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APPLICATION OF COHERENCE FUNCTIONS OF VIBROACOUSTIC SIGNALS FROM PISTON ENGINES, RECORDED IN SET STATES, FOR THEIR TECHNICAL EVALUATION

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Abstract

This paper presents the results of the test carried out on the Sulzer 6 AL 20/24 engine. The study was carried out during the testing following a restoration of two turbochargers of the type Napier C 045 / C. The article attempts to evaluate the suitability of the coherence function between the signals coming from diagnostically sensitive selected points of turbocharged piston engine. The study primarily focused only on the turbocharged piston engines, as it is this type of engine, which is currently the most widely used in the shipbuilding industry, both for main propulsion boats and marine plants. The paper contains results of first step of researches, focused on possibilities of using new methods in nondestructive technical state monitoring.

Keywords: *vibration, reciprocating engines, coherence*

Introduction

The aim of the study was to record vibration signals at selected points of the engine, and using the coherence function, to determine the degree of usefulness of this method of analyzing noise and vibration signals for technical inspection of piston turbocharged marine engines. Authors consider application of results coherence function as a symptom of qualitative diagnostic of combustion engines. Researches results were verified with results of the active experiments made in test bed of the engine.

The study was conducted in three stages. In the first stage, spatial selection of vibration signals of a marine piston engine was carried out. The remaining phases focused on the measurement of vibration signals and their analysis. The study used two types of refurbished turbochargers of the type Napier C 045C. It should be noted that the turbocharger has been renovated by an external company and their condition was evaluated just before a substantial part of the study. As a result of evaluation, it was concluded that one of the turbochargers was fully efficient while the latter was characterized by a significant unbalance of the rotor (acceleration value was above a_{RMS} = 20 m/s^2 - implemented to measure the bearing of the motor when the maximum power was reached).

The analysis of vibration signals can determine the suitability of the coherence function determined for the signals coming from the cylinder heads and the signal from the turbo, to evaluate the technical condition of marine turbocharged piston engine.

Description of the research

The study was carried out on six-cylinder, linear, four-stroke, turbocharged engine SULZER 6 AL 20/24 with the following specifications: diameter of the cylinder D - 0.2 m; stroke S - 0.24 m; the compression ratio π - 12.7; rated speed n - 750 rev / min; rated power N_e - 420 kW; fuel injection pressure p_w - 24.5 Mpa; firing order 1-4-2-6-3-5; number of valves: 2 inlet and 2 outlet. The engine is equipped with a turbocharger Napier C 045 / C at maximum speed n_s = 41000 rev / min; the number of turbine blades equal to 13 and the number of compressor blades to 15. The receiver of the power and torque from the engine is a water brake of type DPY6D securing the motor throughout the full rev range.

Prior to the testing of engine, the condition was verified by carrying out the process of indicating pressure of all cylinders and by making vibration measurements of the base frame. The study confirmed the good condition of the engine according to the quality assessment classification of indicated pressure and vibration standards PN-90/N01358. The test engine is shown in Figure No. 1, Figure 2 is a diagram of the position, on which the study was conducted.

