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Method for assessing the technical condition of marine diesel engine driving the synchronous generator

The paper presents an innovative method for assessing technical condition of a marine diesel engine that drives synchronous generator. It is based on the measurement and analysis of generator's phase-to-phase voltage. Additionally, it requires the measurement of a pseudoperiodic signal [3] with a period equal to duration of engine's working cycle. The basis for developing method was the assumption that rotational speed fluctuations of an engine's crankshaft (and also the generator) depend on a course of a working process carried out in it. The generator's phase-to-phase voltage is directly dependent on a rotational speed fluctuation of its rotor. It must therefore be possible to assess a course of a working process of an engine based on a voltage waveform of a synchronous generator that cooperates together.

Key words: *diagnosis, diesel-electric unit, model research, empirical studies*

1. Introduction

An important group of engines used in shipbuilding (it is estimated that about 50% [10]) diesel engines propelling ship's generators. According to the SOLAS Convention, each ship must have at least two independent power supply units [1]. In most cases, there are more (usually three or four). These are usually diesel engines not equipped with indicator valves [10]. This makes it difficult to apply operation strategies according to technical condition to them. They are operated according to so-called hourly recharge (time resource for correct work). Such a strategy imposes an exchange of their elements of a construction structure every specific number of working hours (regardless of their actual technical condition, often fit) [9].

Therefore, works were carried out to develop parametric, non-invasive methods for assessing their technical condition. One of them is method presented in the article based on the measurements of an phase-to-phase voltages of an synchronous generator constituting with a diesel engine (DG). The basis for the development of the method was the observation that both a load of the engine with torque and its technical condition affect on phase-to-phase voltages of a synchronous generator cooperating with it [5, 8] (which in theory should have a sinusoidal shape [2, 10]). An example of a phase-to-phase voltage of a generator as a function of time recorded during empirical studies is shown in Figure 1. In addition, the figure shows the reference waveform of the phase-to-phase voltage (theoretical).

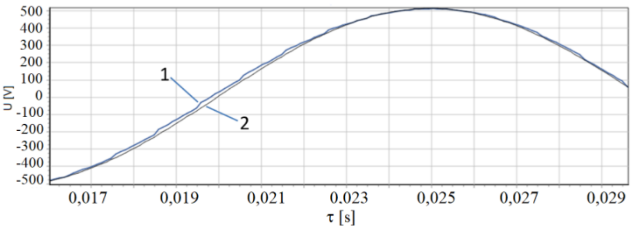

Fig. 1. The chart of line voltage synchronous generator as a function of time: 1 – waveform measurements obtained from 2 – course model

On the basis of analysis of a phenomena occurring in the DG, it was considered that a reason for a observed deformations of the interfacial tension waveform is fluctuations of the angular velocity of a generator rotor (Fig. 2).

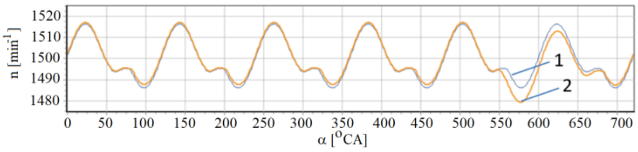

Fig. 2. The rotational speed of the generator rotor as a function of an angle of rotation of an engines crankshaft for: 1 – for an operational engine, 2 – for a damaged engine (reducing the dose of fuel supplied to the No. 1 cylinder by 50%)

The direct cause of rotation speed fluctuation of a generator rotor are the rotational speed fluctuations of an engine crankshaft. They result from the variable torque of a crankshaft and depend on the value of indicated pressure in the engine cylinders [7]. Figure 3 shows the torque curve obtained in the result of modelling for the six-cylinder engine 1 – operational, 2 – damaged.

