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VIBRATION DIAGNOSTICS OF THE NAVAL PROPULSION SYSTEMS

ABSTRACT

The paper presents examples of vibration performances of the naval propulsion systems. It describes the methodology of preparation for measurement, used gauges and their restrictions. The necessity of synchronous measurements had been justified. The work contains also samples of analysis, to facilitate the reader with the components of amplitude-frequency spectra of naval propulsion systems. An overview of the existing normative documents had been presented. At the same time limitations of applying of them during technical monitoring of marine propulsion systems had been presented.

Key words:
propulsion system, shaft lines, vibrations, warships.

INTRODUCTION

Variations of technical state of the machine may occur as change of one or more operating parameters hence multi symptom technical diagnostics is currently the most useful tool in machine diagnostics. Among the parameters that describe the dynamics of machine, the vibration signal is important and sensitive. It characterizes the residual processes of working machines. All working machines, including in good technical state, emits vibrations. In most cases (but not always e.g. vibrations caused by fluid flow), these vibrations can be linked to cyclical phenomena occurring in the machine, e.g. a rotating shaft, meshing gear teeth or the frequency of the power supply in case of electrical machines. Typically, linking the value of the amplitude with its

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frequency source gives us evidence to indicate the cause of the increased vibroactivity. This makes vibration diagnostics very useful tool for rapid and accurate assessment of the technical condition of the machine. Vibration diagnostics compared to other methods of technical diagnostics of machines has a major advantage, namely in the case of continuous measurements responds immediately to changes in the technical condition of the machine had been tested. It is due to the fact that the change of technical state immediately changes the machine vibration spectrum. Furthermore, using appropriate tools of signal processing it is possible to extract symptom or symptoms of damage in a very, early stage and tracking its development. It is especially useful when machines are operated according to their current technical condition. This approach is the most economical and is gaining admission among the personnel in charge of operating the equipment. The essential advantage of systems based on continuous measurement of vibrations parameters is immediate detection of changes in these parameters. It allows to capture defects that are impossible to predict. It is also important that such a system after exceeding certain thresholds by the machine might be an emergency stopped. Unfortunately, installation of such systems is a significant expense of the overall cost of installation and operation. Furthermore, due to the large amount of data, on-line systems basing on measurements with a lower sampling frequency and simpler analysis of the recorded signals. Therefore, it often happens that desktop systems are supplemented by periodic measurements using portable systems. The biggest advantage of systems based on periodic measurement of vibration is their much lower cost. It should be emphasized that when properly selected in subsequent periods the measurement method is also characterized by a high level of adequacy [2–5, 8]. The most difficult cases from the point of view of the diagnostician are cases when the user reports the need for measurements when the machine is already in a bad technical state and there are no previous measurements. Diagnostician being unable to refer to past results of measurements had to used only his knowledge and experience. Many researches of such cases were conducted in PNA they could be found in [9–11]. The reference of the obtained results to the vibration standards, unfortunately, does not give the possibility to indicate the cause of damage. It is only an indication that from the normative point of view, further operation of the device is not permitted.

OVERVIEW OF BINDING STANDARDS

All standards dealing with measurements of vibration parameters are agreed with the minimum requirements of the measurement equipment, methods of mounting the sensors as well as their mutual position. In most cases the requirements are similar to the deployment of sensors on diagnosed machines.

Responsible for development of international standards related to the vibration diagnosis is the Vibration Committee ISO/TC 108/SC 2, *Measurement and evaluation of mechanical vibration and shock as applied to machines, vehicles and structures*.

Unfortunately, not all of international standards (ISO series) related to discussed problems have counterparts in the Polish regulatory documents. The exception here is the standard ISO-10816-1:1998, *Mechanical vibration — evaluation of machine vibration by measurements on non-rotating parts*). The limit values listed in this standard for individual states shows table 1.