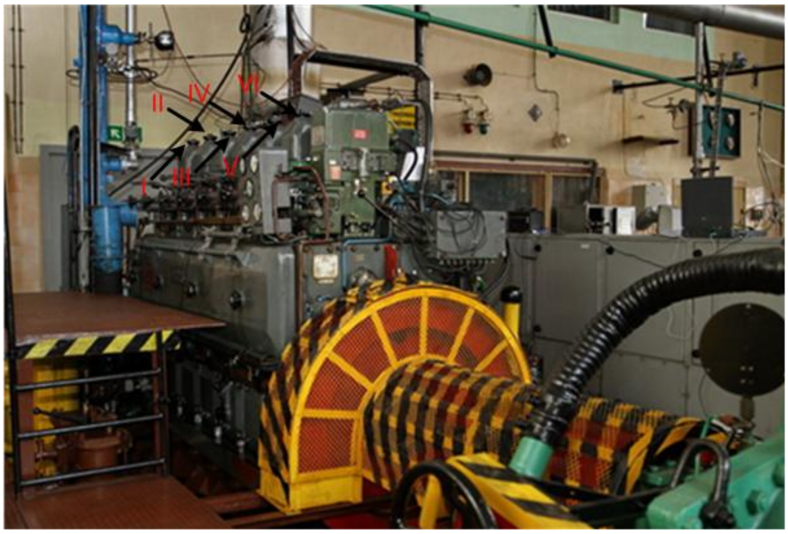

Fig. 1 The position of the piston marine engine type SULZER 6AL20/24

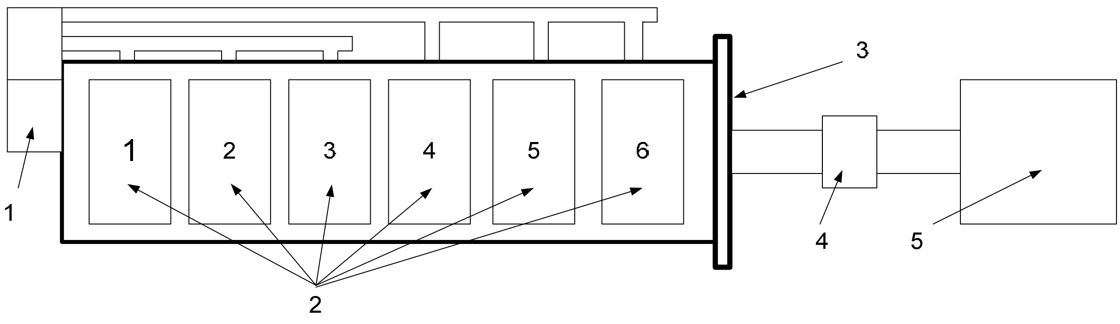

Fig. 2 Test set up. 1 – Napier C - 045 / C turbocharger, 2 - cylinder heads, 3 - flywheel, 4 - bearing bracket, 5 - DPY6D water brake

Spatial selection of vibration signals for the determination of the values, locations and ways of the measurement

The analysis of vibration signals of the piston engine is complicated due to the complex nature of the signal that is caused by the simultaneous operation of multiple sources [6].

Marine piston combustion engine is an object subject to the action of direct and secondary excitation and external influences. Vibration signal recorded in a random part of the body is the sum of responses to all elementary events occurring at the functioning time, such as: reciprocating movements of the piston systems, valves, needle injectors, crankshaft rotational movements, timing, turbocharger, gear drives of suspended mechanisms, and pressure pulses associated with the combustion and fuel delivery to the cylinders.

Vibration signals generated by each kinematic pair and accessories of the piston engine can be considered as non-stationary due to the prevalence of different types of backlashes, and non-linear characteristics of elastic elements. Frequency characteristics of the signals depend significantly on transmission path of the propagation of component signals from the source to the measurement point [6]. For this reason, it is advisable to measure as close to the selected source of vibration as possible.

After a theoretical analysis of extortion occurring in the engine and structural analysis of potential data points as the accelerometer mounting locations, the motor heads from I to VI were selected (Figure 1 and 2) – as the most sensitive to changes in pressure in the cylinder, and the body of the plain bearing turbocharger.

During the measurements using two accelerometers type B & K 4514B were used. One of them was permanently fixed on the hull of the turbocharger, and the other mounted successively on all of the cylinder heads. Measurements were carried out in the vertical direction, in line with the gas-dynamic forces occurring during operation. Simultaneously with the measurement of vibration signals, measurements of the rotational speed of synchronous signal were carried out on the motor shaft using optical probe MM024.

After measuring the still warm accelerometers recalibration was done in order to find out the influence of temperature on the work of calibration of the transducer.

Methodology

Measurements were carried out at an engine speed of n = 600 rev/min. For each of the turbochargers two series of measurements were performed. In the first series, the aim was to analyze the relationship between vibration signals coming from the measuring points for a fully efficient fuel system of the engine. The second option predicted simulation of the injector failure of one of the cylinders. For this purpose, the dose of fuel was reduced using the overflow valve located on the injection pump (motor has an independent one-section injection pump for each cylinder). The degree of simulated damage was examined by driving continuous indicating of pressure waveforms in the engine cylinder [4]. By reducing the dose of fuel, a reduction of its combustion in the pressure cylinder was obtained. The results of this procedure are shown in the graph - Figure 3, where the upper gray line shows the course of the pressure in the cylinder during normal operation of the fuel system whereas the red curve underneath represents the pressure after reduction of the dose of fuel. As you can see the value of the maximum pressure in the cylinder of a simulated inoperative injector decreased from $p = 6.92$ MPa to $p_1=5.13$ MPa which confirms that the damage was simulated correctly. All measurements were carried out after stabilization of the operating parameters of the engine. At the time of registration of vibration signals sampling frequency of $f_p = 8192$ Hz was used, while the analysis bandwidth was limited to f = 0.5 Hz - 3.2 kHz.

