)	$\lambda = 0.41 \cdot 10^{-6} \text{ h}^{-1}$
leakage in closed position	$\lambda = 2.02 \cdot 10^{-6} \text{ h}^{-1}$
plugged	$\lambda = 0.56 \cdot 10^{-6} \text{ h}^{-1}$
the sum of others	$\lambda = 3.62 \cdot 10^{-6} \text{ h}^{-1}$

Let's imagine now a following situation: pump *P1* is working, valve *v1b* failed. The failure event is an external leakage of medium to environment. In such a situation it doesn't matter which of pumps is working at the moment. Even if we stop the pump *P1* and use the pump *P2*, a part of medium still will be pumped outside through a leaky valve. Another situation will occur when a valve *v1a* will leak on the suction side of the pump. This time, the outside air will be sucked into the medium, regardless of which of the pumps is working. Certainly, a significant leakage to the environment and a lot concentration of air in pumped medium cause the system does not meet the requirements. Therefore, it must be concluded, that the structure of reliability model of pumping subsystem is not purely parallel. The structure is a serial – parallel.

5. The impact of redundancy on the system reliability

To assess the impact of redundancy on the reliability of the subsystem with pumps, shown in Fig. 3, two solutions will be compared: one without redundancy and the second with redundancy. Reliability data needed for pumps are presented in Tab. 2. As we can see those pumps were working in redundant structure, because the failure rates for calendar time are about 50 % of the failure rates for operational time. This means that the pumps work alternately, each of them for half of calendar time.

Tab. 2. Critical failure modes of pumps [3]

Critical failure mode	Failure rate (calendar time)	Failure rate (operational time)
external leakage	$\lambda = 3.46 \cdot 10^{-6} \text{ h}^{-1}$	$\lambda = 7.71 \cdot 10^{-6} \text{ h}^{-1}$
failed to start	$\lambda = 26.66 \cdot 10^{-6} \text{ h}^{-1} *$	$\lambda = 60.26 \cdot 10^{-6} \text{ h}^{-1} *$
failed while running	$\lambda = 55.34 \cdot 10^{-6} \text{ h}^{-1}$	$\lambda = 101.76 \cdot 10^{-6} \text{ h}^{-1}$
low output	$\lambda = 5.87 \cdot 10^{-6} \text{ h}^{-1}$	$\lambda = 20.49 \cdot 10^{-6} \text{ h}^{-1}$
vibration	$\lambda = 5.6 \cdot 10^{-6} \text{ h}^{-1}$	$\lambda = 10.86 \cdot 10^{-6} \text{ h}^{-1}$
the sum of others	$\lambda = 9.37 \cdot 10^{-6} \text{ h}^{-1}$	$\lambda = 16.01 \cdot 10^{-6} \text{ h}^{-1}$

* probability of the event fail to start on demand is $P = 8.6 \cdot 10^{-4}$.

Using the OREDA database we have to notice, that one very important simplifying assumption has been made there. The life of a technical item may generally be split into three different phases: the burn - in phase, the useful life phase and the wear - out phase. The failure rate function has then a form of a so called “bath - tub” curve. The failure rate is decreasing in the burn - in

phase, then is close to constant in the useful life phase and at the end is increasing in the wear - out phase. The main part of the failure events in the database come from the useful life phase. All the failure rate estimates presented in the book [3] are based on the assumption, that the failure rate is constant and independent of time, so the item is considered to be “as good as new” as long as it is functioning. Of course the assumption is not always true, but because of the simplicity is widely used in reliability analysis. According to the exponential law the reliability of the item is given by the formula 2.

$$R(t) = e^{-(\Sigma\lambda)t}; \quad (2)$$

where:

$\Sigma\lambda$ – the sum of failure rates of item,

t – time to be taken account.

Now let’s compare reliability of two solutions of pump system.

System without redundancy.

The failure event (so called top event) is a pump system failure during operation, which may make it necessary to stop the main engine. The reliability of the system means the ability of the engine to run on. Valves *v1a* and *v1b* are in open position. The pump *P1* is working. Operating time of the pump *P1* is close to the calendar time.

The reliability structure of pump system without redundancy is shown in Fig.4. The reliability of the system is given by the formula (3). The calculations of reliability of items and whole pump system are given in Tab. 3.

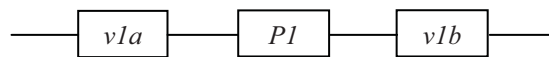


Fig. 4. Reliability structure of pump system without redundancy

$$R_s(t) = R_{v1a}(t) \cdot R_{P1}(t) \cdot R_{v1b}(t), \quad (3)$$

where:

- $R_{v1a_I}(t)$ – reliability of item *v1a* versus failure mode *_I*,
- $R_{P1}(t)$ – reliability of item *P1* versus failure modes *_I* till *_5*,
- $R_{v1b_I}(t)$ – reliability of item *v1b* versus failure mode *_I*,
- t [h] – time to be taken into account.

Tab. 3. Reliability of pump system without redundancy

Item	Failure mode critical for the system	λ [h ⁻¹]	$\Sigma \lambda$ [h ⁻¹]	Reliability of item $R_i(t)$			
				t = 2500 h	t = 5000 h	t = 7500 h	t = 10000 h
v1a	1 external leakage	$0.76 \cdot 10^{-6}$	$0.76 \cdot 10^{-6}$	0.99810	0.99621	0.99432	0.99243
v1b	1 external leakage	$0.76 \cdot 10^{-6}$	$0.76 \cdot 10^{-6}$	0.99810	0.99621	0.99432	0.99243
P1	_1 external leakage	$7.71 \cdot 10^{-6}$	$156.83 \cdot 10^{-6}$	0.67565	0.45651	0.30844	0.20840
	_2 failed while running	$101.76 \cdot 10^{-6}$					
	_3 low output	$20.49 \cdot 10^{-6}$					
	_4 vibration	$10.86 \cdot 10^{-6}$					
	_5 others	$16.01 \cdot 10^{-6}$					
Reliability of system $R_s(t)$				0.67309	0.45305	0.30494	0.20526

System with redundancy.

The reliability of the system, as stated above, means the ability of the engine to run on. Valves *v1a*, *v1b*, *v2a*, *v2b* are in open position. One of the two pumps is working, the second is a stand-by pump. But during the time taken into account the pumps work alternately, each of them for half of calendar time. So operational time of one pump is a half of calendar time.

The reliability structure of the pump system with redundancy is given in Fig. 5. The reliability of the system is given by the formula (4). The calculations of reliability of items and whole pump system are given in Tab. 4.

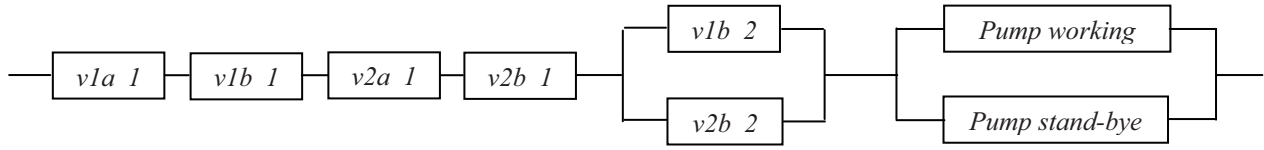


Fig. 5. Reliability structure of pump system with redundancy

$$R_s(t) = R_{v1a_1}(t) \cdot R_{v1b_1}(t) \cdot R_{v2a_1}(t) \cdot R_{v2b_1}(t) \cdot \left\{ 1 - [1 - R_{v1b_2}(t)] \cdot [1 - R_{v2b_2}(t)] \right\} \cdot \left\{ 1 - [1 - R_{Pw}(t)] \cdot [1 - R_{Psb}(t)] \right\}; \quad (4)$$

where:

- $R_{v1a_1}(t)$ – reliability of item $v1a$ versus failure mode $_1$,
- $R_{v1b_1}(t)$ – reliability of item $v1b$ versus failure mode $_1$,
- $R_{v2a_1}(t)$ – reliability of item $v2a$ versus failure mode $_1$,
- $R_{v2b_1}(t)$ – reliability of item $v2b$ versus failure mode $_1$,
- $R_{v1b_2}(t)$ – reliability of item $v1b$ versus failure mode $_2$,
- $R_{v2b_2}(t)$ – reliability of item $v2b$ versus failure mode $_2$,
- $R_{Pw}(t)$ – reliability of item P_w versus failure modes $_1$ till $_5$,
- $R_{Psb}(t)$ – reliability of item P_{sb} versus failure modes $_6$ till $_7$,
- t [h] – time to be taken into account.

Tab. 4. Reliability of pump system with redundancy

Item	Failure mode critical for system	λ [h ⁻¹]	$\Sigma \lambda$ [h ⁻¹]	Reliability of item $R_i(t)$			
				t = 2500 h	t = 5000 h	t = 7500 h	t = 10000 h
v1a	1 external leakage	$0.76 \cdot 10^{-6}$	$0.76 \cdot 10^{-6}$	0.99810	0.99621	0.99432	0.99243
v1b	1 external leakage	$0.76 \cdot 10^{-6}$	$0.76 \cdot 10^{-6}$	0.99810	0.99621	0.99432	0.99243
v2a	1 external leakage	$0.76 \cdot 10^{-6}$	$0.76 \cdot 10^{-6}$	0.99810	0.99621	0.99432	0.99243
v2b	1 external leakage	$0.76 \cdot 10^{-6}$	$0.76 \cdot 10^{-6}$	0.99810	0.99621	0.99432	0.99243
v1b	2 internal leakage	$0.41 \cdot 10^{-6}$	$0.41 \cdot 10^{-6}$	0.99898	0.99795	0.99693	0.99591
v2b	2 internal leakage	$0.41 \cdot 10^{-6}$	$0.41 \cdot 10^{-6}$	0.99898	0.99795	0.99693	0.99591
Pw 1)	1 external leakage 2 failed while running 3 low output 4 vibration 5 others	$7.71 \cdot 10^{-6}$ $101.76 \cdot 10^{-6}$ $20.49 \cdot 10^{-6}$ $10.86 \cdot 10^{-6}$ $16.01 \cdot 10^{-6}$	$156.83 \cdot 10^{-6}$	0.82198	0.67565	0.55537	0.45651
Psb	6 fail to start on demand 7 fail after starting	2) 3)	- $156.83 \cdot 10^{-6}$	0.99914 0.99671	0.99914 0.99671	0.99914 0.99671	0.99914 0.99671
Reliability of system $R_s(t) =$				0.99170	0.98359	0.97565	0.96786

Remarks to Tab. 4.

- 1) Operational time of working pump is a half of calendar time “t” so $R_{Pw}(t) = e^{-(\Sigma\lambda) \cdot t/2}$.
- 2) The probability that the stand-by pump will fail to start on demand, according to OREDA [3], is equal 0.00086, so the probability that the failure event will not occur is 0.99914.
- 3) The probability, that the stand-by pump will fail after starting, before the first pump will be repaired, was calculated assuming that the repair time is 21 hours. The mean value of repair time is based on OREDA [3].

The results of calculations are presented in Fig. 6.

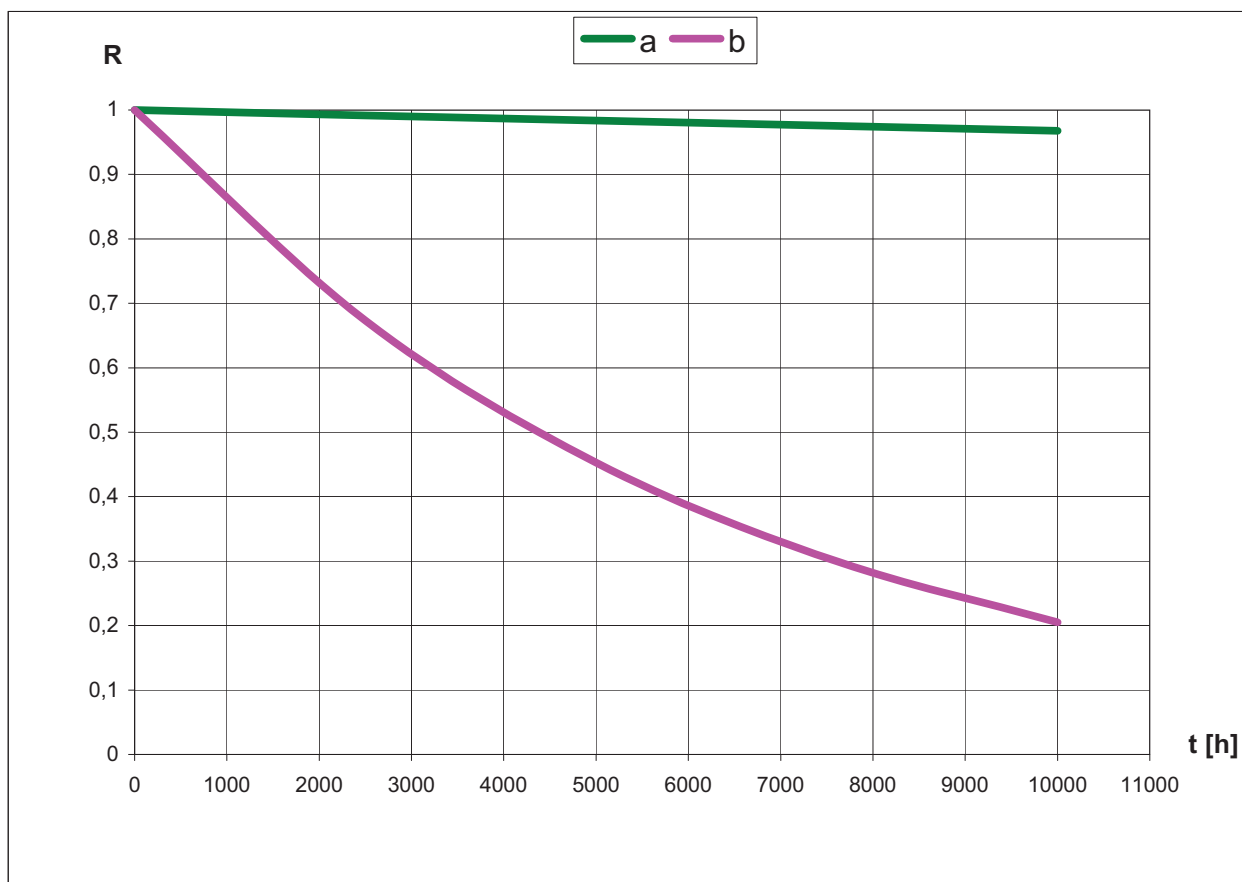


Fig. 6. Reliability function of pump system a) with redundancy b) without redundancy

6. Final remarks

Duplication of pumps makes sense. Reliability of pumps is very low compared with the reliability of other system components. In practice, the reliability of pumps determines the reliability of the whole subsystem, as we can see in Tab. 3. and Tab. 4. Possible failure events of valves reduce system reliability, but very little in comparison with pumps. But it is worthy to note, that relatively new system have been considered there. In the old pipe systems the failures of pipes and valves occur much more frequently.

The reliability structure of pump subsystem with redundancy is not clearly serial, but mixed. Fortunately the serial part of the structure is created by valves (with low failure rates). The parallel structure is created by pumps (with high failure rates). As we can see in Fig. 6. redundancy of pumps gives a very high reliability level of the whole subsystem. First, due to the creation of partially parallel reliability structure. Secondly, due to the fact, that active work time of each of two pumps is a half of active work time in the case of one pump installed in the system. It is clear, that the pumps working alternayively wear up more slowly than a pump that runs continuously.

A question of keeping the redundancy by the crew is still open. In a case of one pump failure the system is not redundant until the pump is repaired. In the above calculations an assumption has been made, that the fitness pump recovery time is 21 hours. However, in practice, the crew can did not make the repair at all, for various reasons.

The issue of redundancy in marine systems is more complex than it seems to be. The author believes it is necessary to pay more attention to this matter. The first step has been done in the article.

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USE ASSESSMENT OF MODERN DIAGNOSTIC SYSTEMS OF INTERNAL MARINE COMBUSTION ENGINES AT THE SUPPORT PHASE OF EXPLOATATION DECISIONS IN THE ASPECT OF ECONOMIC CRITERIA

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Abstract

Modern diagnostics systems despite being equipped with the latest technical and technological solutions are usually systems only informing an engineer about values of tested parameters. Based on this information, an engineer has to determine the condition of the engine and undertake exploitation decisions based on his knowledge and experience under the pressure of knowing that any operational decision is associated with costs. It is the cost, which is the most important criterion for evaluation of a mechanic by the owner. Fear of negative evaluation by the owner is often the cause of late or Incorrect decisions which lead to breakdown. The article assesses gradation of the consequences of the decision-making performance by a mechanic on the engines of different economical purpose. An evaluation of selected diagnostic systems was made and a model for diagnosing system was proposed, which on the basis of economic criterion would facilitate making exploitation decisions by a mechanic.

Key words: diagnostics systems, model for diagnosing system, basis of economic criterion, exploitation decisions

1. Introduction

Marine engines can be divided according to use into main three groups:

- Main propulsion Engines (ME)
- Auxiliary Engines (AE)
- Emergency propulsion Engines (EE)

Each of these types of engines has its work performance determined by cost-efficiency, navigation safety and environmental protection. Especially because of the consequences (positive and negative) of the engine exploitation, for further analysis a main engine was chosen, which is used for direct propulsion of the ship.

Analyzing the importance of the criteria effecting decision-making, particularly related to a different types engine handling, paradoxically, the greatest importance should be attributed to an economic criteria.

Modern diagnostics systems (SDG) despite the latest technical and technological solutions are often only systems informing an engineer about values of the parameters or their changes. Based on this information, an engineer has to determine the condition of the engine and undertake exploitation decisions based on his knowledge and experience under the pressure of knowing that any operational decision is associated with costs. It is the cost, which is the most important

criterion for evaluation of a mechanic by the owner. Fear of negative evaluation by the owner is often the cause of late or Incorrect decisions which lead to breakdown.

2. Engine exploitation

The main aim of the operation of the ME is to provide energy for the propulsion of the vessel to perform the designated exploitative tasks. Readiness of the engine to allow a vessel to perform designated tasks, the efficiency of operation and reliability of the engine when performing tasks and safety of its functioning depend on the quality of the exploitative process. In the exploitative system, the engine may be used or operated, or operated and used at the same time [5,6]. The specificity of the main engine operation in marine conditions requires process planning.

- ME use under "normal" circumstances, in which the efficiency is most important while keeping environmental protection requirements,
- ME use in conditions other than normal (complex, dangerous or emergency, or even catastrophic), where the priority is to get to the place which guarantees safety for crew and vessel,
- scheduled operating, during which there is no threat to life of the crew and loss of the ship, and the goal is the restoration of full functioning of ME
- unplanned use (needed in case of damage), often carried out in the sea, during unfavorable external conditions creating health risk to the crew and the risk of loss of vessel, which is aimed at restoring to at least to a state of partial functioning, allowing to get to a safe location.

During the exploitation of ME, while vessel is at sea, marine conditions create danger due to accumulation of adverse events, which forces the crew to put the necessity of keeping ME running as a priority over efficiency and environmental care - which is the only guarantee of saving the life of the crew and preventing the sinking of a ship. In critical conditions, the only criterion for the safety of the crew and the ship, in addition to buoyancy, may be depending on the condition of the ME, minimum maneuvering speed.

Analyzing the damage, including those that were considered failures of engines it can be concluded that at least some of them could have been avoided. The causes can be divided into several categories:

- design errors,
- hidden defects or damage to the structure of the material due to overheating during the heat treatment
- incorrect assembling
- incorrect exploitation (working outside the field of engine performance, poor supervision of the engine and so on)
- inappropriate selection and incorrect preparation of means, including incorrect mechanical processing, inadequate filtration, centrifugation, homogenization, lack of control and incorrect chemical treatment of energy agents), incorrect values of thermal parameters, lack of control and crossing of time intervals between handling of all kinds.

To avoid or reduce the occurrence of above causes, it is necessary to take appropriate steps individually to each cause:

- development of construction
- using original parts and elements or parts authorized by the manufacturer
- handling and montage according to Technical Documentation (TD),
- careful recruitment of the crew controlling and developing skills of the crews
- application of diagnostics to the needs of process of operation control of engines, use of databases obtained in the process of diagnosis for the analysis of the occurring damage.

3. Diagnosis systems (SDG) – research and assumptions

ME is a complex object and its model enabling to obtain diagnostic information can be a combination of different forms of models.

The proper work of ME (in the so-called normal state) depends on the proper state of all its elements. Therefore it is important to identify the impact of the individual components or subsystem, as well as system, for the proper functioning of other elements, together with consequences being reflected in the quality of the processes occurring in the engine.

The variable and difficult marine conditions, in which exploitative decisions can cause even the loss of a ship and life of the vessel crew, the relevance of exploitative decisions is of particular importance.

The value of the consumption of the engine structure approaching the limits should be indicated, and even the replacement should be recommended. Manufacturers such as MAN and Wartsila have catalogue parts databases in their CoCoS and CBM systems.

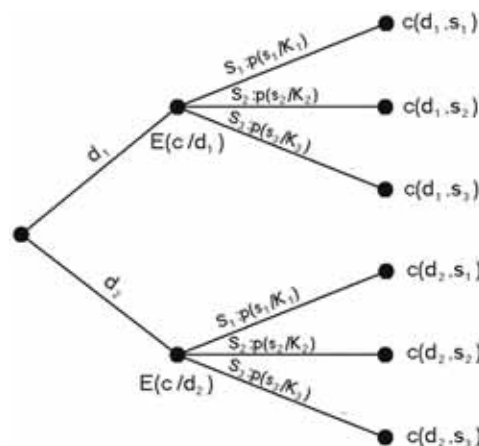
Damage to main engine (ME) occurring in realistic conditions is a random event. The effects of each failure will depend on:

- time of identification of change of condition leading to damage
- accuracy of the identification of changes in the ME,
- accuracy of decisions being consequence of the identification of the condition change of ME

In the sea conditions, in which it is assumed that the crew can only rely on its own skills and technical capabilities, timely detection of the existence of partial worthiness can help to rescue the crew and cargo, as it allows crew to ensure the safety of the ship. Therefore, it is important to use diagnostic system (DS) adopted for operational needs following a necessity of making decisions by the staff and the owner [6].

The main issues, which exploiter has to consider when deciding, are traffic safety of ME, environmental protection [9] and exploitative efficiency of the ME. There is therefore a need to construct a model of such decision-making process, that reflects these issues, while reducing to minimum risk of taking wrong decisions in-service [5,6].

In order to make the right operational decision, it is needed to estimate the importance of this decision that is predict the consequences. Despite of the complexity of this issue, there are solutions developed by means of mathematical formula [5,6]. However, in real terms, particularly in random and variable sea conditions, it is very difficult to predict the consequences of exploitative decisions all the more because there are variable whether conditions and crew operating ME changes practically on random basis.



Pict.1 decision making dendrite, showing measurements of accuracy of diagnosis of the existence of the technical condition of the engine, provided there is an adequate diagnostic parameter vector K [6]

ME is a complicated object, model being information carrier can be a combination of different forms of models. On the basis of allocation of the selected engine operating states to the relevant diagnostic parameters, a diagnostic model was developed for the relations shown in Figure 2.

