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Influence of Butanol-Diesel Oil Fuel Blends on Marine Engine Vibration Characteristics

Marcin Kluczyk[1]*

[1] Mechanical and Electrical Engineering Faculty, Polish Naval Academy, ul. Śmidowicza 69, 81-127 Gdynia, Poland
* Corresponding author's e-mail: m.kluczyk@amw.gdynia.pl

ABSTRACT

One of the primary sources contributing to vibrations in operational marine diesel engines is the combustion process of fuel injected into the cylinders. Hence, alterations in the injection process and the quality and type of fuel supplied to the engine can modulate the combustion parameters, consequently impacting noise and vibration levels. A literature review on this subject suggests that while some research has been conducted, mainly focusing on small engines in the automotive sector, there's been a limited exploration in the marine domain. Despite the recent surge in manufacturers' interest in electrifying road transport vehicles, a similar trend has not been observed in sea transport besides short-range ferries, mainly due to the substantial range requirements of vessels. It is conceivable that the utilisation of liquid fuels in shipbuilding will persist. Presently, the predominant marine fuels are fossil-based, the reserves of which are progressively declining. However, the widespread adoption of alternative fuel additives like butanol holds promise in curbing fossil fuel consumption. One of the conditions to be met by a new commonly used fuel for marine engines is its good properties in limiting the parameters of accompanying processes like vibrations.The article delineates a comparative analysis of parameter values related to the vibrations of a marine engine fueled by different blends of butanol and diesel oil. Laboratory tests were conducted on a six-cylinder marine engine under load using a water brake, encompassing various engine loads to replicate real-world operating conditions accurately.

Keywords: vibrations, butanol, marine diesel engine.

INTRODUCTION

Marine engines burned the poorest quality residual fuels for many years. The emission of harmful compounds by ship engines has a significant share in the global production of air pollutants. The reason for the constant search for alternatives to fossil fuels, also in relation to marine engines, are the increasingly restrictive requirements of the Marpol convention [1]. IMO has set a global limit for sulfur in fuel oil used on board ships of 0.50% m/m (mass by mass) from 1 January 2020. The addition of butanol to residual fuels will easily reduce its mass share in the fuel.

Butanol exists in the form of four isomers: n-butanol (normal butanol), sec-butanol, isobutanol and tert-butanol, differing in both the position of the hydroxyl group and the structure of the hydrocarbon chain (straight or branched). Due to differences in structure, these isomers show specific differences in physicochemical properties (including boiling and ignition points). N-butanol was added to diesel oil obtained from crude oil during the tests.

Normal butanol (C_4H_9OH) (Figure 1), with a molecular weight of 74.12 g/mol, is a colourless liquid of medium volatility originating from alcohol, characterised by a distinctive banana-like unpleasant odour. It possesses flammability, evident from a flash point of approximately 35 °C and a boiling point of around 117.40 °C at 1013.25 hPa [2, 3]. Its favourable evaporative properties enhance both air and fuel vapour mixing rates, thereby improving combustion in fuel blends.

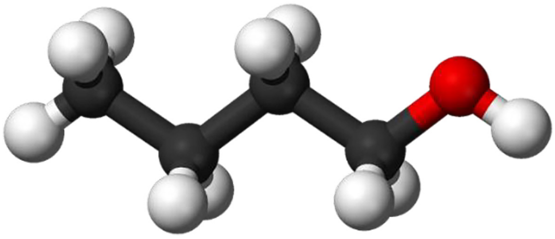

Figure 1. Normal butanol molecule [2]

Due to its molecular structure containing fewer carbon atoms compared to traditional diesel fuel, n-butanol facilitates enhanced combustion, leading to reduced emissions of both CO_2 and CO below the levels typically expected from straight diesel [4]. A comparison of the most important physicochemical parameters of n-butanol and diesel oil is presented in Table 1.

Butanol is used as an intermediate for organic synthesis, an additive to oils, and a raw material for producing solvents. The butanol production process is described in many publications. Butanol derived from biological sources seamlessly integrates into the present fuel framework, offering heightened energy density and performance when contrasted with ethanol. Moreover, its production can rely on more environmentally sustainable feedstock options than those utilised for biodiesel manufacture [8].

Compared to fuel blends using diesel and ethanol, the incorporation of butanol can effectively address certain issues related to phase separation due to its superior miscibility in diesel fuel. Moreover, blends consisting of diesel and n-butanol exhibit characteristics akin to pure diesel. Low-concentration n-butanol blends emerge as a viable substitute for compression ignition engines without requiring cetane booster additives, offering nearly identical specific fuel consumption rates. Additionally, there is the added benefit of reduced carbon accumulation in injectors and pistons [9].

