GDANSK UNIVERSITY OF TECHNOLOGY
FACULTY OF OCEAN ENGINEERING AND SHIP TECHNOLOGY
SECTION OF TRANSPORT TECHNICAL MEANS
OF TRANSPORT COMMITEE OF POLISH ACADEMY OF SCIENCES
UTILITY FOUNDATIONS SECTION
OF MECHANICAL ENGINEERING COMMITTEE OF POLISH ACADEMY OF SCIENCE

ISSN 1231 – 3998
ISBN 83 – 900666 – 2 – 9

Journal of

POLISH CIMAC

DIAGNOSIS, RELIABILITY AND SAFETY

Vol. 8 **No. 2**

Gdansk, 2013

Science publication of Editorial Advisory Board of POLISH CIMAC

Editor in Chief: Jerzy Girtler Editorial Office Secretary: Jacek Rudnicki

Editorial Advisory Board

J. Girtler (President) - *Gdansk University of Technology*
L. Piaseczny (Vice President) - *Naval Academy of Gdynia*
A. Adamkiewicz - *Maritime Academy of Szczecin*
J. Adamczyk - *University of Mining and Metallurgy of Krakow*
J. Błachnio - *Air Force Institute of Technology*
C. Behrendt - *Maritime Academy of Szczecin*
P. Bielawski - *Maritime Academy of Szczecin*
T. Chmielniak - *Silesian Technical University*
R. Cwilewicz - *Maritime Academy of Gdynia*
T. Dąbrowski - *WAT Military University of Technology*
Z. Domachowski - *Gdansk University of Technology*
C. Dymarski - *Gdansk University of Technology*
M. Dzida - *Gdansk University of Technology*
J. Gronowicz - *Maritime University of Szczecin*
V. Hlavna - *University of Žilina, Slovak Republic*
M. Idzior *– Poznan University of Technology*
A. Iskra - *Poznan University of Technology*
A. Jankowski – *President of KONES*
J. Jaźwiński - *Air Force Institute of Technology*
J. Kiciński - M*ember of MEC*
O. Klyus - *Maritime Academy of Szczecin*
Z. Korczewski - *Gdansk University of Technology*
K. Kosowski - *Gdansk University of Technology*
L. Ignatiewicz Kowalczuk - *Baltic State Maritime Academy in Kaliningrad*
J. Lewitowicz - *Air Force Institute of Technology*
K. Lejda - *Rzeszow University of Technology*
J. Macek - *Czech Technical University in Prague*
Z. Matuszak - *Maritime Academy of Szczecin*
J. Merkisz *– Poznan Unversity of Technology*
R. Michalski - *Olsztyn Warmia-Mazurian University*
A. Niewczas – *Motor Transport Institute*
Y. Ohta - *Nagoya Institute of Technology*
M. Orkisz - *Rzeszow University of Technology*
S. Radkowski - *Member of MEC*
Y. Sato - *National Traffic Safety and Environment Laboratory, Japan*
M. Sobieszczański - *Bielsko-Biala Technology-Humanistic Academy*
A. Soudarev - *Russian Academy of Engineering Sciences*
Z. Stelmasiak - *Bielsko-Biala Technology-Humanistic Academy*
Z. Smalko - *Air Force Institute of Technology*
M. Ślęzak *– Automotive Industry Institute*
W. Tarełko - *Maritime Academy of Gdynia*
W. Wasilewicz Szczagin - *Kaliningrad State Technology Institute*
F. Tomaszewski - *Poznan University of Technology*
J. Wajand *– Lodz University of Technology*
W. Wawrzyński - *Warsaw University of Technology*
E. Wiederuh - *Fachhochschule Giessen Friedberg*
M. Wyszyński - *The University of Birmingham, United Kingdom*
S. Żmudzki - *West Pomeranian University of Technology in Szczecin*
B. Żółtowski - *Bydgoszcz University of Technology and Life Sciences*
J. Żurek - *Air Force Institute of Technology*

Editorial Office:

GDANSK UNIVERSITY OF TECHNOLOGY
Faculty of Ocean Engineering and Ship Technology
Department of Ship Power Plants
G. Narutowicza 11/12 80-233 GDANSK POLAND
tel. +48 58 347 29 73, e – mail: sek4oce@pg.gda.pl

www.polishcimac.pl

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.

All papers have been reviewed
@Copyright by Faculty of Ocean Engineering and Ship Technology Gdansk University of Technology
All rights reserved
ISSN 1231 – 3998
ISBN 83 – 900666 – 2 – 9

Printed in Poland

CONTENTS

GDAŃSK UNIVERSITY OF TECHNOLOGY
Journal of POLISH CIMAC
Faculty of Ocean Engineering & Ship Technology
GDAŃSK UNIVERSITY OF TECHNOLOGY

TRIBOLOGICAL WEAR OF DIESEL ENGINE ATOMISERS

Piotr Bielawski, Zygmunt Raunmiagi

Maritime University of Szczecin
ul. Podgórna 51/53, 70-205 Szczecin, Poland
tel.: +48 91 4318540, fax: +48 91 4318542
e-mail: {p.bielawski; z.raunmiagi}@am.szczecin.pl

Abstract

The authors indicate design changes in injection systems that result in increased tribological loads of atomizers. It is observed that mechanisms of tribological wear of atomizers should be examined in detail. The following four tribological nodes were identified in an atomizer: guide-cylindrical part of the needle, atomizer seat-closing cone of the needle, needle front surface-front surface of injector spring, atomizer front surface-body front surface. A limited set of one type of atomizers was visually examined. Typical images of damage for each node are presented and wear mechanisms are described as well as the feedback between the technical conditions of atomizer tribological nodes and the node load. The authors indicate that: the technical condition of the needle-guide node affects the force imposing a load on the other nodes; the wear of needle front surface-spring node and the seat-needle cone node results in an increased travel of the needle; the time to failure should be considered as the time to the loss of tightness and depends on the distribution of wear on the ring circumference of the conical seat-needle contact.

Keywords: *technical diagnostic, combustion engine, injection system, atomizer, tribological nodes, tribological wear*

1. Introduction

Until recently injection systems of marine engines were not essentially changed for decades, and statistics of engine failures showed that components ranked high. At present growing requirements relating to exhaust emissions and fuel consumption force manufacturers to introduce dramatic modifications in injection systems. In case of atomizers it is predicted that their design will not change significantly, however their mechanical and thermal loads will be increasing. In order to maintain the efficiency and acceptable loads of atomizers it becomes necessary to examine closely the mechanisms of their wear, particularly tribological wear.

2. Atomizer defects

Atomizers are affected by various loads. As a result of these loads, atomizer elements get worn out. Due to the specific construction and load acting on atomizer elements, possible wear can be of various type: erosive, tribological, mechanical fatigue, thermal fatigue, corrosion and creep. Specialist publications lack comprehensive descriptions of atomizer wear mechanisms, considering mostly causes and effects of damage and providing relevant images.

In order to meet requirements on emissions of exhaust gases imposed by the EPA and IMO, fuels used in ships contain less sulphur (below 4.5% depending on the trading range of the ship), and injection system makers increase injection pressures and implement a possibility of multiple injection. Here are example data: injection pressures ranging from 250 to 2200 bar (even 2500 bar is projected), flow intensity in the injector – 400 to 1300 cm^3/30 s at trial oil pressure of 100 bar, injected fuel dose 1.5 to 450 mm^3/stroke, a sequence of up to seven injections will be possible [2]. With such operating conditions, we can expect that corrosive load will decrease, mechanical and thermal loads will increase and so will friction path length.

Mechanical load that acts along the friction path results in tribological wear of atomizer elements that make up tribological nodes. Four tribological nodes can be identified in an atomizer:

1. Guide–cylindrical part of the needle.
2. Atomizer seat–closing cone of the needle.
3. Needle front surface–front surface of injector spring.
4. Atomizer front surface–body front surface.

The latter of the mentioned nodes usually makes up a stationary connection and becomes a tribological node only in certain conditions, while tribological wear in such node is an effect of wrong workmanship and assembly of the injector.

It should be assumed that there exists a feedback between the nodes, so that the wear of one node affects the wear process of the others. Conclusions from the relevant literature are that the process of tribological wear depends on thermal load and condition of the separating liquid, and that apart from tribological wear in the nodes there may occur chemical and erosive wear.

The tribological nodes were visually examined in a limited set of one type atomizers.

3. The node: guide–needle cylindrical part

The function of this node is to provide the movement of the needle so that the centre line of the needle–closing cone is aligned with the centre line of seat cone preventing any seizure of the needle in the guide. The guide–needle node is a congruent node lubricated by overflow fuel. In ideal conditions the load and friction are next to zero. Unavoidable deviations of shape and position, such as misalignment of the cones, orifices and cylinders, and solid particles cause pressures perpendicular to the needle centre line resulting in significant increase of friction. Abrasive wear is the main type of damage. Solid particles that get into the node may cause damage in the form of grooves and cracks, mostly parallel to the needle and guide centre lines, Fig. 1.

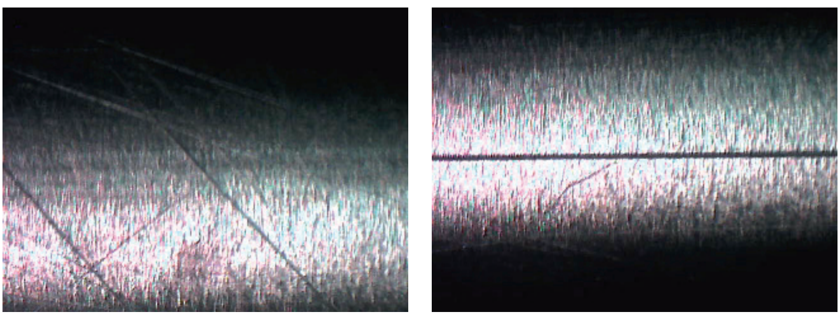


Fig. 1. Cracks and grooves on the surface of needle guiding part

Cracks are caused by hard particles pushed into the needle guiding surface, while grooves are an effect of particles rolling between the guide and the needle. Hard particles pushed into the guide may cause on the needle guiding cylinder the formation of strips of cracks parallel to the generatrix. The strip length is measurable and can be a measure of the actual needle travel.

4. The node: seat–needle cone

The function of this node is to provide tight closing of the injector in both directions: fuel to the combustion chamber and exhaust gases to the injector and to deliver an optimal amount of fuel to the combustion chamber as a function of crankshaft rotation.

In the cone-in-cone shape of the node, the internal cone has a larger top angle which makes the contact similar to that in non-congruent nodes. Under a load deformations occur and the linear contact changes into a ring contact (Fig. 6). The node will be tight if all defects on the surface disappear as a result of elastic or plastic strains.

The load on the needle is due to the difference between the force of fuel pressure acting on the needle cone and the force applied by spring tension.

The seat load consists of the force from spring tension (when the atomizer is closed) and the dynamic force resulting from needle movement speed relative to the seat, fuel viscosity and the materials elasticity – friction force in the guide.

The needle movement speed = f(resultant force, needle travel). The needle travel is a constructional parameter. As it can increase due to wear, it can be a measure of atomizer technical condition.

The construction and movement direction make the atomizer liable to abrasive and adhesive wear, pitting and spalling.

Other types of wear are also possible: erosion from fuel and exhausts, thermal wear, corrosive wear and action of particulate matter.

Images of worn elements of the tribological node seat–needle are presented in figures 2 to 5.

Visual inspection of the seat–needle node results in these remarks:

- both seat cone and needle cone surfaces are subject to wear. The wear of the two surfaces around their circumference is quasi uniform;
- uniform circumferential wear causes the mating needle–seat area to shift as the wear increases along the generatrix of the seat cone, Fig. 6;
- the node loses its tightness the moment it becomes a non-congruent node: non-uniform surface wear of one of the cones results in a break of the seat–needle contact ring;
- as the wear increases, the needle travel also increases; consequently, fuel charge is increased, exhaust gas temperature rises, etc.

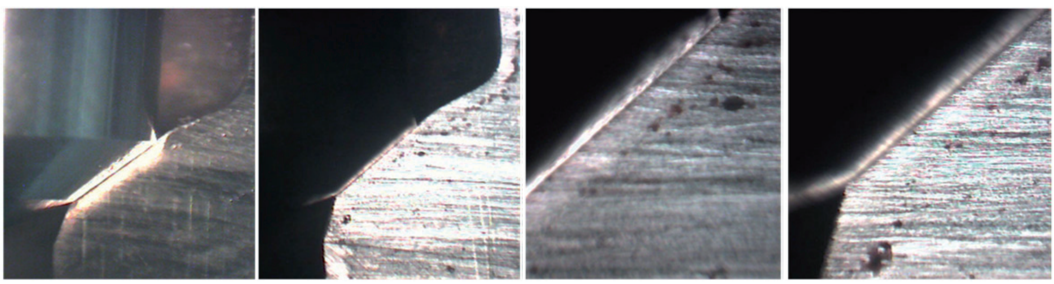


Fig. 2. A new atomizer: the edge of seat cone with a needle

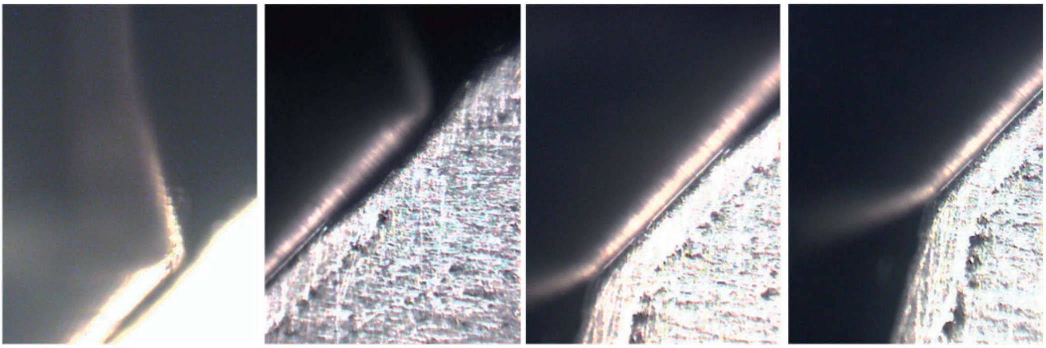


Fig. 3. A worn atomizer: edge (generatrix) of the seat cone with the needle

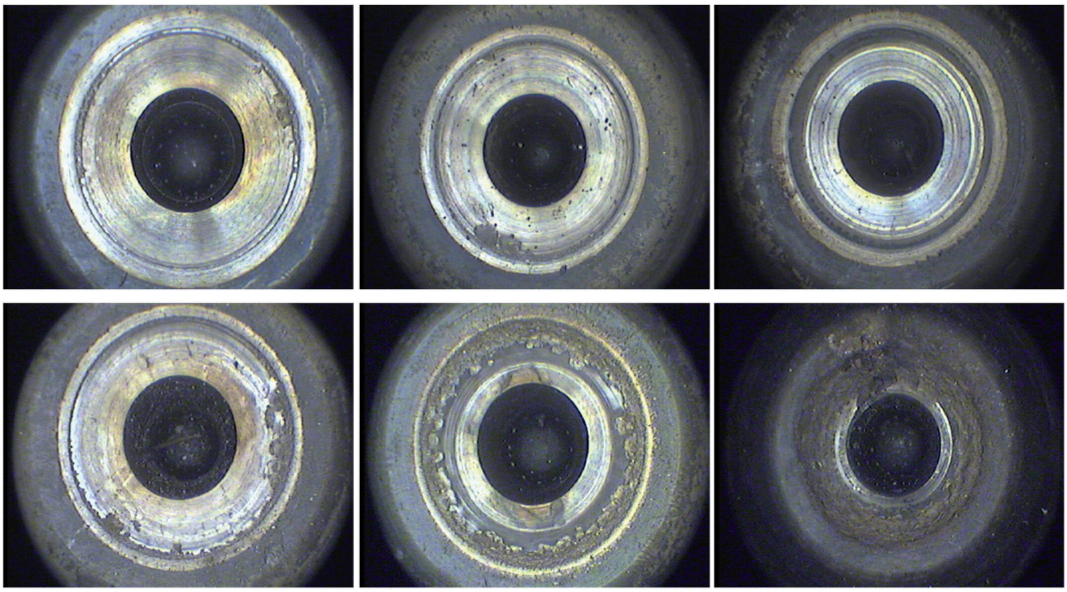


Fig. 4. Images of atomizer seat wear: from the smallest to largest degree of wear

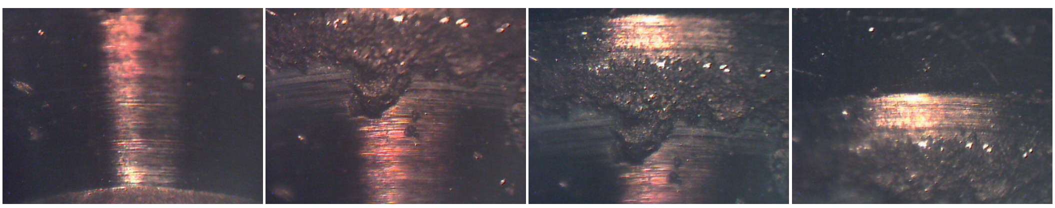


Fig. 5. Fragments of a worn seat: sequence of images from the orifices towards the needle

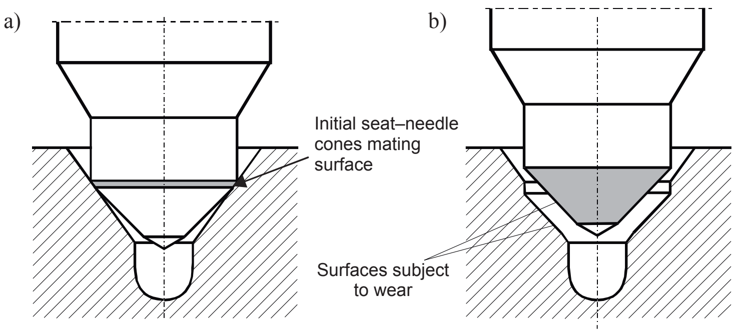


Fig. 6. The tribological node seat–needle cone: a) the shapes of cones before operation, b) shape of worn out seat cone [3]

5. The node: needle front surface–front surface of injector spring

This node conveys the spring pressure force onto the needle. In ideal conditions there should not be a relative motion between the spring and the needle front surface. Deformations and shape / position deviations of the two node elements lead to micro-motions perpendicular to the needle centre line while the spring is squeezed and expanded. Possibly, also relative motions occur of both elements along the needle centre line.

The node load depends on the spring tension and condition and is a function of spring lift.

An image of the wear of needle front surface is shown in Fig. 7.

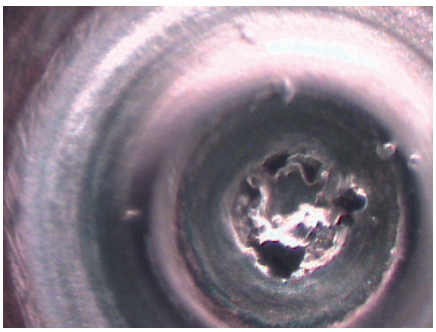


Fig. 7. Wear by spalling of the needle front surface

The prevailing wear on the surfaces of the node under consideration is abrasive wear and spalling. It follows from [1] that it can lengthen the needle travel, consequently increasing the speed of needle striking the seat. This leads to higher load, which in turn may be a cause of fatigue wear: atomizer nipple fractures.

6. The node: atomizer front surface–body front surface

The atomizer and injector body make up a metal-metal contact, therefore both front contacting surfaces have to be manufactured to meet requirements specifying the allowable deviations of dimensions, shape and position, assumed by the designer. For the joint to be tight, there cannot be any assembly errors (e.g. too small a moment of tightening the nut connecting the atomizer and injector body may lead to fuel leaks into injector coolant). At certain combinations of shape, position and assembly deviations, the front surfaces of the atomizer and injector may become main elements of the tribological node and, apart from erosive and corrosive wear and surface cracks, abrasive wear will be likely.

Figure 8 presents an example front surface of the injector body: after removing a worn atomizer (Fig. 8a), and after reconditioning (Fig. 8b).

a) b)

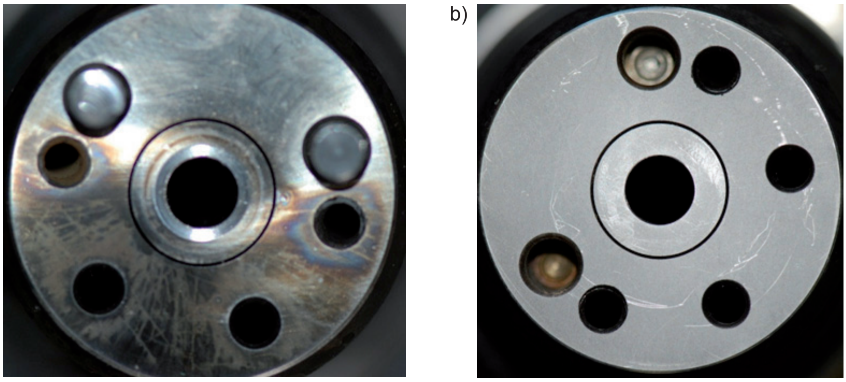


Fig. 8. Front surface of an injector body: a) worn, b) after reconditioning

7. Conclusion

Tribological wear is one of the main types of atomizer wear. At least three tribological nodes can be distinguished in atomizers. There is a feedback between the technical condition of these nodes and their loads. The technical condition of the needle–guide node affects the force imposing a load on the other nodes. The wear of needle front surface–spring node and the seat–needle cone node results in an increased travel of the needle, which not only accelerates the wear of surfaces of the mentioned nodes abut also may lead to a sudden fracture of atomizer bottom (the atomizing part). The time to failure, considered as the time to the loss of tightness, depends on the distribution of wear on the ring circumference of the conical seat–needle contact.

References

[1] Greuter, E., Zima, S., *Motorschäden. Schäden an Verbrennungsmotoren und deren Ursachen*, Vogel Buchverlag, Würzburg 2000, 2. Alflage.

[2] Leonard, R., Parche, M., Kendlbacher, Ch., *Einspritztechnik für Schiffsdieselmotoren*, MTZ 04/2011 (72. Jahrgang), 262–269.

[3] Raunmiagi, Z., *Naprawy wybranych okrętowych elementów maszyn za pomocą obróbki ubytkowej*, Wydawnictwo Naukowe Akademii Morskiej w Szczecinie, Szczecin 2010.

Journal of POLISH CIMAC
Faculty of Ocean Engineering & Ship Technology
GDAŃSK UNIVERSITY OF TECHNOLOGY

POSSIBILITY OF IDENTIFICATION OF TECHNICAL CONDITION OF BEARINGS FOR SELF-IGNITION ENGINES BY APPLICATION OF ACOUSTIC EMISSION AS A DIAGNOSTIC SIGNAL

Jerzy Girtler
Gdańsk University of Technology
Faculty of Ocean Engineering and Ship Technology
Department of Marine and Land Power Plants
tel. (+48 58) 347-24-30; fax (+48 58) 347-19-81
e-mail: jgirtl@pg.gda.pl

Abstract

This paper presents the results of empirical studies where the acoustic emission (AE) method was applied to identify the technical condition of sliding surfaces of main and crank bearings for main diesel engines. The test results indicate that the measurements of the AE parameters allow the technical condition identification for bearings of this type. The results refer to the measurements of the parameters for AE generated in the bearings whose sliding surfaces are in various conditions. The results illustrate the changes in AE parameters over time, like RMS (Root Mean Square), hits, counts, and also signal energy, amplitude, radial loads on bearing, friction torque, time of the mixed friction occurrence, rotational speed, temperature of bearing shell and oil film. It has been shown that AE can be an important diagnostic signal that allows disclosure of changes in technical condition of bearings in piston-crank mechanisms for the mentioned engines, in the early stages of the changes.

Keywords: *diagnostics, acoustic emission, slide bearing, diesel engine, damage*

1. INTRODUCTION

For operation of internal combustion engines, especially those of marine application, the information on occurrence of changes in technical condition of their components, especially bearings in the piston- crank mechanisms which are the most loaded systems, is of significant meaning [2, 4, 5]. To obtain such information, diagnostic methods and the associated diagnosing systems that allow early detection of changes in the engine components, which can be considered as microdamages, are useful in particular. Such methods may include the methods of analysis of vibroacoustic signals *(SWA)* and acoustic emission signals *(SAE)*. When comparing to the other diagnostic parameters, the characteristic feature of the vibroacoustic parameters and acoustic emission parameters, as the carriers of the information on the internal combustion engine condition, is a much greater information volume and transfer speed of the information on bad condition. Preliminary studies have shown that the acoustic emission, however, is more useful because it discloses changes in the structure condition of engine components in the early stage of their formation. This is due to the fact that acoustic emission *(AE)* is a low-energy elastic wave generated by a sudden release of energy stored in the material of the engine components, in the result, for instance, of:

- microslides occurring at the grain boundaries in the micro-regions subject to high stress up to the material plasticity limit,
- movement of vacancies and dislocations, particularly combined dislocations and movement of dislocation groups,
- microgaps and their propagation in the materials of engine components.

The last mentioned reason in particular, is a strong source that generates *AE*. That is why the application of the acoustic emission as a diagnostic signal for diagnosing diesel engines, is necessary. The article raises this issue in relation to the main and crank bearings for this kind of engines.

2. DESCRIPTION OF THE METHOD OF ANALYSIS OF DIAGNOSTIC USEFULNESS OF THE ACOUSTIC EMISSION PARAMETERS FOR IDENTIFICATION OF THE TECHNICAL CONDITION OF SLIDE BEARINGS FOR COMBUSTION ENGINES

For diagnosing the sliding surfaces of the shells of main and crank bearings for diesel engines, the acoustic emission *(AE)* method is useful to analyze and evaluate their technical condition. Such usefulness results from the fact that emergence of the low-energy elastic wave inside the elements of a slide bearing shell, in consequence of release of the energy accumulated therein, may be registered by a relevant measuring apparatus, whose diagram is shown in Fig. 1 [5, 7, 10].

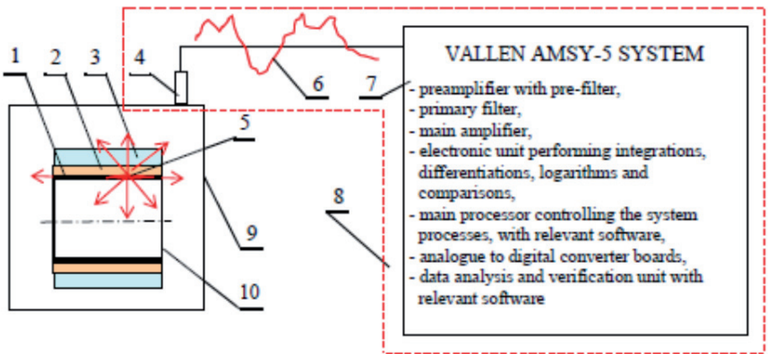


Fig. 1. Block diagram of the system for testing the elastic waves propagation in shells of three-layer slide bearings: 1 – sliding surface, 2 – bearing layer, 3 – support material, 4 – digital converter, 5 – damage (e.g. a microcrack) in the sliding surface, 6 – signal, 7 – measuring system with software, 8 – measurement unit, 9 – engine block, 10 – bearing shell

Thus, the acoustic emission method for testing a slide bearing shell 9 consists in (Fig. 1) registration of the elastic waves as signals 6, by the measurement unit 8. The elastic waves are the result of release of the internal elastic energy accumulated in the material of the shell sliding surface. Further on, the waves are subject to relevant statistical processing in the result of measuring the acoustic emission parameters [1, 2, 3, 7, 9].

Acoustic emission *(AE)* occurs in the bearings of internal combustion engines, as a result of both: microprocesses (microcracks, slides at boundaries, movement of vacancies and dislocations), and macrophenomenon e.g. macrocracks due to shell volume wear and considerable clearances due to wear in bearing shell and journal surfaces [6].

The use of acoustic emission *(AE)* for diagnostics of bearing shells for the combustion engines allows registration of the low-energy signals occurring in the shell, with the converter 4 (Fig. 1). This allows to detect a damage in the structure of the shell sliding layers [1, 2, 4, 7].

3. DETERMINATION OF USEFULNESS OF ACOUSTIC EMISSION PARAMETERS FOR IDENTIFICATION OF THE TECHNICAL CONDITION OF SLIDE BEARINGS FOR COMBUSTION ENGINES

Determination of the diagnostic usefulness of the acoustic emission parameters requires making a comparison of the registered *AE* signals corresponding to the particular technical conditions for the bearing metal alloy, to the signals characteristic for the undamaged alloys (which are in full ability). The usefulness should be determined through measurement of the *AE* parameters of and their analysis including [2, 3]:

- specification of time when the fluid friction in the bearing becomes a mixed friction,
- disclosure (signal) of first microdamages occurred in the material of bearing elements, in the form of micro-deformations or microcracks in the shell sliding surface.

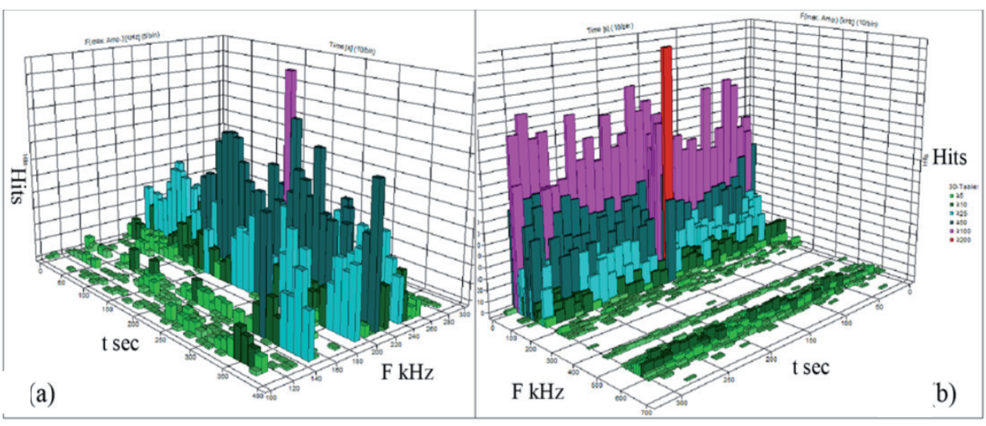
The mentioned usefulness was determined through laboratory tests of slide bearing shells at the test bench, and they included [7]:

- changing the rotational speed value, measuring and registration of the values,
- measuring and registration of the time when the mixed friction occurred in the bearing,
- measuring and registration of the temperature of the tested bearing and oil film,
- changing the radial load on the bearing, measuring and registration of the values.

The studies on the diagnostic usefulness of the acoustic emission *(AE)* parameters through determination of the dependence of the changes in the *AE* parameters on the shell technical condition, were carried by using the Vallen AMSY-5 System (Vallen - Systeme GmbH). The system is equipped with various types of AE sensors providing registration of signals in a wide frequency band [7]. The studies involved such sensors as WD-PAC, WD-PAC with waveguide, VS 30-V, VS 75-V, VS 150-RIC, VS 150-RIC with waveguide, VS 375-RIC, SE 45-H. The sensors were mounted on the measurement head at the test bench and the side surfaces of the tested bearings [7].

The measurements of the acoustic background and noise generated by operation of the test bench systems were carried in the first phase of the tests. The distribution of the frequency bands of the signals registered during the tests is shown in Fig. 2.

a) b)



Fig, 2. Distribution of the frequency bands of the signals registered for wide-band sensors: a) for the range of 100-300kHz, b) for the range of 20-850kHz

The frequency analysis of the recorded *AE* signals allowed identification of the main ranges of noise and selection of the frequencies for high-pass and low- pass filters, for further measurements to eliminate the noise generated by the test bench and other noise sources inside and outside the laboratory [7].

In order to determine the diagnostic usefulness of the *AE* signal parameters, the values of the signal parameters, registered during the tests of a new bearing shell, were compared to the parameters of *AE* signals generated by the shells of bearings with simulated damages. The studies covered three shells as follows:

- a new bearing shell with two holes (Fig. 3a),
- a shell with additional four holes simulating damages from excessive wear (Fig.3b),
- a bearing shell (Fig. 3c) with fatigue damage in the bearing alloy (sliding surface and bearing layer) presenting surface cracks and detachments of bearing alloy particles, which result in interrupted flow of the oil film,
- a bearing shell having longitudinal and circumferential grooves which simulate damages in the shell surface due to rolling some foreign bodies between the shell and the journal (Fig. 4).

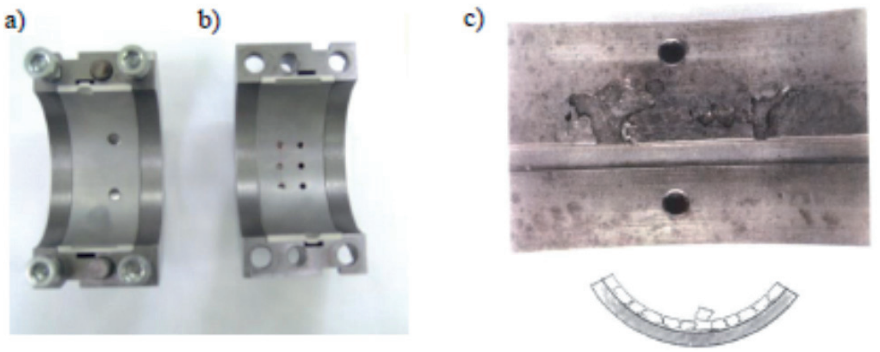


Fig. 3. A new shell (a) and a shell with fatigue damage in the bearing alloy: b) simulated damage in the form of holes with a diameter of 4 mm (Ø = 4 mm) every 15^{O}, c) cracks in hard substructure and detachments of the bearing alloy particles

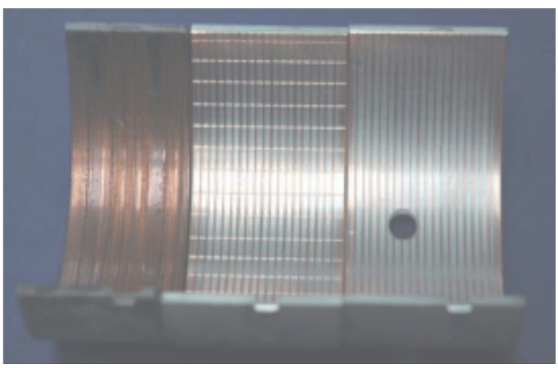


Fig. 4. Simulated damage in the form of grooves, which occurs as a result of rolling foreign bodies in the bearing

The relationships between the damages in slide bearing shells of diesel engines (Fig. 3 and Fig. 4) and the measured *AE* parameters were established during the studies.

During the tests the following values were registered: hits - the basic parameter of AE source activity, counts, signal energy, amplitude, RMS (root mean square) that contains information about the energy of the tested signal, radial load on the bearing, time of the mixed friction occurrence, rotational speed, temperatures of the bearing and the oil film. The mentioned *AE* parameters were used for monitoring the technical condition of slide bearings [1, 5, 6].

The outputs of registration of *RMS* values for a new bearing and the bearings with damages shown in Fig. 3 and Fig. 4, are presented in Fig. 5, 6 and 7 [7].