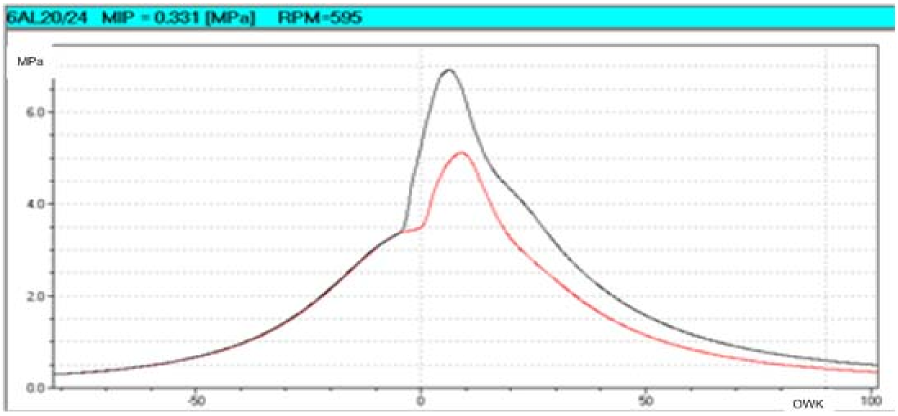

Fig. 3 Graph of cylinder number 6 - upper curve shows the course of the pressure in the efficient fuel system, lower curve shows it at partially inefficient system

Results of the study and their analysis

Aim of this study was to analyze the vibration parameters and assess the usefulness of the coherence function in the diagnosis of supercharged marine reciprocating engines. In order to achieve the task PULSE software was used, in which spectral analysis was performed using a linear velocity scale. An example of such analysis is shown in Figure number 4. It shows the velocity spectrum of vibrations during the measurements using the efficient turbocharger. The continuous red line represents the spectrum recorded in the sixth cylinder head during its normal operation. The green dotted line refers to the spectrum recorded at the same point in time as simulating a damaged fuel system of that cylinder. Table 1 shows the velocity values read for 10 consecutive harmonics

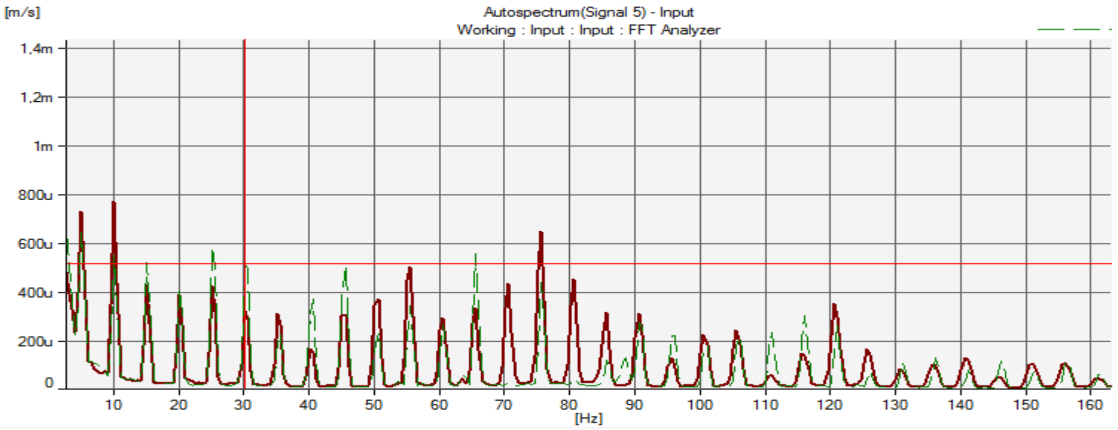

Fig. 4 Amplitude-frequency spectrum of velocity recorded at six cylinder during normal operation - solid line, and the damaged fuel apparatus - the dotted line

Table 1 Velocity amplitude measured at the head of 6-efficient and faulty injector

Number of the harmonics	I	II	III	IV	V	VI	VII	VIII	IX	X
value of v [mm/s] – injector “efficient”	0,77	0,38	0,32	0,16	0,37	0,24	0,23	0,45	0,31	0,22
value of v [mm/s] – injector "inefficient"	0,54	0,41	0,51	0,22	0,37	0,23	0,26	0,03	0,04	0,16

It should be noted that in spite of such a large change in simulating the fuel injection pressure it is not possible to diagnose a malfunction of the unit on the basis of the measurements, since the values of the amplitudes do not exceed the limits set out for example in the standard

PN-ISO 10816 [9]. Therefore, in the search for more sensitive symptoms, the authors reached for the coherence function and the cross - spectrum as potentially sensitive, dimensionless, intermediate parameters.
Coherence function which is a measure of the consistency of vibroacoustic two processes is defined as follows [1,4,6,10]:

$$\gamma_{xy}^{2}(f)=\frac{\left|G_{xy}(f)\right|}{G_{xx}(f)G_{yy}(f)}, \tag{1}$$

where:
x - the signal recorded on the hull of the turbocharger,
y - the signal recorded on the next cylinder heads,
G_{xy} (f) - the function of the cross-spectrum of signals x and y,
G_{xx} (f) - the function of the auto spectrum of the signal x,
G_{yy} (f) - the function of the autospectrum signal.

