DIAGNOSING ELEMENTS OF SHIP PROPULSION OF VIBRATION MEASURMENT

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Abstract

In the present time the technical progress make us use more and more complicated machines in our everyday life. In the case of the technology used at sea the necessity of highly specialised service is especially evident. The diagnostic systems elaborated to support the exploitation of the vessel power plant with gas turbines are presented in the paper. Application of computer simulation for diagnosing a technical state of gas turbines rotor sets should be applied during calculation and project process. During engine assembly, the rotating components are mounted with great care with the main objective of minimising shaft unbalance. However, even with the best of care, such factors as machining imperfection, differential thermal expansion etc cause a small residual unbalance of gas turbine rotor. The dynamic problems of Marine Gas Turbine Engines are connected with such basic elements as rotors, bearings, struts of bearings, engine body and type of substructure.

Keywords: *diagnosing, vibroacoustics, gas turbine engines, ship propulsion plant Diagnosing, vibroacoustics, gas turbine engines, ship propulsion plant*

1. Introduction

The propulsion systems of warship vessels and especially of combat vessels are constructions of great power. The power of the installed propulsion system reaches 100 MW. The necessity of high power production makes the use of gas turbine engines. The contemporary gas turbines used on warships can achieve power up to 30 MW and little unit mass that can reach even 0,2 kg/W.

The marine gas turbine engines work in specific conditions which to a certain degree influence its exploitation conditions and can be a reason of their increased wear and even a break-down.

The marine peculiarity has its influence on the engines of all types but it is especially notorious in the case of gas turbines [1]. It is especially due to:

- great volume intensity of the air flow through the engine, up to 80m3/s,
- high level of the load of the engine,
- complexity and sometimes impossibility of the thorough inspection of the engine,
- requirement of the high level of purity of fuel, oil and air,
- work mostly on partial load.

The engines on the vessels work in the conditions of permanent waving and great stroke loads, etc. These kinds of loads have their influence on the elements of the engine, especially on the labyrinthine seals and bearings. Air passing through the engine brings sea-water and salt, vapours of oils, sucked exhausts of the working engines and, in the coastal regions, the industrial dusts.

2. Base diagnostic system of naval gas turbine engines

The usage of naval gas turbines requires a professional technical supervision. Such a requirement cannot be fulfilled by crews of small vessels. Therefore, it was decided to support the crews of such vessels by the „Base Diagnostic System of Naval Gas Turbine Engines" (BDS) [2].

The system is introduced for periodical inspections of engine condition and particularly in case of:

- annual maintenance,
- necessity of the prolongation of mean time between major repairs,
- identification of an abnormal running found during routine maintenance.

The Base Diagnostic System consists of a series of diagnostic positions and provides the possibility of complex examination of engine conditions by EDP (Electronic Data Processing) application. The BDS is capable of working out the prognosis for the engine future operation. An operating decision is worked out on the basis of appropriately prepared measurements of the engine parameters. They are subsequently converted into diagnostic parameters according to the elaborated flow diagrams for computer programs.

From the technical point of view the BDS is equipped with a special supervising-measuring device capable of carrying out numerous (foregoing) tasks on the grounds of measured values of various parameters of the engine.

In order to work out all tasks securing the proper gas turbine operation the system is equipped with the following special apparatus:

- computer measuring system of start-up and lay-off parameters, and of operational parameters,
- for measurements of vibration parameters and their analysis,
- position for oil examinations on metal particle contents and other impurities,
- programmable analyser of high-changeable signals,
- endoscopes,
- automatic test equipment for safety devices and supervising-measuring apparatus of the engines,
- computer data base.

The methods of gathering diagnostic parameters for the condition evaluation of different sub-assemblies of the engine are presented in Figure 1.