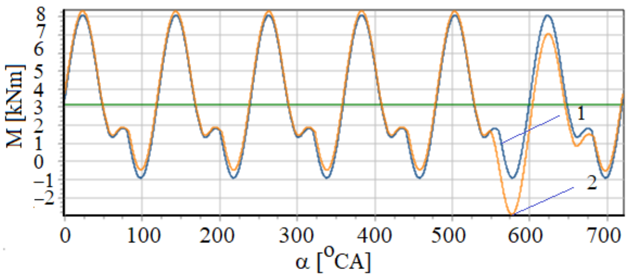

Fig. 3. The chart of engine torque as a function of an angle of crankshaft rotation for: 1 – operational engine, 2 – damaged engine (reducing the dose of fuel supplied to cylinder No. 1 by 50%)

The analysis of the waveforms presented in Fig. 1 and 2 clearly indicates that a working process occurring in cylinders (indicated pressure) affects the torque values. However, the torque directly affects course of a rotational speed of an engine crankshaft (generator rotor).

2. Model of diesel-electric unit

Development of presented method for assessing technical condition of a marine diesel engine required conducting a thorough analysis of selected phenomena occurring in engine and generator. For this purpose, a mathematical model of a diesel-electric unit was developed. The mathematical model includes a possibility of simulating known and recognizable engine damage such as: change of fuel dose, change of valves cross-section area, change of the injection opening angle, leakage in a piston-rings-cylinder system. Development of the DG mathematical model has been divided into two stages (Fig. 4).

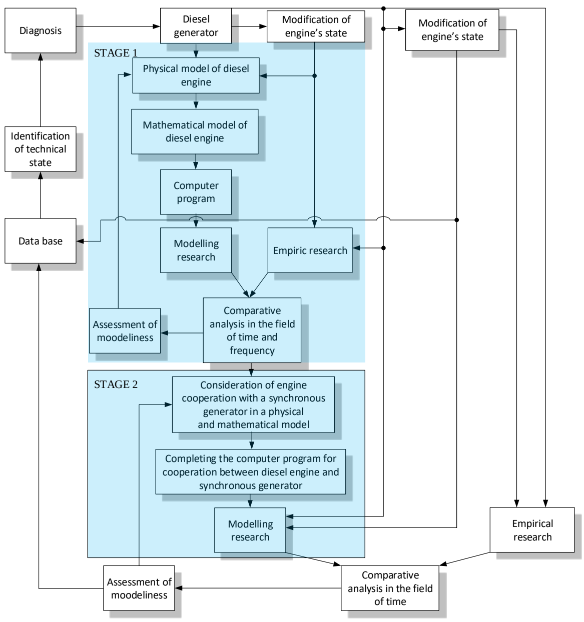

Fig. 4. Research program

The first stage involved development of a mathematical model of a diesel engine. The adequacy of this model has been verified on a basis of a comparative analysis of a results of model and empirical studies. Empirical studies were carried out on a laboratory engine with high diagnostic susceptibility. Obtaining a positive result of an adequacy assessment (quantitative and qualitative) of the mathematical model of the engine allowed for a transition to the second stage – the development of the DG mathematical. This approach to modelling issue was dictated by the fact that in the case of engines driving marine generators, model verification would be extremely difficult. In most cases, these engines are not equipped with indicator valves.

The stage of developing the mathematical model of the engine was preceded by the development of a physical model of the processes taking place in the DG. The basis for the development of the physical model was identification of phenomena occurring in team and a mutual relations between a functional components of a subprograms. The identification was based on the built models: functional and topological.

The developed mathematical model of the unit was the basis for writing a computer program (often called a numerical model) that allows solving the equations included in the model.

The result of the solution of the equations of the mathematical model of the DG were a phase-to-phase voltages of a $L_{1\text{-}2}$, $L_{2\text{-}3}$, $L_{3\text{-}1}$ generator, waveforms of a crankshaft of an engine (generator rotor) as a function of time or angle of rotation of a crankshaft. Course of factor parameters in engine cylinders such as: temperature, pressure, mass, individual gas constant, etc. as functions of an angle of a crankshaft rotation.

3. Model and empirical research

3.1. Research plan

Recognition of the DG model as adequate enabled development of a determined, selective research plan [6, 10]. It was assumed that according to the same program model and empirical studies will be carried out. Empirical research was carried out on three DG powered by 6SW 400 type engines cooperating with GCPf – 94c/1 type generators. Research objects are installed at the stand in the Laboratory for the Operation of Electric Ship Equipment (Fig. 5).

