ISSN 0554-6397
Prethodno priopćenje
(*Preliminary communication*)

Andrzej Grzadziela
E-mail: a.grzadziela@amw.gdynia.pl
Marcin Kluczyk
E-mail: m.kluczyk@amw.gdynia.pl
Polish Naval Academy, Smidowicza 69 str, 81-127 Gdynia, Poland

A Non-invasive Method of Marine Engines Fuel System Diagnostics

Abstract

Small naval vessels are equipped with high- and medium-speed engines with low diagnostic compliance. Faults in fuel installations are the most common cause of failure or inability to perform operational scenarios adequately. Identification of injector damage is severe as small engines are not equipped with indicators and thermocouples to measure the overall exhaust gas temperature in the exhaust manifold. The paper presents a vibration method for assessing the technical condition of a fuel installation. The proposed method is non-invasive and allows the indication of a damaged injector within a relatively short time. The paper presents simulation results verified with stand-bed tests. The research aimed to show the sensitivity and uniqueness of vibration symptoms to changes in the technical condition of fuel injection pumps. The conducted experiment confirmed the possibility of using vibration tests in the professional diagnostics of the fuel installation. These results are essential for the use of marine engines that do not have indicator valves.

Keywords: diagnostics, fuel system, injector, vibration

1. Introduction

One of the most hazardous problems in the operation of marine engines is the technical state of fuel installation. Despite the widespread use of filters and efficient purifiers on ships, the quality of fuel is the most common cause of engine malfunction and its shut-off during the operation [11].

The research results presented in the paper concern the possibilities of using vibration techniques in health monitoring of the engine fuel installation. The test results relate to high-speed and medium-speed marine engines. The main objective of researches are to confirm the sensitivity and unambiguous of vibration symptoms to changes in the technical condition of fuel injection pumps.

The next objective was to determine the sensitivity of vibration symptoms analysed in the domain of time and frequency. Both goals were to fulfil the task of diagnosing fuel installations using portable, commonly used analysers.

So far, the diagnosis of the fuel engine installation has been carried out by measuring the in-cylinder gas pressure or by measuring IAS (Instantaneous Angular Speed) of the crankshaft [5]. The first method requires an assembly of indicator valves in the engine while the second one is effective at the laboratory stand because the hull vibrations at sea bring a significant error of measurements.

Vibration methods in the diagnostics of marine combustion engines have been widely used for many years [6, 7, 8]. The most commonly used diagnostic activity is Torsional Vibration Analysis (TVA). The procedure is mainly used in propulsion systems with low - speed engines. The main task of this action is to determine the shaft speed irregularity, torsional vibration and natural frequencies of the system: main engine -shaft line -propeller [2, 4].

Torsional vibration tests are mainly related to changing different timings and flows of the low-speed engines. Besides tests focus on specific fuel oil consumption and oxides emission. Such actions result from the possibility of measuring pressure gases in the engine cylinders [3]. The problem increases when the analyses relate to medium- and high-speed engines, most often used in Gen Set, which usually do not have indicator valves. This situation points out that gas pressure measurements cannot be made and the use of laser or strain gauge techniques is significantly impeded and subject to significant errors. Vibration tests are one possible and practical diagnostic technique.

Theoretical backgrounds for the identification of changes in vibration parameters caused by dysfunction of the fuel installation are presented in the paper [10]. Paper presents the numerical simulations of failures of fuel system components and the vibration response in the form of amplitude - time and amplitude - frequency performances. The simulation results were validated in the engine-stand experiments, and the obtained mean relative errors are satisfying.

The identification of engine's turbochargers wear has been relatively well identified and implemented in the [1] exploitation process. The work presents the identification of lubricating oil vortex and radial run-out in bearings in the rotor of the turbochargers. The symptom analysis was carried out in the frequency domain. Literature analysis points to the increasing importance of vibration in technical diagnostics in operational problems of the marine engines.