In a not so sophisticated, fully operational devices coherence function between the vibration signals from different points of the device will take a value of 1 or close to 1. However, any damage will be a new source of vibration signals and will affect the consistency of the existing functions i.e. decrease the value of the coherence function [2,3]. It is slightly different in the situation of such complex device i.e. supercharged piston engine. Sample coherence function between the signal recorded on the turbocharger (reference signal) and the signal recorded on the sixth cylinder head, Figures 5 and 6. Figure 5 shows the situation in which the engine is fully operational, whereas Figure 6 shows the results of a series, in which a failure of the injector of sixth cylinder is simulated.

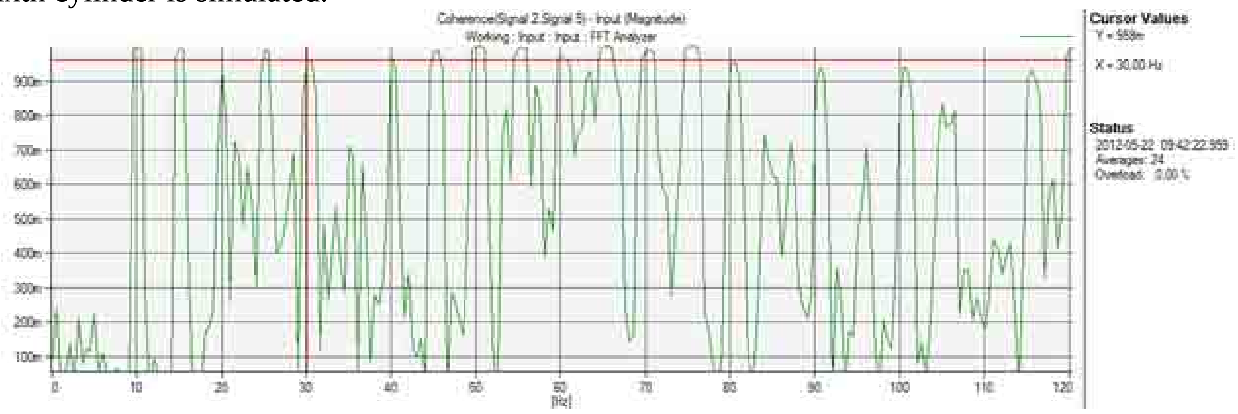

Fig. 5 Running of the coherence function calculated for the signal from the turbocharger (reference signal) and signal from the 6th cylinder head during totally smooth engine operation

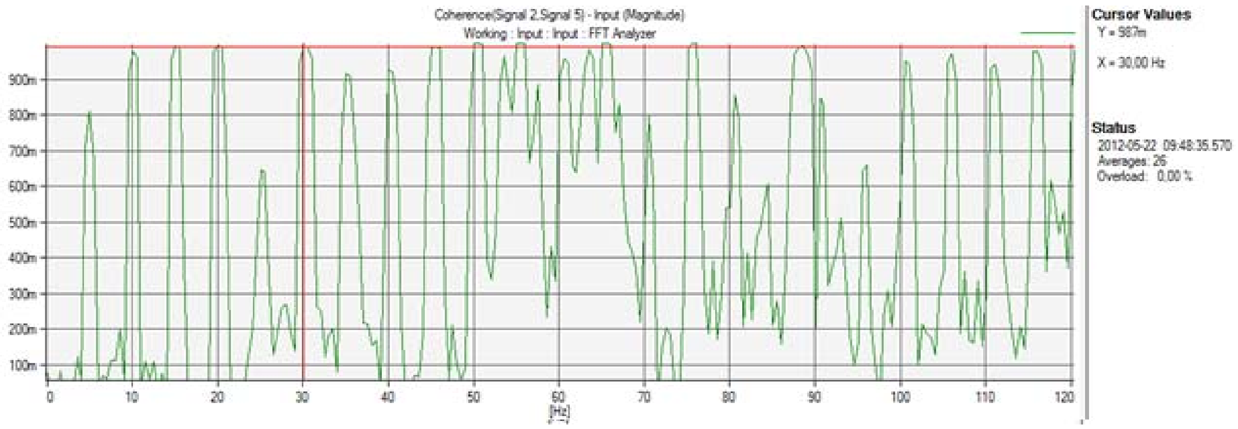

Fig. 6 Running of the coherence function calculated for the signal from the turbocharger (reference signal) and the signal from the 6th cylinder head registered during a simulated fuel apparatus damage of the 6th cylinder

The analysis of all recorded signals was made in a similar matter and the values of the coherence function between the signals recorded on the hull of the turbocharger and the signals from the consecutive engine heads for all previously presented series of measurements. It should be noted that the vibration signal coming from the hull of the turbocharger was always treated as a reference signal. The values of the cross-spectrum function and the autospectrum of the two signals were also recorded. Readings were performed at the frequency corresponding to the harmonic of the speed of the engine (I to X harmonic).