Fig. 5. Research object in the Laboratory for the Operation of Electric Ship Equipment

The test program is shown in Tables 1 and 2. Table 1 shows the test program for the engine in full technical condition. However, Table 2 presents the test program for the damaged engine. The tests were carried out for the engine damaged for a following partial technical condition. First, cylinder No. 1 was turned off. Then cylinder No. 6 was turned off. The last stage of the research consisted in excluding cylinders no. 1 and 6 from operation.

Table 1. Study plan for DG in full technical condition

Load with electrical loads	Measurement number
2 kW	1
10 kW	2
20 kW	3

Table 2. Study plan for DG in full technical condition

Load with electrical loads	Measurement number
Cylinder No. 1 excluded from work	
2 kW	1
10 kW	2
20 kW	3
Cylinder No. 6 excluded from work	
2 kW	1
10 kW	2
20 kW	3
Cylinders No. 1 and 6 excluded from work	
2 kW	1
10 kW	2
20 kW	3

3.2. Measuring apparatus

The implementation of the research required the development of proprietary measuring apparatus [4]. It was assumed that the apparatus must allow for implementation of measurements of a synchronous generator voltage (three channels) while maintaining the galvanic isolation of high voltages at the terminals (user's computer). An additional role of the developed measuring instrument was to adjust a levels of measurement signals to the range accepted by the Advantech USB-4711A measuring card used. In addition, it was necessary to measure a parameter enabling a synchronization of recorded phase-to-phase voltages with an engine working cycle. The acceleration measured at the engine head in the injector needle's operating axis was considered to be an optimal parameter. It was assumed that measurements must be carried out with a sampling frequency of not less than 10 kHz (for each measurement channel). This frequency provides about 400 signal samples per revolution of an engine crankshaft at a typical (for DG) rotational speed of 1500 min^{-1}. The Advantech USB-4711A card with a resolution of 12 bit was used for the measurements. It allows measuring the voltage signal in the following ranges:

- ±10 V measurement accuracy is 0.00244 V,
- ±5 V measurement accuracy is 0.00122 V,
- ±2, measurement accuracy is 0.00061 V,
- ±1.25 measurement accuracy is 0.000305 V,
- ±0.625 V measurement accuracy is 0.000153 V.

The computer cooperating with the measuring card was used to acquire values of measured parameters.

3.3. The research data analysis

Regardless of the source (model or empirical study), the data was saved in a same format. This allowed to use a proprietary computer program for their processing. In addition, it ensured that an analysis of a research results will be carried out (regardless of whether the results will come from empirical or model studies) in the same way.

The first stage in the analysis of measurement data consists in use of so-called averaging synchronic [9]. The acceleration of an injector (Fig. 6) is registered with the reference signal in the averaging process.

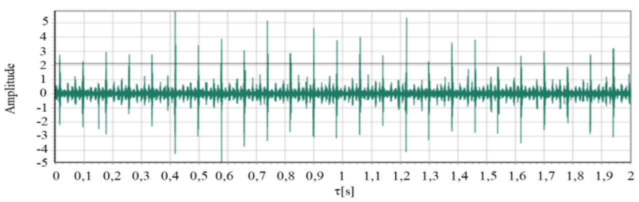

Fig. 6. The chart of accelerations measured in the axis of the injector needle

As a result of synchronous averaging of recorded phase-to-phase voltage waveforms, the waveforms corresponding to the engine cycle shown as a function of time were obtained (Fig. 7).

