RIGA TECHNICAL UNIVERSITY
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DEVELOPMENT OF THE ACOUSTIC DIAGNOSTIC METHODOLOGY FOR MARINE DIESEL ENGINE TECHNICAL CONDITION

Field: Transport and Communication

Sub-field: Maritime Transport and Infrastructure

Summary of Doctoral Thesis

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DOCTORAL THESIS
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To be granted the scientific degree of Doctor of Engineering Sciences, the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council "RTU P-22" on 4 July 2016 – 3:30 p.m., at the Institute of Aeronautics, Riga Technical University, 1A Lomonosova Street, Room 218.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Engineering Sciences is my own and does not contain any unacknowledged material from any source. I confirm that this Thesis has not been submitted to any other university for the promotion to other scientific degree.

Andris UNBEDAHTS …………………………….(Signiture)

Date: ………………………

The Doctoral Thesis has written in English. It contains an introduction, 4 chapters, conclusions, list of references, and 8 appendices. It has been illustrated by 80 figures and 6 tables. The volume of the present Thesis is 120 pages. The list of references consists of 130 sources.

CONTENT

GENERAL DESCRIPTION OF THE PRESENT RESEARCH

Topicality of the Research

Today transatlantic trade is carried by ships, the length of which reaches 400 meters and deadweight (load + the other variable weight of fuel, water, passengers, etc.) reaches 500 000 tonnes, while the number of containers has reached 20 000 TEU. Main diesel engine exhaust approaches 100 000 kW (usually slow speed engines), auxiliary engine power exhaust reaches 10 000 kW (medium speed engines), more and more high-speed diesel engines are used thanks to their small size (more space for cargo) and new materials are applied that provide longer operation. Modern marine engines are operating in high zone of stresses, such as medium speed 4-stroke diesel engine fuel injection pressure reaches 196 MPa, while the combustion pressure of 21 mPa [71]. It is clear that such power plant damage can lead to catastrophic consequences to ships, environment, constructions etc.

To substantiate the research topicality, two interrelated important factors are considered: firstly, improvement of maritime safety; secondly, increase of fleet economic indicators (the main expenditures are fuel and repair costs), so more and more ships (mostly newly built) are going to the ship mechanism inspection schedule, according to real technical condition without mechanism unnecessary dismantling (Condition Based Maintenance (CBM)), i.e increase of safe engine running time. For this reason, diagnostics of the mechanism technical condition takes a leading role, using modern diagnostic techniques that allow controlling engine parameter condition during operation.

We also have to take into consideration that a large number of ships, mainly dry bulk carriers built between 1970 and 1980 are still in operation. These vessels constitute a high risk group, although on a large number of these ships the engines (mostly auxiliary) have been replaced; the technical condition monitoring plays an important role.

At present, within the CBM for the engine control thermography and vibration diagnostics devices are used but these methods do not provide a full picture; therefore, the development of non-destructive method (Non-Destructive Testing (NDT)) determines the topicality of the research in accordance with the classification society's recommendations and in line with the CMB requirements.

The Aims and Tasks

The aim is to develop the acoustic diagnostic methodology of marine diesel engines for the early detection of engine failure by using acoustic emission (AE) measurements in order to meet the technical condition of the system (Condition Based Maintenance (CBM)) requirements.

To reach the aim, the following tasks are carried out:

1. To perform the analysis of ship engine damage and diagnostic methods.
2. To create a mathematical model of acoustic emission signal generation sources in the engine cylinder due to exhaust gas leak.
3. Based on the gas dynamic calculations, to determine the range limits of the gas turbulent subsonic flow in defect (gas leak between exhaust valve and valve seat).
4. To perform experimental measurements during engine operating in order to establish criteria for the diagnosis of acoustic emission and its informative assessment.
5. To develop the acoustic diagnostic methodology of a marine diesel engine for early detection of defects that match the technical condition monitoring system requirements.
6. To perform the analysis of the Classification Society's requirements for CBM implementation and make proposals for implementation of acoustic emission techniques.

Scientific Novelty of the Thesis

1. Analyzing engine generated noise using acoustic emission method there are possibility to obtain results online

2. The developed mathematical model of the gas flow in defective channel and its generated acoustic effect.

3. The developed acoustic diagnostic methodology for diesel engine failure early detection to meet CBM requirements.

The Author of the present Thesis defends:

1. The developed matematical model of acoustic emission signal in damaged cylinder valve channel.

2. Acoustic emission signal measurement results obtained in the engine operation mode.

3. Diesel engine diagnostic methodology for engine failure early detection according to CBM requirements.

Methods of Research

1. Mathematical modelling.
2. Theory of probability and mathematical statistics.
3. AE signal measurements using divice according to standards BS EN 13554:2011, BS EN 1330-9:2009.
4. AE data processing using AEwin ™ software.

Practical Value of the Thesis

The Doctoral Thesis can be used as a basis for further research. High-speed diesel noise experimental research results and proposed methodology can be used for all types of ships and diesel engines in order to control the operating characteristics corresponding to the technical specifications.

The developed metodology and practical recommendations can be used in the CBM program, thus increasing the fleet economic indicators, taking into account that the CBM is focused on safe engine running time increase without disassembly.

Positive feedback was received from Transport Consultants Network, Ltd. (Belgium), Africa Marine Surveys, Ltd. (Belgium), Witraktor, Ltd. (Latvia) as well as recommandations to continue further studies on acoustic emission diagnostic for condition monitoring of diesel engines.

In the Doctoral Thesis, the analysis of classification Society's requirements concerning CBM implementation was performed and recommendations were formulated for acoustic technique implementation into practice.

Publications

The results of the research were presented at the following international conferences:

1. Urbahs A., Unbedahts A. Acoustic Emision Signal Mathematichal Modeling in Case of Engine Cylinders Tightness Disappereance. Power and Energy Systems, Ischia, Italy, 2016.
2. Urbahs A., Unbedahts A., Feščuks J. Ship Diesel Engines Technical Condition Acoustic Diagnostic Results. Transport Means, 2016.
3. Urbahs A., Unbedahts A. Acoustic Emission Method Evaluation for High Speed Ship Engines Condition Monitoring. 19th International Conference Transport Means, Klaipeda, Lithuania, 2015.
4. Unbedahts A., Carjova K., Urbaha M. Acoustic Emission Method Implementation for Medium and High Speed Ship Engines Condition Monitoring**.** 18th International Conference Transport Means, Klaipeda, Lithuania, 2014.
5. Unbedahts A., Banovs M. Use of the Acoustic Emission for the Vessels Engines/Hull Condition Monitoring. 17th International Conference Transport Means, Klaipeda, Lietuva, 2013.

6. Unbedahts A., Banovs M., Rijkuris G. Influence of Ship's Hull and Engines Monitoring on Maritime Safety Improvement. Transport and Engineering, vol. 35, 2013.
7. Urbahs A., Unbedahts A. Acoustic Emission Application for Ship Structures Strength Assessment. 53rd International Scientific Conference of Riga Technical University dedicated to the 150th anniversary and the 1st Congress of World Engineers at Riga Technical University, 2012.
8. Unbedahts A., Vindergauz L. Application of the Acoustic Emission Method for Cracks Early Detection in the Ship Constructions. 16th International Conference Transport Means, Klaipeda, Lithuania, 2012.
9. Unbedahts A., Vindergauz L. Utilization of Acoustic Emission as a Ship's Damage Prevention Method**.** 14th International Conference Maritime Transport and Infrastructure, Riga, Latvia, 2012.

Some results of the Doctoral Thesis were presented and discussed in lectures at Riga Technical University, Latvian Maritime Academy and the University of Kaunas (Lithuania).

Structure of the Thesis

The Doctoral Thesis consists of the introduction, four chapters, conclusions, bibliography and appendices.

The first chapter deals with marine engine disorders and diagnostic methods for their analysis. The second chapter describes the experimental measurement methodology of acoustic emission signals and technical support. The third chapter discusses acoustic emission signal in the defefective channel mathematical modeling. The fourth chapter presents the results of the engine technical condition diagnostic studies.

1. SHIP ENGINE DAMAGE AND ANALYSIS OF ITS DIAGNOSTIC METHODS

All the forces exerted on the engine can be divided into two broad categories: external forces that are transferred from the vessel hull (mainly they may be affected by the crankshaft and the bearings) and forces that occur as a result of engine operation: inertia, pressure, etc. These forces can adversely affect the engine, contributing to increased wear and cracks.

This chapter discusses:

Load on vessel units

Vessel hull during operation is continuously exposed by forces with different size, directions and frequency; it bends and twists by impact of the outer forces. These forces can be transferred to the engine bedplate, which is attached to the hull, but the bedplate affects some engine parts: crankshaft, bearings, etc. If external forces are not sufficiently taken into account at the design stage of the engine, insufficient strength can lead to engine components/structure serious defects [17].

Forces in engine

Both in the running and in the stop mode engine components are exposed to a number of forces and loads. If in the stop mode engine components are effected by gravity forces, vibration forces (from mechanisms working adjacently) and low thermal stress, in running engine, there are the enormous inertia forces (variable sign), gas pressure and centrifugal forces, as well as a massive increase of the thermal load and friction forces. Timely undetected defects of engine parts, these forces can cause the engine breakdown and possibly shipwreck.

Ship diesel engine damage and defect analysis

The available statistics shows that the number of engine damage is increasing, and here reflect the direct losses; indirect losses can be many times higher. It is clear that unexpected appearance of the damage represents a serious threat to navigation, environment and people's lives [20].

The main causes of engine failure:

a) contaminated oil;
b) engine inspection (overhaul) performed without the presence of an expert;
c) use of unsuitable fuel;
d) fuel / oil separators operated based on inadequate instructions;
e) insufficiently qualified engine room staff;
f) engine turbochargers damaged by influence of the external foreign body.

Table 1.1

Five Major Defects in Vessel Engines According to "The Swedish Club. Main Engine Damage Study 2012" [40], [41]

No.	Cause	Quatity	Average expenses (USD)
1.	Incorrect maitenance/repair	52	576,000
2.	Substandard quality of oil	33	977,300
3.	Outer foreign object (for TC)	28	350,000
4.	Low quality fuel	27	365,000
5.	Latent defects	25	500,000

According to statistics, cylinder heads, pistons / rings, cylinder liners and crank bearings are most exposed to defects. The least number of hours worked to failure are demonstrated by fuel injectors, piston rings, as well as inlet and exhaust valves.

Fig. 1.1. Damaged exhaust valve

Fig. 1.2. Damaged exhaust valves and cyl.head

Figures 1.1–1.4 show high-speed diesel engine valve damage that has caused the engine and turbocharger breakdown.

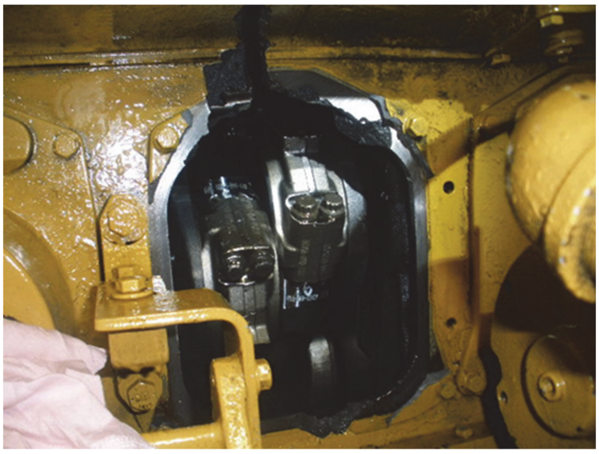

Fig. 1.3. Crankcase breakdown

Fig. 1.4. Damaged turbocharger

Marine engine diagnostic methods

At present, there are two technical maintenance and control methods.