Particularly important in the aspect of using butanol as an alternative fuel is the possibility of its production from biological waste. However, it should be noted that the vast majority of butanol is currently obtained from crude oil in petrochemical processes. Many centres are working on the possibilities of mass and cheap production of biobutanol as a result of processing biological waste [10]. A detailed description of biobutanol production can be found in [5, 11]. A comparison of the properties of biobutanol and butanol obtained in petrochemical processes can be found in [12]

The impact of adding biofuels and their pure combustion in piston engines has been and is the subject of research by many scientific centres [13–15]. The authors of the publication [16] examined the impact of butanol admixtures on the general vibration level of a car engine, finding that the level increases with the increase in the butanol content. The authors also researched butanol admixtures on emitted vibrations and noise associated with operating a single-cylinder engine [17]. In the case of these tests, a slight increase in vibroacoustic parameters was also found, along with an increase in the share of biobutanol in the fuel. This situation was especially noticeable in the case of higher engine torque loads. The publication [18] presents research conducted on a six-cylinder engine fuelled by n-butanol mixtures. The authors utilised n-butanol blends with conventional diesel fuel at 8% and 16% concentrations. Measurements were taken to assess exhaust smoke opacity and regulated gas emissions. The overarching conclusion drawn is that n-butanol can be safely and beneficially incorporated into diesel fuel blends at high ratios in diesel engines, demonstrating favourable outcomes regarding thermal efficiency and exhaust emissions [18].

During the investigation conducted in [19], sound and vibration signals emanating from a compact car engine were measured and analysed. Both frequency and angle domains were used. Pure diesel oil and diesel-butanol blends were used as fuel sources. Authors noted that the prolonged combustion duration characteristic of biodiesel might induce a notable surge in the kinetic energy associated with lateral piston movements.

Table 1. Basic parameters of n-butanol [5–7]

Specification	Molecular formula	Density [kg/m^3]	Viscosity [mm^2/s]	Auto-ignition temp. [^{o}C]	Flash point [^{o}C]	Freezing point [^{o}C]	Boiling point [^{o}C]	Cetan number
Diesel fuel	C_{12}–C_{25}	810–890	1.9–4.10	210–250	65–68	-30 to -40	180–340	40–55
n-butanol	C_4H_9OH	808–810	2.63–3.70	385–397	35	-89	112	17–25
Ethanol	C_2H_5OH	785–794	1.08–1.20	423–434	8-13	-114	78	5–8
Methanol	CH_3OH	790–796	0.58–0.59	463–470	12	-97	64	3–5

Consequently, this elevation in energy levels can result in heightened vibration intensity near the exhaust's top dead centre.

Butanol is not the only alternative fuel whose mixtures are tested for their suitability to power diesel engines. Many centres are researching the possibility of using biodiesels obtained from various organic sources, which are, therefore, renewable. Interesting research was published in [20], and vibration characteristics were examined, among others. This study aimed to investigate combustion, vibration, and knocking occurrences in diesel engines resulting from various fuel compositions. Interesting research was carried out, but it did not indicate a clear relationship between the type of fuel and its impact on the vibration level of the tested engine. Similar studies relating to the Jatropha biodiesel-fuelled genset engine were performed in the publication [21].

Research on the impact of vibrations and noise emitted by a single-cylinder engine powered by n-butanol and oleic acid methyl ester mixtures is presented in the publication [22]. However, the authors did not conduct tests for an engine powered by pure diesel oil.

Many different options are being considered, such as liquid fuels as an alternative to fuels made from crude oil. The work [23] describes the use of chicken fat biodiesel and its impact on the vibrations of the engine powered by it. Changes in the vibration characteristics of diesel engines after adding ethanol can be found in [24] and methanol in [25]. Research on lemon peel oil as fuel addition in terms of its impact on engine vibrations is presented in [26].

The presented literature review clearly shows that alternative liquid fuels to crude oil are being sought all over the world. Their impact on the performance of existing engines and the emissions of toxic compounds resulting from their combustion are also intensively studied. Much attention is paid to the effect of new fuels on the course of residual processes, including vibrations and noises. However, the literature review shows that small compression-ignition engines are tested in the vast majority of cases, much less often those of larger power trucks. The author found no publications discussing the research results on the impact of n-butanol additions to diesel oil on the vibrations of marine engines.

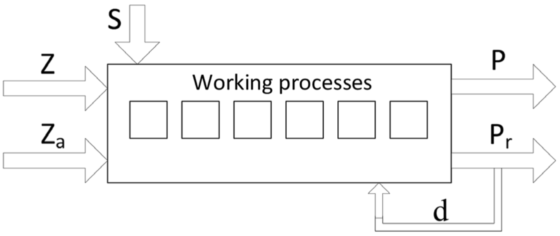

Figure 2. Piston engine as an object of technical diagnostics. Z – input parameters, Za – disturbances inengine operation, S – control, P – output product (power, torque), Pr – residual processes, d – destructive feedback

MATERIALS AND METHODS

One of the primary sources of noise and vibrations in a working marine diesel engine is the phenomena accompanying the combustion process of fuel injected into the cylinders. Therefore, the course of the injection process, as well as the quality and type of fuel supplied to the engine, may also change the parameters of the combustion process. If combustion parameters change, values describing noise and vibration may also change. The piston engine as an object of technical diagnostics might be presented in Figure 2. Currently, there is significant interest in the field of machine diagnostics, which is focused on tracking and inferring information based on observations of residual processes. These observations typically enable assessment of the technical condition of engines without the need for stop operations and disassembly. This publication explicitly addresses vibration parameter measurements among the various methods, such as acoustic and thermographic measurements. While alterations in vibration parameters of operational machinery serve as diagnostic indicators, it's crucial to recognise the detrimental effects of vibrations on engine performance. Consequently, a fundamental criterion for alternative fuels is that they must not exacerbate engine vibroactivity. It's important to acknowledge that vibrations in piston engines are inherent due to their design and operational principles. Figure 3 illustrates the distribution of forces in the crank-piston mechanism of a four-stroke marine diesel engine. A detailed description of the dynamics of the engine's crank-piston system can be found in many publications, e.g. [27]

The combustion process is one of the primary sources of vibrations in the engine, with unique amplitudes due to load changes or imperfections of the fuel injection equipment and differences in the combustion process itself.