To obtain reliable data on diagnostic parameters, investigations of the gas turbines installed in the presented propulsion system were carried out by means of the multi-symptom diagnostic model whose one of the main features is recording and analysing vibroacoustic signals [3]. The investigations were aimed at determination of permissible in-service unbalance and appropriate assemblage of turbine rotors on the basis of selected vibroacoustic parameters, and - finally – determination of their permissible operation time resources. The investigations were based on the following assumption: if technical state degradation of gas turbine rotor sets is a function of their operation time (at a load spectrum assumed constant) then it is possible to select from the recorded vibration signal spectrum such parameters whose changes can be unambiguously assigned to the operation time [4, 5]. Second one important problem is shaft misalignment between engines and reduction boxes and propeller and reduction box. Dynamic reactions, resulting from exceedance of allowable alignment deviations of the torque transmission elements are able to cause failure of the propulsion system and even lead to loss of movability of the vessel in a relatively short time. Therefore diagnostic control of the gas turbine power plant in operation became necessary.

Appropriate assembling the main engines and the other torque transmission elements inclusive of propellers is practically determined by a set of tolerated dimension and geometrical location requirements, called geometrical dimension assembling chain. Both typical and modular power plants are prone to coaxiality deviation from its permissible values and in consequence to possible failures one or more elements of the propulsion system. The excessive deviation can lead to the loads on bearings and gear teeth much higher than calculated and in result to their premature failures.