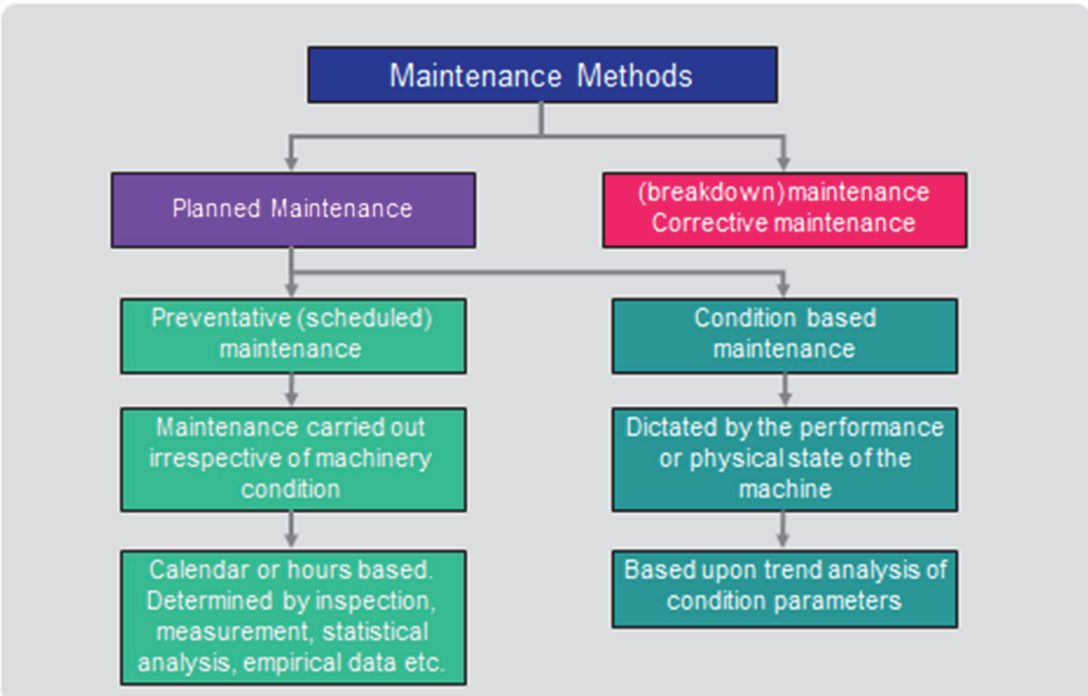

Fig. 1.5. Current maintenance methods

Engine item periodic/preventive control is carried out in accordance with a specific timetable established by a manufacturer together with the Classification Societies. The engine is subjected to inspection (i.e. stopped and upset) after a certain number of hours worked. Decision on item technical condition and the possibility for further use is made by means of non-destructive test methods: ultrasonic, magnetic particles, capillary, eddy current or rentgenoscopy.

Condition Based Maintenance (CBM) is a relatively new method, which has been used for about 10 years. It can be approved for any vessel by the Classification Society if the vessel fulfills and satisfies certain requirements of Classification Societies. This method is based on the object periodic or continuous monitoring in order to determine its technical condition without decommissioning. Using this monitoring system, today mainly vibration diagnostic and thermography measuring devices are used, but they can not provide complete information about the technical condition of the engine; therefore, the use of acoustic emission devices are considered the most promising ones [29].

Vibration monitoring is one of the most effective methods for mechanism rotating part control. This is the most widely used method for the rotating machinery diagnostics and monitoring, because it covers most of the possible defects. As an example, a centrifugal pump defects can be determined with vibration diagnostics: damaged impeller, bearings, seals, imbalance of the pump, motor axis mismatch.

Vibrodiagnostic is the closest type to AE diagnosis, just frequency range is lower: 1000–5000Hz.

Vibrodiagnostics use vibrations as a diagnostic parameter which are caused by dynamic stress to machine. This very important parameter gives information for determining actual technical condition of rotary machinery.

Main application for vibrodiagnostics:

a) unbalance of rotors
b) mechanical relaxation
c) damaged anti-friction bearing
d) hydraulic and aerodynamic problems
e) resonance
f) deformations
g) cracks

In vibration diagnostics three types of sensors are commonly used: displacement sensors, velocity sensors and accelerometers.

Displacement sensors uses eddy current to detect vertical and/or horizontal motion. Velocity sensors use a spring-mounted magnet that moves through a coil of wire.

Accelerometers use a piezoelectric crystal (that converts sound waves to electrical impulses and back) attached to a equipment that vibrates due to the motion of the part to which the sensor casing is attached. Accelerometers are very effective for detecting the high frequencies created by high speed turbine blades, gears and ball and roller bearings that travel at much higher speeds than the shafts to which they are attached.

Termographic inspection

Thermographic device determines radiation within the electromagnetic spectrum (about 900 to 1400 nanometers, or from 0.9 to 14 µm) and gives the radiation image. The amount of radiation emitted by an object increases with increasing temperature; therefore, thermography allows seeing the changes in temperature. The device by receiving infrared radiation can detect unequal / increased warming of parts, such as in mechanism bearings.

CBM advantages:

a) saves engine maintenance costs thanks to the skill maintenance planning;
b) saves the survey/inspection costs thanks to the skill of inspection planning;
c) improves the profitability of the ship due to the improved performance of engines;
d) improves engine and maritime safety due to better and more dynamic (on-line) control;
e) enables the operator (shore / ship) or PC (if programmed for automatic data) to obtain a full picture of the condition of the machinery of a given vessel;
f) allows comparing vessel technical and economic indicators between certain groups of vessels and the whole fleet;
g) stores long-term data for further analysis and for improvement of the system.

Legislative acts regulating the CBM implementation

The requirements of the Russian Maritime Register of Shipping (RS) were taken as an example for CBM implementation and the equipment used. Since the RS is a member of the International Association of Classification Societies – IACS, which brings together 12 major world classification societies such as LR – Lloyds Register, DNV – GL Det Norske Veritas - Germanisher Lloyd, BV – Bureau Veritas, NK – Nippon Kaiji Kyokai, etc., then it can be said that the RS requirements are similar to requirements of other members of IACS.

In accordance with the requirements of RS, CBM implementation is governed by the following documents:

1) Rules for the Classification Surveys of Ships in Service.
2) Instruction manual for use of data derived from the built-in and portable non-destructive test diagnostic equipment items to be checked during the control.
3) Instruction for ship continuous control.
4) Guidelines on Technical Supervision of Ships in Service. (Collection of Regulating Documents. Book twelve, 2004.)
5) Rules for the Classification and Construction of Sea-Going Ships.

Taking into account the engine CBM program benefits, the RS allows for the use of vibration diagnostics and thermographic inspection. RS recognises:

a) vibrometers: DN-DN-3 and 4 (Vibropribor, Russia), the MTO 33 AB (Hugo Tillguist, Sweden), MK 310 (Kawatetsu Instrument, Japan);

b) distance infrared thermometers Thermopoint 30; 40; 80 (AGEMA, Sweden) [36].

Physical basics and benefits of the acoustic emission methods

Acoustic emission method is a method that uses material mechanical wave radiation caused by internal structure dynamic changes that are initiated by external or internal force (Fig. 1.6). AE agents can include plastic deformation, crack formation and growth, fluid/gas flow in pipelines, etc. [1], [2], [5], [7].

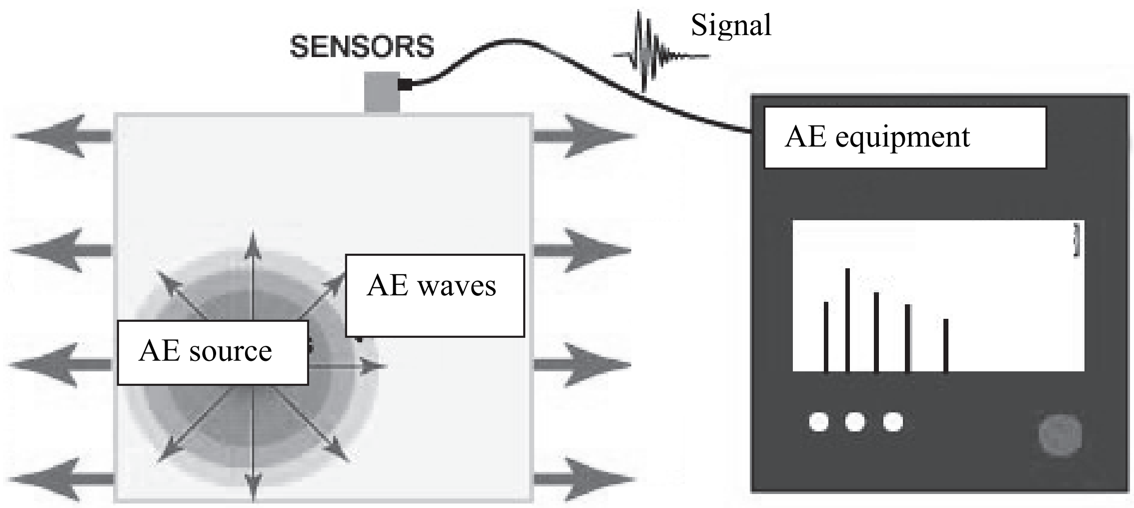

Fig. 1.6. Working principle of the AE method

Key benefits of the method:

1) High degree of probability; it is possible to detect structural defects in material and fatigue damage in hard-to-reach places, as well as to determine the coordinates of the defect.
2) Available in continuous diagnostics.
3) Possibility to follow development of the damage during engine lifetime.
4) It is possible to fix the defect at early stage of development.

5) It is possible to classify the damage in acordance with the hazard level.
6) Equipment preparation for work and control is significantly lower than it is for other methods of NDT.
7) High sensitivity and less restrictive factor in comparison with other methods.
8) One or more sensors positioned in the surface of an object to be controlled can control the whole object (important advantage for hard--to-reach places).
9) Careful surface preparation prior measurement is not required.
10) High productivity.
11) Can be used in different materials.
12) Relatively simple for user [4].

Installing a number of sensors on the object, the whole object control is carried out, during which the occurrence of defect and locations of its development (locating mode) are determined. This allows performing a continuous control of the object (diagnostics) during operation and moveing from planned technical inspections to condition based inspections; it also allows for full object diagnostics without interrupting the operation mode or stop for a short time, providing obvious economic effect.

However, in practice the application of AE method for engine part control has a number of hindrances:

a) level of the signal energy and its parameters depend on the material properties and its condition during measurement;
b) failure control/development process is usually accompanied by noise (engines, machinery operation, cargo operation noise, etc.) with the parameters close to the AE signal parameters.

Potential objects for AE method application in monitoring and control:

a) engine turbochargers and reducers;
b) bearings;
c) engine gas distribution mechanism;
d) vessel shaft;
e) high pressure fuel system.

A typical AE system comprises:

a) sensors detecting the AE waves;
b) pre-amplifer reinforcing the signal obtained;
c) data processing processor (signal filtering, analysis, transformation to transparent form) with display;
d) data transmission cables, typically up to 300 m, which is quite enough for modern ships.