The next stage in the analysis of a measurement data was to obtain the plot considered to be a reference (corresponding to the work of the generator rotor with constant rotational speed). The course found to be a reference one was obtained by using a Fourier transform relative to the registered phase-to-phase voltage waveform. Subsequently, the output course was reconstructed on the basis of the inverse Fourier transform for a first harmonic. This is illustrated by dependence:

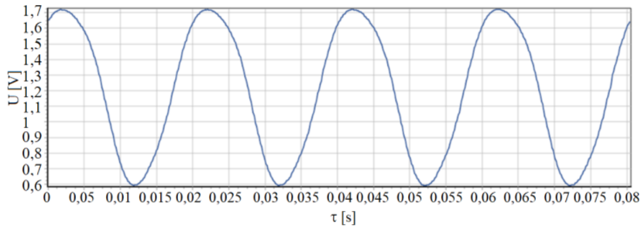

Fig. 7. Synchronous average of the generator phase-to-phase voltage as a function of time for one engine working cycle

$$a_1 = \frac{2}{T} \cdot \int_{-\frac{T}{2}}^{\frac{T}{2}} f(\tau) \cdot \cos\left(\frac{2 \cdot \pi}{T}\right) d\tau \qquad (1)$$

$$b_1 = \frac{2}{T} \cdot \int_{-\frac{T}{2}}^{\frac{T}{2}} f(\tau) \cdot \sin\left(\frac{2 \cdot \pi}{T}\right) d\tau \qquad (2)$$

$$U_{wz} = \frac{a_0}{2} + a_1 \cdot \cos\left(\frac{2 \cdot \pi}{T} \cdot \tau\right) + b_1 \cdot \sin\left(\frac{2 \cdot \pi}{T} \cdot \tau\right) \qquad (3)$$

The course of interfacial tension $L_{1\text{-}2}$ and the reference waveform as a function of time are shown in Fig. 8.

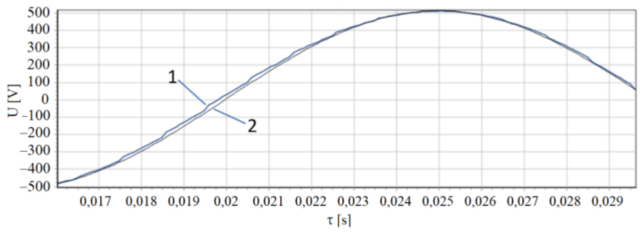

Fig. 8. A fragment of the registered phase-to-phase voltage waveform as a function of time: 1 – waveform obtained from measurements, 2 – reference waveform

The next stage of the analysis of the courses obtained as a result of empirical and model research was development of measures proportional to the value of an engine crankshaft angular velocity fluctuation. The decision was made that the most promising method would be to conduct time-domain analysis. It is based on a calculation (for each value of the ordinate of an average wave) of the difference between the time values for the runs of the synchronously averaged and the reference $\Delta\tau_i = \tau_{ave\,i} - \tau_{refi}$. The time difference can take both: positive and negative values. The value $\Delta\tau_i$ greater than zero means that for a given moment of time an angular velocity of a crankshaft is greater than an average for a working circuit. The negative difference indicates a lower value of an angular velocity of a crankshaft from an average for a working circuit. The applied method of data analysis is shown in Fig. 9.

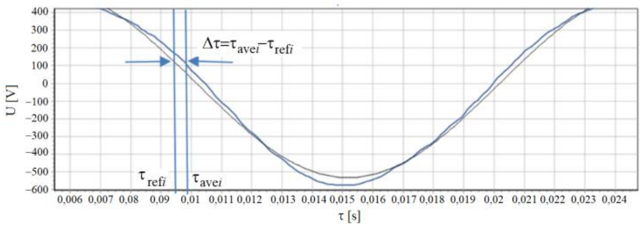

Fig. 9. A fragment of generator's phase-to-phase voltage with the method of calculating the time increment value

Analysing the voltage waveforms shown in Fig. 9, it can be seen that in a range of a largest amplitude values of a generator phase-to-phase voltage there may be areas for which it is not possible to meet the condition $U_{refi} \approx U_{avei}$. In this case, it was decided to take the value of the time difference $\Delta\tau_i$ as equal to „100" – a difference of this value does not occur during the research, so it could act as a marker.