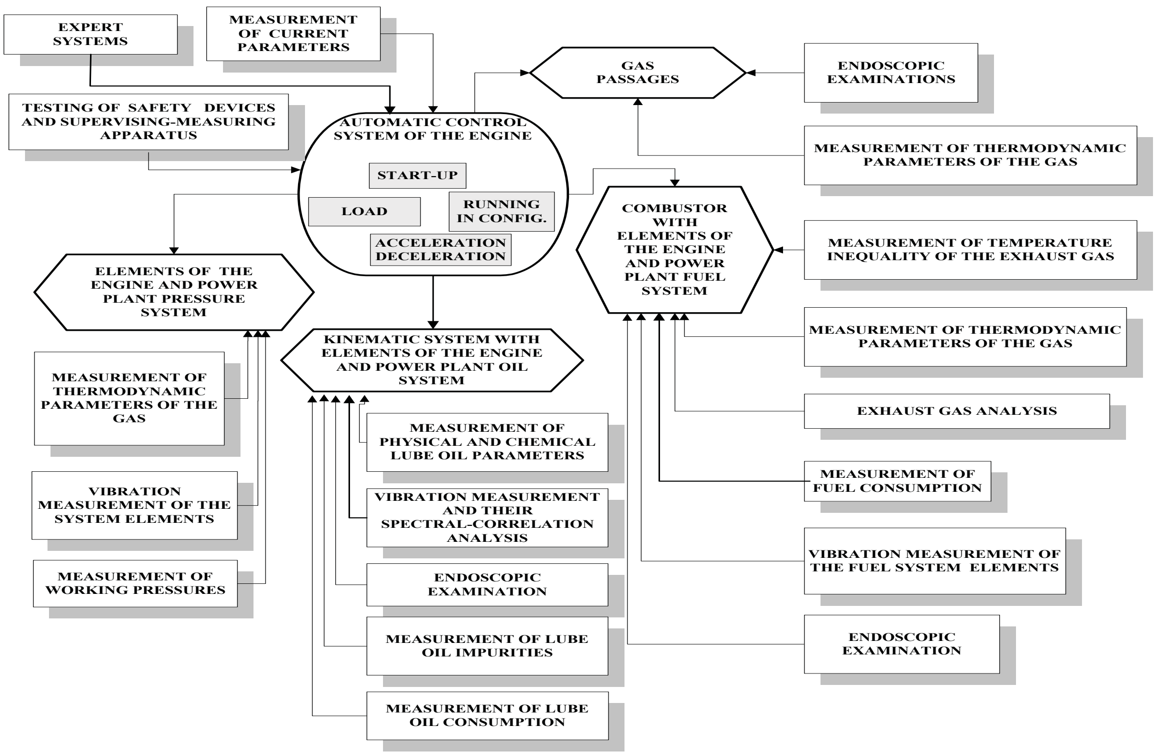

Fig. 1. Methods and means of gathering diagnostic parameters

3. Theoretical assumption of rotor dynamics

Application of computer simulation for diagnosing a technical state of gas turbines rotor sets should be applied during calculation and project process. In fact it is acted. A problem is started when the producer does not include this kind of know-how in the technical specification for user. Such situation steps out for the export objects like navy vessels equipped with gas turbine engines. During engine assembly, the rotating components are mounted with great care with the main objective of minimising shaft unbalance. However, even with the best of care, such factors as machining imperfection, differential thermal expansion etc cause a small residual unbalance of gas turbine rotor. The dynamic problems of Marine Gas Turbine Engines (MGTE) are connected with such basic elements: rotors, bearings, struts of bearings, engine body, type of substructure, hydro- and meteorological conditions during sea trials and gas flown parameters inside the engine. The quality of work process and stability of MGTE are connected with the state of such parameters as well. Dissipation of energy in rotating machines displays as a torque, revolutions, temperature, gas flown and vibration. Vibrations are connected to: rotors unbalancing, oversize of tolerated axis slope of shafts, abrade of blade tips with the inner roller, wear of axis and radial bearings, asymmetry of springiness and damping characteristics of rotor and their parts and irregularity gas flown forces. Emission of vibration brings a lot of information including opinion of the technical state [5]. Measurements of vibration, their identification, classification, mathematical analysis, including trend function bring information on actual technical state and it allows predicting wear process in the future.

Every rigid body has six degrees of freedom, however a deformation body has unlimited degrees of freedom. Rotating machines like MGTE have an amount of degrees of freedom equal sum of all degrees of freedom engines' parts reduced by amount of rigid nodes connecting these elements of engine. Each part of engine can be represented by physical characteristics obtained from vibration measurements or from modelling of geometry and material – a rigidly joined structure. Application of specified model of rigid body gives ordinary differential equations. The deformation body needs partitive differential equations. The second assumption is much more complicated but it can approach to the real object, especially when it works in wide range of rotary speed. It was a reason of choice the second model. Scheme of diagnostics model MGTE is presented on figure 2.

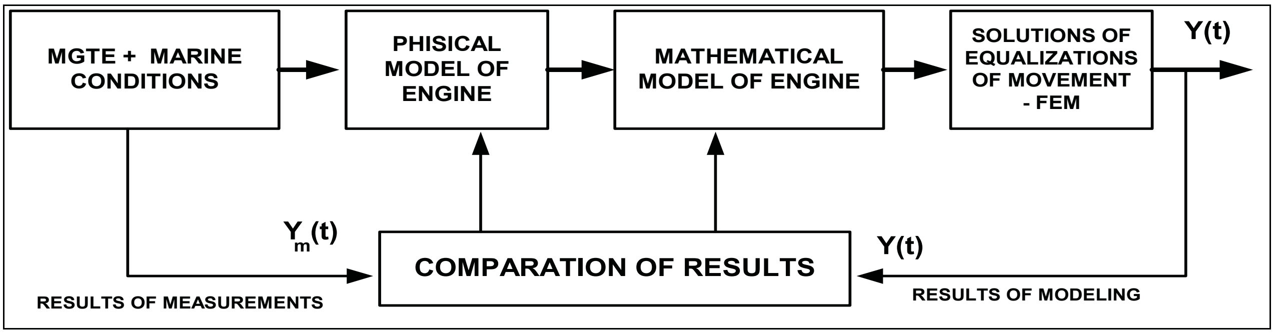

Fig. 2. Scheme of diagnostics model

The residual unbalance occurs on each and all stages of rotor but two vectors of unbalance at both ends of shaft can represent effect of that. They have different values and phase shift. This FE individual and average model creates responses of unbalancing and it can be compare with vibration reports of measurements. The most sensitive unbalance response point at the GT engine is the front frame over a vertical strut. It is an effect of minimal thermal expansion for radial and axis vibration in this point. The model is linear so it is clear that response is directly proportional to the amount of unbalance [4]. It should be noted here that the real engine response is unlikely to be linear over wide range. Furthermore, the received effect can be accepted only as a statistical approximation of the dynamic engine response.