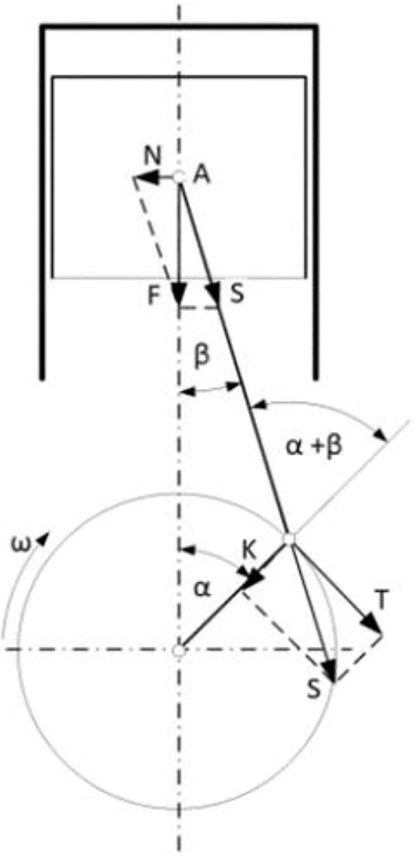

Figure 3. Basic forces in the crank-piston mechanism

Figure 4 shows an example of the courses of pressure indicated during fuel combustion at an engine load steady state recorded in individual cylinders of the 6 AL 20/24 engine.

The object of research on the influence of the addition of n-butanol to fuel on changes in vibration parameters was an engine, the indicator diagrams of which are shown in Figure 4. A photo of the research object is shown in Figure 5. The Sulzer 6AL 20/24 engine is a 4-stroke marine, in-line, non-reversing diesel engine, water-cooled with direct fuel injection. The engine is charged with a turbocharger, and the charged air is cooled. The test object is a clockwise rotating engine with a firing sequence 1-4-2-6-3-5, equipped with a multi-range Woodward PGA speed controller. The cylinder diameter is 200 mm, the stroke is 240 mm, the compression ratio is 1:12.7, the rated speed is 750 rpm, the rated power is 420 kW.

During the measurements, three rotational speeds were performed for each fuel mixture. Each measurement was carried out in the steady state of engine operation. For each engine speed, measurements were carried out for three constant torque loads, giving a total of nine measurements for each of the three tested fuel mixtures. The Figure 6 shows the detailed course of the research. Tests were carried out for three fuel blends:

- pure diesel fuel,
- 15% butanol and fuel mixture,
- 30% butanol and fuel mixture.

The presented results of vibration characteristics are part of larger studies that consider particular aspects related to the emission of toxic compounds. The interested reader can find the mentioned results in the publications [13, 28, 29]. During measurements, four identical accelerometers were used (type B&K 4514 B). A multi-purpose 6-channel input module

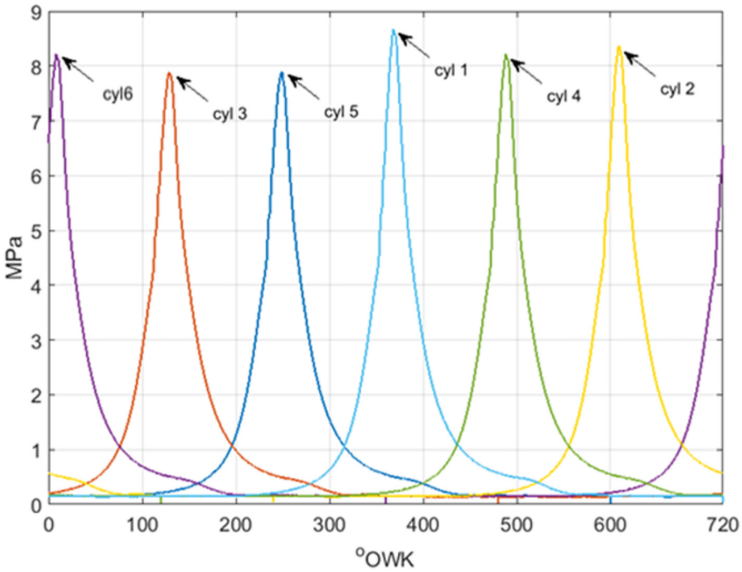

Figure 4. Actual pressure obtained when indicating the pressure inside the 6 AL 20/24 engine cylinder

Figure 5. Test stand of Sulzer 6 AL 20/24 marine engine with a water brake on the right

