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AN ANALYSIS OF THE ASSESSMENT OF THE TECHNICAL CONDITION OF A MARINE DIESEL-ELECTRIC SET BASED ON THE EXHAUST GAS PRESSURE AND OTHER ENERGY PARAMETERS MEASUREMENTS

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Abstract:

In the paper an analysis of the assessment of the technical condition of a marine diesel-electric set with limited monitoring susceptibility, on the basis of the diesel engine and generator energy parameters measurements, is presented. The proposed method is based on the assumption, that there is a relationship between technical state of engine and generator, and measurable parameters of the generating set. The structure of the power station has been analyzed to select parameters for measurements. The chosen parameters are as follows: exhaust gas pressure in the outlet manifold, phase-to-phase generated voltage, and acceleration of some parts of the diesel engine and synchronous generator. The research program, characteristics of the equipment, and representative results for various technical conditions of the engine are presented.

Keywords: *generating set, marine auxiliary diesel engine, synchronous generator, diagnostic*

1. Introduction

One of the most important research problems taken up on the Mechanic-Electric Faculty of the Polish Naval Academy, is to develop some alternative methods of the assessment of the technical condition of selected parts of marine diesel engines [1, 2, 3, 5, 6, 12].The concern in alternative diagnostic methods results from the fact that in the Polish Navy there is a great number of marine diesel engines, both auxiliary and main propulsion, not equipped with indicator valves. For example, engines ZVIEZDA M401, M503 and M520 type, DETROIT DIESEL DDA149TI type, and licensed by LEYLAND diesels SW400 type. Since that is not possible to operate them with applying to them classical diagnostic methods, they are exploited according to so-called overhaul life strategy. The main goal of developing alternative methods of assessment of the technical condition of marine diesel engines, is to implement in the Navy strategies according to technical state of such engines. During the research it was assumed that due to the lack of possibility to measure the pressure inside engine's cylinders, one should seek other measurable parameters of interest carrying diagnostic information. After an analyze, the following diagnostic parameters were determined: exhaust gas pressure in the manifold, phase-to-phase voltage of the synchronous generator, and acceleration of the certain diesel and generator elements. Exhaust gas pressure measurements performed at two cross-sections of the outlet channel, allowed to determine the speed of the peak amplitude of the pressure wave propagation and the enthalpy flux there. Usefulness of such an attitude was proved during tests in order to evaluation of the technical condition of three supercharged marine diesel engines: ZVIEZDA M401 type, DIETROIT DIESEL DDA149TI type and SULZER 6AL20/24 type [5, 6, 12]. Another parameter providing an important diagnostic information is phase-to-phase voltage of the synchronous generator [2]. It is because of the fact that for the synchronous generator the phase-to-phase voltage strictly depends on the angular speed of the engine's crankshaft. The accelerations of selected engine and generator elements were chosen as well as an important diagnostic parameter.

2. Test stand description

A marine generating set type ZE400/52 was the object of the research. It is equipped with a diesel engine type SW 400 and a three phase synchronous generators GCP-94c/1, installed in the laboratory of Mechanic-Electric Faculty of the Polish Naval Academy (Fig. 1). Such generating sets are installed on small Polish warships as well. The tested engine SW400 type is a four-stroke, six cylinders, in-line, undercharged auxiliary diesel engine. Its main technical data are shown in Table 1. Each set can generate electric power as a single set or in parallel, synchronously on a common net. Exhaust gases from running engines are directed to one manifold as it is shown in Fig.2. Rated constant rotational speed of the engine crankshaft 1500 rpm is connected with the frequency f = 50 Hz of the generated electric power. Diesel engine load with the brake torque can be changed by means of effective resistance of air resistors which makes electric load of generators. They enable loading each generator in the range of 0 ÷ 25 kW.

Fig. 1. General view of marine generating set ZE400/52 mounted on the test bed

Table 1. Technical characteristic of SW400 diesel engine [13]

Rated output	54,06 kW	Injection type	Direct
Rated crankshaft speed	1500 rpm	Injection order	1-5-3-6-2-4
Number of cylinders	6	Injection pressure	16,18 – 16,67 MPa
Piston stroke	120,65 mm	Specific fuel consumption	190 g/kWh
Cylinder bore	107,19 mm	Intake valve opening commencement	10^0 before the TDC

Schematic diagram of the exhaust gas system in the laboratory is shown in Fig. 2.

