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HIGH AND MEDIUM SPEED MARINE DIESEL ENGINES INJECTION INSTALLATION VIBRATION DIAGNOSTICS

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Abstract
In recent years, diagnostics of marine reciprocating engines devote more and more attention. In principle, all methods for the diagnostics of marine engines can be divided into based on the measurement of work parameters (mostly changes in internal cylinder pressure), and measuring the residual energy. For this study the authors focused on the measurement of vibration parameters and their analyzes. Acceleration of vibration measurements was carried out on the engine head. During the tests, fatigues to the injection installation were simulated, it had affected to the value and the course of the gas pressure inside the cylinders. The results of research proving the usefulness of the proposed method.

Keywords: piston engines, marine engines, injection installation, vibration diagnostics

DIAGNOSTYKA DRGANIOWA INSTALACJI WTRYSKOWEJ SZYBKO
I ŚREDNIOOBROTOWYCH OKRĘTOWYCH SILNIKÓW SPALINOWYCH

Streszczenie
W ostatnich latach zagadnieniu diagnostyki okrętowych tłokowych silników spalinowych poświęca się coraz więcej uwagi. Zasadniczo wszystkie metody diagnostyczne dotyczące tych urządzeń można podzielić na bazujące na pomiarach procesów roboczych (głownie zmian ciśnienia wewnątrz cylindrowego) oraz na pomiarowych procesów resztkowych. W przypadku niniejszego opracowania autorzy skupili się na pomiarach parametrów drganiowych i ich analizie. Pomiary przyspieszeń drgań realizowano na głowicy silników. W trakcie badań symulowano uszkodzenie aparatury paliwowej mające wpływ na wartość oraz przebieg ciśnienia wewnątrz cylindrowego. Przedstawiono wyniki badań dowodzące użyteczności przyjętej metody.

Słowa kluczowe: silniki tłokowe, silniki okrętowe, instalacja wtryskowa, diagnostyka drganiowa

1. INTRODUCTION

The main components forcing engine vibrations associated with its proper work are:

- shock pulse related to the working injectors, intake and exhaust valves;
- operation of the crankshaft mechanism, including piston slaps and the inertia forces of components performing a reciprocating motion transmitted to the engine frame by a bearing system;
- the rapid increase of gas pressure value coming from the combustion of a fuel and air mixture.

There are much more spectral components of the marine engine vibrations however, from energetic point of view these should be considered as the most important. In the next paragraphs authors had focused on issues related to the injection installation understood as installation assembled of: injection pump - high pressure pipe - injector.

As a result of fatigues to components of fuel injection installation ie. injection pumps and injectors, comes to disorders of the combustion process. Most often it causes a reduction in the maximum combustion pressure. Due to the fact that cylinder head closing upper part of the combustion chamber and is attached to the block by stud bolts so registered on them vibration waveforms have to give information about inside cylinder pressure. There were many attempts to determine the value of this pressure using vibration signal [1, 2, 5, 16], however from the point of view of a clear mathematical description this case appears to be very complicated. Authors focused on the estimation of qualitative parameters of vibration to determine changes of the inside cylinder pressure without making efforts to determine its specific value. This approach should allow for non-invasive detection of fatigue to the engine fuel injection installation without the need for measuring the inside cylinder pressure.

It should be noted that in multi-cylinder engines effect of adjacent cylinders to the recorded vibration parameters are very large. In most cases there is a disturbance of the vibration recorded on the cylinder working with fatigue injection installation by the other proper working cylinders. In order to prevent this phenomenon authors proposed an implementation of the analysis in crank angle domain.

2. CRANKSHAFT ANGLE DOMAIN VIBRATION ANALYSIS

Analysis of the piston machines vibration parameters as a function of crankshaft angle is not a new issue. Most attention is paid to it in the following papers [3,4,6,7,8,9,10,11,12,13,15]. J. Antoni in [1,2] proposes to treat the engine vibration signal as a cyclostationary process. It means that signal is stationary in the crankshaft angle domain.

There are two basic approaches to the diagnostics of reciprocating machines vibration in crank angle domain. First presented in [1,2] impose sampling of measured signal with a constant angular step. A key advantage of this approach is that the same cycle length is always obtained (eg. for the four stroke engine $4\pi = 720^o$). However, this requires the use of a rotational speed measurement encoder to track unevenness of engine speed during a single cycle.