The analysis of the vibration signals recorded during a smooth engine operation

Measurement 1,2…,6 (meas. 1,2…,6) responds to measurements made during recordings on head 1,2…,6, one of the accelerometers was permanently mounted on turbocharger the second one was mounted successively on all engine heads.

Figures 7 - 10 show the results of analysis of the smooth engine vibration. On Figure 7 we can see fairly high velocity amplitudes of harmonic VII of engine speed resulting from additivity of velocity amplitudes of the basic harmonic of the rotational speed of the turbocharger.

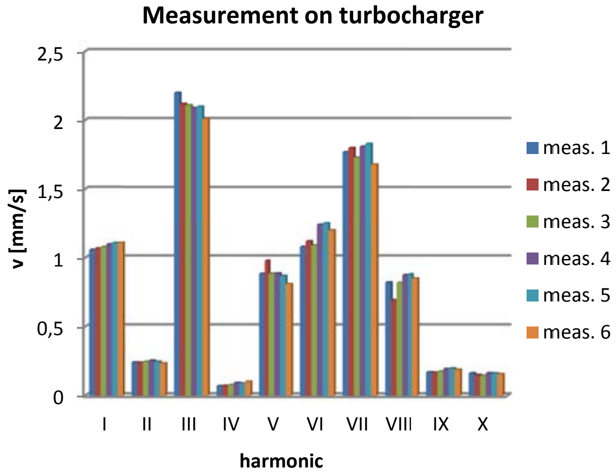

Fig. 7. Velocity amplitudes of turbocharger vibrations – efficient engine

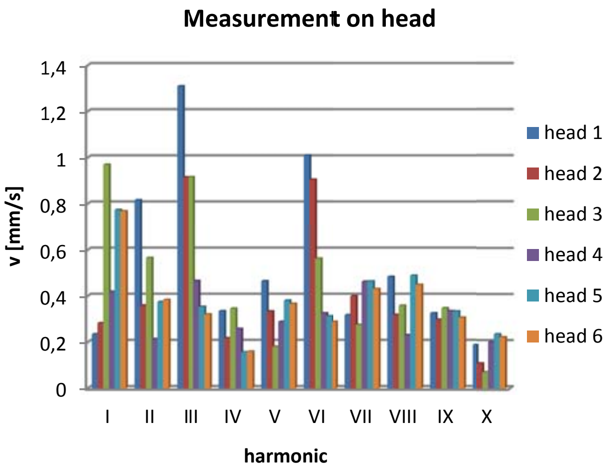

Fig. 8. Velocity amplitudes of engine heads – efficient engine

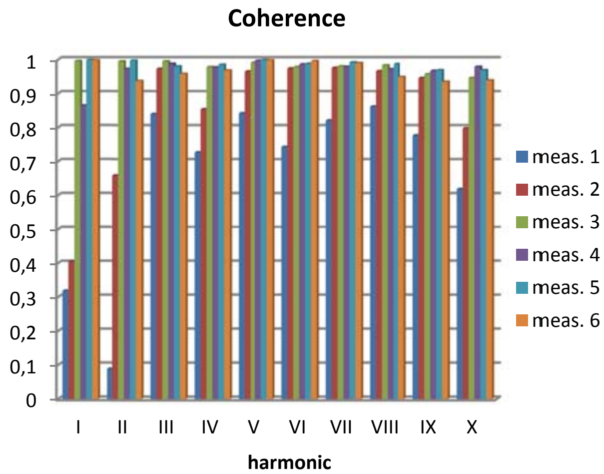

Fig. 9. Values of coherent functions – efficient engine

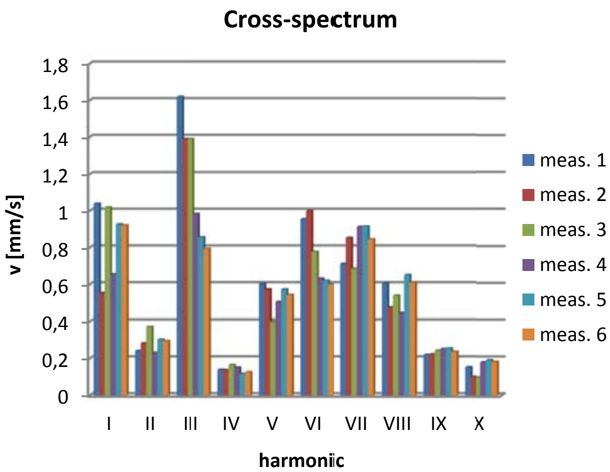

Fig. 10. Values of the cross – spectrum function – efficient engine

In addition, the dominant values are the values of harmonic III and VI of rotational speed of the engine, which is associated with the combustion process (three times to force the turn - six-cylinder four-stroke), and the forces of inertia (six excitations per revolution). You'll also see a low value of the coherence function for the signals coming from cylinder 1 and 2 and the turbocharger.

