Vibroacoustic analysis of marine engine supplied with mixture of fuels

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Abstract. The main purpose of this paper is to obtain the differences in the vibrations of engine (Doosan MDT196TI) which was powered using two different fuel mixtures – liquefied natural gas with diesel pilot and diesel only. LNG and diesel oil differ in combustion temperature, density, and cetane number; the combustion process of various fuels proceeds differently, so it has an impact on the generated vibroacoustic vibrations (vibrations have a direct impact on the degree of machine degradation). In the research, the diagnostic system is based on piezoelectric accelerometers and Digital Signal Processing operations (windowing, Fast Fourier Transform). In the conclusions section the obtained results are analysed, indicating how the tested fuels have an effect on vibrations.

1. Introduction

From the very beginning of the use of internal combustion engines, the most optimal fuel combination has been searched. First the engines operated at excessive fuel to air ratio which generated great losses in the system of both fuel and power [1, 2]. At the same time with great automotive technological advancements (electronics control system for injectors) it was also crucial to design new types of fuel that would be in compliance in new standards of both emissions and power control. Engines needed high octane or cetane number fuels that provided enough heat to make them work.

Researchers at top crude oil companies are working on various eligible options like biodiesel, hydrogen, alcohols, compressed natural gas (CNG) and liquefied petroleum gas (LPG). However, with further development of oil chemistry new fuels have been introduced, which were both reliable in terms of preventing engine knocking (high octane) and ecological. The need for more engineered fuels instead of products of crude oil was also driven by a more green approach of society and politics. LNG gas is the last, widely tested and approved for popular use in heavy vehicles and ships [2-4]. The mixture of LNG and diesel (dual fuel) makes it possible to obtain more power (torque), which is used in engines that drive ships (table 1). We cannot overlook the ecological aspects of supplying with a mixture of these fuels.

2. Dual fuel

The values presented in table 1 are the reason why manufacturers are introducing dual fuel combustion into their engines. It is an indirect solution to the problems occurring when using diesel or LNG only.
The tests that were conducted by leading massive engine manufacturers show that the use of methane in its liquidized form can be a great addition to normal diesel combustion. It provides up-close combustion parameters that the diesel engine has to meet, but visibly limits fumes toxicity and flowing particles out of the exhaust system. Engines that were powered with LNG only lacked enough power and torque, but were much more eco-friendly than their diesel counterparts. By using double fuel systems operators can benefit from both solutions – diesel for power and torque, – LNG for price reduction and ecological aspects [1, 4]. With the reduction of costs and increased greenness of that solution more and more transport solutions providers will favour the combination. The adaptation for a dual fuel solution to a pre-era diesel engine is simple and many qualified workshops in Europe provide solutions for operators to install the system. As a diesel engine does not have spark plugs that could ignite the fuel mixture the Diesel working principle cannot be fully fulfilled. Thus the engine cannot run on LNG only and it needs to be replenished with gas oil.

| Table 1. Power/Torque of different fuel composition in diesel engine [4]. |
|-----------------------------|-----------------------------|
| Maximum torque, Nm          | Maximum power, HP           |
| Diesel powered engine       | 1800-2300                   | 400-550                      |
| LNG powered engine          | 1500                        | 330-340                      |
| Dual powered engine         | > 2000                      | > 500                        |

On the other hand, there was an issue that can be observed when the engine runs on LNG only. Natural gas consists mostly of methane, which has a much bigger and stronger greenhouse effect than CO2. The problem that is widely addressed when powering the machine with LNG is called methane slip. It occurs when the unburned fuel leaves the engine through the exhaust. Methane poses a real threat to the environment when released as it has 86x more GWP (global warming potential). If the methane slip is not controlled properly the environmental benefits from using LNG powered engines are wasted and completely cancel the advantages. Another hazardous thing about using LNG on vessels or trucks is how the gas is stored as it needs to be cool enough to stay in its liquid state [4].

In spite of the many hazards that still need to be taken care of LNG powered engines lay a bright future of the ICE as the future means of powering transport. LNG implementation in future solutions depends on key factors:

- Gas availability;
- Demand for ships and heavy trucks;
- Emission limits (especially greenhouse gases);
- LNG tank installation and operation;
- Safety requirements.

To ensure that the climate will be taken into consideration future rules of emission compliance will be harsher and harder to fulfil. The use of LNG reduces sulphur oxides by nearly 100% and nitrogen oxide by about 90% [1, 4]. Such limitations should not pose a threat to manufacturers with great experience in dealing with much more complicated diesel engines and their equipment.