2. ACOUSTIC EMISSION SIGNAL EXPERIMENTAL TECHNICAL SUPPORT AND MEASUREMENT METHODOLOGY

The object of study was 20 cylinders V-type four-stroke engine, the cylinder head is with two intake and two exhaust valves (Fig. 2.1.) that opens from cam shaft, but closes by spring.

Due to ecological and economic reasons, the engine runs on natural gas. To make this possible, high-pressure fuel pumps are dismantled from the engine, but gas distributor is installed, as well as fuel nozzles are replaced with glow plug because gas is flammable approximately at 700 °C (diesel is flammable at 300–400 °C depending on the type).

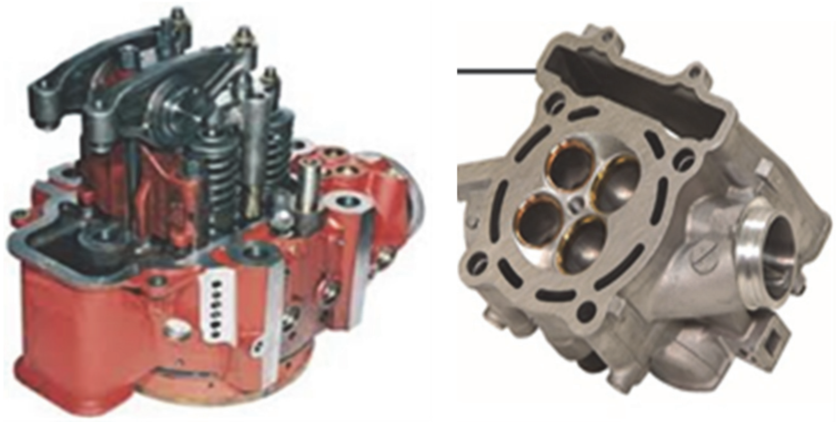

Fig. 2.1. Medium and high-speed diesel engine heads

Diesel engine intake and exhaust valves are suitable as a fatigue fracture process research object, and valves are among the most heavily loaded engine structural elements [28], [44], [45].

Valve performance analysis was carried out in a series of experimental measurements using industrially operated high-speed engine. Measuring the performance of the engine, previous experience and data obtained from the Institute of Aeronautics of Riga Technical University and studies were taken into account [46], [49], [65].

During operation valves are subject to shock, heat stress, increased wear, variable signs of inertia forces and high pressures.

The main faults of engine cylinder head valves are as follows:

a) fatigue cracking of the valve stem;
b) burnt valve plate;
c) the presence of combustion product slump;
d) increase/decrease of valve clearance.

The most dangerous defects for valves are fatigue cracks in the material and burnt valve plates, which contributes to the further collapse of the material. Usually cracks result in stress concentration areas – areas with significant changes in strength: the rounded transitions milling sites, etc.

The Equipment

Portable device "Pocket PACK AE-2", N°: 8520232001 was used for measurements.

"Pocket AE-2" is a high-performance, computer-based, two-channel acoustic emission system in a durable, hand-portable device. It offers all the performance features of larger and more expensive systems AE, including a wide range of bandwidth speeds, different sampling frequencies, waveform processing capabilities in a compact, battery-powered device. The device is an excellent tool for the "field" surveys, particularly in situations where electricity is not readily available. It is useful in the laboratory – the system performs laboratory tests using the two-channel AE input and single-channel parametric input in order to compare AE activity depending on the load or stress.

For greater versatility, there is a built-in noise filtering block. With Pocket AE-2 traditional AE distributed signal processing can be made, as well as improved waveform acquisition and processing. Results are displayed on the integrated colour LCD touch screen (240x320 pixel resolution). The software provides the opportunity to view waveforms, histograms, line graphs and mark single blocks. Additional system has a built-in capability for fault detection and its linear location detection.

AE data files are stored in Mistra standard DTA format and can be transferred to a computer using a Compact Flash card and/or USB; for full analysis of the data AEwin ™ software can be used.

Pocket AE-2 has an internal AE pre-amplifier, and it is able to operate low-power external preamps and line sensors. The user can choose to use an internal or external preamplifier using the software. When the machine uses an internal preamplifier, standard, passive sensors can be connected directly to AE input. Pocket AE-2 is delivered with R15α (Alpha) sensors and the cables connecting the sensors to the system.

Alpha Series sensor is a general purpose, low-cost sensor and can be widely applied. Pocket AE-2 system can be switched in external preamp mode. If the machine is in this mode, the power is supplied to external preamplifier. In this way it is possible to take measurements when the distance is large between the sensors and the equipment.

AE system components

Pocket AE-2 kit includes: two channel portable device, two R15α passive AE sensors, two sensor cables of one meter, 2-meter cable with BNC connector, 1GB CF card and the battery power supply. Optional battery charger, extra battery packs and AEwin Replay ™ Software Suite are available separately.

Fig. 2.2. Measuring Pocket AE-2 equipment

Pocket AE-2 main characteristics

Dimensions: 241 mm × 89 mm × 36 mm
Weight: 1.13 kg with batteries
Screen: 3,52 "color LCD, 240 pixels × 320 pixels, with LED backlight
Control panel: built-in touch-sensitive screen (spec. Pencil)
Memory: 128 MB
Ports: one for the memory card, one USB 2.0
Consumed power: 4 W
Source of energy: external DC converter (12V @ 1A) or internal 7.2V NiMH rechargeable batteries
Battery life 4–6 hours with brakes
Temperature: -5 °C to 45 °C

Connectivity: AE 2 – SMB and parametric 1 – SMB

AE channel description

Two-channel AE input through the SMA connection (F socket)

Input voltage: +/− 10 V

AE channel frequency: 1,0 kHz to 1,0 MHz +/− 1,5 dB

Software filters

System "Pocket AE" is equipped with high- and low-frequency digital filters in additional to analogue which is activated by software. It gives an excellent ability to filter out noise and improve signal-to-noise ratio.

Signal processing: filtering and the final curve in real time. Waveforms can be recorded and processed.

Extracted results: Typical AE characteristics include the first case, which exceeds the threshold level, time to the maximum level, the maximum level of the amplitude, signal strength and duration of the signal rise time, energy value and side noise average level. For control, low-frequency converter R3α is used.

Two-meter cables that connect devices, sensors and power supply are used.

Piezoceramic sensors record the elastic waves corresponding to AE pulses and convert mechanical oscillations to the electrical signals that goes into the AE registrator via cables.

In our measurements, dual-channel digital oscillographs were also used: Rigol DS1052E PICOSCOPE and 3204, as well as analogue oscillograph C8 17th for signal determination from the Hall sensor – its amplitude, form and location in engine circle.

Description of the Research Object

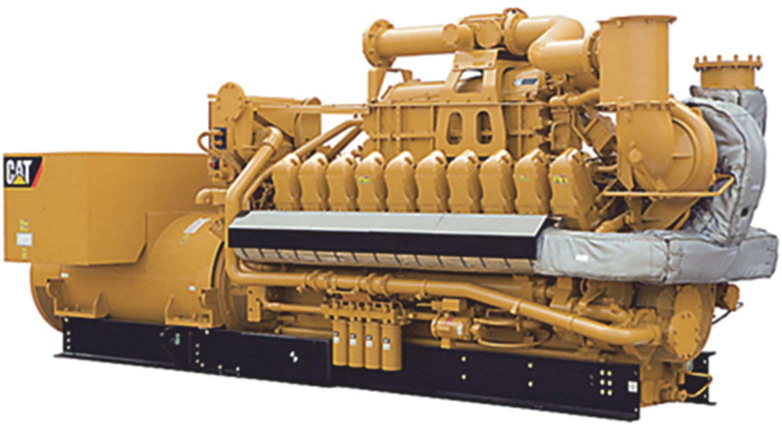

Fig. 2.3. Engine overview

Type: G3520C

Serial number: GZN00302

Year Built: 2006

Power rate: 2000 kW

Speed: 1500n^{-1}

Number of cylinders: 20

Cylinder arrangement: V-type

Fuel: natural gas

Ignition type: glow plug with the forechamber

The engine is equipped with a powerful microprocessor that controls all the key parameters with particular emphasis on the fuel and combustion control.

To minimise the possibility that the engine may stop due to failure of the microprocessor, the main electronic unit every 50 seconds sends the information to the backup unit, receiving the response, it will continue to work in normal mode. If the signals from the main unit break, engine running control functions go to backup unit.

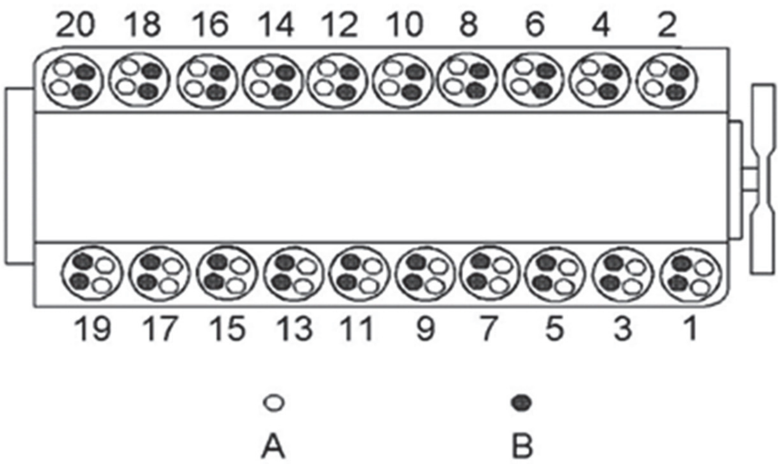

Fig. 2.4. Engine cylinder and valve location scheme

Information on the engine and the duty cycle (see Fig. 2.4):

A – inlet valves; B – exhaust valves.
Number of valves in the cylinder – four.
Bore – 170 mm.
Stroke – 190 mm.
Inlet valve clearance – 0,38 mm.
Exhaust valve clearance – 1,12 mm.
Number of cylinders – 20
Ignition sequnce – 1, 2, 11, 12, 3, 4, 15, 16, 7, 8, 19, 20, 9, 10, 17, 18, 5, 6, 13, 14.
Crankshaft cheek expansion – 18 °.
Inlet valve opening – 9° from TDC and closing –21° after the BDC.
Exhaust valve opening – 18° before the BDC and closing – 10° after the TDC.

Methodology of the Research

Experimental measurements of engine acoustic emissions were performed with calibrated measuring equipment “Pocket PACK AE-2”, N °: 8520232001.

Experimental measurements were carried out during the period from February 2012 to April 2015 (including). Total: seven measurements.

On 20 February 2012 the **first experiment** on diesel AE measuring took place. AE sensors were attached to Riga Port Authority tugboat “Sfinksa” main engine “Caterpillar”, Ne = 2 × 1500 kW, n = 1600 n^{-1}.

Cylinder arrangement: V-type, number of cylinders: 12

The goal – to fix the AE waves at different engine crankshaft revolutions: 650 (minimum persistent) 900 and 1200 (75 %) rpm.

The sensors were placed at the turbocharger bearings, exhaust manifold before the turbocharger, to the engine bedplate in the fifth crank bearing area.