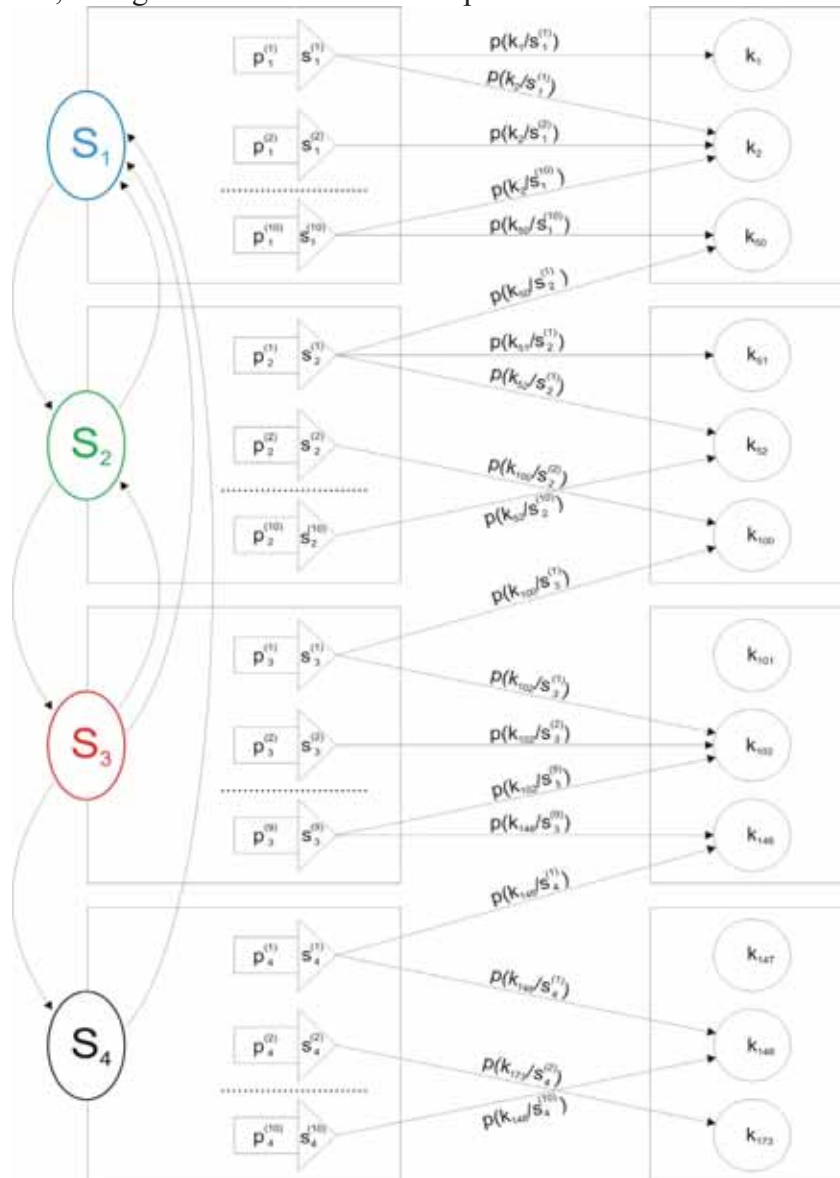


Fig. 2. Relations in the ME diagnostic model: p_{ij} - probability of the s_{ij} , s_{ij} condition - the state of the engine from the set S (s_1, s_2, s_3, s_4), $p(s / s_{ij})$ - probability of occurrence of the diagnostic parameter s in the presence of the s_{ij} , s - Diagnostic parameter, S_1, S_2, S_3, S_4 - ME classes of conditions [8]

It should be emphasized that the results of decisions, which will enable verification (in real life), taken by human-operator, are the consequences of those decisions.

4. Existing diagnosing systems (EDS) - CoCoS (MANBW), CBM (Wartsila)

Modern computer programs are designed to imitate human thinking and eliminate human emotions. Therefore, work is underway to create "artificial intelligence" [9]. However, that programs creating "artificial intelligence" are as good as good is man (men) - "knowledge engineer" creating these programs. Therefore, the quality of the result of EDS, which is diagnosis, is dependent on the accuracy and reliability of diagnostic data, proper processing and use of that

data to determine the diagnostic parameters, to be used to correctly identify the technical condition of the engine, in order that the engineer (operator) undertakes rational exploitation activities..

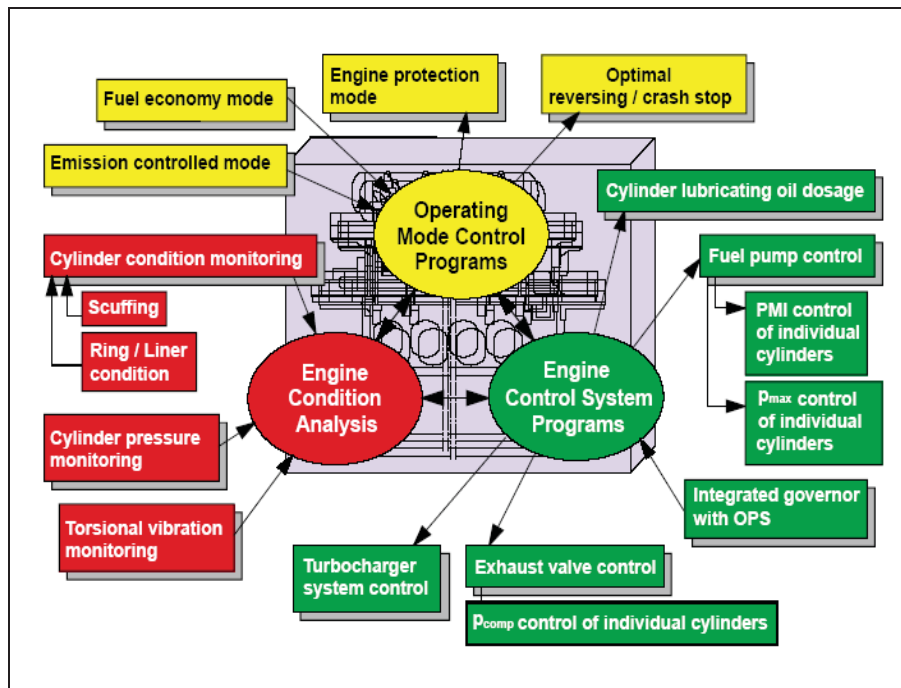


Fig. 3. Diagram of intelligent engine conception [10]

Engine manufacturers MAN and Wartsila, created their own models of the rational exploitation of engines. In the construction of systems (Cocos-MANBW, CBM - Wartsila) ship's reality, engine crew needs and the needs of the owner are visible. In both models a hierarchy of values of data measurement is displayed, access levels, considerate data archiving system and attention to detail in planning and reporting, saving time of a mechanic. Both systems based on Windows operating systems make it easy to use. Cooperation of the modules of the system, good communication and information flow are visible. Manufacturer's knowledge, acquired during the research and development, the experience of service and from engines users is a basis for ongoing development and improvement of "expertise know how" of EDS systems and DENIS, and a basis for adjusting the engine to the diagnostic instrumentation.

►► CBM system - Condition-Based Maintenance (Wartsila)- [4, 11]

Wartsila decided to bring together the experience and expertise of its staff to support crews of vessels. Wartsila is aware that the user experience in the area of reliability of engines of the of the same type are different and result from the difference between knowledge and experience of crews, differences between the decisions of the owners, and thus the use of different grades of fuel, lubricating oils, spare parts quality, frequency and quality of scheduled handling. At the same time knowing that the first alarm signal can generate different decisions when operating in conditions of limited access to the highest level of marine technical knowledge and experienced servicemen.

CBM system consists of following panels:

- a) **DENIS - (Diesel Engine CoNtrol and optImizing Specification)** contains data needed to control the engine, it uses systems of companies: the Norwegian KMSS and Japanese NABCO,
- b) **WECS-9500 - (Wartsila Engine Control System)** contains the elements needed for a computerized RT-flex engine type control, including programs, connectors, sensors, instrumentation, signal converters,

c) MAPEX- (Monitoring and mAintenance Performance Enhancement with eXpert knowledge) panel containing technical solutions used as a tool to perform a specific task.

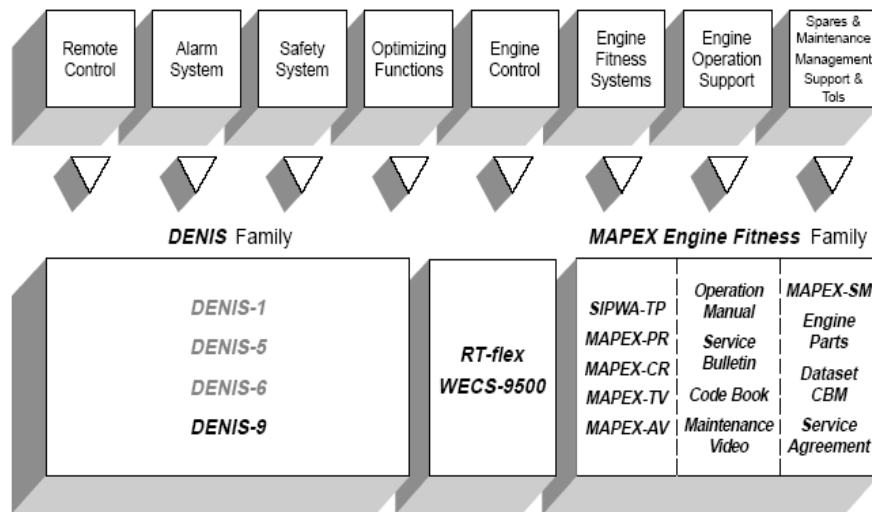


Fig. 4. General outline of CBM diagnosing system [5,12]

►► CoCoS - Computer Controlled Surveillance system (MANBW) [1,2,3]

Cocos System was created specifically to manage the operation and maintenance of the two-and four-stroke ME and AE. Tasks, which were set for the Cocos system are: collection, processing and analyzing data, planning, control, Ships assets management, crew training.

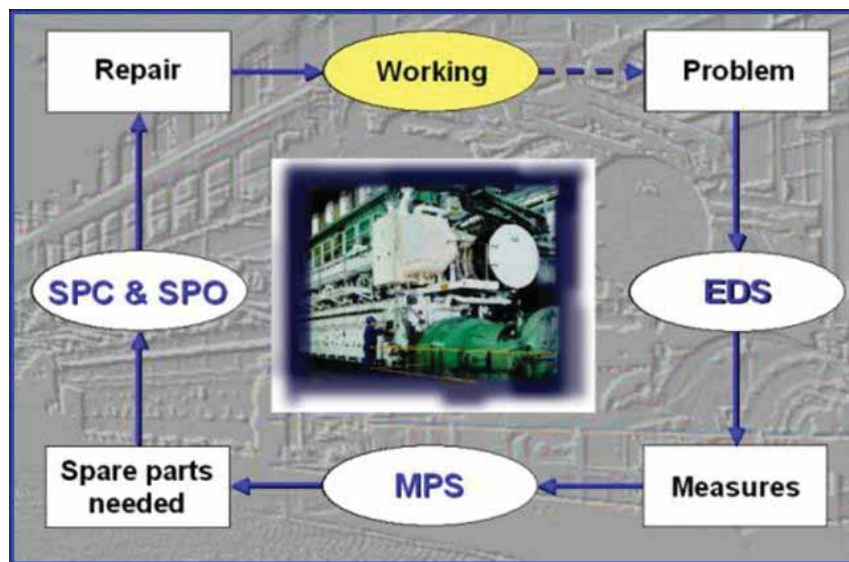


Fig. 5. outline of the CoCoS system functioning [4,11]

System consist of four modules [3]

- a) CoCoS EDS (Engine Diagnosis System) – which includes fixed and portable instrumentation of the engine, computer equipment (hardware) and software operating the engine.
- b) CoCoS MPS (Maintenance Planning System) – consists of: application software, and hard copies archive which are sets of papers and set prints
- c) CoCoS SPC (Spare Parts Catalogue) – comprising of: application software, and hard copies archive

d) **CoCoS SPO** (Stock Handling and Spare Part Ordering) - includes the application software, and hard copies archive.

5. Exploitational decisions

Mechanics, based on the identification of the ME condition propose the concept of (reasonable) operating activities to the owner. Often fail to convincingly justify a decision on a specific preventive service (as diagnostic parameters do not exceed the limits) and they fear liability for any decision taken, which generate measurable cost. The value of these costs exceeds a dozen or several dozen times earnings of the decision maker, therefore it strongly affects the psychological area (fear of the opinion that worker generates costs) and influences taking irrational decisions. At the same time working conditions in the engine room, way of work on the ship, cultural diversity of the crew, random, changing working conditions (weather, sea conditions, operating situations that cause crashes, move cargo, etc.) require constant attention, causing fatigue, loss of sensitivity for stimuli and, paradoxically (to always changing conditions of life on the ship) routine, mindless exercise of their official duties, which reduces the capacity for rational action.

In exploitational reality, identification of the operational condition of the engine is based on the sequence of events making up the diagnostic process, which include:

- Collecting operating data by the diagnosing system (DS) of the engine in real time
- Comparing the current performance indicators with the indicators from the database developed by the manufacturer and with conditions designated by the manufacturer $s_1, s_2, s_3,$
- Reviewing by the engineer on the basis of his knowledge (theoretical knowledge and experience) and organoleptic tests, namely his psycho-physical abilities. Note that every engineer (SD operator) has a different knowledge and different experience (which make up his competency), which does not always produce positive results in the form of accurate and reliable diagnosis,
- Elaboration of an assessment result of these diagnostic measures, which sets the course of changes (forecasting)
- Elaboration of suggestions of actions to support the decisions of a mechanic to take reasonable action in service.

Exploitation operations of a mechanic may be results of diagnosis, which was made on the basis of information obtained through own research, and based on information from the DS as a tool to support rational decision-making service. Its mechanic's competence to decide what decision will he tak and the consequences of those decisions.

Factors effecting proper operation and adoption DS to testing main engine (SDN) is shown in Figure 6 [8]. The process of collecting, analyzing and processing of data is divided into seven blocks:

- I - The organizational structure of the diagnostic system (SOSD)
- II - The technical structure of the measurement of parameters (STPP)
- III - organizational structure of measurements (SOP)
- IV - current diagnostic parameters (BPD)
- V - data analysis (AD)
- VI - diagnosis (DGZ)
- VII - operational decision-making (PDE).

The shape of each block is dependent on many different factors. This structure shows how complex operational decision-making process is and how important is the visualization of diagnosing system performance SDG.

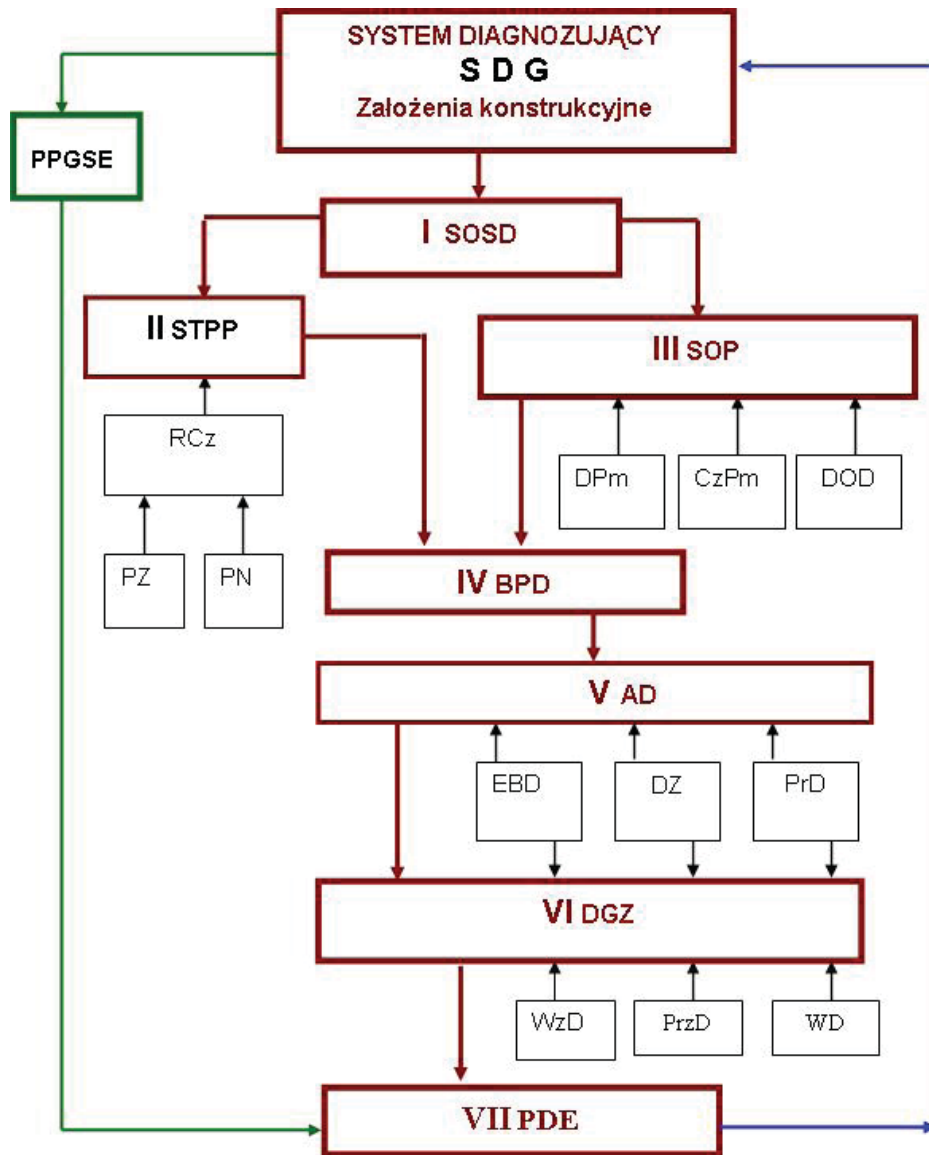


Fig.6. Factors effecting proper operation and adoption of SDG: I SOSD - organizational structure of the SD, II STPP - Technical structure of parameters measurement, RCz - the deployment of sensors, PZ - complex parameters, BS - required parameters, III - The measurement of organizational structure, DPm - accuracy, CzPm - measuring time, DOD - accuracy of data capture, IV BPD - current diagnostic parameters, V AD - data analysis, EBD - Expert database, DZ - the experience of the crew, PRD - diagnostic program, VI DGZ - diagnosis, WzD - diagnosis visualization, PrzD usefulness of the diagnosis, WD - reliability of diagnosis, VII PDE - operational decision making, PPGSE - designed limit states of performance potentials [8]

Visualization of "genesis" and "forecast" should be clearly identified by a mechanic.

According to the author's belief, as a result of developing a "genesis" (the sequence of events preceding the change) further consequences can be determined (especially negative) and on the basis of experience in the manufacturer's continued operation, when determining the probability of an event or set of operating conditions of the engine, take into account the potential for lasting change of element node, or an entire system of main engine. Therefore the ongoing registration of limit values exceeding is suggested. It seems that the degree of reduction of potential may be determined by manufacturer who has a thorough knowledge of the experimental studies [10,11]. In the existing DS alarms and courses of changes of parameters are well marked and visible, but there is no clear suggestion of a mechanic activities. Therefore, the figure shows clearly an outline which allows suggesting a pattern of mechanics performance, based on economic calculation.

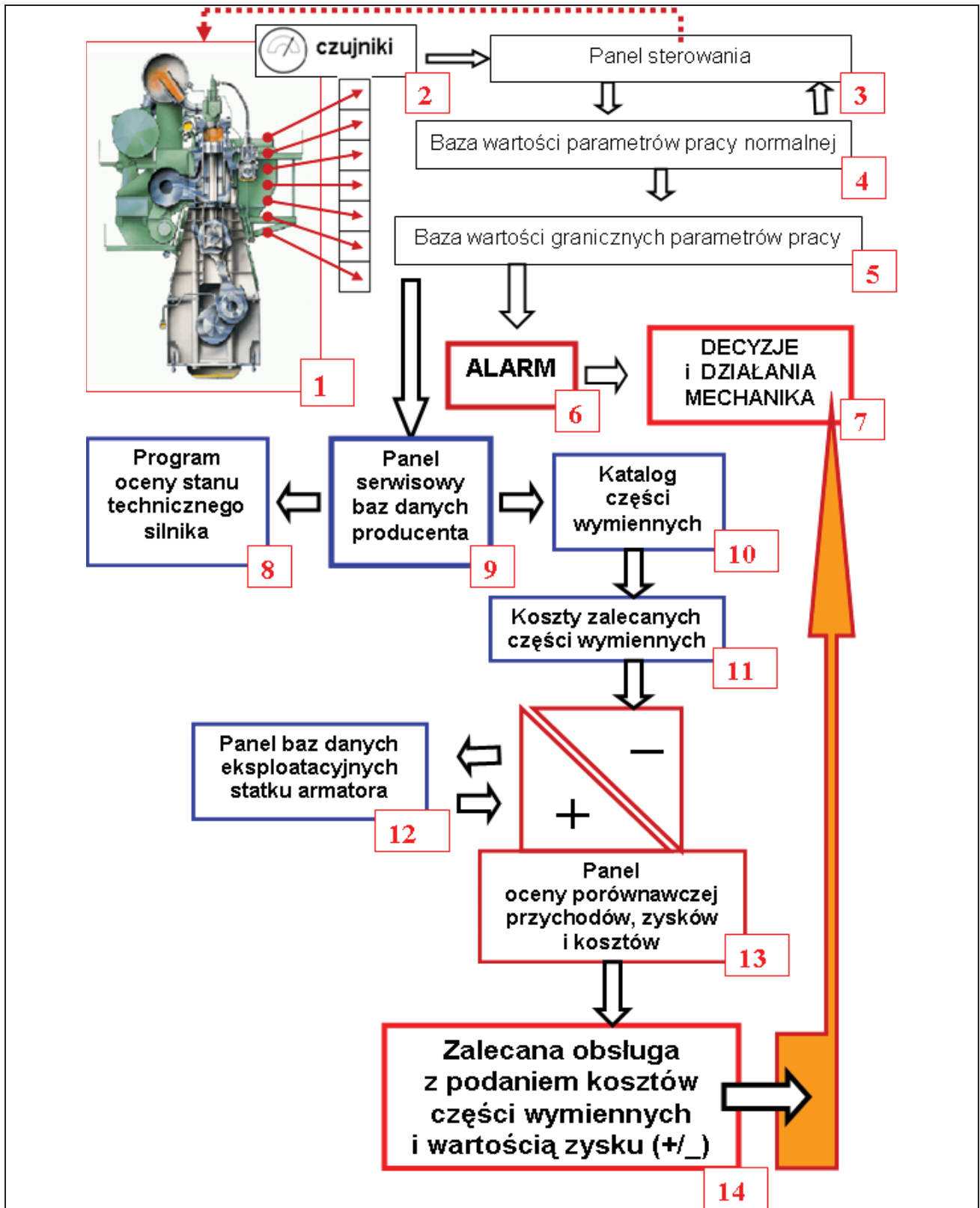


Fig. 7. DS outline enabling engineer's operational decision support through a clear suggestion of actions based on economic calculation. : 1. Main Engine (ME), 2. detectors, 3. control panel, 4. the values database for normal operation, 5. database of performance limits, 6. alarm, 7. mechanic's operations, 8. evaluation of technical condition of the engine program, 9. the service panel for the manufacturer's database, 10. catalogue of spare parts, 11. the cost of recommended spare parts, vessel operating databases panel, - of the owner, 13. a panel of comparative assessment of revenues, profits, and costs, 14 recommended servicing giving the cost of replacement parts and value of profit

Conclusion

Modern systems CoCoS and CBM have many features suggesting an attempt by the manufacturers to find an optimal model diagnostic system. "By continuous monitoring of activities of mechanics, systems are forcing them to constant skills improvement. They also enable to install instructional, simulation programs on board, and verification tests controlling knowledge and perception of mechanics. At the same time allowing insurance companies to accurately assess the classification and operation of the engine and allow manufacturers to compare the actions of the machine crew with the instructions contained in system programs. At the same time it should be noted that the full effectiveness of systems can only be achieved using the CoCoS on the engines from MAN B & W, and the CBM only Wartsila-Sulzer engines, and in close cooperation with the manufacturers [1,2,10,11].