By analysing the phase-to-phase voltage waveform as a function of time shown in Fig. 9, it can be observed that the time difference values are not linear with respect to the phase-to-phase voltage value and depend on a generator's phase-to-phase voltage. The largest values of time differences occur for a voltage value of 0 V. However, closer to the maximum and minimum voltage amplitude, these values decrease. To minimize an effect of nonlinearity, it was decided to use a proportionality factor described by the dependence:

$$wsp_\tau = \frac{a_0}{2} + a_1 \cdot \cos^2\left(\frac{2\cdot\pi}{T}\tau\right) + b_1 \cdot \sin^2\left(\frac{2\cdot\pi}{T}\tau\right) \quad (4)$$

where: a_1 – factor calculated from the equation 1, b_1 – factor calculated from the equation 2.

The calculated time differences $\Delta\tau_i$ have been multiplied by the proportionality coefficient wsp_τ (described by the dependence (4)). According to a described method, the time difference values for all three generator's phase-to-phase voltages were calculated. Then, for each moment of time, the arithmetic mean of the time difference values was determined (for all analyzed phase-to-phase voltage waveforms). In the case when the value of time difference for any of runs was indeterminate (the $\Delta\tau_i$ tag equals 100), the mean value from a smaller number of passes was determined for a given abscissa (time) value (the uncertainty values were omitted). An exemplary course of time differences as a function of time is shown in Fig. 10.

In addition, in Fig. 10, an areas corresponding to individual engine cylinders were determined, an influence of which was the highest on the engine speed fluctuation (from a cylinder opening of a given cylinder until a cylinder cylinder's next cylinder opening). Next, an area under a obtained time differences was calculated as a function of time within integration limits corresponding to an opening times injector of a given cylinder injector until the next cylinder injection opening (according to the order of cylinders).

$$Z = \int_{\tau_{owtr\ i}}^{\tau_{owtr\ i+1}} \Delta\tau(\tau)d\tau \quad (5)$$

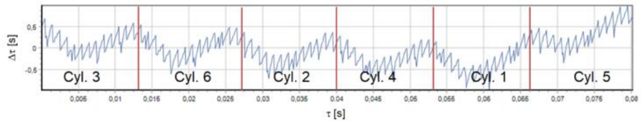

Fig. 10. The chart of time differences as a function of time for the engine with a damaged cylinder no. 1 (measurement of acceleration of the injector carried out on cylinder No. 3)

The values of a surface area under a plot of time differences as a function of time for individual damaged engine cylinders (Z measure values) are shown in Fig. 11.

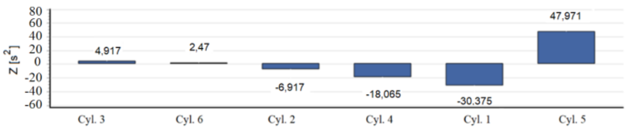

Fig. 11. Z measure as a function of time for individual engine cylinders for a damaged engine (disabling fuel supplying cylinder No. 1)

The proposed measure Z allowed to analyse a results of model and empirical research. The tests were carried out on a basis of the test plan proposed in section 3.1.

3.4. Research results

Conducted research [10] allowed to conclude that the developed mathematical model of a diesel-electric unit is not adequate in quantitative relation to the examined real objects. Whereas values of the Z measure calculated for the efficient and damaged cylinders in a case of model and empirical tests are convergent, which allows the model to be considered qualitatively adequate. Noteworthy is the fact that results of empirical research (Z measure) differ in a fundamental way. However, in a case of damaged engines, some regularities can be observed, which allowed to draw the following conclusions:

- For all simulated partial technical airworthiness states, in each case a value of the Z parameter calculated for a damaged engine cylinder is clearly smaller (this is evidenced by on a decrease of angular velocity of a crankshaft) from the other cylinders.
- All empirical research results are subject to significant errors resulting from the limitations of the measuring instrument used (optoisolation and low signal sampling frequency of 10 kHz).
- The significance of errors decreases with the increase of the engine load with the moment of resistance (increase of the generator load).
- Failure of any of a cylinder sections results in a significant change in a value of the Z measure both in an area of a damaged cylinder and other cylinders. Values of the damaged cylinders are always negative, while as a result of a work of an engine speed controller values of the other cylinders usually have values greater than those of an efficient engine.