2. Aims and Objectives

The study aims to quantify the sensitive vibration parameters that identify the proper combustion process of marine diesel engines. The primary assumption is the unambiguity of vibration parameters that play a crucial role in performance load characteristics — the main driving force for the diagnosis of the fuel installation [9].

The study investigates the effects of vibration induced by malfunctions of fuel installation components and the usefulness of time domain and spectral vibration analyses. The main objectives of this researches are the following:

- Gain sufficient understanding about the effects of single and multiple malfunctions of injectors on combustion characteristics as a vibration signal.
- Investigate the impact of wrong the injection in the time waveform domain and the FFT analyses.
- Highlight the benefits of the vibration diagnosis for marine diesel engines.
- Investigate the effects of the number malfunctioned injectors on the quality of the diagnose.

3. The object of the researches

The research object was a marine engine Sulzer 6AL20/24 type, which is a 4-stroke, in-line diesel engine, non-reversible, water-cooled with direct fuel injection and firing order 1-4-2-6-3-5– Figure 1. The main elements of the engine injection system are Bosch single-section injection pumps and six injectors. The injection pump can adjust the end of injection. The pump construction allows simulation of its malfunction by changing the discharge pressure. It is advantageous because the most common inefficiencies affecting the combustion process are the reduction in the pressure of the fuel delivery pressure and the change in the moment of the pressing start.

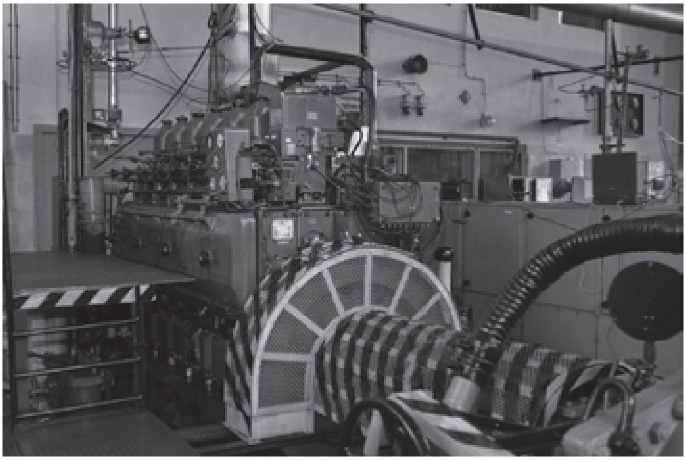

Figure 1: The research object - a marine engine Sulzer 6AL20 / 24 type.

Simulation of injection pump damage was carried out while the engine was running in laboratory stand. The malfunction was simulated by adjusting the dose of fuel poured in the pump. The tests were carried out for engine speeds of 500 rpm and

750 rpm and loads resulting from the propeller characteristics of the tested engine, i.e. 1.3 kNm for 500 rpm and 3.3 kNm for 750 rpm. This goal was accomplished using a hydraulic Froude type brake, integrated with the engine. The measurements were carried out for three technical states of the engine fuel installation, i.e. for a properly operating installation, for the simulated malfunction of the injection pump cylinder No. 1 and simulated failures of injection pumps of cylinder No. 1 and No. 3.

During the tests, measurements of the combustion pressure were carried out, and the amount of fuel from the pump to the injector was adjusted to achieve a maximum combustion pressure of 20% lower than for a fully operational fuel installation.

The vibration accelerations in the vertical direction to the plane of the engine foundation were recorded while the measuring points were the head bolts of the subsequent engine cylinders [10]. The choice of sensor assembly directions resulted from the spatial selection of signals and the distribution of the primary vibration, primarily gas forces. Triggering signals were recorded in the freewheel of the engine, which allowed identification of ignitions in subsequent cylinders.