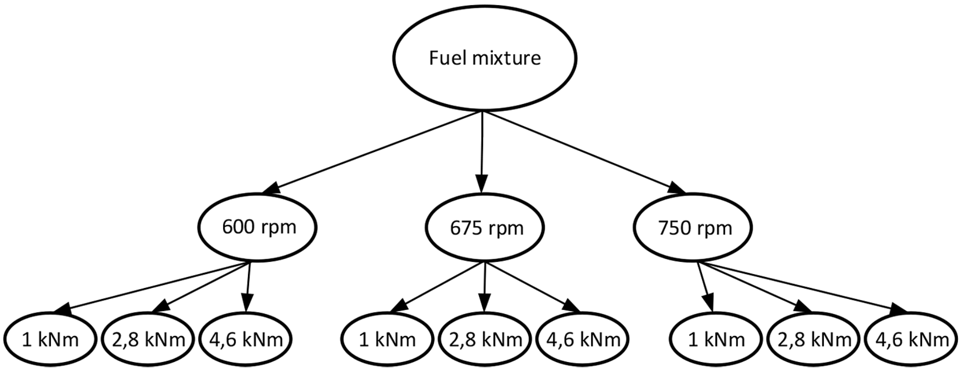

Figure 6. Measurement flow diagram

with a maximum frequency range of 51.2 kHz per channel was used as a measuring card. The measuring lines were calibrated before and after the measurements. A signal sampling of 8192 Hz was used. A simplified engine model with measurement points marked is shown in Figure 7. All sensors were mounted in an identical manner using magnetic bases. The sensors were dismantled only after all measurements were completed, which allowed errors related to variable installation conditions to be avoided. Before starting and after completing each series of measurements, the sensors and the complete measurement paths were calibrated.

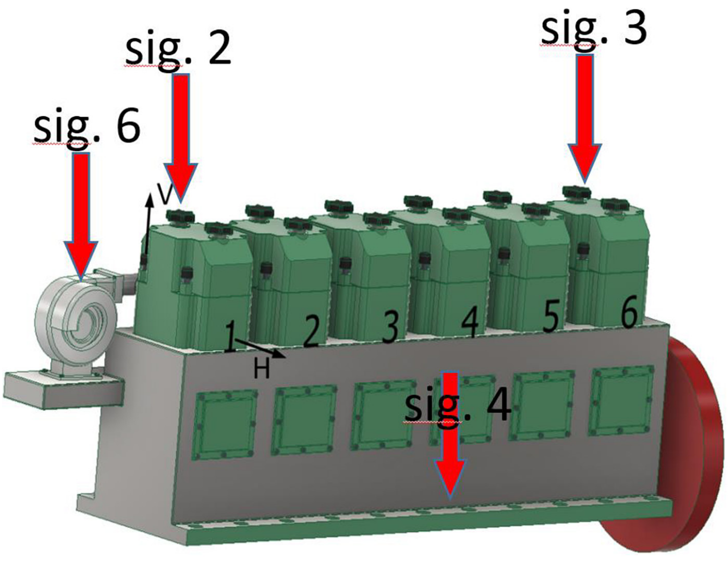

Figure 7. Engine model with the marking of measurement points

RESULTS

Throughout the energy conversion process in a diesel engine, various factors induce vibrations, markedly compromising both its efficiency and longevity. These vibrations stem from unidirectional combustion forces resulting from fluctuations in gas pressure within the cylinder, structural resonance, and alternating inertia forces acting upon diverse engine components [30]. In the author's process of assessing the influence of the type of fuel on changes in the vibration parameters of the tested engine, it becomes necessary to find measures that will clearly allow for the presence or absence of this influence. It is also advisable to identify possible changes. The time courses of the vibration accelerations were recorded during the measurements, an example of which is shown in Figure 8.

When recording, the vibration acceleration waveforms were filtered using an analogue high-pass filter built into the measuring equipment, and the cut-off frequency was set to 0.7 Hz. Despite the possibility of reading a lot of information relating to cyclic phenomena occurring in the engine, such as combustion and opening and closing of injectors or valves, the waveforms presented in Figure 8 are of little use in comparative diagnostics. Due to the above, based on the values shown in Figure 8, average vibration acceleration values were calculated for 1.0 s intervals. This procedure significantly facilitates the comparative procedure between individual waveforms corresponding to recordings for different fuel mixtures, see the description at the top of Figures 9–12, there is a legend identifying each waveform. In the figures below, the term "relative time" is used, which refers to the time counted from the beginning of each recorded individual measurement.

The results presented in graphs 9–12 represent average vibration acceleration values calculated for the entire measurement range of 3.2 kHz (this range was chosen during the experiment phase), providing information about the change in the overall vibration acceleration level in this frequency range. Importantly, no significant and permanent effect of adding butanol to diesel fuel on the vibration parameters presented in this way was observed. An exception may be the results obtained during measurements on cylinder No. 6 (at load 4.6 kNm – Fig. 10), but they are not confirmed by the results obtained from cylinder No. 1 or other measurement points. Moreover, similar dependencies were obtained by analysing the waveforms recorded during engine operation with lower torque loads, i.e. 1 and 2.8 kNm.