Encoders are relatively soft devices and in hard marine environment difficult to apply. For this reason, authors had decided to use the classical sample with a constant time step. The resulting signal is then subjected to post-processing stage. It is divided into fragments corresponding to approximately individual engine strokes. Signal pieces obtained in such way are subjected to Fast Fourier Transformation. As a result the amplitude-frequency spectra of engine head acceleration during individual strokes had been obtained.

3. VERYFICATION ON ONE CYLINDER ENGINE

Verification of usefulness of the proposed method had been started from the initial measurements on the one cylinder diesel engine. The object of the tests was the Kipor 170F engine type, which at the time of measurement worked without any load. For the measurements of vibrations, the acceleration sensor with magnetic base had been used. It had been attached to head cover screw. Also rotational speed of the engine was recorded using optical speed sensor – fig 1.
Recorded during the measurements time waveforms were analyzed using the idea presented on fig. 2.
Figure 2 presents the time waveform corresponding to one operating cycle of four-stroke engine. On the time signal sampled at a frequency of 8192 Hz signal coming from the speed sensor giving one pulse per revolution was applied – blue line on fig. 2. On the course, which has not been filtrated, only amplitude increases corresponding to the fuel injection and the subsequent combustion are visible. However if the marker for measuring rotational speed corresponds to the piston top dead point (TDC), it is possible to divide the time course into fragments corresponding to each stroke of the engine. The proposed allocation of time course does not coincide exactly with the different strokes. It overtakes them with a 0.1 revolution. The aim of such approach is to capture the essential information such as opening and closing of the injector. The spectra obtained from divided time waveform of acceleration signal are shown in Figures 3-6.

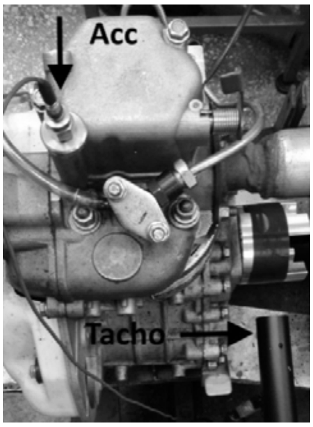

Fig. 1. Lay out of measuring instruments on the Kipor 170 f engine.

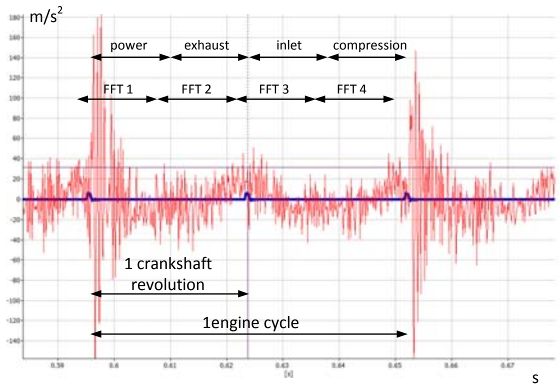

Fig. 2. Time waveform fragment obtained from Kipor 170F engine working with rotational speed of 2100 rev/min

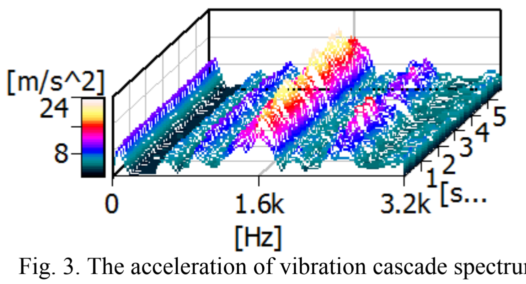

Fig. 3. The acceleration of vibration cascade spectrum approximately corresponding to power stroke.

Analyzing spectra presented in figures 3-6, differences in the distribution of maximum amplitudes and the corresponding frequencies are clearly visible. They are changing depend on the examine engine stroke. In the power stroke the maximum acceleration values of vibrations occur at a frequency of about 1.6 kHz, and the amplitude reaches 20 m/s^2. The stroke of exhaust and inlet greatest amplitudes occur at a frequency of about

2.4 kHz, but they do not exceed a value of 7 m/s^2. In the inlet stroke they are also significantly higher amplitude in the band of about 1 kHz. In the compression stroke as in the power stroke amplitudes reaches the highest value at frequency of about 1.6 kHz, but they do not exceed 10 m/s^2.