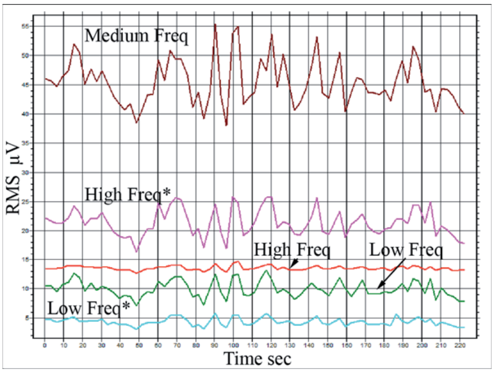


Fig. 5. RMS for filters of different frequency ranges - a new sliding bearing

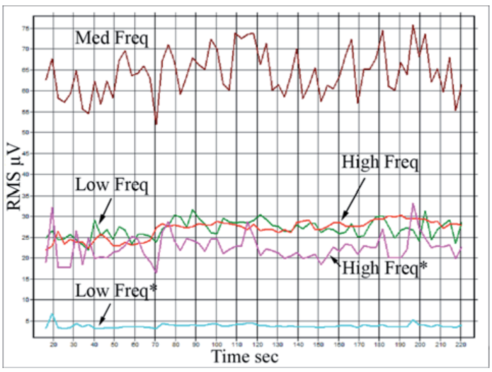


Fig. 6. RMS for filters of different frequency ranges - fatigue damage in the bearing alloy

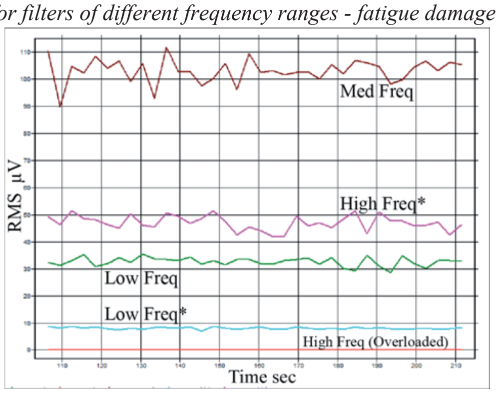


Fig. 7. RMS for filters of different frequency ranges - damage in the form of grooves in the bearing alloy

Stability in values is found for *RMS* with high frequency (red line) (Fig. 7 and, to a lesser extent, in Fig. 5 and 6). A general increase in the values of ***AE RMS*** can be stated in all channels, except for *Low Freq**.

The Figures 5, 6 and 7 show the values of measurements obtained in the channels with low, medium and high frequency for a new bearing (Fig. 5), and for damaged bearings (Fig. 6 and 7). However, the Fig. 8 presents the emission process in a new bearing and a bearing with simulated detachments of alloy particles, for the same acquisition parameters, by using VS75-V and VS150-RIC resonant sensors and the frequency filters installed on the measurement channels [7].

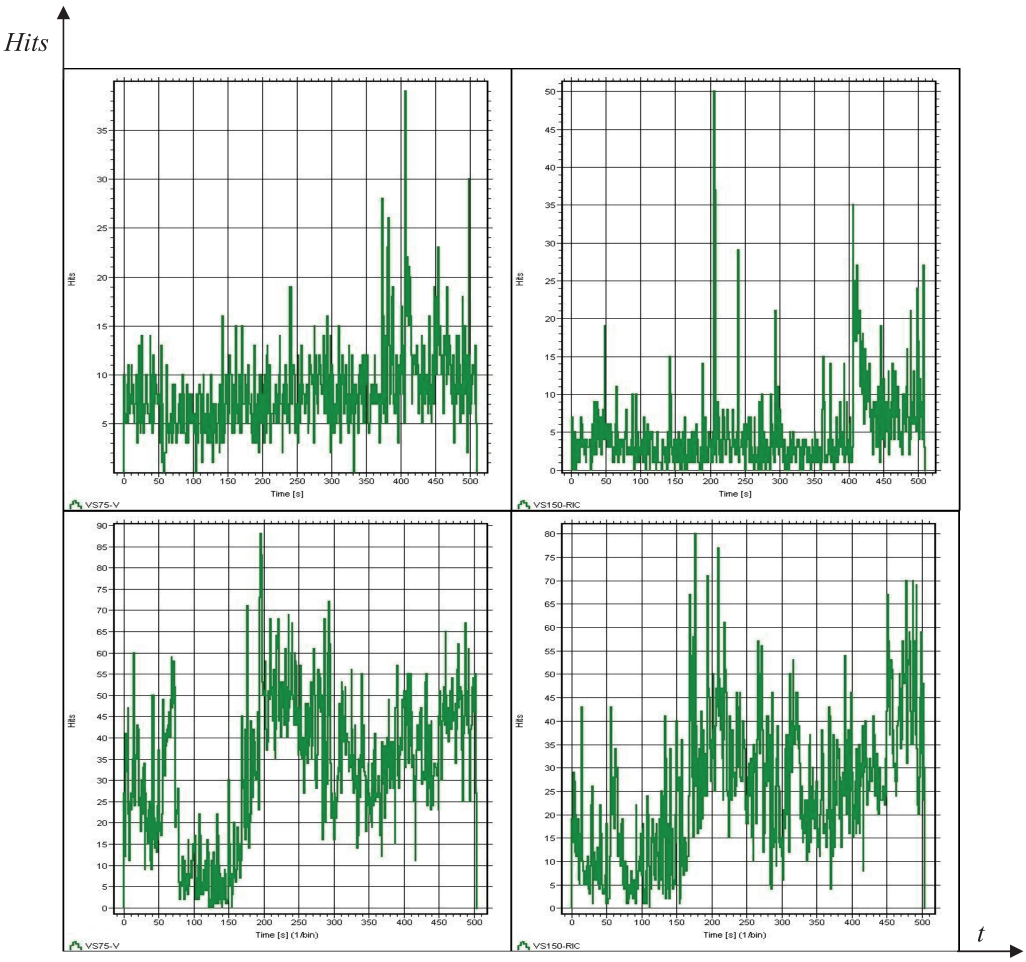


Fig. 8. Process of acoustic emission depending on time for: a) a new bearing b) a bearing with a hole that simulates detachments of alloy particles, when the axles are denoted as follows: Hits - ordinate, Time [s] – abscissa

Fig. 9 illustrates the sum of the signals registered during the determined operation of a bearing. It demonstrates a change in activity of the signals registered with the VS150-RIC sensor, which indicates a change in the bearing condition. The early signs of significant wear in the shell sliding surface were the reason for the sudden increase in AE (Hits) activity.

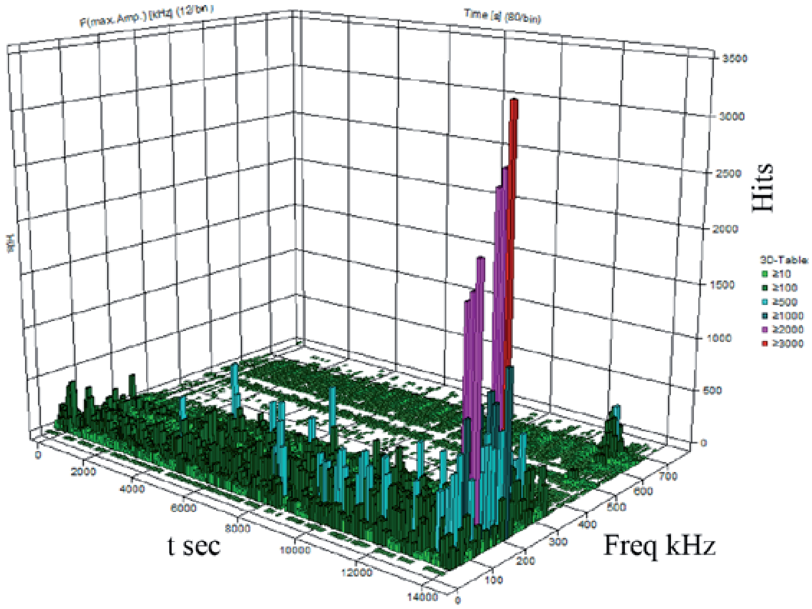


Fig. 9. The sum of Hits distribution for the frequency bands

In turn, the Fig. 10 presents the condition of the sliding layer surfaces of bearing half-shells type MB10 and MB35, after the tests.

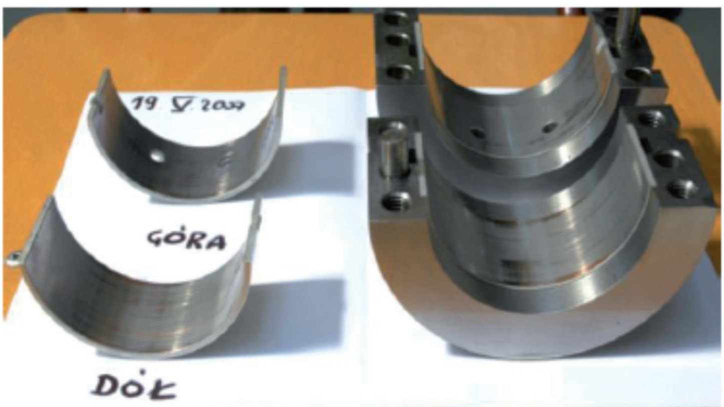


Fig. 10. Bearing half-shells type MB10 and MB35 after the tests - early signs of wear in sliding surface are visible

One of the important targets of the studies was measurement of the *AE* parameters during disappearance of the fluid friction and emergence of the mixed friction, at the time of the first contact of the journal micro-roughness with the bearing shell micro-roughness. During the tests the rotational speed was gradually reduced at the constant stress maintained. Reduction in the rotational speed resulted in reduction in oil film thickness, which in consequence led to a drop in the friction torque generated in the bearing (Fig. 11) and emergence of the contact of the journal micro-roughness with the shell micro-roughness. The mixed friction which then occurs, causes an increase in friction torque in the bearing. Therefore, the minimum value of the friction torque measured in the tested bearing corresponds exactly to the time of the first surface contact between the rotating journal and the stationary shell, which, in the first place, polishes the roughness tops. From this moment the value of torque increases.

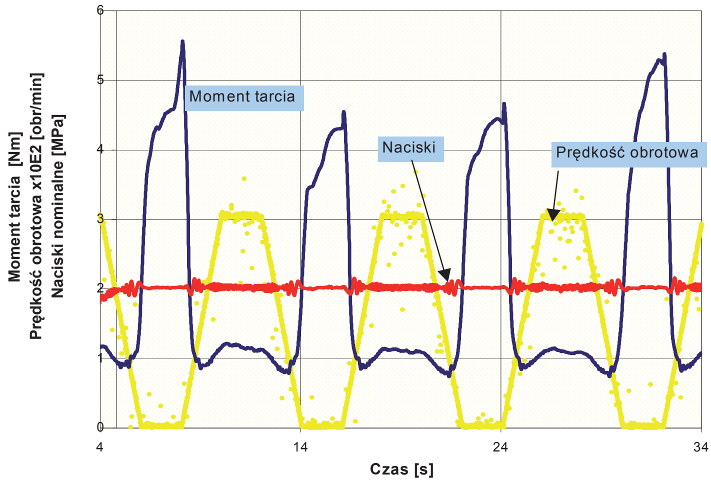


Fig. 11. Diagram of changes in the friction torque and the rotational speed, that proceed in the conditions of interrupted fluid friction, at constant nominal stresses

After stopping the journal in the bearing, the friction torque is proportional to the static friction coefficient. With the increase in peripheral speed the hydrodynamic pressure starts emerging, which causes gradual lifting of the journal in the bearing and reducing the amount of micro-roughness being polished off. This makes a decrease of the friction coefficient to the minimum value, which is achieved at the time of occurrence of the fluid friction. Further increase in the rotational speed results in the increase in the speed of the oil flow in the gap and increase of the friction coefficient [7]. The friction coefficient increase is the result of deteriorating lubrication conditions due to reducing the rotational speed till the journal is stopped in the bearing. However, while starting-up and gradually increasing the rotational speed of the journal, the friction coefficient decreases due to improving lubrication conditions. After reaching the minimum value by the friction coefficient, its value begins to increase with the increase in rotational speed of the journal. The activity of *AE* which was registered at that time, shown in Fig.13, indicated a decrease of the friction coefficient because of loss of activity of the *AE* signals. However, an increase of the friction coefficient between the surfaces of the journal and shells, indicates a sudden increase in the value of the parameters of *AE* signals. The activity of *AE*, registered at that time (Fig. 13), indicated a decrease of the friction coefficient, due to the loss of the activity of the *AE* parameters (Fig. 12). However, the increase of the friction coefficient between the surfaces of the journal and shells, was accompanied by a sudden increase in values of the *AE* parameters (Fig. 13). Fig. 13 shows the changes in the *AE* activity in the form of hits for different frequency bands. The value of the shaft rotational speed is equal to zero when the friction is the greatest. In these studies, no *AE* activity was recorded while reducing the rotational speed of the bearing journal until its rotational speed reached the value of 700 rpm (Fig. 13b).

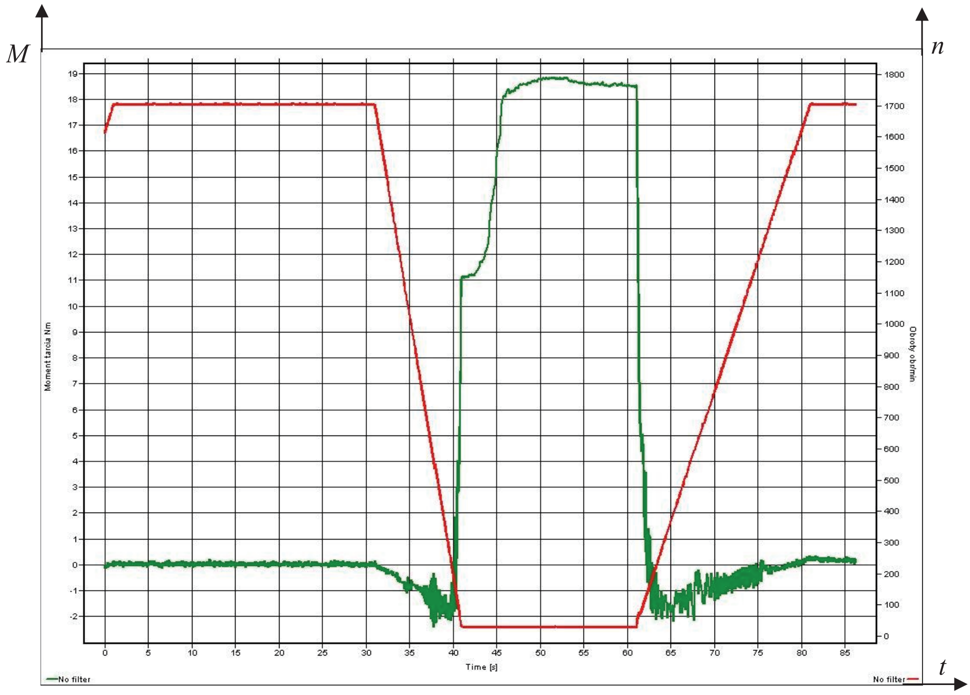


Fig. 12. Behavior of the parameters like: rotational speed (n) [rpm] - the red line, friction torque (M) [Nm] - green line, and loss of activity of the AE signals when the type of friction in the bearing undergoes changing, t - registration time of the changes

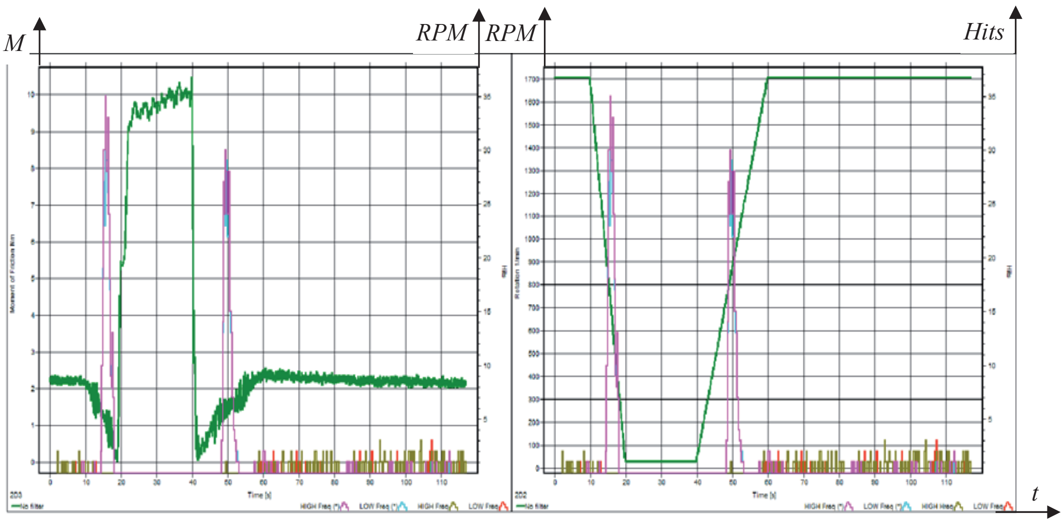


Fig. 13. Changes in AE parameters and activity: a) - friction torque (left) and RPM (right), b) - RPM (left) and number of hits (right), when the type of friction in the bearings undergoes changing, t - registration time of the changes

4. REMARKS AND CONCLUSIONS

The conducted tests show that application of the frequency filters allowed to eliminate most of the operation noise of the test bench. For this type of studies it is necessary to define the noise when the tested diesel engine is operated.

From the presented results it can be concluded that application of the acoustic emission *(AE)* for identification of the technical condition of slide bearings for combustion engines is possible. The sensitivity of the *AE* method allows registration of the *AE* signals when testing the bearings in laboratory conditions, which show the disappearance of the fluid friction in the bearings and occurrence of the mixed friction.

For such studies, it is important to have the classifiers with the Visual Class application and a large library of measurement data obtained from the tests carried at a laboratory stand.

Such classifiers allow identification of the *AE* signals generated by damage, when analyzing the *AE* signals spectrum, obtained during tests of diesel engine bearings in laboratory conditions.

REFERENCES

1. Baran I, Marek M., Darski W.: Foundry Research Institute, Laboratory of Applied Research, 30-418 Kraków, Poland, Gdańsk University of Technology, Ocean Engineering and Ship Technology, Poland. 50 Międzynarodowa Konferencja Emisji Akustycznej, Acoustic Emission Working Group Like Tahoe, Nevada. U S A, October.,Application of Acoustic Emission in Monitoring of Failure in Slide Bearings.
2. Gill J.D., Rauben R.L., Scaife M., Bron E.R., Steel J.A.: Detection of Diesel Engine Faults Using Acoustic Emission. Proc. 2 Conference. Planned Maitenance, Reliability and Quality, 2-3 April, pp.57-61, Oxford, 1998.
3. Malecki I., Ranachowski J.: Emisja akustyczna, źródła, metody, zastosowanie, PWN, Warszawa 1994.
4. Ono K., Fundamentals of acoustic Emission, University of Kalifornia, Los Angeles 1976.
5. Włodarski J. K., Makowski L.: Sposób i układ do sygnalizacji stanów zagrożenia awaryjnego łożysk silników spalinowych. Patent nr 112916, 1982.
6. Włodarski J. K.: Uszkodzenia łożysk okrętowych silników spalinowych. Wydawnictwo Akademii Morskiej w Gdyni, Gdynia 2003.
7. Girtler J., Darski W., Sprawozdanie nt. „Pomiary parametrów emisji akustycznej generowanej przez zmęczeniowe uszkodzenia panwi łożysk MB50, MB02 na stanowisku badawczym SMOK Część VIII (wykonanie pomiarów na stanowisku, opracowanie wyników, wnioski z badań)" z wykonania badań w ramach realizacji projektu badawczego Ministerstwa Nauki i Informatyzacji (nr. 3480/TO2/2006/31) pt.: „Identyfikacja stanu technicznego układów korbowo-tłokowych silników o zapłonie samoczynnym ze szczególnym uwzględnieniem emisji akustycznej jako sygnału diagnostycznego". Prace badawcze Wydziału Oceanotechniki i Okrętownictwa Politechniki Gdańskiej nr 05/2009/PB, Gdańsk 2008.
8. ASME, Acceptance Test Procedure for Lass II Vessels, Article RT – 6, Section X, Boiler and Pressure Vessel Code (December 1988 Addendum and latter editions).
9. Course Handbook for SNT-TC-1A Qualification/Certification COURSE FOR Acoustic Emission Personal, Level II, Physical Acoustic Corporation 1991.

Journal of POLISH CIMAC
Faculty of Ocean Engineering & Ship Technology
GDAŃSK UNIVERSITY OF TECHNOLOGY

MODEL OF BUS ELECTRICAL SYSTEM FAILURE PROCESS

Leszek Knopik

University of Technology and Life Science in Bydgoszcz
Faculty of Management Science
Fordonska 430 st, 85-789 Bydgoszcz, Poland
e-mail: knopikl@utp.edu.pl

Abstract

The lifetime distribution is important in reliability studies. There are many situations in lifetime testing, where an item (technical object) fails instantaneously and hence the observed lifetime is reported as a small real positive number. Motivated by reliability applications, we derive the branching Poisson process and its property. We prove that the branching Poisson process is adequate model for the failure process of the bus electrical system. The method is illustrated by two numerical examples. In the second example, we derive the times between the failures of a bus electrical system.

Keywords: *mean residual life function, equilibrium distribution, Poisson process, branching Poisson process, primary and secondary failures, early and instantaneous failures.*

1. Introduction

The standard practice in modeling statistical data is either to derive the appropriate model based on physical properties of the system or choose a flexible family of distributions and then find a member of the family that is appropriate to the data. In both situations it would be helpful if we find the model of lifetime that explains the distribution using important measures of indices. For example, in reliability theory and survival analysis, identification of probability models is often achieved through studying the characteristic measures such as failure rate function, mean residual life function, mean time to failure, burn-in time etc.
Occurrence of instantaneous and early failures in lifetime testing is observed in sets of failures of machines. These occurrences may be due to faulty construction or inferior quality. Some failures result from natural damages of the machine while the other failures may by caused by inefficient repair of previous failures resulting from incorrect organization of the repair process. These situations can be modeled by modifying commonly used parametric model such exponential, gamma and Weibull distributions. In the papers [14,15,16] the set of the failures of machines is divided into two subsets, namely into the set of primary failures and secondary failures. This division suggests that the population of the lifetime is heterogeneous. The set of secondary failures is "similar" to the set of instantaneous and early failures. The population of time to failures can be described by using the statistical concept of mixture of distributions. The lifetime distribution as the mixture of exponential and Rayleigh's distributions is considered in [14]. The mixture of a distribution with distribution function F and one-point distribution is often analyzed in literature. The problem of statistical inference about the set of parameters when F is exponential is analyzed in [2, 11, 12, 13, 18, 19]. Statistical inference when F is a two parameter gamma distribution is

investigated in [20] and when F is two parameter Weibull distribution is considered in [21]. In this paper, we consider the stationary branching Poisson process as a model of the failure process of bus electrical system. The idea of application of the branching Poisson process to the failure process was first introduced by Bartlett [4] and Lewis [17].

2. Definitions and background

Let T be a non-negative random variable denoting the life length of a component having the distribution function F(t) with F(0) = 0, the reliability (survival) function R(t) = 1− F(t), and the probability density function f(t). Then the failure rate function is given by λ(t) = f(t) / R(t). We also assume that f(t) is continuous and twice differentiable on (0,∞). In renewal theory and maintenance the equilibrium distribution corresponding to lifetime distribution play an important role. The distribution function of the equilibrium distribution corresponding to the lifetime T is defined as

$$F_E(t) = \int_0^t R(u)du / ET$$

The probability density function of the equilibrium distribution is (see [6])

$$f_E(t) = R(t) / ET$$

and the failure rate function of the equilibrium distribution is

$$\lambda_E(t) = R(t) / (ET\, R_E(t)), \text{ where } R_E(t) = 1 - F_E(t)$$

A key role in this paper will be playing by the mean residual life function. If ET < ∞, then the mean residual life function of T is defined by

$$m(t) = E(X - t \mid X > t) = \int_t^\infty R(u)du / R(t) \ \text{ if } R(t) > 0$$

and m(t) = 0 for t such that R(t) = 0. Then

$$ET = m(0) = \int_0^\infty R(u)du$$

It is well known that the mean residual function uniquely determines by the reliability function through the following inversion formula

$$R(t) = \frac{m(0)}{m(t)} \exp\left(-\int_0^t \frac{du}{m(u)}\right)$$

for all t ≥ 0 such that and R(t) > 0 (see [8, 10]).
The mean residual life function m(t) can have various shapes of those labeled increasing, decreasing, bathtub and upside-down bathtub (unimodal) are given the most attention. Many authors [7, 9] convincingly argue that the shapes of m(t) and λ(t) provide useful information with

regard to, for example, the quality of a product. The shape of the mean residual life function m(t) also provides a good idea about behavior of failure rate function and vice versa, but the relationship between the two is usually very complex. Thus $\lambda(t)$, m(t) and R(t) are equivalent in the sense that, given one of them, the other two can be determined.
The idea of total time on test (TTT – transformation) processes was first defined by Barlow and Campo [3]. The TTT – transform has been found useful to study the ageing properties of the underling distribution. For the distribution function F(t), we define

$$F^{-1}(t) = \inf\{ x: F(x) \geq t \}, \text{ where } p \in < 0, 1).$$

The function

$$H^{-1}(t) = \int_0^{F^{-1}(t)} R(x)dx$$

is called the TTT – transform and the function

$$\Phi_F (t) = H^{-1}(t) / ET$$

is the scaled TTT – transform.
It is known that

$$H^{-1}(1) = ET.$$

Note that if F(t) is the exponential distribution function then scaled TTT – transform is given by $\Phi_F (t) = t$ for $0 \leq t \leq 1$.
Now let $t_{(1)} \leq t_{(2)} \leq, \ldots, \leq t_{(n)}$ to be an ordered sample from life distribution, and let

$$Dj = (n - j + 1) (t_{(j)} - t_{(j-1)}), \text{ where } t_{(0)} = 0,$$

then $$S_j = \sum_{k=1}^{j} D_k \quad \text{for } j = 1,2,\ldots, n.$$

denotes the TTT – transform at $t_{(j)}$, where $S_0 = 0$. The value S_j / S_n is an estimate of the scaled TTT – transform. The TTT – plot is obtained by plotting $u_j = S_j / S_n$ against j / n for j = 0, 1, 2, …, n and joining the points by straight lines. Scaled TTT – transform for some families of the lifetime distributions are given by Barlow and Campo in [3].

3. Model for failures process

In this chapter of paper, we will construct the model of failures process of bus electrical system. This process is built up as follows. There is a series of primary failures, separated by the random variables Z_1, Z_2, … and each of these primary failures generates a subsidiary series of failures. In each subsidiary process there are a random number S of failures separated by random variables Y_1, Y_2, …, Y_s although S may have the value zero in which case no subsidiary failure follows the primary failure. The subsidiary process is assumed to be independent of one another and have identical structure. The complete process is then the superposition of primary failures and subsidiary failures processes, the assumption is that two types of events are indistinguishable. This process is called the stationary branching Poisson process. When this process is used as model for bus failures, a primary event is associated with the initial failure of a component. However, repair of the bus may not always be effected and then, because the bus uses all of its components all the time, a subsidiary failure occurs Y_1 later when the failed component is again needed for the correct operation of the bus The failed component is finally located and removed after S + 1 attempts as repairs have been made. Fortunately, this Poisson assumption is reasonable in some applications and from here we assume that Z_i, i = 1, 2, … are independent and identically distributed with the probability density function.

$$f_Z(t) = \lambda \exp(-\lambda t), \text{ where } \lambda > 0 \text{ and } t \geq 0.$$

Then the series of the random variables Z_i generates the stationary Poisson process. By the random variable T, we denote the time between successive failures in stationary branching Poisson process. Then by [5,17] the reliability function of the random variable T is

$$R_T(t) = \frac{1 + ES \times R_Y(t)}{1 + ES} \exp\{-\lambda t - \lambda \times ES \int_0^t R_Y(u)du\} \quad (1)$$

Then it is possible to derive almost all of the probabilistic properties of the failure process. Now, the failure process is the stationary branching Poisson process. We denote by T the time between successive failures in the stationary branching Poisson process.
Let

$$ET_T(t) = \int_0^t R_T(u)du$$

By (1), we have

$$ET_T(t) = (1 - \exp(-\varphi(t)) / (\lambda (1 + ES))$$

where $\varphi(t) = \lambda t + ES \int_0^t R_Y(u)du$

We observe that

$$ET_T(0) = 0$$

$$ET_T(\infty) = ET = 1/(\lambda (1 + ES))$$

By [5] and [17] the formula for the variance D^2T is given by

$$D^2T = (1 + 2\, ES \exp(-\lambda (1 + ES))\, EY) / (\lambda (1 + ES))^2$$

The coefficient of variation of random variable T is

$$V(t) = 1 + 2\, ES \exp(-\lambda (1 + ES)\, EY)$$

Lower and upper bound for the variance and the coefficient of variations can be written as

$$1 / (\lambda^2 (1 + ES)^2) \leq D^2T \leq (1 + 2\, ES) / (\lambda^2 (1 + ES)^2)$$

$$1 \leq V(t) \leq 1 + 2\, ES$$

This shows that the coefficient of variations of intervals between the failures in stationary branching Poisson process is always greater than or equal to1. The mean residual life function of T can be written as

$$m(t) = (ET - ET(t)) / R_Y(t)$$

and

$$m(t) = 1 / \varphi'(t)$$

From the above, it is clear that the random variable T has the following properties:

Property 1. The mean residual life function m(t) of the life time T is increasing.

Property 2. For the function $\varphi(t)$, we conclude that $\varphi'(t) > 0$ and , $\varphi''(t) \le 0$.

Property 3. The failure rate function of the lifetime T is

$$\lambda_T(t) = \varphi'(t) - \varphi''(t) / \varphi'(t)$$

Property 4. The distribution function of the equilibrium distribution is given by

$$F_E(t) = 1 - \exp(-\varphi(t)) \text{ for } t \ge 0$$

Property 5. The failure rate function of the equilibrium distribution is given by

$$\lambda_E(t) = \varphi'(t)$$

4. Numerical examples

Example 1. In this example, we assume that the random variable Y has Weibull distribution with the reliability function

$$R_Y(t) = \exp(- a\, t^{\,b}) \text{ for } t \ge 0,\ a > 0,\ b > 0.$$

Also, we assume that ES = 1, a = 0.5, $\lambda = 1$ and $b \in \{1.5, 1.75, 2\}$. For its parameters sets, we obtain unimodal failure rate functions $\lambda_T(t)$ of T. Figure 1 shows the realization of numerical calculation of $\lambda_T(t)$.

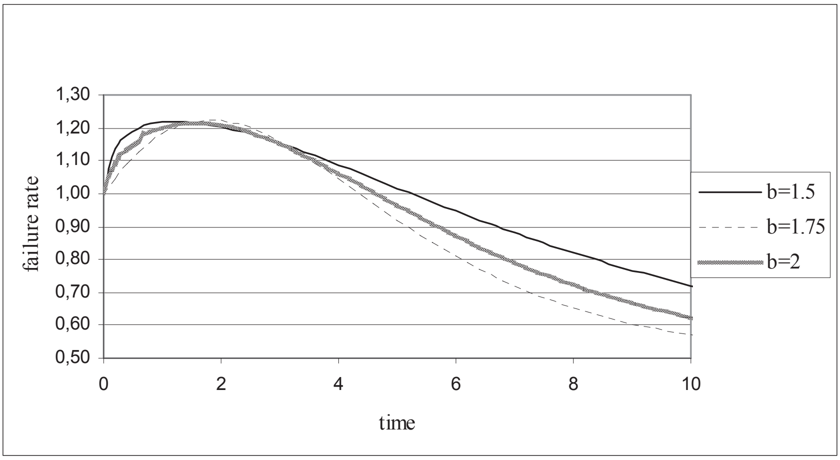


Fig.1. Failure rate function for $b \in \{1.5, 1.75, 2\}$

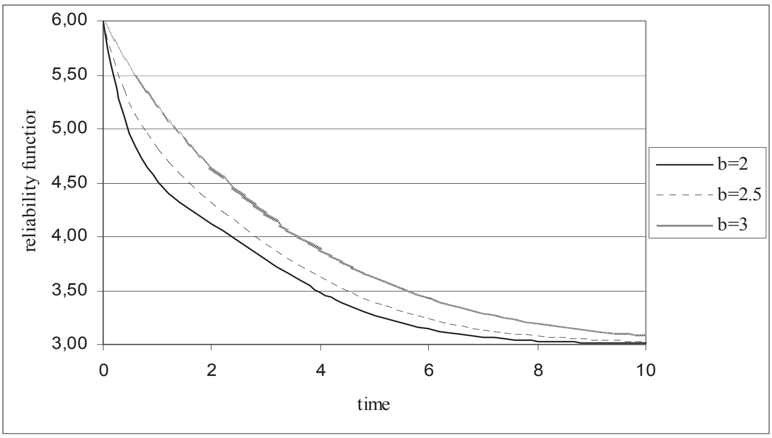


Fig.2. Failure rate function for $b \in \{2, 2.5, 3\}$

In the second part of this example, we assume that $a = 0.5$, $\lambda = 1$ and $b \in \{2, 2.5, 3\}$. Realization of these computation shows Figure 2. All the failure rate functions are decreasing.

Example 2. The object of the investigation is a real municipal bus transport system within a large agglomeration. The analyzed system operates 190 municipal buses of various types and makes. In this example, we consider a real time data on failure of the electrical system of a bus. The data set contains n = 2565 times between successive failures of the electrical system of a bus. We apply the maximum likelihood estimates of the parameters a, b and λ. As the initial solution of the likelihood equation, we give b = 1. We calculate the values of the parameters a = 0.8744, b = 0.40729, λ = 0.05457, and ES = 1. For these values of parameters, we prove the Kolmogorov's test of goodness of fit and compute the associated p–value = 0.87. It shows a good conformity of the empirical data with the distributions with reliability function (1). Figure.3 shows the reliability functions for this example. Figure 4 shows the graphs of the function $\varphi_T(t)$ for estimated parameters, $\varphi_E(t)$ for data set and $\varphi_{EXP}(t)$ for the exponential distribution. Figure 5 shows the graphs of the empirical TTT–transformation of empirical distribution (TTTe), estimated distribution (TTTt) obtained by (1), and for the exponential distribution (EXP) (see[1]).

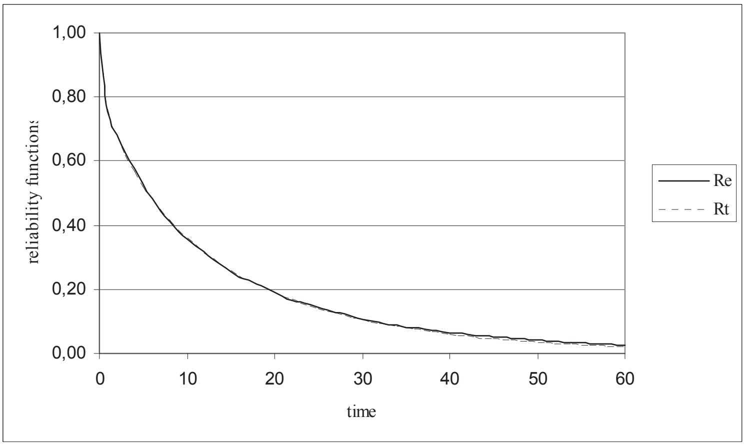


Fig. 3. Reliability functions empirical and theoretical

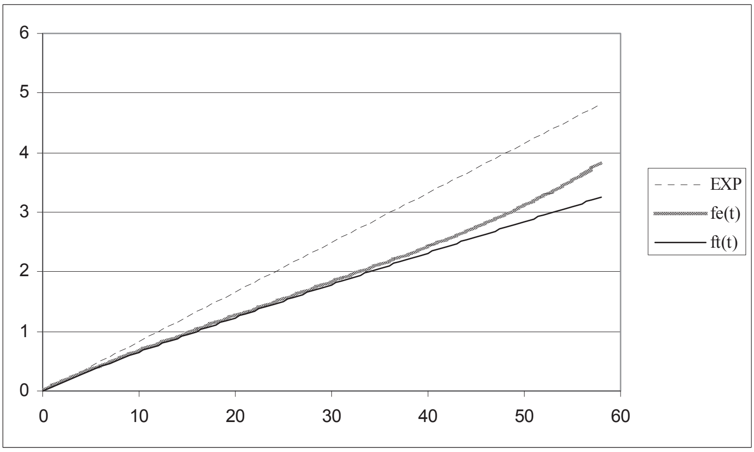


Fig.4. Graphs functions $\varphi_e(t)$, $\varphi_t(t)$ and $\varphi_{EXP}(t)$

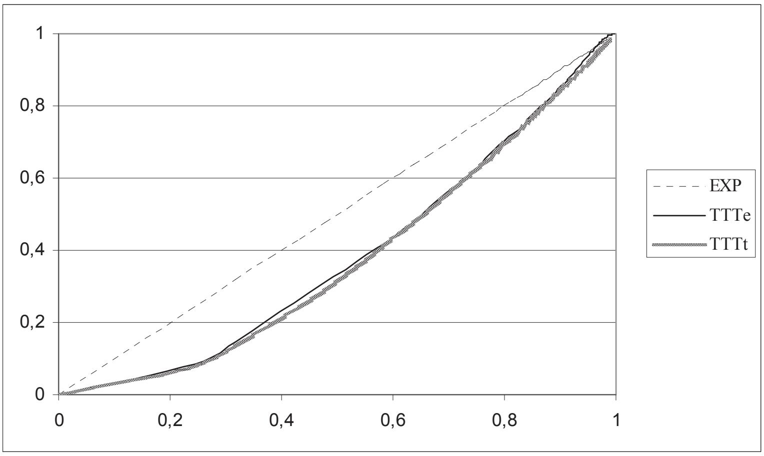


Fig. 5. Plots TTT-transform empirical, theoretical and exponential

5. Conclusions

In this paper, we study the lifetime model for instantaneous and early failures of bus electrical system. When the parameters are estimated, it is possible to apply for further calculations, such that as MTTF (Mean Time to Failure), burn–in time, the failure rate function and the replacement time. The development of efficient parameters estimation methods for this failure process model and their application for times to failure modeling are topics for further study. An application to a real data set shows that this model may be applicable in practice.