In order to assess the amplitudes of vibration accelerations in the entire frequency range, taking into account their recording time, the signals were analysed using STFT (short-time Fourier transform). The STFT spectrum is created when applying windowing techniques with overlapping to divide the signal into equal sections and then performing the DFT (discrete Fourier transform). It is, therefore, a three-dimensional spectrum of amplitude changes for individual signal frequencies, taking into account their recording time. The exact procedure with a mathematical description can be found in publications [31, 32]. Figures 13 and 14 show STFT spectra recorded

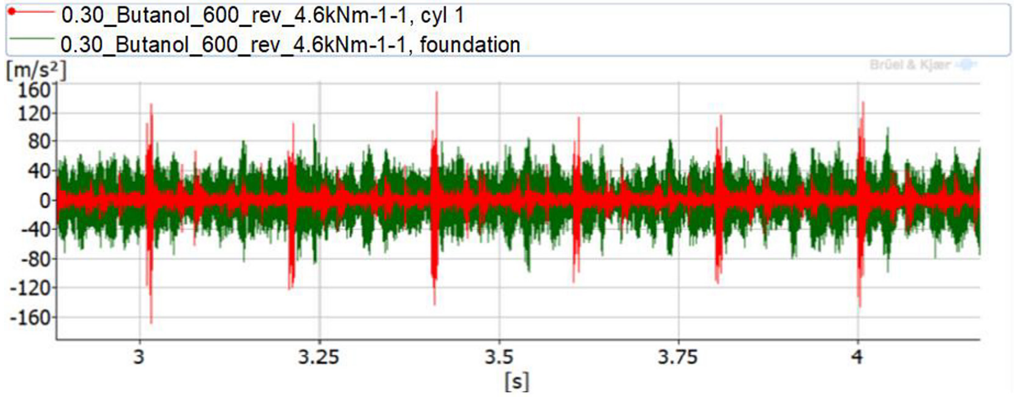

Figure 8. The "raw" vibration acceleration signals were recorded for 70% fuel and 30% butanol blendduring engine operation at a constant rotational speed of 600 rpm and a constant torque load of 4.6 kNm. Signals were recorded in two points: red waveform on engine cylinder 1 and green waveform on engine foundation

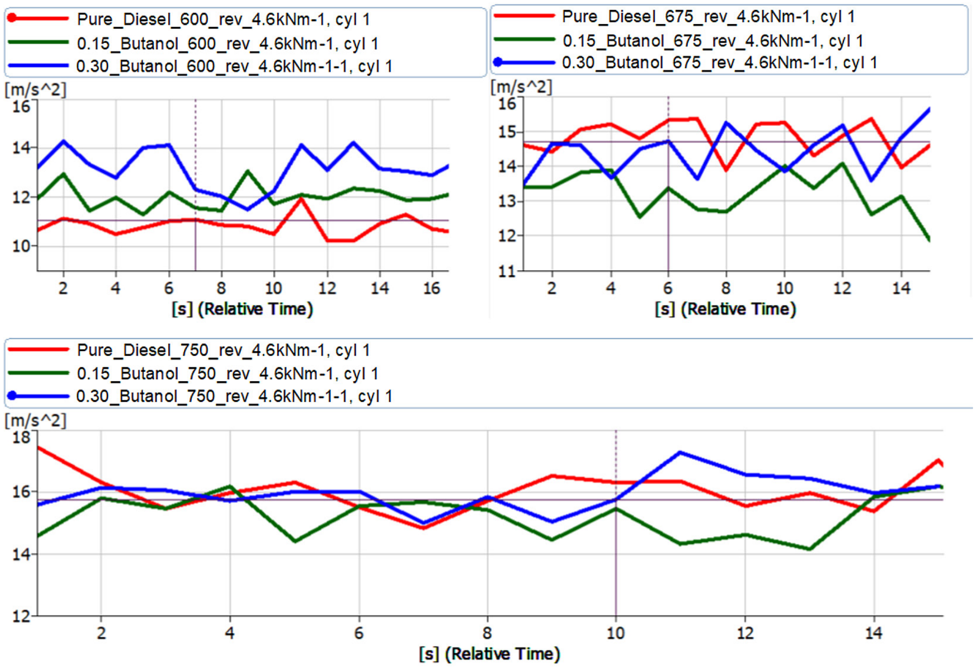

Figure 9. Average vibration acceleration values for all fuel blends, constant torque load 4.6 kNm and rotational speeds 600, 675 and 750 rpm, measuring point located on cylinder no. 1