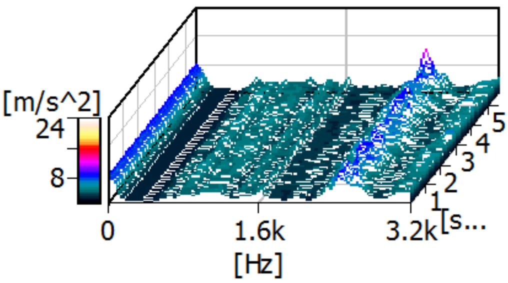

Fig. 4. The acceleration of vibration cascade spectrum approximately corresponding to exhaust stroke.

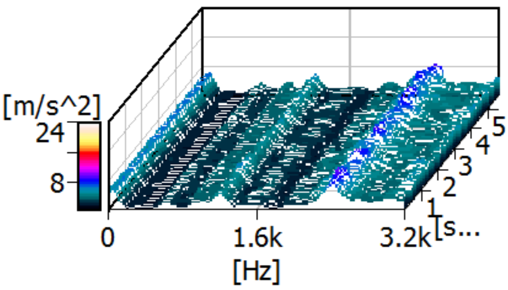

Fig. 5. The acceleration of vibration cascade spectrum approximately corresponding to inlet stroke.

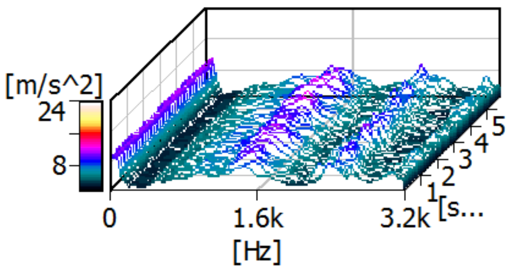

Fig. 6. The acceleration of vibration cascade spectrum approximately corresponding to compression stroke.

Preliminary analyzes demonstrate the usefulness of the proposed method and the results obtained have its own features different from the other engine strokes. The dominant values of the amplitudes occurs as predicted during power stroke. This is further illustrated in figure 7.

On the presented in figure 7 amplitude-frequency spectra components corresponding to accelerations of vibrations registered in the power stroke are clearly predominant - color green.

4. MEASUREMENTS RESULTS RECORDED ON THE MULTI-CYLINDER ENGINES

The next stage of measurements were tests on two marine six-cylinder inline diesel piston engines. Both tested engines are turbocharged four-stroke engines cooperating with the water brakes. It enables simulation of engine cooperation with marine propeller. During the measurements of acceleration sampling rate of 65536 Hz were used. The signals were recorded on the cylinder head stud bolt and head cover bolt. Sensors lay out on the Sulzer 6AL20 /24 engine is shown in Figure 8.

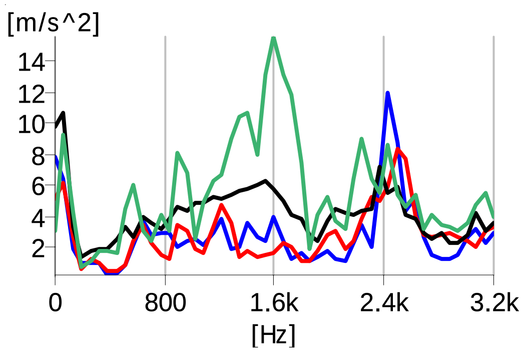

Fig. 7. Selected amplitude-frequency courses corresponding to approximately individual engine strokes: green - power stroke, blue - exhaust stroke, red - inlet stroke, black – compression stroke.

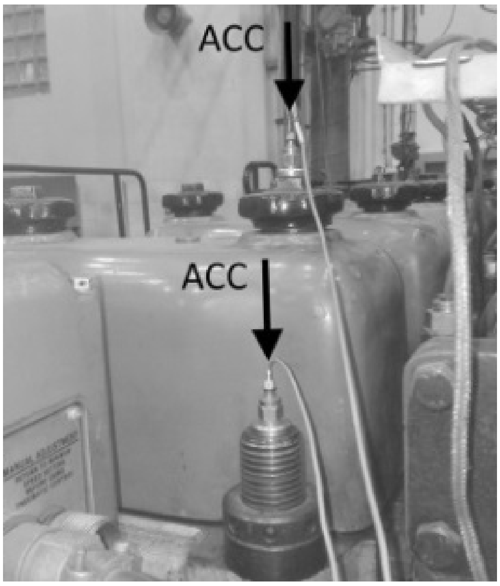

Fig. 8. Arrangement of the sensors during measurements of vibration on Sulzer 6AL 20/24 engine.