References

[1] Aarset, M.V., *How to identity to bathtub hazard rate*, IEEE Transactions on Reliability, vol. 36, pp.106−108, 1987.

[2] Aitchison, I., *On the distribution of a positive random variable having a discrete probability mass at origin,* Journal of the American Statistical Associations, vol. 50, pp. 901−908, 1955.

[3] Barlow, R.E. and Campo, R., *Total time on test processes and application to failure data analysis*, Reliability and Fault Tree Analysis eds. Barlow R.E., Fussel J. and Singpurwalla N.D., SIAM Philadelphia pp. 451−491, 1975.

[4] Bartlett, M. S., *The spectral analysis of point processes*, Journal Royal Statistical Society, Series B 25, pp. 264−296, 1963.

[5] Cox, D.R. and Lewis, P.A.W., *The Statistical Analysis of Series of Events*, Methuen, NewYork, John Wiley, 1966.

[6] Deshapande, J. V. and Kochar, S.C., *Aspects in positive ageing*, Journal of Applied Probability, 23, pp. 748−758, 1986.

[7] Ghai, G.L. and Mi, J., *Mean residual life and its association with failure rate*, IEEE Transactions on Reliability, vol. 48, No. 3, pp. 262−266, 1999.

[8] Guess, F. and Proschan, F., *Mean Residual Life: Theory and Applications*, Handbook of Statistics, Editors: Krishnaiah, P.R. and Rao, C.R., Elsevier Science Publishers, Amsterdam, vol. 7, pp. 215−224, 1988.

[9] Gupta, R.C., *On the monotonic properties of residual variance and their applications in reliability*, Journal of Statistical Planning and Inference, vol.16, pp. 329−335, 1987.

[10] Hall, W.J. and Wellner, J.A., *Mean residual life*, Statistics and Related Topics, Eds. Csorgo J.N., Rao J.N.K. and Saleh A.K. Md, E., North Holland, Amsterdam, pp.169−184, 1981.
[11] Jayade, V. P. and Parasad, M. S., *Estimations of parameters of mixed failure time distribution,* Communications Statistics, Theory and Method, vol.19, pp. 4667−4677, 1996.
[12] Kale, B. K. and Muralidharan, K., *Optimal estimating equations in mixture distributions accommodating instantaneous or early failures*, Journal Indian Statistical Associations, vol. 38, pp.317−329, 2000.
[13] Kleyle, R.M. and Dahiyam R.L., *Estimation of parameters of mixed failure time distribution from censored data*, Communications Statistics, Theory and Method, vol.4, pp. 873−882, 1975.
[14] Knopik, L., *Mixture of distributions as a lifetime distribution of a technical object*, Scientific Problems of Machines Operation and Maintenance, vol.45, 2(165), pp. 53−60, 2010.
[15] Knopik, L., *Model for instantaneous failures*, Scientific Problems of Machines Operation and Maintenance vol. 46, 2(166), pp. 37−48, 2011.
[16] Knopik, L., *Statistical analysis of failures*, Journal of Polish CIMAC, diagnosis, reliability and safety, vol. 7, No. 2, pp. 91−96, 2012.
[17] Lewis, P.A.W., *A branching Poisson process model for the analysis of computer failure patterns*, Journal Royal Statistical Society, B 26, pp. 398−456, 1963.
[18] Muralidharan, K., *Test for mixing proportion in mixture of a degenerate and exponential distributions*, Journal Indian Statistical Associations, vol. 37, pp.105−119, 1999.
[19] Muralidharan, K., *The UMVUE and Bayes estimate of reliability of mixed failure time distribution*, Communications Statistics, Simulation Computer, vol. 29, No. 2, pp. 603−158, 2000.
[20] Muralidharan, K. and Kale B.K., *Modified gamma distribution with singularity at zero*, Communications Statistics, Simulation Computer, vol. 31, No1, pp.143−158, 2002.
[21] Muralidharan, K. and Lathika, P., *Analysis of instantaneous and early failures in Weibull distribution*, Metrika vol. 64, pp.305−316, 2006.

Journal of POLISH CIMAC
Faculty of Ocean Engineering & Ship Technology
GDAŃSK UNIVERSITY OF TECHNOLOGY

ANALYSIS OF PARAMETERS OF RAIL VEHICLES

Leszek Knopik

University of Technology and Life Science in Bydgoszcz
Faculty of Management Science
Fordonska 430 st, 85-789 Bydgoszcz, Poland
e-mail: knopikl@utp.edu.pl

Abstract

In this paper, mixture of two normal distributions is proposed to accommodate the values of rail vehicles parameters. We also present the most commonly used maximum likelihood estimation to fit the two component mixture of normal distribution using data sets of rail vehicles.

Keywords: *rail vehicles, speed of train, mass of train, mixture of distributions, maximum likelihood method, normal distribution, EM algorithm*

1. Introduction

Monitoring the values of parameters of rail vehicles is a very important factor of safety in rail transportation. In this paper, we analyze some parameters of rail vehicles. Values of these parameters are collected by DSAT system. This system screens the values of parameters of rail vehicles with various types of construction of bearing axles and train brake. It is applicable to various diameters of the wheels. System DSAT is installed on a straight rail line. System DSAT finds the following symptoms:

(a) improvement of temperature of a bearing axle – function GM,
(b) non working brakes – function GH,
(c) exceeded pressure on axle (NO) or exceeded linear pressure (NL) – function OK,
(d) deformation of surface wheels – function PM (PO),

The system DSAT registers the following values of parameters:

(e) speed [km/h],
(f) number of axles,
(g) length of train [m],
(h) number of railway carriage,
(i) mass of train [t].

The values of these parameters are the heterogeneous sets. It is a result of the fact that the rail vehicles moving on the analyzed path execute different tasks, such as transportation of people and cargo.

In this paper, we use the mixture model for investigating a complex distribution of parameters of the rail vehicles. The mixture model has a wide variety of applications in technical and life science. Because of their usefulness as extremely flexible method of modeling, finite mixture models have continued to receive increasing attention over the recent years, from both practical and theoretical points of view, and especially for lifetime distributions. The problem application of the mixture of distributions to lifetime analysis is considered in [4, 5, 6, 7]. Fitting the mixture distributions can be handled by variety of techniques, this includes graphical methods, the methods of moments, maximum likelihood and Bayesian approaches (see Titterington et al. [14], McLachan G.J. and Basford K.E [9], Lindsay [8], McLachlan and Peel [10], Furhwirth- Schnatter [3]). Now extensive advances have been introduced in the fitting of the mixture models especially via maximum likelihood method. Among all, the maximum likelihood method becomes the first preference due to the existence of an associated statistical theory. The maximum likelihood method is making by expectation maximization algorithm (EM algorithm). The key property of the EM algorithm has been established by Dempster et al. [1] and McLachan G.J. and Krishan [11]. The EM algorithm is a popular tool for solving maximum likelihood problems in the context of a mixture model. We will focus on maximum likelihood techniques in this paper since the estimates tend to converge to true parameters values under general conditions. Maximum likelihood estimation procedures seek to find the parameters values that maximize the likelihood function evaluated at the observations.

2. Analysis of measurements

The research object is a real transportation rail system. In this rail system, the gauge registers four parameters for n = 360 of trains for 6 days.
It is known that the measurement parameters are dependent. For this purpose, we calculate the matrix of correlation of a random variables (X_1, X_2, X_3, X_4), where X_1 is speed, X_2 is number of axles, X_3 is the length of train, X_4 is the mass of train. The correlation matrix K of the random variable X = (X_1, X_2, X_3, X_4) is given as

$$K = \begin{bmatrix} 1 & & & \\ -0.81601 & 1 & & \\ -0.75576 & 0.923385 & 1 & \\ -0.68109 & 0.782682 & 0.689303 & 1 \end{bmatrix}$$

All correlation coefficients are statistical significant under p – value, $p < 0.0001$. In Fig. 1, we illustrate the relation between the mass and the length of the train, however Fig. 2 illustrates the relation between the mass and the speed.

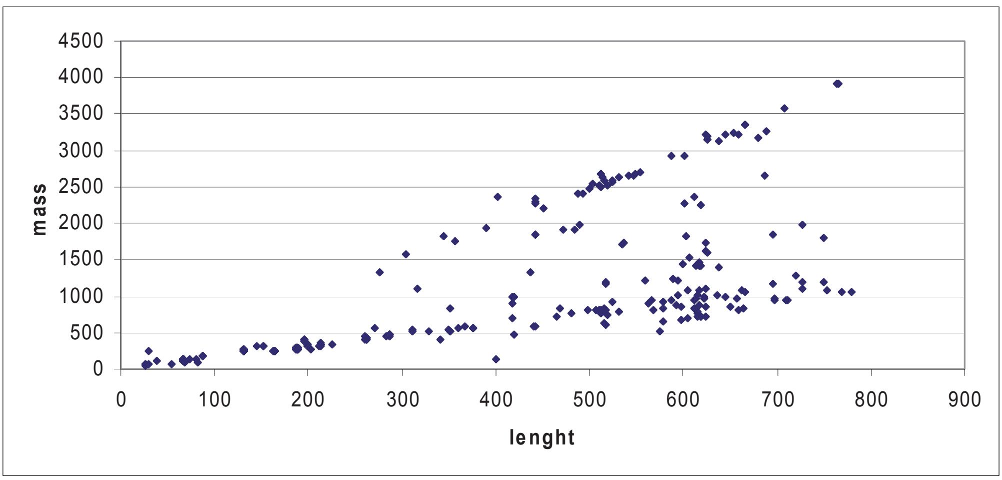


Fig. 1. Relation of mass versus length

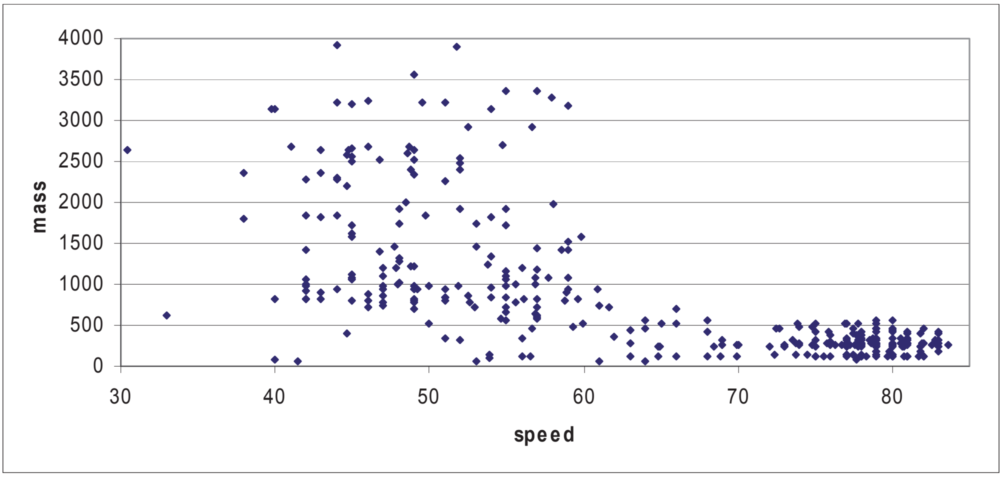


Fig. 2. Relation of mass versus speed

3. Model of distribution of parameters

The fact that the analyzed sets are heterogeneous caused that in order to analyze of the probability distribution of parameters of the rail vehicles is not applicable to the various distributions such Weibull and gamma. In this paper, we analyze two-component mixture distribution of distributions as the distribution of examined parameters. Let X and Y be the independent random variables with the density functions $f_1(x)$ and $f_2(x)$, the cumulative distribution functions $F_1(x)$ and $F_2(x)$, the reliability functions $R_1(x)$ and $R_2(x)$, the failure rate function (hazard function) $\lambda_1(t)$ and $\lambda_2(t)$. Distribution function of the mixture X and Y is described by the following formula:

$$F(x) = p\,F_1(x) + (1-p)\,F_2(x),$$

where p is the mixing parameter and $0 \le p \le 1$.
Analogously for the density function f(x) and the reliability function R(x), we can write as

$$f(x) = p\,f_1(x) + (1-p)\,f_2(x),$$

$$R(x) = p\,R_1(x) + (1-p)\,R_2(x).$$

The mean value of the random variable X is

$$EX = p\,m_1 + (1-p)\,m_2,$$

however the variance of X is

$$D^2X = p\,\sigma_1^2 + (1-p)\,\sigma_2^2.$$

The failure rate function of the mixture can be written as the mixture [4]:

$$\lambda(t) = \omega(t)\,\lambda_1(t) + (1-\omega(t))\,\lambda_2(t),$$

where $\lambda(t) = f(t) / R(t)$, $\omega(t) = pR_1(t) / R(t)$, $\lambda_1(t)$ and $\lambda_2(t)$ are the failure rate functions of the lifetimes X and Y. Understanding the shape of the failure rate function is important in reliability theory and practice.

Teicher [12, 13] introduced the concept of identifiability and developed a theory of identify mixtures. The concept of identifiability plays a vital role in the analysis of the finite mixture model. A mixture is identifiable if there exists a one to one correspondence between the mixing distributions and resulting mixture. The inference procedures on the mixture distributions can be meaningfully discussed only if the family of mixture distributions is identifiable.

The basic problem is to infer about unknown parameters, on the basis of a random sample of size n on the observable random variable X. The first opinion of the data from the DSAT system shows that the mixture of two normal distributions is a proper model for analyzed parameters. The density function of the mixture of two normal distributions can be written in the following form

$$f(x; m_1, m_2, \sigma_1^2, \sigma_2^2, p) = \frac{p}{\sqrt{2\pi\sigma_1^2}}\exp[-\frac{(x-m_1)^2}{2\sigma_1^2}] + \frac{1-p}{\sqrt{2\pi\sigma_2^2}}\exp[-\frac{(x-m_2)^2}{2\sigma_2^2}] \tag{1}$$

We will estimate five parameters $m_1, m_2, \sigma_1, \sigma_2, p$ of the density (1). To estimate parameters $\Theta = (m_1, m_2, \sigma_1^2, \sigma_2^2, p)$ we will use the likelihood method. The likelihood function for the mixture (1) is

$$L(x_1, x_2, \ldots, x_n: m_1, m_2, \sigma_1^2, \sigma_2^2, p) = \prod_{i=1}^{n} f(x_i : m_1, m_2, \sigma_1^2, \sigma_2^2, p)$$

The logarithm of the likelihood function is

$$\ln L(x_1, x_2, \ldots, x_n: m_1, m_2, \sigma_1^2, \sigma_2^2, p) = \sum_{i=1}^{n} \ln f(x_i : m_1, m_2, \sigma_1^2, \sigma_2^2, p)$$

We compute the first partial derivative:

$$\frac{\partial \ln L}{\partial m_1} = \sum_{i=1}^{n}\left(\frac{1}{A}\frac{p}{\sqrt{2\pi\sigma_1^2}}\exp[-\frac{(x_i-m_1)^2}{2\sigma_1^2}] \times \frac{(x_i-m_1)}{\sigma_1^2}\right) = 0$$

$$\frac{\partial \ln L}{\partial m_2} = \sum_{i=1}^{n}\left(\frac{1}{A}\frac{1-p}{\sqrt{2\pi\sigma_2^2}}\exp[-\frac{(x_i-m_2)^2}{2\sigma_2^2}] \times \frac{(x_i-m_2)}{\sigma_2^2}\right) = 0$$

$$\frac{\partial \ln L}{\partial \sigma_1^2} = \sum_{i=1}^{n}\left(\frac{1}{A}[-\frac{p}{2\sqrt{2\pi}}(\sigma_1^2)^{-\frac{3}{2}}\exp[-\frac{(x_i-m_1)^2}{2\sigma_1^2}] + \frac{p}{\sqrt{2\pi\sigma_1^2}}\exp[-\frac{(x_i-m_1)^2}{2\sigma_1^2}]\frac{(x_i-m_1)^2}{2(\sigma_1^2)^2}]\right) = 0$$

$$\frac{\partial \ln L}{\partial \sigma_2^2} = \sum_{i=1}^{n}\left(\frac{1}{A}[-\frac{p}{2\sqrt{2\pi}}(\sigma_2^2)^{-\frac{3}{2}}\exp[-\frac{(x_i-m_2)^2}{2\sigma_2^2}] + \frac{1-p}{\sqrt{2\pi\sigma_2^2}}\exp[-\frac{(x_i-m_2)^2}{2\sigma_2^2}]\frac{(x_i-m_2)^2}{2(\sigma_2^2)^2}]\right) = 0$$

$$\frac{\partial \ln L}{\partial p} = \sum_{i=1}^{n}\left(\frac{1}{A}(\frac{1}{\sqrt{2\pi\sigma_1^2}}\exp[-\frac{(x_i-m_1)^2}{2\sigma_1^2}] - \frac{1}{\sqrt{2\pi\sigma_2^2}}\exp[-\frac{(x_i-m_2)^2}{2\sigma_2^2}])\right) = 0$$

where $A = f(x_i; m_1, m_2, \sigma_1^2, \sigma_2^2, p)$.

To find the maximum log-likelihood function, we set the first partial derivative equal to zero. In finite mixture model, the EM algorithm has been used as an effective methods to find maximum likelihood parameters estimation.

4. Real data set

In this chapter of paper, we will estimate the parameters m_1, m_2, σ_1^2, σ_2^2, p of the mixture two normal distributions for the random variable X_1– speed of train, X_2 – number of axles, X_3 – length of train, and X_4 – mass of train. By λ-KS we describe the value of the goodness of fit statistics λ- Kolmogorov.- Smirnov We used o procedure EM algorithm given for special case of normal mixtures by Hastie et al. [2]. The estimated parameters, K-S test statistics and p – values for four random variables are given in Table 1. All considered the parameters of rail vehicles shown good conformity the empirical distributions and the mixture distributions.

Tab.1. Values of parameters of mixtures

Random variable	Parameters of mixture					goodness of fit statistic λ – KS	p– value
	m_1	m_2	σ_1	σ_2	p		
X_1– speed	51.270	78.115	7.8284	2.6947	0.5315	0.3780	0.99
X_2 – axles	37.609	151.49	12.570	43.104	0.5310	0.6102	0.85
X_3–length	191.92	599.77	72.529	109.84	0.5476	0.9153	0.56
X_4– mass	381.66	2051.8	39.215	788.59	0.7381	0.8543	0.53

The graphs of the components (ft and ft-1) of the mixture and the density function (ft-2) of mixture are shown in Figure 3.

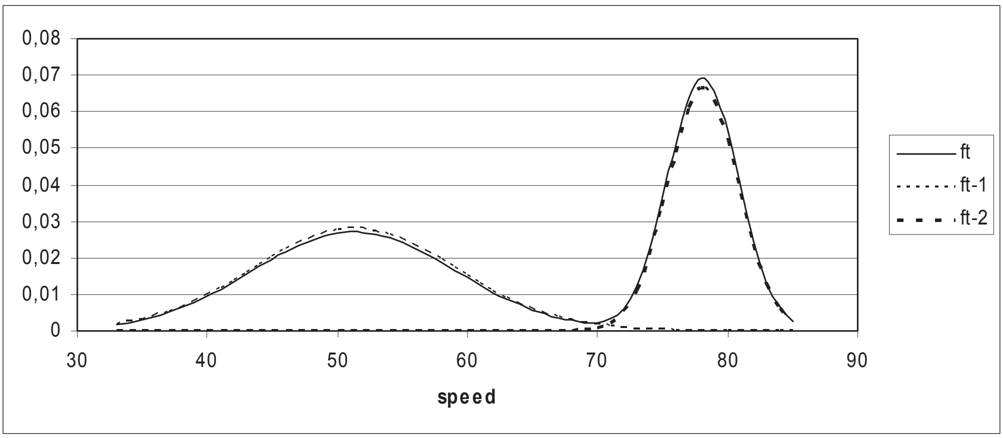


Fig. 3. The factors of mixture and the density function of mixture

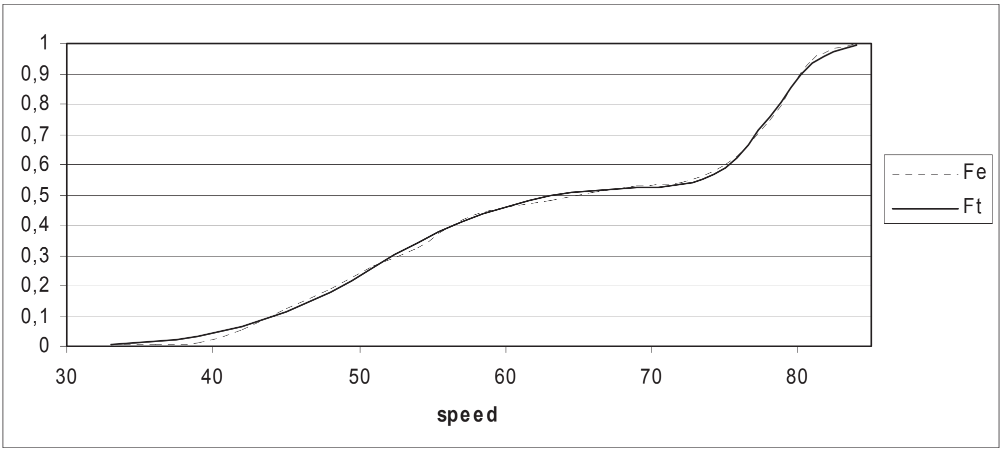


Fig. 4. The distribution function of speed (Fe) and the mixture (Ft)

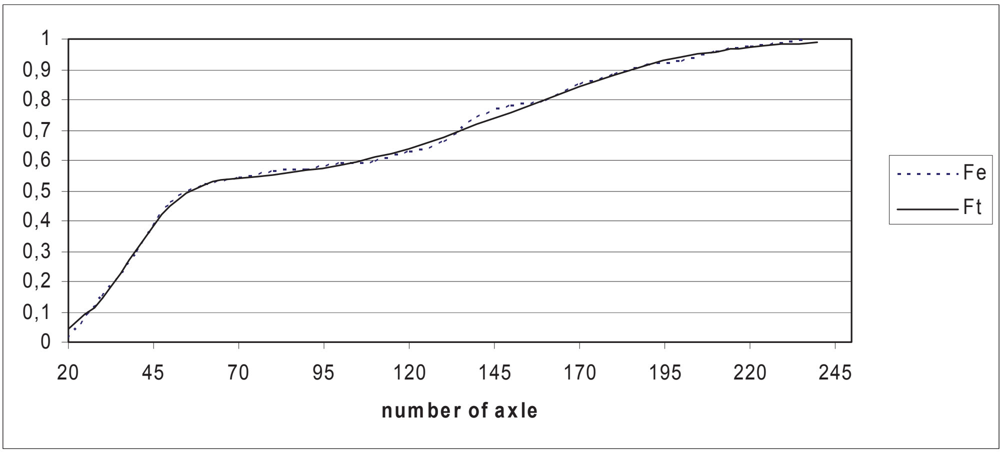


Fig. 5. The distribution function of number of axles (Fe) and the mixture (Ft)

The graphs the distribution function of the speed and distribution function of mixture are shown in Figure 4. We conclude that the mixture two-normal distributions is consistent model with the empirical distribution of the speed. The graphs of empirical distribution of the number of axles and the distribution function of mixture two-normal distributions are shown in Figure 5. In this case, we observe that both distribution are consistent too. The distribution functions for the length and the mass is given in Figure 6 and Figure 7.

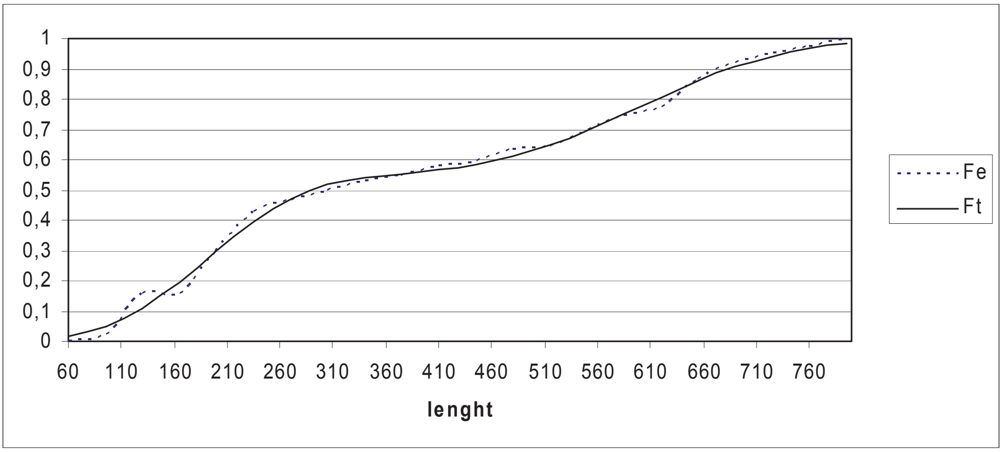


Fig. 6. The distribution function of the length (Fe) and the mixture (Ft)

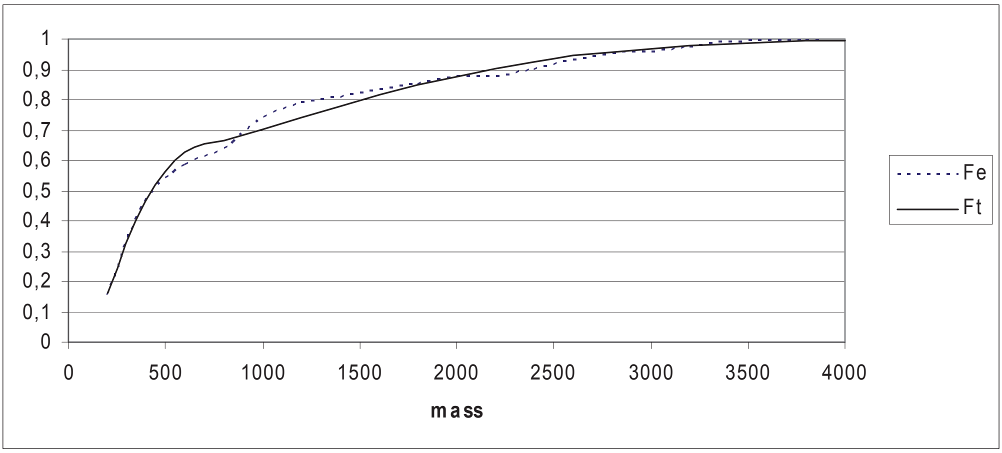


Fig. 7. The distribution function of the mass (Fe) and the mixture (Ft)

5. Conclusions

We use the mixture of two-normal distribution model for investigating complex distributions of the rail vehicles. It is shown that the mixture of two normal distributions is useful for exploring the complex distributions. Lastly, we fit the two component mixture normal distribution to data set using EM algorithm to maximize the likelihood function.

References

[1] Dempster, A.P., Larid, N.M. and Rubin, D.B., *Maximum likelihood from incomplete data via the EM algorithm*, Journal Statistical Society, Series B, 39, pp. 1–38, 1977.

[2] Hastie, T., Tibshirani, R. and Friedman, J., *The Elements of Statistical Learning: Data Mining, Inference and Prediction*, Springer Verlag, 2001.

[3] Fruhwirth-Schnatter, S.,Finite Mixture and Markov, *Switching Models*, New York, Springer, Verlag 2006.

[4] Knopik, L., *Mixture of distributions as a lifetime distribution of a technical object*, Scientific Problems of Machines Operation and Maintenance, Vol.162, No2, pp.53─61, 2010.

[5] Knopik, L., *Mixture of distributions as a lifetime distribution of a bus engine*, Journal of Polish CIMAC Vol.6, No1, pp. 119─129, 2011.

[6] Knopik, L., *Model of instantaneous failures*, Scientific Problems of Machines Operation and Maintenance, Vol.163, No4, pp. 123─133, 2011.

[7] Knopik, L., *Statistical analysis of failures*, Journal of Polish CIMAC Vol.7, No.2, pp. 91─95, 2012.

[8] Lindsay, B.G., *Mixture Model: Theory*, *Geometry and Applications*, Hayward Institute of Mathematical Statistics, 1995.

[9] MacLachan, G. J. and Basford K. E., *Mixture Model: Inference and Applications to Clustering,* Marcel Dekker, New York, 1988.

[10] MacLachlan, G. and Peel, D., *Finite Mixture Models*, John Wiley and Sons, New York, 2000.

[11] MacLachan, G.J. and Krishan, T., *The EM algorithm and extensions*, John Wiley & Sons, New York, 1997.

[12] Teicher, H., *Identifiability of mixtures*, The Annals of Mathematical Statistics, vol. 32, No.1, 244-249, 1961.

[13] Teicher, H., *Identifiability of finite mixtures*, The Annals of Mathematical Statistics, vol. 34, No.4, 1265- 1269, 1963.

[14] Titterington, D.M., Smith A.F.M. and Makov U.E., *Statistical Analysis of Finite Mixture Distribution*, John Wiley and Sons, New York, 1985.

Journal of POLISH CIMAC
Faculty of Ocean Engineering & Ship Technology
GDAŃSK UNIVERSITY OF TECHNOLOGY

USE OF LANGMUIR PROBE IN DIESEL ENGINE DIAGNOSTIC RESEARCH

Part I
MEASUREMENT TECHNOLOGY

Zbigniew Korczewski
Jacek Rudnicki

GdanskUniversity of Technology
ul. Narutowicza 11/12, 80-233 Gdańsk, Poland
tel.: +48 58 3472973, fax: +48 58 3471981
e-mail:jacekrud@pg.gda.pl

Adam Cenian
Leszek Piechowski

The Szewalski Institute of Fluid-Flow Machinery
PolishAcademy of Sciences
Fiszera 14 st., Gdańsk 80-231, Poland
e-mail:lpiechowski@imp.gda.pl

Abstract

In the paper, the basic assumptions of diesel engine cylinder system's diagnosing method, based on observation of emerging and moving electric charges of ionized gas in the combustion workspaces, using Langmuir's probe. In the first part of the paper, only the technology of the measurement and results of the preliminary diagnostic tests of laboratory engine Farymann Diesel D10 were presented. The primary purpose of the research was confirmation of susceptibility of a control diesel engine to a completely original measurement method that enables a precise determination of the angle of fuel's self-combustion. To verify the diagnostic utility of the obtained measurement data, simultaneously, the measurement of the cylinder pressure and generated vibrations coming from injection system and engine valve train (measured on the cover of the head or its tie bolt) were carried out.

The reaserch were financed as a part of a Reaserch Task No 4 "Elaboration of integred technologies of fuel and energy production using biomass, agricultural waste and other" under a strategical programme of scientific research and development works "Advanced technologies of energy production", co-financed by NCBiR and ENERGA S.A.

The solution of the measurement of the angle of fuel's self-combustion presented in the article was applied to Polish Patent Office. The application number is P.402669, titled:„Układ monitorowania kąta samozapłonu paliwa, zwłaszcza w cylindrze silnika o zapłonie samoczynnym z zastosowaniem sondy Langmuira”. (The monitoring system of the angle of fuel's self-combustion, in the cylinder of a diesel engine using Lagmuir's probe")

Keywords: *technical diagnostics, diesel engine, Langmuir's probe*

1.Introduction

In spite of dynamic development of diesel engine cylinder system's diagnosing methods, the basic method of the evaluation of the workspace technical condition is parametrical evaluation of the work process, based on measurements of the pressure change in cylinders, using more precise digital indicators. The development of optical-electronically technique is so enormous that the measurements, concerning low-speed marine diesel engines, are carried out almost continuously (on-line) for it is enabled by high durability of modern fiber pressure converters (Optrand) [2].

Most of presently used, more excellent digital indicators, enables the obtainment of expanded indicator graphs, i.e. the course of pressures in the cylinder (measured on or ahead of indicator valve), imposed on properly filtered course of accelerations of generated vibrations from injection system and engine valve train (measured on the cover of the head or its tie bolt) that are referred to the angle location of the crankshaft (piston GMP). They are the basic source of diagnostic information for engine's workspace.

On the basis of simultaneous measurements of pressures in cylinders, vibrations of cylinder heads and the rotational speed of crankshaft it is possible to calculate the following diagnostic parameters of the engine workspace (figure 1):

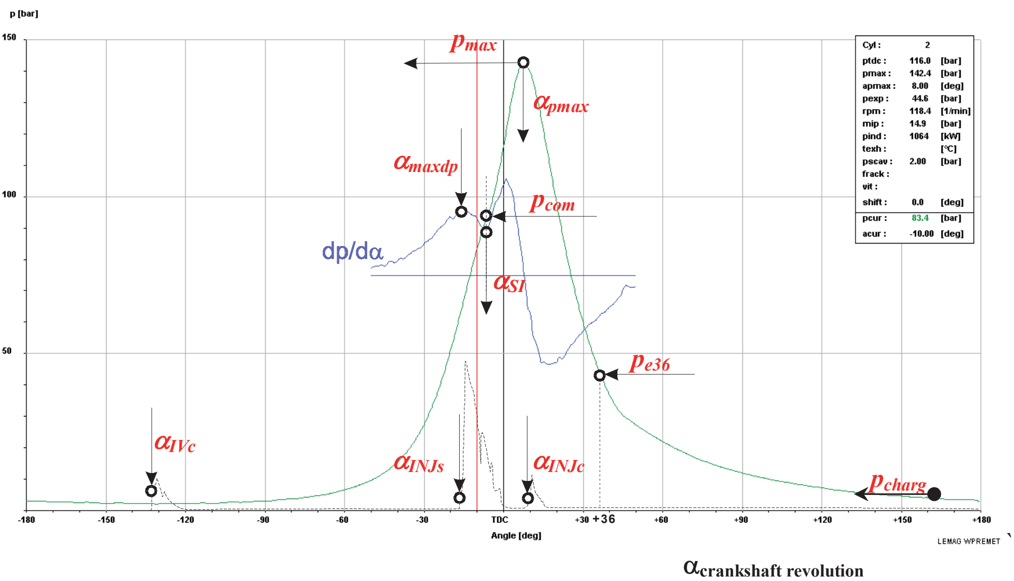


Fig. 1. Parameters characterizing expanded indicator diagram and the graph of the vibration envelope generated from the cylinder head cover: p_{max} – maximum pressure of combustion, p_{com} – maximum pressure of compression (optionally compression pressure for an angle 10^0 before TDC), p_{e36} – expansion pressure for an angle 36^0 after TDC, p_{charg} – charge air pressure, α_{pmax} – angle of maximum combustion pressure, α_{SI} – self-ignition angle of fuel, α_{maxdp} – angle of maximum dp/dα, α_{IVc} – intake valve closing angle, α_{INJs} – fuel injection timing, α_{INJc} – fuel injection end angle

- maximum pressure of compression and combustion - p_{comp} [bar], p_{max} [bar],
- mean indicated pressure of individual cylinders - MIP [bar]
- power indicated of individual cylinders and whole engine - PIND [kW],
- speed of pressure increase in cylinder - dp/dα [bar/0OWK],
- angles of opening and closing the injector - α_{INJs}, α_{INJc} [0OWK],
- angle of fuel's self-ignition beginning in cylinders - α_{SI} [0OWK],
- angles of opening and closing cylinders' valves - α_{IVc} [0OWK].