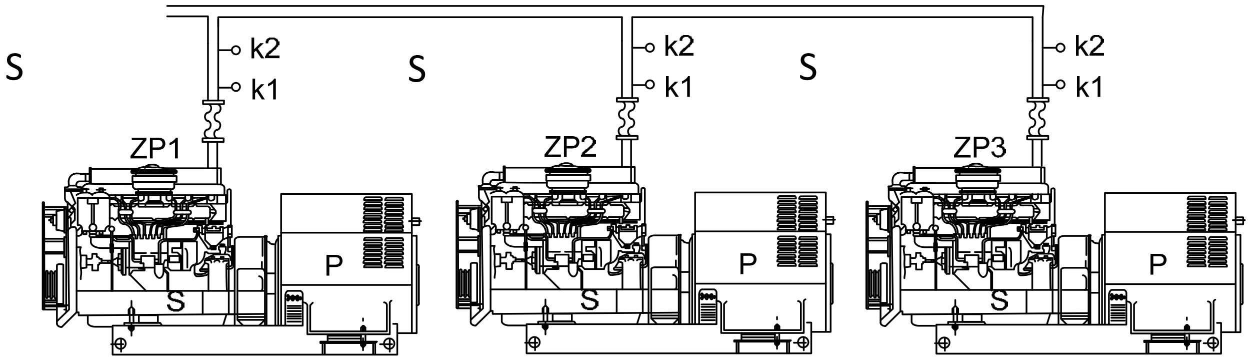

Fig.2. Schematic diagram of the exhaust gas system in the laboratory: S – diesel engine, P – generator, ZP – generating set, k_1, k_2 – control cross-section [2, 3, 13].

3. Measuring equipment

Multifunction data acquisition module Advantech type USB-4711A (Fig. 3) was used for measurements. The module characteristics: 16 analog input channels, input range ±10V, ±5V, ±2.5V, ±1.25V, ±0.625V, resolution 12bits, and max. sampling rate 150 kS/s. It has a USB 2.0 interface, too. Measured quantity converter PWM-2010 (Fig. 3) was designed and constructed for the needs of conducted tests. It enables adjustment signals from sensors to USB module features. Besides it makes generated voltage up to 400V measurements safe due to voltaic separation from the module and computer. PWM-2010 is compatible with pressure sensors OPTRAND type C11294-Q, and accelerometer KD35 type or Brüel & Kjaer 4384 type [1].

Fig.3. Measuring equipment: 1-computer, 2-multifunction data acquisition module Advantech USB-4711A, 3-converter PWM-2010.

The measuring instrument PWM-2010 provides simultaneous, inertia-less and accurate measurement of certain physical quantities and adjusts the level of signals from transducers and phase-to-phase voltage of the synchronous generator to values acceptable for data acquisition module.

The way of instantaneous value of the exhaust gas pressure measurement in the selected sections of the outlet channel is shown in Fig. 2. Transducers OPTRAND type C11294-Q were used in measurements because of their resistance to exhaust gas high temperatures. Due to the so-called temperature drift, those transducers eliminate the constant component of the pressure and allow to measure the pressure pulsation in the range of 0÷0.7 MPa, with the sampling frequency to 30kHz. The range of the transducer output signal value is 0.5÷5 V and resolution of the multifunction data acquisition module 12 bits what enables recording with an accuracy of 171 Pa.

Instantaneous value of the generator phase-to-phase voltage (~400V) was another measured parameter. Due to safety of the personnel and to prevent the slotted line from damage phototransistors were used for galvanic separation such relatively high generator voltage from the measuring instrument.

The measuring circuit contains phase-to-phase converter. Its function is to match the generator voltage to voltage accepted by the data acquisition module. This converter is composed of adjustable voltage dividers and enables to achieve ±5V at the output so as to adapt currents in the system to provide the optocoupler linear characteristic.

A constant voltage component was added in order to ensure proper working conditions of the optocoupler. Due to an analog voltage signal at the output of the optocoupler in the range of 0.5÷5V and the resolution of the module 12 bits voltage measurement with the precision of 1.22V is possible. However, it should be taken into consideration that both characteristic of the voltage divider and the optocoupler are dependent on the temperature. To minimize the temperature effect on the measurement results, all the instruments were switched on for 5 minutes until their temperature become steady during measurements.

Vibrations of selected elements of the generating set construction structure were measured, too. The measuring vibrations line was calibrated by means of standard oscillator. In addition, while the measuring line was calibrated, acceleration test was conducted by means of another instrument but in the same measuring points.