When developing a method of assessing a technical condition of an engine, one had to find an unambiguous measure informing about the damage and identifying the damaged cylinder section. The process of technical condition evaluation was divided into two main stages:

- the first stage consisted in determining whether there is damage in the case of the tested DG,
- the second stage consisted in locating the damage occurring on an indication of a particular cylinder section.

In the first stage, it was decided to use a standard deviation value – σ calculated for the Z measures for each of engine's cylinders.

This step is based on observation made regarding a value of the standard deviation of the Z measure for the engine in various technical states. It was observed that in the case of a defective engine, standard deviation takes on a value higher than in the case of engine that is efficient for same loads. This is due to larger fluctuations in an angular velocity of a crankshaft of a damaged engine, which results in a greater spread of the Z value. The standard deviation values for engine cylinders in various technical conditions are shown in Table 3.

Table 3. List of values of standard deviations for various technical states of the engine

Technical state and load	Empirical research for DG no. 1			Model research
	1	2	3	[σ]
	[σ]	[σ]	[σ]	
Efficient – 2 kW	5.98	5.47	6.21	2.51
Off cyl. 1 – 2 kW	10.66	8.92	8.35	5.40
Off cyl. 6 – 2 kW	7.29	7.78	6.44	5.90
Off cyl. 1 and 6 – 2 kW	6.79	4.93	5.31	5.65
Efficient - 10 kW	8.90	8.74	7.23	0.72
Off cyl. 1 – 10 kW	15.05	11.59	15.26	11.46
Off cyl. 6 – 10 kW	13.68	16.14	11.77	11.90
Off cyl. 1 and 6 – 10 kW	11.03	10.38	10.54	10.72
Efficient – 20 kW	8.60	7.55	5.98	1.82
Off cyl. 1 – 20 kW	22.67	17.81	19.14	21.52
Off cyl. 6 – 20 kW	18.09	23.02	18.82	22.21
Off cyl. 1 and 6 – 20 kW	16.40	18.18	19.66	19.63

Based on value of standard deviation of the Z measure, it was possible to assess whether an engine was functional or damaged. At the same time, it can be observed that discrepancies in standard deviation values for a damaged engine increased as load of generator increased. It was considered that in a case of a generator loaded with 10 kW and 20 kW load power, standard deviation value of less than 10 means a motor for which no damage was introduced, while a deviation value greater than 10 indicates engine damage.

The second stage is based on observation that in a case of a damaged engine value of the Z measure for damaged cylinders is significantly greater than value of standard deviation. The value of standard deviation beyond range of standard deviation also exceeds a value of Z for undamaged cylinders, but absolute value of Z is less for them than those of damaged cylinders. The value of Z measure in the case of cylinders with a given damage (for one cylinder turned off) exceeds a value of product 1.5 σ in each case. However, in case of undamaged cylinders, in none of cases examined, value of adopted measure exceeded value of 1.5·σ. It was considered that measure allowing identification of a damaged single cylinder is whether any of the measures Z exceeds 1.5·σ. Exceeding it clearly shows that cylinder is turned off. Failure to meet this condition may indicate that there is no damage or damaged cylinders.

With information from first stage of the analysis (whether there is damage) and knowing if the measure Z exceeds value of one-and-a-half times standard deviation, it is possible to distinguish between engine that is efficient and a damaged cylinder with more than one cylinder. In a case of damage to a larger number of engine cylinders, unambiguous statement of which cylinder was damaged is possible. When conducting analysis, the standard deviation σ should be used to identify damaged cylinders, instead of product 1.5·σ. The proposed method of analysing technical condition of an engine is shown schematically in Fig. 12.

