Analyzing vibration parameters of a modern high-speed engine during operation

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Abstract. The paper presents results of experimental research into vibration parameters of a modern electronic control-enabled main high-speed engine, Caterpillar CAT 3516B as obtained during a running trial of a sea tug. CAT 3500 series Caterpillar high-speed engines are extensively used in sea tugs; there are about 40 units installed in vessels operating in the Azov and Black Sea region. The research technique involved measurement of vibration displacement, vibration velocity, vibration acceleration at an engine and its turbocharger components. The conducted experimental research has shown that in order to evaluate the technical state of an engine, it is necessary to measure vibration displacement and vibration velocity in a frequency range from 1 to 1000 Hz at 0.1 Hz intervals. For turbochargers, the vibration acceleration shall be measured in a frequency range from 1 to 15000 Hz at 1 Hz intervals. The results of the experimental research allowed determining necessary conditions for measurement of vibration parameters of Caterpillar CAT-3500 series modern high-speed engines commonly used in sea tugs. The experimental research into vessel installations by in-place diagnostics at operating sea-going vessels forms a foundation of an autonomous ship control system.

1 Introduction
Currently, sea tugs commonly employ high-speed engines as main engines. Many scientific works are dedicated to management systems and methods aimed at operation of vessel installations and their components [1-8].

One of the main operating mode of sea tug main engines is a running mode used when a vessel goes from the port and gathers speed. Rotation speed of the engine during the running mode varies in a range from 1000 to 1500 min⁻¹. In order to evaluate and monitor the technical condition of the engine, an experimental research was conducted into vibration parameters of a modern high-speed engine CAT 3516B (Caterpillar), power 1500 kW with a portable instrument VIBXPERT II. Vibration measurement results were processed and dependences were constructed with the VIBXPERT OMNITREND software.

2 Subjects of research
The subject of experimental research is the modern high-speed main engine with a turbocharger used at sea tugs. The main operating modes of the main engine are a mooring mode and a running mode. Turbo compressors with a POC turbine are used as chargers.
Due to that, experimental studies were conducted in the running mode under the following conditions:

- a vessel leaves the port, gathers a set speed (running mode);
- the main engine is a high-speed engine Caterpillar CAT 3516B;
- rotational velocity of the engine crankshaft in the running mode varies between 1000 and 1500 min\(^{-1}\);
- ABB turbocharger with a centrifugal turbine;
- the time of each measurement is 15 minutes at already set engine operating mode;
- vibration studies were conducted with local diagnostics means: VIBXPER OMNITREND software using a portable instrument VIBXPERT II.

3 Experimental technique

Experimental research was conducted for diesel engine and turbocharger. Vibration transmitters were put simultaneously in the vertical direction at the engine body and at the topmost point of the turbocharger body (Figure 1). The following values were taken as criteria for evaluation of vibration and monitoring of technical conditions during the experimental study of the diesel engine and turbocharger: displacement \(S_{r.m.s.} \text{ \mu m}\); velocity \(v_{r.m.s.} \text{ mm/s}\); acceleration \(a_{r.m.s} \text{ m/s}^2\), measured in a wide range of frequencies.

4 Experimental results

As an example, Figures 2 and 3 present spectra of vibration acceleration and vibration velocity of the Caterpillar CAT 3516B high-speed engine and its turbocharger at a rotation speed of 1000 min\(^{-1}\). From Figures 2 and 3 it is evident that

- the vibration speed spectrum is informative over a frequency range of up to 5000 Hz;
- the vibration acceleration spectrum is informative over a wider range of frequencies.
It seems that analysis of high-speed engine vibration spectrum would benefit from using vibration displacement and vibration speed at low frequencies, while turbocharger needs measuring vibration acceleration at high frequencies.

Table 1 shows examples of the high-speed engine and turbocharger vibration in different operating modes.

![Figure 2. Vibration parameters of the turbocharger on Caterpillar CAT 3516B high-speed engine measured over a frequency range from 1 to 25000 Hz for a rotation speed of 1000 min⁻¹: a) vibration acceleration; b) vibration speed.](image-url)
Figure 3. Vibration parameters of the Caterpillar CAT 3516B high-speed engine measured over a frequency range from 1 to 25000 Hz for a rotation speed of 1000 min⁻¹: a) vibration acceleration; b) vibration speed.

Table 1. Vibration parameters of the Caterpillar CAT 3516B high-speed engine measured over a frequency range from 1 to 25000 Hz.

| RPM  | Engine a_{\text{rms}}, mm/s² | Engine v_{\text{rms}}, mm/s | Engine S_{\text{rms}}, µm | Turbocharger a_{\text{rms}}, mm/s² | Turbocharger v_{\text{rms}}, mm/s | Turbocharger S_{\text{rms}}, µm |
|------|-----------------------------|-----------------------------|--------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| 1000 | 11.26                       | 5.3                         | 25.12                    | 19.63                             | 3.37                              | 7.75                              |
| 1300 | 9.37                        | 6.68                        | 26.33                    | 17.98                             | 3.26                              | 18                                |
| 1500 | 7.55                        | 3.67                        | 18.23                    | 16.9                              | 2.8                               | 5.12                              |
From the results shown in Table 1, a graph of vibration parameters was constructed for the Caterpillar CAT 3516B high-speed engine, this graph is shown in Figure 4.

Figure 4. Vibration acceleration and vibration speed as a function of rotation speed of the Caterpillar CAT 3516B main engine.

Figure 5 presents vibration spectra of the turbocharger installed on the Caterpillar CAT 3516B high-speed engine for various rotation speeds. From Figure 5 it is evident that in a frequency band from 700 to 1100 Hz there are 2 peaks in all the operating modes of the engine (1000, 1300 and 1500 min⁻¹), which change only the vibration acceleration value. From Figure 5b we may see that the vibration accelerations at these peaks are 4.4 mm/s² and 720 Hz and 4.2 mm/s² at 1100 Hz, much higher than in other operating modes of the diesel engine. From Figure 5c we may see that in the engine operating mode of 1500 min⁻¹, the value of the vibration acceleration at a frequency of 720 Hz decreased.
Figure 5. Vibration spectra of the turbocharger installed on the Caterpillar CAT 3516B high-speed engine at various engine rotation speeds: a) 1000 min\(^{-1}\); b) 1300 min\(^{-1}\); c) 1500 min\(^{-1}\).

5 Experimental results
The following conclusions may be made from the research conducted and results obtained:

1 In order to evaluate and monitor the technical condition of a high-speed engine and its turbocharger for their vibration parameters it is necessary:
   - to measure vibration displacement and vibration speed over a frequency range from 1 to 1000 Hz at a 0.1 Hz increment for the diesel engine;
   - to measure vibration acceleration over a frequency range from 1 to 15000 Hz at a 1 Hz increment.

2 Currently existing regulations for turbocharger vibrations [9,10] do not reflect characteristics and design features of modern turbochargers, where depending on the engine operating mode, a rotation speed may vary between 25000 min\(^{-1}\) and 60000 min\(^{-1}\).

The conducted experimental research allowed determining necessary conditions for measurement of vibration parameters of modern turbochargers and high-speed engines produced by Caterpillar and commonly used in sea tugs [9,11,12].
Unique data obtained for indirect assessment of technical condition of electronically controlled Caterpillar high-speed engines will allow applying this experience to remote control systems to be installed at new autonomous ships.

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