Tab. 1. Values of the amplitude of the vibration speed by PN ISO 10816-1:1998 [14]

<table>
<tr><td colspan="2" rowspan="2">Value of v_{RMS} in $m/s \cdot 10^{-3}$
range: 2–1000 Hz</td><td colspan="4">Grup</td></tr>
<tr><td rowspan="2">I</td><td rowspan="2">II</td><td rowspan="2">III</td><td rowspan="2">IV</td></tr>
<tr><td>exceds</td><td>up to</td></tr>
<tr><td></td><td>0.71</td><td>A</td><td rowspan="2">A</td><td rowspan="3">A</td><td rowspan="4">A</td></tr>
<tr><td>0.71</td><td>1.12</td><td rowspan="2">B</td></tr>
<tr><td>1.12</td><td>1.8</td><td rowspan="2">B</td></tr>
<tr><td>1.8</td><td>2.8</td><td rowspan="2">C</td><td rowspan="2">B</td></tr>
<tr><td>2.8</td><td>4.5</td><td rowspan="2">C</td><td rowspan="2">B</td></tr>
<tr><td>4.5</td><td>7.1</td><td rowspan="4">D</td><td rowspan="2">C</td></tr>
<tr><td>7.1</td><td>11.2</td><td rowspan="3">D</td><td rowspan="2">C</td></tr>
<tr><td>11.2</td><td>18</td><td rowspan="2">D</td></tr>
<tr><td>18</td><td></td><td>D</td></tr>
</table>

A — good condition,
B — satisfactory,
C — still permitted,
D — unacceptable.

From the series 10816 it must be mentioned the ISO 10816-6:1995, *Mechanical vibration — evaluation of machine vibration by measurements on non-rotating parts,* Part 6, *Reciprocating machines with power ratings above 100 kW*.

Classification of machines to the corresponding zones (A–D) is performed after determining the level of one of the parameters of vibration in the frequency range from 10 Hz to 1 kHz. The content standards are not given guidelines on the qualifications of machines to individual groups (1 to 7). Any specific qualifications should be introduced after consultation with the user. Figure 1 shows the recommended placement of measuring points on the reciprocating machines in accordance with ISO 10816 series.

Tab. 2. The values for vibration on the basis of ISO 10816-6:1995 [6]

<table>
<tr><th rowspan="3">Degree o severity</th><th colspan="3">Maximum value</th><th colspan="7">Machine grup</th></tr>
<tr><th rowspan="2">displacement µm</th><th rowspan="2">Speed mm/s</th><th rowspan="2">acceleration mm/s²</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th></tr>
<tr><th colspan="7">Zones</th></tr>
<tr><td>1.1</td><td>17.8</td><td>1.12</td><td>1.76</td><td rowspan="4">A/B</td><td rowspan="5">A/B</td><td rowspan="6">A/B</td><td rowspan="7">A/B</td><td rowspan="8">A/B</td><td rowspan="9">A/B</td><td rowspan="10">A/B</td></tr>
<tr><td>1.8</td><td>28.3</td><td>1.78</td><td>2.79</td></tr>
<tr><td>2.8</td><td>44.8</td><td>2.82</td><td>4.42</td></tr>
<tr><td>4.5</td><td>71.0</td><td>4.46</td><td>7.01</td></tr>
<tr><td>7.1</td><td>113</td><td>7.07</td><td>11.1</td><td>C</td></tr>
<tr><td>11</td><td>176</td><td>11.2</td><td>17.6</td><td rowspan="7">D</td><td>C</td></tr>
<tr><td>18</td><td>283</td><td>17.8</td><td>27.9</td><td rowspan="6">D</td><td>C</td></tr>
<tr><td>28</td><td>448</td><td>28.2</td><td>44.2</td><td rowspan="5">D</td><td>C</td></tr>
<tr><td>45</td><td>710</td><td>44.6</td><td>70.1</td><td rowspan="4">D</td><td>C</td></tr>
<tr><td>71</td><td>1125</td><td>70.7</td><td>111</td><td rowspan="3">D</td><td>C</td></tr>
<tr><td>112</td><td>1784</td><td>112</td><td>176</td><td rowspan="2">D</td><td>C</td></tr>
<tr><td>180</td><td></td><td></td><td></td><td>D</td></tr>
</table>

A — new machines,
B — machinery in which vibration is not interfering in long-term operation,
C — machinery where the vibration level exceeds the limit, but they can be conditionally operated until the time of repair,
D — machines which are so intense vibration that their continued operation would lead to their destruction.