It enables us to perform:

- the evaluation of engine's cylinders tightness,
- the evaluation of equality of the load for individual cylinders,
- the evaluation of injection system and valve timing regulation,
- the evaluation of whole engine's achievements,
- the evaluation of engine and powertrain mechanical loss,
- the prognosis of time of engine's proper work.

The key metrological issue of the diagnostic process algorithm above is precise determination of the combustion beginning (the point of fuel's self-ignition) in the indicator graph. There are two methods of conduct:

a) on the basis of a derivative waveform of the cylinder pressure registered [9, 3, 6],
b) b) on the basis of the course of polytropic compression exponent [8].

The research carried out by the Authors of this paper enabled to suggest the original method of determination of the combustion beginning in the Diesel engine, based on entering the electrical probe, so called Langmuir's probe [1,4,5] directly to its combustion chamber. It enables the record of plasma generated in the combustion front fuel's parameters, after the initiation of air-fuel mixture self-ignition. The verification of the diagnostic method used is based on comparative analysis of measurement results acquired in simultaneous indication of cylinder and measurement of electrical signal course (voltage U_{wz}), acquired in standard resistor $R_{wz}=1\Omega$ included in the measurement system with Langmuir's probe.

2. The description of measurement system with Langmuir's probe.

The construction of Langmuir's probe is shown in Figure 2. It consists of two spaced metal electrodes positioned in space, where electrical charges can occur. The electrodes are connected to the power source U_{pol} and there's a voltage in between them and is consistent with the voltage of the power source used. If an electrical charge occurs in the space between electrodes (as electrons or ions), it causes flow of electric charge in seemingly detached electrical network.

Time of electric current flow (and its value) depends on time of electric charges occurring in the space between probe's metal electrodes. If Langmuir's probe is successfully entered to the workspace of diesel engine cylinder during the combustion process, it is expected that fuel self-ignition initiation will be accompanied by electrical charges formation. Electrical charges occurring along with combustion will be registered by Langmuir's probe.

If the moment of charge's formation (the beginning of fuel's self-ignition) with angular location of crankshaft, this time correlation enables to determine the angle of fuel self-ignition αsi. In order to determine the time of charges formation occurring during the combustion process in relation to the course of pressure changes in the cylinder space, it is necessary to carry out simultaneous measurement of the pressure and voltage parameter of plasma generated.

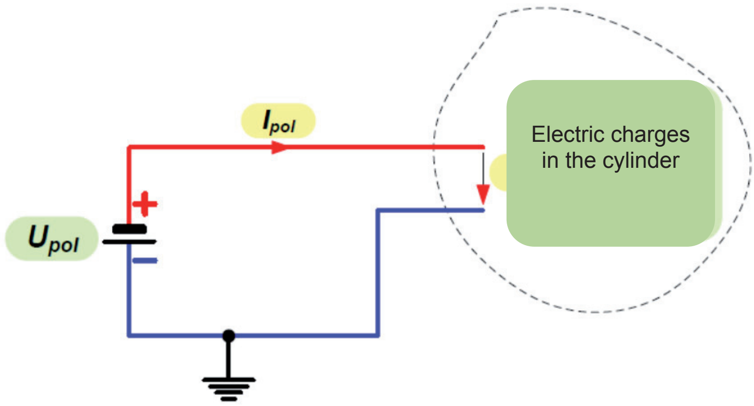


Fig.2 Structure and operation of the Langmuir probe

The operation of Langmuir's probe shown in figure 2 indicates when it is entered to the cylinder space, in the case of hydrocarbon flame initiation, in probe's electrical network an I_{pol} amperage occurs. Langmuir's probe consists of metal electrode polarized with U_{pol} voltage. An engine's trunk usually consists of a long electrode, which is why the probe should be isolated from the trunk. The simple measurement system shown in figure 3 allows an observation of I_{pol} amperage change. Oscilloscope allows both observation and registration of U_{wz} voltage change existing on R_{wz} dimmer, as a result of electric current flow with I_{pol}.

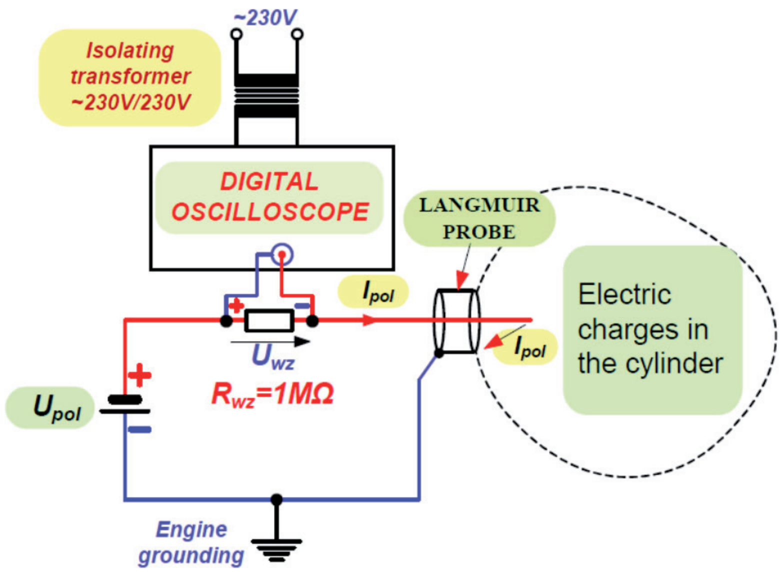


Fig.3. Langmuir probe circuit and registration setup with oscilloscope. It has to be noticed that the power source of an oscilloscope must be isolated (separated).

In passing it should be noted that it is vital to use the isolated (separated) power source for oscilloscope. Lack of this separation results in short circuit of oscilloscope's probe screen with electrical mass of diesel engine.

3. Technical capabilities of Langmuir's probe use in diagnostic research - the results of operating preliminary research.

The access to the serial engine cylinder space is possible only through indicator and due to that, it is imposed to manufacture Langmuir's probe in a way that enables simultaneous measurement of electrical charges and pressure in cylinder workspace. It means that an appropriate intermediate connector is required, so called adapter. It is vital to account a limit of measurement technology used that is existence of high temperatures and pressures in cylinder workspace. Furthermore, if the engine was not standard equipped in indicator valve (or it is impossible to enter the probe through indicator valve), an additional technical hole should be performed in its head.

Preliminary experimental research was carried out in laboratory conditions using one cylinder diesel engine Farymann Diesel type D10, loaded with hydraulics power system.

The research place consists of the following compounds:

- diesel engine, four-stroke, one cylinder, "Farymann Diesel" type D10, with power N= 5,8 kW and nominal rotational speed n=1500 rotations/minute, displacement - 765 cm3, cylinder diameter - 90 mm and compression level 1:22,
- hydraulics pump, meshed, of series No21, produced by „Waryński Hydraulika" Sp. z o.o.- Warsaw,
- hydraulics engine, meshed, of series No21, produced by „Waryński Hydraulika" Sp. z o.o. – Warsaw,
- measurement and control equipment,
- installation and fittings of hydraulics system,
- hydraulic oil tank,
- diagnostic equipment.

The whole installation is built into the foundation of multi-machine auxiliary system produced by MotorfabrikenBukh A.S. Dania.

The engine is equipped in the cast of ignition paper, a screwed cylinder head. The hole of screwed cast of ignition paper has a cut thread M14x1,25 that is used in indicator valve installation (figure 4).

a) b)

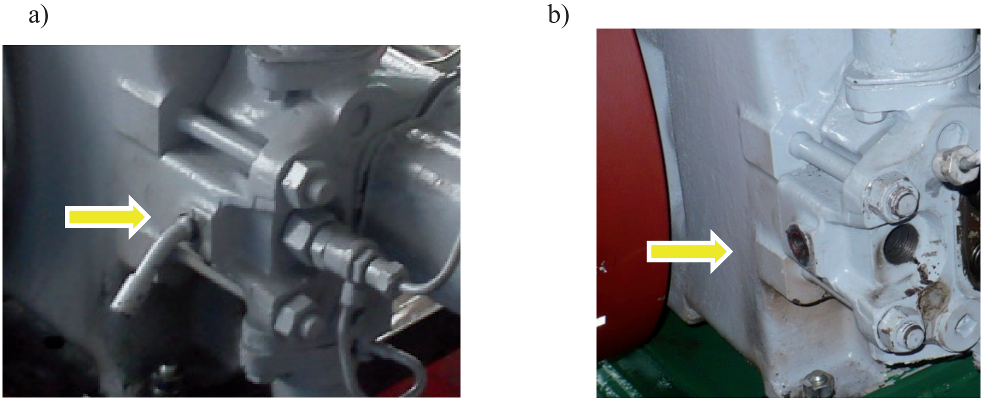


Fig. 4.The view of indicator valve installation seating in place of ignition paper - a) and b)

Figure 5 presents an applied prototype of Langmuir's probe, measurement equipment used and the method of its installation on the engine, with simultaneous application of electronic indicator. An important limitation of the technology used is a necessity of such probe's electrode leading so the required isolation from ship's trunk. It is still necessary to carry out an experimental research in order to discover the influence of exhaustion gases on condition (loss) of the isolation.

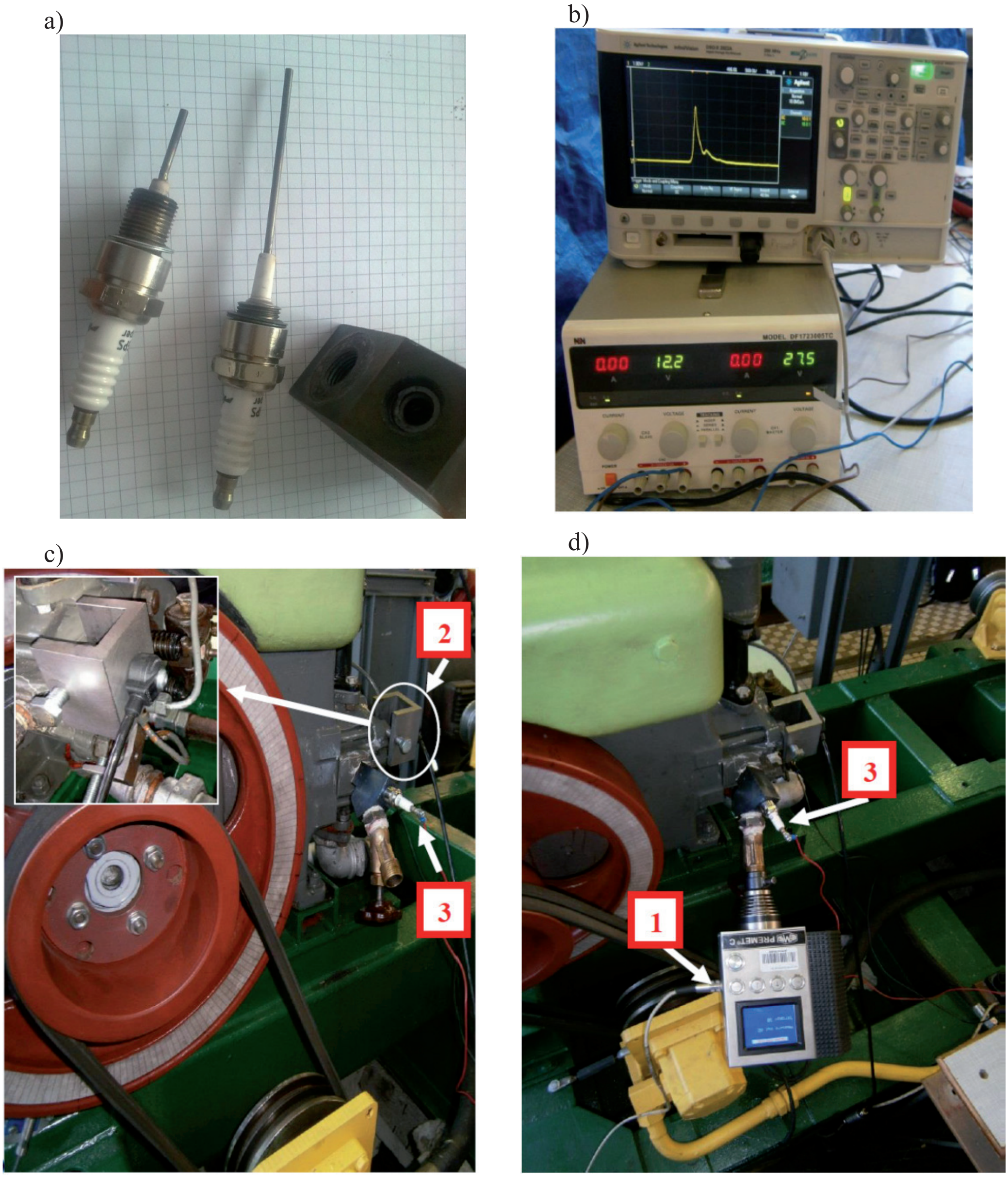


Fig. 5. Research equipment: a) the structural form Langmuir probes used in the study (on the right is shown the adapter which enables the simultaneous measurement using Langmuir probe and the electronic indicator), b) the plasma current combustion front recorder, c) mounting the electronic indicator "C LEMAG PREMET" (1), d) mounting acceleration sensor of vibration generated on the cylinder head (2) and Langmuir probe (3).

There is a strong influence of soot existing in exhaustion gases, which is a good electrical conductor, can cause a short circuit in the probe's construction.

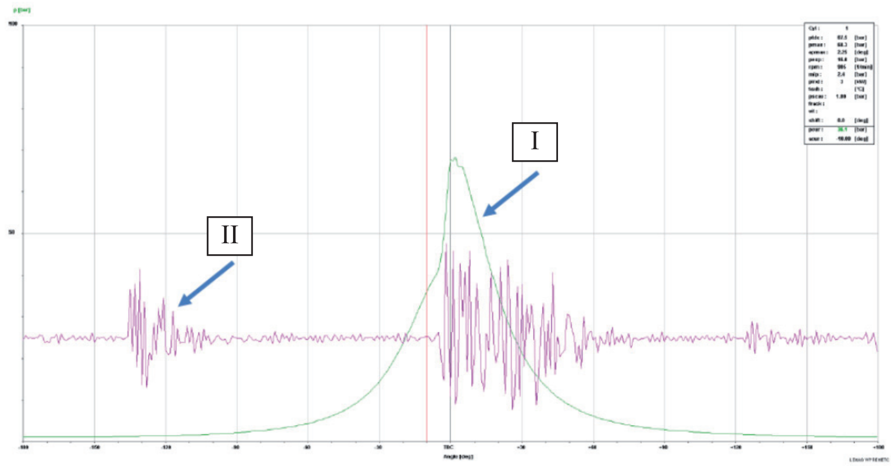
The implementation of preliminary research program, that had confirmation of theories described above as its basic purpose, required simultaneous measurement and registration of the following control parameters:

- pressure in the cylinder,
- acceleration of the generated vibration of cylinder head,

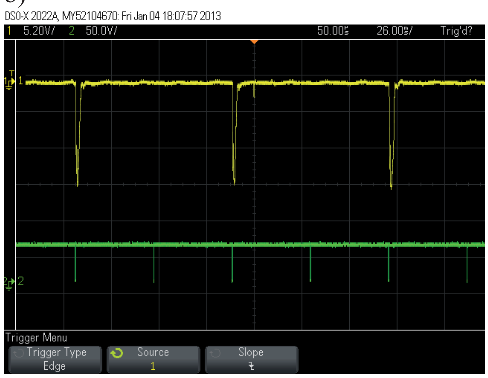
- rotational speed of the crankshaft,
- plasma potential.

The measurements were performed in the condition of established engine work in idle and an example results (presented as indicator graphs and registered oscillograms) are presented in Figure 6.

a)



b)



c)

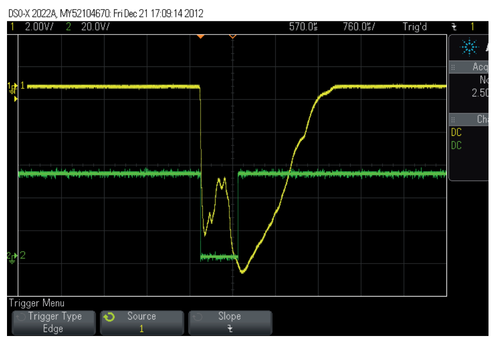


Fig. 6. Recorded signals: a) cylinder pressure (I) and cylinder head vibration (II), b) and c) electric potential of the plasma.

The analysis of registered time courses of plasma potential changes (fig. 6 b and c) indicates an occurance of steep time signal slope, characteristical for beginning of fuel's combustion process in the cylinder of diesel engine. Its shape is analogus to the course of heat discharge in workspaces of such engines [7]. Numerical data shows that the time of signal increase is about 0.1 ms, which enables precise determination of fuel's self-ignition moment in the engine examined.

4.Summary

The precise determination of angular location that accompanies fuel's self-ignition in diesel engine is a primary condition of expressing a reliable diagnosis of its workspaces and fuel reinforcement system. The observation of emerging and moving electrical charges of ionized exhaustion gas using Langmuir's probe, that is entered into engine's workspace through indicator valve, brings completely new possibilities.

The preliminary research of a laboratory diesel engine using Langmuir's measurement method confirmed its high utility values and diagnostic usefulness. The object characterized in very good control susceptibility, which is a good prognosis for further diagnostic research in conditions of using biofuel.

Further works will be focused on perfecting the technology of the measurement and software in order to precise synchronization of all observed engine's control parameters registration, allowing the comparative analysis of their courses and angular location of the crankshaft.

References

[1] CENIAN A., *Diagnostyka procesu spalania węglowodorów,* Raport końcowy projektu badawczego PB1071/T10/2002/22. IMP PAN, Gdańsk 2002.

[2] KORCZEWSKI Z., *Określenie zasad weryfikacji modelu diagnostycznego układów korbowo-tłokowych i jego ewentualnej modyfikacji dla potrzeb racjonalnego sterowania procesem eksploatacji silników,* Opracowanie w ramach realizacji projektu badawczego finansowanego przez MNiSW Nr N N509 494638, Politechnika Gdańska, Gdańsk 2012.

[3] ŁUTOWICZ M., *Identyfikacja procesu sprężania okrętowego tłokowego silnika spalinowego dla potrzeb diagnostyki jego przestrzeni roboczych,* Rozprawa doktorska, Akademia Marynarki Wojennej, Gdynia 2006.

[4] MACLATCHY C.S., *Charge depletion downstream of a cylindrical Langmuir probe immersed in flowing, high-pressure plasma,* IEEE Transactions on Plasma Science, Vol. 17, NO. 1. February 1989.

[5] MACLATCHY C.S., SMITH H.C.L., *The electron Current to a Langmuir probe in flowing high-pressure plasma. IEEE Transactions on Plasma Science*, Vol. 19, NO. 6. December 1991.

[6] POLANOWSKI S., *Studium metod analizy wykresów indykatorowych a aspekcie diagnostyki silników okrętowych,* Monografia habilitacyjna, Zeszyty Naukowe Akademii Marynarki Wojennej, nr 169A, Gdynia 2007.

[7] RYCHTER T., TEODORCZYK A., Teoria silników tłokowych, WKiŁ, Warszawa 2006.

[8] STELMASIAK Z., Gilowski T., *Metody Określania początku spalania w obliczeniach wykorzystujących wykresy indykatorowe uzyskane z badań silnika,* Konferencja „TRANSCOMP", Zakopane 2001, s. 309-314.

[9] TOMCZAK L., *Metoda pośredniego określania położenia kątowego wału korbowego silnika okrętowego i jej wykorzystanie w indykatorze elektronicznym,* Rozprawa doktorska, Politechnika Gdańska, Gdańsk 2001.

Journal of POLISH CIMAC
Faculty of Ocean Engineering & Ship Technology
GDAŃSK UNIVERSITY OF TECHNOLOGY

ANALYSIS OF LANDING OPERATION INCLUDING THE EMERGENCY STATES

Anna Kwasiborska, Anna Stelmach

Warsaw University of Technology
Faculty of Transport
Ul. Koszykowa 75, 00-662 Warszawa
e-mail: akw@it.pw.edu.pl, ast@it.pw.edu.pl

Abstract

Air transportation as a fast-growing transport mode provides the constantly innovating constructions. Security is an integral factor in determining the movement of the aircraft. The paper contains an analysis of landing operations including emergency states. Describes the flight rules with inoperative engine. All these parameters have a direct impact on ensuring safety of passengers and crew members.

***Keywords**: air transportation, security*

1. Introduction

Air transport plays a major role in the development of world economic activity and remains one of the fastest growing sectors of the international economy. One of the key elements that contribute to the maintenance of civil aviation development is to secure safe, efficient and environmentally sustainable means of transport, at the global, local and regional level.

Air transport is the safest mode of transport, but still air accidents remain inevitable. The causes of air accidents are different and largely dependent on the current flight phase of an aircraft. Most critical phases of flight are takeoffs and landings, due to potentially dangerous proximity of the earth's surface [5]. These two flight phases must be performed with adherence to basic safety rules and the procedures for takeoff and landing must be strictly followed.

2. Characteristics of the landing operations

A very important operation that the aircraft has to perform before coming to a safe standstill is landing [4]. This part of flight can be defined by applying two main guidelines. The first one is meeting the premise that the distance needed to land should not be greater than the distance available. Considering the length available for landing it should be realised that this phase begins at 50 feet above the runway, whereas landing ends once a complete standstill has been reached.

The speed to be achieved when coming to 50 feet should not be less than 123% of V_{SRO}[1] and not less than V_{MCL}[2]. This speed is called V_{REF}[3].

Another prerequisite to be fulfilled during the landing operation is to make sure that the aircraft can be quickly taken off the runway while maintaining an appropriate climb angle. Included both in the JARs[4] and the CS-25[5], these requirements are slightly complicated and divided into the two parts: for the climb angle of the aircraft with all engines operative and that with one engine inoperative.

With the climb angle values required for the aircraft with all engines operative, the right parameters can be achieved to take off the aircraft and make a go-around. These requirements specify the constant climb angle value of at least 3.2% of the engine power available eight seconds after the initiation of the go-around procedure, but the climb speed has to meet the following conditions [1]:

1) should not be less than:
    a. 108% of V_{SR}[6] for aircraft with four engines in which increasing the power results in a substantial reduction of the stall speed,
    b. 113% of V_{SR} for all other aircraft types,
2) should not be less than V_{MCL},
3) should not be greater than V_{REF}.

The climb angle required after take-off with one engine inoperative is another part of the second requirement included in the JARs and the CS-25 that should be met by the aircraft for safety reasons. This requirement is supposed to ensure the right climb angle for the aircraft with one engine inoperative to go around. For such an aircraft configuration, the constant climb angle should not be less than 2.1% with the operative engine's power sufficient for take-off. This value is referred to the maximum landing weight, the extended landing gear and the climb speed based on the normal landing operation, but it should not be greater than 1.4 of V_{SR}. The described values are reasonable for twin-engine aircraft only. For three-engine aircraft, the climb engine should not be less than 2.4%, whereas for four-engine aircraft, it should not be less than 2.7%. It should be noted that all climb angle values are referred to the air, i.e. they depend on weather conditions.

The JARs specify the climb angle requirements in more detail, concluding that the weight of the aircraft climbing after a failed landing should be sufficient to achieve the projected climb angle values. If this weight were exceeded, the aircraft would not be capable of meeting the requirements in this respect.

Landing takes place not only in the air, but also on the ground [2, 3]. The most important issues in this segment are the criteria for the length of the distance necessary for landing. The regulations state that the pilot has to make sure that the weight of the aircraft for the correctly estimated time required for landing enables a complete standstill from a height of 50 feet and falls within:

- 60% of the available landing distance for turbojet aircraft,
- and 70% of the available landing distance for turboprop aircraft.

Landing is that stage of flight when the aircraft reaches a height of 50 feet above the runway before it comes to a complete standstill. Such landing can be divided into two stages. One relates

[1] V_{SRO} – indicative landing stall speed

[2] V_{MCL} – minimum landing speed at which the aircraft with one engine inoperative is controllable

[3] V_{REF} - the speed values associated with achieving V_{SRO} and V_{MCL}

[4] JARs (Joint Aviation Requirements) – European aviation regulations of the Joint Aviation Authorities

[5] CS 25 – Certification Specifications 25 – specifications of the European Aviation Safety Agency for large passenger aircraft.

[6] V_{SR} – stall speed used to determine other speeds of the aircraft as a percentage reference.

to the time when the aircraft is in the air and the other to the time when the landing gear constantly touches the ground. In a projection onto the ground plane, the airborne part usually is 1000 feet and specific steps have to be taken within this distance. After reaching a height of 50 feet the pilot completely reduces the thrust of the engines and raises the nose of the aircraft. With such a configuration in place, the main wheels of the aircraft are the first to touch the runway when landing. One should also bear in mind that descent techniques vary depending on the aircraft and will be totally different for lightweight aircraft and different for large aircraft, e.g. operated by transport companies.

Another landing stage relates to the ground part, which comprises the movement of the aircraft from touchdown until a complete standstill [10]. Similar to the airborne part, there are specific operations that have to be performed. After the wheels of the main landing gear touch the ground, reverse thrust and an appropriate flap configuration can be used. By introducing such solutions, the aircraft can securely lose speed. Nevertheless, in reality the aircraft cannot come to a complete standstill on the runway, but only at a certain location beyond it. Therefore, the aircraft is brought to an appropriate minimum speed so as to reach the destination point.

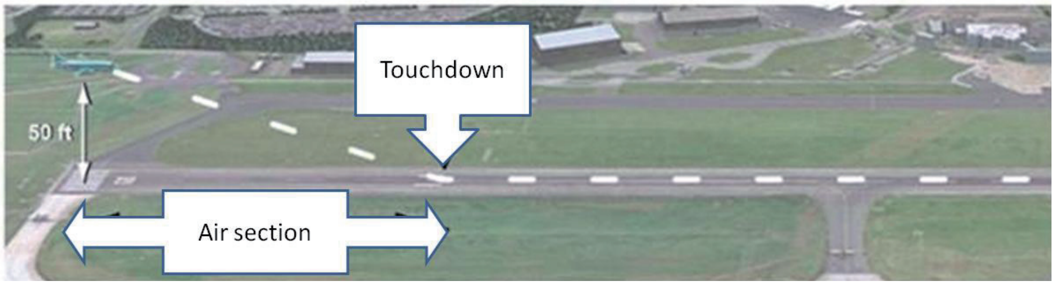


Fig. 1. Landing Descent Diagram

Another factor affecting the characteristics of aircraft movement during landing is resistance force. This force is responsible for the reduction of forward progression. The two forms of this force should be taken into consideration when landing: aerodynamic resistance force and wheel rolling resistance.

Wheel resistance force and braking force are further components affecting the total resistance. The first force relates to the resistance of the wheels rolling down the runway, whereas the second one to the resistance generated by applying the brake shoes to the brake disc. The wheel rolling resistance comes to analysis when the first wheels of the main landing gear touch the ground. As the lift force in the initial landing phase on the ground, immediately after touchdown, is still significantly low, the rolling resistance will not be so efficient as it is when the lift force decreases. It is so because the force of gravity is somewhat balanced by the lift, resulting in a low efficiency of such resistance. If you change the flap configuration, the lift force decreases, increasing the share of the rolling resistance in the total impact of resistance forces. An increase in this force can be observed for the entire time of the retarded movement down the runway, and its maximum value can be recorded just before a complete standstill.

The resistance force generated by the wheel brakes is several times higher than the resistance caused by reverse thrust and approximately two and a half times higher than that caused by the wheels rolling. A prerequisite for achieving such a high braking efficiency is, however, a proportionally high wheel rolling speed because it will not be possible to obtain such a high braking force without a relatively high abrasion of the wheels against the ground. Therefore, right after touching the runway, when the rolling resistance is low, the brake efficiency will be low as well. Such a correlation between rolling resistance and braking force implies the pilot's need to get rid of the lift force during touchdown.

3. Identification of the parameters during the flight phase

For more detailed analysis was performed to identify landing operations as part of the research process. It was prepared computer identification of parameters, which consist of developing the mathematical model using the results of the measurements carried out on a real object. Simplified scheme of identification process can be presented as shown on below figure [11, 12].

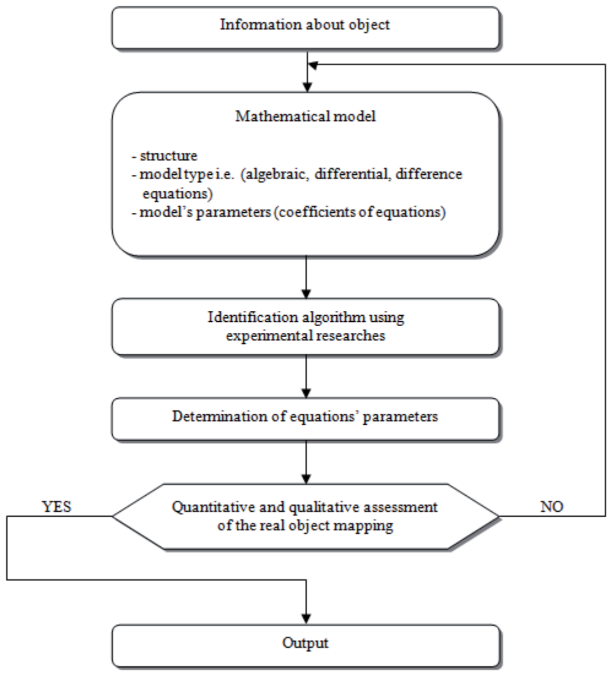


Fig. 2. Scheme of identification. Source: own elaboration

The model in its generality is represented by:

- the structure, expressed by mathematical provisions, block diagrams, joint matrices , flow diagrams or graphs;
- the values of model parameters (coefficients of equations).

The chosen structure depends on the scope of application of the built model. The simpler the structure is the easier the computation procedures are and potentially there is a bigger possibility of interpreting the obtained results [12]. Of course, there is a certain limit of simplifications, which if it is exceed the model will not map the real object or process. However, in most technical applications, the structure of an object or a process is known and the knowledge which has to be gained is limited to the numerical values of certain parameters (coefficients of equations directing the dynamics of the process, the coefficients of linear or nonlinear model) and / or numerical values of state variables. Then the problem of identification is reduced to the estimation of the process parameters and / or its state. Sometimes detailed knowledge of the process or the object is required, what cause that identification will lead to state estimation [6, 7].

During identification [9] of the mathematical models parameters are sought using the method of the least sum of the squares of the errors. In accordance with this method functional ***F*** is determined:

$$F = \sum_{i=1}^{N} \varepsilon^2_i \,, \tag{1}$$

$$\varepsilon_i = y_i - y_{Mi} \tag{2}$$

where:
y_i - output signal from the object,
y_{Mi} – input signal of model,
ε_i – difference between output signal from the object and model,
N – number of measurements.

In this article the model reproduces the true airspeed during landing phase. This form of the model is sufficient for the purpose of the study i.a. runway occupancy time or other type of research aiming to increase throughput and safety in the area of the airport [4]. Aircraft's flight parameters used to develop the model come from flight data recorder of Embraer 170. These parameters include i.a.: indicated airspeed and ground speed, barometric altitude, geographical coordinates, course, pitch and roll angle, longitudinal and normal acceleration, Mach number, thrust, flaps/landing gear position, the total mass of the aircraft [7]. To develop the model the characteristic parameters were recorded for flights to and from Warsaw Chopin Airport, for landing on runway 33 with the same STAR (standard terminal arrival route). Data recorded from the moment when the plane reaches the speed of 220 knots during approach to the moment of landing has been taken into account. This way, the beginning of the landing phase has been defined for the purpose of the modeling, depending on the configuration (landing gear position, flaps, wings' mechanization). Searched model includes segments of landing phase presented in Table 1. Figure 2 presents the landing scheme with specification of the characteristic segments.

Table 1. Description of the individual segments of the landing phase

Segment	Beginning of the segment	End of the segment
I	indicated airspeed 220 kt, flaps position 0	indicated airspeed 180 kt, flaps position 1
II	indicated airspeed constantly equals 180 kt, flaps position 2	
III	Indicated airspeed decreases below 180 [kt]	indicated airspeed equals 160 kt, flaps position 3, lower the landing gears
IV	indicated airspeed equals 159 kt and steadily decreasing, flaps position 5	indicated airspeed equals 130 kt
V	indicated airspeed constantly equals 130 kt	
VI	indicated airspeed equals 129 kt and steadily decreasing	indicated airspeed steadily decreasing to 30 kt

Source: own elaboration kt **- knot (1 [NM/h]),** NM **- nautical mile (1852 [m]).**

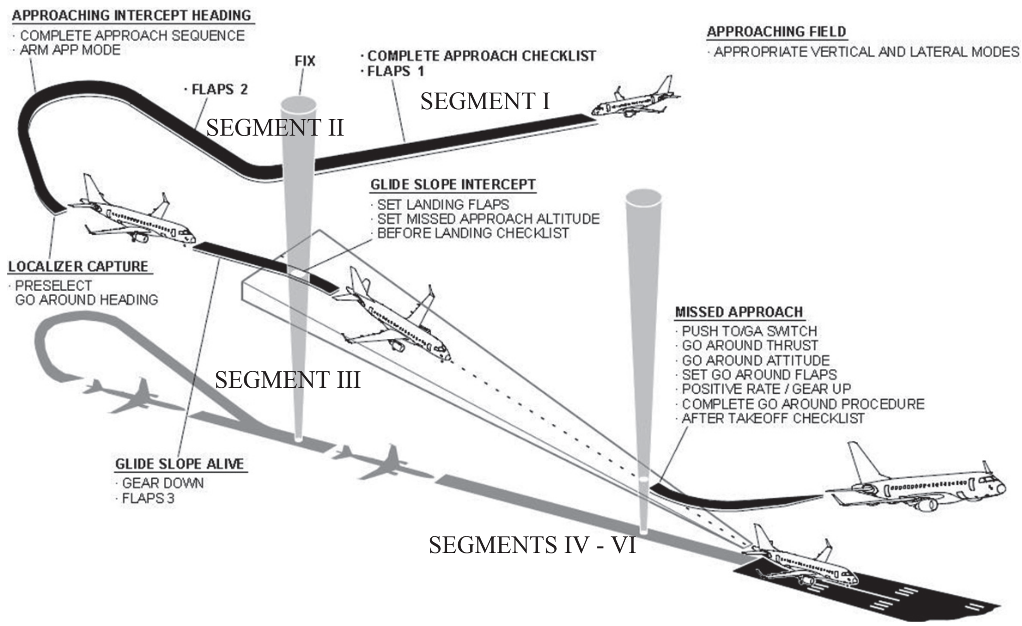


Fig. 3. Scheme of aircraft landing operation. Source: own elaboration

In this case, from the purpose of mathematical modeling point of view, the flight speed characteristics are interesting. Model mapping speed variation V_{i+1} at the time i+1 has the form:

$$V_{i+1} = \underline{x}_i \underline{a} \qquad (3)$$

where:

$\underline{x}_i$ - row matrix inputs for *i* – th time moment with elements,

$$\underline{x}_i = [x_{1i}, x_{2i}, x_{3i}, ..., x_{7i}] = [1, t_i, t_i^2, s_i, t_i s_i, V_{i-1}, V_i] \qquad (4)$$

$\underline{a}$ - seeking vector of model's parameters (3) described as;

$$a^T = [a_1, a_2, a_3, ..., a_K] \qquad (5)$$

t_i - *i* – th time moment of the flight [s],

s_i - segment's number for i-th time moment ; s = 1, 2,...,6; i = 1, 2, ..., N.

