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THE VIBRATION BASED DIAGNOSTICS OF SHIP PROPULSION SYSTEMS

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Abstract. The article has been worked out on the basis of the report devoted to the conducted diagnostic investigations of the ship main propulsion unit's mechanical system. Gdansk University of Technology has been ordered with such investigations by the repair Shipyard carrying out the ship's overhaul. Diagnostic tests involved measurements and analyses of the vibration signals generated in selected constructional kinematic pairs of the identical (twin) starboard and portside marine propulsion lines. The vibration signals have been registered at the representative load ranges. By this way the stability of the considered mechanical unit has been estimated both in a global and local sense. Appearing at that time the resonance phenomena which result in a kinetic energy dissipation of the ship main propulsion unit's masses being in a rotational movement have been identified. There have been also localized places of the largest growth of the changeable internal tensions' amplitudes, what considerably constrains cycles number of the load alterations at which elements transmitting the propulsion torque from engines to propellers crack, as a result of the material fatigue phenomenon.

The most probable reasons of the mechanical unit's enlarged vibration level have been pointed out on the basis of a carried out analysis of the alignment results, the specifity of the applied main engine running on the partial loads as well as the range of constructional changes that had been made during the propulsion unit's overhaul. Results of the repeated diagnostic sea trials, carried out after the reduction gears' modification recommended by the Authors, confirmed a relevance of the earlier formulated diagnosis. The modification works aimed to perform a resonance offset by the damping correction of hydraulic devices additionally founded on the gears frames.

A technology of the marine propulsion shaft line's transverse and longitudinal vibration measurements carried out by means of the portable vibration register as well as a method of the vibration spectral analysis have been focused within the program description of the performed diagnostic investigations. They represented the base for a diagnostic inference about the considered mechanical unit's dynamic state.

1 INTRODUCTION

One of the parameters which impacts on durability of the marine propulsion unit's mechanical system the most is a fatigue strength of material of which its structure is built. During an engine's operation on a sailing ship because of multifold changes of mechanical loads (caused by periodically changeable reactions of forces and torques generated by propulsion engines, propellers and a ship hull operating on waves) cyclic elastic and plastic shaftings deformations take place. They give rise to transverse, axial and torsional vibrations – Fig. 1. The increasing amplitudes of changeable internal stresses stand for the cause of a considerable limitation of the cycle number of load alterations, at which elements transmitting torque from the engine to the propeller are subject to the accelerated wear and tear process until the irreversible failures occur because of material fatigue [5]. The loss of stability of the mechanical system within marine propulsion unit under operation results from an occurrence and development of the following detrimental phenomena: a slowly worsening unbalance state of shaftings and propeller resulting from sediments, erosion, corrosion and bent shafts or a loss of their alignment, a sudden increase of shafting unbalance state resulting from deformations or broken-off fragments of propeller blades, excess of allowable load of bearings, shafts seizing in slide bearings, failures within rolling bearings etc.

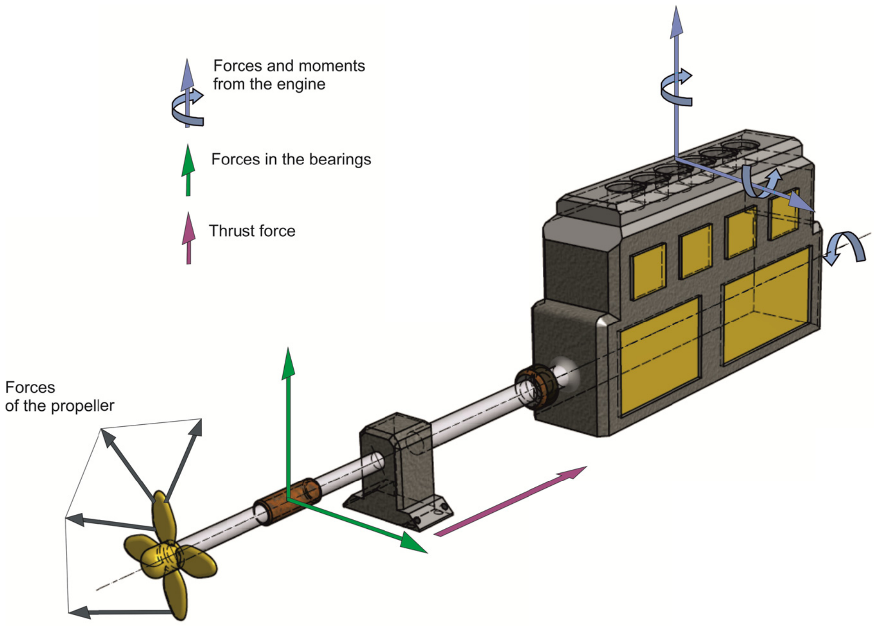


Figure 1: Force and torque system that impels a marine shafting vibration [4]