It was concluded that the AE signals reflected cylinder valve operation, as well as the state of the turbocharger bearings. Consequently, it was decided to focus further measurements on cylinder inlet and exhaust valves, crankshaft bearings as these parts were most exposed to defects and their repair or change was costly.

Analysing the data collected and taking into account the difficulties with the parametric signal acquisition, as well dificulties with schedule coordination with tug owner, it was decided to carry out further experiments elsewhere.

Further measurements were carried out: Valmiera, 7 Dzelzcela Street; the engine is located at JSC "Valmiera Energy" premises. Engine service is performed by Ltd. "Witraktor", official "Caterpillar" dealer in Latvia**.**

The measurements were carried out before the engine' renovation, immediately after renovation and after the engine operation for several months.

Taking into account the engine design features, it can be said that the main source of mechanical waves registrated with AE handsets is sounds from the inlet and exhaust valves – their closing and opening.

If there is engine AE portrait with voltage changes from the Hall sensors, then knowing the engine cylinder arrangements, valves characteristics may be obtained. Full work cycle occurs from the Hall sensor curve first higher point, corresponding to the first cylinder TDC until the Hall sensor curve third highest point corresponds to the second revolution of the krankshaft.

Preparing Experimental Measurements

Using cables, Pocket A2 is connected to the engine Hall transducer to obtain parametric signal corresponding to the first cylinder TDC. During subsequent measurements, cylinder 9 TDC is determined in relation for the 1st cylinder TDC. It consists of 216° crankshaft angle.

To find the AE signal power and waveform, at the beginning sensors were fixed to the engine in three places: at cylinder heads 7 and 9, crankcase (respectively cylinder area) and to the flywheel housing. Contact between the engine and the AE sensors is provided through the "Silagel" grease.

Since AE data obtained during the first measurements allowed evaluating its engine places where utility AE signals were the strongest, it was decided to focus on the AE signal measurement on cylinder heads 7 and 9.

Measuring performance conditions

The engine is located in a closed space, reconstructed boiler house. The engine itself with an electric generator is placed in the container-type sound absorbing structure.

Specification during measurements:

a) exhaust..…………………………………………………1,5–2 MW
b) revolutions per minute...…………………………………...1500
c) exhaust gas t°...……………………………………………450–480° C
d) cooling liquid t°…………………………………………87–90° C
e) luboil t°……………………………………………………87–91° C
f) inlet air t°……………………………………………….....20–26° C

AE hardware adjustment and preparation for work:

1. Acoustic signal testing and measurement range adjustment were made using automatic calibration impulses after the hardware connection, according to the "Pocket AE^{TM}" instruction manual and the "Pocket AEwin^{TM}" software.
2. Device operating frequency was adjusted to 20–1000 кHz and 100–1000 кHz.
3. Amplification factor for channels was set to 14 dB, as instead of built-in preamp sensors, external preamps were used with amplification factor of 26 dB.
4. Both channels were set to self-noise level – 37 dB (40 dB cylinder heads).
5. Threshold: 26 dB.
6. Gain: 40 dB.
7. Waveform length: 15 000 pixels.
8. Fixation speed: 100 000 measurements per second.
9. High-frequency filter: 100 kHz.
10. Low-frequency filter: 1 mHz.
11. Parametric signal: ± 10 V.

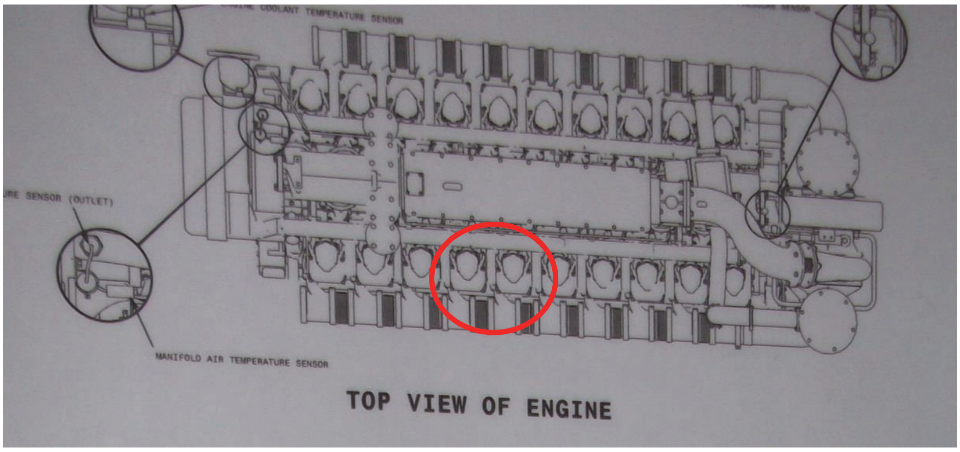

Fig. 2.5. AE sensor mounting location (cylinder head 7 and 9)

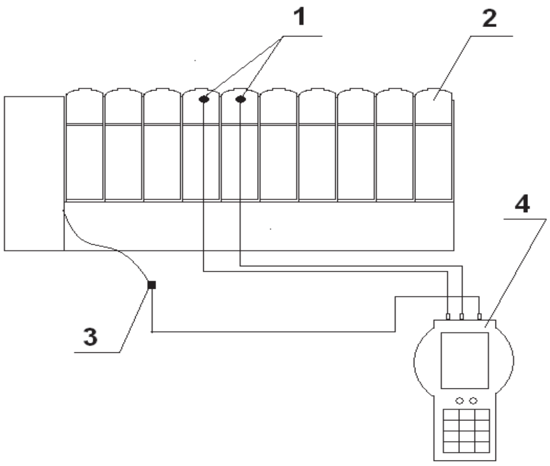

Fig. 2.6. Principal experimental measurement scheme

Legend:

1. AE sensor on the cylinder head.
2. Cylinder head.
3. Exhaust wire from the hall sensor.
4. Oscilloscopes/AE gauge.

Fig. 2.7. AE sensor strengthening at the cylinder head and connection to the hall transducer

Duration of the measurements

Background noise is measured at least 60 seconds, and this level must be at least 6 dB lower than the level of the measured source. Before and after each measurement session, the measurement circuit is calibrated.

AE data files are stored in MISTRAS standard DTA format and can be transferred to a computer using a Compact Flash card and/or USB; for a full analysis of the data AEwin ™ software was used.

In laboratory conditions it is relatively easy to determine the formation of cracks. For that purpose, on the beams or pipes, or other parts the sensors are deployed and by reading the results, we can tell the time of the crack/defect formation. When the engine is in the operating mode, it is extremely important to receive full details of the technical condition of the object. Despite the fact that there are certain requirements from CS regarding database maintenance, for a number of reasons it may be incomplete or even misleading.

Using AE method for engine control it is possible to get more information about the state of the object continuously and in real time.

However, there is a considerable difference between data capture and processing in laboratory and in the real world, when the vessel is at sea and engines being affected by number of forces (caused by vibration and noise), which is almost impossible to simulate in the laboratory.

3. ACOUSTIC EMISSION SIGNALS MATHEMATICAL MODELLING FOR TURBULENT GAS FLOW IN THE DEFECTIVE CHANNEL

Analysis of the Acoustic Emission Signal Sources in Diesel Engines

AE application sectors in the economy for mechanism and its components control have already been studied in the past, also at Riga Technical University [68]. Acoustic emission (AE) flow signal measurement allows us to explore the damage accumulation kinetics, control various defect formation and diagnose the fault early stage for various controlled objects – elements, units and power plants [3], [9], [10], [11], [13], [18], [21], [23], [24], [25], [27], [32]–[35], [37], [38], [39], [48], [50]–[64], [66], [68], [69], [70], [72].

From an acoustic point of view, marine diesel engine is a very complex system composed of many independent sources having individual physical and acoustic properties. It is practically impossible to analytically describe the entire system as a whole, taking into account a number of components and all sources of radiation influencing AE parameters.

For AE signal better understanding in engines it is necesseary to make meassurements in the engine cycle phases mentioned below [1], [6], [7], [12].

From the acoustic point of view, marine diesel engine is a very complicated system composed of many independent sources, having individual physical and acoustic properties. It is practically impossible to analytically describe the entire system as a whole, taking into account all components of all AE sources and influencing parameters. Previous studies have shown [11], [49], [53], [64], [65] that AE measurements carried out on cylinder heads contain the main causes of AE: fuel combustion, fuel injection, mechanical noises of cylinder-piston group and valve action.

Combustion phase

Considerable and rapid increase of pressure in the cylindermakes the piston move down. Pressure rise rate during combustion can be compared to an explosion, thereby causing the impressive waves on cylinder liners and cylinder heads. Previous studies have confirmed that the initiative is periodic and spread to several kHz band. Pressure in cylinder has direct impact on the cylinder head, it can be observed easily by placing the AE sensors on the cylinder head.

The main sound sources in cylinder are generated from the piston slap, fuel injection and operation of inlet and exhaust valves.

Piston slap

This is another major source of AE in diesel engines. It is caused by inversion inertia forces acting on the piston when it changes direction at the top dead center (TDC) and at the bottom dead center (BDC) – piston slap. Basically, the piston is subjected by two powerful impacts. Piston slap causes AE waves in wide frequency band, and it is significantly different depending on the engine operating conditions (load, technical condition, etc.). AE intensity determining factor is the gap between the piston and the cylinder liner, so if space is small, AE waves are not observed. However, it should be mentiond that the piston slap is very close to AMP; thus, these AE waves could be suppressed by fuel ignition/combustion caused by waves.

Fuel injection

Fuel injection is a process in diesel engine, which takes place at high pressure (several hundred bar) and short term (several micro-seconds). In this process, there are both effects present: mechanical effects and fluid frictional effects. During fuel injection the high pressure fuel wave opens and closes the nozzle needle valve, causing the mechanical impact and accordingly the AE emission. A high-speed high-pressure fuel flow can generate AE signals caused by complex hydrodynamic processes or interaction between fuel flow and nozzle openings. These AE signals are much smaller in amplitude compared to the combustion caused signals.

Infuence of inlet and exhaust valves

The closing and opening of the inlet and exhaust valves are achieved by synchronization of movements of camshaft and valve springs. AE radiation from the diesel engine valve movements occurs in two ways:

a) from mechanical impact, faced with a variety of surfaces, such as the valve with the valve seat, rocker arm to the valve stem, etc. Valve impacts are regarded as the main source of AE in this group;
b) aerodynamic friction resulting from the high-speed gas flow between the valve seat and gas flow along the valve plate. Valve impacts play an important role in diesel AE, and its amplitude depends on several factors, such as the technical condition of the engine and load.

Our previous research [11], [49], [53], [64], [65] and studies of other authors [19], [30] show that the cylinder heads contain key AE causes: combustion, fuel injection, cylinder – piston group of mechanical noise and valve influence.

AE method implementation for engine control is faced with a number of complications associated with a large number of sound sources and their heterogeneity.

When the power of radiated sound is known, it is possible to determine the sound level of a point of reception. However, in order to determine the sound pressure level of point of reception, it is necessary to take into account a number of sound wave propagation characteristics in the specific material.

There are various analytical models and techniques to describe the propagation under different conditions with a relatively high level of accuracy, but a high degree of accuracy often requires considerable computing resources.

The object of the research was 4-stroke engine with a V-type cylinder layout, in the cylinder head there were two inlet and two exhaust valves, which were opened by drive from the camshaft, but closed with spring assistance.