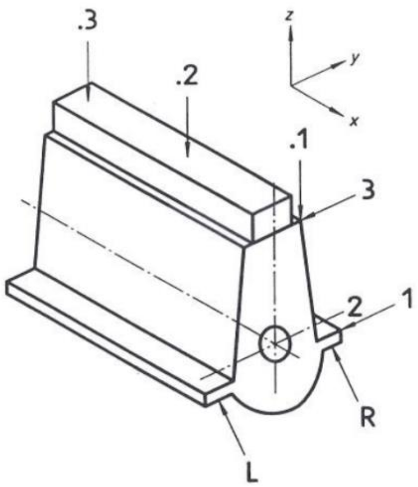

Fig. 1. An example arrangement of measurement points on the piston machine based on ISO 10816-6:1995 [6]

ISO 20283 series of standards (2–5) treat directly with measurements on vessels. As an example, the authors gives ISO 20283-2: 2008, *Mechanical vibration — measurement of vibration on ships,* Part 2, *Measurement of structural vibration*. It presents general information concerning the measurement as well as the requirements to be met by a measurement report. The most important element of the standard is definition of specific measurement points located on the superstructure and in the engine room.

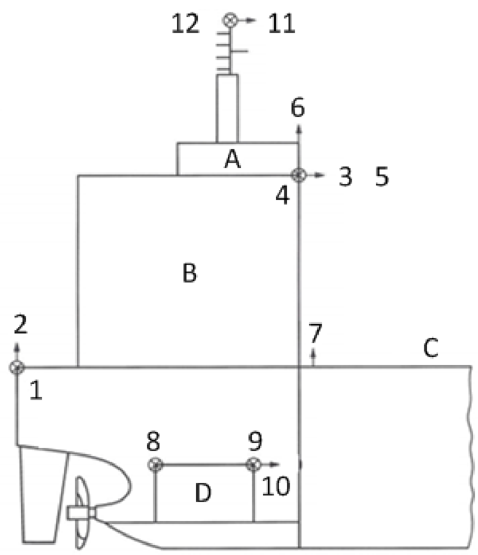

Fig. 2. Location of measuring points on board of vessel's according to ISO 20283-2:2008:
A — navigation bridge, B — superstructure, C — main deck,
D — the main engine [1, 7]

Finally Defense Standard NO-20-A500-3:1999 should be mentioned. The standard does not distinguish machines due to the power. The standard specifies limits for the 1/3 octave band with center frequencies from 1 to 500 Hz, and therefore allows for more accurate comparison of the spectrum over the narrowband than the aforementioned standards which take into account only one band in the range from 10 to 1 kHz. Various machine groups had been shown in table 3, and examples of acceptable levels of vibration velocity for the first five bands 1/3 octave in table 4. Due to the big size of the table it is not presented in this work in its entirety.

Tab. 3. Classification of marine equipment to various groups according to NO-20-A500-3:1999 [12]

Machine grup	Machine subgrup	Machine and devices
A	 Aa Ab Ac	Piston engine with stroke: - smaller than 700 mm - 701–1400 mm - equal and bigger than 1400 mm
B		• Vertical pumps, centrifugal fans etc. • Machines driven by electric motors with vertical shaft • Propeller shaft and shafting
C		• Horizontal pumps, centrifuges, axial flow fans, etc. • Machines driven by electric motors with horizontal shaft turbine engines • Gears and berings of shafting

Tab. 4. Acceptable values of vibration velocity according to NO-20-A500-3:1999 [12]

Center frequencies of 1/3 octave bands [Hz]	Velocity RMS x 10^{-3} m/s				
	Machine group				
	Grup A			Grup B	Grup C
	Aa	Ab	Ac		
2	8	8	8	8	8
2.5	10	10	10	10	10
3.15	13	13	13	13	10
4	16	16	16	14	10
5	20	20	20	24	10

The use of standards in diagnosis is an important tool, however, should not be forgotten that the values specified in the standards are qualitative rather than quantitative. Such an understanding of research-based standards clearly define their limited range and accuracy.