The analysis of the vibration signals recorded at the time of the experiments - damage to the fuel system of the 6th cylinder, efficient turbocharger

In the case of a decrease in the fuel injection pressure in one of the cylinders, values of the individual harmonics measured on both the heads and the turbocharger do not vary much, however clearly visible is the increase of the coherence function between the signals of 1st and 2nd cylinder (simulated damage on the cylinder No. 6) - figure 13

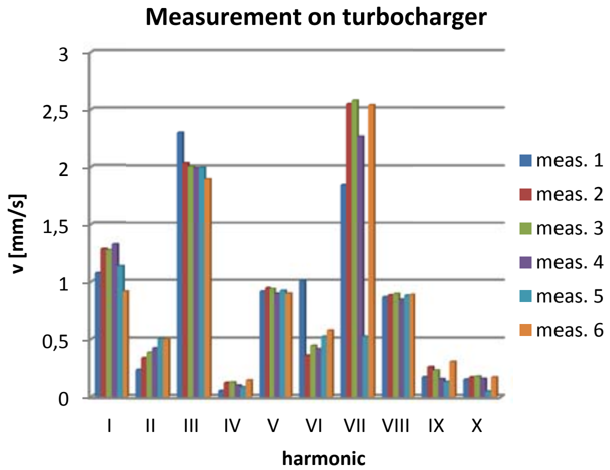

Fig. 11. Velocity amplitudes of turbocharger vibrations – damaged cylinder no. 6

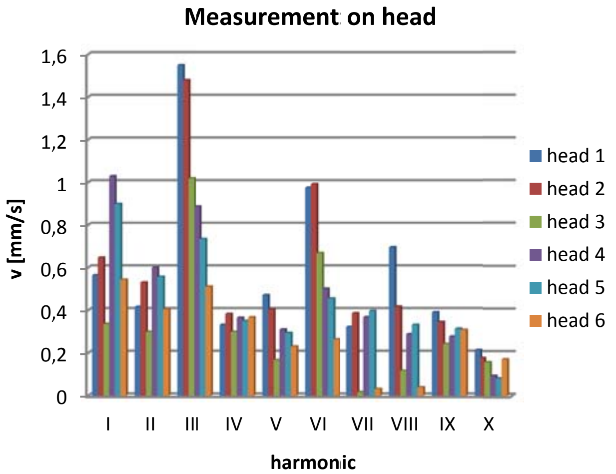

Fig. 12. Velocity amplitudes of engine heads vibrations – damaged cylinder no. 6

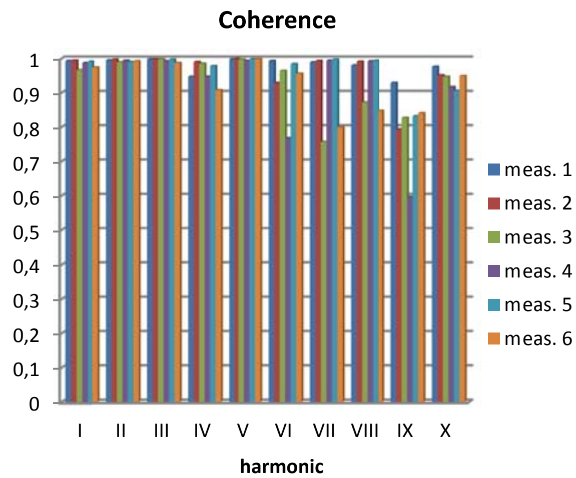

Fig. 13. Values of the coherent function – damaged cylinder no. 6

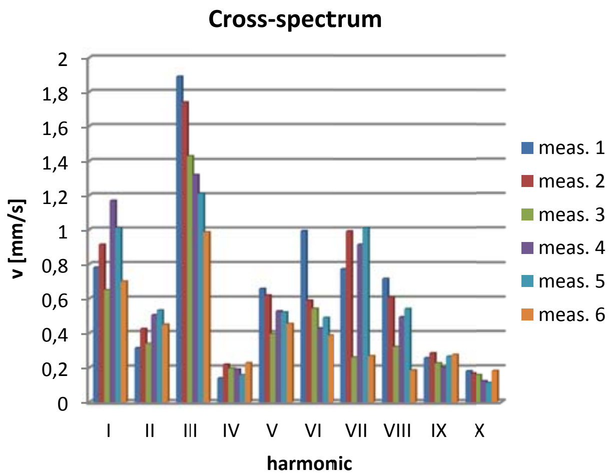

Fig. 14. Values of the cross- spectrum function – damaged cylinder no. 6

Efficient fuel system, turbocharger failure due to unbalance

In case of a turbocharger rotor unbalance, while maintaining proper operation of the fuel system of all cylinders, still the dominant harmonic are the III and VI harmonic of engine speed. Looking at the values of the coherence function, a decrease in its value for the signals coming from the turbocharger and the 2nd, 3rd and 4th cylinder is seen - Figure 17.