How large is the role of human powers is evidently seen in today's DS and especially SDG. The most advanced mechanic's decision support systems on a ship are based on the joint actions:

- Engineer on board (the operator) collecting data from SDG
 - Owners experts who evaluate on the basis of data supplied from the ship, use owner's database, use own (subjective experience), but are not in direct contact with the engine,
 - Manufacturer's experts who will evaluate on the basis of data supplied from the ship, use the manufacturer's database (including data from unpublished trials failed and the failure of other engines), use their own (subjective) experience, but are not in direct contact with the engine.
- These actions can produce synergetic effect, but a mechanic has to decide which operating action to take. A mechanic is responsible for any decision.

At the same time, it appears that these are systems targeted at mechanics with extensive knowledge of the subjects of science and highly skilled.

The proposed model of developing suggestions for mechanic's operations based on economic calculation gives the mechanic a tool to justify rational exploitation activities to the owner.

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THE SVD METHOD APPLICABILITY IN COMBUSTION ENGINE DIAGNOSTICS INVESTIGATION

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Abstract

Conducted researches of combustion engine depended on delimitations of vibroacoustics measures for fit engine and comparison of this measures, with measures appointed for damaged engine (e.g. damaged injector) and accomplishment the assessment of received results influence on engine state. The present research use vibration methods to recognize the technical state of the engine and SVD method (Singular Value Decomposition) was used for results validation.

Keywords: *diagnostic inference, singular value decomposition, combustion engine*

1. Introduction

Combustion engines technical state diagnostic investigations with use of vibration are very difficult and only few proposed methods could have wider technical use in diagnostics. The paper contains application of operational modal analysis and SVD methods focused to a combustion engine, identify the technical state. The combustion engine No. 138C.2.048 with 1.4l. swept capacity, power 55 kW / 75 KM, generally applied to Fiat Uno 75i.e., is the investigation object. The engine is situated in the investigative laboratory of combustion engines in UTP Bydgoszcz. It makes possible to introduce generated vibration signals as well as the investigation of his adjustment influence on the combustion engine vibration signals change.

New approach to investigation of combustion engine technical state is vibroacoustics as a diagnostic tool. The main idea of vibroacoustics investigation is following the changes of vibration estimators as a result of engine maladjustment, waste, damages or its failure is the main idea of operational modal analysis. The present research use vibration methods as Operational Modal Analysis and SVD to recognized the technical state of the combustion engine. Operational modal is the name for the technique to do modal analysis on operational data - cases where we do not excite the structure artificially but just allow the natural operating loads to excite the structure.

As a validation of investigation results in this paper is shown presentation of Singular Value Decomposition (SVD) method. The SVD method is the appropriate tool for analysing a mapping from one vector space into another vector space, possibly with a different dimension.

2. Model of diagnostics signal generation

The investigations object was a combustion engine no. 138C.2.048 applied to the Fiat and Lancia cars. Basis on this system during investigations was created model of diagnostics signal generation [2,3,5]. The proposed model of combustion engine diagnostic signal generation is shown on Figure 1.

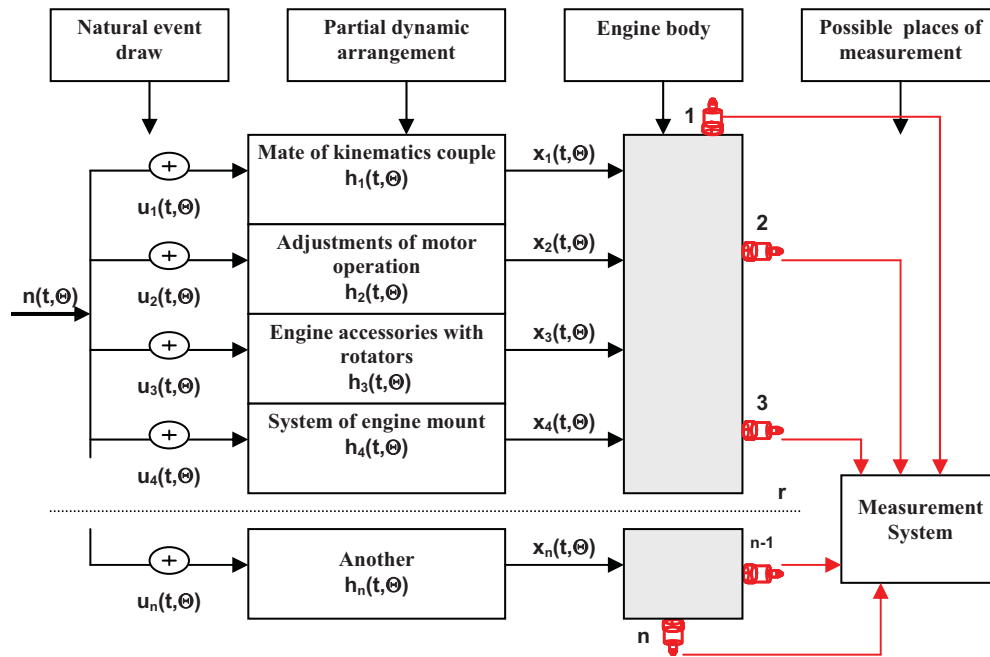


Fig.1. Combustion engine diagnostics signal generation model[2,3,5,7]

The received signals in the any point of engine body are the sum of the answer at all elementary events $u_n(t, \Theta)$, outputs in individual partial dynamic arrangements with the pulse function of input $h_n(t, \Theta)$. These influences after passing by proper dynamic arrangements are sum up on the engine body, on chosen points was measured by the vibration transducers. As a result of conducted measurements output signals was used to estimation. By $n(t, \Theta)$ was marked accidental influence stepping out from presence of dynamic micro effects such as friction [2,3,4,5].

Conducted investigations of combustion engine depended on delimitations of vibroacoustics measures for fit engine and comparison them with measures appointed for damaged engine (eg. damaged injector) and accomplishment the assessment of received results influence on engine state by operational modal analysis methods.

3. Operational modal analysis and vibroacoustics methods investigations results

In this paper Least Squares Complex Exponential method was used to determine the modal model parameters, by which the correlation function is approximated by the sum of exponentially decaying harmonic functions. This method, applied to impulse response of system is a well-known method in modal analysis yielding global estimators of system poles – the root of the transfer function denominator. The modal model of combustion engine was created for put dynamic states on the basis of received measuring results. During investigations have been done vibroacoustics measures for fit engine and for engine with damaged injector and spark plug for each cylinder [2,3,4]. As a results of engine modal tests was created the stabilisation diagrams for each technical state. Basis on the stabilisation diagrams was created the modal model includes modal order, natural frequency and damping [2,3,4,7]. Figure 2 display the window with the stabilization diagram of engine in fit state.

Table 1 present the results of modal investigations – modal model for put engine technical states. Basis on modal model parameters and estimators of vibroacoustics signal received during investigations in table 2 was shown the main observation matrix for engine performance. The final observation matrix of engine performance described 13 symptoms. The matrix have six modal symptoms (ω_1 - first natural frequency, rząd1 - modal order of first natural frequency, ξ_1 - modal damping coefficient of first natural frequency, ω_2 - second natural frequency, rząd2 - modal order of second natural frequency, ξ_2 - modal damping coefficient of second natural frequency) and the last seven symptoms are vibration process ($H(f)$ – real part of transfer function, $H(f)L$ – imagine part of transfer function, γ^2_{xy} – coherence function, $A_{RMS(t)}$ – Root Mean Square in time domain, β_{kurt} – Kurtosis, C_s - Crest factor, I - Impulse factor). [4]

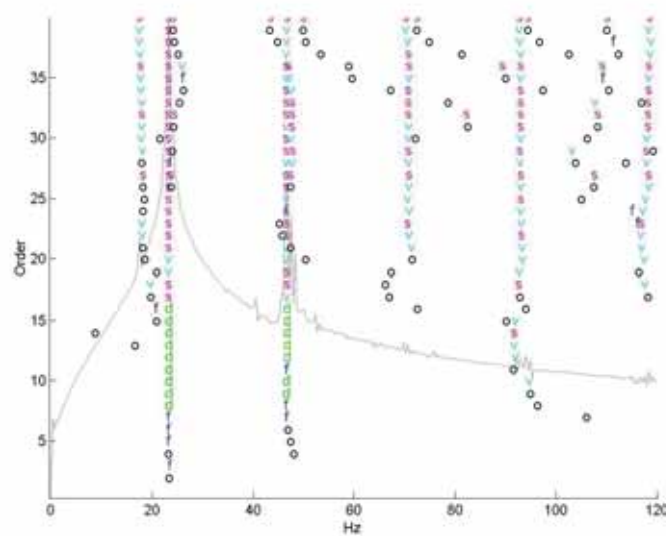


Fig. 2. Operational Modal Analysis stabilization diagram of investigated engine in fit technical state: *s* – stable pole, *v* – the frequency of vibration and modal vector is stabilized, *d* – the frequency of vibration and the stifling is stable, *f* – only the frequency of the vibration is stable, *o* – the pole is unstable [6]

Tab. 1. Parameters of modal model received during investigations for put of 9 technical states of combustion engine: ω – is the free vibration frequency, Order – order of the model, ξ – is the modal damping coefficient

Technical state	Parameters of modal model						
1- fit engine	ω (Hz)	23.27	46.96				
	Order	18	17				
	ξ (%)	0.67	1.34				
2 - damaged injector on 4 th cylinder	ω (Hz)	16.62	21.82	38.09			
	Order	20	19	20			
	ξ (%)	4.08	0.68	4.33			
3 - damaged injector on 3 th cylinder	ω (Hz)	17.81	22.57	27.94	39.74		
	Order	19	17	28	18		
	ξ (%)	4.81	1.47	4.82	2.00		
4 - damaged injector on 2 th cylinder	ω (Hz)	16.33	22.13	27.99	38.59	49.13	
	Order	29	18	31	17	23	
	ξ (%)	7.05	3.11	7.13	4.09	5.51	
5 - damaged injector on 1 th cylinder	ω (Hz)	17.36	22.82	29.24	40.03	50.87	91.64
	Order	23	19	34	27	25	16
	ξ (%)	6.69	1.18	6.17	3.21	2.90	2.24
6 - damaged spark plug on 4 th cylinder	ω (Hz)	20.13	22.05	39.08	49.60		
	Order	18	24	23	23		
	ξ (%)	1.93	7.93	6.98	4.80		
7 - damaged spark plug on 3 th cylinder	ω (Hz)	16.52	20.70	25.51	41.43	47.43	
	Order	19	17	29	27	26	
	ξ (%)	10.11	2.48	6.73	4.61	4.07	

8 - damaged spark plug on 2 th cylinder	ω (Hz)	16.50	21.89	37.74	46.34		
	Order	23	18	24	20		
	ξ (%)	11.47	1.21	6.33	1.78		
9 - damaged spark plug on 1 th cylinder	ω (Hz)	17.59	23.58	45.93			
	Order	25	17	18			
	ξ (%)	3.83	0.71	1.27			

Tab. 2. The main observation matrix for engine performance

State	ω_1	rząd 1	ξ_1	ω_2	rząd 2	ξ_2	H(f)	H(f)L	γ^2_{xy}	$A_{RMS(t)}$	β_{kurt}	C_s	I
1	23,27	18	0,67	46,96	17	1,34	68,56	-2,18	108,18	0,2177	1,5567	1,7239	1,9268
2	21,82	19	0,68	38,09	20	4,33	47,08	30,59	100,22	0,1392	1,8989	2,1204	2,4456
3	22,57	17	1,47	39,74	18	2,00	36,42	8,84	104,40	0,2040	1,7532	1,8656	2,1198
4	22,13	18	3,11	38,59	17	4,09	31,34	-15,28	91,11	0,1769	1,9245	2,0762	2,3992
5	22,82	19	1,18	40,03	27	3,21	46,16	-75,94	101,15	0,2312	1,7148	2,0982	2,3673
6	20,13	18	1,93	39,08	23	6,98	42,24	-8,50	83,73	0,1702	2,5205	2,8157	3,3986
7	20,70	17	2,48	41,43	27	4,61	38,76	22,77	82,34	0,1363	2,2943	2,2926	2,7564
8	21,89	18	1,28	46,34	20	1,78	40,51	-19,29	83,29	0,1726	1,7401	2,0176	2,2929
9	23,58	17	0,71	45,93	18	1,27	19,45	-23,34	99,63	0,1904	1,6144	1,8260	2,0527

4. Results validation

As a results of investigation in this paper is shown presentation of singular value decomposition (SVD) method usage for combustion engine technical state results validation. Figure 3 display the window with the SVD module, that was used for analysis.

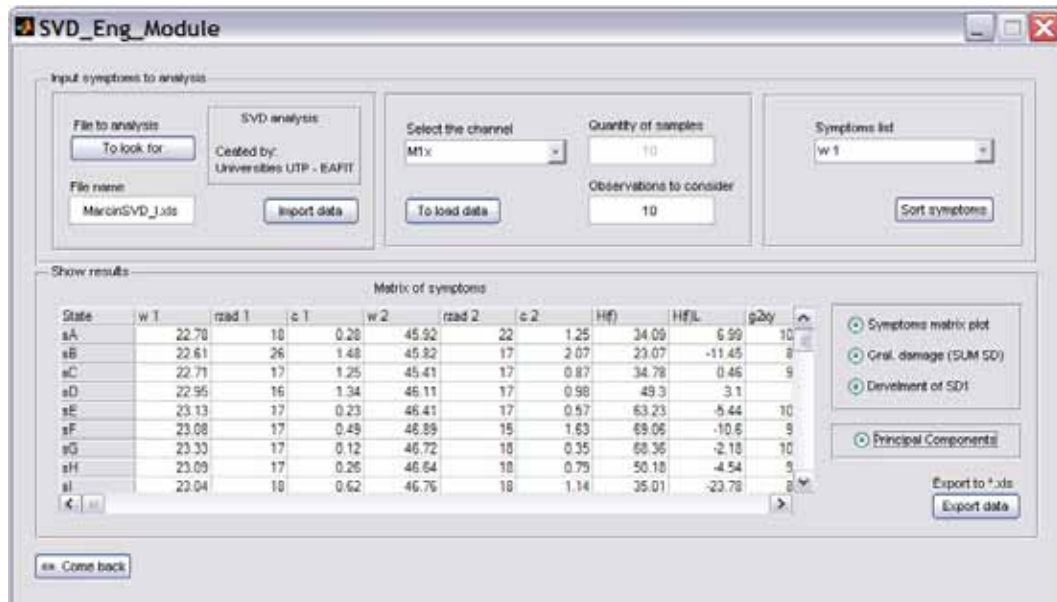


Fig. 3. SVD module window

The SVD method is the appropriate tool for analyzing a mapping from one vector space into another vector space, possibly with a different dimension [1]. The first step of SVD procedure is to centre and normalization all symptoms given in table two relative to the initial value of symptom vector. The observation matrix of transformate symptoms relative to the initial value is shown on Figure 4.

The second step of SVD procedure is to calculate the first generalized damage and evolution of damage [1]. Graphical interpretation of this calculations is given in Figure 5.

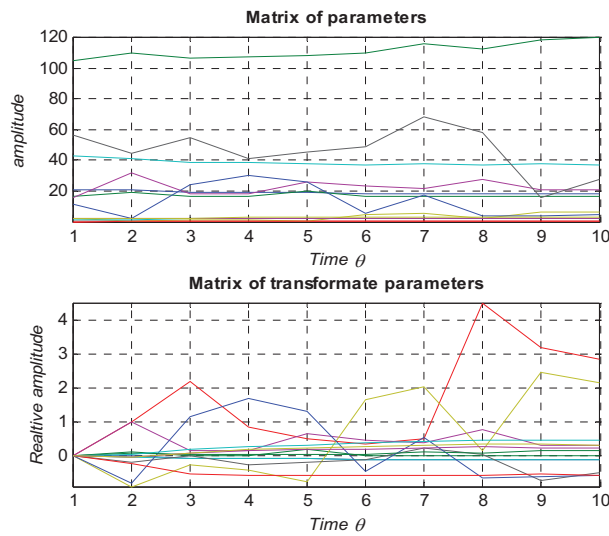


Fig.4. Matrix of symptoms before and after transformation

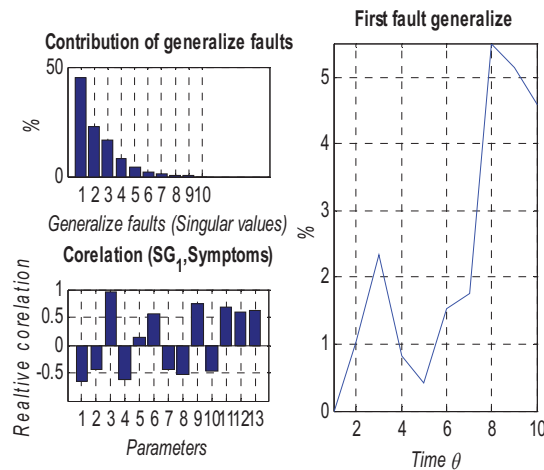


Fig.5. Graphical interpretation of first generalized damage and evolution of damage

The graphical results of SVD methods for put engine technical states are given in Figure 6,7 and Figure 8.

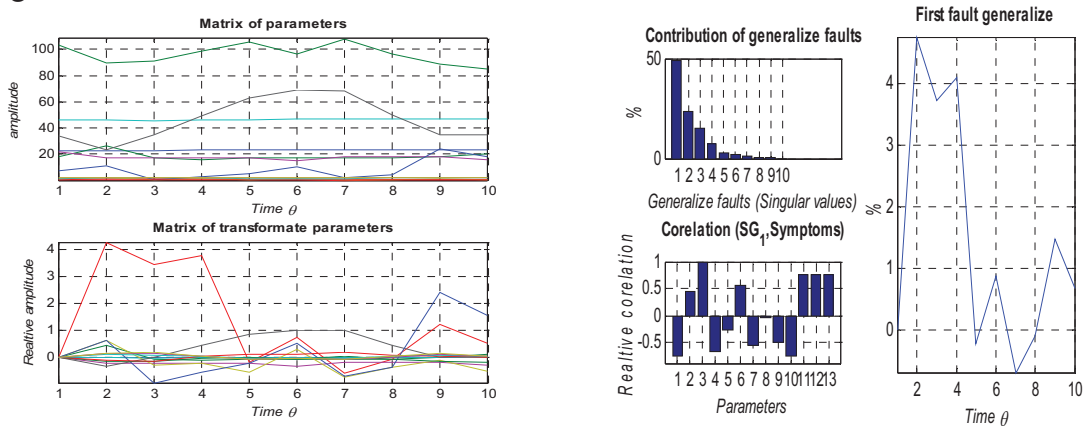


Fig.6. Matrix of symptoms before and after transformation and graphical interpretation of first generalized damage and evolution of damage for fit engine

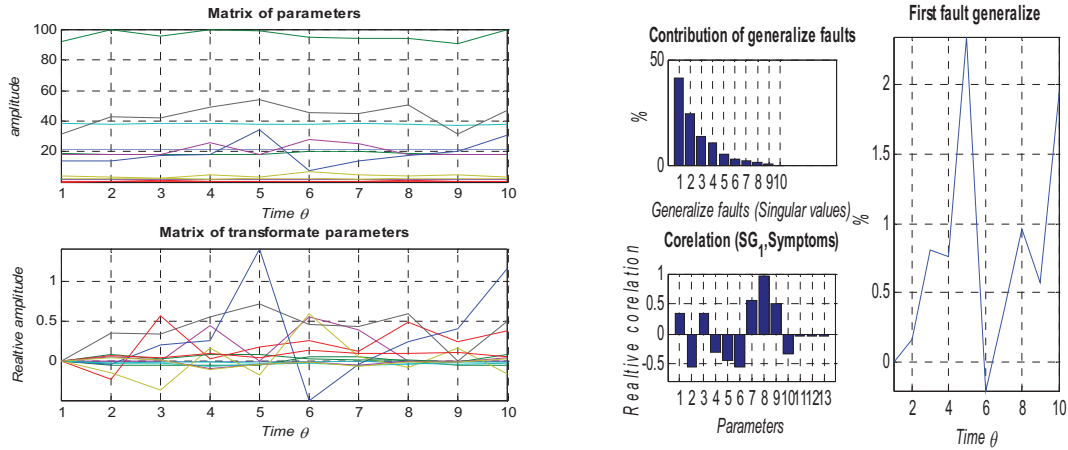


Fig.7. Matrix of symptoms before and after transformation and graphical interpretation of first generalized damage and evolution of damage for engine with damaged injector on 4th cylinder

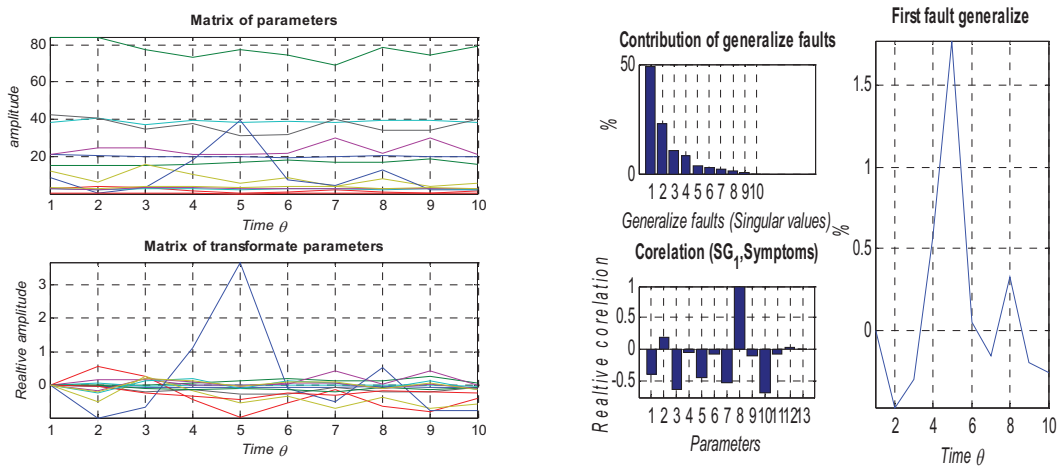


Fig.8. Matrix of symptoms before and after transformation and graphical interpretation of first generalized damage and evolution of damage for engine with damaged spark plug on 4th cylinder

In SVD procedure as a result we got a line up of five best symptoms given in Table 3 that are most important in description of set technical state of combustion engine.

Tab. 3. Results of SVD method with five best symptoms for set of engine technical state

State	1 symptom	2 symptom	3 symptom	4 symptom	5 symptom
1	ξ_1	ω_1	$A_{RMS(t)}$	β_{kurt}	C_s
2	H(f)L	rząd 1	ξ_2	H(f)	γ_{xy}^2
3	ξ_1	H(f)L	rząd ₁	ω_1	H(f)
4	rząd ₂	H(f)L	ω_2	ξ_2	ξ_1
5	ξ_1	rząd ₁	β_{kurt}	$A_{RMS(t)}$	γ_{xy}^2
6	H(f)L	ξ_1	$A_{RMS(t)}$	H(f)	rząd ₂
7	ξ_1	C_s	I	rząd ₁	γ_{xy}^2
8	H(f)L	ξ_1	ξ_2	γ_{xy}^2	ω_1
9	H(f)L	ξ_1	β_{kurt}	C_s	I

Making data analysis in SVD method as a result we got the lineup of symptoms together with the proportional description of given individual symptom of combustion engine technical state. At the end of SVD procedure at Figure 9 is displayed the contribution of the third Principal

Components (PC*). The PC₁ is the first principal component of analyzed data, it described the direction of fault in the system and it take 56,44 % of importance degree of the symptoms. Thanks to SVD methods we could decide which symptom given in observation matrix is the best to recognize a set of combustion engine technical state [1].