OBJECT OF RESEARCHERS

Exemplary measurements were conducted on vessels equipped with two main engines and two shaft lines with five-blade propellers (fig. 3). The propulsion systems are characterized by a high degree of complexity primarily due to the use of a hydrodynamic coupling that allows smooth control of speed at the minimum navigation speed of vessel (1–5 knots).

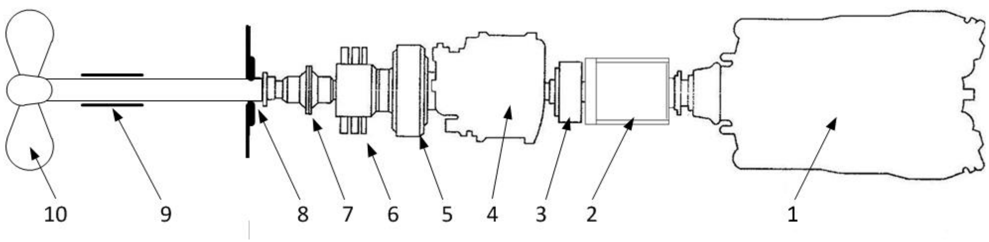

Fig. 3. Diagram of single drive system diagram on which the test was carried out:
1 — main engine, 2 — hydrodynamic coupling, 3 — Vulcan type clutch, 4 — reduction-reversing gear, 5 — Vulcan type clutch, 6 — thrust bearing, 7 — flange to block the shaft lines, 8 — gland, 9 — supporting bearing lubricated with water, 10 — five-blade propeller [own work]

Each engine has the power of P = 588 kW. These are V 12 engines working with a nominal speed of n = 1550 rpm. The fluid coupling has nominal slip of rotational speed of 2%, the reduction-reversing gear has a ratio of 3.5:1.

PREPARING FOR THE MEASUREMENT

In the measurements of vibration parameters three basic types of sensors are used. Depending on measured value it could be used sensors for measuring displacement, velocity or vibration acceleration. Each of these sensors are different in design and principle of working, it also has some limitations. The most versatile and most widely used are acceleration sensors. Most of the accelerometers is intended to measure the frequency range of 1 Hz — 10 kHz. In special realization from 0.1 Hz up to 100 kHz. Using the internal amplifier reduces the temperature of use of accelerometers up to 403° K and in special versions up to 523° K.

The most commonly used in marine measurements sensors are accelerometers. Velocity vibration spectrum is obtained by integral calculus. Selecting a sensor a special attention to its sensitivity and linear range should by paid. Each time they are given on the calibration sensor card supplied by the manufacturer. The use of sensor with too low sensitivity (expressed in the case of accelerometers with integrated amplifier in [mV/g]) might bring to cut off low amplitudes while too large can prevent the registration of large amplitudes or damage the sensor. It should be also mentioned about the dynamic range of used analog-digital converter. It means the possibility of a system to record extremely different values. Typical dynamic range of the A/C should be at least 120 dB.

Regardless of the selected type or model of sensor all normative documents impose an obligation on diagnosticians to calibrate all sensors before starting the measurement and after their completion. This element is essential for ensuring the accuracy of the measurements. After choosing the proper sensor and carry out its calibration decision about mounting the gauge to the measured machine must be taken. Each of the methods is characterized by a resonant frequency (fig. 4). Lack of awareness about the impact of different types of mounting the sensor on recorded spectrum can make the wrong decision on the further operation of the machine.