The first stage of measurements was carried out on fully efficient engine running with the efficient fuel injection installation. Condition of the engine was confirmed by earlier measurements of inside gas cylinder pressure. The second stage of the research was to simulate fatigue to the injection installation by reducing the discharge pressure injection pump. This resulted (at the same load on the engine torque) by the reduction of the maximum combustion pressure in the cylinder 6 from 8.071 MPa to 6.1 MPa. Unchanged resultant torque is connected with the increase of the maximum combustion pressure in the residual, efficient cylinders. Both series of measurements were conducted for the same rotational speed of 750 rev/min and the same engine load. Measurements were synchronized by speed marker corresponding to the TDC of cylinders 1 and 6. In the following part of paper only comparison of acceleration of vibration cascade spectra corresponding to power stroke were presented.

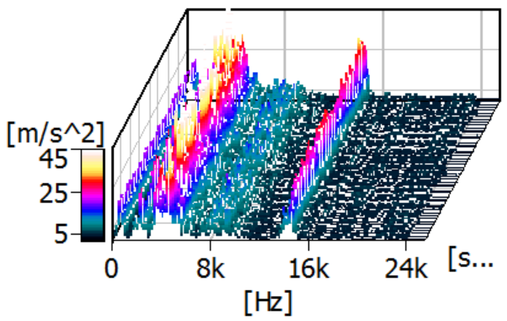

Fig. 9. The acceleration of vibration cascade spectrum obtained from cylinder 6 for power stroke with fully efficient injection installation of Sulzer engine loaded by torque 1.8 kNm.

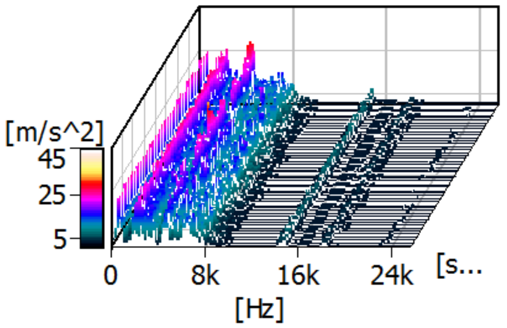

Fig. 10. The acceleration of vibration cascade spectrum obtained from cylinder 6 for power stroke with simulated defect of fuel injection installation of Sulzer engine loaded by torque 1.8 kNm.

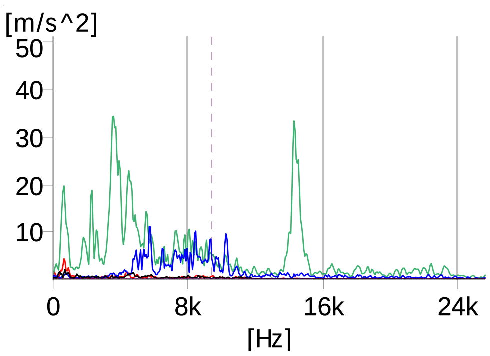

Fig. 11. The acceleration of vibration amplitude-frequency spectra obtained from cylinder 6 corresponding to approximately individual engine strokes with fully efficient injection installation of Sulzer engine loaded by torque 1.8 kNm. Green - power stroke, blue - exhaust stroke, red - inlet stroke, black – compression stroke.

Analysis of spectra presented on Figures 9 to 12 indicates that, in the case of engine fuel injection installation damage, eg. injection pump defect what causes a decrease in the maximum combustion pressure, gives a significant change in the amplitude-frequency spectrum. Presented charts are representing approximately the power stroke.

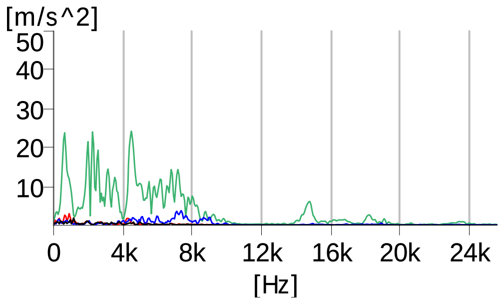

Fig. 12. The acceleration of vibration amplitude-frequency spectra obtained from cylinder 6 corresponding to approximately individual engine strokes with simulated defect of fuel injection installation (cylinder 6) of Sulzer engine loaded by torque 1.8 kNm. Green - power stroke, blue - exhaust stroke, red - inlet stroke, black – compression stroke.