The affected transverse and axial vibration occur within propulsion shafts practically in the whole range of rotational speed alterations. Nevertheless, the largest amplitudes appear at the resonance rotational speeds. In order to identify the resonance's sources vibration a spectral analysis of the registered vibration signal should be conducted. It consists in the signal decomposition into harmonic components of the determined resonance frequencies [3]. The condensation of amplitude spectrum as well as the growth of amplitudes of the characteristic harmonic components testifies about the existence of local resonances and the deterioration of the propulsion unit's dynamic state threatening with the damages of elements which transmit a torque to the propeller.

The transverse and axial vibration issue in terms of their measurements and spectralcorrelation analysis has been introduced in numerous publications in detail. However, there is still perceptible lack of bibliographic positions presenting this question in the aspect of the widely understood operation diagnostics.

2 RESEARCH OBJECT CHARACTERIZATION

An experimental testing, carried out on the two shaft homogeneous drivetrain (Fig. 2) while the ship was operating, was designed to check a stability of the propulsion's mechanical system after ship repair in the shipyard.

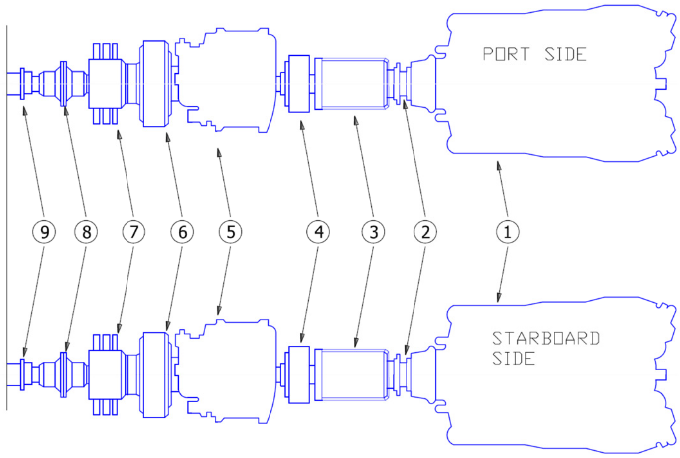


Figure 2: Schematic diagram of the ship drivetrain:
1 – starboard side (SB) main engine of M401A type, 2 – flexible coupling, 3 – hydrokinetic coupling SHOR720, 4 – flexible coupling, 5 – main gearbox R25A, 6 – flexible coupling, 7 – thrust bearing, 8 – flange coupling, 9 – stern tube stuffing - box

The diagnostic investigations were conducted on the Baltic Sea, at the sea state about 2÷3.

During the measurements, the main engines were running simultaneously (a common work) and the vibration signals were observed.

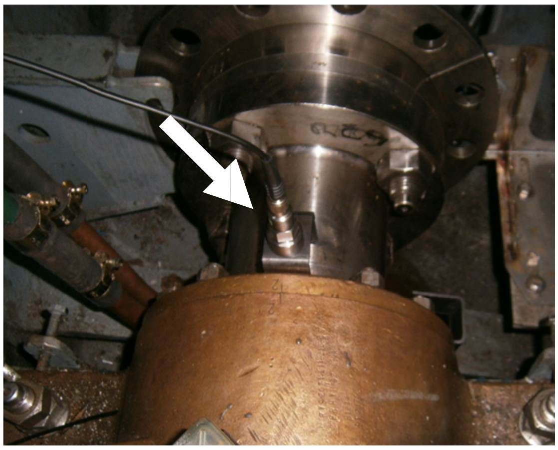
Operation diagnostic measurements were worked out by means of SVAN 956 digital vibration measuring instrument of SVANTEK Ltd. production [http://svantek.com]. It gives a possibility of the following trends of values' alterations of the spectrum parameters in different characteristic frequency bands, for the well-known and recognizable states of operation unfitness.