Data obtained from flight data recorder are a discrete form and in order to be able to use the received data sequence in further calculations they were subjected to the interpolation process. Flight parameters characteristic were interpolated using a polynomial. It is essential to determine polynomial parameters using the points of characteristic of this polynomial. The value calculated in the middle of timestamp interval is taken as a value of the interpolated characteristic. In the next step, interpolation is performed similarly as in the previous points, with a shift by one timestamp. In the article interpolation for 9 points was applied, based on points obtained from the measurement, using a polynomial of degree 2. Examples of interpolated characteristics are shown in Fig. 4.

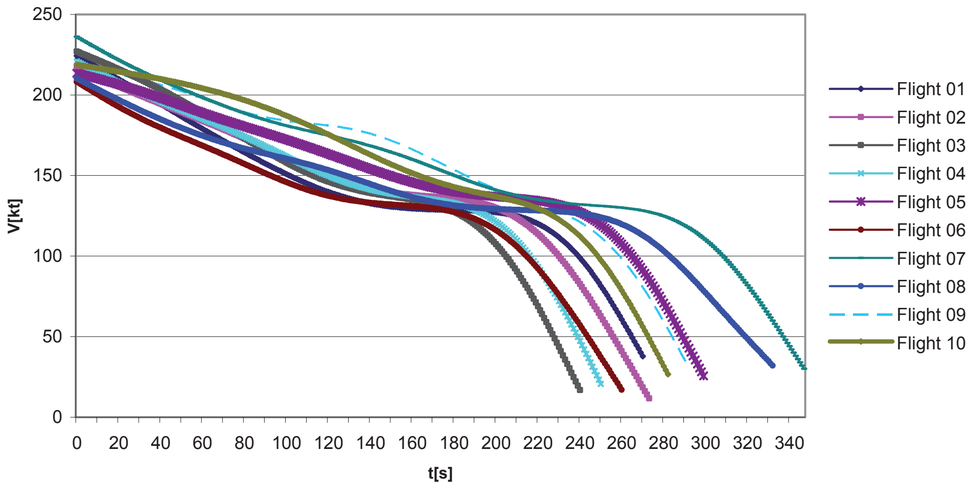


Fig. 4. Interpolated characteristics of indicated airspeed during landing for selected aircraft landing.
Source: own elaboration

For numerical reasons it is profitable to use standardized parameters for modeling (reduced to characteristic with values from the interval (0-1)). Normalization process is presented below. Normalized value of characteristic $\overline{x}_{1i}$ in the individual moments of flight is determined as follows:

$$\overline{x}_{1i} = \frac{x_{1i} - x_{1min}}{\Delta x_1} \tag{6}$$

where:

$i = 1,2 \ldots, N$

$\Delta x_1 = x_{1max} - x_{1min}$

Inverse dependence has formula

$x_{1i} = \Delta x_i \cdot \overline{x}_{1i} + x_{1min}$

Analogous dependencies define residual normalized elements of matrix (4) and normalized flight speed.

Model parameters for normalized data can be determined from dependencies of the following equation (4), (6)

$$\underline{a} = (\underline{\underline{U}}^T \underline{\underline{U}})^{-1} \underline{\underline{U}}^T \underline{Y} \tag{7}$$

where $\underline{\underline{U}}$ indicates matrix, which in each row contains the flight parameters $\underline{x}_i$ in the consecutive moment of time (1, 2..., N), where N represents number of analysed moments of time.

$$\underline{\underline{U}} = \begin{bmatrix} 1, & \bar{t}_1, & \bar{t}_1^{\,2}, & \bar{s}_1, & \overline{t_1 s_1}, & \bar{V}_0, & \bar{V}_1 \\ 1, & \bar{t}_2, & \bar{t}_2^{\,2}, & \overline{t_2 s_2}, & \bar{s}_2, & \bar{V}_1, & \bar{V}_2 \\ .. & .. & .. & .. & .. & .. & .. \\ 1, & \bar{t}_i, & \bar{t}_i^{\,2}, & \bar{s}_i, & \overline{t_i s_i}, & \bar{V}_{i-1}, & \bar{V}_i \\ .. & .. & .. & .. & .. & .. & .. \\ 1, & \bar{t}_{N-1}, & \overline{t^2}_{N-1}, & \bar{s}_{N-1}, & \overline{t_{N-1} s_{N-1}}, & \bar{V}_{N-2}, & \bar{V}_{N-1} \end{bmatrix} \tag{8}$$

$$Y^T = \left[V_2, \quad V_3, \quad \dots \quad \dots \quad \dots \quad \dots \quad V_N \right]$$

Due to characteristic of true airspeed recorded by flight data recorder and the method of determination of the coefficients of the model equations the coefficient obtained from equation (7) are treated as random variables. Interesting information about the accuracy of mapping the actual flight parameters by model are in the determined quantitative and qualitative indicators. The basis for their determination are the differences between the outputs of the model and the object. Expressions determining the coefficient of identification quality was specified assuming that the disturbances are characterized by: a normal distribution, zero mean value, are stochastically independent and have constant variance. To check whether these differences are characterized by a normal distribution, i.a. the Kolmogorov compatibility test can be applied. Detailed information concerning the identification of emergency states including will be the subject of further publications.

4. Emergency Landing

It happens in aviation that emergency landing has to be made during flight or when landing. Maximum safety and minimum risk for the aircraft crew and passengers, and where possible, the integrity of the fuselage have to be ensured in such a situation. There are many emergencies, from a slight degrading of aircraft performance to large (often catastrophic) structural damage to the aircraft or power units. It is also possible that the speed at which the aircraft performance is compromised will determine the type of action to be taken. Nevertheless, all considerations of what to do should be made early enough for the pilots to retain full (or slightly limited) control over the aircraft. In extremely dangerous emergencies it is most often the engine which becomes damaged (or stops operating for various reasons) or the aircraft structure becomes destroyed. Such a situation forces immediate landing, with the need to ensure the proper spatial orientation of the aircraft. If there is no opportunity to land in an area specially designed for this purpose or in a landing field within the aircraft's range, it has to land on an unsuitable surface such as field or water.

Statistically, emergency landing on water ends up in most cases successfully, but the subsequent survival of passengers and crew members and the assistance they can receive depend on many factors. As it appears from the data compiled by the UK and US aviation, 88% of water landings result in few or no injuries to pilots and passengers. Sporadically, deaths during emergency landing on water are caused by subsequent circumstances such as drowning. The success of water landing depends to a large extent on what kind of preparations have been made. The survival of passengers and crew members after landing is contingent on how soon they receive assistance, which can be ensured only through good communication between pilots and rescue services when starting an approach to land on water. Ditching is an intentional landing on water, but not an uncontrollable collision. Passenger injuries can be reduced only by maintaining an appropriate body posture when the aircraft touches the water surface. It is also compulsory to wear a life-jacket and the crew has to give details on what the passenger can expect and what they should do after landing.

If emergency landing has to be made in the sea or ocean, it is recommended to land along waves, if any, or their crests. Nevertheless, if the wind force exceeds 35-40 knots, the waves may reach a height of even ten feet. Then the most appropriate thing is to land 'against the wind'. The force of hitting the water will in any case be much stronger than that that can be felt during normal runway landing. It is recommended, therefore, to carry out such an emergency operation with the lowest possible speed (landing gear retracted), at such a height that the tail is the first part of the aircraft to touch the surface of the water. The aircraft should sit smoothly on the water. If the height and approach speed are correct, one or two minor hits are inevitable before the main collision. The impact may result in a high rotational speed of the aircraft with an equally high increase in load factor G and finally the immersion of the nose below the water surface, exacerbating this effect even more. In reality, the effects of this situation may be compounded, as the water level rises with the wave and may lead to an uncontrollable tilt of the aircraft. It is a major adverse consequence, but taking the right decision quickly and making meticulous preparations before landing will prevent the effects of this declaration. After emergency water landing the aircraft will very quickly lose its speed, and if the structure of the fuselage is not substantially damaged, it should float on the water surface for a certain time. The certain time is understood as a period from when the aircraft loses its speed and gets stabilised on the water surface until the crew and passengers leave the aircraft.

5. Flying with an Inoperative Engine

The first basic rule for the aircraft with one engine inoperative is to achieve the best climb performance. This performance is defined as the so-called speed V_{YSE} [7]. After retracting the flaps and landing gear and protecting the engine, the aim is just to achieve the best possible climb performance and parameters while avoiding lateral drift.

For single or multiple engine aircraft with all engines inoperative, lateral drift is eliminated by setting the aircraft so that the indicator on the measuring gauge showing the turn and angle of roll is in its central position. This is the only prerequisite for achieving 'zero' lateral drift, and with such a setting, the aircraft represents the lowest possible air resistance profile achievable.

In multiple engine aircraft with one engine inoperative, putting the said indicator in its central position will not already reflect the 'zero' lateral drift due to asymmetric thrust. In fact, there is no such device that would show the pilot which conditions have to be met in respect of basic flight parameters to eliminate lateral drift. Obviously, if the aircraft does not move around its vertical axis, the minimisation of lateral drift will be limited to bringing the aircraft into a certain angle of roll and setting the turn indicators. All data contained in the *Aircraft Flight Manual* that refer to the situation in which one engine is inoperative are specified for eliminated lateral drift. Such procedures can be accepted for use even if zero lateral drift is close to naught.

Conclusions

The article contains a preliminary review of aircraft landing operations. The real phenomena occurring within the airfield can be examined using various methods. One of them is tests using mathematical models. An issue related to these tests is assessments and simulations of aircraft movement dynamics. As it is generally the case for mechanical systems, these tests can be conducted in many ways.

---

[7] V_{YSE} - the speed for which the aircraft with one engine inoperative is to achieve the best climb performance.

In terms of the quality with which real aircraft flights are mapped, it is interesting to verify the stability of the model. In this case stability is understood as the consistency of the flight speed timings derived from the model with similar timings of real flights under variable initial conditions. The characteristics and procedure in emergencies as well as the rules for flying with one engine inoperative are described.

An important aspect is to create appropriate documentation that can be used for a detailed analysis of emergencies. Unfortunately, no data are available to identify and map the flight in such settings. Reports and documents prepared after emergencies result in more aircraft checks, however. Emergencies are followed by experts' continuously reviewing such reports, official flight manuals published by manufacturers and aviation manuals and regulations regarding aircraft control during asymmetric thrust. As a result, many imperfections and shortages have been identified and eliminated. When reading these imperfect documents, pilots, instructors, teachers and writers create incomplete and consequently incorrect VMC[8] speeds, which has surely caused many aviation accidents.

The most important conclusion that should be drawn from all the amendments and additions made to aviation documentation over the years is that speed V_{MC} specified in the flight manuals accompanying an aircraft is used by the pilots of multiple engine aircraft in reality, when flying with an inoperative engine, but it is not just a constant value specified in these operating guidelines. Pilots assume a constant value of this speed, but in reality this speed largely depends on the roll and power settings. The standardised speed V_{MC} to which pilots so often refer is determined for a straight preservative flight, assuming the worst possible variant of variables affecting this speed and a angle of roll of 3-5º from the failed engine side and the maximum one for takeoff. The actual speed V_{MC} can reach values that are even 60 times higher than those specified in operating instructions if the angle of roll does not remain at an appropriate level in relation to the failed engine. As a result, such a situation may lead to a loss of control over the aircraft and finally a catastrophe. Unfortunately, the influence of the angle of roll on the minimum speed at which the aircraft is controllable is not clearly specified in flight manuals (except perhaps for a few cases), aviation regulations or any other documents regarding performance.

The V_{MC} speed mentioned in operating instructions is the minimum speed that is necessary only to control the aircraft, it is surely not a manoeuvring speed and it is valid as long as the angle of roll used to determine this speed is maintained.

It is important to be fully prepared for an emergency during flight. Unfortunately, no clear answer exists, but complying with the following recommendations will certainly increase the chances for the pilot to take correct, appropriate and considered decisions in a critical moment:

- all information regarding the flight mechanics of multiple engine aircraft has to be presented to aviation students, regulatory authorities, aircraft accident investigators, authors of manuals and operating instructions, companies that design flight simulators, instructors and all other people engaged in the operations of multiple engine aircraft. All would understand then that the most critical manoeuvres after realising that a power unit is inoperative is to configure the rudder and wing ailerons properly so as to reduce speeds V_{MC} and V_2 down to safe pre-calculated values.
- the most important conditions of the flight technique used to determine the values of the V_{MC} speed should be properly combined based on the FARs/CS 23 and 25 as well as operating and flight instructions. All techniques of test flights are available from the FAA[9] and EASA[10] Test Flight Manuals, but for unexplainable reasons they have never been applied by pilots to revisions of the regulations.

[8] V_{MC} – minimum speed that is needed only to control the aircraft.
[9] FAA – Federal Aviation Administration – an agency of the US Department of Transportation responsible for all the civil aviation regulations in the United States.,
[10] EASA – European Aviation Safety Agency.

A full analysis of all mechanical aspects would increase the correctness of the information presented in operating instructions, flight manuals and specialist books. The pilot should keep abreast of technological progress in this domain, which is the basis for ensuring an increasingly higher security threshold both for passengers and crew members as well as for the environment. The ability to proceed correctly in a critical situation and take the most appropriate and secure decision is a key part in ensuring safety.

References

[1] Aneks 14 – ICAO – Aerodromes volume aerodrome design and operations. Wydanie 4, 2004.

[2] "Joint Aviation Authorities Airline Transport Licence Theoretical Knowledge Manual", 070 Operational Procedures , Second Edition, Oxford Aviation Services Limited 2001, Chapter 2: JAR OPS Requirements, Chapter 12: Operations and Procedures, Chapter 18: Emergency and Precautionary Landing.

[3] "Joint Aviation Authorities Airline Transport License Theoretical Knowledge Manual", Flight Performance and Planning 1, 030 031 Mass and Balance, Oxford Aviation Services Limited 2001, Chapter 2: General Principles: Take off, Chapter 3: General Principles: Climb and Descent, Chapter 5: General Principles: Landing, Chapter 13: Class A: Take Off, Chapter 14: Class A: Additional Take Off Procedures, Chapter 15: Class A: Take Off Climb, , Chapter 16: Class A: Landing.

[4] Kwasiborska A.: Wybrane aspekty zarządzania operacjami lotniskowymi, czasopismo LOGISTYKA, Szczyrk 2007.

[5] Kwasiborska A.: Modelling of ground handling operations at airport, Journal of KONES Powertain and Transport, No. 3 Vol. 17, Institute of Aviation, Warszawa, 2010.

[6] Manerowski J.: Identyfikacja modeli dynamiki ruchu sterowanych obiektów latających. Wydawnictwo Naukowe Akson, Warszawa 1999.

[7] Manerowski J.: Modelling of aircraft dynamics using manoeuvrability characteristics, "Recent research and design progress in aeronautical enginering and its influence on education". Biul. 6, PW Wydz. MEL 1997, pp. 242-246.

[8] Roskam J., E. Lan, Airplane Aerodynamics and Performance" Kansas, USA, 1997, s. 435-442.

[9] Stelmach A.: Identification of the mathematical model representing the operation of an aircraft's take-off with use of parameters recorded by the board exploitation flight recorder, 13th EWGT Conference, płyta CD, Padova 2009.

[10] Stelmach A.: Ruch lotniczy w rejonie lotniska – metody analizy i oceny. Prace Naukowe Politechniki Radomskiej Transport z. 2 (20), Wydawnictwo ITE, str. 505-510, Radom 2004.

[11] Stelmach A., Beuth K.: Identyfikacja modelu matematycznego operacji startu samolotu, Prace Naukowe seria Transport z.69, OW PW, Warszawa 2009.

[12] Stelmach A., Manerowski J.: Identyfikacja modelu matematycznego operacji lądowania samolotu. Czasopismo Logistyka, nr 4/2011, płyta CD, Poznań 2011.

[13] Torenbeek E., H. Wittenberg, " Flight Physics, Essentials of Aeronautical Disciplines and Technology, with Historical Notes" London, New York 2009, s. 253, 302-313.

Journal of POLISH CIMAC
Faculty of Ocean Engineering & Ship Technology
GDAŃSK UNIVERSITY OF TECHNOLOGY

MOTOR VEHICLE DIAGNOSIS IN TERMS OF TECHNICAL FACILITIES REQUIREMENTS

Kazimierz Lejda, Edyta Zielińska

Rzeszow University of Technology
Al. Powstańców Warszawy 6, 35-959 Rzeszów, Poland
tel./fax: +48 17 854 31 12, e-mail: klejda@prz.edu.pl

Abstract

This paper presents the importance of motor vehicle diagnostics for proper and safe operation of motor vehicles - safe to drivers, other road users and the natural environment. Other benefits of diagnostic testing, such as a reduction in the vehicle operation costs, a narrower scope of required technical service, a reduction in the purchase costs of spare parts or minimization of service labour intensity are also presented. The paper lists and describes the essential requirements to be met by those who carry out business activity involving diagnostic testing, i.e. the requirements regarding appropriate marking, types and sizes of control stands, adjustment of the equipment to the needs and scope of the offered services, documentation required to carry out technical inspections, qualifications of inspection station staff and training courses for inspection staff. The paper further presents the regulations regarding deadlines for diagnostic tests, the scope and the method for carrying out vehicle technical inspections, the measurement conditions, the course of testing, the evaluation of test results and, depending on the vehicle type, the required additional tests.

Keyword: *technical facilities, diagnostic tests, regulatory requirements*

1. Introduction

The development of the automotive industry as a result of the growing demand for motor vehicles, both private and corporate ones, contributes to the need for establishing specialist technical facilities to ensure proper, that is, safe operation of transport means. Cars in good working order are also a guarantee that the transport tasks are performed to high standards.

Diagnostic stations are motor transport facilities designed to check the technical condition of vehicles in use. In terms of safety, they are very important [7]. They localize faults in the vehicle assemblies and sub-assemblies without disassembling the vehicle or with disassembling some parts only. Diagnostic stations carry out tests in order to compare the current technical condition of the vehicle with the nominal parameters that correspond to good structural systems, assemblies and subassemblies. On this basis, the vehicle is assessed as roadworthy or unroadworthy. A roadworthy may either be in good or bad technical condition, however, any fault found is to be repaired as soon as possible.

In order to ensure high quality services, diagnostic stations must meet many applicable requirements, including those related to suitably qualified staff. Stations should carry out diagnostic tests using specialist equipment. The instruments used for diagnostic purposes can be very simple or advanced, as are, for example, universal sets for diagnostic testing of electronics. Also becoming more and more popular are on-board diagnostic systems. The integrated vehicle diagnostic systems monitor the sensors installed in the vehicle at the manufacture stage and some of the actuators, which enables the execution of the self-diagnosis process, thus detecting faults as early as possible.

2. The importance of diagnostics for proper vehicle operation

Diagnostic tests carried out in Vehicle Inspection Stations have a fundamental influence on safe operation of transport means. They enhance the availability of cards and increase the efficiency of the transport process due to reduced downtime of and the reduced number of repairs on the vehicles. Vehicle diagnosis also contributes to reduction of vehicle operation costs. The scope of technical services is narrowed, the purchase costs of spare parts are reduced. It is often the case that the staffing levels are subject to review and the service labour intensity is minimized. Diagnostics help keep the vehicle in good working order for an extended time and improve road safety.

Diagnostics is a fundamental operating tool that helps keep the vehicle in good technical condition. It is assumed that, as a result of diagnostic testing, the car utilization ratio is increased by ca. 15-20%, the fuel consumption is reduced by ca. 15%, the wear of spare parts is reduced by ca. 20%, and the car's mileage is 1.3 to 1.5 times higher before it undergoes a major repair [5]. Diagnostic tests allow for:

- evaluation of the current condition of the car, thus providing the user with basic information,
- prediction of future conditions of the car, creating bases for proper scheduling of diagnostic tests and services,
- designation of worn out vehicles as end-of-life vehicles.

The examination, assessment and determination of the causes of the bad technical condition of a vehicle is possible using diagnostic methods (diagnosis), suitable diagnostic instruments and algorithms for condition control and damage localization. Diagnostic methods are an effective procedure to achieve these goals. During the diagnostic process, it is to determine the condition of the technical facility. This process is an action algorithm including diagnostic testing and concluding. The diagnostic process can be carried out through:

- periodical of constant tests and technical condition assessments by use the vehicle's diagnostic instruments (on-board diagnostic systems),
- periodical tests and assessments by use of diagnostic instruments (external diagnostic systems) that are connected to the vehicle,
- a combination of the above.

The fundamental task in the vehicle diagnosis is to determine its overall condition, without distinguishing the conditions of the vehicle's separate components. The aim of the testing called a vehicle condition check is to establish whether the vehicle as a whole is roadworthy or not. Obtaining at least one negative result during the check means that the car is unroadworthy and should be subject to further testing and evaluation of malfunctions, that is, to determination of the condition of the vehicle components in order to adjust, repair or replace them. Such testing is called damage localization [6].

All technical inspections carried out at diagnostic stations should be made to the highest possible standards, in accordance with relevant guidelines, at appropriately prepared and equipped control stands and by duly authorized employees.

2.1. Specification of modern internal-combustion engine diagnostics

Special attention is to be paid in the motor vehicle diagnosis to the technical assessment of the internal-combustion engine that is the vehicle's drive. Engine designs have been subject to deep changes particularly in the recent years. This is primarily due to the legislation relating to relevant standards and environmental barriers in transport means. Moreover, the distinct trends to replace conventional fuels (such as petrol, diesel fuel) with alternative energy sources involve introduction of previously unknown solutions including new generation assemblies, sub-assemblies and control systems to piston engine designs. All that requires a use of new testing methodologies, diagnostic equipment with high performance parameters and diagnostic personnel with knowledge appropriate to the modern solutions in order to ensure an effective and reliable assessment of the technical condition.

Meeting the requirements regarding the correct course of the diagnostic process is determined by possessing of suitable technical facilities with specialist equipment that fulfil the contemporary criteria. Before setting about any activity involving diagnostics of vehicles and internal-combustion engines, one should organize appropriate potential, which, in most cases, would be determined by [2]:

- creative personnel managing the diagnostic tests and having knowledge that allow them to formulate conclusions,
- executive personnel preparing the apparatus and devices for the tests, carrying out the tests and treating the results,
- support personnel responsible for the technological and administrative aspects of the diagnosis,
- test stands (for engines, accessories etc.),
- specialist measuring and recording apparatus,
- applied testing and measuring methods,
- diagnosticians' testing qualifications as required by law.

In the testing of engines, the assessment of their current technical condition is the overriding aim, however, their recorded parameters may not change during the extensive diagnosis or during the diagnosis of separate assemblies and sub-assemblies. If this was the case, it would be significantly difficult to formulate a correct assessment. Then, this would indicate such a degree of wear and tear of the engine that it engine should be subject to repair.

The majority of tests carried out as part of the diagnosis are performed on engines, the condition of which meets the technical requirements that define an engine in good working order. Achieving the so called allowable or limit parameters for the technical condition is referred to a specified run rate of the engine that may be in good or bad working order but yet not non-operational [2].

In the literature, there is no information on specific requirements regarding solely engine diagnosis in regard to technical facilities. It is assumed that an internal combustion engine is an element of the car design, and the relevant requirements should be worked into the construction concept for the whole facility designed for diagnostic testing. However, during diagnosis with the engine running, special attention is to be paid to safe exhaust gas offtake and noise emission. Therefore, a test stand should be separated (shielded) from other stands where other car systems, which do not need to be assessed with the engine running (like the steering and suspension systems), are diagnosed. Exhaust gas must be taken through an offtake system to the outside of the facility, taking into account the immediate vicinity of the diagnostic station to ensure the environment is not in danger (residential buildings, amenity areas etc.). The noise emission should be taken into account when designing the facility's walls that are to dampen the emission to the outside.

The diagnostics of modern internal-combustion engines is essentially based on verification of the operational data recorded in the on-board diagnostic (OBD) system. Since the creation of the OBD system, its development is divided into three periods [4]:

- OBD I - legal and technical regulations concerning car diagnostics and signalling of damages in the injection/ignition system components (date of introduction – 1984r.),
- OBD II - active diagnostics of the emission assemblies and the elements of the power transmission system (date of introduction – 1996r.),

- OBD III - active diagnostics of the other functional systems if the motor vehicle's body and chassis (no fixed date of introduction).

Currently, the OBD II standard (the European equivalent is EOBD) is in force. As mentioned previously, this standard addresses damages causing increased emission of toxic compounds from the exhaust system and increased fuel consumption in the fuel system. Such damages are called emission damages because they affect the units and components of the power transmission system that are responsible for the emission of toxic compounds.

According to the OBD II standard, a unit of component is considered inefficient if its operation may cause an increase in the emission of toxic compounds from the exhaust or fuel system. An increase in emission by 50% in relation to the maximum allowable value for a given type of car is defined as a limit increase.

The introduction of the OBD system and its further development create a quite new situation in respect to vehicle diagnostics. The assessment of the car's current technical condition during the current operation, which has previously been the sole task of Vehicle Inspection Stations and vehicle users themselves, now becomes also a duty of manufacturers of transport means, which is guaranteed by laws regarding compulsory type-approval tests.

3. Requirements relating to technical facilities enabling diagnostic testing

All motor transport facilities, including diagnostic stations carrying out technical inspections of vehicles are subject to specific regulations relating to their operation. Diagnostic stations should have signboards appropriately marked and prominently displayed outside, i.e. the signboards should be blue with white notices including at least an identification code, a designation of the station type and the opening hours. For proper operation, the stations should also have at least one control stand to carry out technical inspections of vehicles and an outside stand for noise measurement. The requirements for diagnostic station stands are presented in Table 1.

Tab 1. Requirements relating to control stands, test benches and inspection channels

Stands	Requirements
Control stand	• Should be situated in a separate room. • Should consist of: - a flat horizontal surface, the so called "test bench", - an inspection channel and a device to elevate the vehicle axle, - measuring and control devices and instruments, - technological equipment, - a noise measuring stand, • The length of a control stand should be more than that of the inspection channel (not less than 3 m). • The width of a control stand should not be less than 6 m (widths below 5 m are allowed). • The sizes of the entry and exit gates should be: height 4.2 m (3.2 m is allowed with regard to inspection of a vehicle with a weight of 3.5 t). • The ratio of the windowpane surface to the floor surface is to be at least 0.15. • A control stand should be equipped with: - device operating manuals, - data concerning the criteria for assessing the inspected vehicles, - a set of relevant regulations.
Test benches	• Should provide a possibility to put any vehicle with all its wheels on the bench. • Should enable placing the inspected vehicle before the lighting lamps of the device designed for the inspection. • The edge spacing should not be less than: - 2.4 m for vehicles with a maximum allowable total weight of 3.5 t, - 2.8 m for all other vehicles. • The maximum allowable irregularity for test benches should be: - 2 mm for vehicles with a maximum allowable total weight of 3.5 t,

	- 3 mm for all other vehicles. • The maximum allowable deviation from the level should be: - 2 mm/lm for vehicles with a maximum allowable total weight of 3.5 t, - 3 mm/lm for all other vehicles.
Inspection channel	• The channel width should be within the following limits: - 0.65 to 0.60 m for vehicles with a maximum allowable total weight of 3.5 t, - 0.70 to 0.90 m for all other vehicles. • The depth should be within the range of 1.40 to 1.70 m. • Must have drainage and ventilation systems. • There should be lighting and tool/key shelves in the channel. • There should be device installed in the channel to elevate the vehicle.

The applicable laws also specify the technical conditions to be met by diagnostic stations, i.e. requirements relating to [8,11]:

- the station's equipment that must be adjusted to the needs and scope of the offered services,
- documentation required to carry out technical inspections of vehicles,
- types of control stands,
- diagnosticians and training courses offered to them.

The applicable laws relating to the operation of diagnostic stations also regulate the deadlines for diagnostic tests, provide information on the vehicle inspection scope and methods, define the measurement conditions, the course of testing, evaluation of results and, depending on the vehicle type, additional tests to be made. The applicable laws distinguish the following types of diagnostic station:

- Basic Vehicle Inspection Stations that cover basic technical inspections including checks and assessments of the operation of particular vehicle systems, especially in terms of driving safety and environmental protection (exceptionally, the scope of services can be extended to include some tests that are not covered by BVISs),
- Regional Vehicle Inspection Stations that cover an extended scope of technical inspection, including:
  - basic scope of inspection,
  - inspection of buses for which the speed limit on the highway and expressway is 100 km/h,
  - inspection of vehicles designed for transport of hazardous materials,
  - inspection of gas-powered vehicles,
  - inspection of vehicles referred by the traffic control authorities or the starost,
  - periodical inspection of vehicles designated as "self-constructed",
  - inspection of vintage vehicles and vehicles designated as "self-constructed" as to their compatibility with technical specifications,
  - granting and stamping numbers on the vehicle bodies (chassis) and engines, making substitute plates,
  - giving opinions in regard to individual applications for permission for derogation from the technical conditions to be met by vehicles,
  - clarifying doubts and settling disputes arising between the basic inspection station and the vehicle user.

The relevant regulations also address the types of diagnostic devices that are subject to compulsory assessment by an accredited body. All instruments and devices making up the equipment of a diagnostic station are subject to certification carried out by the Motor Transport Institute. The basis for certification is accreditation from the Polish Centre for Accreditation, confirming the competence of the certifying body (the Motor Transport Institute) to carry out this kind of activity. The formulated technical requirements are a basis for assessment of usefulness of devices and for issuing compliance certificates in accordance with the European standards.

3.1. Requirements relating to periodic operational inspections and diagnostic equipment

A diagnostic station performing technical inspections of motor vehicles must possess a statement of conformity for the equipment and instruments with reference to its requirements prepared in Polish. It is permitted to have a declaration of conformity issued in another language along with a translation into Polish. Additionally, the measuring and inspection equipment of diagnostic stations are subject to periodic operational inspections, which do not apply to devices and instruments that are subject to periodic metrological controls (e.g. exhaust analysers, sound level meters and manometers) or to periodic tests by the technical inspection authorities (i.e. jacks). The operational inspection includes:

- organoleptic examinations, if the device or appliance is whole and mechanically undamaged,
- an inspection of the operations and indications made in accordance with the manufacturer's instructions provided in the operation and maintenance manual (user manual),
- other monitoring activities stipulated by the manufacturer carried out in accordance with its recommendations.

The periodic operational inspections are carried out on the dates specified by the manufacturer. They are performed by an authorised station employee. Inspection results shall be entered in the periodic operational inspection card. The station's managing director should also have the documents from the periodic operational, metrological and technical inspections of the equipment and instruments constituting the measuring and inspection equipment of the Motor Vehicle Inspection Station.

The control stand equipment at a Motor Vehicle Inspection Station includes at minimum the following devices and instruments [10]:

- a roller device or overrun device for inspecting brake operation,
- a mechanism to assess the correct wheel settings,
- an instrument to measure and regulate air pressure in tyres,
- an instrument to measure the settings and brightness of the vehicle's lights,
- an instrument to measure the light transmission coefficient on the vehicle's windows,
- a sound level meter,
- a smokemeter,
- an instrument to inspect the electric connector between the vehicle and the trailer,
- an instrument that puts a defined amount of pressure on the mechanism controlling the trailer's overrunning brakes,
- an instrument to force jolting on the vehicle's wheels while in motion,
- a microreader for diagnostic information for the OBD-II/EOBD system,
- a multicomponent exhaust gas analyser for spark ignition engines,
- a decelerometer for inspecting the operation of the brakes,
- a set of assembler's tools,
- a basic set of general-purpose measuring instruments.

However, a test stand in the Regional Vehicle Inspection Station should have the following additional equipment [8]:

- an instrument to measure wheel and axel alignment,
- an electronic gas detector to inspect for gas leaks,
- equipment for monitoring the effectiveness of the vehicle's shock absorbers with a maximum allowable total weight of 3.5 t,
- a set of torque wrenches in the range of 20 to 400 Nm.

The measuring and inspection equipment may be shared by several control stands of one station. The measuring and inspection equipment as well as other equipment of the station may be used to carry out technical inspections on vehicles if it has been subject to the conformity assessment and also has the CE marking.

3.2. Qualification requirements for diagnosticians and industrial safety and fire regulations

Technical inspections at Vehicle Inspection Stations should be carried out by authorised diagnosticians who meet the following conditions [9]:

- have completed higher technical education with a speciality in motor vehicles or two years of professional experience at a vehicle service station or at a vehicle repair and service station in a vehicle repair shop,
- have completed secondary technical education with a speciality in motor vehicles and four years of professional experience at a service station or at a vehicle repair and service station in a vehicle repair shop,
- have completed professional training in accordance with the training programme and have received positive results on the qualification exam.

In cases where the diagnostician's technical education is in an area other than automotive, his or her professional experience should be at least twice as long. All candidates who wish to become licensed diagnosticians carrying out technical examinations for motor vehicles must complete all parts of the training presented in Table 2.

Tab. 2. Types of training for diagnosticians [9]

No.	Training type	Features
1.	Part I; Basic training	Deals with the carrying out of periodic vehicle inspections with regard to checking and assessing the operation of particular vehicle assemblies and systems (mainly concerning aspects of traffic safety and environmental protection).
2.	Part II; Specialist training	Deals with technical inspections of busses for which the speed limit on the highway and expressway is 100 km/h.
3.	Part III; Specialist training	Deals with the carrying out of technical inspections of vehicles used in transporting hazardous materials.
4.	Part IV; Specialist training	Deals with the carrying out of technical inspections of gas-powered vehicles.
5.	Part V; Training in technical inspections of:	• vehicles registered for the first time abroad - of a new type, produced or imported in the amount of one per year, • vehicles that have been referred by the traffic control authorities or the starosta if they require special inspections and vehicles, the design or structure of which has been altered, which requires a change to be made to the registration data, • vehicles designated as "self-constructed" as to their compatibility with technical specifications.

Diagnosticians who, after receiving positive results on their exam, earn the right and qualifications to carry out technical inspections on vehicles shall retain these qualifications in the scope that they were issued and that they are recognised as meeting the requirements outlined in the instructions. They can also obtain permission to carry out new types of vehicle inspections after completing the relevant parts of the training and pass the qualification exam with positive results.

In addition to possessing the qualifications mentioned above, a diagnostician to be employed at a Vehicle Inspection Station must be familiarized with health and safety regulations and provided with introductory general and stand-specific training as well as basic and recurring training. In accordance with the appropriate requirements, the employee should receive work clothing and footwear as well as personal protective equipment (e.g. work gloves, glasses).

The diagnostic station's building should be constructed of non-flammable materials and be equipped with all necessary fire-fighting equipment in the form of two 6 kg ABC_E dry powder fire extinguishers, three 6 kg carbon dioxide extinguishers and a fire blanket. It is forbidden to store flammable materials unnecessary for diagnostic tests inside the station. There is also an absolute ban on smoking and open flames in the station. Warning and informational signs should be posted around the area of the station.

The station's control stand is required to have sensors for excessive concentrations of carbon monoxide that will automatically start ventilation. The ventilation system in the station automatically prevents dangerous levels of exhaust gases. To maintain safety at work, additional safeguards shall be applied in the diagnostic stations, including:

- resetting machines and electrically-powered devices,
- installing low-voltage lighting and insulation grates in the channel,
- air injection into the channel,
- floors made of non-slip material.

3.3. Requirements for environmental protection in diagnostic stations

The functioning of the technical facilities for motor vehicle diagnostics should do as little as possible to negatively impact the environment. The use of the diagnostic station should have a minimal impact on air quality and the acoustic environment. The manner of conducting services and the range of activities should also not negatively impact the quality of the surrounding water and soil, the inhabitants of nearby areas and the surrounding environment. Direct impacts associated with the emission of noise, dust and gas should only be local in scope and limited to the area on which the facility is located.

A problem associated with the carrying out of diagnostic tests may be noise from the work equipment used in the station. It is important, however, that they are used only during the station's hours of operation in accordance with their intended use. The choice of location for the diagnostic station is in this matter significant, in that it should be away from single-family housing and should have thermal-acoustic insulation in the form of expanded polystyrene and airtight seals on the entry/exit gates and windows.