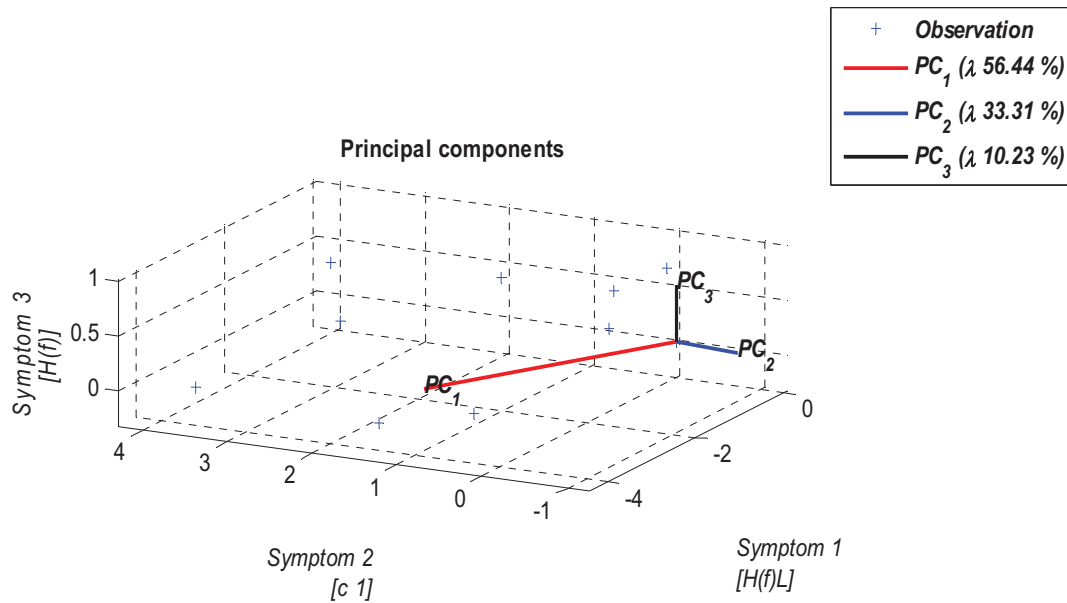


Fig.9. Contribution of the Principal Components

Relationships cause - consecutive expressing quantitative relation between studied variable symptoms results in this work were qualified using the function of the multiple regression. Basis on SVD results as a best symptoms in multiple regression were given: ω_1 – first natural frequency, ξ_1 - modal damping coefficient of first natural frequency, ξ_2 - modal damping coefficient of second natural frequency, $H(f)L$ – imagine part of transfer function, γ^2_{xy} – coherence function. The equation of multiple regression is obtained in the form:

$$y = -1,44923\omega_1 - 0,61558\xi_1 - 0,35989\xi_2 - 0,06520H(f)L + 0,14424\gamma^2_{xy} + 35,9994, \quad (1)$$

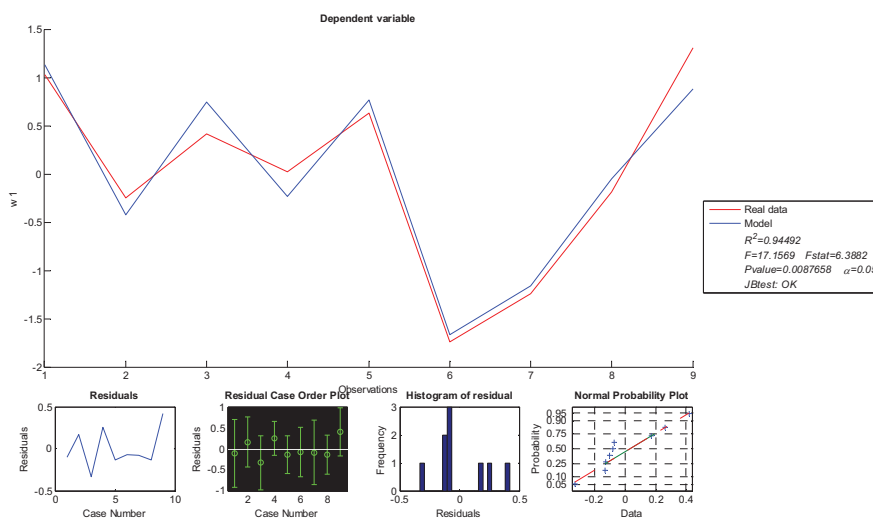


Fig. 10. Graphical interpretation of multiple regression for first dependent variable ω_1

Graphical interpretation of this calculations for first dependent variable ω_1 is given in figure 10. The red line present real data received during investigations, the blue line – estimated model for dependent variable.

5. Conclusion

Received in the experiment modal parameters and numerical estimators of vibroacoustics signal unambiguously show that the previously assumed conditions of the combustion engine's state reflect themselves in modal as well as other parameters characterising the vibrations and they are possible to be identified.

The use of the operational modal analysis in diagnostic investigations finds its use as one of many methods of marking the actual technical state of studied object. To complete the analysis process a SVD method and multiple regression were used. SVD methods marked most important symptom in description of engine technical state. On the basis of the results, it is possible to determine the actual technical state of an object of the same type by means of comparison of the achieved results with the model ones and assigning them to the particular model's state, which answers to a particular damage, or its loss, in the object.

The introduced in paper results of investigations are the part of realized investigative project and they do not describe wholes of the investigative question, only chosen aspects.

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ASSESSMENT OF WHETHER MARINE POWER PLANT STEAM SYSTEM FAILURES BELONG TO ONE GENERAL POPULATION

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Abstract

In the paper a number of various types of vessels' power plant steam system failures have been analyzed with regard to the general population they come from. For the purpose of the analysis the Kruskal – Wallis rank sum test and Kruskal – Wallis ANOVA rank test from the statistical packet STATISTICA 8.0 have been used. The analysis was based on the observations of the failure of marine power plants steam systems elements. Failures to the marine power plant systems of 10 ships owned by the Polish Steamship Company of Szczecin was the subject of a statistical data analysis. All the ships differed in respect to their place and time of construction as well as their technical parameters. The data on marine power plants failures was collected in similar conditions, that is, they were supplied by an engine crew member working in the marine power plant. The data on the failures of particular marine power plant systems was obtained accordingly to the test schedule $[N, W, T]$, which means that N renewable objects were the subject of the test within the time T . Since the recovery time of the damaged system appeared negligibly short, when compared to the time of the test, it was assumed that consecutive recoveries overlap the failure moments. The statistical analysis dealt with moments $t_1 \leq t_2 \leq \dots \leq t_n$ of the particular systems' consecutive failures and the length of time intervals τ_n between the objects' consecutive failures.

Keywords: marine power plant, steam system, failures, the Kruskal-Wallis rank test

1. Introduction

In failure analysis of complex technical systems, especially when searching for failure distributions, it needs to be determined whether collected statistical data on failures come from the same general population. It needs to be specified, whether they may be analyzed as a set of data characterized by common statistical features. In the paper it has been presented on the basis of marine power plant steam system failures.

The statistical analysis of the data on selected marine power plant steam system failures has been done for the following ships, which were assigned symbols for the ease of description: S1 – m/s "ZIEMIA OLSZTYŃSKA", S2 – m/s "ZIEMIA SUWALSKA", S3 – m/s "HUTA ZGODA", S4 – m/s "GENERAL BEM", S5 – m/s "SOLIDARNOŚĆ", S6 – m/s "ZAGŁĘBIE MIEDZIOWE", S7 – m/s "KOPALNIA RYDUŁTOWY", S8 – m/s "OBROŃCY POCZTY", S9 – m/s "MACIEJ RATAJ", S10 – m/s "UNIwersytet GDAŃSKI".

The data on power plant failures was collected in similar conditions, that is, supplied by an engine crew member working in the power plant [5, 6].

All the ships differ in respect to their place and time of construction as well as their technical parameters.

Information on failures was collected during an average voyage lasting for up to six months. For the statistical analysis the time accepted is 180 days, with one day as the time unit defining the moments of failures.

The data on failures deals with six systems: lubricating system – IOS, sea water cooling system – IWM, fresh water cooling system – IWS, fuel system – IPal, compressed air system – ISP and steam system – IPar.

The procedure of the statistical analysis refers to individual power plant systems as research objects in spite of the fact that each of them is actually a system combined of many components of complex reliability structure. Causes of the individual system failures were not the subject of consideration. For reliability analysis of complex technical systems, which undoubtedly power plant systems belong to, a number of various methods of the system reliability assessment have been applied, e.g. network [1, 3, 4], various logarithms [2, 7] or a combination of other methods [8, 9, 10].

2. Data on failures

Data on failures of the individual power plant systems was obtained in compliance with the research schedule $[N, W, T]$, which means that N renewable objects were the subject of the research during the time T . Since the time of renewal of the damaged systems turned out negligibly short, when compared to the time of research, an assumption was made that the consecutive moments of renewal overlap with the moments of failures.

Moments of the consecutive failures $t_1 \leq t_2 \leq \dots \leq t_n$ and the lengths of time between consecutive failures τ_n of the objects in question became the subject of the statistical analysis.

The following assumptions were made:

- 1) for vessels S1 – S5 the time is measured from the moment of the first failure repair,
- 2) for vessels S6 – S10 the lengths of time period τ_n between the consecutive failures do not include the time between the beginning of the voyage and the first failure,
- 3) time period between the last failure and the end of the observation after 180 days have been taken into consideration.

Table 1 shows cumulative number of failures of individual systems on all ships. The next tables contain failure moments and lengths of time between consecutive failures of individual systems for all ten ships.

Table 1. Cumulative number of failures of individual power plant systems on all surveyed ships

Name of the system	Cumulative number of failures										
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	Sum
Lubricating system – IOS	3	1	5	6	2	3	21	8	8	9	66
Sea water system – IWM	7	3	4	4	2	11	5	8	8	5	57
Fresh water system – IWS	6	2	6	3	2	7	8	9	5	7	55
Fuel system – IPal	8	12	5	12	6	19	23	17	7	12	121
Compressed air system – ISP	2	1	2	2	2	5	5	8	3	6	36
Steam system – IPar	4	6	3	2	3	10	4	9	3	6	50
Total	30	25	25	29	17	55	66	59	34	45	385

In tables 2 and 3 data on failure of the steam system – IPar, the subject of the analysis, has been presented.

Table 2. Consecutive failure moments of the steam system – IPar

Number of failure	Moments of consecutive failures (days)									
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
1	19	8	76	53	11	3	14	10	37	8
2	52	19	114	110	27	13	27	17	109	34
3	99	25	161		100	21	71	28	149	66
4	123	50				47	91	37		80
5		89				51		45		106
6		93				65		72		122
7						89		111		
8						92		119		
9						119		128		
10						155				

Table 3. Time between consecutive failures of the steam system – IPar

L.p.	Time between consecutive failures (days)									
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
1	19	8	76	53	11	10	13	7	72	25
2	33	11	38	57	16	8	44	11	40	33
3	47	6	47	70	73	26	20	9	31	14
4	24	25	19		80	4	89	8		25
5	57	39				14		27		16
6		4				24		39		58
7		87				3		8		
8						27		9		
9						36		52		
10						25				

3. Assessment of whether steam system failure moments and periods of time between failures come from the same population

Data on marine steam system failures come from different ships of various technical parameters [5, 6]. Thus, it is necessary to verify the hypothesis stating that they come from one population, in other words, that they may be treated as a realization of the same random sample. Only such verification allows for determining general reliability characteristics of particular systems due to the collected statistical data.

The hypothesis was verified by the Kruskal – Wallis rank sum test.

In the test it is assumed that there are k general populations of data with optional distributions and continuous distribution functions $F_1(x), F_2(x), \dots, F_k(x)$. Out of each population n_i ($i=1,2,\dots,k$) random sample elements were independently drawn. Since steam system failure data is not numerous, it is essential that the test does not require any specific sample size.

The verification of the hypothesis $H_0: F_1(x) = F_2(x) = \dots = F_k(x)$ is presented below.

For that purpose all sample values are arranged in ascending order and assigned ranks. In case of a repeated value the ranks are assigned by averaging their rank positions they would be given if they were not identical. Next the rank sum T_i ($i=1,2,\dots,k$) of each sample is calculated separately.

Statistic

$$H = \frac{12}{n(n+1)} \sum_{i=1}^k \frac{T_i^2}{n_i} - 3(n+1), \text{ where } n = n_1 + n_2 + \dots + n_k, \quad (1)$$

assuming that the hypothesis H_0 is true, has asymptotic distribution χ^2 with $k-1$ degree of freedom.

The critical region in the test is built on the right side, which means that the hypothesis H_0 is rejected when the statistic value $H \geq \chi_{1-\alpha}^2$, where $\chi_{1-\alpha}^2$ is the quantile of the distribution χ^2 of $k-1$ degrees of freedom and accepted significance level α .

Making a decision about rejection of H_0 hypothesis or lack of bases for its rejection is also facilitated with knowledge about the test *significance level* $\hat{\alpha}$ for the statistic value H_n , obtained from:

$$P(\chi_{\hat{\alpha}}^2 \geq H_n) = \hat{\alpha} \quad (2)$$

If $\alpha > \hat{\alpha}$, the hypothesis H_0 is rejected, otherwise there is no basis for its rejection.

The test was performed for both t_n moments of consecutive failures and τ_n periods of time between consecutive failures of a given system.

In all tests the accepted significance level was $\alpha=0,05$.

When verifying the hypothesis $H_0: F_1(x) = F_2(x) = \dots = F_{10}(x)$ stating that the consecutive failure moments' t_n distribution of all ships steam systems (IPar) was identical, the data in table 2 was assigned ranks and in table 4 the rank sum T_i and the summands $\frac{T_i^2}{n_i}$ of the sum from formula (1) separately for each of the vessels were calculated.

Table 4. Computation of ranks of the steam system (IPar) consecutive failure moments

Number of failure	Ranks of consecutive failure moments of steam system – IPar									
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
1	9,5	2,5	29	24	5	1	7	4	17,5	2,5
2	23	9,5	42	40	13,5	6	13,5	8	39	16
3	36	12	50		37	11	27	15	48	26
4	46	21				20	33	17,5		30
5		31,5				22		19		38
6		35				25		28		45
7						31,5		41		
8						34		43,5		
9						43,5		47		
10						49				
Rank sum T_i	114,5	111,5	121,0	64,0	55,5	243,0	80,5	223,0	104,5	157,5
T_i^2	13110,3	12432,3	14641,0	4096,0	3080,25	59049,0	6480,25	49729,0	10920,3	24806,3
$\frac{T_i^2}{n_i}$	3277,57	2072,05	4880,33	2048,0	1026,75	5904,9	1620,06	5525,44	3640,1	4134,38

Due to $n_1 = 4, n_2 = 6, n_3 = 3, n_4 = 2, n_5 = 3, n_6 = 10, n_7 = 4, n_8 = 9, n_9 = 3, n_{10} = 6$, so $n = \sum_{k=1}^{10} n_k = 50$.

Thus the statistical value $H = \frac{12}{50 \cdot 51} \cdot 34129,6 - 3 \cdot 51 = 7,6099$. Comparing the statistical value

$H=7,6099$ with the quantile value of the distribution χ^2 of $k-1=9$ degrees of freedom $\chi_{0,95}^2 = 16,9258$ ($H < \chi_{0,95}^2$), it is to be concluded that reasons for rejecting the hypothesis H_0 do not exist; the *significance level* $\hat{\alpha} = 0,5739$.

Further on the subject of verification was the hypothesis $H_0: G_1(x) = G_2(x) = \dots = G_{10}(x)$ that distribution of time τ_n , between consecutive failures of steam system (IPar) on all ships is identical.

Data in table 3 was assigned ranks and in table 5 the rank sum T_i and the summands $\frac{T_i^2}{n_i}$ of the sum from formula (1) separately for each of the vessels were calculated.

Table 5. Computation of ranks of the periods of time between failures of steam system (IPar)

No	Ranks of the periods of time between failures of steam system – IPar									
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
1	21,5	7,5	52	45	14	12	16	5	50	27,5
2	34,5	14	37	46,5	19,5	7,5	41	14	40	34,5
3	42,5	4	42,5	49	51	30	23	10,5	33	17,5
4	24,5	27,5	21,5		53	2,5	55	7,5		27,5
5	46,5	38,5				17,5		31,5		19,5
6		2,5				24,5		38,5		48
7		54				1		7,5		
8						31,5		10,5		
9						36		44		
10						27,5				
Rank sum T_i	169,5	148,0	153,0	140,5	137,5	190,0	135,0	169,0	123,0	174,5
T_i^2	28730,3	21904,0	23409,0	19740,3	18906,3	36100,0	18225,0	28561,0	15129,0	30450,3
$\frac{T_i^2}{n_i}$	5746,06	3129,14	5852,25	6580,1	4726,57	3610,0	4556,25	3173,44	5043,0	5075,05

Due to $n_1 = 5, n_2 = 7, n_3 = 4, n_4 = 3, n_5 = 4, n_6 = 10, n_7 = 4, n_8 = 9, n_9 = 3, n_{10} = 6$, so $n = \sum_{k=1}^{10} n_k = 55$.

Thus, the statistical value $H = \frac{12}{55 \cdot 56} \cdot 47491,9 - 3 \cdot 56 = 17,0334$. Comparing the statistical value

$H=17,0334$ with the quantile value of the distribution χ^2 of $k-1=9$ degrees of freedom $\chi_{0,95}^2 = 16,9258 (H > \chi_{0,95}^2)$, the hypothesis H_0 needs to be rejected; the *significance level* $\hat{\alpha} = 0,0482$. So, data about periods of time between failures is steam system of the vessels do not belong to the same general population.

The analysis of the failure data from table 1 leads to the conclusion that the steam system (IPar) failure frequency on ships S6 and S8 turns out significantly higher than on the other vessels. Thus, an assumption is to be made that the data should be divided into two groups of high and low failure frequency.

Further on the subject of verification was the hypothesis $H_0: G_1(x)=G_2(x)=G_3(x)=G_4(x)=G_5(x)=G_7(x)=G_9(x)=G_{10}(x)$ that τ_n distribution of time between consecutive failures of steam system (IPar) on all ships S1, S2, S3, S4, S5, S7, S9 and S10 is identical.

Data in table 3 was assigned ranks and in table 6 the rank sum T_i and the summands $\frac{T_i^2}{n_i}$ of the sum from formula (1) separately for each of the vessels were calculated.

Table 6. Computation of ranks of the periods of time between failures of steam system (IPar)

No.	Ranks of the periods of time between consecutive failures of steam system – IPar							
	S1	S2	S3	S4	S5	S7	S9	S10
1	10,5	3	33	26	4,5	6	31	15
2	18,5	4,5	20	27,5	8,5	23	22	18,5
3	24,5	2	24,5	30	32	12	17	7
4	13	15	10,5		34	36		15
5	27,5	21						8,5
6		1						29
7		35						
T_i	94,0	81,5	88,0	83,5	79,0	77,0	70,0	93,0
T_i^2	8836,0	6642,25	7744,0	6972,25	6241,0	5929,0	4900,0	8649,0
T_i^2/n_i	1767,2	948,89	1936,0	2324,08	1560,25	1482,25	1633,33	1441,5

Due to $n_1 = 5, n_2 = 7, n_3 = 4, n_4 = 3, n_5 = 4, n_6 = 10, n_7 = 4, n_8 = 9, n_9 = 3, n_{10} = 6, n = \sum_{k=1}^{10} n_k - n_6 - n_8 = 36$.

Thus, the statistical value $H = \frac{12}{36 \cdot 37} \cdot 13093,5 - 3 \cdot 37 = 6,9595$. Comparing the statistical value $H=6,9595$ with the quantile value of the distribution χ^2 of $k-1=7$ degrees of freedom $\chi_{0,95}^2 = 14,0738$ ($H < \chi_{0,95}^2$), it is to be concluded that reasons for rejecting the hypothesis H_0 do not exist; the significance level $\hat{\alpha} = 0,4331$.

Further on the subject of verification was the hypothesis $H_0: G_6(x) = G_8(x)$, that distribution of time between consecutive failures (τ_n) of steam system (IPar) on ships S6 and S8 was identical.

Data on periods of time between failures of steam system on ships S6 and S8 was assigned ranks and in table 7 the rank sum T_i and the summands $\frac{T_i^2}{n_i}$ of the sum from formula (1) separately for each of the vessels were calculated.

Table 7. Computation of ranks of the periods of time between consecutive failures of steam system (IPar)

No	Ranks of the periods of time between consecutive IPar failures of steam system – Ipar	
	S6	S8
1	9	3
2	5	10
3	14	7,5
4	2	5
5	11	15,5
6	12	18
7	1	5
8	15,5	7,5
9	17	19
10	13	
T_i	99,5	90,5
T_i^2	9900,25	8190,25
T_i^2/n_i	990,03	910,03

Because $n_6 = 10, n_8 = 9, n = n_6 + n_8 = 19$, so the statistical value $H = \frac{12}{19 \cdot 20} \cdot 1900,06 - 3 \cdot 20 = 0,0019$. Comparing the statistical value $H=0,0019$ with the quantile

value of the distribution χ^2 of $k-1=1$ degrees of freedom $\chi_{0,95}^2 = 3,842$ ($H < \chi_{0,95}^2$), it is to be concluded that reasons for rejecting the hypothesis H_0 do not exist; the *significance level* $\hat{\alpha} = 0,9652$.

Therefore of the above presented the Kruskal – Wallis tests point out that for steam system (IPar) consecutive moments of failures on all 10 ships can be treated as a sample coming from the same general population with periods of time between failures which need to be divided into two groups: the first one including ships S1, S2, S3, S\$, S5, S7, S9, S10 of low frequency failure and the second one comprising S6 and S8, ships of steam system high frequency failures.

Next stage of the work was a similar test performed by computer packet *STATISTICA 8.0*.

Available tests to be performed for n independent samples are ANOVA rank Kruskal – Wallis and median test from the packet *STATISTICA 8.0*.

The Kruskal – Wallis test is a nonparametric equivalent to one – factor variance analysis. Due to the test it was estimated whether n independent sample data come from the same population or from the population of the same median. Individual samples do not need to have identical sample sizes. Median test appears a less accurate version of ANOVA Kruskal – Wallis test, that is, the survey statistic is not built on the basis of raw data or ranks.

In order to analyze marine power plant steam systems there are no bases for rejection of null hypothesis concerning the distribution of consecutive failure moments t_n coming from one general population at the accepted significance level $\alpha=0,05$, which is confirmed by the results of ANOVA Kruskal – Wallis test shown in fig. 1. Box plots for all distributions have been presented in fig.2.

The Kruskal-Wallis test: $H(9, N=50) = 7,611853$; $p = 0,5737$		
Marking of the steam system	N - number of all observations	Rank sum
1	4	114,5000
2	6	111,5000
3	3	121,0000
4	2	64,0000
5	3	55,5000
6	10	243,0000
7	4	80,5000
8	9	223,0000
9	3	104,5000
10	6	157,5000

Fig. 1. Results of Kruskal – Wallis test for the consecutive failure moments t_n of the steam system presented in *STATISTICA 8.0* table; N – number of all observations, 9 – number of degrees of freedom of distribution χ^2 of statistic H , H – value of Kruskal – Wallis statistic, p – value

In case of distributions of periods of time t_n between consecutive failures of marine steam system, probability level obtained in the ANOVA Kruskal-Wallis test approximates to 0,05 and equals $p=0,0479$ (fig. 3). However, from the formal point of view, the null hypothesis that distributions of periods of time t_n between consecutive failures come from one general population on the assumed significance level $\alpha=0,05$ should be rejected. Therefore, additional median test (fig. 4) accessible in the window *Nonparametric statistics>comparison of a number of independent samples (groups)* from *STATISTICA 8.0* was performed. The median test [13, 14] is the less accurate version of ANOVA Kruskal-Wallis test, that is, the test statistic is not built on the basis of raw data or their ranks – the presented calculations are based on contingency table.