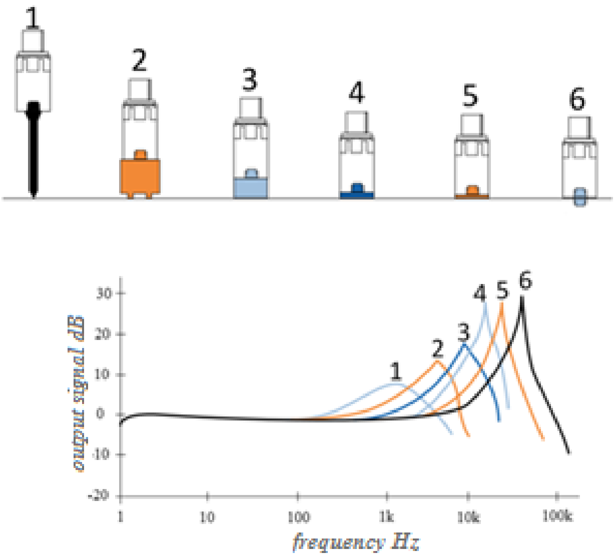

Fig. 4. Different ways of mounting accelerometer:
1 — probed hand, 2 — using a double pole magnet, 3 — with a flat magnet, 4 — with the pad is attached by epoxy glue, 5 — only with glue, 6 — by the threaded connection [own work]

Analyzing chart presented on figure 4 it could be find that the best way to mount is threaded connection. It ensure linear transition of measured signal up to 10 kHz and with acceptable error of 10% up to 25 kHz. On the other hand during marine measurements it is not possible to drill boreholes. This is the reason why most commonly used are methods 3, 4 and 5. During measurements authors had used fourth method of mounting. After installing the sensors and turn on the equipment the measurements should not be stared immediately due to the fact that system needs time to stabilize. Too early start measurements typically causes recording of very large amplitude at a frequency close to zero (DC component).

MEASUREMENTS AND ANALYSIS OF RESULTS

During the measurements, time waveforms of vibration acceleration (fig. 5) had been recorded. Records were taken on bearings of the shaft line elements indicated on figure 4. Recorded frequency band was limited to the range of 1 Hz to 3.2 kHz using sampling frequency of 8192 Hz. Measurements were conducted in accordance to the normative documents in three mutually perpendicular directions.

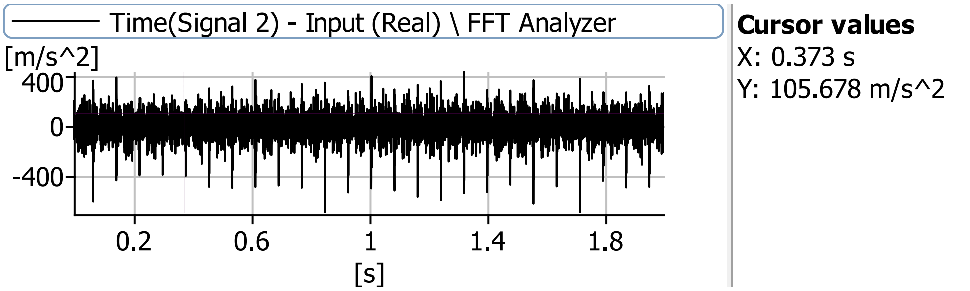

Fig. 5. Timing vibration acceleration recorded at the main motor [own work]

No standards or recommendations for vibration diagnostics do not indicate the need to conduct research on the time spectrum of vibration acceleration. But with this type of data it is possible to get a lot of information such as the occurrence of misfires in cylinders (fig. 6).