SVAN956 is equipped with DYTRAN piezoelectric acceleration sensor 3185D type. A magnetic connection of the sensor makes a quick exchange of the measurement place possible, which has got the very essential meaning in case of variable and limited conditions of the measurement's realization. Three independent measuring profiles applied in the analyzer permit selecting three filter sets and time-constants for the simultaneous measurement of vibration's acceleration, velocity and displacement within the frequency range from 0.5 kHz to 20 kHz (limited with a transfer band of the applied transducer). Thanks to the large power of a signal processor the simultaneous narrowband analysis FFT, the simultaneous frequency analyses within the octave- and tercial- bands as well as the simultaneous analysis of vibration envelope are possible during the measurements.

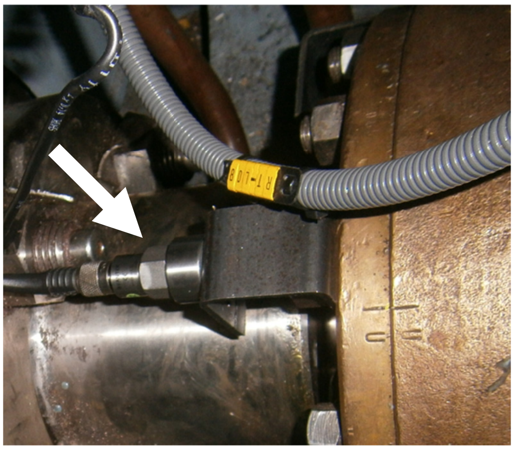
3 RESEARCH PROCEDURE

The measurements of the vibration speed and acceleration generated through constructional joints of the marine propulsion unit were executed after the ship's repair in the Polish Shipyard "Nauta". The main aim of the measurement was to evaluate a current state of dynamic balance and alignment within the propulsion shaftings. The registration of the transverse vibration was executed in vertical (V) and horizontal (H) plane of the tube stuffings, thrust bearings, gearboxes and main engines by assembling the accelerometer in direct closeness of bearing joints by means of a magnetical connection. The registration of longitudinal (L) vibration enforced by an impact of the periodically variable trust force from propellers (5 impacts of the trust force per 1 revolution of the propeller shaft) was executed by assembling the accelerometer on the thrust bearings housing, from the side of output shafts transmitting a power to the propellers. An example manner of the accelerometer sensor's assembly is shown in Fig. 3.

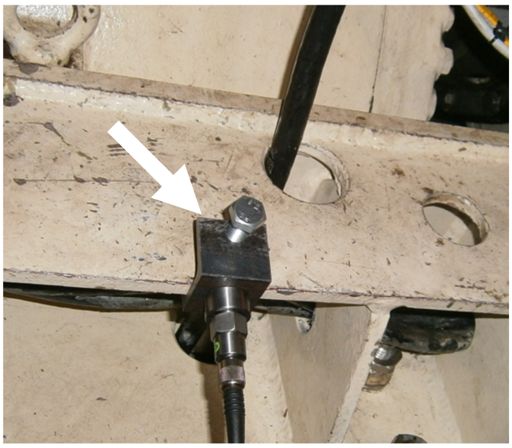
a) Thrust bearing – vertical plane



b) Thrust bearing – longitudinal plane



c) Gearbox – vertical plane



d) Main engine foundations – vertical plane

Figure 3: Manner of DYTRAN 3185 D accelerometer sensor's assembly in the point of shaftings vibration speed and acceleration measurements [6]

The vibration measurements were worked out in 26 measuring points (the points' numbering is consistent with the measurement order) presented in Fig. 4.