Construction of rotor is forced from different sources. There are not only unbalancing or gas-flown forces but vibration of vessel's hull, enclosure module, propeller, shaft and gearbox as well. List of potential sources is very long. Generally, there are axis slopes, crack of shaft, blade tip, crack or wane. These sources were focused during modelling and investigation on real object. Losses of material make an influence for changes of moments of inertia of rotated parts. They cause the displacement of main axis of inertia, which is not coincident to the axis of rotation. Finally, it is main sources of unbalancing – vibration of rotor. Mathematical model of this question is difficult because of assessments of damping and stiffness coefficients of struts and bearings.

Shape of the axis deflection is defined as discrete sets: of static deflections - us; and of dynamic deflections– ud.

Both sets depend on actual technical state of rotor and geometry, which are changed through cracks and wanes of engine parts.

$$u(\omega t) = u_s u_d(\omega t). \tag{1}$$

This equation is a discrete set of displacement values points of axis of rotor. Taking into account damping and stiffness of bearing's supports, it can be posit that they are functions of the temporary positions, so:

$$k_{ik} = f(u), \qquad c_{ik} = f(u). \tag{2}$$

Simplifying problem, it cans asses that for constant rotation these values are constant as well. Using FE method the model presents a three-dimensional discrete model. Rotors of MGTE because of circular symmetry have been described by one-dimensional, two hatches balk – rod symmetry FE which have six degrees of freedom. All of parts have geometrical and material characteristics.

Movement parameters of discrete model have been found by solution of following equation:

$$Ku + C\dot{u} + M\ddot{u} = F(t), \tag{3}$$

where:

K – matrix of structure's stiffness,
C – matrix of structure's damping,
M – matrix of structure's inertia,
F – vector of forces,
$u, \dot{u}, \ddot{u}$ – displacement and their derivatives (velocity and acceleration).

The issue can be solved as a linear problem but in turbines rotor has to allow changes of stiffness and damping which are functions of movement's parameters. In this case equation [3] can be expressed as:

$$K(u,\dot{u})u + C(u,\dot{u})\dot{u} + M\ddot{u} = F(t). \tag{4}$$

Main purpose of researches had been found sensitive vibration symptoms represented residual unbalancing of rotors and forces from misalignment of shafts. FEA (Finite Element Analysis) are used successfully for a wide range of problems and it may also be used for the modelling and analysis of rotor system. Presently, diagnostics teams commonly use FEA and rotordynamics in conjunction with vibration analysis for detection and identification of unbalancing and misalignment of shafts. A linear model obeys the basic principle of linear superposition. Applied to a structure, this means that displacement resulting from a combination of structural loads is the sum of the displacements due to each individual load making up the combination. Unfortunately we had not enough structural information to create FEA model of marine gas turbine engines. It is a typical situation that the product of operation is made abroad. So, it was decided to apply passive method of investigation that to find reliable symptoms of unbalancing and misalignment using statistical methods and verified them by endoscopic examination [9]. For initial analysis from first to fourth harmonics of amplitude of velocity of vibration, the dimensionless parameters S1 and S2 were taken as sensitive symptoms.

4. Diagnosing the rotors unbalancing

The quality of work process and stability of MGTE are connected with the state of such parameters as well. Dissipation of energy in rotating machines displays as a torque, revolutions, temperature, gas flown and vibration. Vibrations are connected to:

- rotors unbalancing;
- oversize of tolerated axis slope of shafts - misalignment;
- blade tips with the inner roller;
- wear of axis and radial bearings;
- asymmetry of springiness and damping characteristics of rotor and their parts;
- irregularity gas flown forces.

Emission of vibration brings a lot of information including opinion of the technical state. Measurements of vibration, their identification, classification, mathematical analysis, including trends, provide information on the actual technical state and it allows predicting wear process in the future. Vibration analysis of MGTE during sea trials are accomplished by two different procedures: on-line – in real time, and off-line – periodic or single measurements.