The mixture of fuels affects the engine power. It is associated with the combustion process, which has a direct impact on vibration (ergonomics). In many scientific works, vibrations have been shown as the factor of the degree of engine degradation. Therefore, it should be checked whether LNG, in addition to the above-mentioned beneficial economic and ecological features, does not affect the degradation of the machine by introducing redundant vibrations.

3. Research object

The object of the research was heavy duty marine diesel engine with 320 HP of power. Its characteristics are mentioned table 2 [5]. DOOSAN MD196TI is one of products of Korean based engine manufacturer which specializes in marine powering units and transmission. MD196TI is one of its key product with great capabilities and wide applicability – from small vessels to smaller cargo ships. Eleven litters of
Displacement in inline 6 type engine creates much power and torque which is further accompanied with turbocharger. Direct injection of fuel which is combined with precise computer management system allows for accurate control over fuel metering and exact point of injection in time. This type of fuel feed is great for optimal spray pattern which breaks the fuel droplets into atomized fog. With the use of direct injection the engine gets better power/ emission ratio as more fuel is burned and the air/fuel mixture can stay at stoichiometric level for the whole combustion. What is more as the engine is a heavy duty type it was subjected to a test of fuel type change that consisted of direct feed of liquefied natural gas into the intake manifold. Further with the use of diesel pilot the combustion may take place and the engine was easily transformed into one with dual fuel set. This work focuses on a comparison of the engine characteristics after fuel change.

Table 2. Engine characteristics of DOOSAN MD196TI marine engine [5].

| Engine type | 4 cycle, in-line, direct injection, water cooled with turbo charger and inter-cooler |
|-------------|----------------------------------------------------------------------------------|
| Rating output, kW/rpm | 235 / 2000 |
| Displacement, cc | 11051 |
| Cylinder number – bore (⌀) × stroke, mm | 6- ⌀123×155 |
| Low idling, rpm | 725 ± 50 |
| No load, max. Idling, rpm | 2300 |
| Compression ratio | 16,5 : 1 |
| Firing order | 1 – 5 – 3 – 6 – 2 – 4 |
| Governor type of injection pump | Mechanical Variable Speed (R. S. V.) |
| Fuel consumption, l/h | 58.61 |
| Starting system | Electrical by motor |

4. Research methodology

Measurements were taken using piezoelectric accelerometers and a National Instruments Data Acquisition – DAQ equipment. The accelerometer characteristic of gathered data is one of the most critical issues to be addressed when conducting vibration tests, because wrongly selected measurement device will cut out the most important data or the accelerometer can even be destroyed in the process.

For collecting the data from the accelerometer (PCB 353A – table 3) National instruments data acquisition card was used together with NI cDAQ-9215. The NI cDAQ-9215 is a 1-slot NI CompactDAQ USB chassis designed for small, portable sensor measurement systems.

Table 3. PCB353A accelerometer used in tests [6].

| Sensitivity, mV | 10.19 ± 10% |
|----------------|-------------|
| Measuring range, m/s² | ± 491 |
| Frequency range, Hz | 1-4000 ± 5% |
| Frequency range, Hz | 0.7-6500 ± 10% |
| Resolution, g RMS | 0.0005 (for 1-10 Hz) |

The engine was placed on a measuring stand, which complies with the industry standards for testing equipment and mounting points. A stationary mounting stand prevents overemphasis of the engine movement and gives the accelerometers the opportunity to conduct the test correctly. The engine was supplied with every medium it needed to run through the whole operation.

As can be seen in the diagram (figure 1) the engine was supplied with all the media and accompaniments that made it easier for the data logging process to be correctly carried out. Engine load during operation was connected via clutch to electro wired brake steered directly by electronic controlled system. That allowed the operators to specify the load with great precision and get correct result, which
could later on be compared. Fumes from the exhaust system were discharged from the testing room using a pipe that was specially chosen for that kind of application.

![Diagram of the research stand.](image)

**Figure 1.** Diagram of the research stand.

The mounting point of the piezoelectric accelerometer has been chosen with great accuracy and several places have been considered, but as the engine characteristic shows the greatest amplitude of vibration should have come from the engine piston movement. Having that in mind and the purpose of this work, which is to determine the difference in the vibration characteristic with different fuel feed, it was determined that the best place was the engine head in one of the already threaded apertures. The sensor was placed on the engine head.

Four different states were taken from the original test results for comparison. The states differ from each other per rpm and load under which the engine was tested. States which were taken into consideration for vibration measurement were the standard states of the engine during operation taken from the characteristic given by the producer (1000 rpm / 500 Nm, 1400 rpm / 700 Nm, 1600 rpm / 1300 Nm, 2000 rpm / 1100 Nm [5, 7]).