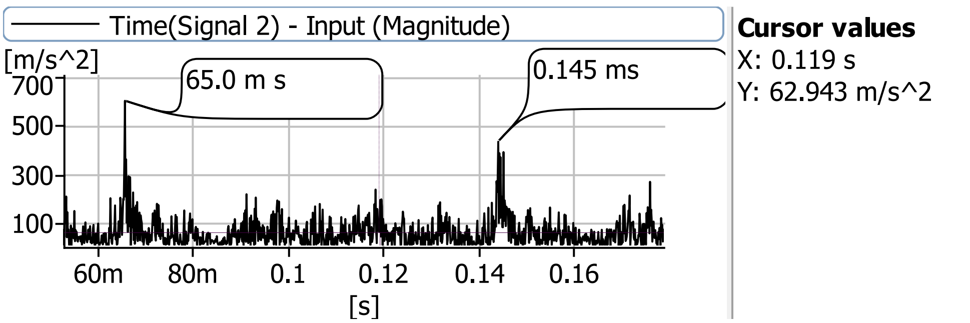

Fig. 6. Identification of ignition in individual cylinders of the V 12 engine [own work]

Figure 6 shows the absolute vibration amplitude as a function of time which is according to the authors the best form of analysis for the time spectra of vibration. It had been marked two consecutive pulses of amplitude caused by the combustion pressure for a cylinder nearest to the sensor (in this case 6 right). Spectrum had been recorded at the speed of main engine n = 1500 rpm = 25 Hz, with crankshaft time one rotation of the –0.04 s.

In the four-stroke engine ignition in individual cylinders occurs once per two revolutions — in this case at 0.08 s. Knowledge of the number of cylinders and firing order we are able to point out the course of time all the other cylinders. Comparison of the amplitudes of vibration acceleration of individual cylinders gives general information about the accuracy of the combustion process in the cylinders. Such information cannot be obtained by analyzing the frequency spectrum. It is due to the fact that it is a masking of damaged cylinder by the other cylinder (the same frequency of detonation inside all cylinders). The authors, however, lead the study which will eventually have to permit an assessment of the technical condition of fuel system by analysis the frequency spectra.

The primary way to identify the causes of increased vibroactivity of marine equipment is using Fast Fourier Transformation. It allows to obtain the amplitude--frequency spectrum of vibration acceleration or after integration the spectrum of vibration velocity. With such spectrum it is possible to calculate the root mean square value of velocity (v_{rms}) in the bands specified in standards. It must be emphasized that referring the values to the specified in the standards gives us only information about exceeding the limits without indicating any reasons of this state. In addition, there are frequent situations where the limit values of vibration velocity in a wide band are exceeded, however, after careful analysis, it is sometimes concluded that the machine is fully technically efficient.

Accordingly, after the FFT spectra had been obtained it is necessary in each case to control as precisely as possible sources of each characteristic frequency. Unfortunately, in most cases, there is no a key that allows to quickly identify all characteristic frequencies, it is usually required to know the rule of the operation, and the machine kinematics.

Figure 7 shows the amplitude-frequency spectrum of the engine under tests. There was indicated the characteristic spectral lines of working V 12 four stroke engine running at a speed of n = 1500 rev/min.

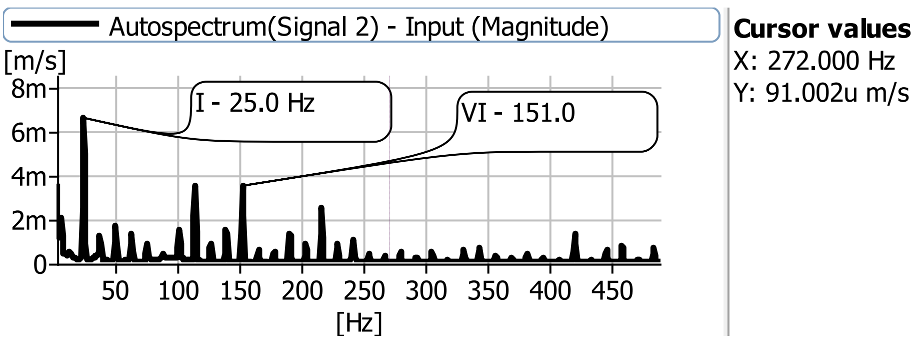

Fig. 7. Characteristic frequencies of engine under tests [own work]

Analyzing the spectrum shown in figure 8 diagnostician may not notice the characteristic frequency of gear related to the tooth meshing. The characteristic values related with work of gear (for efficient gear) have low amplitudes and the frequencies are relatively high (depending on the number of the teeth of the gears, and the rotational speed of shafts). It is clearly visible that only the amplitude of the first harmonic of shaft is clearly visible. It could indicate unbalanced of rotating elements or misalignment of sections of shafting. However, a more detailed analysis allows to identify the characteristic frequency of gear.