For realisation of the investigations the measurement instruments: FFT-2148 analyser and PULSE v 9.0 software of Bruel & Kjaer, were used making it possible to collect and process measured data. Measuring transducers (accelerometers) were fixed to steel cantilevers located on the flange of the low-pressure (LP) compressor only. It was decided to carry out the investigations with the use of the transducer fixed to the LP compressor flange for lack of transducers and equipment suitable for measuring signals at the temperature as high as 200^{o} - 300^{o} C occurring on the high-pressure (HP) compressor flange.

The fixing accelerometers' cantilevers are characterised of a vibration natural resonance frequency value, differ enough from harmonic frequencies, due to rotation speed of the turbine rotors and their harmonics. The measurements were taken perpendicularly to the rotation axis of the rotors over main bearings. Such choice was made on the basis of theoretical consideration of excitations due to unbalanced shaft rotation, and results of preliminary investigations of the object [6]. As signals, usable for the „defect-symptom" relation, the following magnitudes were selected by the turbines' producer:

- Y - 1st harmonic RMS value of vibration velocity amplitude connected with the LP and HP rotor of compressor;
- Yrms – RMS value of vibration velocity amplitude within the range of 35 Hz - 400 Hz.

The choice was justified by the time-between-repair values scheduled by the turbines' producer. For the purpose of these investigations a simplification was made consisted in assuming values of the after-repair turbine vibration symptoms as those of the new turbine. The turbines' producer specified the following limit values of RMS vibration velocity amplitude: Yrms = 24 mm/s, Y = 17 mm/s.

In order to obtain uniform diagnostic procedures regarding unbalance assessment of the turbine rotors the dimensionless parameters characterising that states were applied. On the basis of theoretical considerations as well as results of other diagnostic investigations carried out for some years the following parameters were selected as the most sensitive, [8]:

S1 - ratio of the mean vibration velocity amplitude of a given rotor (1st harmonic) and the velocity component relevant to 2nd harmonic excitation frequency of the rotor in question; S1 > 1,

S2 - ratio of the mean vibration velocity amplitude of a given rotor (1st harmonic) and the velocity component relevant to 3rd harmonic excitation frequency of the rotor in question.; S2 >1,5.

One of the most important elements of the off-line system is data base. For further consideration idle load and full power were taken. Each spectrum were transferred as matrixes MS and copied like fingerprints to the database. Spectra were not synchronized to the revolutions of rotors, at the same loads in different air temperature conditions vary each other, and it caused the preparation at the procedure of identification as follows. It appeared as an important point of analysis because of sensitivity of typical spectra – figure 3.