In particular, in each of the samples the *STATISTICA* program computes the number of cases above or below the common median and calculates chi-square statistic value for contingency table

results $2 \times n$ samples. According to the null hypothesis (that all samples come from a population with identical medians) it is to be expected that approximately 50% of all cases occur above or (below) the common median. The test appears especially useful in cases where the measuring scale includes artificial limits and a number of cases occur at the scale end. In such a situation the median test turns out to be the only method to be applied for comparing samples.

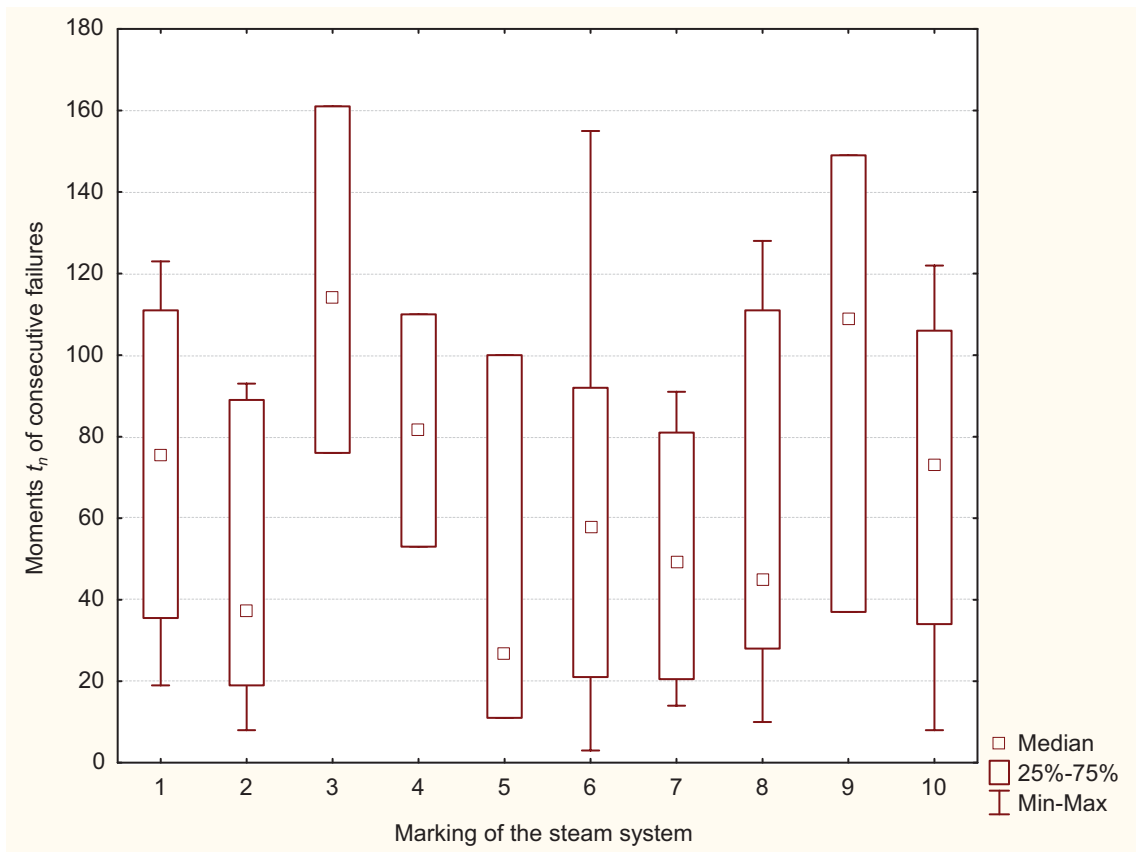


Fig. 2. Box plots for distribution moments t_n of steam system consecutive failures developed due to STATISTICA 8.0

The Kruskal-Wallis test: $H(9, N=55) = 17,05462$; $p = 0,0479$		
Marking of the steam system	N - number of all observations	Rank sum
1	5	169,5000
2	7	148,0000
3	4	153,0000
4	3	140,5000
5	4	137,5000
6	10	190,0000
7	4	135,0000
8	9	169,0000
9	3	123,0000
10	6	174,5000

Fig.3. Results of the Kruskal – Wallis test for distributions of periods of time τ_n between consecutive steam system failures presented in STATISTICA 8.0 tables; N – number of all observations, 9 – number of degrees of freedom of asymptotic distribution χ^2 of statistic H, H – statistic value of Kruskal – Wallis test, p – value

Median test, general median = 25,0000; Independent (grouping) variable: marking of the steam system Chi square = 11,62333; df = 9; p = 0,2354											
	1	2	3	4	5	6	7	8	9	10	Total
<=medians:observed	2,00000	5,00000	1,00000	0,00000	2,00000	7,00000	2,00000	6,00000	0,00000	4,00000	29,00000
expected	2,63636	3,69091	2,10909	1,58182	2,10909	5,27273	2,10909	4,74545	1,58182	3,16364	
observed-expected	-0,63636	1,30909	-1,10909	-1,58182	-0,10909	1,72727	-0,10909	1,25455	-1,58182	0,83636	
>medians:observed	3,00000	2,00000	3,00000	3,00000	2,00000	3,00000	2,00000	3,00000	3,00000	2,00000	26,00000
expected	2,36364	3,30909	1,89091	1,41818	1,89091	4,72727	1,89091	4,25455	1,41818	2,83636	
observed-expected	0,63636	-1,30909	1,10909	1,58182	0,10909	-1,72727	0,10909	-1,25455	1,58182	-0,83636	
Total: observed	5,00000	7,00000	4,00000	3,00000	4,00000	10,00000	4,00000	9,00000	3,00000	6,00000	55,00000

Fig.4. Results of median test for the distributions of periods of time τ_n between failures of steam system presented in STATISTICA 8.0 table

On the basis of the median test there are no bases for rejection of the null hypothesis with the distributions of periods of time τ_n between consecutive failures coming from one general population (probability level $p=0,2354$) with the accepted significance level $\alpha=0,05$. For that purpose additional multiple (double – sided) comparisons of all sample ranks were performed. The probability values *post - hoc* obtained by means of multiple comparisons and rated values „z” do not prove significant statistical differences among particular pairs of distributions (fig. 5 and 6).

p-value for multiple (double-sided) comparisons; Independent (grouping) variable: marking of the steam system The Kruskal-Wallis test: $H(9, N= 55) = 17,05462$; $p = 0,0479$										
	1	2	3	4	5	6	7	8	9	10
	R:33,900	R:21,143	R:38,250	R:46,833	R:34,375	R:19,000	R:33,750	R:18,778	R:41,000	R:29,083
1		1,000000	1,000000	1,000000	1,000000	1,000000	1,000000	1,000000	1,000000	1,000000
2	1,000000		1,000000	0,906151	1,000000	1,000000	1,000000	1,000000	1,000000	1,000000
3	1,000000	1,000000		1,000000	1,000000	1,000000	1,000000	1,000000	1,000000	1,000000
4	1,000000	0,906151	1,000000		1,000000	0,373978	1,000000	0,387875	1,000000	1,000000
5	1,000000	1,000000	1,000000	1,000000		1,000000	1,000000	1,000000	1,000000	1,000000
6	1,000000	1,000000	1,000000	0,373978	1,000000		1,000000	1,000000	1,000000	1,000000
7	1,000000	1,000000	1,000000	1,000000	1,000000	1,000000		1,000000	1,000000	1,000000
8	1,000000	1,000000	1,000000	0,387875	1,000000	1,000000	1,000000		1,000000	1,000000
9	1,000000	1,000000	1,000000	1,000000	1,000000	1,000000	1,000000	1,000000		1,000000
10	1,000000	1,000000	1,000000	1,000000	1,000000	1,000000	1,000000	1,000000	1,000000	

Fig. 5. View of the table of post – hoc probability values for the comparison of pairs of distributions for periods of time τ_n between consecutive steam system failures and mean ranks value of R distributions for calculations performed in STATISTICA 8.0 program

Value 'z' for multiple comparisons; Independent (grouping) variable: marking of the steam system The Kruskal-Wallis test: $H(9, N= 55) = 17,05462$; $p = 0,0479$										
	1	2	3	4	5	6	7	8	9	10
	R:33,900	R:21,143	R:38,250	R:46,833	R:34,375	R:19,000	R:33,750	R:18,778	R:41,000	R:29,083
1		1,359916	0,404761	1,105418	0,044198	1,698013	0,013957	1,692283	0,606840	0,496508
2	1,359916		1,703631	2,323791	1,317735	0,271414	1,255494	0,292935	1,796146	0,890871
3	0,404761	1,703631		0,701476	0,342060	2,031010	0,397231	2,022602	0,224745	0,886405
4	1,105418	2,323791	0,701476		1,018162	2,639183	1,069240	2,626790	0,445941	1,566854
5	0,044198	1,317735	0,342060	1,018162		1,622170	0,055171	1,620101	0,541431	0,511698
6	1,698013	0,271414	2,031010	2,639183	1,622170		1,556228	0,030189	2,086060	1,218807
7	0,013957	1,255494	0,397231	1,069240	0,055171	1,556228		1,555182	0,592509	0,451261
8	1,692283	0,292935	2,022602	2,626790	1,620101	0,030189	1,555182		2,080626	1,220500
9	0,606840	1,796146	0,224745	0,445941	0,541431	2,086060	0,592509	2,080626		1,051926
10	0,496508	0,890871	0,886405	1,566854	0,511698	1,218807	0,451261	1,220500	1,051926	

Fig. 6. View of the table of normal values „z” for comparison of pairs of distributions of periods of time τ_n between consecutive failures of steam system and the value of mean ranks of R distributions for calculations performed in STATISTICA 8.0 program

Box plots of all distributions were presented in fig. 7. The obtained results of nonparametric tests do not explicitly verify the null hypothesis that distributions of periods of time τ_n between consecutive failures come from one general population at the assumed significance level $\alpha=0,05$.

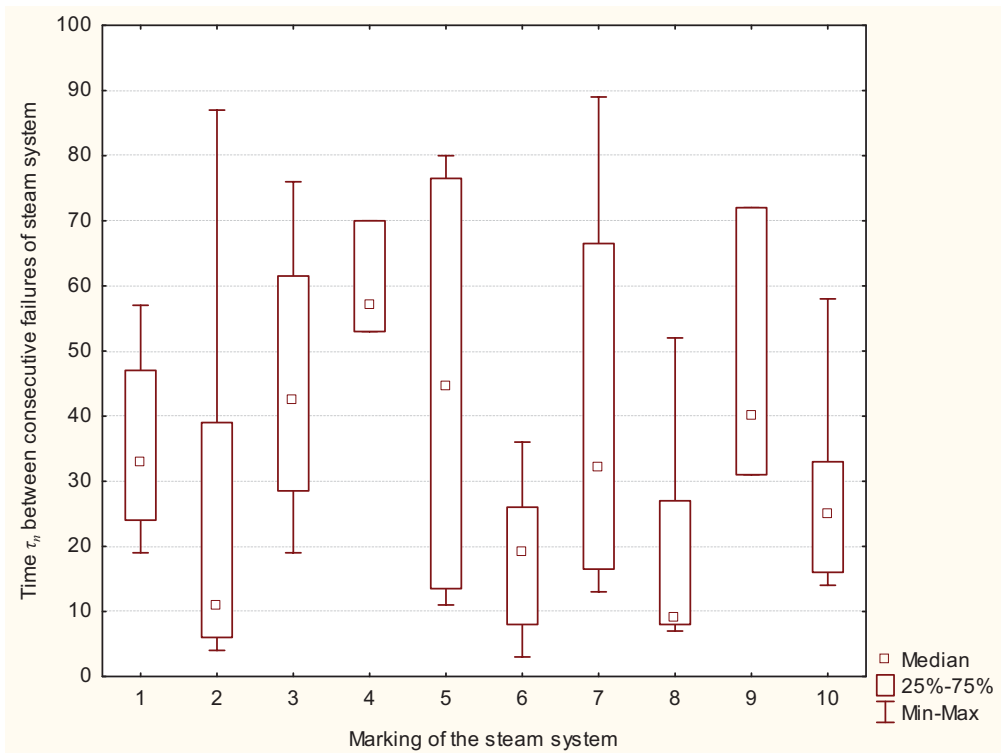


Fig. 7. Box plots of distributions of periods of time τ_n between consecutive steam system failures developed by means of STATISTICA 8.0

The performed multiple comparisons (fig. 5 and 6) do not show which distributions differ statistically from others. Because ANOVA rank Kruskal – Wallis test can be performed by means of STATISTICA 8.0 program relatively quickly, it was performed several times for distributions of periods of time τ_n between consecutive failures without data from one or two marine steam systems considered. The distributions were selected according to sample sizes, that is, the biggest and smallest sizes, e.g. S4, S3, S9, S6, S8, S4 and S3, S4 and S9, S6 and S8 were considered. Each time the test results did not provide bases for rejection of the null hypothesis that the distributions came from one general population. Thus, it is to be assumed that the null hypothesis stating that all 10 considered distributions of periods of time τ_n between consecutive steam system failures come from one population, is true and the outcome of ANOVA Kruskal – Wallis test ($p=0,0479$) is the result of too short period of steam system observation.

The disadvantage of nonparametric tests is their smaller potential in reference to parametric tests. The nonparametric test power can be enhanced due to the increase of sample sizes of the considered random variables.

4. Conclusion

Nowadays consecutive stages of statistical inference aided by statistical computing software packages got fairly shortened. Classic stages of statistical inference (with no statistical computing packages) used to run in the following way [13, 14]:

1. data input;
2. formulation of null hypothesis;
3. checkup of the selected test assumptions;
4. calculation of the test value on the basis of the sample results;
5. finding critical values in statistical tables at the fixed significance level;
6. making decision about rejection or acceptance of the null hypothesis at the fixed significance level;
7. interpretation of the obtained results;

The software package application allows for omitting computing stages 4 and 5, yet, it does not perform the job for a researcher at the other statistical interference stages [11, 12].

While verifying hypotheses by means of statistical packages, the notion of probability level p occurs. It is the lowest significance level, often referred to as p – value [13, 14], computed in the computer packages, at which the calculated value of test statistic leads to the rejection of null hypothesis. Following the formulation of the null hypothesis and acceptance of the significance level α , the test is performed and its outcome is the test spreadsheet with the computed probability level p . If $p < \alpha$, at a given significance level α , the null hypothesis is rejected, but when $p > \alpha$, on a given significance level, there is no basis for rejection of the null hypothesis. Actually, the value of α is not usually given, whereas p provides the information on hypothesis verification results [13].

Nonparametric tests are used in cases where the assumptions for parametric tests [13] are not met, e.g. in case of measurable random variables, normal distribution or equal variance of random variables etc. They are also applied in cases of quality data or when they can be ordered only according to specified criteria and in cases of small size groups.

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USAGE OF SEMI-MARKOV PROCESS IN OPERATION EVALUATION OF DIESEL ENGINE

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Abstract

In paper, the proposition of quantitative evaluation of operation using semi-Markov processes theories has been presented. Basic assumptions, essential for creating mathematical model on example of diesel engine were shown. Special attention was given to practical aspects of using established mathematical model. Example of characteristic of analyzed process – temporary distribution of probability was assigned.

Keywords: *semi – markov process, operation, diesel engine*

1. Introduction

Precise establishing of task realized by analyzed technical object requires except for assumption of conditions in which it will be performed, also refining its duration. This issue is especially important in such domains as eg. sea transport, where specificity of tasks usually is connected to necessity for long-term functioning of essential mechanisms and devices (eg. ship).

Ipsa facto, particularly important becomes not only what is worth of energy which can be disposed using specific energetic device (eg. diesel engine), but also time in which it can be provided.

Presented way of approach becomes possible to accomplish by examining engine's work (in following part of deliberation were restricted only to main ship propulsion engine) in that kind of evaluative view, to make it possible to be defined by energy and time simultaneously. Similar approach is also presented eg. in papers [5, 8, 9, 10].

Method of such appraisal of energetic device's work (in this case main ship propulsion engine) involves undoubted values of cognitive nature, but as in every case of real object of exploitation, a need of implementation of issues considered on theoretical field into practical use, appears as well.

During exploitation of ship, decisions about usage and servicing devices of marine power plant (especially power transmission system) are made permanently. Making any of that kind of decision, in particular moment, is to choose this one, from amongst possible to choose, which is considered to be the best. Choice of that decision, essential for defining rational operating strategy, including:

- proper planning of tasks

- providing required level of ship's safety
- planning preventive service adequate for needs
- right organization of service-remedial back-up facilities (eg. planning demand for replacements)

is possible to make after taking into consideration many different information, but in every case it should be based on possibly full information about exploitation object [7].

Especially precious in decision situation description is evaluative (quantitative) approach to this issue and searching for measures that would describe examined features of ship power plant's components at all and in this case, main propulsion engine, in most objective way.

Every new decision-making premise enhances probability of making apt decision [11, 12], so generally speaking, it influences safety level during realization of task.

One of many opportunities of gathering information about exploited engine is created by using semi-Markov's processes theories in mentioned before evaluative appraisal of working (in this case, main propulsion engine).

2. Description of engine's operation using semi-Markov's process theories.

Engine's operation (D) in time period [0, t] can be interpreted as physical quantity described as product of multiplication of energy variable in time $E=f(t)$ and time, which can be generally depicted by following equation [5]:

$$D = \int_0^t E(\tau) d\tau = 2\pi \int_0^t M_0 n t dt \quad (1)$$

where:

D – engine's operation

M_0 – torque

n – rotational speed

With elapsed time during engine's functioning, as an outcome of mostly disruptive influence of expenditure process, its general efficiency defined eg. as [3]:

$$\eta_e = \frac{1}{g_e \cdot w_d} \quad (2)$$

where:

g_e – specific fuel consumption

w_d – fuel's lower calorific value

decreases, which obviously causes changes referring to operation value of possible D_M (which can be realized by engine in specific technical condition and specific functioning conditions).

In case of ship engine of main propulsion, in view of compliance so-called sea margin and spare exploit power for engine [13] used on nominal load and partial loads during design time, process of decreasing available power (functioning of possible D_M as well) will proceed in two stages:

- in first stage only increase of hour fuel consumption (with relatively constant value of developed torque) will occur, enhancing usage costs,
- in second stage as effect of structural restrictions and lack of possibility of increasing of fuel dose, limitation in useful power developed by engine will appear.

Graphically, this occurrence can be illustrated in a way shown on Fig.1.

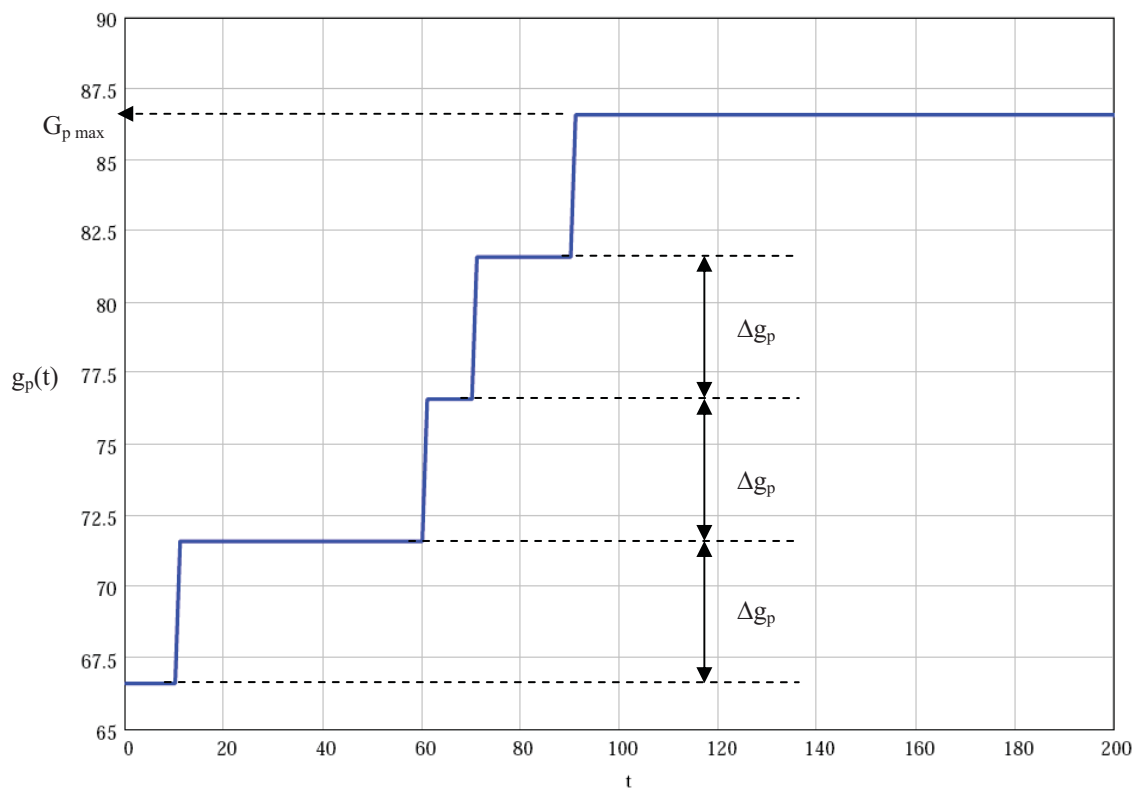
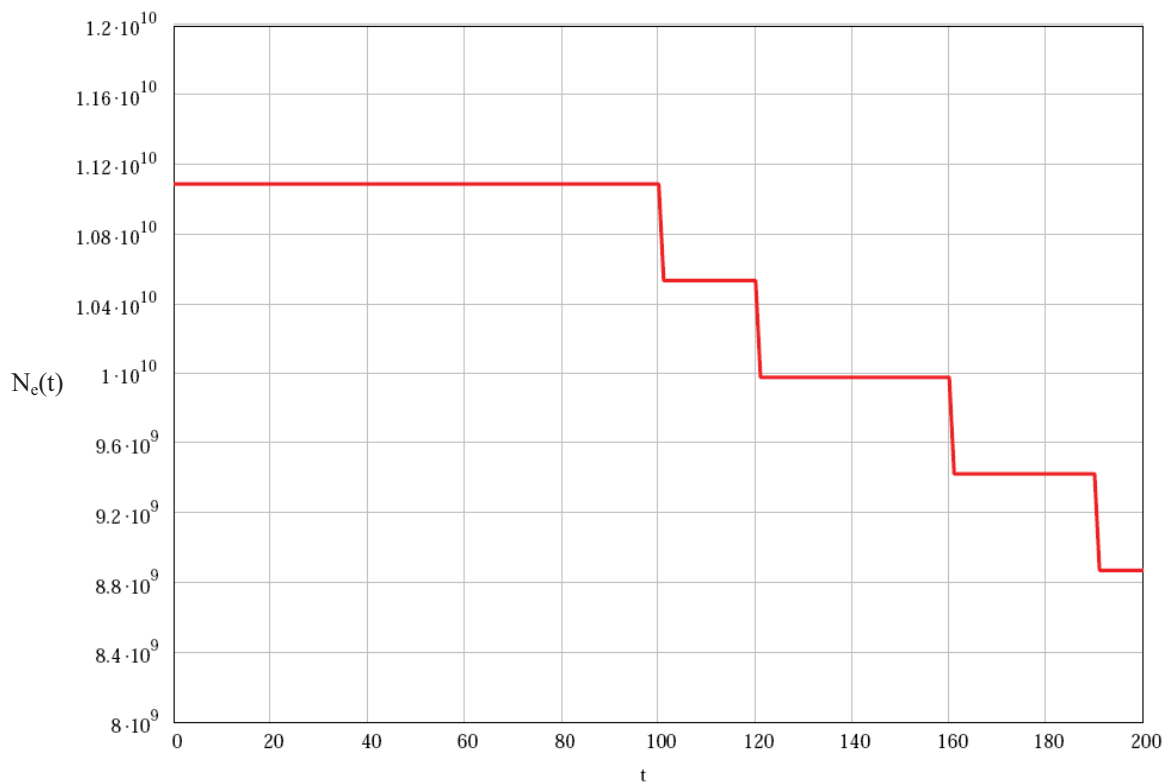


Fig.1 Stages of decreasing available power (functioning of possible D_M) process of diesel engine working on partial loads (description below)

Described occurrences are caused by control reaction of fuel injection apparatus, which be enhancing temporary fuel dose in particular interval of values – g_p ($g_p^{i\%}$ - dose of fuel for $i\%$ engine's load in technical efficiency state and full task ability, assuming that maximum engine's

load is 110% of nominal load, $i < 110$) until achieving it maximum value – G_{pmax} . Every following decreasing of engine's general efficiency value will cause noticeable decline of M_0 .