A good solution that should be taken into account in many technical facilities, including diagnostic stations, is the use of storage tanks to collect rainwater from the roof as well as installations for reusing waste water, which would significantly reduce the amount of water taken from the mains [1,3]. The collection and use of rainwater allows for reduced costs, thereby increasing the profitability of each automotive facility. It is, however, important to remember that rainwater and snowmelt may be contaminated with petroleum derivatives, and therefore must be purified prior to their release into the environment. In accordance with the regulations of the Ministry of Environment, waste of this type should be passed through a petroleum derivative separator to adequately reduce suspensions and pollutants to appropriate levels.

All waste produced by the diagnostic station should be segregated and stored separately in a designated area until it is of the appropriate amount that can be removed by an authorised company, but for not longer than 3 years. Please note that cleaning the separators can be dealt with only specialised companies. Caution should also be exercised in the case of hazardous wastes. Until they are collected by the appropriate firm, they must be stored in sealed containers made of materials resistant to the elements contained in the waste and placed on paved, sealed surfaces in places inaccessible to unauthorised persons.

Among the many activities aimed at eliminating the adverse impacts of diagnostic stations on the environment, the ones carried out in accordance with the regulations from the Ministry of Infrastructure deserve special attention, i.e.:

- control of the technical condition of the exhaust system and control of the level of external noise while the vehicle is stationary,
- control of the gas pollutants from vehicles with petrol engines whose first registration was made after 1 July 1995,

- control of the smoke opacity of vehicles with compression-ignition engines,
- control of the proper adaptation of a vehicle to gas power when performing periodic technical inspections of the vehicle.

4. Conclusions

Ensuring the safe operation of motor vehicles for their owners, other drivers and the environment, is largely dependent on the vehicle's technical condition. Thanks to the compulsory periodic technical inspections that must be performed on every vehicle travelling on the roads, it is possible to maintain their good working order. Technical inspections can detect any defects in a vehicle before they become the cause of a serious breakdown, accident, injury or major environmental pollution. The technical condition of vehicles is checked in diagnostic stations equipped with specialised equipment and highly qualified workers. They need to upgrade their skills due to the dynamic development of the automotive industry as well as the rapidly increasing advances with regards to vehicle design and technology.

All requirements for the operation of diagnostic stations are intended to ensure a high level of service performance. The relevant legislation governs both the sizes of the control stands, the equipment for carrying out the tests, the inspection procedures, as well as the amount and types of training enabling diagnosticians to carry them out. Many of the laws were also created with the goal of eliminating adverse effects on the environment by diagnostic stations. Vehicle Inspection Stations have had an increasingly important role in improving the technical conditions of traffic safety vehicles and environmental protection. Every defective vehicle is a potential threat to people's health and safety. However, while the risks associated with mechanical malfunctions are easier to diagnose even for vehicle owners, failures and deficiencies resulting in increased emissions are harder to notice. In this respect, all of the work carried out in diagnostic stations is a vital element in ensuring the proper functioning of all transport means.

References

[1] Biedrońska J., Figaszewski J., Kozak K.,. Lisik A, Mikoś-Rytel W., *Projektowanie obiektów motoryzacyjnych*, Wyd. Politechniki Śląskiej, Gliwice 2010.
[2] Bernhardt M., *Badania trakcyjnych silnków spalinowych.* WKŁ, Warszawa 1977.
[3] Chaciński, J., Jędrzejewski, Z., *Zaplecze techniczne transportu samochodowego*, Wyd. Komunikacji i Łączności, p. 423, Warszawa 1982.
[4] Merkisz J., Mazurek St., *Pokładowe systemy diagnostyczne pojazdów samochodowych.* WKŁ, Warszawa 2007.
[5] Niziński S.: Diagnostyka samochodów osobowych i ciężarowych, DW Bellona, Warszawa 1999.
[6] Trzeciak K., *Diagnostyka samochodów osobowych.* WKŁ, Warszawa 2008.
[7] Zielińska E., Lejda K., *Bezpieczeństwo ekologiczne w zapleczu technicznym transportu samochodowego,* Czasopismo Logistyka Nº 2/2010.
[8] Rozporządzenie Ministra Infrastruktury z 17 września 2009 r. w sprawie zakresu i sposobu przeprowadzania badań technicznych pojazdów oraz wzorów dokumentów stosowanych przy tych badaniach.
[9] Rozporządzenie Ministra Infrastruktury z 4 listopada 2004 r. w sprawie szczegółowych wymagań w stosunku do diagnostów.
[10] Rozporządzenie Ministra Infrastruktury z 31 grudnia 2002 r. w sprawie warunków technicznych pojazdów oraz ich niezbędnego wyposażenia.
[11] Rozporządzenie Ministra Transportu i Budownictwa z 10 lutego 2006 r. w sprawie

szczegółowych wymagań w stosunku do stacji przeprowadzających badania techniczne pojazdów.

Journal of POLISH CIMAC
Faculty of Ocean Engineering & Ship Technology
GDAŃSK UNIVERSITY OF TECHNOLOGY

THE BUGGY VEHICLE TRANSMISSION GEARBOX TECHNICAL STATE VIBRODIAGNOSTICS INVESTIGATION

Marcin Łukasiewicz*, Tomasz Kałaczyński, Joanna Wilczarska, Andrzej Sadowski, Ewa Kuliś

University of Technology and Life Science
ul. S. Kaliskiego 7, 85-789 Bydgoszcz, Poland
tel.: +48 52 3408262
e-mail:m.lukas@utp.edu.pl*

Abstract

Vibrations draw ahead in every mechanical object. The significant part of machines reliability is vibration level, which could be dangerous for machine technical state. Disturbance of balance state is the reason of vibration formation in machine parts. This vibration can exist and propagate even after their source expiration. Vibrations could be essential just after the crossing certain threshold marked by amplitude and the frequency of the phenomenon. They can be harmful for the object after crossing of this threshold of the vibration, or for his surroundings (e.g.: decrease of the durability of the material). In this paper were introduced of beach buggy chosen units and elements diagnostics research results with usage of vibroacoustics methods.

Keywords: *diagnostic inference, modal analysis , vehicle investigations*

1. Introduction

Vibroacoustics is one from these fields of the science which rise on the needs of diagnosing the current machine engines and devices technical condition. Using emitted vibrations, received during machine engine exploitation process as valuable information about dynamic properties of machine and other aspects we could find the relationships among them.

Every technical device in the given moment is in certain definite state. The most generally technical state of object, machine, vehicle can be describe as a set of the all parameters values that defining the given object in given moment of time t. The time sequences of this states could be consider as the time of the device existence. He leads inevitably the destructive influences of external extorting and internal factors to the machine condition change [1]. The use of technical diagnostics methods makes possible to qualification of current technical state of studied object, machine and vehicle.

The necessity of the technical state estimation is conditioned the possibility of making decisions connected with object exploitation and the procedure of next advance with object. The present development of automation and computer science in range of technical equipment and software creates new possibilities of realization of diagnosing systems and monitoring technical condition of more folded mechanical constructions. These new possibilities are connected with the new constructions of intelligent sensors, module software and the modules of transport and data exchange [2].

2. Vibroacoustics in mechanical engineering

The most valuable information about current machine engine technical state we could obtain during machine natural loads without disturbing this process. This kind of information obtainment is the basic domain of the technical diagnostics. The investigations of vibroacoustics processes in many cases are very complicated, in peculiarity when vibration processes step out in real physical arrangements. Up to now existing diagnostic procedures based on state symptoms slowly changes into diagnostics process based on machine engines models that describing their properties analysis.

Nowadays one of the most known ways to structural model creation of machine engines is modal analysis models utilization: experimental or operational modal analysis methods. The method choice depends on this what kind the input function character of the investigative object during the experiment has to have. 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. Thanks to this during investigations we receive investigative data for real object working process in chosen measure points in relation to reference points [3]. Preparation process for diagnostics investigations in these methods contains measure and reference point's disposal and also frequency range define. The advantage of this method in use to identification of objects dynamic profiles are shore conditions and loads retain that is characteristic for these objects exploitation. Basis on measured signals on the output of object received in chosen measure and reference points for unknown natural loads of the arrangement, the estimation of modal parameters is proceed. Modal poles and natural frequencies are identified ant then the mode shapes are estimated.

This way of parameters estimation could procure some doubt – we have to take it into consideration during final analysis. The biggest problem of this method is that we do not know the value of exciting force on the arrangement. The exciting forces with random character doesn't have one point of reaction on investigated mechanical structure so received exploitation forces structural schedule is unable to identification. The more important is also fact that lots of machine engines used in industry cooperates with other technical objects, not necessarily with the same characters of dynamics loads. Best way to solve this problem will be separation from others machines the investigated machine engine. Unfortunately it refers with the machine engines working process stop so this action is unacceptable in this method usage. Disturbances triggered from next machine engines could cause the formation of additional poles on the created stabilization diagram. In modal analysis we had two ways of modal model parameters estimation: in time and frequency domain. Time domain estimation basis on information from vibrations and arrangement response in time domain signal. Estimation of modal model parameters in frequency domain basis on the input and output signal spectrum [3,4,5]. Nowadays during investigative process we often use the modal model estimation in frequency domain because there is possibility of limitation frequency range to this value in which we could recognize change of vibroacoustics signal during machine exploitation. The most valuable advantages of this method are:

- easiest possibilities of investigative data averaging which is used for noise reduction from signal,
- high precision of received results in case when exist an influence of vibration that lay behind of investigative range of vibrations,
- high precision of received results in case when is the high value of damping.

The frequency domain disadvantages are:

- the possibility of local minimum existence for signals with high noise level,
- the possibilities of troublesome mistakes connected with spectrum leak, existence of incorrect frequencies component in the signal and others.

Introduced below disadvantages and advantage of time domain modal model parameters estimation has similar sights to frequency domain, but this method is better in case, when we have to estimate:

- data with high level of noise,
- wide range of frequency during estimation.

It is also possible to use both of these methods in case, when we have measured vibrations in time domain booth from input and output source [6,7,8].

3. Transmission gearbox modal test

The investigations object was a buggy vehicle which was construct and built in the Bydgoszcz University of Technology and Life Sciences investigative laboratory. During construction phase the LMS Virtual.Lab rev 11 were used for construction optimization [9,10]. Figure no 1 present the buggy vehicle virtual model during tension and strain analysis. The final prototype of buggy vehicle was built in spring 2012 and it is shown on figure 2.

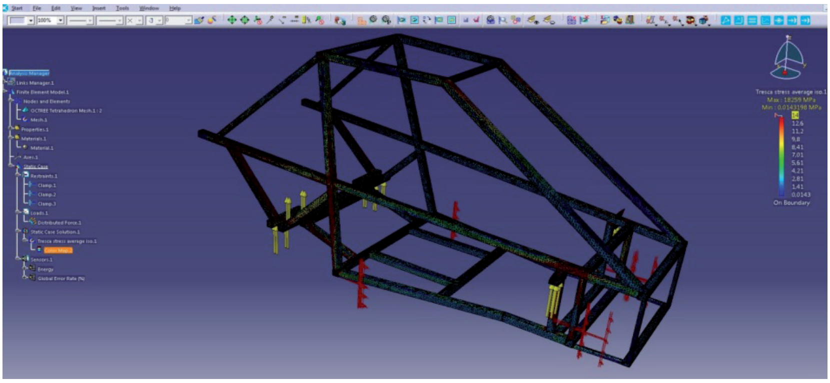


Fig. 1. Model of buggy vehicle created in LMS Virtual.Lab software during virtual tests

Fig. 2. Buggy vehicle during road tests [own source]

During exploitation of the buggy a few problems appear connected with vibration level. The transmission gearbox generated a high level of vibration and after few months the transmission mount points were damaged. To resolve these problems the modal analysis methods were used for vibration analysis. Conducted investigations of gearbox depended on delimitations of vibroacoustics measures for chosen gear sets and accomplishment the assessment of received results influence on transmission gearbox state by operational modal analysis methods. The LMS Test.Lab software with Modal Analysis Lite module was used for modal model poles estimation and analysis of mode shapes for multi degree arrangements with Time MDOF method. For mechanical object analysis several types of function could be used – time or frequency signals: autopower spectrum, crosspower spectrum, coherence and others.

Modal test could be divided into three phases. First phase of modal test is measurement set-up (system calibration, force and response transducers attachment). The second step of modal test is measurement of frequency response data – measured in time domain signal is transformed into the frequency domain functions. The last step of test is modal parameters estimation where measured frequency functions are used for modal model estimation. As a result we received the stabilization diagram with natural frequencies and damping factors, the modal participation factors and estimated mode shapes.

The dynamic signal LMS SCADAS III [11] recorder was used for gearbox signal acquisition. Measurements were realized with gearbox speed 930 min-1 on the various shifts. During measurement 90 seconds time periods of the signals were recorded with the frequency range 128 Hz. Figure no 3 presents transmission gearbox model with signal acquisition points.

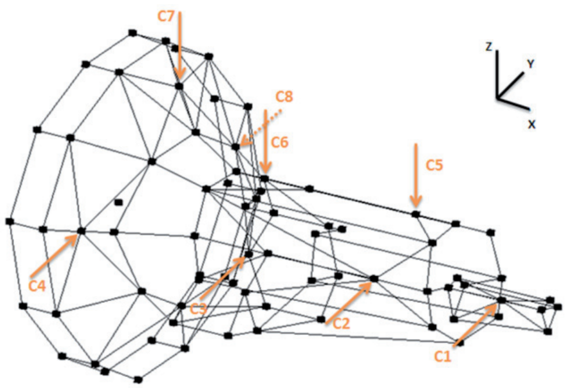


Fig. 3. Transmission gearbox model with signal acquisition points

Basis on modal analysis theory the Time MDOF module with non-linear Least Square Frequency Domain (LSFD) method and Balanced Realisation (BR) was used for modal parameters estimation [12]. LSFD is multiple degree of freedom method that applied for multiple inputs it generates global estimates for stabilisation diagram (system poles), modal participation factors and mode shapes. In first step of Time MDOF method we should define the frequency range within modal test will be done. The geometrical model creation in “Geometry” module will enable the arrangement natural frequencies visualisation. Figure no 4 present “Geometry” module during investigations.

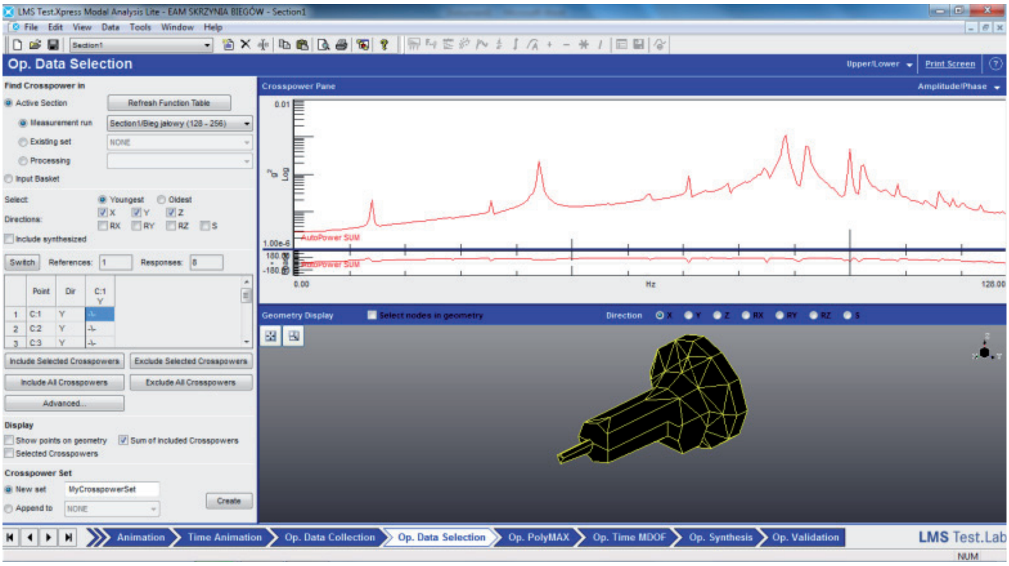


Fig.4. Data selection with "Geometry" module during investigations

In second step of Time MDOF the Balanced Realisation method was used. This is one of the "subspace" techniques which identify natural frequency, damping and mode shapes. A subset of the response functions can be selected as references. These are used in the computation of the cross power functions from the original time domain data. This method is useful in identifying the most dominant modes occurring under operational conditions [12]. Figure no 5 present's sample of Time MDOF stabilisation diagram for investigated transmission gearbox.

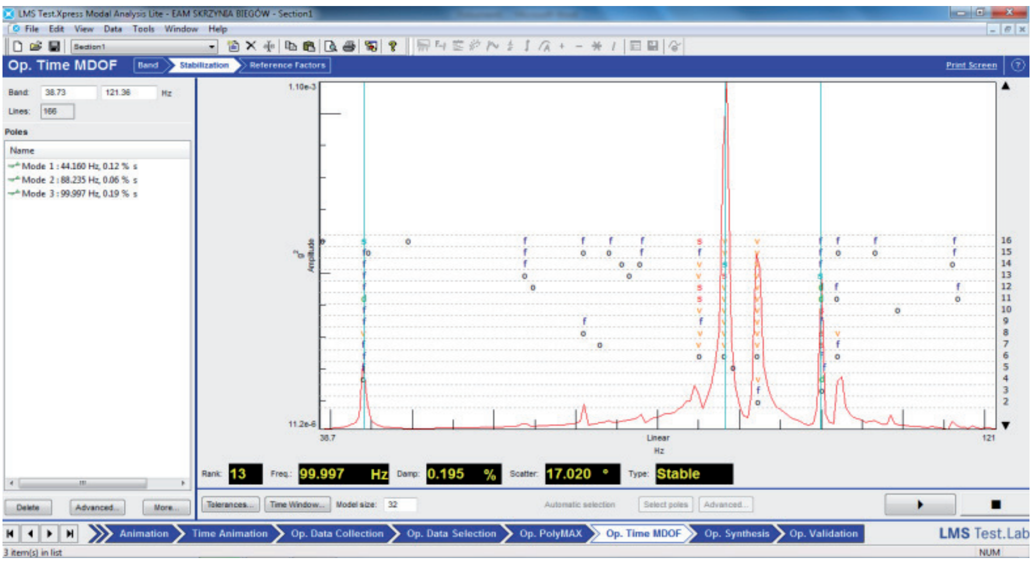


Fig. 5. Time MDOF stabilisation diagram

Analyzing individual simulated cases on the investigative transmission during investigation received set of stabilization diagrams, on which stable poles were mark. The stable pole marks parameters: frequency, modal damping and the mode shapes vector. The results of modal tests were introduced in table 1.

Table 1. Results of transmission gearbox modal tests

	Natural Frequency [Hz]	Modal Damping factor [%]	Modal model Order
Idle run	44,160	0,12	16
	88,235	0,06	14
	99,997	0,19	13
First gear	44,080	0,20	8
	70,976	0,13	14
	88,504	0,13	12
	99,986	0,03	16
Second gear	44,444	0,15	12
	88,890	0,22	10
Third gear	43,844	0,28	7
	70,433	0,25	12
	124,216	0,46	9
Fourth gear	42,627	0,17	8
	81,967	1,01	8
	87,734	3,04	10

The last step of Time MDOF modal parameters estimation were mode shapes estimation with LSFD method that sample results for idle run mode shapes were introduced in figure no 6. As modal tests results validation was used LMS Synthesis module with Auto-MAC criteria estimation - introduced in figure no 7, where we could calculate the error of estimation for all recognized mode shapes of object. As final results we obtain the dynamic state description of real technical object with estimation of predominant properties of natural frequency and mode shapes.

a) b) c)

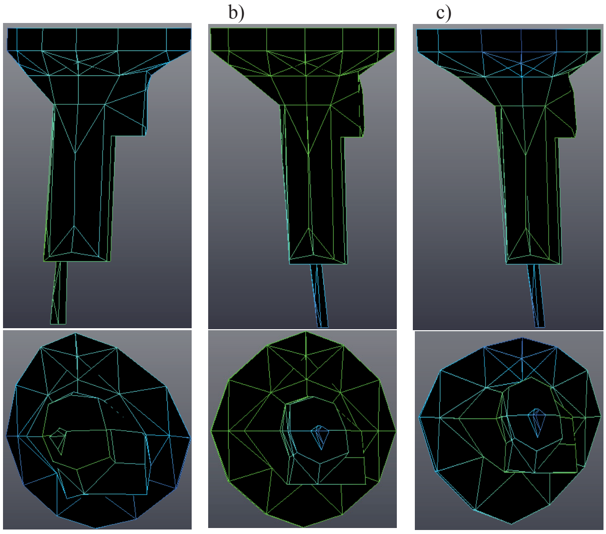
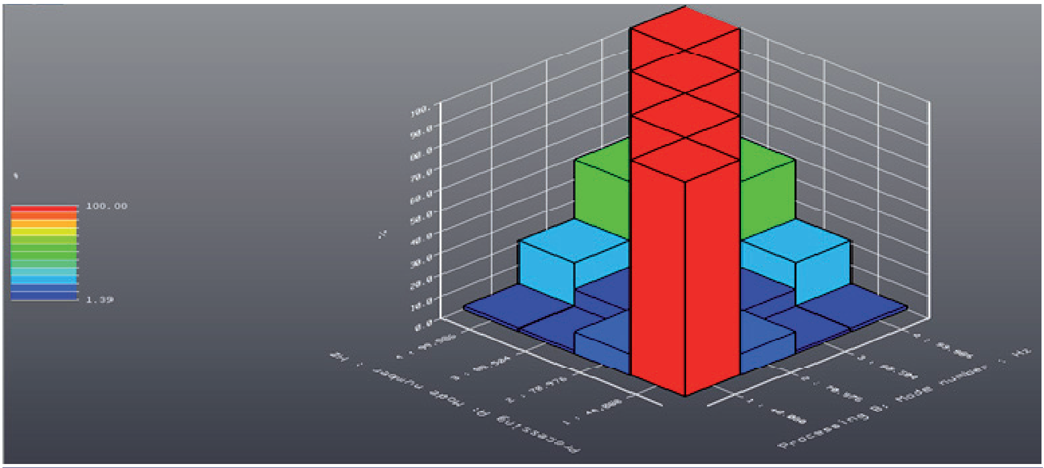


Fig. 6. Transmission gearbox sample mode shapes for frequencies:
a) 44,16 Hz, b) 88,23Hz, c) 99,98 Hz



Auto Modal Assurance Criterion (%)

	Mode No.	Frequency	Mode 1 44.080	Mode 2 70.976	Mode 3 88.504	Mode 4 99.986
1	Mode 1	44.080	100.000	10.140	1.385	1.645
2	Mode 2	70.976	10.140	100.000	9.160	21.413
3	Mode 3	88.504	1.385	9.160	100.000	49.096
4	Mode 4	99.986	1.645	21.413	49.096	100.000

Fig. 7. Sample of LMS Synthesis module and Auto-MAC criteria estimation

The stabilization process ran with tolerance of individual modal parameters: 1% for frequency, 5% for modal damping and 2% for mode shapes vector. In such case as this, where the operational modal analysis is applied, there is only this mode shapes identification possibility which became sufficiently well extorted during the experiment identification.

4. Conclusion

The development and progress of the human civilization is guided by the desire of difficult questions solving often connected with the varied fields of the science. However very often takes place the situation when introduced solutions are more complicated that first solution. In modern technical constructions this problems are also similar. From that reasons new devices and new diagnostics methods are developing which will be able to provide valuable information about technical state of that products.

Presented in this paper conducted investigations and modern engineering application allows to quick process of transmission gearbox identification including their own vibration and gearbox body mode shapes visualisation. The advantage of this method is fact that the studied object can be investigated during normal process of exploitation, the investigations don't generate additional costs and we got results basis of real signals that are generated through the exploitation process of studied object.

Conducted investigations of gearbox depended on delimitations of vibroacoustics measures for chosen gear sets and accomplishment the assessment of received results influence on transmission gearbox state by operational modal analysis methods. As a result we received the stabilization diagrams with natural frequencies with damping factors, the modal participation factors and estimated mode shapes. Analysing results of investigations for idle run, the first identified natural frequency (44,160 Hz) describes the movement of shaft unbalances. The figures of this own vibrations are very well visible on the animation of modal model in the geometry model analysis as determined deformations of model. Second identified figure of natural frequency (88,235 Hz) is caused the differential mass schedule on the gearbox casing and also the unbalances shaft movement - that influences on whole gearbox stiffness. Third figure of natural frequency (99,997 Hz) results from the way of studied gearbox fasten and the kind of the supports on which the whole construction of gearbox leant.

Introduced in this paper results of investigations are only the part of realized investigative project and they do not describe wholes of the investigative question, only chosen aspects. This paper is a part of investigative project WND-POIG.01.03.01-00-212/09.

References

[1] Cempel C., *Fundamentals of vibroacoustic condition monitoring. Handbook of condition monitoring,* Londres, Inglaterra: Chapman and Hall, 1ª Ed. 325 - 333 p. 1998.

[2] Kałaczyński T., Łukasiewicz M., Żółtowski B., *The study of dynamic state industrial machines.* 11th International Technical Systems Degradation Conference, Liptovsky Mikulas 11-14 April 2012, PNTTE Warszawa 2012.

[3] Heylen W., Lammens S., Sas P., *Modal Analysis Theory and Testing*, Katholieke Universiteit Leuven, Heverlee 2007.

[4] Łukasiewicz M., *Investigation of the operational modal analysis applicability in combustion engine diagnostics*, Journal of Polisch CIMAC, vol.3 no.2 Gdańsk 2008.

[5] Parloo E., Verboven P., Guillaume P., Van Overmeire M., *Sensitivity-based operational mode shape normalisation*, Mechanical Systems and Signal Processing, Volume 16, Issue 5, September 2002, Pages 757–767.

[6] Stöbener U., Gaul L., *Active vibration control of a car body based on experimentally evaluated modal parameters*, Mechanical Systems and Signal Processing, Volume 15, Issue 1, January 2001, Pages 173–188.

[7] Łukasiewicz M., *Vibration measure as information on machine technical condition*, Studies & Procedings of Polish Association for Knowledge Management 35, ISSN 1732-324X, Bydgoszcz 2010.

[8] Peeters B., Van der Auweraer H., Guillaume P., Leuridan, *The PolyMAX frequency-domain method: a new standard for modal parameter estimation?* Journal Shock and Vibration, Volume 11, Numbers 3-4/2004, 395-409.

[9] *LMS International, Virtual.Lab, Rev. 11*, December 2012.

[10] Van Der Auweraer H., Van Langenhove T., Brughmans M., Bosmans I., Masri N., Donders S., *Application of mesh morphing technology in the concept phase of vehicle development*, International Journal of Vehicle Design, Volume 43, Number 1-4/2007, p. 281-305.

[11] *The LMS SCADAS III recorder manual* – LMS International 2010.

[12] *The LMS Test.Lab Operational Modal Analysis Lite manual* – LMS International 2010.

Journal of POLISH CIMAC
Faculty of Ocean Engineering & Ship Technology
GDAŃSK UNIVERSITY OF TECHNOLOGY

SOME POSSIBILITIES OF DUAL FUELLING SUPPLY DIESEL ENGINES

Zdzislaw Stelmasiak
University of Bielsko-Biala, Internal Combustion Engines and Automobiles Branch
ul. Willowa 2, 43-300 Bielsko-Biała, Poland

Abstract

In the paper are presented conditions for gaseous fuelling of different engine types: stationary engines and traction engines to trucks and passenger cars. On the base of performed investigations, one made comparison of operational costs of dual fuel gaseous engines and an engines with spark ignition system. In the analysis one took into consideration operation of an engine on natural gas, the most expensive gas, and on the mine gas, so called cheap gas. In case of stationary engines, the analysis showed considerable benefits of the dual fuel system comparing with spark ignition system. One confirmed considerable savings in purchasing costs of the fuels, regardless of size of initial dose and price of the gas. Earnings in purchase of the fuels increase together with growth of price of the gas and reduction of initial dose. In traction engines one should use the CNG or LNG gas. During transitional period of introduction of the gas one should implement systems with full interchangeability of fuelling with gaseous fuel and liquid fuel, both in compression ignition and spark ignition engines. Used in trucks, the dual fuel system gives substantial savings in operational costs and improves conditions of engine operation comparing to systems with spark ignition. In turn, in case of passenger car engines, due to size of the engines and different operational conditions, systems with spark ignition and so called flexi-fuel systems should be used. Due to it, gaseous fuelling in passenger cars should be first implemented in the engines with spark ignition system.

Keywords: *natural gas, dual fuel engine, pilot dose, gas share, operating costs*

1. Introduction

During the nearest feature it will be seen a rapid growth of application of gaseous fuels to fuelling of the engines. It results from general tendency of search for a fuels being alternative to petroleum fuels, and diversification of sources of energy. Gaseous fuels, due to their properties, belong to important among alternative engine fuels, and due to their resources, gaseous fuels may largely replace traditional liquid fuels in future.

To the most important gaseous fuels belong [1, 2, 3, 7, 9]:

- natural gas in form of compressed CNG gas and liquefied LNG gas,
- bio-gases such as gas from sewage-treatment plants, burrow gas and gas from bio-gas plants,
- mine gas,
- waste gases from manufacturing processes,
- hydrogen,
- liquefied propane-butane, popularly known as the LPG.

Due to market supply and price, the first four from the above mentioned gases shall have fundamental importance in the nearest future [1, 2, 4, 9]. Three from them belong to the waste gases, and their rational use is connected with environment protection. The hydrogen is considered as future fuel, but nowadays is very expensive, while implemented methods of production and storage are inefficient [12]. Overall manufacturing efficiency of the hydrogen, *well to wheal,* amounts to about 15%, what makes this fuel also unprofitable from environment protection point of view. In turn, popular in our country LPG gas, due to its small market supply (about 2% of processed crude oil) can not be considered in global scale as a strategic fuel [11].

Method of use of the gases depends mainly on a type of the gas and the engine. Waste gases, due to low energetic density, should be destined to fuelling of stationary generator engines, operated in co-generator systems [1, 5, 7, 9 13]. Such engines are the most often installed near sources of the gas and make use of the gases having pressure close to the atmospheric one, what reduces costs of transportation and storage of the gas. At extremely low energetic values, the waste gases can be enriched with the network natural gas, or in case of lack of such gas, the engines can be run on pure natural gas [9].

Traction engines should be powered by the CNG or LNG gas due to permissible masses of fuel tanks [1, 3, 4, 9, 13]. In the European Union countries, fuelling with the natural compressed CNG gas is preferred, while its market share in 2020 should reach level of about 8% of the whole of consumed engine fuels [7, 9]. Nowadays, development of such fuelling type is limited by mass of the gas cylinders (Fig. 1) and number of filling stations (Fig. 2).

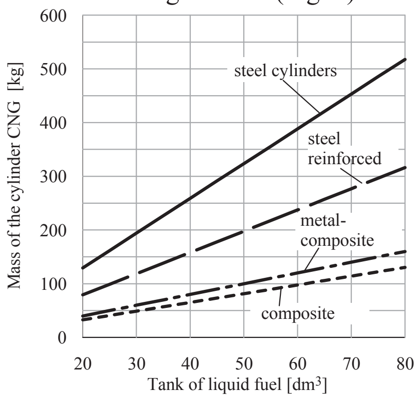
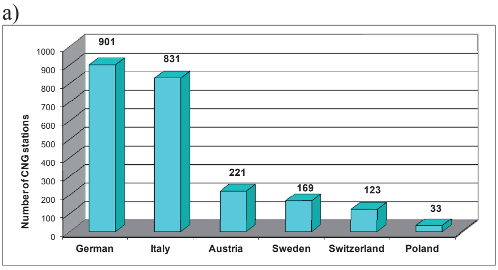


Fig. 1. Estimated mass of CNG gas cylinder, depending on capacity of liquid fuel tank [9]

a)



b)

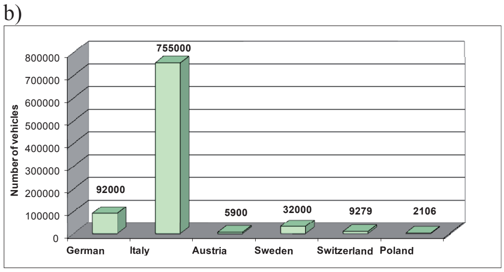


Fig. 2.Number of CNG gas filling stations and number of vehicles run on CNG gas in selected European countries [source: Gas Vehicle Report, May 2011]

The engines running on the gas can operate according to two combustion systems:

- spark ignition system (majority of applications),
- dual fuel system (limited number of applications).

In the past, selection of the system was determined mainly by significant difference in price of the fuels, natural gas and waste gases with low price of unit energy and Diesel oil with high unit prices. At considerable fractions of Diesel oil, production cost of unit energy in dual fuel engines was higher than production costs of energy in spark ignition engines. In result, gaseous engines with spark ignition are the most of practical implementations [2, 7, 9].

Anyhow, a system of gaseous fuelling with spark ignition features many disadvantages, comparing to dual fuel supply, especially with respect to compression ignition engines adapted to gaseous fuelling. To the most important belong:

- necessity of reduction of compression ratio to value 9.0-9.5, what results in reduction of overall efficiency of the engine,
- difficulties in ignition of lean gaseous mixtures, what results in fuelling of the engines with stoichiometric mixture with λ=1.0 or leaned to λ=1.6 (required special ignition systems),
- special requirements for ignition systems (increased energy of spark) and spark plugs,
- reduced durability of spark plugs,
- worsening of engine start-up capability and increased non-uniformity of engine operation at low loads.

Small gaseous engines, used as a power units to passenger and pick-up cars are fuelled with stoichiometric mixtures with λ=1.0. Very often these are *flexi-fuel* engines, possible to run alternately on the gas or the gasoline. Engines used in trucks and big stationary engines are, as a rule, turbocharged or fuelled with the gas only. They operate mainly at lean gas-air mixtures with the excess air number λ=1.6, what reduces susceptibility to knocking combustion, and owing to lower combustion rate, reduces emission of the NO_x. Reliable ignition of leaned mixture is attained due to increased energy of the spark plug, or through incorporation of spark plug's electrode to a special pre-chamber (Fig. 3). During compression stroke, the gaseous mixture gets at the pre-chamber, and is ignited from the spark. Increase of pressure in the chamber results in intense injection of burning mixture to the main chamber and propagation of the combustion into big volume of the chamber. The spark plug having described design is shown in the Fig. 3.

a)

b)

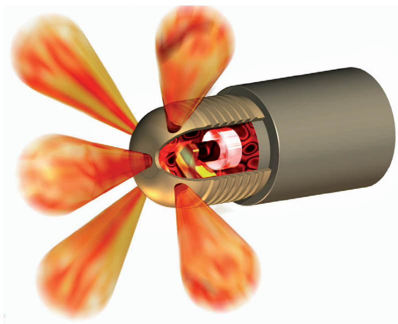


Fig. 3. Spark plugs from gaseous engines operated at lean mixtures (photo of the author): a) view of the spark plug, b) cross-section and outflow of burning gases

Dual fuel engines are constructed, as a rule, on the base of compression ignition engines powered traditionally by Diesel oil. They enable to maintain majority of positive properties of their progenitors, and additionally they can play important transportation role during period of insufficient number of gas filling stations. To the most important benefits of such engines belong:

- high efficiency at full load, considerably higher than in case of gaseous spark ignition engines, and often higher than compression ignition engines fuelled traditionally,
- maintaining operational parameters of base engines (maximal output power, torque),
- combustion of gaseous mixtures in broad range of change of the excess air number, not possible to be obtained in spark ignition engines,
- decreased emission of nitrogen oxides, solid particles and carbon dioxide, comparing to compression ignition engines fuelled traditionally,
- possibility of compensation of composition change of the gas through change of initial dose,

- possibility of alternate operation in dual fuel system or on Diesel oil only, what is of an essential importance in case of some applications (emergency installations, public transportation) or lacking of the gas, or breakdown of installation of the gas,
- engine start-up on Diesel oil, what assures the same start-up capabilities like in case of traditional fuelling,
- smooth engine operation at low loads and in transient states,
- decreased noise of engine operation.