Diesel inlet and exhaust valves are suitable for fatigue failure process investigation and valves are one of the most heavily loaded engine structural elements. To achieve the aims of the research, a series of experiments were carried out, using an industrial high-speed diesel engine as a research object. Performing measurements, the author took into account the previous experience and data obtained in previous studies and works from RTU TMF Institute of Aeronautics (Našibuļins A., Urbahs A., Feščuks J., Banov M., etc).

This chapter describes the methodology for conducting the pilot studies and technical support.

In order to successfully achieve the aim of the research the following methodology components were used:

a) empirical basis – observed and / or the experimentally verified facts;
b) initial theoretical basis – the theory of general rules and assumptions;
c) theory of logic – the evidence and conclusions to be observed during the study;
d) new theoretical knowledge – facts and ideas, on the basis of unproven new knowledge.

In the operating process valves are subjected to shock, heat stress, increased wear, inertia forces of variable signs and high pressures.

The main operating faults of engine cylinder head valves are as follows:

a) fatigue cracking of the valve stem;
b) adust valve plate;
c) increased sediments;
d) increased/decreased clearence between valve and rocker arm.

The most dangerous valve defects are fatigue cracks in the material and adusts in valve plates, which promotes further material collapse. Usually cracks apear in stress concentration areas – areas with significant strength changes: rounded transitions, milling areas, etc.

The closing and opening of the intake and exhaust valves are achieved by precise synchronization of camshaft and valve springs. AE radiation from the diesel engine valves occurs:

a) from mechanical impact, by facing of a variety of surfaces, such as the valve with the valve seat, rocker arm with the valve stem, etc. Valve effect is considered to be the main source of AE in this group;

b) from the aerodynamic friction resulting from the rapid gas flow between the valve and the seat and the gas flow over the valve plate. Valve impacts play an important role in diesel AE and its size depends on several factors, such as the technical condition of the engine and load;

c) from the gas turbulent flow in channels with lost tightness. This defect appears mainly in relation to the valve and valve seat faults, its wear and tear.

Engine power and operational parameters are largely dependent on the amount of air entering the cylinder and purging of combustion products – fuel gases. A great importance in this process is influence of the intake and exhaust valves with their design and technical condition. Most gas exchange processes in the cylinder are affected by:

a) the valve cross-sectional area;
b) the size of the valve opening;
c) deposition on the valve surface;
d) interface wear or uneven and poor fitting to seat;
e) valve defects.

Mathematical Modelling of Acoustic Emission Signals for Turbulent Gas Flow in the Defective Channel

As the subject of the research was a ship engine that runs on gas, a case was considered where the AE signals resulting from the turbulent gas flow channel appeared as a result of failure and caused gas leaks. Tightness may be lost, for example, due to the most common valve and their socket operational defects, such as increased wear, collapse, etc.

AE signals in this case are ultrasonic signals from the gas stream that flows through the defect in the valve and are caused by gas pressure differences in the channel.

The gaseous product movement can be molecular or viscous in defected channel. For a particular object minimum possible pressure in defect is comparable with the atmospheric pressure (about 0.1 Mpa), the free movement path length of gas molecules lb is about 10–4 mm. In this case, the condition lb≫ 2, corresponding to the stream of molecules can not be provided; therefore, only case of the viscous flow is examined.

Viscous flow, in turn, may be laminar or turbulent.

It can be assumed that the AE signals are obtained only at turbulent gas motion, when emergence of unstable vortices causes pressure pulsations (stress waves) in the controlled object and AE signals as turbulence noises are recorded in the ultrasonic range.

It should be noted that the worst case is the gas receiving environment when interaction of different gases creates AE signals. Thus, the acoustic emission levels in case of gas leakage must be sufficiently high. This condition is ensured with a sufficiently high pressure differential that creates turbulent gas movement.

There are well-known methods for theoretical description of the liquid flow for defective areas, based on hydrodynamic calculations [18], [52]. Acoustic effects caused by gas flow should be based on the theoretical description of the gas dynamic calculations, taking into account the complexity and diversity of physical processes.

Based on the gas dynamic calculations, it is necessary to determine a boundary regime for gas flow through the defect, as well make an analysis of the oscillation mechanisms and their role in the formation of a useful acoustic signal.

Taking into account the complexity of the physical processes and the diversity of gas dynamic calculation, some simplifications are made.

In this specific case, when AE is formed as result of valve and valve seat defect, the channel has a complicated configuration. To simplify calculations for acoustic signal theoretical analysis, it is assumed that the channel model is straight with plain walls and with extension *r* (size formed due to the failure between the valve and the socket) and length *L* (valve thickness) and is perpendicularly connected to the main channel (cylinder), (see Fig. 3.1).

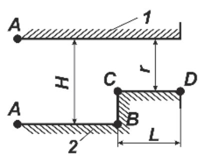

Fig. 3.1. Model of the deffect

Turbulent channel flow occurs when the gas velocity reaches a value $V = V_{cr}$ that meets the critical Reynolds number $Re = Re_{cr}$. Reynolds number flow channel pattern is as follows:

$$R_e = \frac{2\rho V p}{\mu}, \tag{3.1}$$

μ – dynamic viscosity of the product flow

Calculating the gas flow rate, it is necessary to take in account compressibility, i.e., density (ρ) depending on the pressure and the pressure losses associated with friction forces in the channel. A small pressure gradient in the channel with length dl (dl) is determined in accordance with Darcy-Veisbah formula:

$$-dp = \varsigma \frac{dl}{2p} \frac{\rho V^2}{2}, \tag{3.2}$$

$\xi = \xi(Re)$ – resistance, in general, depends on the Reynolds number.

It should be noted that flow continuity is respected:

$$V_\rho = V_c \rho_c = V_D \rho_D \tag{3.3}$$

The gas state equation, in view of the hypothesis of the isothermal flow, results in:

$$\frac{\rho_D}{P_D} = \frac{\rho}{P} = \frac{\rho_c}{P_c} \tag{3.4}$$

Hereinafter the parameters are from Fig. 3.1. As a consequence of the hypothesis of isothermal gas flow, there is a parameter μ, Re, ξ constancy.

Taking into account expressions (3.3) and (3.4) and integrating (3.2) we obtain:

$$V_D = \sqrt{\frac{1}{\varsigma\lambda} \frac{P_c}{\rho_c} \left(\frac{P_c{}^2}{p_c{}^2} - 1\right)} \tag{3.5}$$

ϑ_D – the highest gas velocity in the channel.

Isothermal sound speed in the gas is calculated from equation $c = \sqrt{p_{c/\rho_c}}$.

At subsonic speed and at $p_D = p_a$, $p_C \approx p_A$, $\rho_C \approx \rho_A$ equation (3.5) is:

$$V_D = \sqrt{\frac{1}{\varsigma\lambda} \left(\frac{P_A{}^2}{p_a{}^2} - 1\right)} \tag{3.6}$$

Jointly solving equations (3.6) and (3.1) at $Re = Re_{cr}$, we obtain the pressure ratio at which turbulent flow occurs:

$$\frac{P_A}{p_a} = \sqrt{1 + \varsigma\lambda \left(\frac{\mu R_{ecr}}{2c\rho_D r}\right)^2} \tag{3.7}$$

Or a corresponding pressure drop:

$$\Delta p = p_a \sqrt{1 + \varsigma\lambda\left(\frac{\mu R_{ecr}}{2c\rho_D r}\right)^2} \tag{3.8}$$

$$\left(\frac{P_A}{p_a}\right)_s = \sqrt{1 + \varsigma\lambda} \tag{3.9}$$

$$r_{lim} = \frac{\mu R_{ecr}}{2\rho_D} = \frac{\mu R_{ecr}}{\upsilon\rho_D P_D} \tag{3.10}$$

Further increasing of p_A/p_a leads to condition $p_D>p_a$. Pressure increases in the output channel so that equation ϑ_D =c remains valid. Thus, the gas speed in channel is no longer increasing. Thus, expression (3.9) determines the upper limit of the ratio p_A/p_a right, above which the acoustic emission signals increase due to absence of turbulence.

4. DIAGNOSTIC RESULTS OF THE ENGINE TECHNICAL CONDITION

Measurement results were analyzed and statistically processed using Excel software. The noise spectrum of modeling was performed using MatLAB software.

Figures 4.1–4.2 show AE vaveform (amplitude in mV depending on time in miliseconds) and power spectrum (depending on db and kHz) at different engine locations.

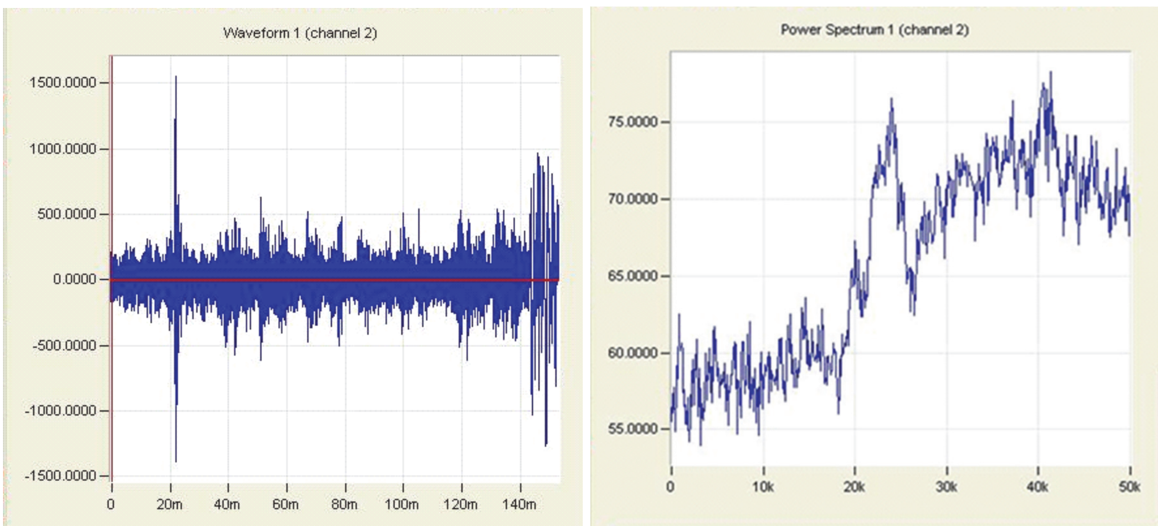

Fig. 4.1. AE waveform and spectrum at the engine flywheel

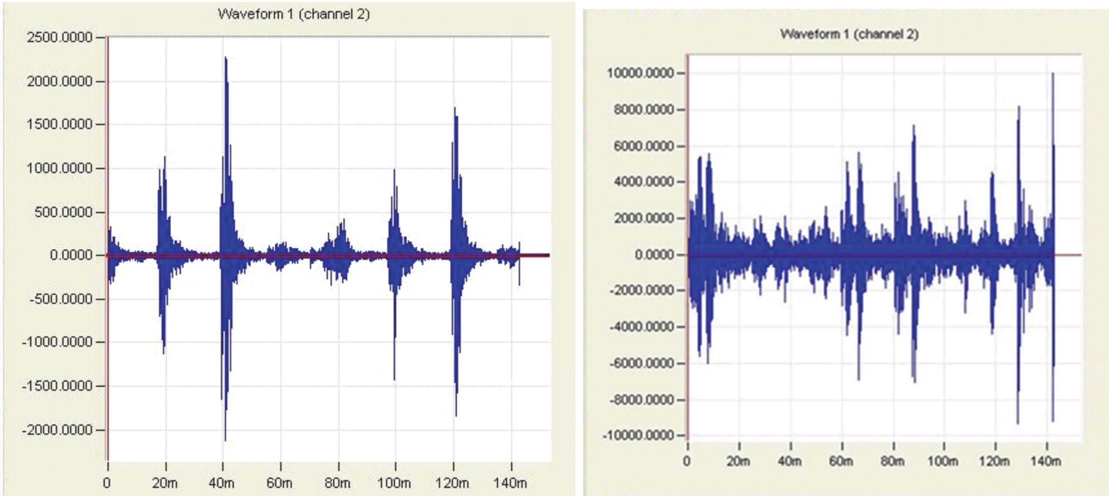

Fig. 4.2. AE waveform at cylinder head and crankcase

Figure 4.2 shows the waveform obtained from a sensor attached to the cylinder head and crankcase. For signal processing Excel program was useed to more clearly highlight smaller signals. Two peaks on picture show AE signals from closing of 2 valves, nearest to the sensor, in this case the signal peak does not matter, because the analysis is performed on smaller signals.