Due to phenomena presented before and regard as true following hypothesis “degradation process of engine's technical condition (understood as random function, which argument is time and values are random variable, meaning both technical and energetic states existing simultaneously), is a process which state considered in any moment t_n ($n = 0, 1, \dots, m; t_0 < t_1 < \dots < t_m$) depends on state directly premising it and doesn't depend stochastically on states that occurred before and their lasting periods” it becomes possible to formulate mathematical models useful for evaluative description of this engine's work, using semi-Markov's processes theories [4, 14].

Graph of states – transitions of analyzed $\{W(t) : t \in T\}$ process, covering phenomena presented in Fig.1 can be presented in this way:

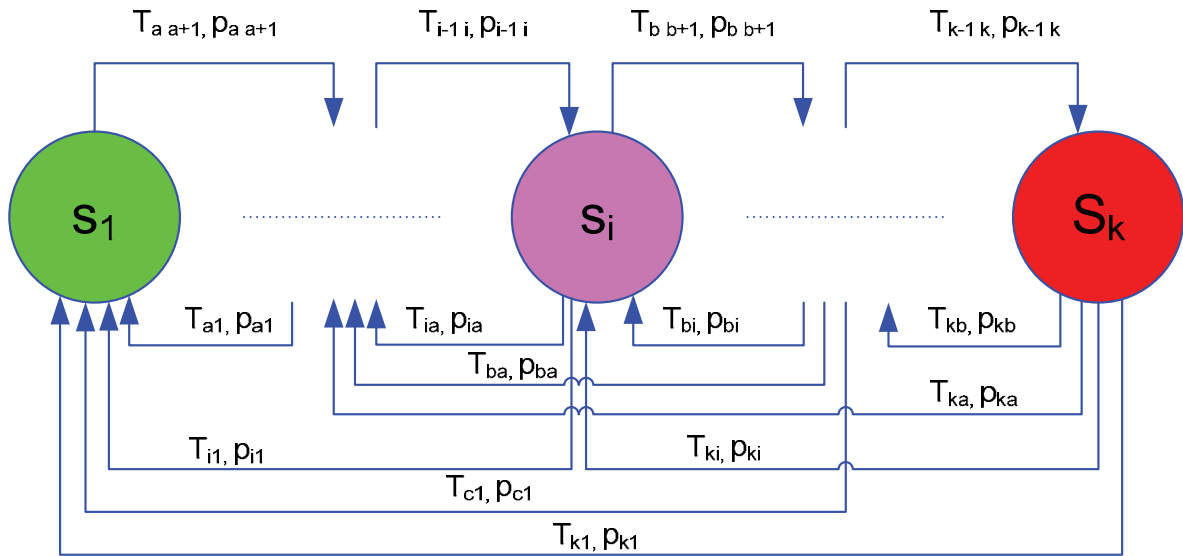


Fig.2 Graph of states – transitions of $\{W(t) : t \in T\}$. process, s_a – state of engine in which increase of unit fuel consumption emerges without noticeable increase of N_e value, $a=1, 2, \dots, i-1$, s_b – state of engine in which due to structural restrictions and lack of possibility to increase fuel dose, limitation in useful power developed by engine will appear, $b=1, i+1, \dots, k-1$, s_k – state of engine in which due to degradation of structure, it's not used any more (no engine functioning – no operation)

Ipsa facto, matrix of function $Q_{ij}(t)$ of analyzed process has (as it's shown on graph above) following shape:

$$Q_{ij}(t) = \begin{bmatrix} 0 & Q_{12}(t) & 0 & 0 & 0 & \dots & 0 & \dots & 0 \\ Q_{21}(t) & 0 & Q_{23}(t) & 0 & 0 & \dots & 0 & \dots & 0 \\ Q_{31}(t) & Q_{32}(t) & 0 & Q_{34}(t) & 0 & \dots & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & 0 \\ Q_{k-1,1}(t) & Q_{k-1,2}(t) & Q_{k-1,3}(t) & Q_{k-1,4}(t) & \dots & Q_{k-1,i}(t) & \dots & 0 & Q_{k-1,k}(t) \\ Q_{k,1}(t) & Q_{k,2}(t) & Q_{k,3}(t) & Q_{k,4}(t) & \dots & Q_{k,i}(t) & \dots & Q_{k,k-1}(t) & 0 \end{bmatrix} \quad (3)$$

Elements of that matrix depend on distribution of random variables that are time intervals of process being in convex conditions as follows [6]:

$$Q_{ij}(t) = P\{W(\tau_{n+1}) = s_j, \tau_{n+1} - \tau_n < t \mid W(\tau_n) = s_i\} = p_{ij} \cdot F_{ij}(t); s_i, s_j \in S; i, j = 1, 2, \dots, k; i \neq j \quad (4)$$

where:

p_{ij} – probability of converting from state s_i to state s_j

$F_{ij}(t)$ – cumulative distribution function of random variable T_{ij} , which is duration of state s_i providing converting process into state s_j ;

Initial distribution of process:

$$p_i = P\{W(0) = s_i\}, s_i \in S; i=1, 2, 3, 4, \dots, k \quad (5)$$

can be accepted depending on specific task situation, and eg. in case of analyzing engine in technical condition and full task ability:

$$\begin{aligned} p_1 &= P\{W(0) = s_1\} = 1, \\ p_i &= P\{W(0) = s_i\} = 0 \text{ dla } i = 2, 3, 4, \dots, k \end{aligned} \quad (6)$$

Example of $\{W(t) : t \in T\}$ process realization has been shown on Fig. 3.

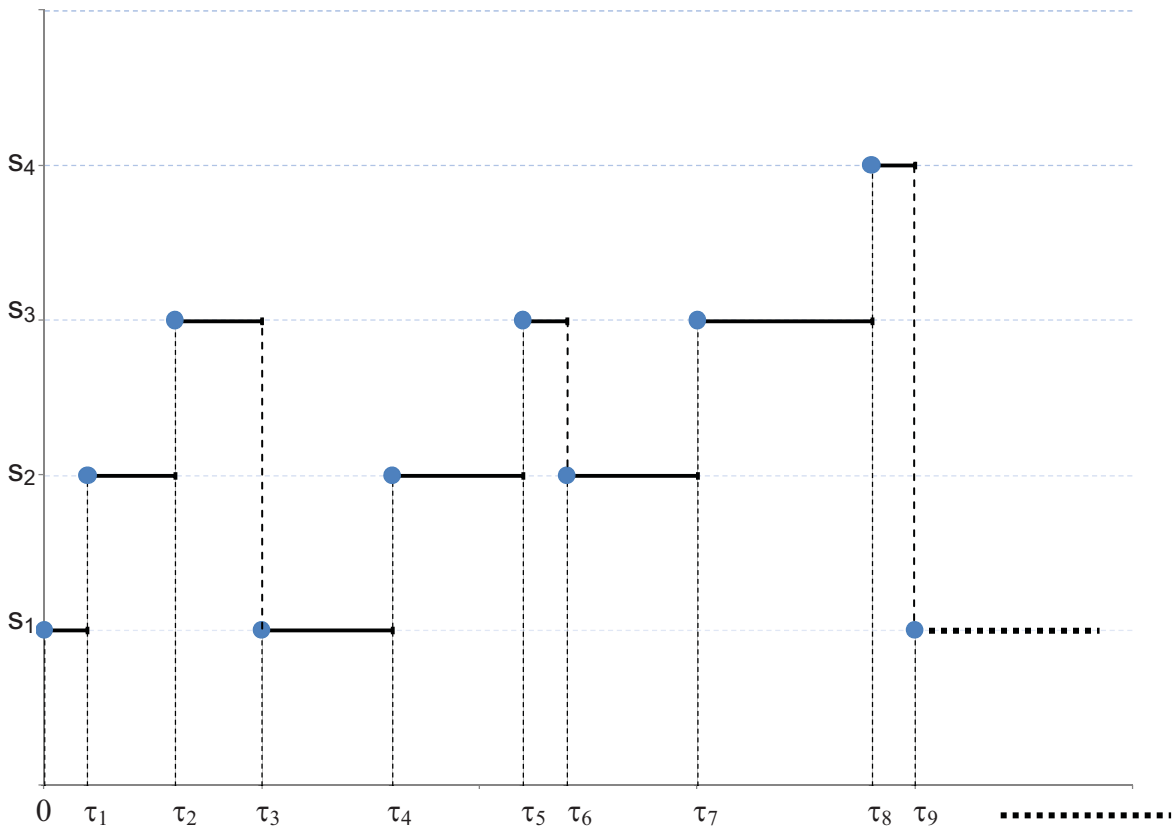


Fig.3 Example of $\{W(t) : t \in T\}$ process realization

Any definition of presented conditions determines entirely analyzed semi – Markov process, enabling assigning all of necessary characteristics of it (including time of first transition), application value of process defined this way is rather limited.

This limitation is effect of difficulty in model's verification, connected to assigning necessity of values of parameters of cumulative distribution function of random variable T_{ij} , describing duration of state s_i providing converting process into state s_j and estimations presented in formula due to probabilities p_{ij} . That activities require inter alia usage in exploit researches of advanced diagnosing systems, enabling identification of every possible state s_i , what in practice can be very difficult to implement or even impossible.

Due to that, to enhance utilitarian qualities of presented model, simplification enabling verification using standard control – measuring systems, which are equipment of majority ship power plants, seems necessary. That kind of verification will be possible as long as set of possible

process states will be restricted to nominated subsets of states classes, important from engine's working and possible to identify using mentioned systems point of view.

3. Reduction of $\{W(t) : t \in T\}$ process' states set

Analyzing engine's operation in quantitative approach, practically speaking, four subsets of states classes of process presented in previous point will have meaning, namely:

- states class s'_1 – engine is in condition of technical efficiency and full task ability, no usable parameters restrictions occur and efficiency indexes achieve values established by producer,
- states class s'_2 – engine is in condition of technical inefficiency and deficient task ability, no usable parameters restrictions occur for loads less than nominal loads and efficiency indexes (eg. specific fuel consumption) have values different from those established by producer,
- states class s'_3 - engine is in condition of technical inefficiency and deficient task ability, restrictions in it's usable parameters for loads close to nominal and bigger occur and efficiency indexed (eg. specific fuel consumption) have values widely different from those established by producer
- states class s'_4 – engine is in condition of technical inefficiency and deficient task ability, restrictions in it's usable parameters for wide spectrum of loads prevent from using engine according to specifications.

Due to that we can define new semi-Markov $\{W'(t) : t \in T\}$, process, which graph of states - transitions will look as follows:

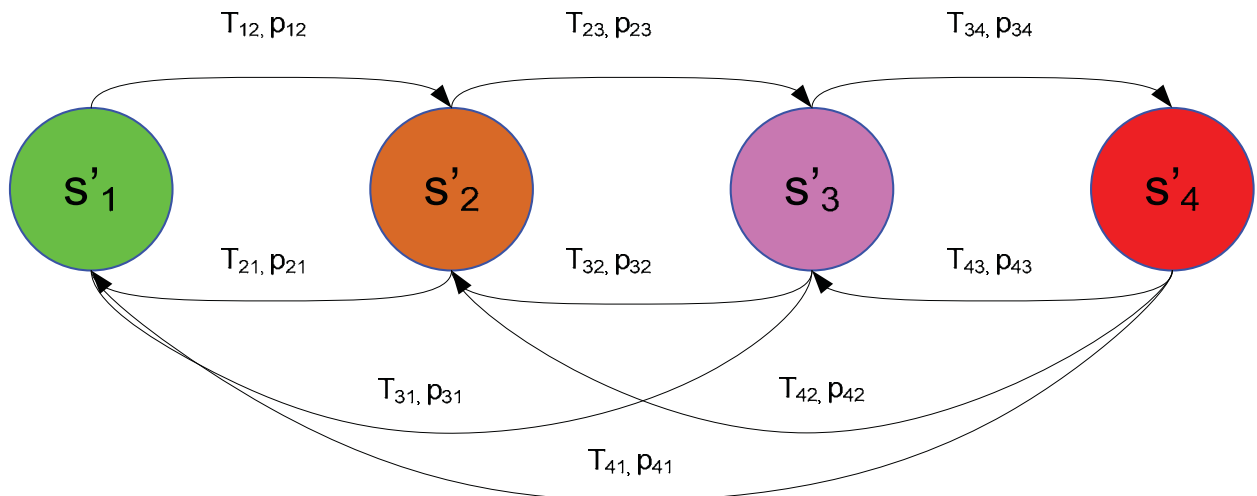


Fig. 4 States – transitions graph of $\{W'(t) : t \in T\}$ process

Matrix of function $Q'_{ij}(t)$ of analyzed process has (as it comes from graph) following form:

$$Q'_{ij}(t) = \begin{vmatrix} 0 & Q_{12}(t) & 0 & 0 \\ Q'_{21}(t) & 0 & Q'_{23}(t) & 0 \\ Q'_{31}(t) & Q'_{32}(t) & 0 & Q'_{34}(t) \\ Q'_{41}(t) & Q'_{42}(t) & Q'_{43}(t) & 0 \end{vmatrix}, \quad (7)$$

which can be presented basing on formula (4) as well as:

$$Q'_{ij}(t) = \begin{vmatrix} 0 & p_{12} \cdot F_{12}(t) & 0 & 0 \\ p_{21} \cdot F_{21}(t) & 0 & p_{23} \cdot F_{23}(t) & 0 \\ p_{31} \cdot F_{31}(t) & p_{32} \cdot F_{32}(t) & 0 & p_{34} \cdot F_{34}(t) \\ p_{41} \cdot F_{12}(t) & p_{42} \cdot F_{42}(t) & p_{43} \cdot F_{43}(t) & 0 \end{vmatrix}. \quad (8)$$

Using the formula (...) requires analysis of individual random variables T_{ij} assembled during exploit realization researches, estimation of parameters of cumulative distribution function and determining sequence and number of conversions n_{ij} of process from s'_i to s'_j state ($i, j = 1, 2, 3, 4$ $i \neq j$).

Realization of that conditions enables estimating individual probabilities p_{ij} values, using following statistics [4]:

$$P_{ij}^* = \frac{n_{ij}}{\sum_j n_{ij}} \quad (9)$$

where:

n_{ij} – number of conversions from s'_i to s'_j state ($i, j = 1, 2, 3, 4$ $i \neq j$).

Final defining of initial distribution of $\{W(t):t \in T\}$ process, eg. in case of analyzing engine in technical efficiency and full task ability as:

$$\begin{aligned} p_1 &= P\{W(0) = s_1\} = 1, \\ p_i &= P\{W(0) = s_i\} = 0 \text{ dla } i = 2, 3, 4 \end{aligned} \quad (10)$$

completely defines analyzed process, ipso facto enables assigning of its characteristics, including one of the most important from practical point of view – instantaneous distribution of $P_j(t)$ process, meaning probability of finding process in s_j state, in moment t .

4. Temporary distribution of $\{W'(t):t \in T\}$ process' probability

Assignment of probability distribution $P_j(t) = P\{W'(t) = s'_j\}, j \in S'$ first of all requires appointing of conditional probabilities $P_{ij}(t)$ with following interpretation [4, 6]:

$$p_{ij}(t) = P\{W'(t) = s'_j / W(0) = s'_i\}. \quad (11)$$

Basing on [6] unknown Laplace transforms of $P_{ij}(t)$ function can be achieved by solving system of equations :

$$\tilde{P}(s) = \frac{1}{s} \cdot (I - \tilde{g}(s)) + \tilde{q}(s) \cdot \tilde{P}(s) \quad (12)$$

where :

$$\tilde{P}(s) = \begin{bmatrix} \tilde{p}_{11}(s) & \tilde{p}_{12}(s) & \tilde{p}_{13}(s) & \tilde{p}_{14}(s) \\ \tilde{p}_{21}(s) & \tilde{p}_{22}(s) & \tilde{p}_{23}(s) & \tilde{p}_{24}(s) \\ \tilde{p}_{31}(s) & \tilde{p}_{32}(s) & \tilde{p}_{33}(s) & \tilde{p}_{34}(s) \\ \tilde{p}_{41}(s) & \tilde{p}_{42}(s) & \tilde{p}_{43}(s) & \tilde{p}_{44}(s) \end{bmatrix}, \quad I = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (13)$$

$$\tilde{q}(s) = L \left\{ \begin{bmatrix} 0 & p_{12} \cdot \frac{dF_{12}(t)}{dt} & 0 & 0 \\ p_{21} \cdot \frac{dF_{21}(t)}{dt} & 0 & p_{23} \cdot \frac{dF_{23}(t)}{dt} & 0 \\ p_{31} \cdot \frac{dF_{31}(t)}{dt} & p_{32} \cdot \frac{dF_{32}(t)}{dt} & 0 & p_{34} \cdot \frac{dF_{34}(t)}{dt} \\ p_{41} \cdot \frac{dF_{41}(t)}{dt} & p_{42} \cdot \frac{dF_{42}(t)}{dt} & p_{43} \cdot \frac{dF_{43}(t)}{dt} & 0 \end{bmatrix} \right\}, \quad (14)$$

$$\tilde{g}(s) = L \left\{ \begin{bmatrix} \frac{d(p_{12} \cdot F_{12}(t))}{dt} & 0 & 0 & 0 \\ 0 & \frac{d(p_{21} \cdot F_{21}(t) + p_{23} \cdot F_{23}(t))}{dt} & 0 & 0 \\ 0 & 0 & \frac{d(p_{31} \cdot F_{31}(t) + p_{32} \cdot F_{32}(t) + p_{34} \cdot F_{34}(t))}{dt} & 0 \\ 0 & 0 & 0 & \frac{d(p_{41} \cdot F_{41}(t) + p_{42} \cdot F_{42}(t) + p_{43} \cdot F_{43}(t))}{dt} \end{bmatrix} \right\} \quad (15)$$

with notation :

$$\tilde{q}_{ij}(s) = L \left\{ p_{ij} \cdot \frac{dF_{ij}(t)}{dt} \right\}, \quad i, j \in S', \quad i \neq j \quad (16)$$

$$\tilde{g}_i(s) = L \left\{ \frac{d \left(\sum_j p_{ij} \cdot F_{ij}(t) \right)}{dt} \right\}, \quad i, j \in S', \quad i \neq j \quad (17)$$

solution of system of equations (12) can be shown as [6]:

$$\tilde{P}(s) = \frac{1}{s} \cdot [I - \tilde{q}(s)]^{-1} \cdot [I - \tilde{g}(s)] \quad (18)$$

System of equations (18) is a system of linear equations in transforms field. By solving it and then replacing particular transforms and reversed Laplace transform – L^{-1} [2] analytical dependencies can be obtained, which show $P_{ij}(t)$ values as matrix:

$$P(t) = \begin{bmatrix} P_{11}(t) & P_{12}(t) & P_{13}(t) & P_{14}(t) \\ P_{21}(t) & P_{22}(t) & P_{23}(t) & P_{24}(t) \\ P_{31}(t) & P_{32}(t) & P_{33}(t) & P_{34}(t) \\ P_{41}(t) & P_{42}(t) & P_{43}(t) & P_{44}(t) \end{bmatrix} \quad (19)$$

That dependencies enable to make assignation of $P_{ij}(t)$ distribution, because basing on complete probability formula [1] and for estimated initial distribution for $\{W(t): t \geq 0\}$ this distribution can be shown in following way:

$$P_j(t) = P_{1j}(t) \quad (20)$$

$P_j(t)$ probabilities are indeed elements of first line of $P(t)=[P_{ij}(t)]$ matrix.

In this case, very important is analysis of probabilities, which for $t \rightarrow \infty$ can be interpreted as $P_{11}(t) = P_1(t)$, $P_{12}(t) = P_2(t)$, $P_{13}(t) = P_3(t)$ and $P_{14}(t) = P_4(t)$, and mean probabilities of finding

process in engine in following states: s'_1 , s'_2 , s'_3 and s'_4 , under condition that engine's initial state was s'_1 .

Practical advantage of obtained $P_j(t)$ values in presented aspect of analysis of engine's main power transmission work lies in assigning value of probability of occurring situation in which:

- there is no restrictions in engine's usable parameters for loads no bigger than nominal loads and efficiency indexes (eg. unit fuel consumption) have values different from those established by producer, increasing using costs,
- enhancement of $g_p^{i\%}$ fuel dose to G_{pmax} occurs, causing limitations in ship's ability to move.

5. Summary

Semi-Markov processes theory gives us many useful methods and tools helpful in technical objects' examination. Semi-Markov processes as models of real exploit processes eg. marine engines, seem to be useful in quantitative description of work as well, which results from fact that in case of analyzing processes with constant time parameter and finite set of states, intervals of that processes' presence in particular states are random variables with facultative distribution. Practical use of described models requires as well:

- gathering appropriate statistics during exploit researches,
- reasonable complication of model, differentiate as little necessary number of class states as possible and rather simple in mathematical sense its matrix of function – $Q(t)$.

Second condition is important in case of calculating instantaneous distribution of $p_k(t)$ process' states. That distribution can be, as is well known, calculated knowing initial distribution of process and $p_{ij}(t)$ function. Calculating the $p_{ij}(t)$ probability lies in solving Voltera's system of equations of second type, in which known quantities are $Q_{ij}(t)$ functions, elements of $Q(t)$ function's matrix of process. In case, where number of process' states is small and function's matrix of this process – uncomplicated, this system can be solved by using Laplace transformation. However, when number of process' states is big or its function's matrix (core of the process) is very complex, only numeric solution of this system of equations can be calculated. That solution doesn't give an answer for very important for exploit practice question: how do probabilities of semi-Markov process' states change, when t approaches to the infinity? From the theory of semi-Markov processes comes, that those probabilities, in case of ergotic semi-Markov processes, with the passage of time, aim to specific, constant numbers. Those numbers are called terminal probabilities of states and sequence of those numbers creates terminal distribution of process, which can be used during decision-making procedure, with use of probabilistic decision-making models. In those models, as is well known, in spite of defining a repertory of possible decisions to make, there is, amongst others, necessity of assigning values of conditional probabilities – $p(s_i)/d_j$, which describe probability of achieving s_i state by analyzed object, but only when d_j decision has been made. Estimations of these values can be terminal probabilities of states, which create terminal distribution of process.

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PREDICTION OF THE INFLUENCE OF EMERGENCE OF PROPELLER ON THE PROPELLER THRUST AND SPEED REDUCTION DURING SHIP NAVIGATION ON A GIVEN OCEAN ROUTE

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Abstract

During ship navigation on waves the relative motions i.a. occur which result in propeller emergence, and in consequence they cause the propeller thrust reduction. The article presents the algorithm for calculating the propeller thrust reduction as a result of the ship motions on waves having preset parameters: significant wave height H_s , period T_1 and geographical direction.