Raw data from accelerators cannot be taken into consideration as valuable information data. Accelerometers data will be used to calculate the dominant harmonics of the engine with Fast Fourier Transform (FFT) [8]. In digital signal processing, filtration in the form of windowing (Hamming window) was used to extract the appropriate diagnostic information.

5. Results

The signal that was collected from the accelerometer had 8192 samples which lasted 2 seconds. That gives the 4 kHz as the sampling frequency of signal. From the Nyquist rule of frequency which states that for the maximum frequencies to be possible to be exact and correct they should not exceed half of the sampling frequency. Thus the frequency has been limited to 2 kHz. Most of the vibrations were already in that scale so it did not interfere with the final accuracy of the periodograms. What is more the ISO standard says that engine vibration analysis should cover the bandwidth of 0 Hz (DC component) to 1 kHz as those frequencies carry the most energy which could destroy the machine [9]. To obtain more accurate diagnostic information, a windowing operation was performed (figure 2).
Figure 2. Example of measured (and conditioning via windowing) vibroacoustic signal.

Figure 3 is an example of comparative periodogram of engine vibrations powered by various fuels.

Figure 3. Frequency answer of one of engine tested state – 1600 rpm/1300 Nm (red – oil, blue- LNG).

The vibration amplitude value of the engine changed depending on the burning characteristics, engine load and rotations per minute. Each set of rpm and power has its own harmonic which is a result of the combustion in the cylinders [10, 11]. Dominant harmonics were calculated based on the principle of firing order that could be seen in the engine data characteristics. According to the literature inline 6 should have its harmonics that are connected to CF as 3rd order of the rotations per minute frequency. Table 4 presents the harmonics that were calculated directly from CF and rpm. As the engine in question was the inline 6 it has one of the best inherited balance. It is a result of the working principle and firing order of that kind of cylinder numbers. Each piston has its own pair and they work as a counter balance to each other – meaning that the vibration that comes from combustion force, the 2nd order vibration is well balanced in that engine. The periodograms corroborate with that statement. Further harmonics of the CF for each rpm and load could also be seen in the diagram [12].

Further harmonics that were not result of combustion force or engine order taken from rotation but further dominant frequencies of other oscillation are: 150, 200, 765 Hz and high frequent 1250 Hz.
Table 4. First engine harmonic depending on rpm and corresponding magnitude of vibration.

| Engine speed, rpm | Fuel type | Dominant harmonic, Hz | Magnitude, abs |
|------------------|-----------|-----------------------|---------------|
| 1000             | LNG       | 50                    | 0.01037       |
|                  | Oil       |                       | 0.01038       |
| 1400             | LNG       | 70                    | 0.00785       |
|                  | Oil       |                       | 0.00901       |
| 1600             | LNG       | 80                    | 0.01370       |
|                  | Oil       |                       | 0.00904       |
| 2000             | LNG       | 100                   | 0.00732       |
|                  | Oil       |                       | 0.00568       |

The values in table 5 show the magnitude of the engine harmonics at different loads and rpm. From a direct comparison of the rpm values it is clearly visible that the engine was at a higher level of vibrations that were in the frequencies from 1 Hz to 1 kHz and lower in the spectrum above those values. It means that lower frequencies that transfer greater energy are more present in the engine operation. The above statement was true for both LNG and diesel, but it is also viable to ascertain that LNG produced vibrations with greater frequency wave. It was observed that for all frequencies above 500 Hz the LNG produced more energetic oscillation, which may be a direct product of the fuel characteristics of combustion.

Table 5. Further engine harmonics depending on rpm and corresponding magnitude of vibration.

| Engine speed, rpm | Fuel type | Harmonics, Hz |
|------------------|-----------|---------------|
|                  |           | 150           | 200 | 765 | 1250 |
| 1000             | LNG       | 0.00494       | 0.00338 | 0.00077 | 0.00174 |
|                  | Oil       | 0.00562       | 0.00433 | 0.00010 | 0.00032 |
| 1400             | LNG       | 0.00324       | 0.00532 | 0.00103 | 0.00142 |
|                  | Oil       | 0.00250       | 0.00312 | 0.00130 | 0.00071 |
| 1600             | LNG       | 0.00254       | 0.00362 | 0.00099 | 0.00090 |
|                  | Oil       | 0.00536       | 0.00563 | 0.00053 | 0.00118 |
| 2000             | LNG       | 0.00546       | 0.00488 | 0.00286 | 0.00241 |
|                  | Oil       | 0.00579       | 0.00649 | 0.00097 | 0.00083 |

As it was predicted in the introduction the engine had most vibrations in the low spectrum of frequencies, which is the outcome of the working principle of compression ignition engines. In comparison to the spark ignition engines they have much higher compression ratio, which is a main source for the great combustion force [11]. What is more, diesel engines differ from SI in that they add fuel to cylinders almost at the top dead centre of piston is achieved. Thus, fuel atomization and mixing with the compressed air is not complete. Such incompleteness generates huge force disturbances in the cylinder forces as the pockets of high concentrated fuel burn with greater energy in comparison to the lean mixture.