Measurements taken allowed obtaining acoustic emission changes in the engine AE portrait, which depicted superficial mechanical wave dispersion on engine parts. It must be taken into account that the occurrence of the AE waves depends on noises, which is typical for engine in operation: friction in bearings, knocking in cylinder-piston group, formation of cracks in details, fluid flow in piping etc. Analysing AE images, it can be concluded that the clearest signals are measured at the cylinder head, then at the crankcase and at the flywheel, this signal is the most contaminated by adjacent noise.

Receiving information from “Witraktor” obtained during maintenance and repair, the analysis of certain AE data was performed corresponding to certain condition of the engine.

Subsequent measurements were established specifically for the analysis of engine positions: for experiment technical conditions of six engine valves were selected:

1) Reduced inlet valve clearence.
2) Reduced exhaust valve clearance.
3) Reduced inlet and exhaust valve clearance.
4) Crack in the inlet valve.
5) Increase of combustion products sediments.
6) Increased exhaust valve wear and adust.

In the AE graphics the following was analysed (opening and closing of the valves for particulare cylinder):

a) amplitude of the signal;
b) duration of the signal;
c) time of the signal increasing.

Acording to the information received from “Witractor” after cylinder head inspection the noted valve clearance decremented from the norm:

a) inlet valve: 0,38 to 0,36 mm;
b) exhaust valve: 1,12 to 1,10 mm.

Figure 4.3 (see below) shows the activity of piston No. 1 and No. 9 motion curves and valves, which corresponds to the engine technical operational requirements.

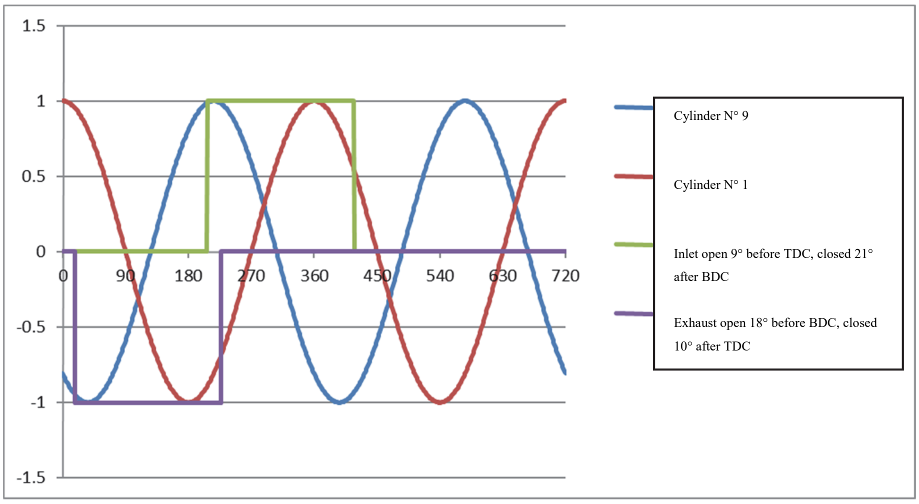

Fig. 4.3. Operation of piston n° 1 and n° 9 motion curves and inlet, exhaust valves (X-axis: crankshaft turning angle; Y-axis: relative value)

It was possible to evaluate the change in the valve operation comparing AE signals from the engine without defect working condithition with measurements obtained from the engine under certain defects. Taking into account changes in the engine, AE portrait can be determined and conclusions made for a specific cylinder valve condition.

In Figs. 4.4.–4.10, X-axis denotes crnakshaft turning angle, Y-axis (left) – relative value and Y-axis (right) – AE amplitude in volts (V).

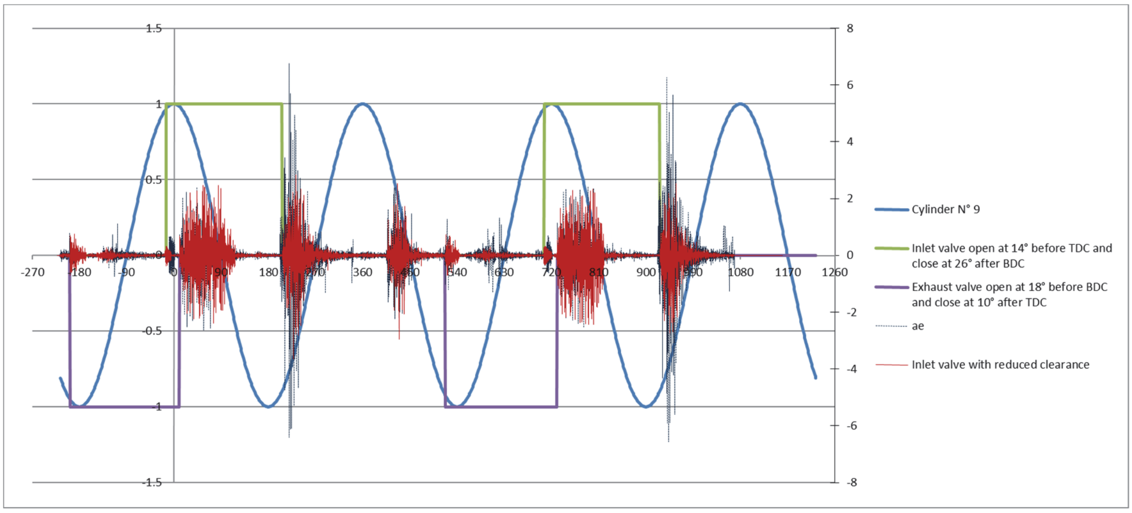

Fig. 4.4. Inlet valve with reduced clearance

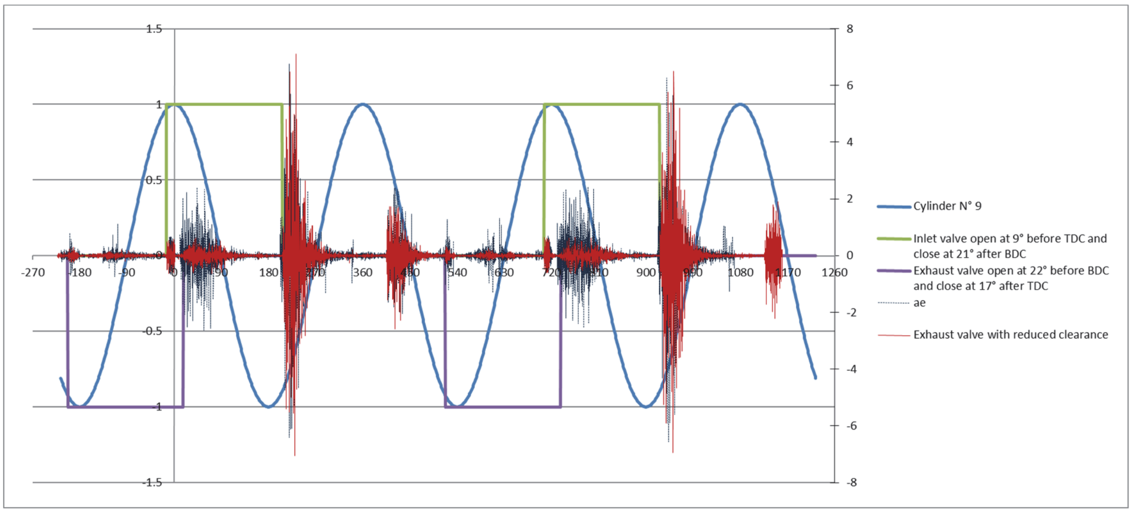

Fig. 4.5. Exhaust valve with reduced clearance

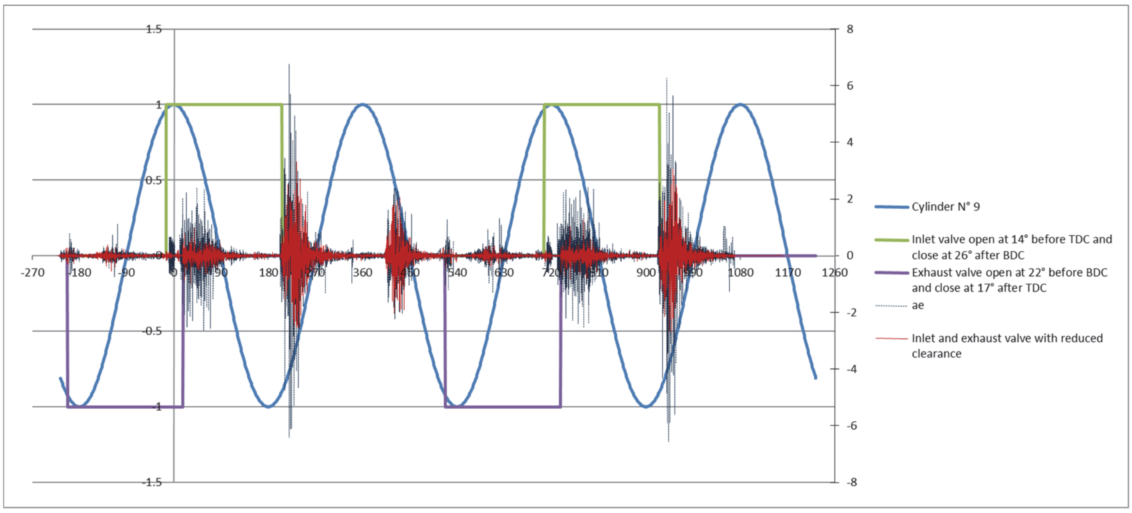

Fig. 4.6. Inlet and exhaust valve with reduced clearance

By reducing clearence in valves, the following changes are observed:
a) the signal amplitude decreases at the valves opening but especially at closing;
b) signal duration decreases slightly;
c) opening of the valve takes place a few degrees more quickly but closing – a few degrees later.

Reduced heat space normally indicates that the error has occurred during the valve adjustment that causes changes in gas exchange cycle. But if the clearence disappears completely, it leads to the valve and gas distribution mehanism breakdown.

Valve clearences are regulated in every 2000 engine running hours with specially customized micrometer. The manufacturer recommends carrying out this procedure every 1000 engine hours, but experience shows that there is no need for such frequent adjustment.