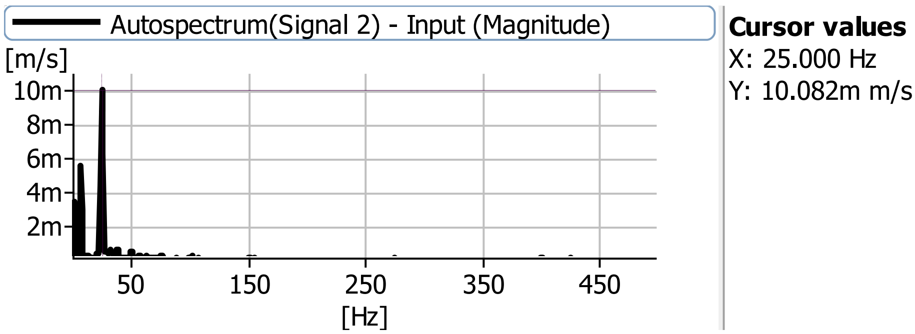

Fig. 8. Amplitude-frequency spectrum of vibration velocity of reduction-reversing gear [own work]

Figure 9 being the zoom of figure 8, it is clearly visible the gear carrier frequency. It is the frequency of engaging of cooperating pair of gear wheels. It is modulated by the first harmonic of shaft rotation speed at the input to the transmission (25 Hz). The conclusion is that this is a specific parameter to the first pair of gears from the input to the reduction-reversing gear. The quantity of the frequency characteristic for the gears depends on the number of cooperating gear wheel pairs. Monitoring of indicated amplitudes is especially justified when we have data histograms or we are doing periodic measurements, then it is possible to analyze changes of trend which might indicate the actual condition of gears.

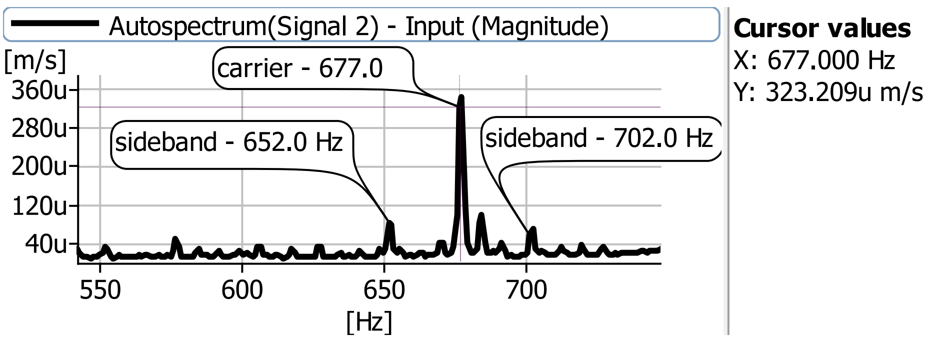

Fig. 9. The characteristic frequency of the working gear [own work]

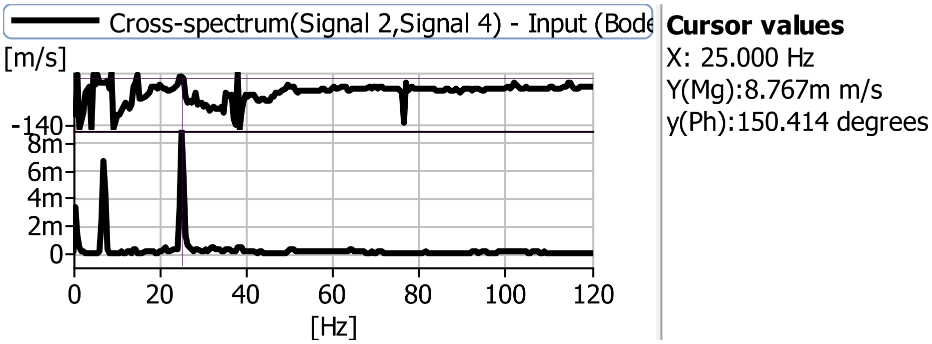

Fig. 10. Cross spectrum and relative phase measurements identifying misalignment [own work]