The fuel injectors vibration accelerations measurement accuracy was not significant due to the fact that the signal has been used for synchronous averaging (qualitative analysis rather than quantitative).

Low-pass filters with a frequency range twice as much as the sampling frequency to avoid the aliasing effect were built in all the measuring lines.

It was assumed that the measurement of all energetic parameters is simultaneous. Time base was considered constant due to quartz resonator class used, and timing accuracy error which does not exceed 2% of the sampling frequency 150kS/s. Besides, PWM-2010 as an analog measuring device without inductive and capacitive elements, introduces very little signal distortion in the time domain.

4. Research methodology

In order to work out the methodology of research it was assumed that all the tests would be carried out for steady operating conditions. That is why a static plan was applied. At the beginning all values of input parameters were assumed. Those parameters were selected on the basis of the logical analysis of the construction structure of the generating set and its working conditions. In conducted tests, the determined plan was applied where input parameters were: engine load with brake torque T (directly proportional to generator load) and implemented to the system certain unserviceable states. For practical reasons a selective plan was adopted so it was possible to confine a number of input parameters [10]. A complete plan would be very complicated because engine loads with the brake torque may change continuously in its operating range. Therefore it was decided to adopt the second degree polyselective plan [10]. It was assigned engine load with the brake torque adequate to diesel engine running idle and when electric power delivered by the generator was 20kW. To know the way of changing the measured parameters as a function of engine break torque, additionally measurements at the generator load 10kW were made. The second input parameter in the investigation plan was technical condition of the generating set. There were assumed two different cases – "good" and "poor" condition of technical suitability of the set [4, 9]. As "good" was recognized the normal condition of the set. "Poor" condition was achieved by cutting off fuel to one of diesel injectors by means of a three-way pass valve as it is shown in Fig.4. Experimental plan is shown in Table 2.

Table 2. Experimental plan

Number of input parameters value arrangement	Generator power	Technical condition of the generating set
	[kW]	[-]
1	0	good
2	20	good
3	0	poor
4	20	poor

Fig.4. Engine SW400 type fuel system with three-way pass valve to cut off fuel supply to the chosen injector

After an analysis of the construction structure, the following energetic parameters of the generating set were chosen for the measurements:

- phase-to-phase generator voltages (after the automatic voltage regulator) [7, 8],
- exhaust gas pressure pulsations in two cross-sections of exhaust manifold,
- fuel injectors vibration accelerations,
- accelerations of the selected elements of the generator driven by the diesel engine [11].

Places where measurements were carried out are shown in Figs. 2 and 5.

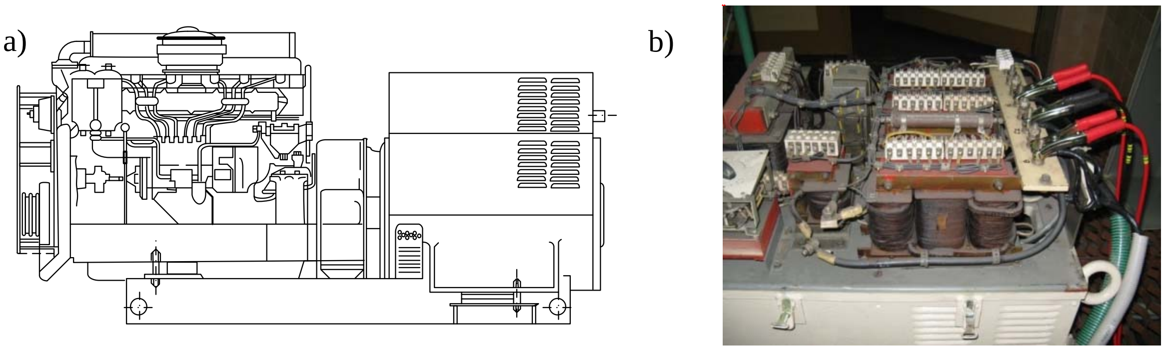

Fig.5. a) arrows point out where accelerometers were placed, b) arrows point out where phase-to-phase voltage was measured