Changes apply to the reduction of the maximum amplitude of the vibration acceleration values of up to 35 m/s^2 for fully efficient engine, to 24 m/s^2 for engine with a simulated failures of fuel injection installation. Concerning the signals recorded on the remaining efficient cylinders their maximum values after simulated damage had slightly increased, as illustrated in Figures 13 and 14.

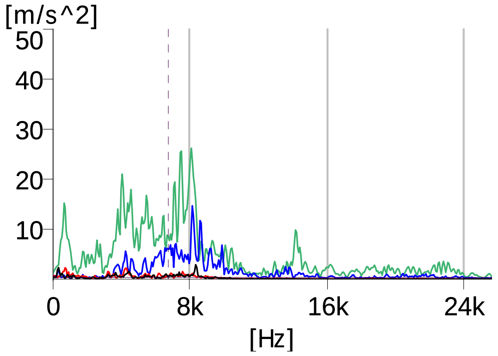

Fig. 13. The acceleration of vibration amplitude-frequency spectra obtained from cylinder 1 corresponding to approximately individual engine strokes with fully efficient injection installation of Sulzer engine loaded by torque 1.8 kNm. Green - power stroke, blue - exhaust stroke, red - inlet stroke, black – compression stroke.

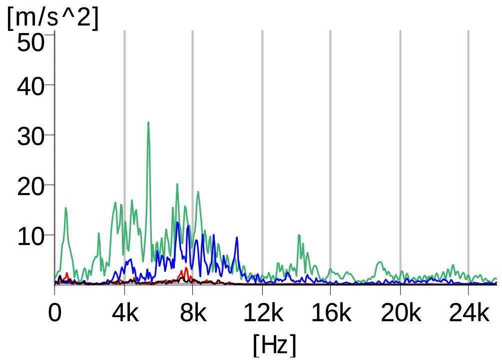

Fig. 14. The acceleration of vibration amplitude-frequency spectra obtained from cylinder 1 corresponding to approximately individual engine strokes with simulated defect of fuel injection installation (cylinder 6) of Sulzer engine loaded by torque 1.8 kNm. Green - power stroke, blue - exhaust stroke, red - inlet stroke, black – compression stroke.

Observable increase in the amplitude of vibration acceleration in the case of the cylinder, which is not working with simulated damage is a quite normal phenomenon. This results from the takeover of engine load by efficient cylinders in situation of constant load and failure of some other cylinders. Speed controller in case of defect have to ensure constant rotational speed of the crankshaft so increases the amount of fuel to all cylinders.

Another object of the researches was the Wola - Henschel 52H6Aa engine with nominal power of 155 kW. Measurements were carried out at engine nominal speed of 1500 rev/min, and for three different loads. As in the previous tests, measurements were divided into two stages. Measurement of engine with an fully efficient fuel injection installation (because the engine does not have indication valves determination of engine technical condition had based on checking the injection pressure of all injectors and measuring the temperature of exhaust gas from each cylinder), and the engine working with simulated fatigue to the fuel injection installation. Damage was simulated by changing the injection pressure on injector in sixth cylinder. Injection fuel pressure was reduced from 18 MPa to 15 MPa. This resulted in increased exhaust gas temperature by 40° K compared to other efficient cylinders. Examples of amplitude-frequency spectrum corresponding to the engine torque load 150 Nm were presented below: fig 15-18.

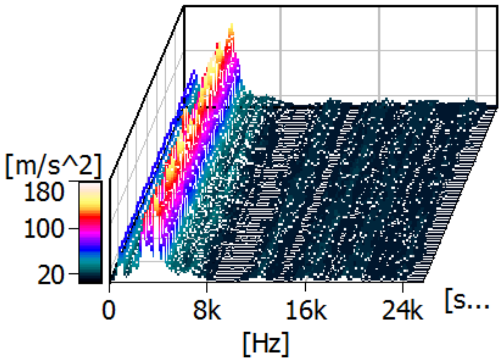

Fig. 15. The acceleration of vibration cascade spectrum obtained from cylinder 6 for power stroke with fully efficient injection installation of WOLA 52H6 engine loaded by torque 150 Nm.