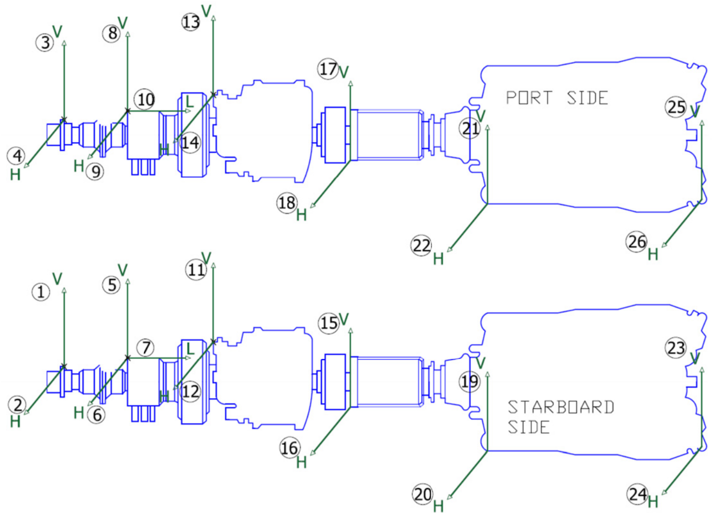


Figure 4: The numbering of measurement points and spatial arrangement of the axis: 1 ÷ 4 Stern tube stuffing - box ; 5 ÷ 10 Thrust bearings; 11 ÷ 14 Gearboxes; 15 ÷ 18 Hydrokinetic couplings; 19 ÷ 26 Main engines; *„V" – measurement on the vertical axis, „H" – measurement on the horizontal axis, „L" – measurement on the axial (longitudinal) axis*

The measurements have been performed in II ranges of established loads for two values of rotation speed of main engines: n_S = 1300 and 1450 rpm, with complete filling of the hydrokinetic coupling. In total: 52 measurements.

4 RESEARCH RESULTS AND THEIR ANALYSIS

The analysis of the measurements results has been conducted in accordance with ISO 10816 guidelines „*Mechanical vibration — Evaluation of machine vibration by measurements on non-rotating parts*":

- root mean square (RMS) value of the vibration velocity - measured in the frequency range of 10Hz to 1kHz,
- amplitude spectrum of the vibration velocity and acceleration in relation to basic frequencies harmonics of the propeller shafts rotational speed as well as characteristic frequencies associated with the main engines work (6 gasodynamical cycles - extortions per 1 crankshaft revolution), the shafting thrust bearings as well as the propellers (5 trust force extortions per 1 revolution of the propeller shaft), for every propulsion unit.

Table 1: The harmonic frequencies of propulsion unit

Engine speed	Propeller shaft speed	1st, 2nd and 3rd shafting harmonic frequency	4th shafting harmonic frequency (5-blades)	1st engine speed harmonic frequency	6th engine speed harmonic frequency (12-cylinder)
rpm	rpm	Hz	Hz	Hz	Hz
1300	365	6,1; 12,2; 18,3	30,5	21,67	130
1450	405	6,75; 13,5; 20,25	33,75	24,17	145

The evaluation of the dynamic condition of main engines (measuring points 19 ÷ 26) was performed according to the ISO 10816 supplement – ISO 10816 - 6 „*Mechanical vibration — Evaluation of machine vibration by measurements on non-rotating parts. PART 6 Reciprocating machines with power rating above 100 kW*".

The gathered RMS vibration date is presented in Fig. 5 - 6. The results of FFT (Fast Fourier Transform) in the plot form of vibration amplitude vs. frequency are demonstrated in Fig. 7 - 9. This is a basic analytical method most often used in diagnosing faults associated with unbalance, misalignment, eccentric components and damaged bearings, shafts or gears [1, 2, 3].

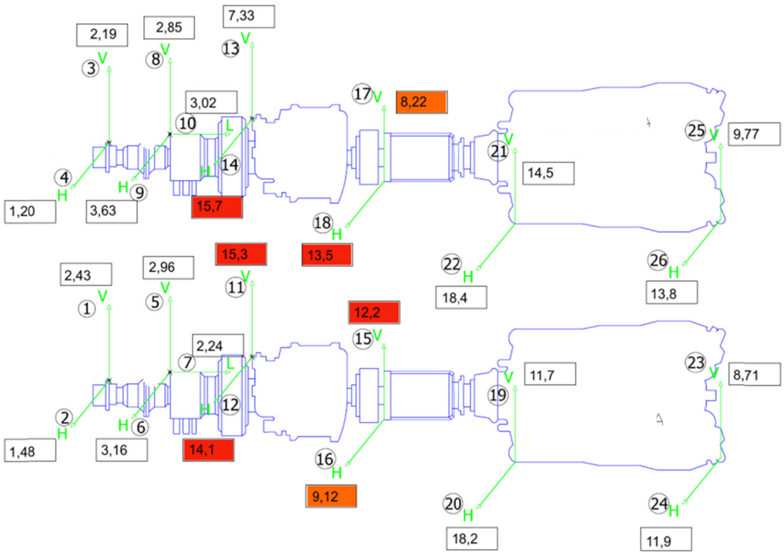


Figure 5: RMS value of the vibration velocity [mm/s] – rotational engine speed 1450 rpm [6]