As already mentioned presented on Figure 8 spectrum provides information about problems of unbalance or misalignment. To identify unequivocally the source of the increased amplitude of the first harmonic of rotational speed, it is necessary to measure the relative phase between the signals from the horizontal and vertical direction (z, y — fig. 1). If the value of the phase oscillates around 90 degrees it is information about unbalanced of rotating elements. When it oscillates around 0 or 180 degrees then it is most likely there is a misalignment between the sections of shafts and we can reject unbalances. In order to obtain confirmation that the source of increasing amplitude is a misalignment it must be taken additional measurements in these directions by two bearings adjacent the concerned coupling. During the measurements it should be also measured the absolute phase (marker on the shaft). If in this case, the phase shifts will not significantly differ from each other it is almost sure that the cause of high amplitude is not misalignment. It is likely to be loose or incorrect tightened foundation bolts.

An important tool in diagnostic of marine engine room equipment with vibration methods is order tracking procedure. The FFT process transforms time domain data to the frequency domain, creating a spectrum. Periodic signals in the time domain appear as peaks in the frequency domain. In order analysis the FFT transforms the revolution domain data into an order spectrum. Signals that are periodic in the revolution domain appear as peaks in the order domain. For example, in a six-cylinder four-stroke engine, gas-dynamic forces occurs three times per revolution, peaks generated by this forces occurs in the third order in the order spectrum [13].

In order analysis normally a signal from tacho probe is used as a tracking reference. It allows a measurement to be related to the revolutions of a rotating part in the machinery. In cases where it is impossible to get access to the rotating parts of the machinery it is possible to use the autotracker which provides the tracking reference. In this case, the fundamental frequency can be extracted indirectly from the measured vibration. It should be notice that still preferred source of tacho signal is tachometer.

CONCLUSIONS

The paper presents the current standard documents in the field of vibration diagnostics of marine propulsion systems. It had been emphasized that the values presented in them should be considered only in general terms. Authors presented the analysis of parameters of vibration of selected elements of the marine propulsion system, which is restricted to the most commonly used methods of processing vibration signals. Clearly identified the need for absolute phase measurements (synchronous measurements). After analyzing the issues presented in the paper it can be stated that in order to perform a correct diagnosis of vibration of ship propulsion system diagnostician must:

1. Knows the geometry and kinematics of the ship's propulsion system.
2. Knows the results of previous studies.
3. Knows the standards in the implementation of measurements, conducting analyzes and reports.
4. Has a measuring equipment that allows simultaneous measurement of at least two sensors and tachometer probes.
5. Has tools for proper signal analysis and processing.
6. Has a team with specific experience of measuring and analytical expertise in the operation of marine power plants of warships.

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DIAGNOSTYKA DRGANIOWA OKRĘTOWYCH UKŁADÓW NAPĘDOWYCH

STRESZCZENIE

W artykule przedstawiono przykłady diagnostycznych pomiarów parametrów drganiowych okrętowych linii wałów. Opisano metodologię przygotowania do pomiarów, stosowanie urządzeń pomiarowych oraz ich ograniczenia. Uzasadniono konieczność stosowania pomiarów synchronicznych.

Przedstawiono przegląd obowiązujących dokumentów normatywnych, zwracając jednocześnie uwagę na ich ograniczenia w procesie monitorowania stanu technicznego okrętowych układów napędowych.

Słowa kluczowe:
układ napędowy, linie wałów, drgania, okręty.