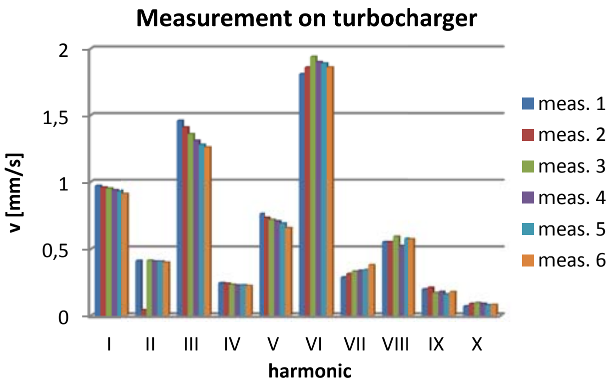

Fig. 15. Velocity amplitudes of the turbocharger vibrations – damaged turbocharger

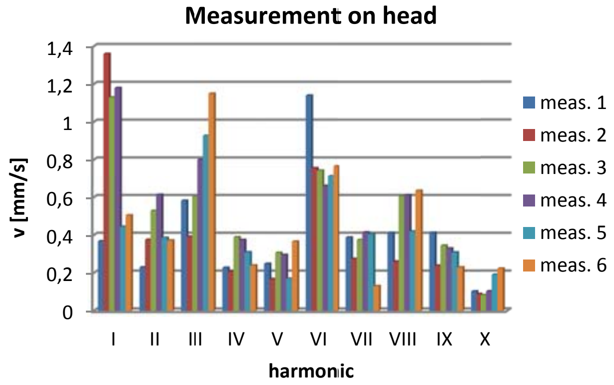

Fig. 16. Velocity amplitudes of the engine heads – damaged turbocharger

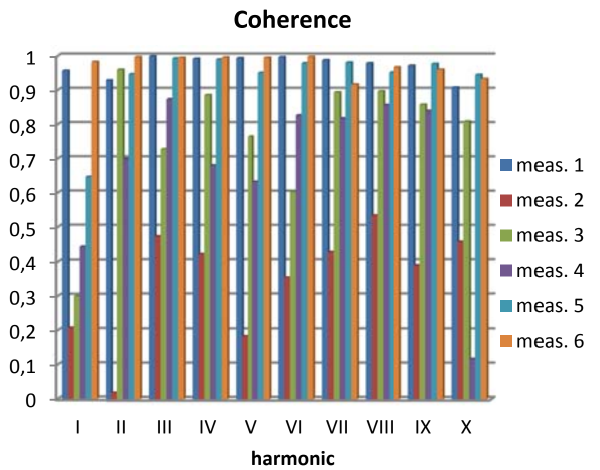

Fig. 17. Values of the coherent function – damaged turbocharger

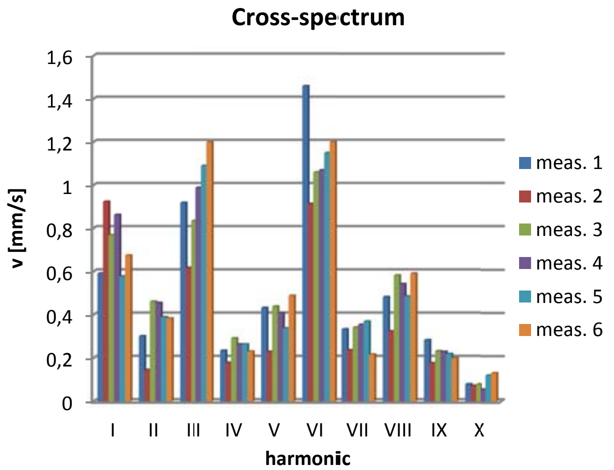

Fig. 18. Values of the cross – spectrum function – damaged turbocharger

Simulating damage to 5th cylinder and turbocharger failure due to unbalance

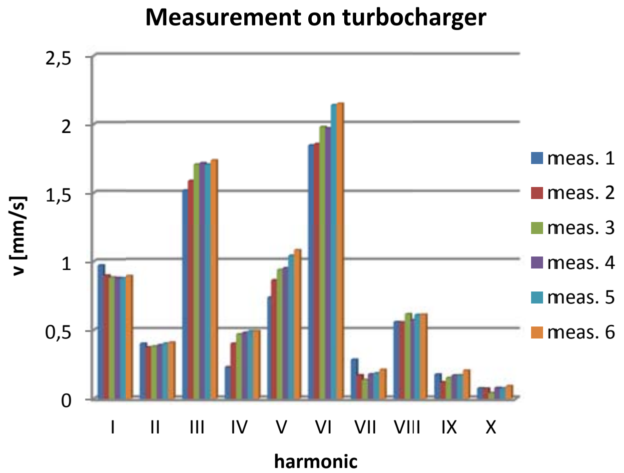

Fig. 19. Velocity amplitudes of the turbocharger vibrations – damaged turbocharger and 5th cylinder