The root mean square values of the engine vibrations that were measured can be seen in figure 4. According to the ISO norm the RMS should be calculated at frequencies from 1 Hz to 1 kHz to be viable for most destructive forces in the engine. Calculations were made in MATLAB software after limiting the frequency scale to the values mentioned above. The values of the obtained accelerations clearly determine the vibration profile of the engine. It is clearly seen that the LNG fuelled engine was at a higher level of vibration in 3 out of 4 measurements taken. Only for the operational speed at 2000 rpm the engine fuelled with liquidized natural gas was subjected to lower oscillation force in this frequency spectrum.
As this work focuses on the comparison of fuel blends it is viable to check which one of the fuels achieved lower magnitude in the harmonics that were created directly from the combustion force. The CF harmonics gives direct information about the combustion process and the forces that were induced from burning the fuel. As both diesel and LNG have different calorific values and different temperature of combustion the forces that were created in the combustion chamber were also much different. With each temperature point difference in the cylinder also the final pressure has changed which is directly connected to the working principle of the compression ignited engine. Table 6 shows that at 1000 rpm the engine achieved more or less the same vibration level that was created by the combustion forces. As the engine was designed and manufactured to operate on diesel fuel only it should not be a surprise if the engine would have a greater value of vibration when different fuel was supplied.

Table 6. Difference of vibration magnitude in the first harmonic of the obtained vibroacoustic signal.

| Engine speed, rpm | Fuel type    | Dominant harmonic, Hz | Lower Magnitude |
|------------------|--------------|------------------------|-----------------|
| 1000             | LNG; Oil     | 50                     | –               |
| 1400             | LNG; Oil     | 70                     | LNG             |
| 1600             | LNG; Oil     | 80                     | Oil             |
| 2000             | LNG          | 100                    | Oil             |

Table 7 presents which of the fuel mixtures had lower magnitude of vibrations at different further (higher) harmonics.

Table 7. Difference of vibration magnitude in higher harmonics.

| Engine speed, rpm | Fuel type    | Harmonics, Hz |
|------------------|--------------|---------------|
|                  |              | 150 200 765 1250 |
| 1000             | LNG; Oil     | LNG LNG Oil Oil |
| 1400             | LNG; Oil     | Oil Oil LNG Oil |
| 1600             | LNG; Oil     | LNG Oil LNG LNG |
| 2000             | LNG; Oil     | LNG LNG Oil Oil |

During the research, it was examined how the vibration volume changes during load changes and rotation speed. It also studied how different fuels affect vibration. Most of the values were part of the G-force, which is inherent to the performance of the in-line engine 6, which is very balanced. It also
shows that the engine has been correctly mounted because no resonance can be seen from the visible attachment points. Most vibrations were visible at 1000 rpm, which was the lowest rpm value recorded in the engine. For the operational rotational speed at which the motor normally operated, the amplitude of the vibrations at all four harmonics took the smallest values. The LNG driven engine had a higher level of vibration when it comes to high frequencies in all of the researches states.

6. Conclusions
Dual fuelled engines that use LNG as the fuel for the operational rotation speed are the future of the marine industry as their capability to generate the same power and lower the fuel consumption is great. The high frequency vibrations that were the result of combustion could easily be counteracted by specialized appliances and should not be problematic to solve. Further fuel consumption reduction and environmental causes should persuade the industry that even supplying existing diesel engine with LNG through the intake manifold, thus removing the need of specialized changes in the structure is a favourable thing. As emission controls and upcoming emission regulations both for marine and land vehicles will be more and more restrictive the engine manufacturers should take the dual fuel solution into consideration as it will greatly help to be in compliance with the standards. The present study clearly shows that there is great change of vibration level when it comes to lower rpm, which are below the operational level of the engine. Thus the engine should not be powered with just one type of fuel, but then after the engine is warm enough to provide better combustion parameters of the liquidized gas it would change. As it has been already mentioned the LNG is often the by-product of the transportation system and could easily be used in marine vessels powering units.

The only real issue that is still to be addressed is the not big enough access to the fuelling stations across the ports around the world. However, that should change when more and more engine manufacturers turn to dual fuel solutions.

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