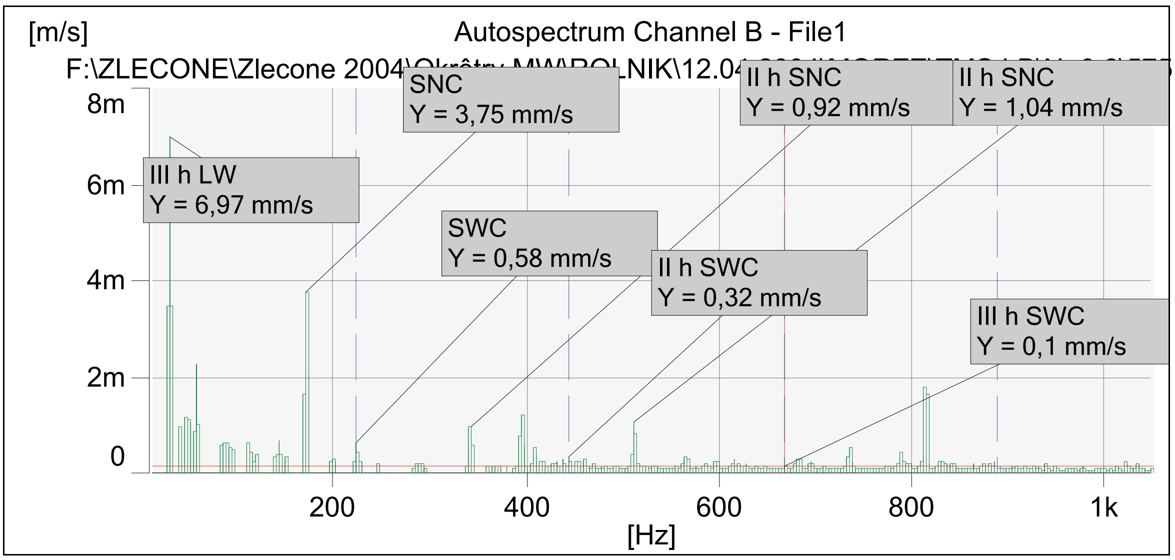

Fig. 3. Typical pattern spectra DR 77 engines
where: SNC – low-pressure compressor rotor, SWC – high-pressure compressor rotor, h – harmonics

5. Diagnosing of shafts misalignment

Usual measurement methods of coaxiality parameters of the propulsion system require disassembling protection covers of shafting between engines and reduction gears. Measurement conditions make it necessary to suspend operation of the COGAG-system for about 8 – 10 days and it is of course intrusive method. A vibroacoustic method presented in this paper allows assessing permissible values of the alignment parameters without stopping exploitive use of the vessel. Moreover, the presented results are intended to form the data base for elaboration of an on-line monitoring system of coaxial of torque transmission elements, applicable to the COGAG propulsion system in question.

Dynamic reactions, resulting from exceedance of allowable alignment deviations of the torque transmission elements are able to cause failure of the propulsion system and even lead to loss of movability of the vessel in a relatively short time [2]. Therefore diagnostic control of the gas turbine power plant in operation became necessary.

Appropriate assembling the main engines and the other torque transmission elements inclusive of propellers is practically determined by a set of tolerated dimension and geometrical location requirements, called geometrical dimension assembling chain [3]. Both typical and modular power plants are prone to coaxiality deviation from its permissible values and in consequence to possible failures one or more elements of the propulsion system. The excessive deviation can lead to the loads on bearings and gear teeth much higher than calculated and in result to their premature failures [4].

The usual control methods of the coaxiality deviations do not fulfil user’s expectations in the case of the gas turbine propulsion system. Difficult access to flange connections, long control time, organisational difficulties and lack of qualified personnel create hazards of taking measurements with errors exceeding allowable values. The proposed vibroacoustic method instead of the usual coaxiality control methods was assumed the aim of this work on result of an analysis of the earlier mentioned operational hazards.

Application of the vibroacoustic diagnostics to technical maintenance makes its possible to lower operational cost of the vessel by basing its operational on its actual technical state and predicted failure states [1].

It was assumed that determination of a relationship between the coaxiality parameters and changes of the recorded vibration signals should bring about identification of the proposed diagnostic model consisting in:

- Choice of geometrical parameters describing the position deviations, i.e. axis slope and displacement;
- Choice of adequate parameters of the vibroacoustic signal;
- Determination of mutual relationships between sets of the coaxiality deviations and vibration diagnostic parameter values;
- Sensitivity assessment of the symptoms in question;
- Establishing the database for statistical analysis and operational decision making.

The research in question was limited to control of the axis slope only. This assumption was made to account for influence of the displacement hull deflection on the element position of the serial multi-shaft system. In this case the axis displacements are controlled solely during assembling the shafting system in the production and repair stages.

The energy emitted in result of a change of technical state of the flange connection was assumed to be reflected in the recorded vibration signal. By using experiments, position and fitting direction of accelerometers were chosen at the transverse cross-section of the transmission gear just over the main, radial bearing of the input shaft. On the basis of detail identification of the main signal against disturbances the lateral measurement direction with respect to the rotation axis was determined. The coaxiality measurements were carried out in the conditions of not transmitting the torque to the ship propeller.