Costs of engine operation, having decisive impact on selection of the dual fuel system, are under considerable impact of extent of operational interchangeability of liquid fuel by gaseous fuel. Due to big differences in price of the fuels (twice cheaper price of unit energy of the gas) in case of such engines one strives after minimization of the initial dose in possibly widest range of changes of engine load. It is determined by design of the dual fuel engine in stationary applications and restricts operational range of dual fuel traction engine.

The work presented in this paper deals with these issues on example of some engine types and their applications.

2. Dual fuel stationary engines

The lowest number of problems connected with engine adjustment is present in case of dual fuel stationary engines operated at constant rotational speeds and loads close to the maximal load [2, 7, 9]. Steady conditions of engine operation enable optimization of size of the initial dose and create possibilities to maintain correct composition of combusted mixture, owing to it, emission of toxic components of exhaust gases is very low [1, 7, 10].

The most often, small initial doses needed to stable ignition of gaseous mixture only, are used in stationary engines. The following sizes of the initial doses are used:

- 3÷5% Q_{zn} (of nominal dose of the engine fuelled traditionally) in case of a smaller engines,
- 1÷1.5% Q_{zn} in case of big power units.

However, use of small initial doses requires changed design of the engine, adapting it to operation in dual fuel system. The changes depend on whether the engine requires alternating operation in dual fuel system and in traditional fuel supply, or with gaseous fuelling only.

Obtainment of initial dose within limits of 5% of nominal dose requires use of a special pump and injectors adapted to injection of small initial doses. In such pumps a smaller diameters and bigger travels of the piston are used. Moreover, one should pay attention on scavenging of the suction chamber, because in case of injection of small doses, quantity of the fuel carried off through overfall decreases, what results in tendency to foaming. An example of the duplex installation is shown in the Fig. 4.

The system of duplex fuel installation is possible to application in bigger engines with lower rotational speed only. Possibility of seizure of idle injectors due to longer time of switching-off from operation of one from the systems can be considered as the main disadvantage of such system. It results in difficulties in transfer from one fuelling system to the second.

Avoiding this disadvantage is possible in a big generator engines, where three injectors in *common rail* system are used per a single cylinder. In case of an engine operated in dual fuel system one uses a single injector, switched over successively from time to time to another one, what prevents seizure of the injectors. In case of engine operation on Diesel oil only, one uses three injectors operating simultaneously, which can be also switched over successively when the engine operates at low loads.

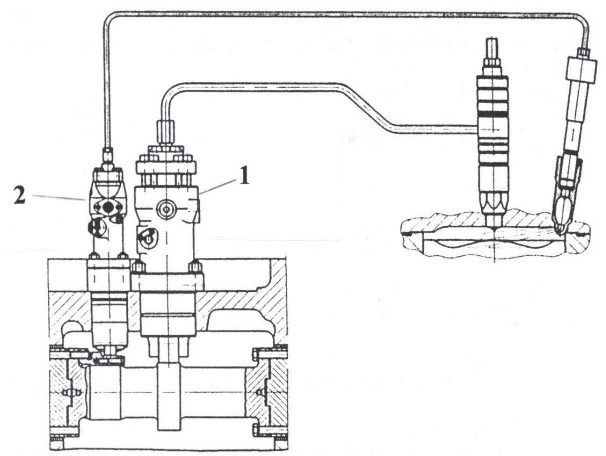


Fig. 4. Fuel supply system with Diesel oil of the 32/40 engine made by MAN B&W [5]:
1 – main pump (engine operation at Diesel oil only),
2 – pump to injection of initial dose (operation in dual fuel system)

In case of *common rail* systems it is possible to use a duplex injector of the main fuel and the initial dose. Mode of engine operation and size of the dose are controlled electronically by the ECU.

In the Fig. 5 is shown a duplex injector from the 50DF engine made by Wärtsila Company [14]. The injector is equipped with two needles, the bigger one to operation on Diesel oil only, and the smaller one to injection of initial dose. Smaller needle is controlled electronically while the bigger one is controlled hydro-mechanically. In dual fuel operation, advance angle and time of the injection are adjusted individually for each cylinder.

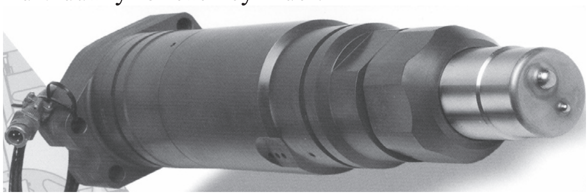


Fig. 5. Duplex injector used in the 50DF Wärtsila engines [14]

Use of extremely small initial doses $1.0 \div 1.5\% Q_{jzn}$ requires special design of combustion chamber, enabling increased energetic and spatial influence of the ignition dose. Injection of initial dose occurs to pre-chamber, where gaseous mixture is present before the end of compression stroke (Fig. 6). After ignition of the gaseous mixture, increase of pressure occurs in the pre-chamber, what results in injection of burning liquid and gaseous fuel to the main chamber. Suitable selection of geometry of holes in the pre-chamber enables maximal increase of spread of burning stream of mixture of the fuels, what favors rapid injection of the gas in the main chamber.

The dual fuel engines in nominal conditions develop efficiencies higher with 5÷6% comparing to their equivalents with spark ignition system. It is possible, therefore, to perform comparison of their operational costs for extreme conditions of fuel supply:

- supply with the network natural gas – the most expensive gas in the market,
- the mine gas with average contents of methane 55% - as a cheap waste gas.

Prices of the gases and liquid fuel (fuel oil) were taken on the base of the prices paid by an enterprise, which operates dual fuel gaseous engines. Results of the comparison are presented in the Fig. 7.

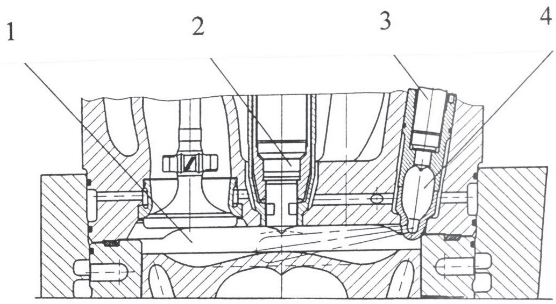
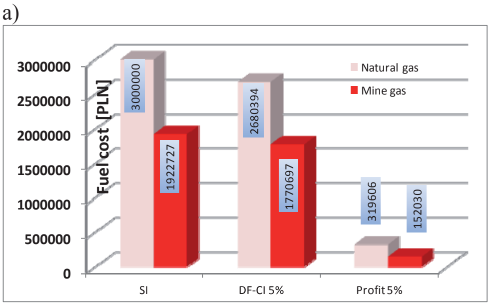


Fig. 6. Combustion chamber of dual fuel, 32/40 DG engine made by MAN B&W [5]:
1 – main chamber, 2 – main injector, 3 – injector of initial dose,
4 – pre-chamber

a)



b)

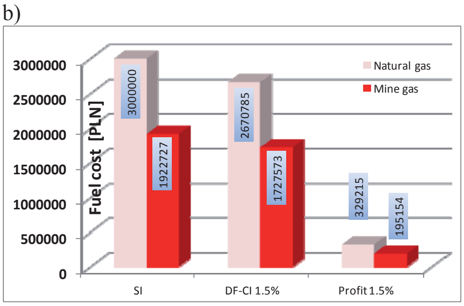


Fig. 7. Comparison of yearly fuel costs to the engines with 1 MW output power, with spark ignition and dual fuel engines run on natural gas and mine gas: a) initial dose of dual fuel engine, 5% of nominal dose, b) initial dose of dual fuel engine, 1.5% of nominal dose

From comparison shown in the Fig. 7 is seen that dual fuel supply is more advantageous in case of more expensive and also the cheapest gases, both in case of 5% dose and 1.5% of nominal dose. Yearly profit in case of the natural gas fuel supply amounts respectively to about 320 000 PLN with 5% dose and 330 000 PLN with 1.5% dose, what gives relative savings, comparing to fuelling costs of a spark ignition engine, of - 10.7% and 12.2%. Profits in case of fuelling with the mine gas amount to about 152 000 PLN with 5% dose and 195 000 PLN with 1.5% dose, what gives 7.9% and 10.1%. From presented comparison is seen, that a bigger profits can be generated when one uses the network natural gas, relatively expensive due to partial networking and transfer costs included in unit price of the gas. Use of dual fuel engines in a 6 MW power plant, when the engines are fuelled with the natural gas can generate profits of about 2 million PLN, what considerably influences on amortization time of purchase costs of the engines. Profits due to fuelling with the mine gas in a similar power plant (6 MW is an average output power of the power plant in the Jastrzębska Spółka Węglowa) are a little bit lower and amount to 0.9÷1.2 million PLN.

To additional beneficial factors belong: long lasting period of failure-free operation of injection systems and smaller tendency to knocking operation of the engine, and in case of generator engines - considerably lower frequency of engine switching-off due to loss of frequency synchronization with external network.

3. Dual fuel traction engines

Traction engines should be absolutely fuelled with the natural gas compressed to 20÷25 MPa pressure and equipped with steel gas cylinder reinforced with carbon fiber, or entirely made from composite material. It enables to maintain required mileages between successive refueling with the gas on the level a little bit lower comparing to the engines fuelled traditionally.

Nowadays as a power units to trucks and buses are used compression ignition engines. Adaptation to gaseous fuelling requires rework of these engines to spark ignition system (reduction of compression ratio, stoichiometric combustible mixtures), what is connected with decreased efficiency in complete range of change of engine load (Fig. 8). Decrease of the efficiency can range from a few to several percent, depending on engine size and load. It is worth to underline, that the biggest differences in the efficiency occur in area of partial engine loads, and hence, in area of the most frequent operation of the engine.

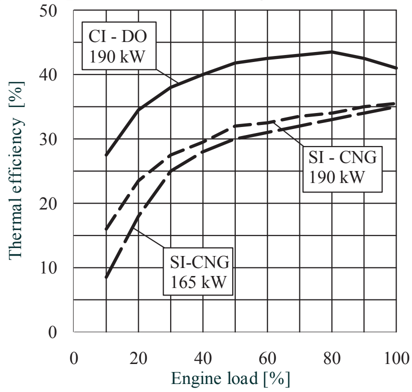


Fig. 8. Comparison of thermal efficiency of SI gaseous engines and CI engines fuelled traditionally [8]

Use of the dual fuel system assures maintaining the efficiency at maximal engine load at the same level as in case of traditional fuelling. As confirmed by investigations performed by the author on various engines, selection of a suitable initial dose enables even increased overall efficiency with 2÷4%, calculated in absolute units. This should contribute to reduction of consumption of energy and the fuels in the engines mounted in trucks operated on long routes, and the same, to reduction of operational costs.

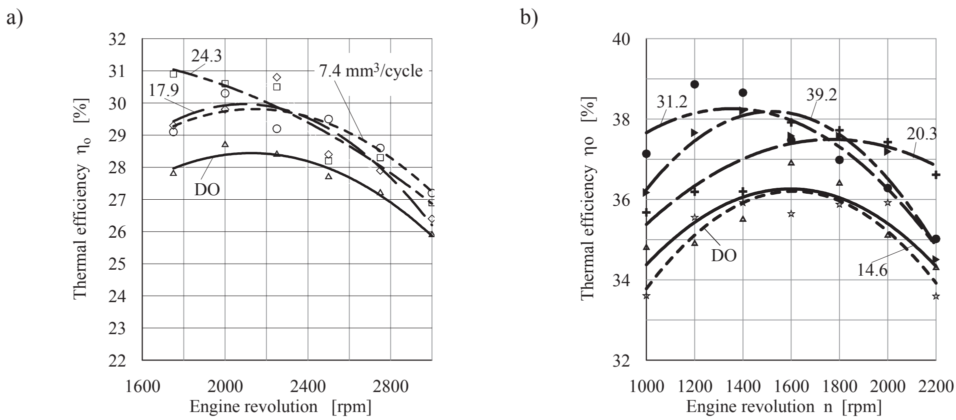


Fig. 9. Influence of rotational speed on overall efficiency of dual fuel engine at maximal load and different initial doses: a) 1CA90 engine [7], b) SB3.1 engine [9]

Investigations of the SB3.1 engine with cylinder bore 127 mm, piston stroke 146 mm and capacity of the cylinder 1.84 dm^3, equipped with common rail system and injection of the gas to area near the inlet valve, have shown that with small initial doses, in area of partial loads, the engine can develop efficiencies close to the efficiency of the engine fuelled traditionally (Fig. 10). Average dose 14.6 mm^3/cycle used in course of the investigations was increased with respect to minimal dose possible to be achieved in common rail system, needed to assure long lasting operation of the injector without risk of overheating.

Additionally, use of increased initial dose leads to reduction of hazard of knocking combustion, what in supercharged engines can be utilized to increase maximal output power of the engine. It should be underlined, however, that increase of the initial dose leads to reduction of overall efficiency of the engine at partial loads, comparing to the engine run on Diesel oil only.

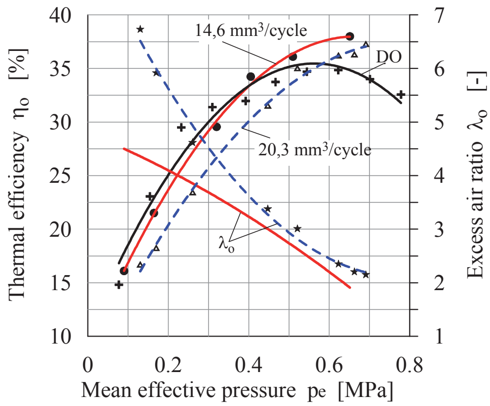


Fig. 10. Dependency of the overall efficiency on the load of the SB3.1 engine fuelled traditionally and run in dual fuel system: λ_o – excess air ratio of gaseous mixture, various initial doses, rotational speed 1400 rpm

Due to insufficient network of CNG filling stations, in case of dual fuels engines one should assure full interchangeability of fuelling with the gas and Diesel oil only. Due to size of the engines, such condition requires maintaining original injection apparatus, used in case of traditional fuelling. This restricts, both in the systems with injection units and in common rail systems, possibility of unlimited reduction of the initial dose. It results from worsening of uniformity of dosing, or decay of injection (from one cycle to another) when very small doses are used. It should be underlined, that the initial doses are most often close to, or smaller than the doses injected at idling speed of the engine, when uniformity of the dosing at traditional fuelling is not so important.

In course of adaptation of the engines to dual fuel supply when serial injection apparatus is utilized, the following sizes of the initial dose can be used:

- 15÷25% Q_{zn} – for serial piston pumps,
- 10÷15% Q_{zn} – for serial common rail systems.

Size of the initial dose is most often referenced to size of Diesel oil injected in the engine at nominal loads and traditional fuelling.

In traction engines operated in conditions of changing load, interchangeability of the liquid fuel with gaseous fuel belongs to important issues. The interchangeability can be evaluated by fraction of gaseous fuel energy U_g in complete dose of energy supplied to the engine.

Changes of fraction of the gas U_g in function of engine load at constant rotational speed, for different initial doses, are presented in the Fig. 11. They show that in case of stationary engines use of the initial dose having energetic size of about 5% enables more than 90% interchangeability of the liquid fuel in complete range of change of engine loads. It requires, however, usage of separate injectors for the initial dose and the dose at traditional fuelling.

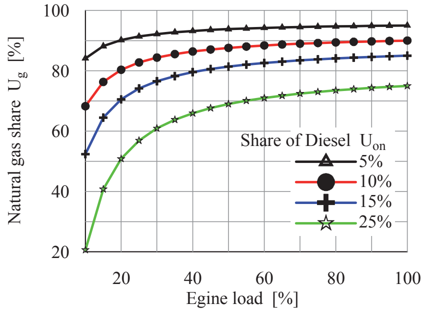


Fig. 11. Effect of dual fuel engine load on energetic fraction of the gas for different initial doses: constant rotational speed; assumed linear change of overall efficiency of the engine from 0.362 for $p_{e\,max}$ to 0.125 for p_e=0.1$p_{e\,max}$

At the doses with energetic fraction of about 10%, possible to be achieved in *common rail* systems when the injector was carefully selected, it is possible to obtain substitution of the gaseous fuel above 80% for engine loads higher than 20% of nominal load.

It is also worth to pay attention, that during adaptations of an older engines, with classic injection apparatus, when doses with energetic value of about 25% are used, it is possible to obtain substitution of the liquid fuel greater than 60% for engine loads higher than 30% of nominal load. This should be a signal that even in older traction engines dual fuel supply can bring about tangible economic benefits.

Selection of the initial dose is very important in the dual fuel traction engines. When serial injection apparatus shall be kept, used initial doses are bigger, as a rule, than the ones needed to robust ignition of the gas. From the other side, they should assure sufficient cooling of the injectors at maximal engine loads. Due to this, selection of the initial dose should be accomplished on the base of engine testing, while reduction of the dose should be limited by requirement of suitable durability of the engine.

In the Fig. 12a are presented fractions of the gaseous fuel achieved in the SB3.1 engine at maximal engine load and various initial doses. The SB3.1 engine is a single cylinder engine constructed on the basis of the SW 680 engine (swept capacity 18.1 dm^3), with size corresponding to the engines used in truck transport. At maximal engine load, energetic fraction of the gas is nearly independent from rotational speed. It results from usage of electronic systems to injection of the gas and initial dose, where doses of the both fuels depend only on opening time of the injectors. Effect of operational parameters of the engine, inclusive of temperature of injectors in common rail system, on quantity of injected fuel is small.

At minimal dose 14.6 mm^3/cycle it is possible to achieve more than 90% substitution of the liquid fuel in complete range of change of rotational speeds. Increase of the initial dose to 39.3 mm^3/cycle results in reduction of fraction of the gas to value of about 60%. Moreover it results in growth of engine load, below which the engine should be fed with Diesel oil only. It is worth to notice, that big initial dose reduces safety of engine operation in range of knocking combustion, while 60% substitution of the liquid fuel can considerably reduce operational costs.

In area of partial engine loads, fraction of the gas in total dose of energy supplied to the engine decreases together with reduction of the load (Fig. 12b). Simultaneously, in area of partial engine loads is seen a distinct tendency to increase of fraction of the gas U_g as rotational speed increases.

In the research SB3.1 engine at initial dose of about 20 mm^3/cycle, energetic fraction of the gas changed in range of 45÷82% in complete investigated area of engine operation, i.e. at changes of engine load in range 0.1÷0.7 MPa and rotational speed 1200÷2000 rpm.

a) b)

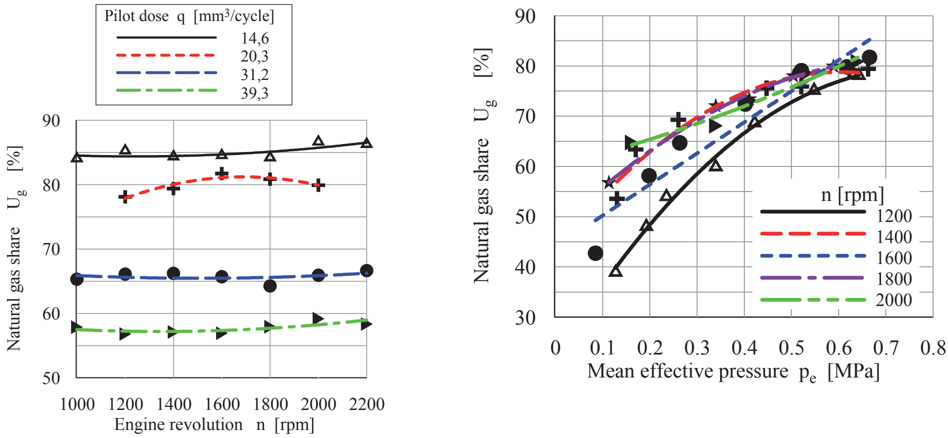


Fig.12. Comparison of energetic fraction of the gas in the SB3.1 engine run in dual fuel system:
a) engine load close to the maximal one, various initial doses, b) changing engine load, different rotational speeds, constant initial dose 19.8 mm^3/cycle

In real conditions of engine operation, substitution of the liquid fuel by the gas depends on conditions of engine operation, is higher in out-of-urban driving and decreases in case of urban driving. Additionally, it depends on weigh of transported load and conditions on a road. Due to it, it is difficult to specify accurate operational substitution of liquid fuel, and the same, real profits from adaptation of the engine to dual fuel supply.

In the Fig. 13 are presented estimated yearly profits for a dual fuel medium size engine with 300 kW output power, used as a power unit to a truck-tractor in international transport. The data concerning consumption of Diesel oil were obtained from an enterprise operating over a dozen truck-tractors of a similar size. Price of Diesel oil was assumed as 5.50 PLN/dm^3 and CNG 2.55 PLN/nm^3, mandatory in filling stations in April 2013.

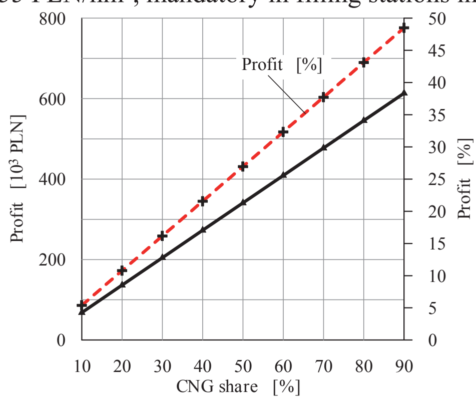


Fig. 13. Effect of fraction of the gas on profit in yearly purchasing costs of the fuel to dual fuel medium size engine used in trucks

From analysis depicted in the Fig. 13 is seen, that 50% substitution of the liquid fuel by the CNG can bring about yearly profits of about 350 000 PLN, what in case of over a dozen operated vehicles, generates significant profits for the enterprise. It seems that due to specifics of vehicle's operation in the analyzed enterprise, real substitution can be even bigger, and generated profits could be higher.

Quite different is the situation in case of the engines used in passenger cars. These engines are mainly operated at partial loads, in urban traffic with limited speed, with big portion of idling operation, as underloaded cars. Due to this, operational substitution of the liquid fuel by the gas in such engines can be considerably smaller than the substitution in the trucks. Due to significantly lower prices of the gas comparing to Diesel oil (more than twice), operational cost of gaseous engine with spark ignition will be lower than operational cost of dual fuel engine. However, rework of compression ignition engine to spark ignition and fuelling with the gas requires numerous design changes, and because of size of the engine could be unprofitable. Moreover, engine after such rework could be run on the CNG only, or after big design changes can be also run on gasoline. Presented considerations lead to conclusion that during transitional period, gaseous fuelling of passenger cars should be introduced to spark ignition engines in so called *flexi-fuel* system, enabling alternate fuelling with gasoline or natural gas.

In compression ignition engines, dual fuel system can be used to reduction of smokiness of exhaust gases, what considerably lengthens time to regeneration of DPF filters and increases their life. Fraction of gaseous fuel in case of such strategy of fuel supply can be smaller (about 30%), and CNG or LPG can be used as the fuel. In spite of relatively low octane number of the LPG, due to big doses of Diesel oil, knocking combustion doesn't occur. Use of the LPG, having price similar to the CNG, reduces costs of engine adaptation to dual fuel supply.

In case of traction engines, particularly adverse conditions of combustion are present in area of low engine loads [10]. In some implementations, necessity of maintaining the same output power like in case of run on Diesel oil only, belongs to important issues. Due to it, dual fuel supply can be limited to range of engine loads of 20÷90% of the nominal load. The controller automatically switches mode of engine operation according to the following scheme:

- load 0÷20 N_{zn} run on Diesel oil only (increase of overall efficiency of the engine and reduction of CO and THC emissions),
- load 20÷90 (95) N_{zn} dual fuel supply with minimal initial dose,
- 90 (95)÷100% N_{zn} run on Diesel oil only (engine output power like in traditional fuelling).

More detailed information on control strategy of the dual fuel engines can be found in the study [9].

4. Conclusions

On the base of performed analyses and investigations it is possible to draw the following conclusions with general character:

- Dual fuel system enables maintaining the most of positive features of compressed ignition engine fuelled traditionally, like high efficiency, low sensitivity to changes in quality of the fuel, smooth operation in conditions of changing load.
- The most advantageous conditions of dual fuel supply are present in stationary engines operated under constant loads and rotational speeds. In such engines one should use a special apparatus to injection of the initial dose, if the engine can be fuelled with the gas only, or doubled system (special to the initial dose and serial to feed with Diesel oil only) in a cases where full alternation is required. It enables decreasing of the initial dose to a value smaller than 5% of nominal dose and increasing of operational fraction of the gaseous fuel.
- Usage of dual fuel supply in stationary engines enables obtainment of a considerable savings in cost of the fuel, comparing with spark ignition engine, regardless of the price of the gas and used size of the initial dose. Value of the profit is bigger in case of more expensive gases, like the natural gas.
- In traction engines one should use compressed natural gas (CNG), what results from requirements of a suitable mileage between successive refueling. During transitional period, in compression ignition engines one should use the dual fuel supply systems with full alternation

of the fuelling, while in case of spark ignition engines one should use the *flexi-fuel* systems, enabling combustion of pure gas or pure gasoline.

- In the engines assembled in trucks one should use dual fuel systems, what promotes rational use of energy. Moreover, such systems enable considerable cost reduction of the fuel. Value of the profits depends on operational fraction of gaseous fuel, and the same on operational condition of vehicles.
- In the engines assembled in passenger cars, due to considerable differences in price of the gaseous fuel and the liquid fuels, dual fuel system can prove unprofitable from economic point of view, comparing to spark ignition. Moreover, extent of changes in compression ignition engine needed to adaptation to gaseous fuelling and spark ignition is too big. Due to this, gaseous fuelling in passenger cars should concern spark ignition engines operated in the *flexi-fuel* system.

References

1. Barroso P, Ribas x, Domingues j, De Sella E, Garcia J M. Study of dual-fuel (diesel+natural gas) particle mater and CO_2 emissions of a heavy-duty diesel engine during transient operation. Combustion Engines; 2/2013 (153) ISSN 0138-0346: 28-39.
2. Friedeman Z.: Gasmotoren, Vogel Buchverlag, Würzburg, 2001.
3. Kowalewicz A.: Adaptacja silnika wysokoprężnego do zasilania gazem naturalnym. Czasopismo Techniczne, Wydawnictwo Politechniki Krakowskiej, nr 7-M/2008.
4. Rudkowski M., Dudek S.: Obecny poziom rozwoju napędów zasilanych płynnym gazem ziemnym (LNG), Journal of KONES Internal Combustion Engines 2003, Vol. 10, 304, 2003.
5. Schiffgens H., Brandt D., Dier L., Rieck K., Glauber R.: Die Entwicklung des neuen MAN B&W Diesel-Gas-Motors 32/40 DG, MTZ Motortechnische Zeitschrift 58 (1997) 10, 1997.
6. Stelmasiak Z.: Analysis of Combustion Phenomena in Dual Fuel Engine Fed With Natural Gas (CNG). Fisita 2002 World Automotive Congress, Paper No. F02 V030, 2002.
7. Stelmasiak Z.: Studium spalania gazu w dwupaliwowym silniku o zapłonie samoczynnym zasilanym gazem ziemnym i olejem napędowym, Wydawnictwo ATH, nr 5/2003.
8. Stelmasiak Z.: Possibility of Improvement of Some Parameters of Dual Fuel CI Engine by Pilot Dose Division. Journal of Polish CIMAC, Vol. 6 No.1/2011, p. 181-189.
9. Stelmasiak Z.: Dwupaliwowe silniki o zapłonie samoczynnym, Instytut Technologii Eksploatacji, Radom 2013, ISBN978-83-7789-200-8.
10. Stelmasiak Z., Larisch J., Gilowski T., Matyjasik M.: Możliwości poprawy składu mieszaniny gazowej przez dławienie powietrza przy częściowych obciążeniach silnika dwupaliwowego, Archiwum Motoryzacji 1/2007, str. 43-57, 2007.
11. Molenda J.: Gaz ziemny. Paliwo i surowiec. WNT Warszawa 1996.
12. Surygała J.: Wodór jako paliwo, WNT Warszawa 2008.
13. Zua CH., Zhao J.: Development of Diesel Engines Fuelled with Natural Gas, SAE Paper No. 2001-01-3505, 2001.
14. Wärtsila 50DF Technology Review, 2010.

Journal of POLISH CIMAC
Faculty of Ocean Engineering & Ship Technology
GDAŃSK UNIVERSITY OF TECHNOLOGY

VIRTUAL TECHNIQUES IN THE OPTIMIZATION OF THE RECOGNIZING THE STATE OF MACHINES

Joanna Wilczarska, Tomasz Kałaczyński, Marcin Łukasiewicz, Ewa Kuliś, Andrzej Sadowski

University of Technology and Sciences in Bydgoszcz
ul. Ks. Kordeckiego 20, 85-225 Bydgoszcz
tel.: +48 52 3408283, fax: +48 52 3408286
e-mail: asiulazol@utp.edu.pl

Abstract

The system of recognizing the state of machines should enable: control of the state, forecasting the state in case of the applicability of the machine, location of damage in case of the unfitness of the machine, genesis of state and describing the probable reason for the appearance of located damage. In the recognition process of the state of the machine a set of diagnostic parameters is being used. He is being favored from the set of output parameters. With the tool an optimization of the set of diagnostic parameters is of help in a process of selection of parameters.

At the work an effect of computer programs which enables the realization of the optimization methodology of the recognition process of the state of machines was described. The program consists of five modules: canvassing of data, optimization of diagnostic parameters, evaluation of the state, forecasting the state, genesis of state.

Keywords: *optimization, recognizing the state of machines, diagnostic parameter*

1. Introduction

The system of identifying the state should enable machines:

- control of the state;
- forecasting the state in case of the applicability of the machine what in practice is being imported for establishing a date of his next diagnosing;
- location of damage in case of the unfitness of the machine;
- genesis of state and describing the probable reason for the appearance of located damage.

Fundamental requirements which a system of identifying the state of the machine should fulfil it:

a) reliability
b) high speed operation;
c) standardization;
d) cost-effectiveness (low manufacture costs and exploitation).

The system of identifying the state of the machine moreover should be characterized:

- ✓ with simple, possibly optimum algorithm of functioning;
- ✓ with the versatility, i.e. possibilities of identifying the state of machines of different types;
- ✓ with possibilities of identifying the state of machines about small and large degree of the complexity;
- ✓ with automatic generating diagnoses;
- ✓ with the explicitness and the legibility of presenting diagnoses;

✓ with simplicity of supporting.

The system of identifying the state should provide machines so that the diagnostician interferes in his action but where:

a) changes of the object of identifying the state;
b) amendment to the algorithm of diagnosing, forecasting and genesis of state;
c) of removing detected automatically damage to the diagnostic device.

The system of identifying the state of the machine should accomplish the requirement concerning the quality of products according to applicable standards [2].

The system specification of identifying the state of the machine should grasp the following issues from the area of the design, the production and the exploitation of machines:

- functional properties;
- of design features
- conditions of using and supporting;
- potential service centers;
- economic calculation.

2. Optimization of the process of examining the state of machines

Set of diagnostic parameters, exploited in the recognition process of the state of machines, stands out from the set of output parameters. Determination of a set of diagnostic parameters in the genesis of engineering should take into account [1]:

a) ability to copy transitions of the machine during the exploitation;
b) quantity of the information about the state of the machine;
c) right changeability of the value of diagnostic parameters during the exploitation of a machine.

Diagnostic parameters $y_j \in Y$ are with changeable sizes during $Y=Y(\Theta)$, because depend on the course of extorting processes grow old and wear and tear..

The set of diagnostic parameters Y is standing out from the set of output parameters Y_{WY} which are describing the course of initial processes (working and associated processes), dependent on the technical condition of the object:

$$Y_{wy} = Y_{wy}(S, \Theta) \tag{1}$$

To the purpose of more thorough distinguishing $Y \subset Y_{wy}$ sets a criterion of the minimal mistake of the diagnosis is most often applicable. The parameters which are characterized by the minimal mistake of the diagnosis and a procedure of choice of diagnostic parameters are distinguished according to the minimal mistake of the diagnosis.

The essence of this method is to determine the diagnosis error of D, i.e. the area of "covering" the conditional probability density function parameter $y_j \in Y$ defined by Serdakow [2] relationship:

$$D = P\left(\frac{S_1}{y_j}\right) \cdot Q_1 + P\left(\frac{S_2}{y_j}\right) \cdot Q_2 \,, \tag{2}$$

whereas probability of the Q_1 type I error consisting in ranking the machine being in the state of the applicability $S_0 = S_1$ to the condition of the unfitness $S_1 = S_2$:

$$Q_1 = \int_{y_{gr}}^{+\infty} f\left(\frac{y_j}{S_1}\right) dy_j \tag{3}$$

and probability of the Q_2 type II error consisting in ranking the machine being in the state of the unfitness $S_1 = S_2$ to the state of the applicability $S_0 = S_1$:

$$Q_2 = \int_{-\infty}^{y_{gr}} f\left(\frac{y_j}{S_2}\right) dy_j \tag{4}$$

Next choice "best" $y^* \in Y$ parameter through the minimization of the diagnosis error:

$$y^* = \min_j \left(D_j\right) \tag{5}$$

Choice of diagnostic parameters according to the presented method is being brought about then to:

1. Of qualitative analysis of parameters, relying on [1]:
   a) for studying the gravity of changes of the value of diagnostic parameters at the change of the technical condition of the machine;
   b) for appointing and estimating limit values y_{gr} according to the criterion of the smallest Bayes risk at assuming the cost value of mistakes and the II kind;
2. Of quantitative analysis which relies on choice of parameters under the angle of criteria connected ability to copy transitions of the machine during the use, quantities of the information about the state of the machine and the changeability of the value of diagnostic parameters in the time of the exploitation of a machine.

Relevant algorithms considering these demands were moved below as methods.

- **Method of the maximum relative variation of the diagnostic parameter**

In this method this diagnostic parameter which has a considerable value of the indicator is going k_j. He is taking into account the average speed of the change of parameters in the time interval (Θ_1, Θ_b). He is being described according to the relation:

$$k_j = \frac{b_j}{\sum_{j=1}^{m} b_j},$$

$$b_j = \frac{1}{K} \sum_{i=1}^{K} \frac{\left| y_j(\Theta_{i+1}) - y_j(\Theta_i) \right|}{(\Theta_{i+1} - \Theta_i) \left| y_j(\Theta_1) - y_{j,g} \right|}, \tag{6}$$

where: K - number of elements of the time series in the period (Θ_1, Θ_b).

- **Method of correlation of the value of diagnostic parameters with the state of the machine**

The method consists in examining correlation of the value of diagnostic parameters with the state of the machine $r_j = r(W, y_j)$ (if necessary with the exploitation time, $((r_j = r((\Theta, y_j))$:

$$r_j = \frac{\sum_{k=1}^{K} (\Theta_k - \overline{\Theta})(y_{j,k} - \overline{y_j})}{\sqrt{\sum_{k=1}^{K} (\Theta_k - \overline{\overline{\Theta}})^2 \sum_{k=1}^{K} (y_{j,k} - \overline{y_j})^2}} \tag{7}$$

$$\overline{\Theta} = \frac{1}{K} \sum_{k=1}^{K} \Theta_k, \quad \overline{y_j} = \frac{1}{K} \sum_{k=1}^{K} y_{j,k}, \tag{8}$$

where: $r_j = r(S, y_j)$; j = 1,..., m - coefficient of correlation between variables S i y_j,
$r_{jn} = r(y_j, y_n)$; j,n = 1,..., m; $j \neq n$ – coefficient of correlation between variables y_j i y_n.

- **Method of the maximum information capacity of the diagnostic parameter**

Nature of the method consists in choice of the parameter delivering a lot to information about the state of the machine. The diagnostic parameter has an all the greater significance in determining the transition, they more strongly are feeling with him correlated and for them more poorly is correlated with other diagnostic parameters.