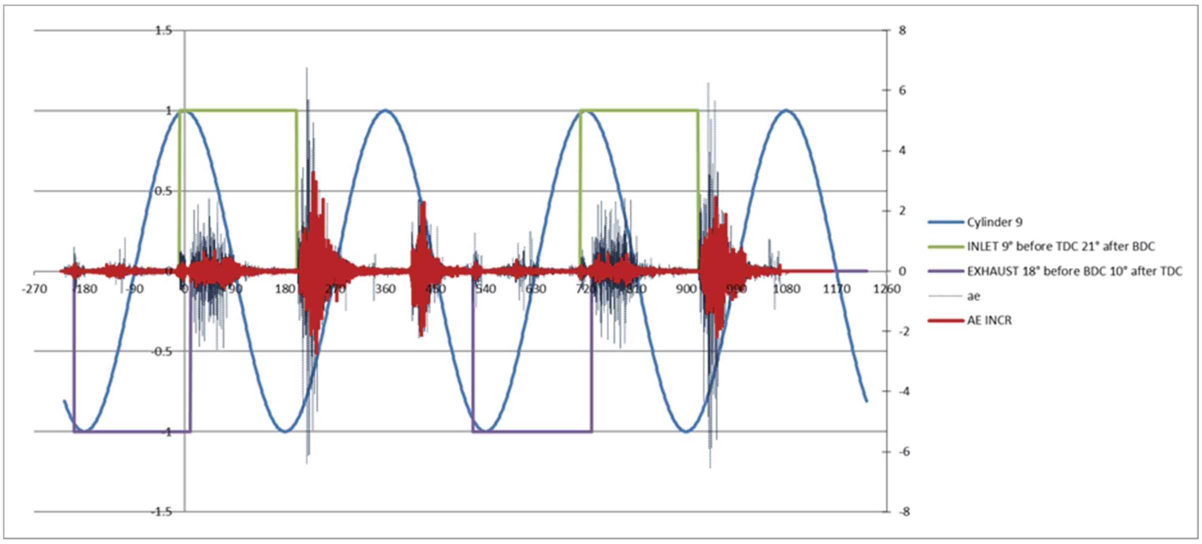

Fig. 4.7. Inlet valve with crack

Usually cracks in engine valves occure due to their overheating or industrial failure. Timely non-disclosure of cracks can lead to valve colapse, which, in turn, may cause the cylinder-piston group and turbocharger damage or breakdown.

In the autumn of 2014, information was received from “Witraktor” that after dismantling the cylinder heads and valves were inspected with a capillary inspection method (Fig. 4.8). In one of the inlet valve, micro crack was found.

Analysing the AE signals obtained shortly before crack detection, it was observed that signal amplitude decreased, but duration of the signal increased. In final stage, the amplitude and signal downtime increased significanty (Fig. 4.11).

Fig. 4.8. Cylinder heads and valves checked with a capillary / liquid penetration method

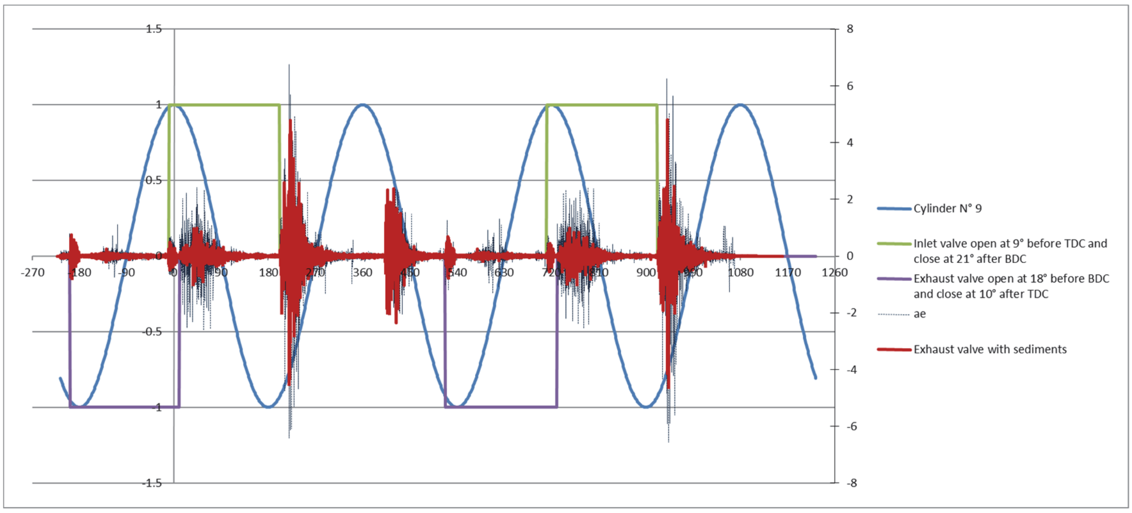

Fig. 4.9. Exhaust valve with sediments

Increased level of sediments on valves and exhaust tract leads to:

a) reduction of the outflow tract cross-sectional area – it leads to bad gas exchange in cylinder, which, in turn, generates less power and increases fuel consumption;

b) decrease in valve cooling that leads to temperature rise in the valve. When the temperature reaches a certain level, the valve structural changes occur, causing cracks.

In the autumn of 2013, we received information from "Witraktor" about results of the overhaul (every 50 000 hours) measurements – it was concluded that the exhaust valves sediments formed brown depressurised products of combustion inside the cylinder head and exhaust tract: 0,3 mm–0,6 mm. The upper layer is loose, but the layer closer to the metal becomes hard and difficult to remove. We analysed AE measurements taken shortly before engine overhaul.

Analysis of the AE signals showed that with the increased number of combustion product sediments on exhaust valves, the AE signal amplitude reduces, but duration increases a little.

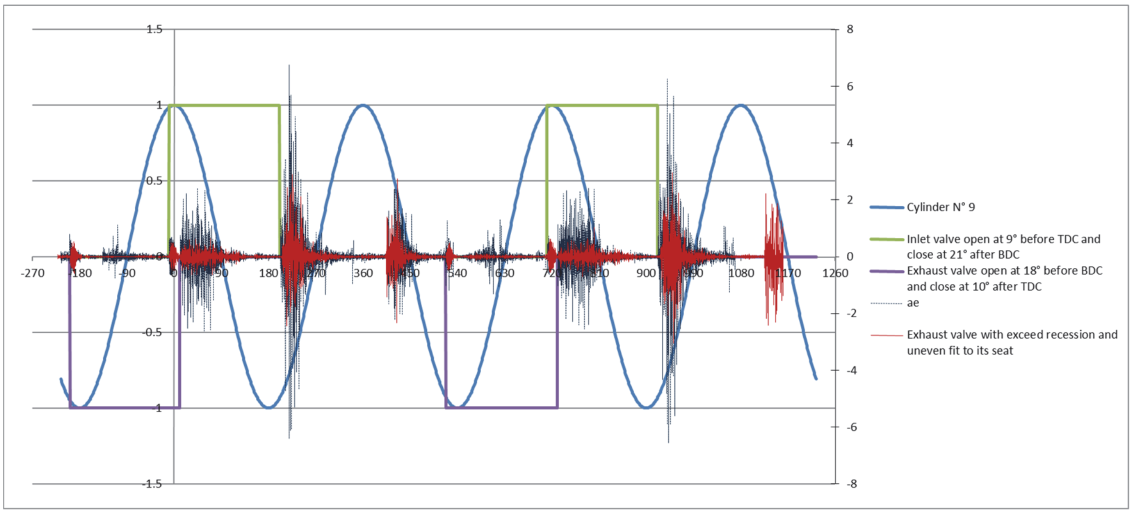

Fig. 4.10. Exhaust valve with exceed recession and uneven fit to its seat

In the autumn of 2014, "Witraktor" informed us that during scheduled recession measurement limit was exceeed and the current valve measurement was found – 2,5 mm, and uneven fit discovered. At the moment of defect discovering valve had just 6000 running hours.

After the cylinder head dismantling and valve inspection, the exhaust valve was with increased wear and lied not evenly on the valve seat.

According to engine producer technical instuction, valve wear is measured every 2000 running hours. Normaly valve wear measurement is labour intensive, and the engine must be stopped. Thus, the valve wear (recession) is measured with a micrometer on disassemble engine from outside (see instruction attached).

Enlarged valve wear and uneven seat may be consequences of valve overheating, poor quality of valve material or failure to comply with the operating rules which may cause engine exhaust reduction (as fall Pz), inlet / exhaust tract overheating, defect increasing and finally the valve collapse causing further dramatic consequences.

In this case, fuel (gas) and the working conditions are very favourable – the valve deposition is minimal (there are rare cases when the valve recession to a maximum permissible limit is earlier than cylinder head replacement – 17 000 running hours). Shortly after a new cylinder head installation (100 running hours) first (basic) valves measurements are taken. Every 4 000 engine running hours, valve recession is measured. The exhaust and inlet valve recession should not exceed 2.3 mm (see appendix).

In this particular case, a detailed analysis was performed on the AE data obtained shortly prior to the valve recession measurement and after it.

If valve contact surface decreases, AE signal amplitude slightly increases.

During experimental measurements it was concluded:

1. If the valves reduce clearence, it turns to the changes in gas exchange cycle in a cylider. Meantime duration and amplitude of the AE signals decrease.
2. If there are sediments on the exhaust valve, AE amplitude and duration of sound reduce.
3. If there is a crack in the inlet valve, amplitude of the AE signal reduces, but duration of the signal increases.
4. If there is an exhaust valve with an increased recession and uneven fit to the valve seat, amplitude of the AE signal reduces but duration of the signal increases.

For a more detailed analysis, the following positions were chosen for the intake valve with the crack:

a) six valves without defect closing position;
b) six valve closing with the crack (initial stage);
c) six valves closing with the crack (final stage) before the planned services.

Figure 4.11 below shows two graphics out of six in each case.