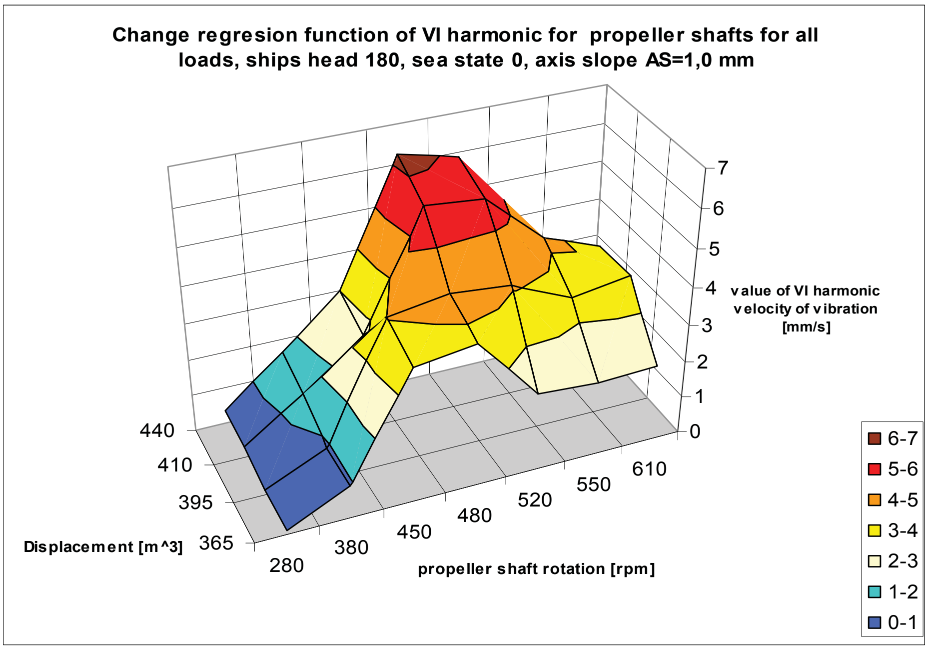

Fig. 4. Exemplified archive charts of the investigation results

The results were analysed by assigning the mean value of the vibration signal, i.e. the VI harmonic connected with the excitation frequency of vibration velocity amplitudes, to the measured axis slope value. Archive charts of the investigation results are exemplified in Fig. 5. In result three conclusions dealing with general measurement principles could be elaborated as far as the investigated vessel is concerned:

1. It is important to determine the limiting values of the selected symptom at different vessel displacements. The proposed method can be applied in the entire range of the vessel's displacement.
2. Assessment of axis slope at the flexible coupling on the basis of the symptom in question is of a secondary importance.
3. Selection of the accelerometer fitting position is the most important because of close vicinity of the propulsion (reduction) gear main radial bearing. Accelerometer cantilevers applied during the measurements did not influence measurement results, as their resonance frequencies were higher than that of the selected vibration symptom.

It was also stated, of the basis of analysis of the investigation result, that the mean signal value VI harmonics of velocity vibration increases as the vessel's displacement increases, at the axis slope Z = const. For much better recognising technical state data base are presented as 3D charts of different axils slope – figure 4.

During the investigation no limit state of the axis slopes of Z = 1 mm/m was found in the propulsion system in question. A regression function of the symptom changes at different vessel displacement was calculated to determine the limiting (tolerated) values of the symptom. In result three conclusions dealing with general measurement principles could be elaborated as far as the investigated vessel is concerned:

Accelerometer cantilevers applied during the measurements did not influence measurement results, as their resonance frequencies were higher than that of the selected vibration symptom.

6. Remarks

- Application of the proposed approach makes managing the engine's operation time much more rational, especially at its end.

- The proposed approach is non-invasive and does not require taking the ships out of service.
- Realisation of investigations of the kind makes it possible to collect data for a database of the future monitoring system of ships which is expected to improve their operational features.
- Experience gained during the investigations would be utilised for other power plants equipped with gas turbines.
- Presented method is enough sensitive in operation of propulsion plant that it enables to find primary symptoms of changes technical state of rotordynamics.

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