In the case of an engine WOLA 52 H6 after a simulated failure of the fuel injection installation significant changes in the acceleration of vibration amplitude corresponding to power stroke are clearly visible. The frequency of their occurrence are not changed.

Despite the promising results of the proposed method it has one major drawback. Due to the fact that very short fragments of time waveforms are taken for spectral analysis using a Fast Fourier Transform algorithm, frequency resolution is very low. For example in the presented case it is 128 Hz.

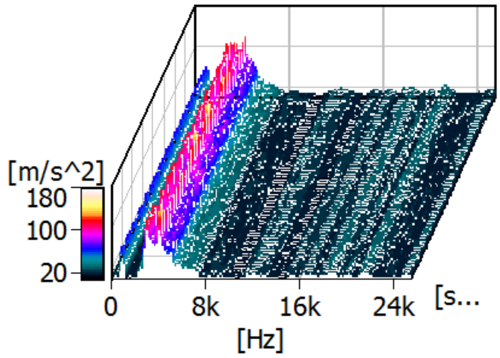

Fig. 16. The acceleration of vibration cascade spectrum obtained from cylinder 6 for power stroke with simulated fault of injector WOLA 52H6 engine loaded by torque 150 Nm.

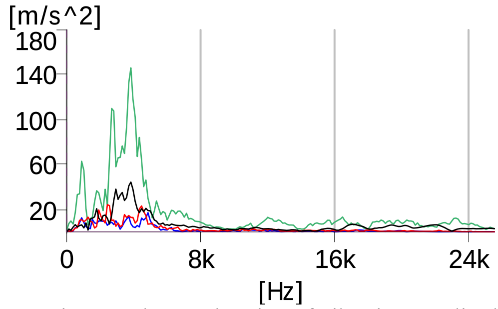

Fig. 17. The acceleration of vibration amplitude-frequency spectra obtained from cylinder 6 corresponding to approximately individual engine strokes with fully efficient injection installation of WOLA 52H6 engine loaded by torque 150 Nm. Green - power stroke, blue - exhaust stroke, red - inlet stroke, black – compression stroke.

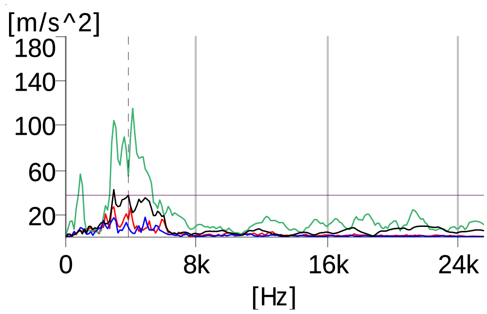

Fig. 18. The acceleration of vibration amplitude-frequency spectra obtained from cylinder 6 corresponding to approximately individual engine strokes with simulated defect of injector (cylinder 6) WOLA 52H6 engine loaded by torque 150 Nm. Green - power stroke, blue - exhaust stroke, red - inlet stroke, black – compression stroke.

In order to obtain a higher frequency resolution longer period of time must be defined. In such situation measurement, will not stop before the end of each stroke. In such case, the spectrum will be averaged for the entire engine cycle. As a result, the most important from diagnostic point of view processes taking place at the end of the compression stroke and the beginning of the power stroke will be masked by the remaining strokes. Additionally they are also be masked by signals from the neighboring cylinders. This does not diminish in any way the usefulness of proposed approach for the diagnosis of marine diesel engines.

5. CONCLUSIONS

The presented method of marine reciprocating engines vibration signals analysis provides opportunities for qualitative assessment of technical condition of fuel injection installation. The method, despite its undeniable advantages which is highly sensitive to changes in the processes taking place during the fuel injection and the subsequent combustion is also characterized by its fundamental drawback. It is low frequency resolution. In order to confirm full usefulness of presented method it is necessary to perform a number of additional measurements on board of ships. Control of fuel injection installation technical state will only be possible if amplitude-frequency characteristics of the good working engine are enable. Acceleration of vibration comparative analysis under the same loads and speeds of tested engines must be carried out. In order to obtain higher frequency resolution authors during their further work are planning to use measuring equipment enabling high oversampling of recorded vibration time waveforms.

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