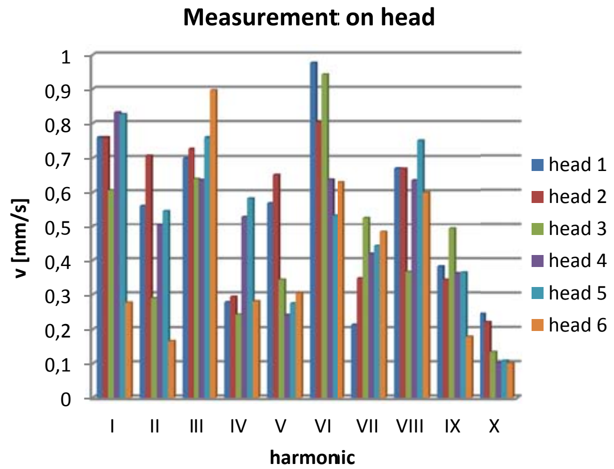

Fig. 20 Velocity amplitudes of the engine heads vibrations – damaged turbocharger and 5th cylinder

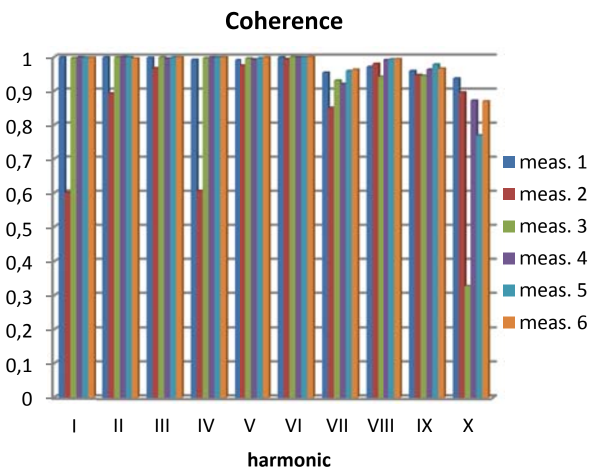

Fig. 21. Values of the coherent function – damaged turbocharger and 5th cylinder

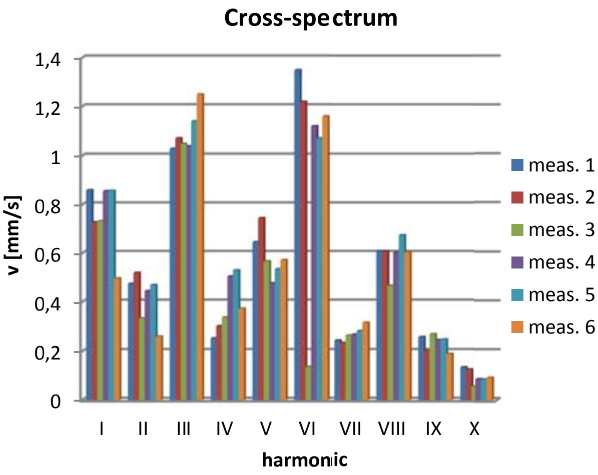

Fig. 22. Values of the cross – spectrum function – damaged turbocharger and 5th cylinder

Considering the situation in which the engine is running with a faulty turbocharger and damaged injector an increase in the value of the coherence function is observed - Figure 21.

Conclusions

The analysis provides a clear statement that the dominant harmonics in all spectra of the two measuring points are III and VI harmonic of vibration speed of the engine speed. The high value of the third harmonic is caused by gas-dynamic forces resulting from the combustion process taking place in the six-cylinder engine, while the VI harmonic is related to the forces of inertia of the crank-piston engine.

The read values of the coherence function vary quite considerably. It is therefore observed here that the fall in the value of the coherent function between the signal from the turbocharger and cylinder heads can mean that one of the cylinders has a faulty injector. Unambiguous quantification of this relationship is the subject of further ongoing research.

It should be noted that the lowest values of the coherence function occurred when the damage was the turbocharger rotor unbalance. It can therefore be a working hypothesis that the declining value of the coherence function between the signal from the turbocharger and cylinder head can mean a poor technical state of the turbocharger.

An essential symptom observed in the course of the analysis is the fact of a significant increase in the value of the coherence function at the frequency corresponding to subharmonic ½ of fundamental frequency of the rotation speed of the engine in cases where the engine is running with a malfunctioning injector (Figure 5 and 6). This phenomenon was observed regardless of the cause of deterioration of the engine condition. This will be further examined during a series of further laboratory tests and a simulation model implemented in a MatLab environment.

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