The measurements of variable pressure in control cross-sections of the exhaust manifold enable to measure the enthalpy flux of the exhaust gas from engine cylinders, speed of the peak amplitude of the exhaust gas pressure wave propagation, and spectral analysis of the registered signal [5, 6, 12]. Analysis of pressure waveforms as a function of time, especially in terms of determining the enthalpy flux of exhaust gas, is troublesome. Much more convenient is to analyze these signals as a function of the engine crank angle. To do this one needs to find any periodically repeated signal (synchronizing) of period T equal to the duration of the engine cycle of operation. Parameters that satisfy above requirements are accelerations measured at the engine injectors. They allow to convert all measured parameters from the time domain into the engine crank angle domain (synchronous averaging). Moreover, vibration accelerations measured at the injectors allow to precise determine average crankshaft speed during the engine cycle of operation. Similarly, based on the synchronous signal, phase-to-phase voltages as a function of crank angle domain were determined. Both the pressure waveforms as a function of time, and phase-to-phase voltages, were analyzed using Fast Fourier Transformation (FFT). The last group of parameters that were measured and recorded, are accelerations of the clutch connecting the engine and generator, generator stator, and generator thrust bearing. The measurement results were analyzed using FFT.

5. Experimental results

The measurements have been carried out according to the presented plan. Rated crankshaft speed 1500 rpm was kept constant so that electric voltage frequency to be constant. Diesel engine load with the brake torque was changed from idle running, 10kW to 20kW. It was assumed that the generating set was in good technical condition and, after cutting off fuel to one of injectors, in poor technical condition. Representative results of experiment when the engine was in good and poor technical conditions are shown in the following figures.

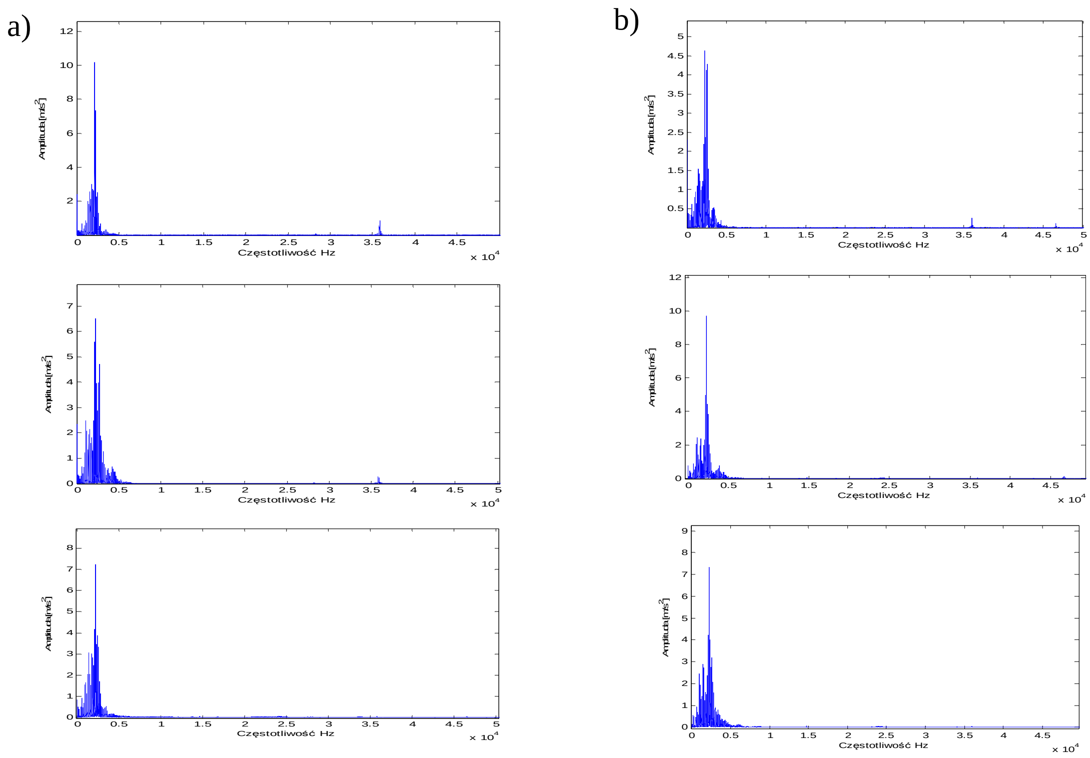

Fig. 6. Amplitude spectrum of vibrations from the generator stator: a) good technical state, b)poor technical state, 1 – idle running, 2 – load 10kW, 3 – load 20kW [3].