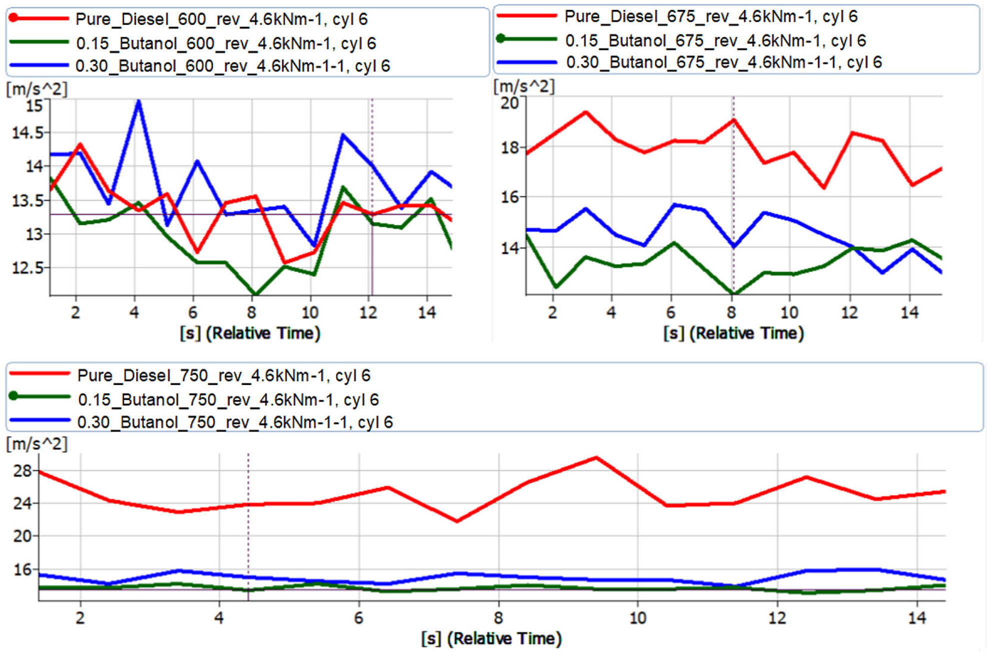

Figure 10. Average vibration acceleration values for all fuel blends, constant torque load 4.6 kNm and rotational speeds 600, 675 and 750 rpm, measuring point located on cylinder no. 6

at an engine load of 4.6 kNm and a rotational speed of 750 rpm for two fuel mixtures, i.e. pure diesel fuel (Fig. 13) and a mixture containing 30% butanol (Fig. 14). The analysis of the spectra presented in Figures 12 and 13 does not indicate any significant differences in the frequency distribution between the vibration parameters recorded during the operation of an engine powered by a mixture of butanol and diesel fuel blend and one powered by pure diesel fuel. The values of vibration acceleration amplitudes recorded in the frequency range of 400–1000 Hz in the case of combustion of a 30% butanol mixture in the engine reach slightly higher values.

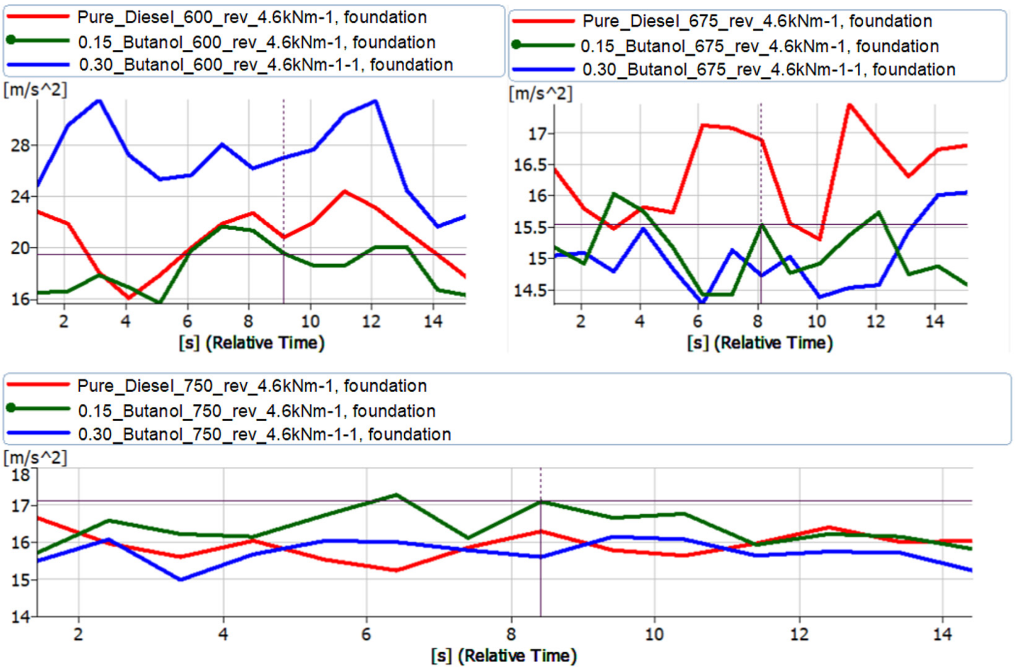

Figure 11. Average vibration acceleration values for all fuel blends, constant torque load 4.6 kNm and rotational speeds 600, 675 and 750 rpm, measuring point located on engine foundation