This relation is being presented in the form of the rate of the information capacity of the diagnostic hj parameter which is with alteration of the indicator referring to the harvest of exogenous variables econometric model:

$$h_j = \frac{r_j^2}{1 + \sum_{j,n=1, j\neq n}^{m} \left| r_{j,n} \right|} \tag{9}$$

$$r_{j,n} = \frac{\sum_{k=1}^{K} (y_{j,k} - \overline{y_j})(y_{n,k} - \overline{y_n})}{\sqrt{\sum_{k=1}^{K} (y_{j,k} - \overline{y_j})^2 \sum_{k=1}^{K} (y_{n,k} - \overline{y_n})^2}} \tag{10}$$

$$\overline{y_j} = \frac{1}{K}\sum_{k=1}^{K} y_{j,k} \quad ; \quad \overline{y_n} = \frac{1}{K}\sum_{k=1}^{K} y_{n,k} \quad , \tag{11}$$

where: $r_j = r(S, y_j)$; j = 1,..., m - coefficient of correlation between variables S i y_j,
$r_{jn} = r(y_j, y_n)$; j,n = 1,..., m; j≠n – coefficient of correlation between variables y_j i y_n.

In case of the no data from the set they are being replaced with the Sec., on the assumption that fixing procedures of recognizing of the state the machine is carried out in the period of the normal wear and tear, sometimes of the operation of a machine.
To the purpose of choice of the set of diagnostic parameters values of scales are being exploited [5]:

a) standardized computational scales w_{1j}:

$$w_{1j} = \frac{w_j}{\sum_{j=1}^{m} w_j} \tag{12}$$

$$w_j = \frac{1}{d_j}, \quad d_j = \sqrt{(1-r_j^*)^2 + (1-h_j^*)^2} \tag{13}$$

$$r_j^* = \frac{r_j}{\max r_j}, \quad h_j^* = \frac{h_j}{\max h_j} \quad , \tag{14}$$

as the criterion for the choice of the diagnostic parameter (of diagnostic parameters) $\max(w_{1j})$ was accepted and choice of diagnostic parameters according to this criterion.

4. Computer program to optimize the process of exploitation of the machines

The program called "Optimization" methodology enables the optimization of the process of recognition of the machines. The scope of capabilities includes the process of testing procedures for recognition of machine condition [4]:

a) examining the set of diagnostic parameters in the aspect of appointing an optimal set of diagnostic parameters for the evaluation of the state of the machine in the moment of the examination, of forecasting and genesis values of diagnostic parameters and on their base forecasting and genesis of state of the machine;
b) examining the quality of the evaluation of the technical condition of the machine in the aspect:
   - f appointing the motherland of the relation: technical condition - exploitation time - value of the diagnostic parameter,
   - of appointing the diagnostic test of the control of the state and the location of damage to the machine;
c) examining the quality of forecasting in the aspect:
   - of fixing the forecasting method of the value of the diagnostic parameter according to the function of the forecast error,
   - of determining the method of setting the next date of supporting according to the function of forecast error,
   - examination of the impact of the value of the horizon of the forecast for the forecast error,
   - examination of the impact of the number of the set of diagnostic parameters for the forecast error;
d) examining the quality genesis in the aspect:
   - of fixing the method genesis values of the diagnostic parameter according to the function of the genesis error,
   - examination of the impact of the number of the set of diagnostic parameters for the genesis error.

The program consists of five modules (fig. 1):

1. **Of canvassing** (leading, edition, data record, import from the csv file). The module of the canvassing consists of five bookmarks (fig. 2):
   a) group of machines,
   b) list of states,
   c) list of parameters,
   d) list of objects,
   e) list of measurements.

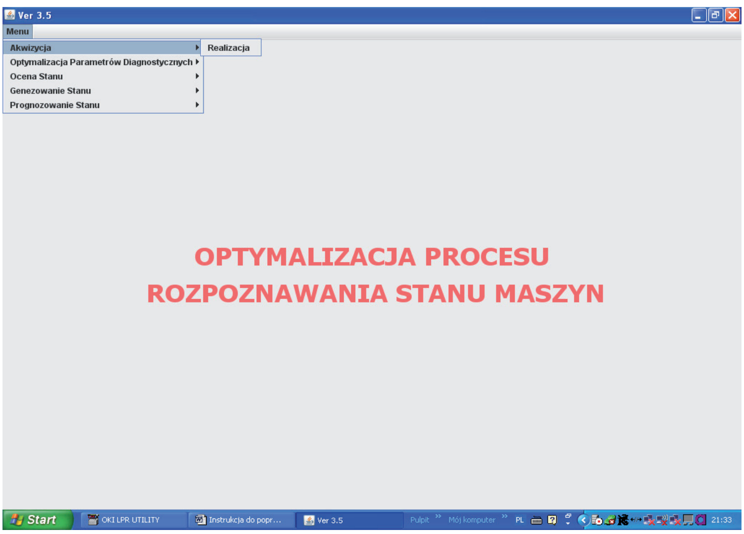
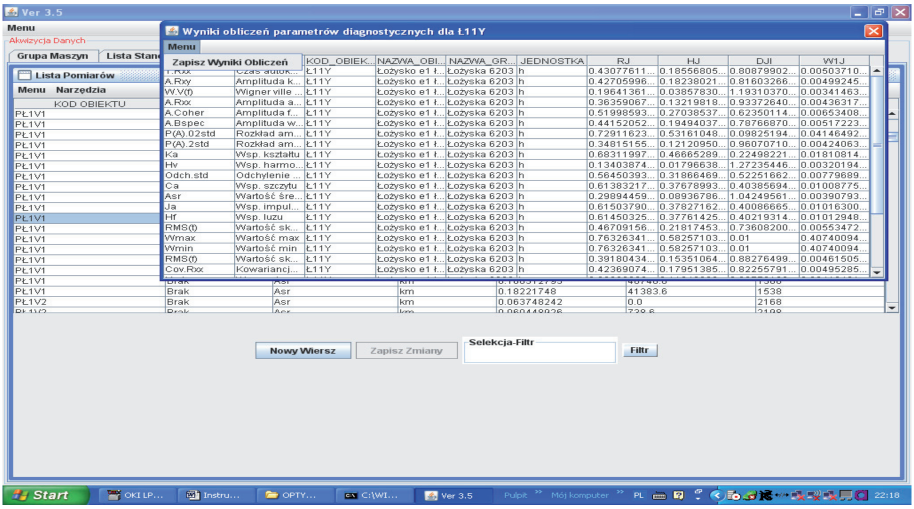


Fig. 1. View of the elaborated menu of the main programme [4]

2. In the module the **Optimization of Diagnostic Parameters** is taking place calculating the value of the criterial function and of scales of diagnostic parameters on the base given entrance for the chosen object with the possibility of the record to a text file (fig. 2).



Rys.2. Module the Optimization of Diagnostic Parameters [4]

3. In the module the **Evaluation of the State** is taking place (fig. 3):
   a) creating the diagnostic motherland based on the input;
   b) possibility of the edition of the diagnostic motherland;
   c) record to a text file.

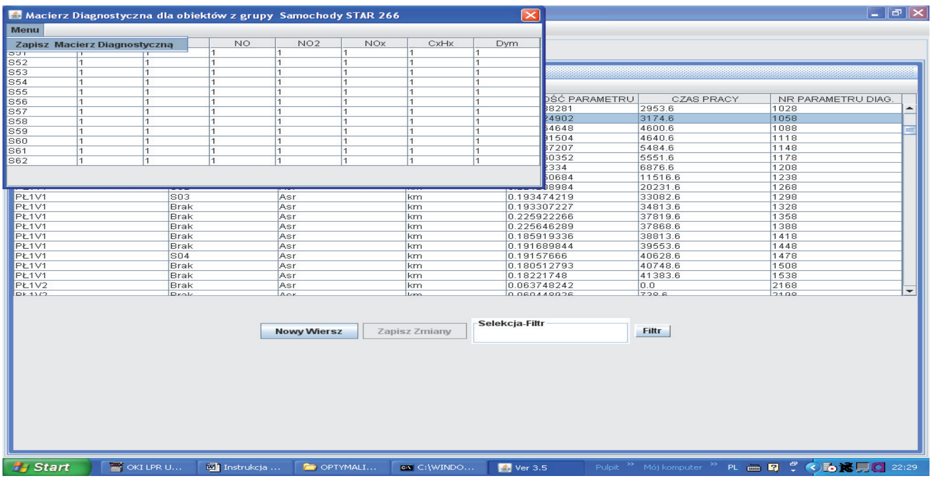


Fig. 3. Diagnostic motherland created in the module Evaluation of the State for the chosen group of machines [4]

4. In the module **Forecasting the State** is taking place (fig. 4):
   a) appointing the forecast value of the diagnostic parameter and the error of the forecast,
   b) of setting the date of diagnosing and operating a machine,
   c) examination of the impact of exploitation factors (number of parameters, number of the time series, value of the horizon of the forecast) to the forecast of the state,
   d) the visualization and the notation of analyzed models of forecasting the object for select parameters chosen in the form of the picture and the report.

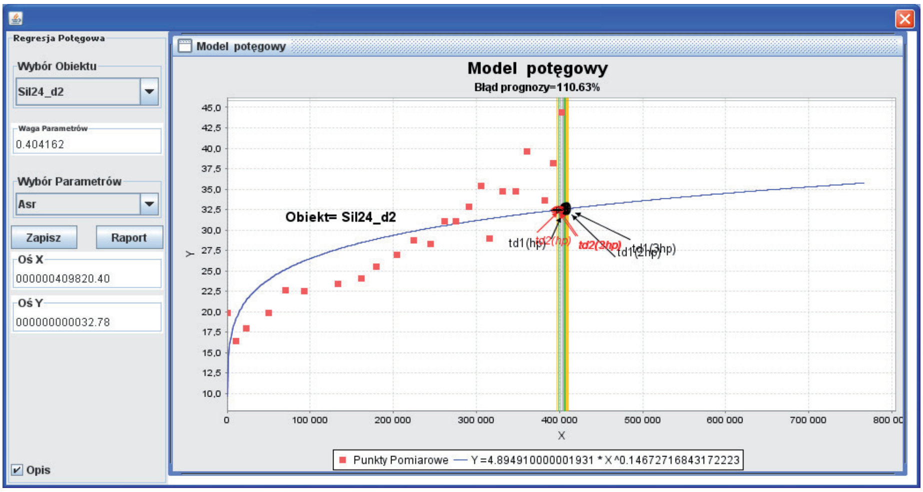


Fig. 4. Function of the exponential regression from the module Forecasting the State [4]

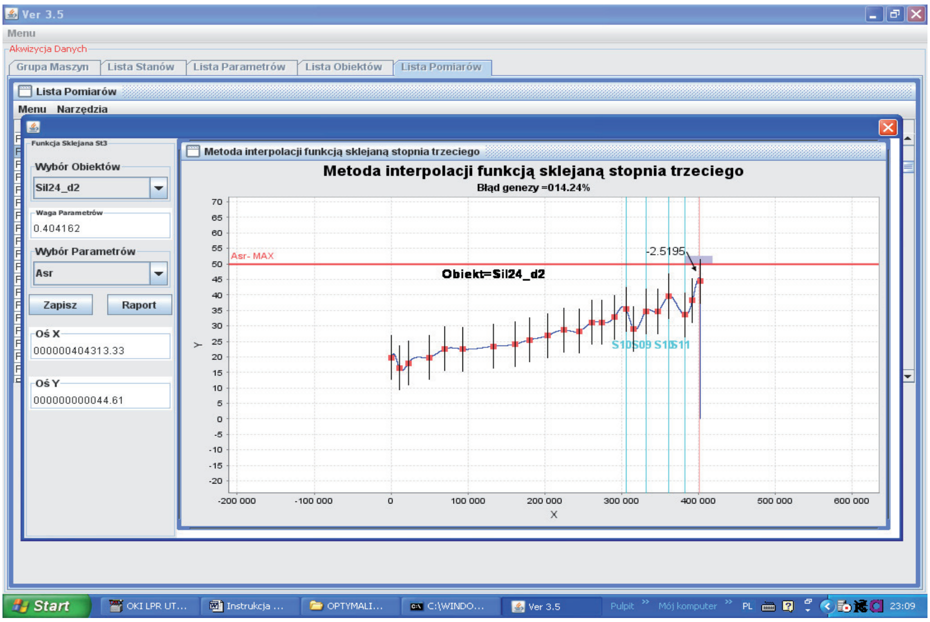


Fig. 5. Method of the interpolation with function glued together of the third step of the module Genesis of the State [4]

5. In the module **Genesis of the State** he is taking place (fig. 5):
   a) appointing the genesis value of the diagnostic parameter and the error of the genesis;
   b) appointing the minimum distance of the genesis value of diagnostic parameter from his threshold;
   c) examination of the impact of exploitation factors (number of parameters, number of the time series) to the genesis of the state;
   d) the visualization and the notation of the function of the approximation or the interpolation of the object for select parameters chosen in the form of the picture and the report.

Conclusions

The recognition process of the state enables machines:

- determining the technical condition of the machine in the current time on the basis of the results of diagnostic investigations. It enables the control of the state and the location of damage in case of the condition of the unfitness of the machine.
- predicting the state of the machine in the future based on the incomplete history of results of diagnostic research. It enables the work to judge the time of reliable using the machine or the value carried out by her in the future.
- determining the state of the machine in the past tense based on the incomplete history of results of diagnostic research what estimating the state of the machine in the past enables.

In the destination of appointing the set of diagnostic parameters, used in the optimization process of the recognition process of the state, a method is proposed correlation of the value of the diagnostic parameter with the state and the exploitation time of a machine and the method of the information capacity of the parameter diagnostic.

Computer programs drawn up aren't a commercial product on account of the specificity and functional redundancy concerning aspects of forecasting, genesis whether of inspections of mathematical models. He can however constitute a point of departure for the creation of the commercial product.

Literature

[1] Będkowski L., *Elementy diagnostyki technicznej*, WAT, Warszawa 1991.

[2] Hohmann L., *Journey of the Software Professional: A Sociology of Software Development. Englewood Cliffs*. NJ: Prentice Hall. 2000.

[3] Tylicki H., Różycki J., Żółtowska J., *Badanie jakości zbioru sygnałów diagnostycznych*. *Diagnostyka*, Olsztyn 2004, str.57-62, vol.32.

[4] Wilczarska J., *Genezowanie stanu maszyn w procesie eksploatacji*. Rozprawa doktorska. Bydgoszcz 2008.

[5] Żółtowski B., Cempel C., *Inżynieria diagnostyki maszyn*. Polskie Towarzystwo Diagnostyki Technicznej, Instytut Technologii Eksploatacji, Warszawa 2004.

Journal of POLISH CIMAC
Faculty of Ocean Engineering & Ship Technology
GDAŃSK UNIVERSITY OF TECHNOLOGY

INFLUENCE OF THE MIXTURE COMPOSITION ON THE CONVERSION DEGREE OF CATALYTIC CONVERTER DURING POWER SUPPLY OF THE ENGINE WITH NATURAL GAS

Barbara Worsztynowicz

AGH University of Science and Technology
Department of Machine Design and Technology
al. Mickiewicza 30, 30 – 059 Kraków, Poland
email: worsztyn@agh.edu.pl

Abstract

The article tackles with a topic of emission of hazardous components of exhaust gases into the atmosphere and a conversion degree of catalytic converter while supplying the combustion engine with natural gas. The natural gas is an example of alternative fuel for fossil fuel characterized by low weight carbon participation. The supply of combustion engines with gas fuel is realized in one- or two-fuel systems. The results of measurements were presented performed on the post of engine braking stand, in the conditions for preparing loading characteristics for the engine with spark ignition. The parameter which was changed, was the composition of the combustible mixture. On the basis of the measurements, the analysis of influence of combustible mixture was presented onto the contents of hazardous components in exhaust gases as well as efficiency of catalytic operation.

***Keywords**: alternative fuel, air excess coefficient, air – fuel mixture, catalytic converter, emission*

1. Introduction

Fast development taking place in many fields of a human being's activity connected with highly advanced technology on one hand facilitates everyday functioning, but, on the other hand, it causes significant degradation of the environment. It affects deterioration of living conditions of all living organisms. Therefore, more and more commonly limitations are introduced concerning negative impact of a human being's operation on the surrounding environment. Among the fields which are subject to the strictest restrictions there is automobile industry, where subsequent standards to limit emission of hazardous substances into the atmosphere are systematically introduced. It forces the necessity to implement far-reaching changes in construction and equipment of the engine in order to reduce the fuel consumption as well as the improvement of the creation process of combustible mixture so as to obtain combustion process parameters as close to complete and total combustion as possible. In addition, also non-engine limitation methods of hazardous substances into the atmosphere are used, mainly by means of purifying exhaust gases discharged from the engine. However, they are not sufficient ones, therefore, alternative motorization energy sources for fossil fuel are introduced. In order to obtain a positive effect in the form of reducing emission of hazardous substances into the environment, this fuel should be taken into account which is characterized by low weight carbon participation [3, 12]. The natural gas is an example of such a fuel, characterized by high energetic value and octane number, however lower density than petrol or diesel fuel.

The supply of combustion engines with gas fuel is realized in one- or two-fuel systems. The one-fuel system will be adjusted much better to combust gas fuel, as there will be no necessity to obtain a compromise between combustion process parameters optimum for the liquid fuel and for the gas fuel, the physical-chemical properties are different. However, factory-mounted systems should be differentiated, which more and more frequently appear in the offer of automobile companies, from so called cover installations which dominate on the personal cars market. The introduction of a version with two-fuel supplied engine by the manufacturer onto the market is a consequence of parameters' optimalization of the engine's operation resulting from the research conducted [11]. In case of cover installations used for many engines which differ in technical solutions and working parameters, it is hard to speak about optimum work of the system, and only about better or worse adjustment thereof. Even more, that the user is interested, to a large extent, in the best exploitation parameters and low costs of the vehicle's usage. As a result, the usage of the fuel, the chemical composition of which is beneficial from the ecological point of view, may not give a positive effect due to improper adjustment of engine's operation parameters to the fuel.

The supply of the engine with natural gas limits the emission of carbon dioxide into the atmosphere due to low contents of carbon therein. Simultaneously, the emission of methane is significantly higher and constitutes about 70 – 80 % hydrocarbons emitted in exhaust gases while during supplying the engine with petrol, it does not exceed 10 %. Methane, the same as carbon dioxide is included into the gases which contribute to the greenhouse effect to occur [7,8,11,12]. Additionally, conversion degree of methane in catalytic converters is low, significantly deviating from oxidation of higher hydrocarbons [4].

While supplying the engine with natural gas, stechiometric composition or poor mixtures are used [6]. Therefore, results of measurements and analyses were presented concerning the influence of the composition of the mixture onto the contents of hazardous substances in the exhaust gases and onto the conversion degree in catalytic converter.

2. Measurement stand

The measurements were performed on the test stand in the laboratory of combustion engines at University of Science and Technology. The stand is equipped with torque dynamometer of Schenck W130 type. A four-cylinder combustion engine was used for conducting the measurements with sparkle ignition Fiat 170A1.00 with stroke capacity of 900 cm^3. The engine is equipped with standard petrol supply system and in the system which enables to supply with natural gas. The amount of the natural gas provided to the engine is steered by means of the gas supply regulator, which allows for changing the composition of the mixture while supplying with natural gas. In the inlet system of the engine, the airflow meter and thermocouple were mounted. The thermocouples were placed also in the engine's cooling system and in the exhaust system – in exhaust manifold and behind catalytic converter. In addition, the stand is equipped with a system for volumetric measurement of liquid fuel consumption, flow system of gas fuel consumption and analyser of exhaust gases of Capelec CAP 3201 type (Fig.1).

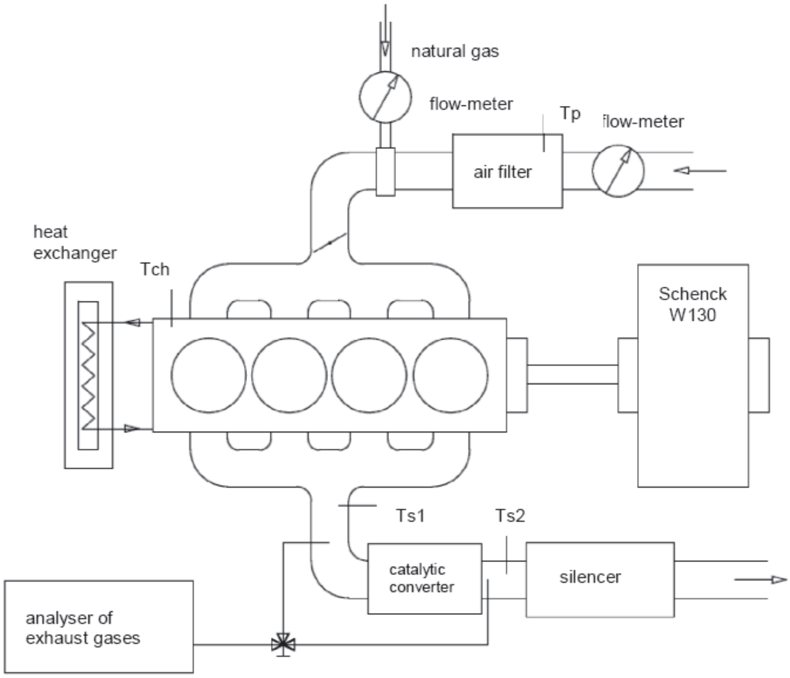


Fig. 1. Schema of the test stand.

3. Methodology of conducted measurements

The assumed methodology of measurements included registration of parameters of the natural gas-supplied engine with a constant working speed of 3000 1/min and constant loading of the engine. The parameter which was changed, was the composition of the combustible mixture, which was obtained while steering the location of the step engine placed in the natural gas supply system. The regulation of the mixture composition required to have the lambda probe disconnected. In each measuring point, the consumption of fuel, air mass stream, composition of fuel and temperature in the inlet, outlet and cooling system were measured. The measurements were conducted by means of making registration of volumetric concentration of exhaust gases' components in front of the catalytic converter and then behind it.

On the basis of the results of the measurements, the analysis was conducted on the influence of mixture's composition on the composition of exhaust gases of the engine supplies with natural gas as well as on the efficiency of catalytic converter operation.

4. Analysis of measurements' results

The usage of the exhaust gases' analyser Capelec CAP3201 allowed to register the volumetric concentration of particular components of exhaust gases, which referred to the volume of dry exhaust gases. Therefore, in order to calculate the emission of particular exhaust gases' components, the volume of dry exhaust gases should have been calculated [1,2,9].

As the high-methane natural gas with methane concentration amounting 96-98 % is the gas used, it was assumed for the calculations that its composition constitutes 100 % of methane.

On the basis of volumetric values of dry exhaust gases (V_{sps}) calculated for each measuring point and measured volumetric fuel consumption ($\dot{V}_e$) and volumetric concentration of particular components of the exhaust gases, the volumetric, and then weight shares were obtained of particular exhaust gases' components, which were referred to the engine power obtained during measurements [2,10,12].

The results of the measurements and calculations were presented in the form of diagrams. The works conducted aimed at analyzing the composition of the combustible mixture with supplying the engine with natural gas onto the emission of hazardous components in the exhaust gases, as a result, the data on the diagrams is presented as a function of air excess coefficient λ.

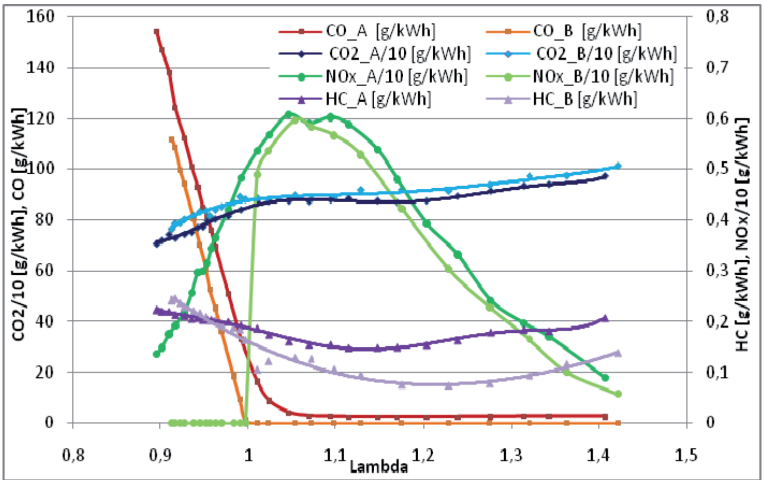


Fig. 2. Emission of carbon oxide (CO), carbon dioxide (CO_2), hydrocarbons (HC) nitric oxides (NO_x) in the function of air excess coefficient (λ) with the engine supplied with natural gas, measured before the catalytic converter (A) and behind catalytic converter (B).

On the figure 2, the emission of carbon dioxide, carbon oxide, hydrocarbons and nitric oxides were presented before and behind catalytic converter. In the scope of air excess coefficient (λ) from 0,9 to 0,95, emission of CO behind the converter is lower by 15 – 20 %, however, both before and behind the converter, it is very high. From the value λ = 0,95 the difference increases until the full conversion of CO in the converter with λ = 1. Simultaneously, the value of CO emission measured before the converter decreases in the scope 8 times and in the range of the λ coefficient from 1,1 to 1,4 has a constant value, which does not exceed 2,8 g/kWh. The emission of CO_2 behind the converter in the whole scope of the air excess coefficient is higher by about 1 to 8 %, which results from the oxidation of CO in catalytic converter. The emission of HC in the whole scope of air excess coefficient does not exceed the value of 0,22 g/kWh. The exception is, in the narrow scope of the λ coefficient (0,9 – 0,93), the emission behind the converter, which slightly exceeds the value and the emission value before the converter reaching up to 0,24 g/kWh. An increase of the HC emission value, both before the converter and behind it, with λ higher from 1,2 results from reducing the speed at which the combustion reaction takes place caused by a significant excess of the air in the combustion chamber. The emission of nitric oxides changes in the wide scope of values depending on the air excess coefficient. Full conversion takes place only in the range λ from 0,9 to 0,99, after which a rapid increase of emission takes place to the maximum value of about 6,0 g/kWh with λ = 1,07. With the air excess coefficient value λ = 0,95 in the engine's exhaust system, the exhaust gases' temperature starts to raise (Fig. 3). In the exhaust manifold, the exhaust gases; temperature changes from the value 690 ^{0}C to 715 ^{0}C with λ from 0,99 to 1,04, and then it reduces its value down to 700 ^{0}C with λ = 1,1, reaching in a further range the value of about 690 ^{0}C. As a result of the combustion temperature's increase, the emission of NO_x goes up, to reach values above 5,0 g/kWh in the scope of the air excess coefficient λ from 1,0 to 1,15, whereas, maximum value is about 6,1 g/kWh. From obtaining the stechiometric mixture, the difference in emission of NO_x before and behind catalytic converter amounts to about 5 – 10 %.

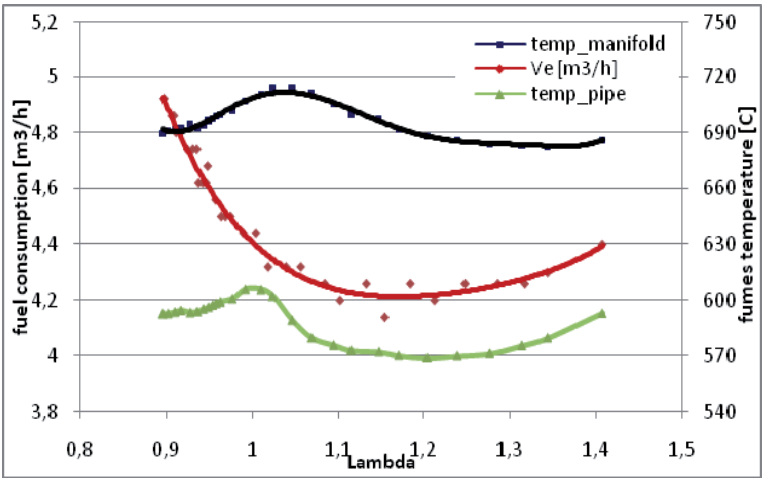


Fig. 3. Consumption of natural gas and exhaust gases' temperature in exhaust manifold and behind catalytic converter in the function of the air excess coefficient function (λ).

On the measurement position, a three-way catalytic converter is mounted, which is characterized by the best operation with the stechiometric composition of the mixture, as there is no competition between NO_x and O_2 then for oxidation of carbon oxides and hydrocarbons. When the mixture is poor in contents, there drop of efficiency takes place in nitric oxides' reduction, whereas when the mixture is rich, it causes a drop of hydrocarbons and carbon oxides' oxidation [4]. The conversion degree of toxic components of exhaust gases is influenced also by exhaust gases' temperature [4,5]. The measurements were performed in stabilized working conditions, therefore, the temperature in the exhaust manifold was in the range from 680 to 715 ^{0}C, whereas behind the catalytic converter between 570 and 610 ^{0}C (Fig. 3). It means that catalytic converter worked in temperatures' range which was optimum for the conversion process.

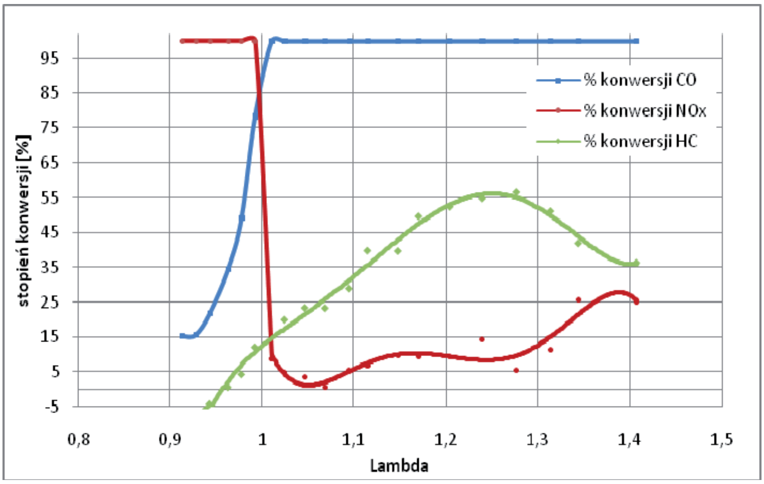


Fig. 4. Conversion degree of toxic components of exhaust gases in catalytic converter in the air excess coefficient function (λ).

Conversion degree of toxic components of exhaust gases in catalytic converter was presented in the figure 4. For stechiometric mixture (λ = 1), conversion degree of carbon oxides amounts to 89 %, nitric oxides 61 %, and hydrocarbons 14 %. Conversion of CO equal to 100 % takes place from the value of λ = 1,01, whereas for NO_x up to the value of λ = 0,99. In case of HC, maximum of conversion degree amounts to 57% and is obtained with λ = 1,27.

5. Summary

The manufacturers of vehicles, more and more often decide to place vehicles with two-fuel supplied engine – petrol and natural gas or only with natural gas, among versions of a given model. It results from the necessity to reduce unfavorable impact of automobile industry on the environment and the economic needs of vehicles' exploitation, which is expected by the users. Brand new mounted system is characterized by precisely adjusted working parameters of the engine to the fuel used, which in case of so called cover systems of gas supply is difficult to obtain, as a result, not necessarily it will give a positive ecological effect.

On the post of engine brake stand the emission measurements of harmful components of exhaust gases were conducted depending on the air excess coefficient being the representative of the older generation of construction solutions, to which natural gas supply system was adjusted.

The emission of carbon dioxide in the analysed period of air excess coefficient was very high, however the same engine supplied with petrol showed even higher emission of carbon dioxide which results from significantly lower contents of coal in natural gas.

There was a similar situation in case of emission of nitric oxides, which was also high in the whole period tested and simultaneously lower than with supply with petrol, which is also the consequence of the fuel's chemical composition. An increase of temperature in the combustion chamber with air excess coefficient about 0,95 caused a rapid increase of contents of NO_x in exhaust gases caused with achieving a thermal-dynamic balance of the component. Simultaneously, a conversion degree with poor mixture is very low. The reasons are thermal conditions, low contents of CO and HC in fumes resulting from chemical composition of fuel and presence of oxygen in exhaust gases, which comes in reaction easier with CO and HC than oxygen created from NO dissociation. Obtaining lower emission value of these components required optimalization of combustion process and increase in compression degree during supplying engine with natural gas.

Volumetric concentration of carbon oxide in raw exhaust gases, in the supply range of the engine with poor mixture, from the air excess coefficient 1,1 was very low. Whereas, in the range from the stechiometric mixture to rich one, emission of carbon oxide grew very rapidly to obtain 8-times higher value. A low conversion degree of CO for rich mixtures results from shortage of oxidizer in exhaust gases.

As the main component of natural gas is methane, variety of hydrocarbons included in exhaust gases is significantly limited with reference to liquid fossil fuels. Also, the number of hydrocarbons in exhaust gases is lower, which is a favorable phenomenon, as they constitute the most difficult component of exhaust gases to remove [4]. Emission of hydrocarbons in the whole range of measurements was very low, but also conversion degree of the component in catalytic converter was not high. It proves high contents of methane in exhaust gases, being the hydrocarbon which oxidized most difficult [4]. In addition, methane, similarly as CO_2, belongs to a group of greenhouse gases, the emission of which is also limited.

From the point of view of emission of particular components of exhaust gases in raw ones, as well as from the point of view of engine's efficiency, its supply with poor mixture of natural gas with air with air excess coefficient of 1,2 seems to be most favorable. However, it would require to replace three-way catalytic converter of TWC type into three-way one – a trap of nitric oxides (LNT) [5]. In order to make a full analysis of influence of composition of combustible mixture onto the composition of exhaust gases, in order to select an optimum scope of air excess coefficient, the measurements for other points of the engine's operation should be conducted.

References

[1] Bernhardt M., Dobrzyński S., Loth E., *Silniki Samochodowe*, WKiŁ, Warszawa 1974.

[2] Brzeżański M., *Emisja toksycznych składników spalin w fazie nagrzewania się silnika o zapłonie iskrowym z zastosowaniem akumulatora ciepła*, Monografia nr 326, seria Mechanika, Kraków 2007.

[3] Brzeżański M., *Emisja dwutlenku węgla w aspekcie stosowanych paliw silnikowych*, Silniki Spalinowe PTNSS 4/2007(131), str.62-68.

[4] Kruczyński S., *Trójfunkcyjne reaktory katalityczne*, Warszawa – Radom 2004.

[5] Kruczyński S., Danilczyk W., *Ograniczenie szkodliwości gazów wylotowych silników spalinowych poprzez zastosowanie reaktorów katalitycznych*, MOTROL, 9/2007, str.93-102.

[6] Merkisz J., Pielecha I., *Alternatywne napędy pojazdów*, Wydawnictwo Politechniki Poznańskiej, Poznań 2006.

[7] Merkisz J., Pielecha I., Radzimirski S., *Pragmatyczne podstawy ochrony powietrza atmosferycznego w transporcie drogowym*, Wydawnictwo Politechniki Poznańskiej, Poznań 2009.

[8] Merkisz J., Radzimirski S., *Analiza metod pomiaru emisji węglowodorów według przepisów europejskich dotyczących emisji zanieczyszczeń z pojazdów*, Silniki Spalinowe PTNSS 1/2009 (136), str. 76 – 89.

[9] Niewiarowski K., *Tłokowe silniki spalinowe*, WKiŁ, Warszawa 1983.

[10] Ochęduszko S., Szargut J., Górniak H., Guzik A., Wilk S., *Zbiór zadań z termodynamiki technicznej*, PWN, Warszawa 1975.

[11] Romaniszyn K.M., *Alternatywne zasilanie samochodów benzyną oraz gazami LPG i CNG. Badania porównawcze dynamiki rozpędzania i emisji spalin*, WNT, Warszawa 2007.

[12] Worsztynowicz B., *Wpływ składu mieszanki na emisję szkodliwych składników spalin podczas zasilania silnika gazem ziemnym*, Czasopismo Techniczne Mechanika, zeszyt 9, Wydawnictwo Politechniki Krakowskiej, Kraków 2012.