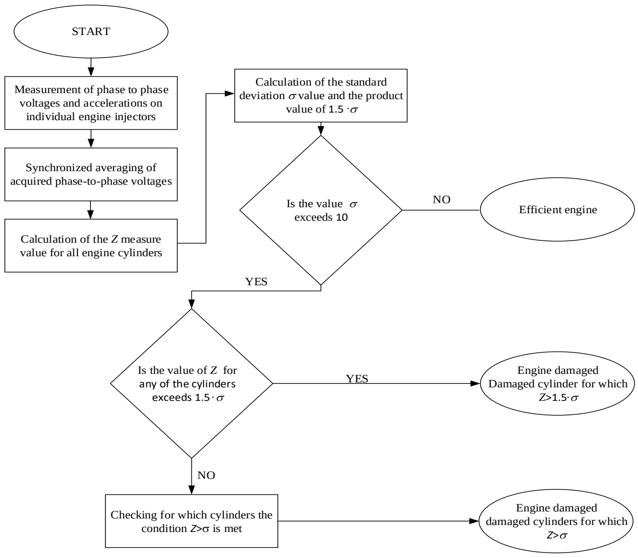

Fig. 12. An algorithm for assessment of technical condition of engine driving synchronous generator based on the phase-to-phase voltages

In addition to presented model and empirical tests, it was decided to carry out additional model tests for partial technical condition, impossible to implement on a real object. Limitations of empirical research resulted from necessity to interfere in the engine, which could potentially lead to its damage.

It was decided to carry out tests for various technical properties and for two loads of loads with a capacity of 10 kW and 20 kW respectively. The tests carried out for a full and partial technical condition were:

- reducing a dose of fuel supplied to cylinders by 10%, 20%, 30%, 40% and 50% in relation to nominal dose,
- reducing an injection advance angle by 5^{o}CA,
- increase of an injection advance angle by 5^{o}CA,
- introduction of a leak in the piston–cylinder–cylinder system of 5% of maximum cross-sectional area of a outlet valves,
- reducing a cross-sectional area of an injector holes by 10% and 20%,
- increase in cross-sectional area of an injector holes by 10% and 20%.

Based on the analysis of the data [10], the following conclusions can be made:

- Simulated partial technical health conditions consisting in reducing a fuel dose delivered to a damaged cylinder and a simulated leak in the TPC system can be detected and located using the developed method.

- Failure conditions consisting in changing an active cross-section of an injector holes and changing an injection advance angle for a damaged cylinder cause some deviations of the Z-measure value in relation to efficient engine. However, the values Z of these deviations are minimal, therefore these damages probably cannot be detected using proposed method.
- The inability to identify part of a damage may be caused by a need to adapt format of data recording from the computer program to a measuring instrument used. (The computer program simulates the measuring frequency of measuring instrument of 10 kHz for each channel, which gives about 800 samples per working cycle of the engine).

4. Summary

Despite the inclusion of a series of partial engine technical states in a diesel-electric unit model, in the case of empirical studies, it was decided to ask only one failure in the individual engine cylinders. It resulted from the inability to introduce modifications to test object due to risk of its damage. However, the study was conducted model for other states of partial technical suitability arguing that it should be possible to detect and identify damage involving:

- reducing a dose of fuel supplied to a cylinder by more than 20% of a nominal dose,
- change of injection timing,
- leaks in the piston-rings-cylinder system,
- changing an active cross-section of an injector holes.

The study proves that selected states of partial technical suitability of a diesel-electric unit's engines cause a deformation of voltage line of the generator's. As a result of conducted tests, control parameters were identified that allow for unambiguous identification of engine damage. The results of model and empirical studies carried out in the work showed that their continuation is justified. Further research should be mainly focused on:

- increasing the accuracy of generator phase voltage measurements, which can be achieved by:
  - increasing a sampling rate,
  - reducing a device's non-linearity,
  - increasing a resolution of a measuring instrument from 12 bits to at least 16 bits;
- conducting tests for other typical engine damages of a diesel-electric unit.

Nomenclature

a_0, a_1, b_1	Fourier ratio
i	iteration
L_{1-2}, L_{2-3}, L_{3-1}	applies to phase-to-phase voltages
owtr	applies to opening of the injector
T	period
U	electric voltage
Uśr	applies to synchronized average values
wsp	proportionality factor
wz	applies to the reference course
Z	measure describing the technical condition of the engine
σ	standard deviation
τ	time

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