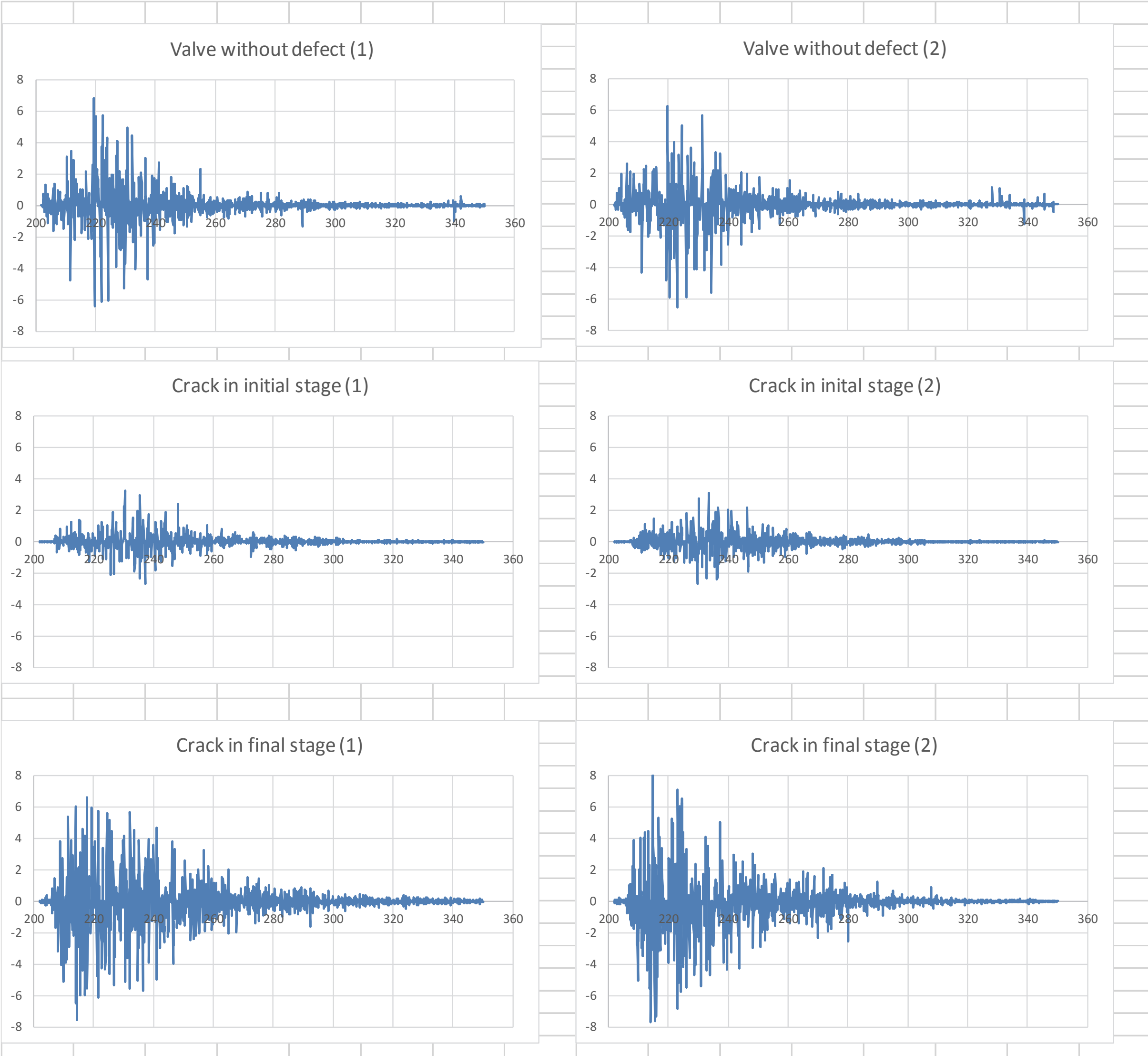

Fig. 4.11. Graphical representation of measurement for valve with the crack (X-axis: crankshaft turning angle; Y-axis: signal amplitude (V))

Table 4.1

Summary of Measurements (Valve with Crack)

	N1	N2	N3	N4	N5	N6	**Valve closing without defect**		
Max	6.770113	6.560149	6.923008	6.658722	6.477751	6.332485	6.620371	Aver	Max
AnglMax	219.51	222.93	218.34	219.96	220.23	220.41	220.2955	Aver	AnglMax
Threshold	0.6	0.6	0.6	0.6	0.6	0.6			
FirstValue	0.765391	0.720835	0.839245	-0.99184	0.79652	0.856945			
FirstAngl	202.68	202.95	203.4	202.14	202.14	203.31	202.77	Aver	FirstAngl
LastValue	-1.32265	0.670175	0.625009	-0.65431	0.602425	-0.71778			
LastAngl	288.99	283.5	280.44	282.6	279.72	281.97	282.87	Aver	LastAngl
Aver	0.317359	0.329929	0.52102	0.598205	0.438794	0.500489	0.47643	Aver	Aver
RiseTime	0.00187	0.00222	0.00166	0.00198	0.00201	0.0019	0.00194	Aver	RiseTime
DownTim	0.00772	0.00673	0.0069	0.00696	0.00661	0.00684	0.00696	Aver	DownTime
Rise	16.83	19.98	14.94	17.82	18.09	17.1	17.46	Aver	Rise
Down	69.48	60.57	62.1	62.64	59.49	61.56	62.64	Aver	Down
TimeFirst	0.02252	0.02255	0.0226	0.02246	0.02246	0.02259	0.02253	Aver	TimeFirst
TimeLast	0.03211	0.0315	0.03116	0.0314	0.03108	0.03133	0.03143	Aver	TimeLast
TimeMax	0.02439	0.02477	0.02426	0.02444	0.02447	0.02449	0.02447	Aver	TimeMax
	IncrF1	IncrF2	IncrF3	IncrF4	IncrF5	IncrF6	**Valve with crack in final stage**		
Max	7.529401	8.032948	8.127249	8.279533	8.260917	8.319512	8.091593	Aver	Max
AnglMax	214.38	214.65	214.11	213.48	214.83	214.02	214.245	Aver	AnglMax
Threshold	0.6	0.6	0.6	0.6	0.6	0.6			
FirstValue	-0.74464	-0.73548	0.680551	0.605782	-0.61036	0.607308			
FirstAngl	206.1	206.28	202.41	205.83	203.76	204.12	204.75	Aver	FirstAngl
LastValue	-0.62714	0.855114	-0.61036	0.637216	-0.62501	0.657663			
LastAngl	304.02	307.89	287.46	299.43	288.54	289.53	296.145	Aver	LastAngl
Aver	0.563609	0.529503	0.541982	0.573304	0.513922	0.57407	0.549398	Aver	Aver
RiseTime	0.00092	0.00093	0.0013	0.00085	0.00123	0.0011	0.001055	Aver	RiseTime
DownTim	0.00996	0.01036	0.00815	0.00955	0.00819	0.00839	0.0091	Aver	DownTime
Rise	8.28	8.37	11.7	7.65	11.07	9.9	9.495	Aver	Rise
Down	89.64	93.24	73.35	85.95	73.71	75.51	81.9	Aver	Down
TimeFirst	0.0229	0.02292	0.02249	0.02287	0.02264	0.02268	0.02275	Aver	TimeFirst
TimeLast	0.03378	0.03421	0.03194	0.03327	0.03206	0.03217	0.032905	Aver	TimeLast
TimeMax	0.02382	0.02385	0.02379	0.02372	0.02387	0.02378	0.023805	Aver	TimeMax
	Incr1	Incr2	Incr3	Incr4	Incr5	Incr6	**Valve with crack in initial stage**		
Max	3.271835	3.07713	3.173872	3.07713	2.453952	2.77134	2.928294	Aver	Max
AnglMax	230.4	233.37	228.69	233.37	232.65	234.36	231.606	Aver	AnglMax
Threshold	0.6	0.6	0.6	0.6	0.6	0.6			
FirstValue	-0.69459	-0.70466	-0.7068	-0.70466	0.817577	-1.08095			
FirstAngl	207.81	210.96	209.97	210.96	208.44	209.97	209.685	Aver	FirstAngl
LastValue	-0.94941	-0.73365	0.63508	0.634469	0.656747	-0.66285			
LastAngl	272.7	266.13	286.47	286.92	279.36	285.12	279.45	Aver	LastAngl
Aver	0.165302	0.178016	0.203024	0.191972	0.17123	0.209758	0.186275	Aver	Aver
RiseTime	0.00251	0.00249	0.00208	0.00249	0.00269	0.00271	0.00263	Aver	RiseTime
DownTim	0.0047	0.00364	0.00642	0.00595	0.00519	0.00564	0.005593	Aver	DownTime
Rise	22.59	22.41	18.72	22.41	24.21	24.39	23.67	Aver	Rise
Down	42.3	32.76	57.78	53.55	46.71	50.76	50.34	Aver	Down
TimeFirst	0.02309	0.02344	0.02333	0.02344	0.02316	0.02333	0.02331	Aver	TimeFirst
TimeLast	0.0303	0.02957	0.03183	0.03188	0.03104	0.03168	0.031533	Aver	TimeLast
TimeMax	0.0256	0.02593	0.02541	0.02593	0.02585	0.02604	0.02594	Aver	TimeMax

Borderline for Compressed Gas Turbulent Subsonic Flow in Defect

Based on the recommendations of Chapter 3, calculation of subsonic turbulent gas flow was made in channel. The aim was to determine the boundary conditions for turbulent flow, which is characterized by ratio pA/pa (see (3.9)).

Limit values for exhaust gas channel geometrical parameters of the system "cylinder-valve", in which the turbulent flow regime is unattainable, are as follows: compressed air temperature 20 °C, product dynamic viscosity = 1,8; D = density in kg / m³; D = pressure in MPa; critical Reynolds number Recr = 2.

Relative channel prolongation $\lambda = L/r$ is assumed:

1) **λ** = 10
2) **λ** =50
3) **λ** =100

The results are shown in Fig. 4.12 below.

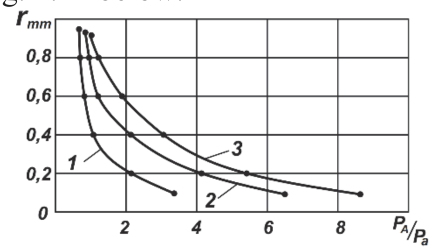

Fig. 4.12. Range limits for compressed air leakage in subsonic turbulent flow mode

The results show that a wide range of ratio pA/pa in subsonic turbulent flow mode in defect can only be provided at large holes (r) and large channel length. Solving equations (3.8) and (3.9), we obtain limit value of the channel hole (defect) in which the turbulent flow regime is unlikely (see (3.10)).

This ratio determines limit of resolution of acoustic emission method for diesel engine cylinder leakage control, which is based on the sound signal registration caused by the turbulent gas flow in damaged channels.

In a particular case, there is limit for AE signal registration if hole opening: rlimit = 0,1 mm.

CONCLUSIONS

1. Marine engine damage and diagnostic analysis of methods, including Condition Based Maintenance implementation of regulatory documents, showed that today Classification Societies do not have strict rules for AE hardware implementation. It shall be determined by each Classification Society, taking into account its own experience. At present, in accordance with the requirements of the CBM, engine control is carried out by using vibration and thermography diagnostic devices that do not provide complete information and have a relatively low resolution.

2. Mathematical model was developed for gas flow in defective channel and its movement caused acoustic effect. Upper limit for the presure drop was found, above which acoustic signal increased due to the absence of turbulence.

3. Gas dynamic calculation was made and range limit determinated for compressed air leakage in subsonic turbulent flow regime. Results showed that in subsonic turbulent flow mode a wide range of pA/pa could be ensured at the relatively large damage length and opening.

4. Experimental measurements were made at the engine operating condition, and the criteria were established for the evaluation of the defect. It was revealed that the AE method was an effective instrument for the detection of fatigue cracks and other valve defects. It was concluded that the most effective AE sensor installation location is cylinder head. AE method showed cracks about 1000 hours before they were fixed by the capillary method. Valve oversize wear was fixed at 1300 running hours. Increase of the sludge on exhaust valve was fixed at 2800 running hours.

5. Acoustic emission diagnostic methodology was developed for engine failure early detection in order to meet Condition Based Maintenance requirements. The main objectives were:

a) research object preparing for measurement;
b) preparing the measuring equipment;
c) AE sensor fixation measurement locations;
d) AE signal measurement;
e) measurement results processing;
f) AE informative analysis of the indicators;
g) defect identification;
h) decide on the technical condition of the engine;
i) technical protocol processing;
j) data storage.

6. The developed acoustic emission diagnostic methodology complies with the basic steps for the diagnosis of marine diesel engines, taking into account standards that apply to accoustic emission measuring equipment and are approved by Clasification Societies.

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