4. Test results

The investigations were carried out in laboratory conditions to obtain repeatability of results and their statistical analysis. The Pulse LabShop measurement systems and Pulse Reflex analysing systems were used in researches [10]. The first level of investigations was performed in the acceleration signals of the time waveform domain. The main goals of the time domain researches were the ability to identify amplitudes change with simulated pressures rate changes and to automate obtaining a correct diagnosis of the fuel installation. The next level was the acceleration signals FFT analysis to get receptive symptoms in the frequency domain. The last level of research was to assess the possibility of identifying malfunction of at least two or more injectors during one session type: measurement - analysis type.

4.1. The results of the time waveform analyses

Studies in vibration acceleration on all head’s bolts have been pre-made on a fully functional fuel installation. The primary task was to determine the Top Dead Center marker (TDC) precisely and to measure the relative error of the acceleration on all cylinders. Before the tests, a routine check of the injection pressure on all injectors was made. The relative error of the values of all injectors were less than 0.6%. The results of an exemplary analysis of signals recorded on the cylinder No. 3 presents Figure 2.

The tests of the vibration acceleration signal on a properly working engine fuel installation were carried out in 60 seconds; the relative error of amplitude of acceleration was 2.85%. The results should be considered satisfactory, confirming unambiguous vibration symptom even in the conditions of disturbances during the engine operation.

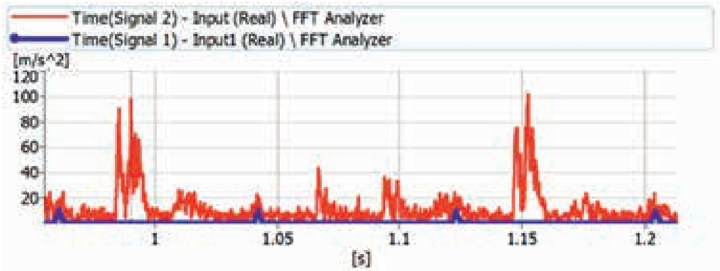

Figure 2: Time waveform of acceleration on cylinder No. 3 - red marker, phase marker signal - blue marker.

The second step was to analyse the impact of 20% fuel injection on the one injection pump – No. 1. The measurement was carried out on the cylinder No. 3 - Figure 3.

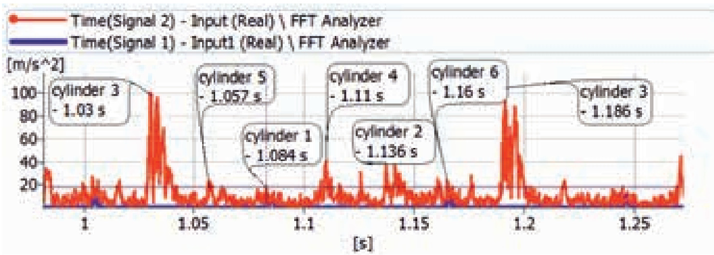

Figure 3: Time waveform of acceleration on cylinder No. 3 - red marker, phase marker signal - blue marker.

It was noted that the value of accelerations forced by the combustion process in cylinders equidistant from the measuring cylinder No. 3 has different values. The value of vibration acceleration for the cylinder 1 was by 12.3% lower than the vibration acceleration values of a correctly operating injection pump on the cylinder No.5. Subsequent tests on cylinders 2, 3 and 4, where the pressure on the cylinder No. 2 injection pump was lowered what confirmed this relationship with a difference of 16.3% compared to the cylinder No. 4. Analyses show that not only the measurement of consecutive cylinders allows the identification of changes in combustion pressure, but single test on one cylinder represented an initial, qualitative diagnosis of a potential reduction in injection pressure at any of the cylinders.

4.2. The results of the FFT analyses

FFT analyses were intended to assess the quality of diagnosis in time and frequency domain. Figure 4 presents a comparative analysis of the spectrum of vibration accelerations measured on cylinder No. 6 at engine speed n = 500 rpm and load N = 45%.