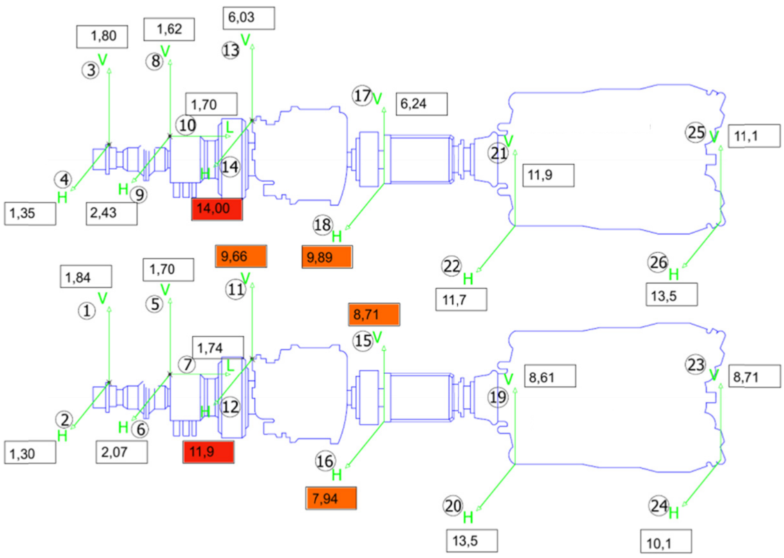


Figure 6: RMS value of the vibration velocity [mm/s] – rotational engine speed 1300 rpm [6]

Upon the results of the vibration measurements, the following conclusions were made:

- the values of vibration parameters that characterize the stability of the propulsion unit's SB and PS during encumbrance "half speed ahead" and "full speed ahead" (n_S=1450 and 1300 rpm) have exceeded the permissable limits covered by ISO-10816. The highest root mean square of the vibration velocity, at "full sped ahead", were registered at following structural nodes:
  - on gearbox casing:
    - port side (PS) – on horizontal plane, YRMS=15,7 mm/s
    - starboard side (SB) – on vertical plane, YRMS=15,3 mm/s and on horizontal YRMS=14,1 mm/s
  - on hydrokinetic coupling case:
    - port side – on horizontal pane, YRMS=13,5 mm/s and vertical, YRMS=8,22 mm/s
    - Starboard side – on vertical pane, YRMS=12,2 mm/s and horizontal YRMS=9,12 mm/s.

The dynamical condition of other parts of the propulsion system were classified as either good or satisfactory accordint to the previously mentioned standard.

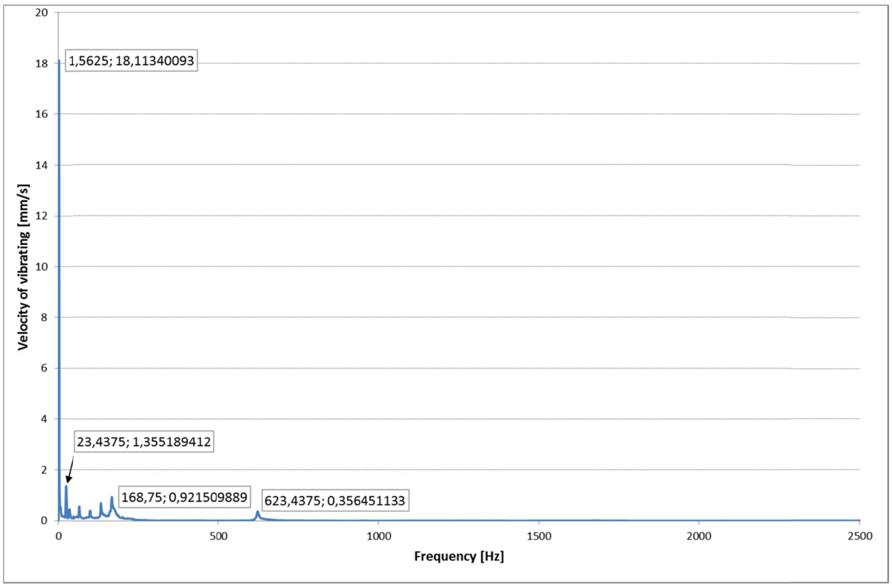


Figure 7: Velocity spectrum of vibrating thrust bearing case, registered in vertical plane – V axis, measuring point number 8, rotational engine speed - 1450 rpm [6]