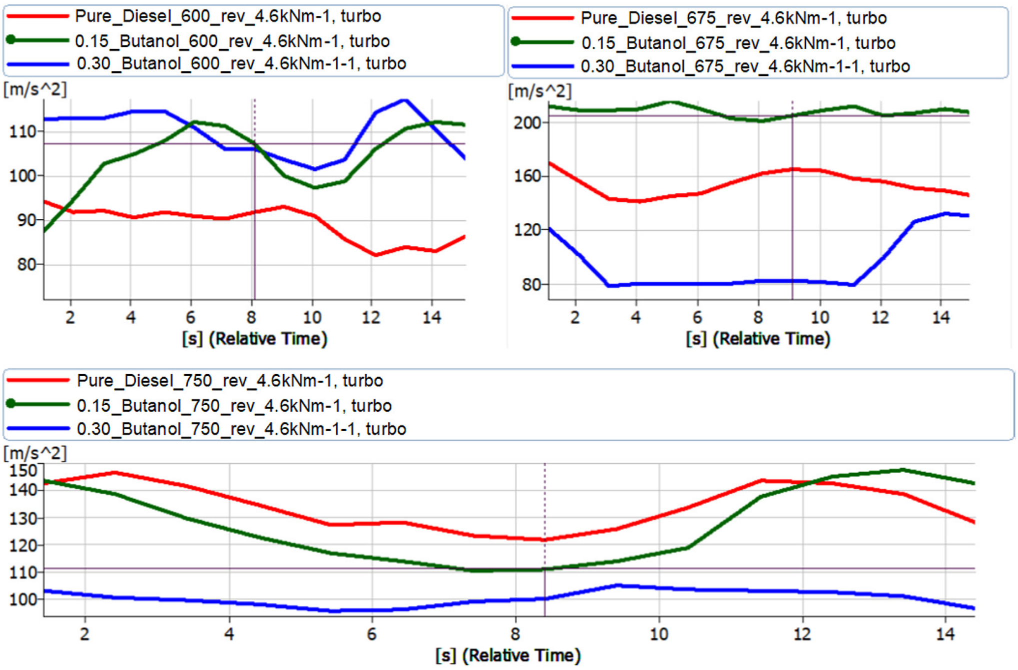

Figure 12. Average vibration acceleration values for all fuel blends, constant torque load 4.6 kNm and rotational speeds 600, 675 and 750 rpm, measuring point located on turbocharger

In both cases, a slight variability of the analysed vibration parameters in the time domain is observed. Similar regularities were observed for the remaining measurement points.

The last stage of the analysis was assessing changes in the broadband r.m.s values of vibration velocity in the frequency range from 2 Hz to 1000 Hz. The adopted frequency range results from the recommendations available in applicable normative documents. For this purpose, a single integration of the vibration acceleration signals was performed, obtaining

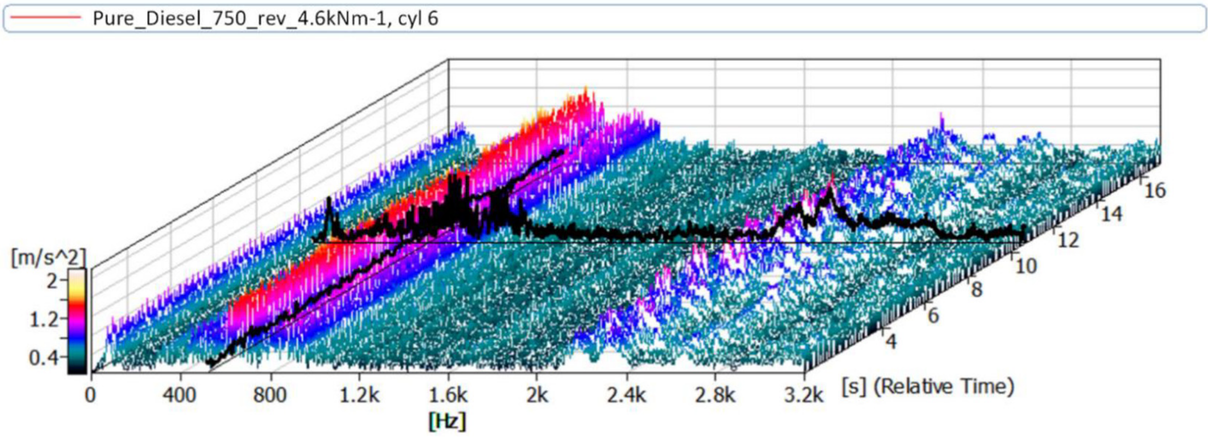

Figure 13. STFT waterfall spectrum was calculated for the measuring point located on cylinder 6, with an engine load of 4.6 kNm and a rotational speed of 750 rpm. Engine fuelled with pure diesel fuel

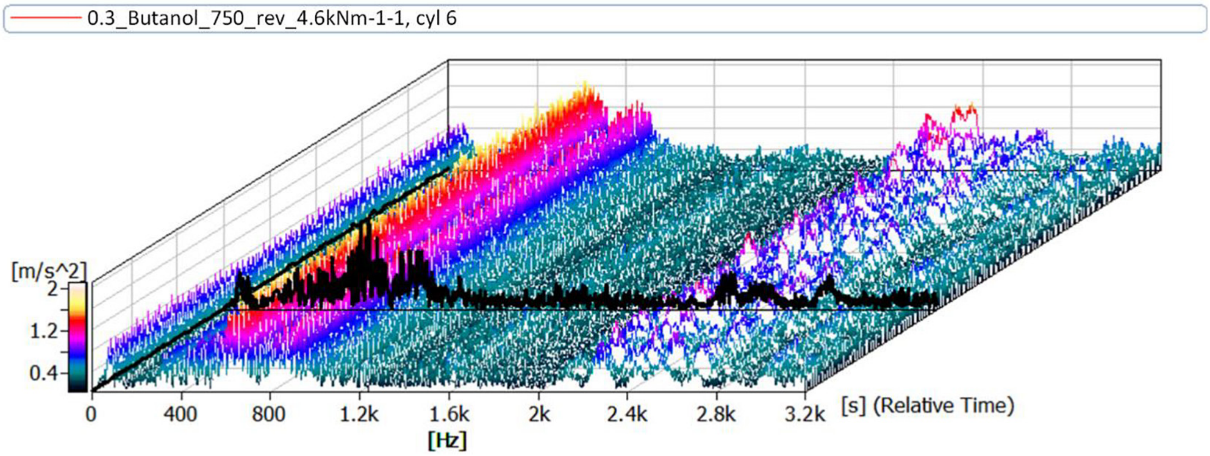

Figure 14. The STFT waterfall spectrum was calculated for the measuring point located on cylinder 6, an engine load of 4.6 kNm, and a rotational speed of 750 rpm. The engine is fuelled with 30 % butanol and a pure diesel fuel blend