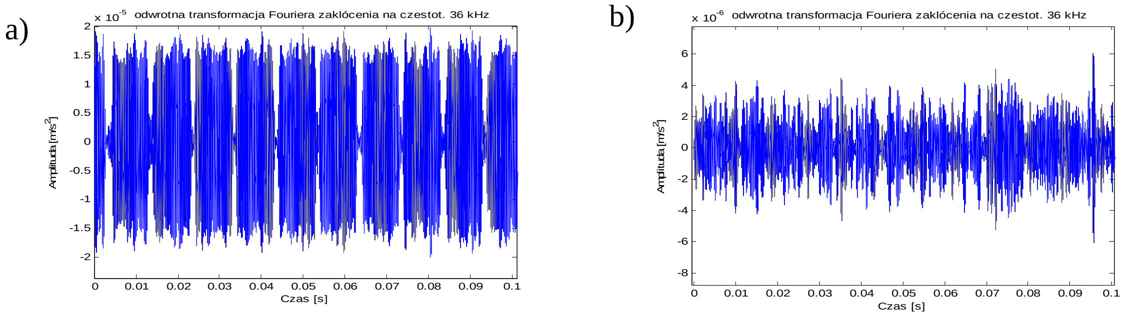

Fig. 7. Time waveforms of vibrations from the generator bearing for frequency between 35 and 37 kHz for 10kW load: a) good technical state, b) poor technical state [3].

The comparison of the pressure waveform in control cross-section k_2 as a function of the crankshaft angle for two technical states of the engine, “good” and “poor”, is shown in Fig.8.

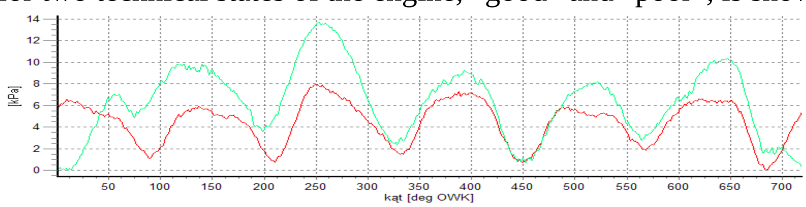

Fig. 8. Exhaust gas pressure in control cross-section k_2 as a function of crankshaft angle (load 10kW): 1 – good technical condition, 2 – poor technical condition [2].

a b)

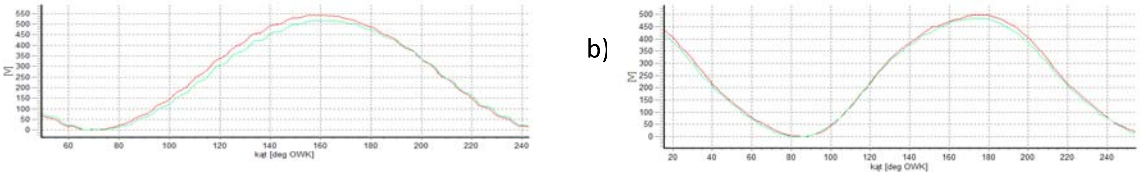

Fig. 9. Phase-to-phase voltage as a function of crank angle: a) idle running, b) load 20kW; 1- good condition of technical suitability, 2-fuel to one cylinder cut off [2].

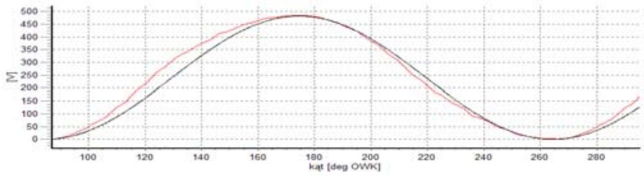

Fig.10. Phase-to-phase voltage as a function of crank angle when engine is idle running and fuel to cyl. no. 2 is cut off. 1-measured value, 2-theoretical value [2].

a) b)

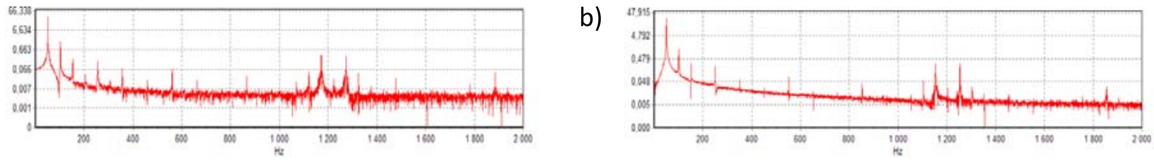

Fig. 11. Amplitude spectrum of phase-to-phase voltage (load 20kW): a) good condition of technical suitability, b) fuel to one cylinder cut off.