Key words: - ship motions on waves, vertical relative motion, propeller thrust and ship speed reduction

1. Introduction

Direct effect of the ship sailing on waves are the ship motions, occurring in continuous way, like the wave inducing them. Also other dangerous phenomena are associated with ship motions, such as e.g. accelerations or relative motions, which also occur in continuous way, as well as phenomena occurring sporadically, as for example: deck wetness, slamming or emergence of propeller. The latter phenomena result i.a. from the ship's relative motions and in this case frequency of their occurrence within one hour or per 100 waves is investigated. Emergence of propeller is a dangerous phenomenon for the whole propulsion system and it also causes the propeller thrust reduction which results in effect in the reduction of the ship's speed on waves (the reduction of the ship's speed on waves is caused also by other factors). When determining the value of the propeller thrust reduction that shall occur and the ship speed it is not enough to know the frequency of emergences of the propeller e.g. per hour but it is also necessary to know how big the emergences will be along a given navigation route. On the basis of knowledge of the size value of emergences it will be possible to determine values obtainable by the propeller thrust reduction, and then - by the reduction of the ship's speed on a given ocean route.

2. Relative movement of the ship and emergence of propeller

Using the commonly applied linear theory of ship motions [1], within the scope of which, on regular waves described by equation:

$$\zeta(t) = \zeta_A \cos(kx - \omega t), \quad (1)$$

the ship motions on these waves are given in the following form:

$$u(t) = u_A \cos(-\omega_E t + \varepsilon_u), \quad (2)$$

where:

- $\zeta(t)$ – ordinate of regular wave,
- ζ_A – amplitude of regular wave,
- ω – frequency of regular wave,
- t – time,
- k – wave number:

$$k = \frac{\omega^2}{g}, \quad (3)$$

- g – acceleration of gravity,
- x – coordinate on direction of wave propagation,
- $u(t)$ – ship motion „u”,
- u_A – amplitude of ship motion „u”,
- ε_u – angle of phase displacement of ship motion „u”,
- ω_E – frequency of encounter of ship motions,

$$\omega_E = \omega - kV \cos \beta_w, \quad (4)$$

- V – ship speed,
- β_w – angle of wave effect acting on the ship, $\beta_w = 0^\circ$ – following waves (from the aft), $\beta_w = 90^\circ$, beam wave, $\beta_w = 180^\circ$ head wave:

$$\beta_w = \mu - \psi + 180^\circ, \quad (5)$$

- μ – direction of waves in geographical direction ($\mu = 0^\circ$ – northern wave, $\beta_w = 90^\circ$ – eastern wave),
- ψ – ship course in geographic co-ordinates ($\psi = 0^\circ$ – northern course, $\psi = 90^\circ$ – eastern course),

The random motions of the ship on the irregular waves can be simply determined on the basis of knowledge about amplitude characteristics of the ship motions on linear regular waves and about function of random ship motions energy spectral density. Then variance of ship motions is equal to:

$$D_{uu}(\beta_w, V) = \int_0^{\infty} [Y_{u\zeta}(\omega_E / \beta_w, V)]^2 S_{\zeta\zeta}(\omega_E) d\omega_E, \quad (6)$$

where:

- D_{uu} – variance of ship motions u , $u = 1, 2, \dots, 6$,
- $Y_{u\zeta}$ – amplitude transfer functions of ship motions u on regular waves,
- $S_{\zeta\zeta}(\omega_E)$ – function of the random wave energy spectral density, the value of which depends mainly on the significant wave height H_s and on period T_1 ,

During ship motions on waves, its movement (displacement) can be determined, related to wavy water surface. The occurring relative movement (relative displacement) has a decisive influence on the emergence of propeller (Fig. 1).

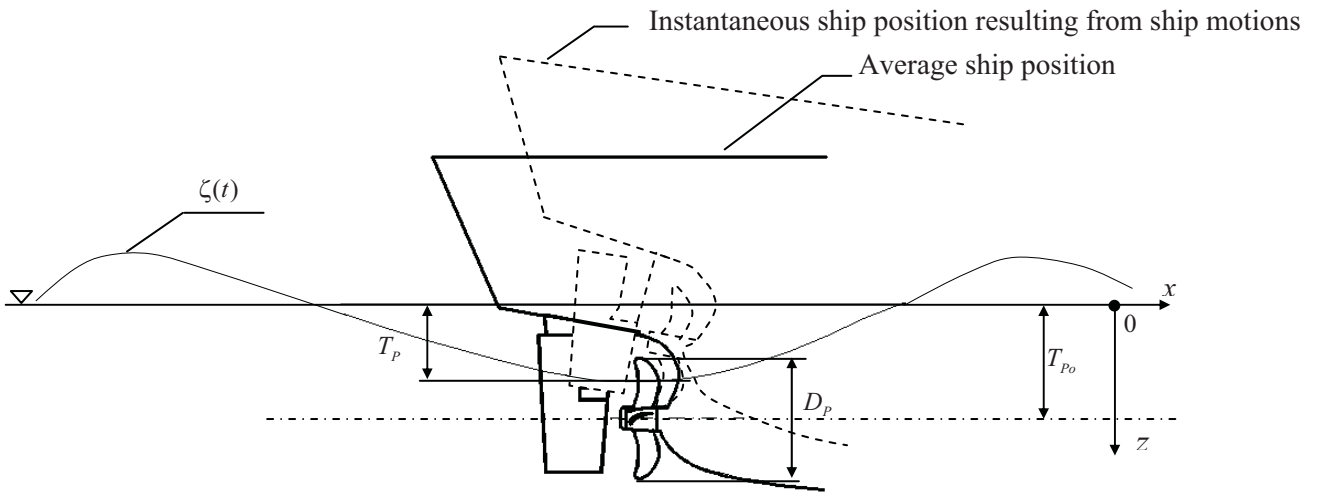


Fig. 1. Influence of relative movement of the ship on emergence of propeller

The vertical, relative displacement of the ship resulting from the ship motions is equal to:

$$R_{ZP} = Z_G + y_p \Phi - x_p \Theta - \zeta(t), \quad (7)$$

where: $\zeta(t)$ is the wave profile described by equation (1),

x_1, y_1 – coordinates of point coordinates of point, for which relative movement is calculated, in this case the point lying on the propeller blade in its upper position is meant, hence $y_p = 0$

However, the value of relative motion of the ship on irregular waves is calculated from the variance described by equation:

$$D_{RZ}(\beta_w, V) = \int_0^{\infty} [Y_{RZ}(\omega_E / \beta_w, V)]^2 \cdot S_{\zeta\zeta}(\omega_E) d\omega_E \quad (8)$$

$$H_{AZ1/3} = 4\sqrt{D_{RZ}} \quad (9)$$

where $H_{AZ1/3}$ is the significant height of the relative motion of the ship on irregular waves.

3. Thrust of propeller during the ship motions on waves

The separated propeller thrust can be calculated from the formula:

$$T = K_T \rho_w D_p^4 n_p^2, \quad (10)$$

where:

D_p –propeller diameter,

n_p –propeller r.p.m.,

K_T –thrust coefficient, that for the propeller of the following parameters given: $\left(\frac{P}{D}\right)$ –

propeller pitch ratio,

$\left(\frac{A_E}{A_0}\right)$ – expanded blade area ratio,

Z – number of blades, is approximated by the expression:

$$K_T = A_0 + A_1 \cdot J + A_2 J^2 + A_3 \cdot J^3, \quad (11)$$

where:

A_0, A_1, A_2, A_3 – coefficients of polynomial describing thrust characteristics, dependent

on $\left(\frac{P}{D}\right), \left(\frac{A_E}{A_0}\right), Z, [5],$

J – advance coefficient:

$$J = \frac{V[1 - w_T(V)]}{D_p \cdot n_p}, \quad (12)$$

$w_T(V)$ –wake coefficient, dependent on ship speed V .

The presented expressions for propeller thrust (10) and (11) are correct for the ship that is sailing on calm water or on wavy water but the occurring motions and relative motions are so small that the emergence of propeller does not occur. During ship navigation on waves at high ship motions and the relative motions the propeller works in rather air-locked water or it emerges from water. This causes thrust fluctuation and reduction of the mean effective thrust in relation to the thrust on calm water (even if the ship is sailing with constant speed and the propeller r.p.m is constant).

The thrust reduction is caused, among others, by influence of water particles velocities in the wave motion on the wake (coefficient w_T), and by propeller emergence as a result of the ship big relative motions on waves. The thrust reduction during ship navigation on waves is presented in various publications in which approximated formulae are included for assessing influence of water relative movements on the propeller parameters.

In the elaboration [3] the formulae are presented for correcting the speed of water reaching the propeller in situation when it is not fully immersed.

The corrected advance coefficient J_w shall be as follows:

$$J_w = J \cdot G, \quad (13)$$

where:

J – advance coefficient according to [3],

G – correction factor, dependent on the propeller parameters and its load, which according to [3] has the following form:

$$G = 1 + 3 \cdot U \left(\frac{T}{\rho_w D_p^2 (1 - w_T)^2 V^2} \right), \quad (14)$$

$$U = \frac{D_p + h_{p0} - T_{Aw} - w_n}{D_p}, \quad (15)$$

$$w_n = 0,6 \cdot c_B \cdot B \cdot c_{21}, \quad (16)$$

$$c_{21} = F_n^2 \quad \text{gdy} \quad F_n < 0,3, \quad (17)$$

$$c_{21} = 0,09 \quad \text{gdy} \quad F_n \geq 0,3,$$

where:

T – thrust of fully immersed propeller,

T_{Aw} – stern immersion on waves, resulting from relative movements (Fig. 2),

h_{p0} – vertical distance from PP to blade tip of the propeller in its lower position (Fig. 2),

c_B – block coefficient of ship's hull,

F_n – Froude number, $F_n = \frac{V}{\sqrt{gL_w}}$,

Emergence of propeller causes not only reduction of thrust but also of the moment which might result is increase of engine speed if it were not for engine speed regulator.

In another publication [4] the thrust reduction coefficient was introduced in the following form:

$$\beta_T = \frac{K_{Tw} \left(\frac{h_p}{R} \right)}{K_T}, \quad (18)$$

where:

$K_{Tw} \left(\frac{h_p}{R} \right)$ – thrust coefficient for the emerging propeller (the quantities h_p and R) are shown in Fig. 2),

K_T – thrust coefficient for fully immersed propeller,

Changes of the β_T coefficient value depending on $\left(\frac{h_p}{R} \right)$ are shown in Fig. 3[3].

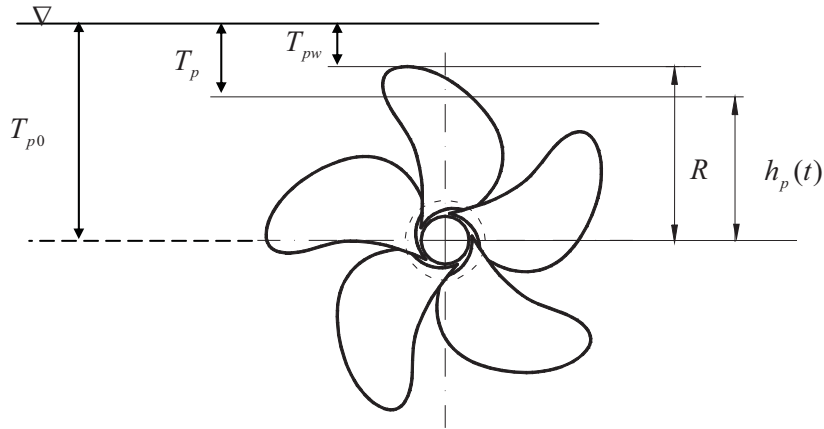


Fig. 2. Propeller immersion draught h_p [3]

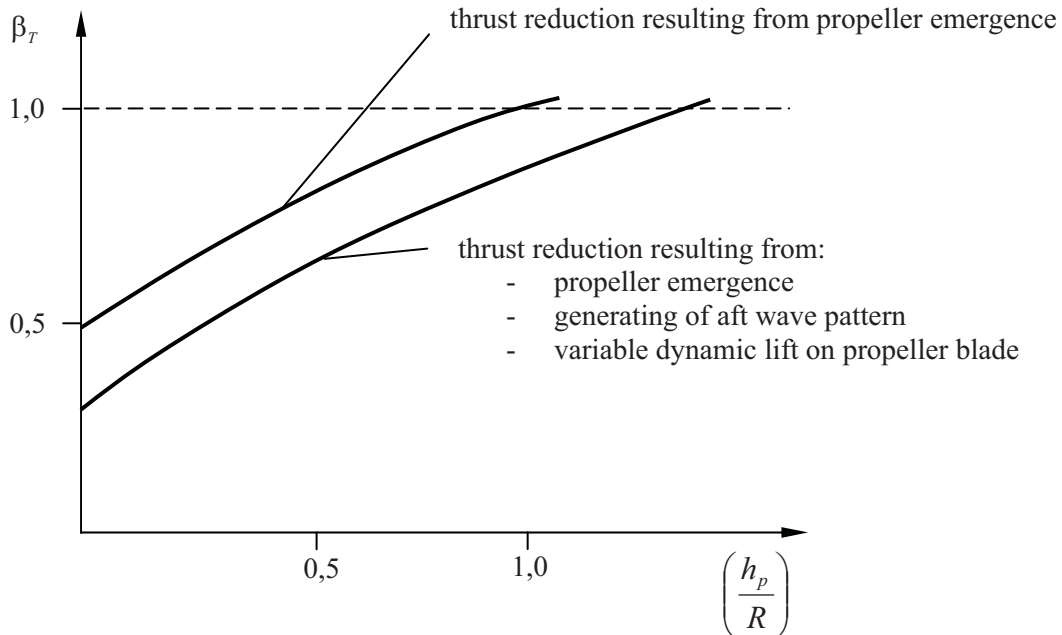


Fig. 3. Thrust reduction [coefficient] during emergence of propeller [4]

Thrust coefficient $K_{T_w} \left(\frac{h_p}{R} \right)$ occurring in equation (18) can be calculated making the expanded blade area ratio $\left(\frac{A_E}{A_0} \right)$ dependent on relative propeller immersion depth $\left(\frac{h_p}{R} \right)$ and taking into account the corrected advance coefficient J_w , equation (13). The instantaneous propeller immersion depth [draught] $h_p(t)$, or $T_{Aw}(t)$ occurring in equation (15) shall be calculated on the basis of the ship motions on waves and emergences of propeller, resulting from them.

The emergence of propeller shall occur when the relative movement (significant amplitude $R_{AZ1/3}$ of the relative movement from equation (9) shall exceed the immersion depth T_{Pw} (Fig. 2) of the blade tip of the propeller in its upper position :

$$H_{AZ1/3} > T_{Pw} \quad (19)$$

hence the size of emergence ΔT_p shall be:

$$\Delta T_p = H_{AZ1/3} - T_{Pw} \quad (20)$$

and the propeller immersion draught $h_p(t)$ in equation (18) shall be:

$$h_p(t) = \frac{1}{2}D_p - \Delta T_p \quad (21)$$

Calculating, for different wave parameters: H_s , \bar{T}_1 and μ occurring on the ocean route and the ship courses ψ and speeds V it shall be possible to calculate the value of the emergence of propeller ΔT_p or propeller immersion draught $h_p(t)$ as well as probability of occurrence of these values. Then the thrust reduction coefficient β_T can be calculated, equation (24) and the ship speed reduction on a given ocean route.

5. Ship and weather parameters on an ocean route

The calculations have been performed for the ship M1 (bulk cargo ship, table 1) and for the ocean route no. 2 from the Western Europe to USA (Fig. 4) which runs through water areas for which the average statistical parameters of waves are included in atlas [2].

Tab.1. Parameters of bulk cargo ship

Length between perpendiculars	L [m]	138,0
Breadth	B [m]	23,0
Draught	T [m]	8,55
Displacement for T	∇ [m ³]	21441
Contractual speed	V_K [m/s]	7,15
Propeller diameter	D_p [m]	5,0
Propeller pitch	P [m]	4,2
Nominal power of the propulsion motor	N_n [kW]	4710
Nominal r.p.m. of the propulsion motor	n_n [1/s]	1,85
Ship resistance on calm water for T and V_K	R [kN]	405,9
The sea margin assumed in the ship propulsion	K_z [%]	15

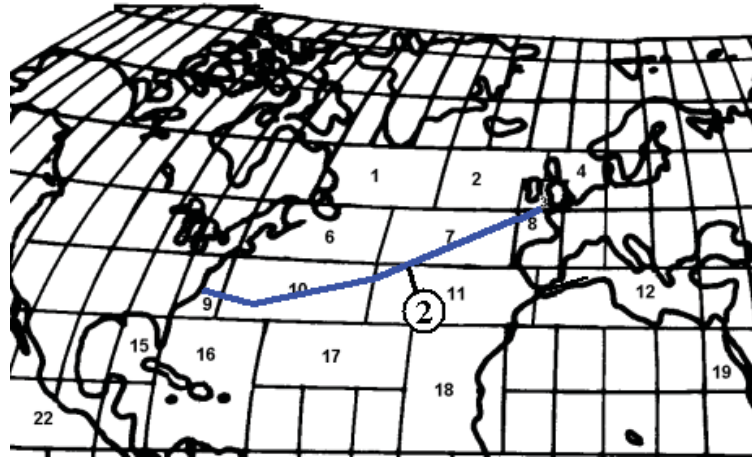


Fig. 4. Ship Navigation Route

The atlas [2] includes, for particular water areas (Fig. 4) mean statistical values of the significant wave height H_s , the period T_1 and the geographical direction μ as well as probability of occurrence of these values (exemplary values are presented in table 2).

Tab. 2. Probability of occurrence of wave height H_s and period T_1 for a given direction μ at a given water area, [2]

Water area: 1											
Season of the year: December – February (winter)											
Direction of waves: $\mu = 000$ deg											
$T_1[s]$ \ $H_s[m]$	calm	<5	6-7	8-9	10-11	12-13	14-15	16-17	18-19	20-21	>21
0.25		0.023									
0.5		0.011	0.011	0.011							
1.0		0.091	0.023	0.011	0.011						
1.5		0.023	0.045	0.057		0.023					
2.0			0.057		0.034						
2.5		0.011	0.057	0.045	0.034						
3.0			0.011	0.034	0.023	0.011					
3.5			0.011	0.045	0.057						
4.0				0.011	0.011	0.045	0.011	0.011			
4.5				0.045	0.023		0.011	0.011			
5.0					0.011						
6.0				0.011							
6.5				0.011	0.023						
7.5					0.011						

6. Instantaneous ship service speed on waves

The instantaneous ship service speed on a given wave having parameters H_s , T_1 and μ shall be obtained by the ship when the total ship resistance will be balanced by the propeller thrust, taking into account its potential drop caused by the emergence, and the moment on the propeller will be equal to the propulsion engine moment. The aforementioned conditions are written in form of the set of 2 nonlinear equations:

$$\begin{aligned}
T \cdot \beta_T - \frac{R_C}{1-t} &= 0, \\
Q - \frac{N \cdot \eta_S \cdot \eta_R \cdot \eta_G}{2\pi n} &= 0.
\end{aligned}
\tag{22}$$

where:

- T – The separated propeller thrust given in equations (16), (17) and (18) in [3],
- β_T – the ship thrust drop coefficient as a result of the propeller emergence during ship navigation on waves,
- R_C – the total ship resistance is dependent on the ship speed V , ship course ψ , waves parameters H_S, T_1, μ and wind parameters V_A, γ_A ,
- t – thrust deduction factor,
- Q – torque on the separated propeller,
- N – power of the propulsion engine (resulting from the motor/engine operation area),
- η_S – shaftline efficiency,
- η_G – efficiency of gear (if it is applied on board. when it is missing then $\eta_G = 1$),
- η_R – rotational “efficiency”,
- n – nominal r.p.m. of the propulsion motor.

Method of calculating the total ship resistance on waves R_C and the moment on the propeller Q as well as the driving engine capacity N from the engine N operation area are presented in [3] and [4].

The solution of the non-linear equations (22) for each set of data concerning:

- ship movement. V, ψ ,
- waves: H_S, T_1, μ ,
- wind: V_A, γ_A ,

gives the instantaneous ship speed V_i .

7. Mean long-term ship service speed on a given ocean route

During the ship voyage on a given ocean route where parameters of wave and wind shall be changing as well as the ship course and preset ship speed, the ship resistance on waves shall be changing, its motions and relative movements and thus propeller emergence and possible thrust drop.

Hence the ship thrust drop and the ship service speed on a given ocean route shall depend on:

- route of navigation and probability of ship’s sailing (staying) at particular water areas.
- statistical parameters of waves (H_S, T_1, μ) wind (V_A, γ_A) and probability of occurrence of these parameters at given water areas.
- the probability of occurrence of the ship movement parameters. i.e. speed V and course ψ (the speed V should first be assumed. so as it could be later calculated and so as its assumed value could be corrected).

Probability of the ship staying in a given situation during navigation on wavy water along the preset navigation route is as follows:

$$P_w = f_A \cdot f_S \cdot f_\mu \cdot f_{HT} \cdot f_V \cdot f_\psi, \quad (23)$$

where:

- f_A – frequency (probability) of the ship sailing at a given water area A ,
- f_S – frequency (probability) of the ship sailing in a given season of the year S at a given water area A ,
- f_μ – frequency (probability) of occurrence of wave direction μ in a given season of the year S at a given water area A ,
- f_{HT} – frequency (probability) of occurrence of waves having parameters H_S and T_1 from direction μ .
- f_V, f_ψ – frequency (probability) of the ship sailing at speed V and at course ψ .

Values of additional resistance due to wind and values of the propeller thrust drop due to the ship motions on waves depend on random parameters of waves and wind. Hence the same (identical) values of additional resistance and values of the propeller thrust drop can occur for different values of parameters $V_A, \gamma_A, H_S, T_1, \mu, V, \psi$. For each value of additional resistance and the propeller thrust drop thus calculated the ship speed is calculated.

Total probability P_{TV} of the ship reaching the speed V at occurrence of additional resistance ΔR and the propeller thrust drop ΔT having specified value is equal to:

$$P_{TV} = \sum_{A=1}^{n_A} \sum_{S=1}^{n_S} \sum_{\mu=1}^{n_\mu} \sum_{H,T=1}^{n_{HT}} \sum_{V=1}^{n_V} \sum_{\psi=1}^{n_\psi} P_{Vi} [V_i(\Delta R_i, \Delta T_i)], \quad (24)$$

where:

- $V_i(\Delta R_i, \Delta T_i)$ – instantaneous ship service speed versus instantaneous additional resistance and instantaneous thrust drop of propeller,
- $n_A, n_S, n_\mu, n_{HT}, n_V, n_\psi$ – are numbers of water areas through which the ship is sailing. seasons of the year waves directions (angles) waves parameters ship speeds and courses.

Calculating the distribution function $f(V_i)$ of probability of occurrence of instantaneous ship speed $f(V_i)$ it is possible to calculate the long-term ship service speed for the preset navigation route:

$$\bar{V} = \frac{\sum_{i=1}^{n_V} P_{TV_i} \cdot V_i(\Delta R_i = \text{const}, \Delta T_i = \cos nt)}{\sum_{i=1}^{n_V} P_{TV_i}}, \quad (25)$$

where n_V is number of ranges including instantaneous ship service speeds of approximate values.

8. Results of calculations of the propeller thrust drop and the ship speed drop on a given ocean route

The calculations of propeller thrust drop as a result of the propeller emergence and of the reached ship service speed have been performed for the container ship (table 1) and for the ocean route from the Western Europe to USA (Fig. 4). The obtained results have been compared with identical calculations but with the assumption that the propeller does not emerge and there is no thrust drop.