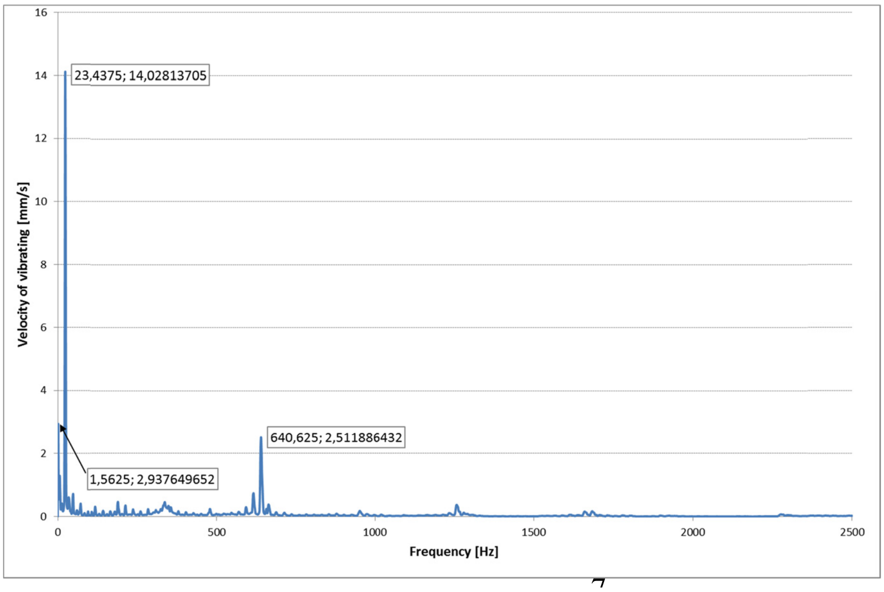


Figure 8: Velocity spectrum of vibrating gearbox case, registered in horizontal plane – H axis, measuring point number 14, rotational engine speed - 1450 rpm [6]

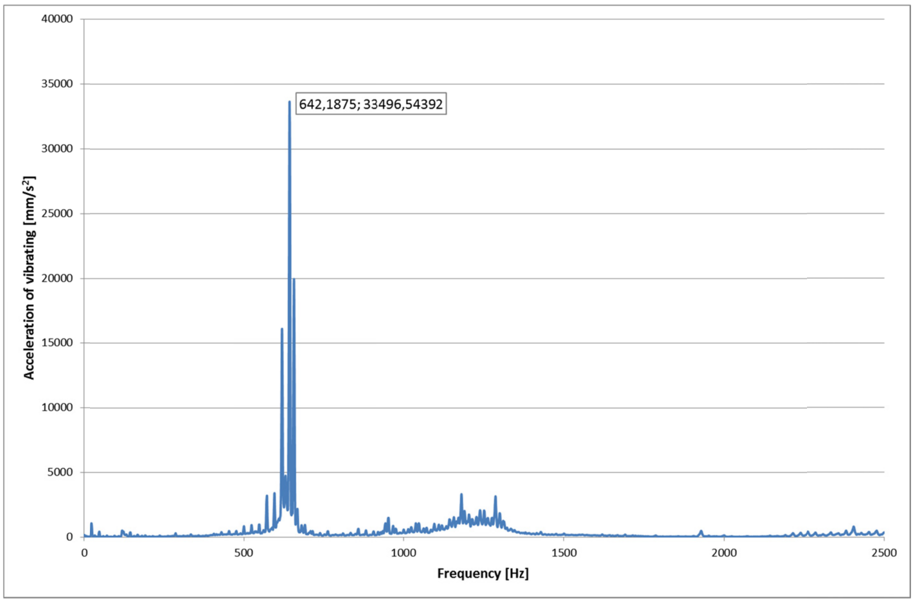


Figure 9: Acceleration spectrum of vibrating gearbox case, registered in vertical plane – V axis, measuring point number 11, rotational engine speed - 1450 rpm [6]

The analysis of registered amplitudal specters of vibration velocity and acceleration of structural nodes of the highest root mean square of vibrations' velocity shows as follows:

- at all specters of velocity of registered vibrations on the vertical plane, the amplitudes of characteristic basic frequency 1,56 Hz are dominant , beginning from global hull vibration, which are caused by the bending moment while working on the wave (the highest value of amplitude at measurement point "8" – Yv=18,1mm/s),

- at all specters of velocity of registered vibration on the horizontal plane, the amplitudes of characteristic basic frequencies related to the work of motors 21,88Hz and 23,44Hz, from gas power inside the cylinders (the highest value of amplitude at measurement point "14"- Yv=14,0 mm/s)

- at all specters of velocity significant increases of density of harmonic components nearby higher frequencies, about 640 – 650 Hz (maximum value of amplitude for measurement point "11" - Ya=33,496 m/s2) appear, whose source can be identified after sharing the constructional documentation of roller bearings, reduction gear and torque converter. One should also consider mechanical characteristics of damping couplings that significantly change dynamic parameters of shaftline that is to detune from resonance and reduce the tensions in shafts, caused by vibrations.