a) b)

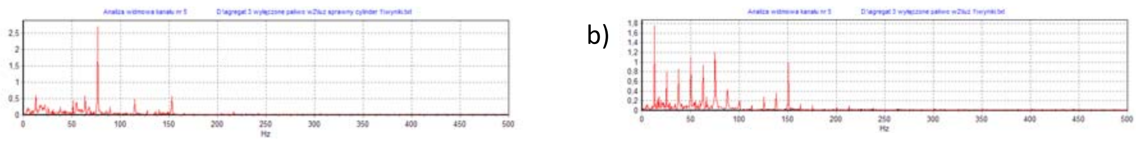

Fig.12. Amplitude spectrum of exhaust gas pressure pulsation in the control cross-section k_1 in the outlet channel (load 20kW): a) good condition of technical suitability, b) fuel to one cylinder cut off.

Time waveforms of measured parameters as a function of crank angle for different values of engine load for good technical state are shown in the following figures:

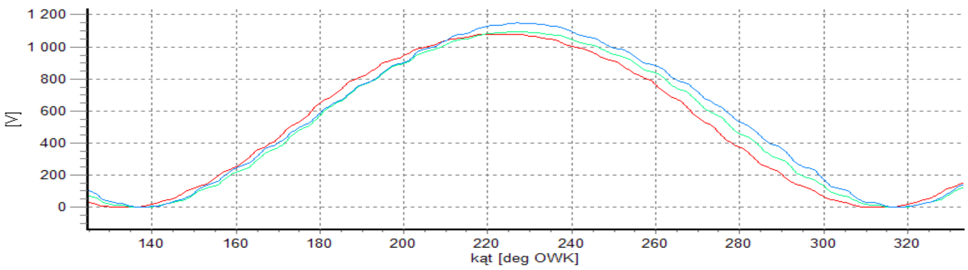

Fig.13 Phase-to-phase voltage as a function of crank angle (a part of the cycle); 1-idle running, 2-load 10kW, 3-load 20kW

Based on qualitative and quantitative analysis of the data presented in Figs .6 and 7 it can be stated that introduced technical unfitness of the engine causes changes in vibrations power spectrum. The increase in the frequency range from 35 to 37 kHz is characteristic for such a failure. It can be seen in Fig.7 where inverse Fourier transform of vibrations is shown.

Analysis of the data presented in Fig.8 allows to conclude that when fuel to one of the engine cylinders is off, it causes visible pressure deformation in the exhaust gas manifold. The usefulness of this parameter for the assessment of the technical condition of the engine is described in literature [1, 3, 12]. The recorded gas pressure waveform as a function of time (Fig.8) was analyzed in frequency domain after Fourier transform (Fig. 11).

Based on a comparative analysis of the spectrum of exhaust gas pressure when the engine is in "good" and "poor" technical condition it can be stated that due to unfitness, the value of the harmonic corresponding to the number of engine cylinders (150Hz) significantly increased. Has also increased the value of the harmonics that are multiples of the fundamental harmonic 8.33Hz.

Analysis of the recorded voltage waveforms as a function of time, after the transition to the angle of the crankshaft rotation, allows to conclude that both the engine load (Fig. 13) and its technical condition affects the shape of the course (Figs.9 and 10). Waveform distortion, their slope, result from changes in the instantaneous angular velocity of the crankshaft during engine cycle of operation. The increase in engine load causes deformations of the course for entire engine cycle of operation, i.e. 720^0 crankshaft revolution. On the other hand, the state of unfitness when one of cylinders does not work causes furthermore the course distortion for a particular crankshaft angle corresponding to the phase of cycle the cylinder that is faulty.

This observation allows to evaluate the technical condition of the generating set. Knowing the injection order it is possible to identify the faulty cylinder section.

6. Conclusions

The results presented in this paper provide an introduction to development of a non-invasive method of assessing the technical condition of a marine generating set when diesel engine is not equipped with indicator valves. Analysis of the experimental data presented in the form of diagrams led to conclusion that changes of certain energetic parameters are the function both the technical condition and the load (electric power) of the generating set. This observation motivates for further research to find out diagnostic relations between the technical condition of the generating set and variations of its energetic parameters. As a consequence, it should allow to point out a set of diagnostic parameters which can identify explicitly technical condition of the generating set.

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