In Fig. 5 the bar chart and probability distribution function of propeller immersion draught are presented (100% means total immersion/draught of propeller). In Fig 6 the propeller bar chart without taking the propeller emergence into account and taking the propeller emergence on a given ocean route into account. After taking into account the emergence of propeller due to the ship motions, on the same ocean route the mean statistical value of the propeller thrust has been reduced by c.a. 2,5 %. In Fig. 7 the propeller bar chart of probability of reaching ship service speed with and without taking the propeller thrust drop into account . In this case the drop of the mean long-term ship service speed was equal to 0,64 m/s.

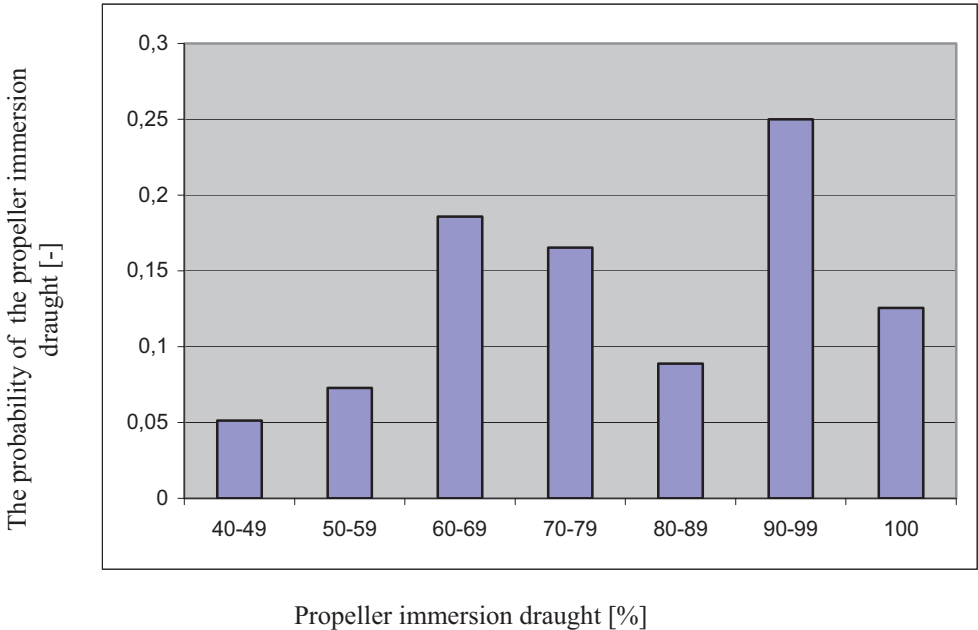


Fig. 5. The bar chart and probability distribution function of ship propeller immersion draught on the Western Europe – USA ocean route

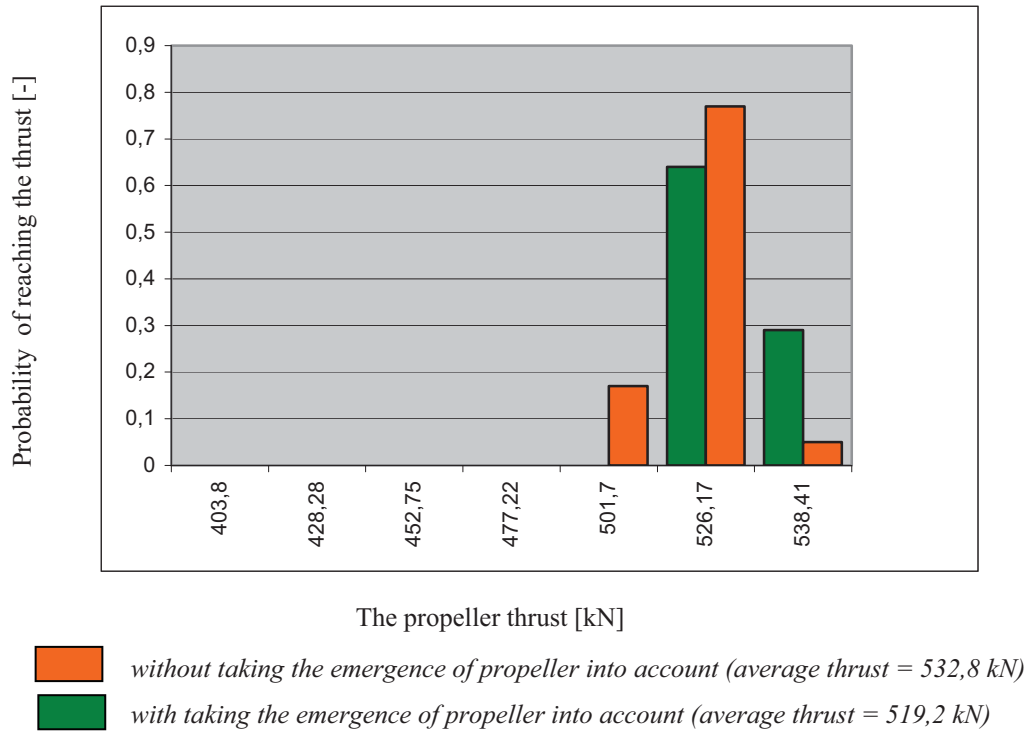


Fig. 6. The bar chart of the ship propeller thrust on the Western Europe - USA ocean route

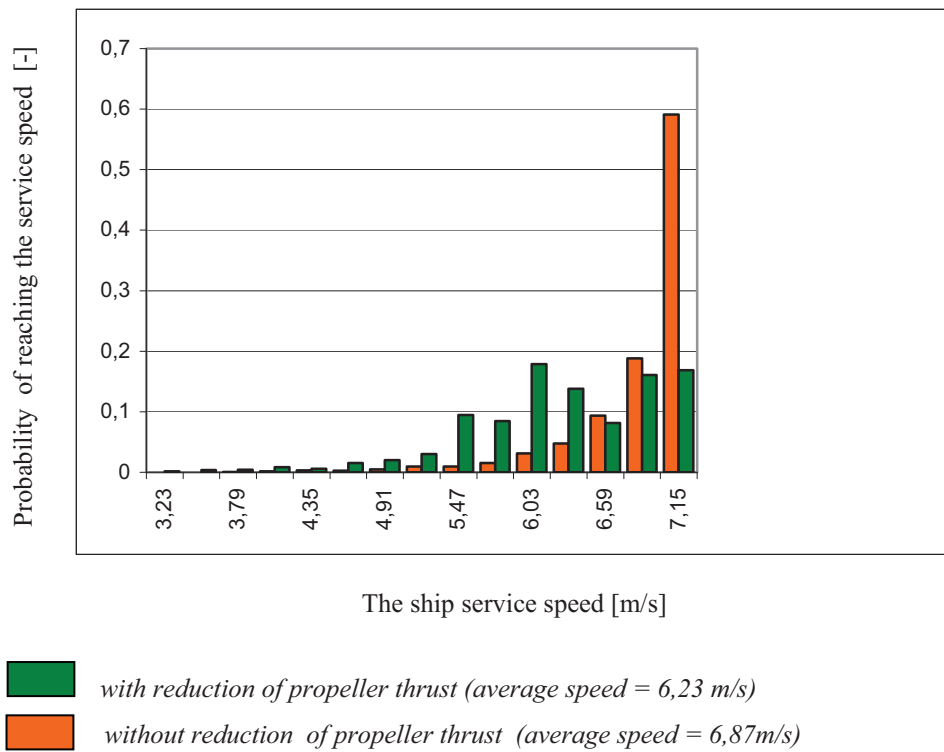


Fig. 7. The bar chart of the ship speed on the Western Europe - USA ocean route

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METHODOLOGY OF DIAGNOSTIC IDENTIFICATION FOR THE TRAIN

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Abstract

This article shows the results obtained during the implementation of a portable diagnosis system to the maintenance routines of the passenger vehicles and permanent track of the Metro de Medellín Company, which made possible the evaluation of aspects as: safety, comfort and technical condition of the track-vehicle interphase. The reports given in this evaluation allowed the identification and the arrangement of the track sections according to its technical condition, relating thus the track condition parameters and the vehicle to the estimators associated to the passenger vehicles dynamics.

Keywords: diagnostic system, technical condition, safety, comfort, dynamic state.

1. Introduction

The portable diagnosis system - SPD is an unique development for the railway systems, which besides evaluating safety, comfort and monitoring the condition of the geometric parameters of the track - vehicle interface, also allows to carry out the multidimensional monitoring of the condition and to determine the generalized failures of the passenger vehicles of the Metro de Medellín. The previous is possible due to the algorithm named Condition Inference Agent – CIA

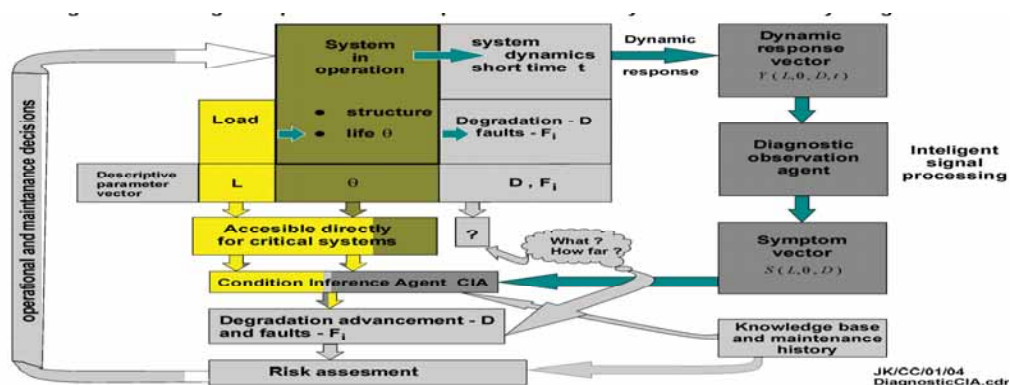


Fig. 1. Flow of information and processing in a system of operation and a subsystem of condition of intelligent monitoring [5]

which was incorporated in the design of the SPD (Fig.1). This algorithm was designed in European diagnosis institutes for the technical critical systems of operation, in order to increase the maintenance indicators of reliability and availability. To develop this diagnosis tool, there were used different methodologies that group several modern and effective methods in the diagnosis tasks, which go from the selection of measurement points, through the method of evaluation of the UIC 518 norm until the utilization of an optimized forecast method. The aim of this article is to show the different methodologies previously pointed out [1,2,3,4].

2. Design of the portable diagnosis system _ SPD

The current operation scheme of the SPD doesn't depart from the initial design approach; the system is composed by eight modules: sensors, signal processing, monitoring of the condition, condition test, incipient failures detection in the wheel-rail interface, decisions support, forecast and presentation. The modules were developed using different methodologies related to the evaluation of current and future technical condition of the devices; these modules required the elaboration of the following diagnosis tasks:

- selection of the SPD measurement points;
- evaluation of the safety and comfort aspects according to the UIC 518 code;
- principal components of the SPD Observation Vector;
- multidimensional monitoring of the condition;
- forecast method to determine the next value parameter of diagnosis in the exploitation.

The selection of measurement points is used during the design of the SPD, due to the quantity of sensors installed in the passenger vehicles during the implementation of the UIC 518 norm and the required time for the configuration of the sensors, record and data analysis. The following mathematical functions were used to obtain the minimum of data acquisition channels that the diagnosis portable system uses to evaluate the safety and comfort of the passenger vehicle:

- coherence between the diagnosis signals:

$$\gamma_{xy}^2(f) = \frac{|G_{xy}(f)|^2}{G_{xx}(f)G_{yy}(f)} \leq 1$$

- coherence function area:

$$A\gamma_{xy}^2 = \int_0^F \gamma_{xy}^2(f) dF$$

- affinity or similarity of the information of the diagnosis points:

$$In_{xy}(\Theta_i) = \sum_{x=1}^l \lg \frac{1}{1 - \gamma_{xy}^2(f_x, \Delta f_x, \Theta_i)}$$

These previous expressions ruled out channels in the vehicle box and in the bogies axle end, under the criteria of maximum coherence $\gamma^2(f)$ in the power spectrum $G_{xx}(f)$ of the obtained signal, which belong to the typical frequencies of the track – vehicle interface, the maximum area under the coherence function curve and the maximum similarity of information in the slow time Θ (see Fig. 2). The number of transducers of the diagnosis portable system in the test vehicle diminished in a large quantity due to this study. The SPD has four low frequency accelerometers and two force sensors to evaluate the safety, the comfort and the technical state of the trains.

With the purpose to evaluate safety and comfort in the passenger vehicles according to the UIC 518 norm, algorithms were developed to carry out the international standard procedures, which include the following:

- conditions of implementation: test speed, cant insufficiency, test zones and test vehicle conditions;
- signals record: right and left lateral force of axle-wheel set, vertical acceleration in the gearbox, lateral acceleration in the chassis of the bogie, lateral and vertical acceleration in the passengers' box ;
- dynamic quantities of evaluation: resultant lateral force, lateral acceleration in chassis of the bogie, safety, quasi-static lateral force, lateral and vertical acceleration in passenger's box for the comfort, r.m.s. lateral and vertical acceleration in passengers box for the comfort, quasi-static lateral acceleration, instability criterion;

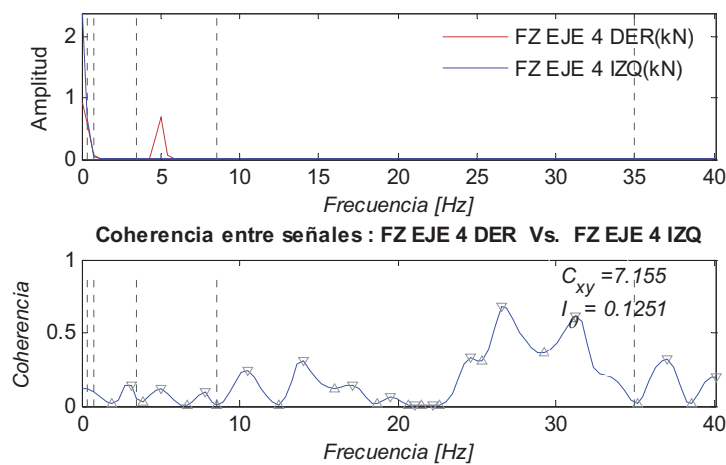


Figure 2: Analysis of affinity of diagnosis information

- selection of the tests track: tangent track zone, with small and large radius curve;
- statistical processing: per section and per test zone.

The principal components of the observation matrix Q (SQM - Symptom Observation Matrix) are calculated from the data obtained in the implementation of the UIC 518 norm. The following matrixes were developed in order to reproduce the evolution of the technical state of a curved or tangent section and its influence in the wheel - rail interaction, the relation between the dynamic quantities evaluated in the tangent and curved sections with the geometric parameters that are monitored in the maintenance routines of the Metro and the function that describes the life average of the passenger vehicles. The following are the arrangements for the previous purpose:

- the $S_i^{(\Theta)}$ vector of the Q observation matrix, is composed by the value of the UIC 518 norm estimators, from which was evaluated the safety and comfort of the Metro system and the geometric parameters of the track (cant, gauge, horizontal and vertical alignment and synthetic coefficient); on the other hand the $\{S\} = \{S_1, \dots, S_S\}$ observation vector represents the train condition in the different curved or tangent sections of the test zone in the permanent track;
- the components of the $S_i^{(\Theta)}$ vector of the Q observation matrix are: the maximum values estimated of the dynamics quantities which evaluated the safety and comfort in the different sections -tangent or curved-, the geometric parameters of the wheel (differences of diameter between axles, the same

vehicle and between adjacent vehicles, flange thickness, flange height, point 70 and diameters of the axles) and the indicators of the internal and external noise that is generated by the trains. The $\{S\} = \{S_1, \dots, S_s\}$ observation vector represents the state of the different test vehicles in different instants of life cycle.

Passive Experiment - BEDIND is the algorithm used to calculate the principal components of the observation matrix, its function is to classify the information that is linearly independent in an orthogonal space of failures[5]. For this purpose the algorithm uses the mathematical theory of eigenvalues and the following functions:

- variability of the experiment:

$$ZZE(S_t) = \sum_{i=1}^s \lambda_i, \text{ where, } \lambda_i \text{ are the eigenvalues of the observation matrix}$$

- redundancy or over dimension of the experiment:

$$R(S_t) = \lg_2 \sqrt{\frac{\prod_{i=1}^s \sigma_{si}^2}{\prod_{i=1}^s \lambda_i^2}} \text{ Bit, where } \sigma_{si} \text{ is the standard deviation of the symptoms}$$

The procedure finally obtains the components of the vector of observation which fulfill with the following criteria:

$$\sqrt{ZZE(S_t)} = \max_{t=1, \dots, s} \quad \text{and} \quad \sqrt{R(S_t)} = \min_{t=1, \dots, s}$$

The algorithm of multidimensional monitoring named CIA (Condition Inference Agent) has as task trace and monitor the widespread failures of the railway system, for this purpose the CIA uses a mathematical tool named SVD (Singular Value Decomposition), which helps to the obtaining of the magnitude, direction and sense of the failures which appear during the development of the technical system. In addition, the Condition Inference Agent gives compound measurements which are associated with the dispelled energy on the outside and inside of the technical system, as the Frobenius norm and the determinant of economic decomposition. The Fig. 3 shows the evolution of the widespread failure of the test units due to the technical state of the test zone.

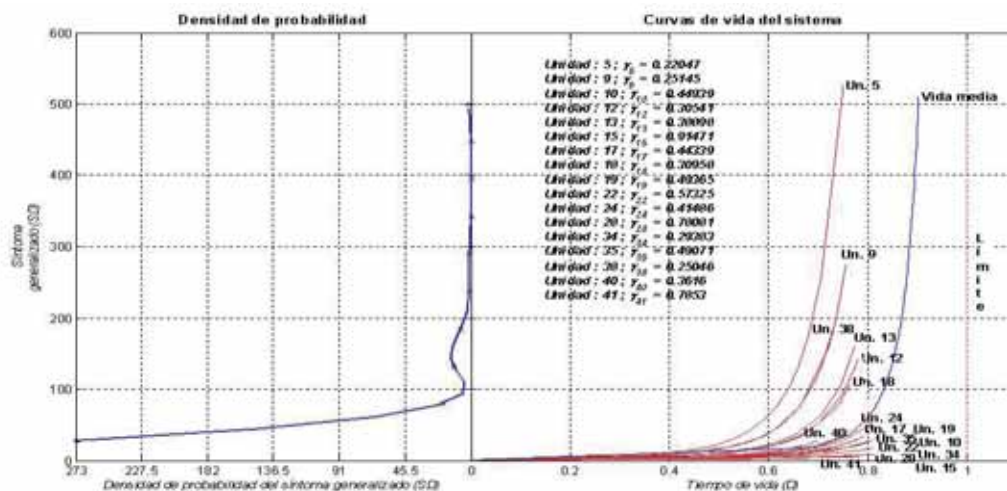


Fig. 3. Evolution of the widespread failure in the test units

The condition test unit gives the necessary information to carry out a technical diagnosis, as the geometric parameters of the track - vehicle interface and the dynamical behaviour data of the railway vehicle during its travel through the tangent and curved sections. The following module "incipient failures detection" was developed based on the studies made by the manufacturer of the passenger vehicle and the experts who have verified the passenger vehicle dynamics. They determined the typical frequencies of the transport system which were corroborated with the signals acquired during the implementation of the UIC 518 norm and analyzed in the domain of amplitude, time and frequency. The "Decisions Support" is the last but one SPD unit which is created by means of an inference motor which integrates the variables records related with the wear of the track. "Forecast" is the last SPD module which is supported in the "Vehicle" algorithm. This algorithm defines a set of diagnosis parameters and the best method of forecast in order to establish the next diagnosis term, the reliable range and the forecast error. The results obtained from this methodology are optimized under the criteria of the minimal coefficient of error relative difference and the minimal error radius of forecast.

3. SPD - portable diagnosis system

The principal function of the SPD modules is to evaluate the safety and comfort of the railway vehicles and the technical state of the track - vehicle interface. The sensors module is the hardware of the SPD system, which means acquisition system with its respective transducers. The units of processing sign and monitoring of the condition are constituted by the configuration of the transducers, the record, the data analysis and the reports according to the UIC 518 norm (Fig.4).



Fig. 4. Portable Diagnosis System Modules – SPD

The three previous modules allow the implementation of the international norm which means the configuration of the conditions of implementation of the test zones, the measurement of the quantities related to the dynamical behavior of the vehicles, the conditions for the automatic and statistical processing of the data, the evaluation of the quantities measured and the limit values.

The maintenance staff of the Metro has access to the module of “Evaluation of the condition” by means of a virtual map of the railway route, where can be selected the tangent or curved section as object of study. This SPD unit contains the historical information and the current state of the variables related to the track - vehicle interface. The Failures Detection Module contains the tools to monitor the frequencies related to the roll of the railway vehicle, the force level in the different track sections and the visualization of the switches effect on the set of axle - wheel railway.

The Decisions Support Module give the necessary recommendations to the staff of the Metro de Medellín about the maintenance activity that must be done in the different tangent and curved sections. These recommendations were designed based on a correlation study realized between the dynamical quantities measured of the UIC 518 norm and the geometric variables of the track - vehicle interface.

Nowadays the Portable Diagnosis System is being used by the maintenance staff of the Metro de Medellín. The SPD is a tool to evaluate the track - vehicle interface based on the condition, which will allow the improvement of the current practices of -corrective, preventive and predictive- maintenance. The diagnosis system is a support that helps in the development of the research project "Dynamical and geometric modeling of the track - vehicle interface ", in which are working the experts of the Metro de Medellín and the research group of the EAFIT University with COLCIENCIAS's funding. Finally, the incorporation of the SPD in the evaluation of the freight railway vehicles that nowadays pass along through the different Colombian routes is being considered (Fig.5).

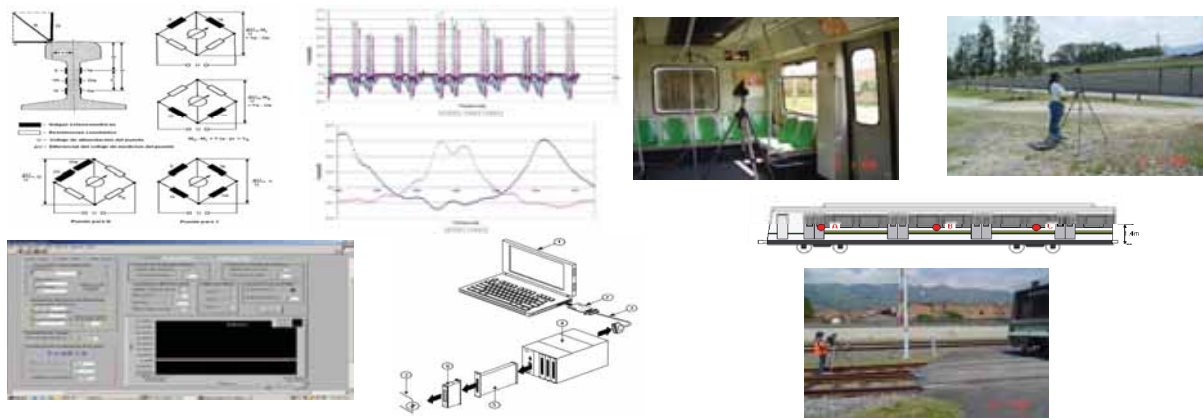


Fig. 5. a). Measurement with the SBB Swiss method. b). Measurement of noise in passenger vehicle

4. Conclusions

The goal of implementation of the UIC 518 international norm in the passenger vehicles of the Metro de Medellín was reached and as result the transport system fulfill with the requirements of safety and comfort stipulated by the norm.

The SPD gives to the Metro de Medellín a tool to evaluate the track - vehicle interface according to its condition, which will allow re-design the current maintenance routines with the purpose to reduce the maintenance costs in the company.

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