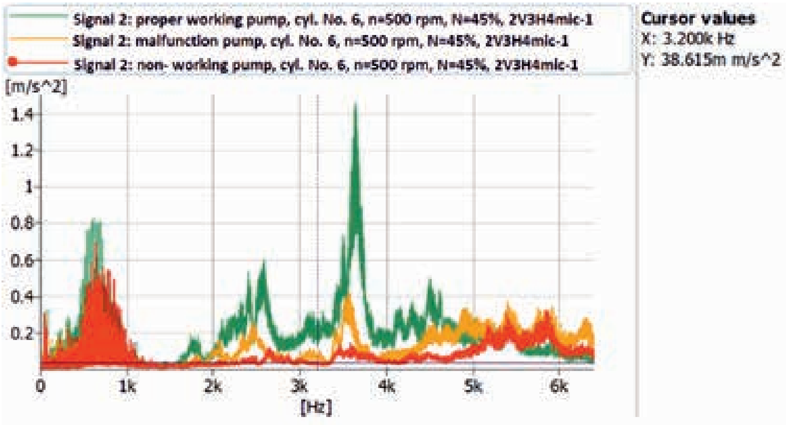

Figure 4: Spectral analysis of acceleration on cylinder No. 6, properly operating pump – green marker, 20% lower injection pressure - yellow marker, non-working injection pump – red marker.

The analysis of the spectra indicates significant differences between the correctly operating injection pump, work with the malfunction and non-work pump. Significantly lower amplitudes of vibration accelerations in almost the entire measurement band, there are no resonant beats in the higher frequency band - approx — 3.7 kHz. The lack of a resonant signal is the result of the lack of hard strokes of the plunger related to the cyclic opening and closing of the injector.

The next tests indicated that the resonant frequencies of all injectors are very close, i.e. between 3.6 kHz and 3.8 kHz. The relative error of the acceleration amplitudes for correctly working injectors was 4.5%.

The tests analysed the possibilities of using harmonic analysis of vibration parameters. Harmonics have identified 6-cylinder operating processes for 4 - stroke engine. An example of harmonic analysis and mid-band analysis for vibration acceleration is presented in Figure 5. The comparative analysis of selected harmonics and their ratio values gives information about the technical condition of the engine injection system. However, it does not provide an unambiguous indication of which of the injectors or injection pumps are malfunction.

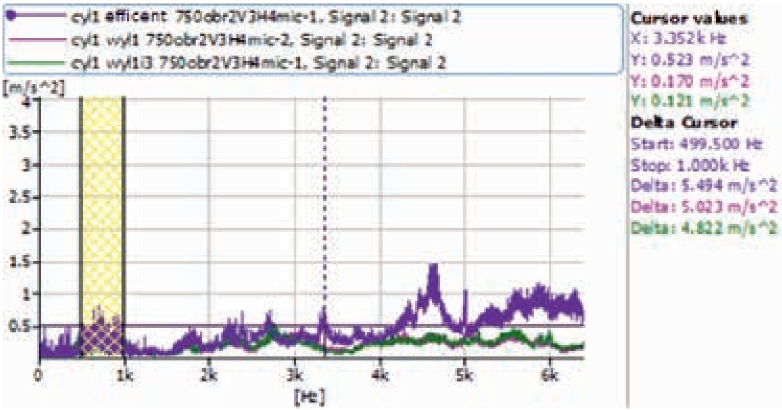

Figure 5: Band-pass filter and harmonic analyses of acceleration on cylinder No. 1, n= 750 rpm, properly operating injection pump – violet marker, non-working injection pump No. 1 – pink marker, non-working injection pumps No. 1 and No. 3 – pink marker

4.3. Rating of the diagnose complex fuel system damages

The use of vibration technology in the diagnostics of fuel installations of marine engines is possible and useful. Malfunction of one injection pump or one injector can be detected quite easily both at time waveform analysis and with the use of FFT analysis. The problem increases when failure is two or more fuel installation elements. What's more, the level of their technical condition is relevant. Qualitative and quantitative diagnosis will be possible when the following recommendations should be taken into account:

- Carry out measurements and analyses for an efficient engine for at least three speeds and three different loads and treat the obtained data as a reference one,
- Use triggering to determine TDC precisely,
- Neglect results that fall within the range of ± 5%,
- Carry out tests on all cylinders, omitting the first and last ones,
- Adjust the sampling to the natural frequency operating of the injector Measurements lead to head's bolts,
- Measures and analyses lead as time waveform of acceleration.