- Due to the fact that in all analyzed specters, the amplitudes of velocity of characteristic, basic frequencies from rotation speed shafting's and propeller's reached minimal values, considering their role as main sources of both radial and axial direction of vibration, caused by unbalanced rotating elements, misalignment and flexure of the shaftline, this situation should be eliminated for both shaftlines. The results of shipyard measurements confirmed that propulsion systems were aligned correctly.

Based on wideband and frequency of vibrations analysis performed, it was stated that the possible cause of increased level of effective value of vibration speed in the area of reduction gears is rigid attachment of additional hydraulic devices of significant mass on their casing – Fig. 10.

a) Oil heat exchanger b) Oil pump

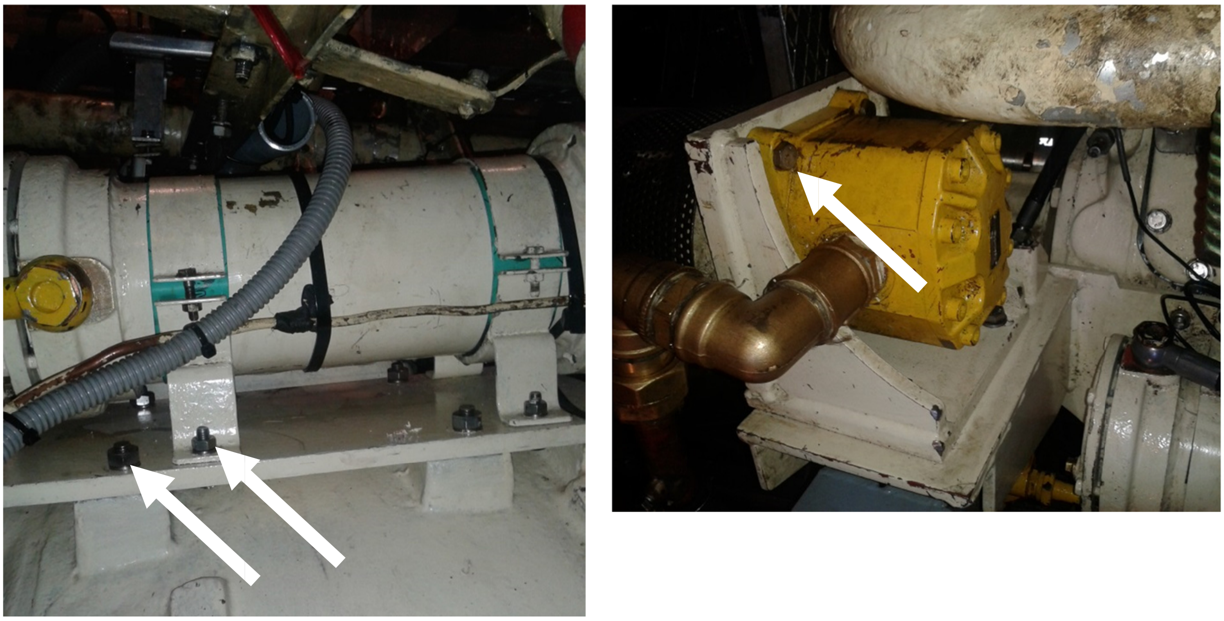


Figure 10: Rigid mounting oil pump (b) and heat exchanger (a) [6]

The recommendation was to change the mount by using flexible pads and to repeat the measurements. All the recommendations were implemented.

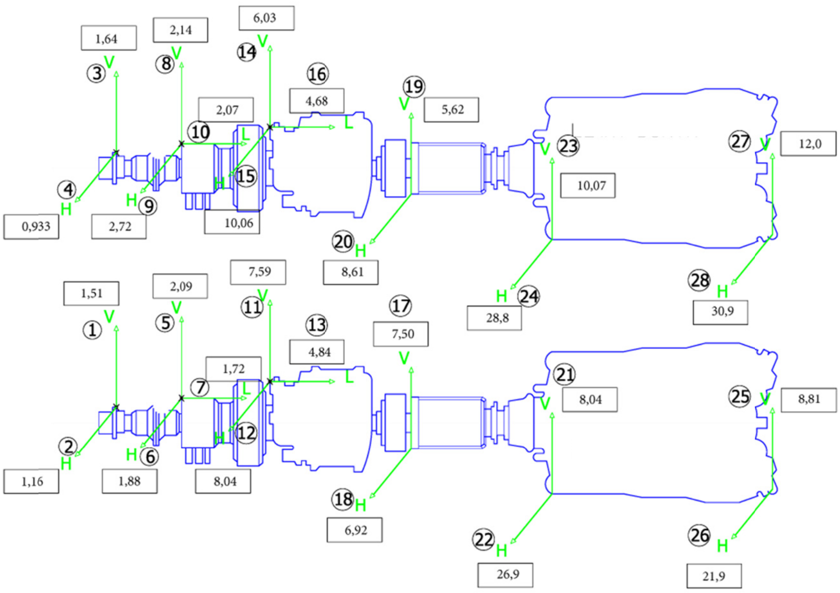


Figure 11: RMS value of the vibration velocity [mm/s] – rotational engine speed 1300 rpm [6]

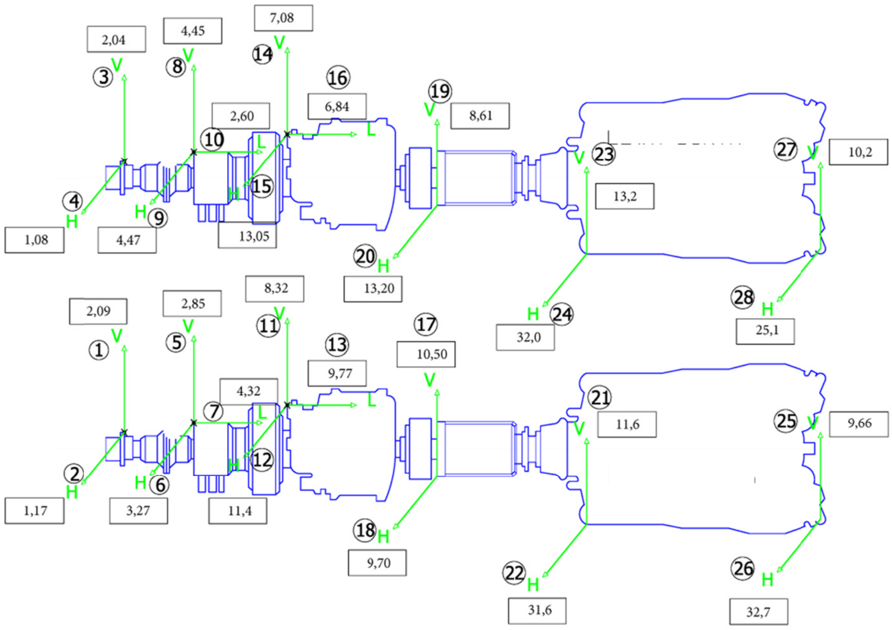


Figure 12: RMS value of the vibration velocity [mm/s] – rotational engine speed 1450 rpm [6]

Re-registration of the vibrations was conducted in 28 measurement poins (in order complying with the order of measurements) in similar conditions.The gathered RMS vibration date is presented in Fig. 11 - 12.

The set of measurement points was expanded by two - the measurement in the longitudinal plane on the casing of the gears (Fig.11 – points 13, 16).

Based on the results of the re-measurement of the vibration of the ship's shaftlines, a conclusion was made that the values of the vibration parameters characterising the stability of the mechanical propulsion system PS and SB during work, in the conditions of established load are within the acceptable limits of the operational area of tolerance defined by ISO – 10816.

5 CONCLUSIONS

Vibration measurements and analysis represent an important indicator of the current stability state of a marine propulsion unit's mechanical system. The authors aimed to prove that the operational vibration investigations can be conducted easily, effectively and successfully even by means of a very simple measurement apparatus.

Presented results of the diagnostic research and its analysis enabled the elimination of a simple design fault.

The use of flexible placement of coolers of hydraulic oil, on gearboxes casing, resulted in prominent reduction of effective value of velocity of vibration in the area of the gears, even as much as 7 mm/s (measurement point 11).

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