5. Conclusions

The analysis of time waveform and FFT type vibration parameters confirmed the sensitivity and unambiguity of results for simulated malfunction of one injection pump or injector as well as for complex failures of the installation elements. The fundamental issue is to obtain reference values of vibration parameters in the state of full efficiency of both the fuel installation and the engine.

The choice of measuring and analytical tools should meet the requirements, i.e. triggering and at least 2 - channels recording. It means that the proposed method is cheap and can be carried out by the ship's technical staff. The issue of the database is a separate topic but also does not require specialised diagnostic tools.

References

1. TOMASZ LUS: *„Vibro-acoustic methods in marine diesel engines diagnostics"*, Journal of KONES Powertrain and Transport, Vol. 18, No. 3 2011.
2. PRZEMYSŁAW KOWALAK: *„Speed irregularity characteristic of low speed, two - stroke marine diesel engine appliedas vessel's main propulsion"*, Journal of KONES Powertrain and Transport, Vol. 15, No. 4 2008.
3. JOHN-HARLEY MAASS JOHNSSON, JAN SALDH: *„Analysing the effects variable injection and exhaust valve timing have on a two-stroke diesel engine"*, Mekanik och maritima vetenskaper/ Mechanics and Maritime Sciences, Chalmers University Of Technology, Gothenburg, Sweden 2018.
4. DON CHOOL LEE, RONALD D. BARRO: *„A Study on the Torsional Vibration Characteristics of Super Large Two Stroke Low Speed Diesel Engines with Tuning Damper"*, Journal of the Korean Society for Noise and Vibration Engineering Volume 19, Issue 1, pp. 64-75, 2009.
5. ADAM CHARCHALIS, MIROSŁAW DERESZEWSKI: *„Experimental method of evaluation of diagnostic value of the angular speed discrete signal from free end of the Crankshaft",* Diagnostyka - Applied Structural Health, Usage and Condition Monitoring' 3(63)/2012, pp. 18-22.
6. L.BARELLI, G. BIDINI, C. BURATTI, R.MARIANI: *„Diagnosis of internal combustion engine through vibration and acoustic pressure non-intrusive measurements"*, Applied Thermal Engineering 2, 1707–1713, ISSN:13594311, 2009
7. A.P. CARLUCCI, F.F. CHIARA, D. LAFORGIA: *„Analysis of the relation between injection parameter variation and block vibration of an internal combustion diesel engine",* Journal of Sound and Vibration, 295, pp. 141–164, 2004.
8. G. O. CHANDROTH, A. J. C. SHARKEY, N. E. SHARKEY: *„Cylinder Pressures and Vibration in Internal Combustion Engine Condition Monitoring"*, Neural Computing and Applications, vol. 9, Pp. 152–160, ISSN 0941-0643
9. ANDRZEJ GRZĄDZIELA, MARCIN KLUCZYK: *„Simulation Model of Four Stroke, Six Cylinder Marine Diesel Engine",* Solid State Phenomena (Volume 236), pp. 113-118, 2015.
10. MARCIN KLUCZYK., ANDRZEJ GRZĄDZIELA: *„High and medium speed marine diesel engines injection installation vibration diagnostic",* Diagnostyka, vol. 18, no. 2, s. 37-42, 2017.
11. DAMIAN MARKUSZEWSKI, "*Poszukiwanie przyczyn wzrostu poziomu drgań i hałasu w koparce hydraulicznej*," Przegląd Mechaniczny, no. 5/18, pp. 45–48, 2018 [eng: *Investigation of the causes of increased levels of vibration and noise in a hydraulic excavator*]