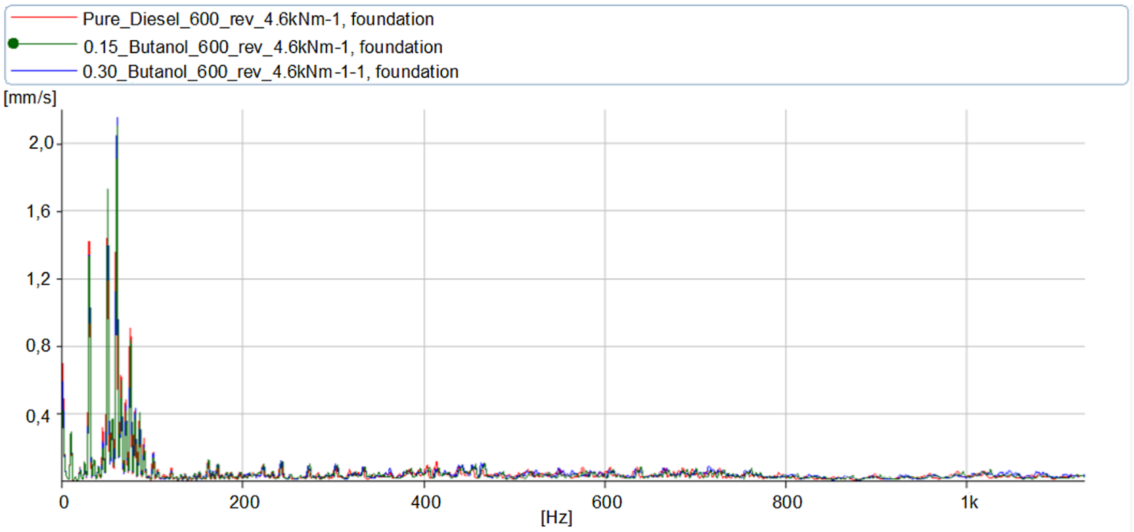

Figure 15. The vibration velocity spectrum was recorded on the engine foundation while operating at a rotational speed of 600 rpm and a torque load of 4.6 kNm

a vibration velocity spectrum, an example of which is shown in Figure 14.

During the analyses of the vibration speed amplitudes, an example of which is shown in Figure 15, the amplitude values of the first, third and sixth harmonic of the rotational speed were also compared. In particular, the value of the third harmonic amplitude identifying combustion processes in a four-stroke, six-cylinder compression-ignition engine should be susceptible to changes in the type of fuel supplied to the engine. No regularities related to the type of fuel were observed in this case. Therefore, the author determined the average values of vibration velocity in the frequency range from 2 Hz to 1000 Hz, which are presented in the Tables 2–5.

CONCLUSIONS

Considering the numerous advantages of butanol as an additive to diesel oil described in the article, as well as the potential for mass and cost-effective production from municipal waste in the future, it is imperative to carefully consider the issue of its combustion in existing ship engines.

Considering that in a marine engine, the combustion process is the primary source of vibrations, affecting not only the engine but also the entire vessel structure, it is essential to conduct research on the effects of using fuels other than fossil fuels and their blends. The need to minimize vessel vibration parameters is crucial for ensuring crew safety, operational reliability, and

Table 2. Broadband r.m.s values of vibration velocity in the frequency range from 2 Hz to 1000 Hz recorded on cylinder no. 1

Cylinder 1				
RPM	Torque [kNm]	Butanol 0%	Butanol 15%	Butanol 30%
		The average value in the frequency range 2–1000 Hz [mm/s]		
600	1	4.01	5.04	7.35
	2.8	4.11	4.20	4.81
	4.6	4.44	4.17	4.57
675	1	5.13	5.04	5.37
	2.8	5.21	5.23	5.57
	4.6	5.14	5.94	5.24
750	1	6.29	6.93	8.09
	2.8	5.02	6.05	6.78
	4.6	5.00	5.41	5.60
Average		4.93	5.33	5.93

Table 3. Broadband r.m.s values of vibration velocity in the frequency range from 2 Hz to 1000 Hz recorded on cylinder no. 6

Cylinder 6				
RPM	Torque [kNm]	Butanol 0%	Butanol 15%	Butanol 30%
		The average value in the frequency range 2–1000 Hz [mm/s]		
600	1	4.35	11.04	12.60
	2.8	15.31	3.65	12.24
	4.6	3.81	4.48	4.58
675	1	5.51	13.58	14.29
	2.8	4.66	4.75	7.78
	4.6	4.62	5.16	10.96
750	1	5.80	10.16	19.18
	2.8	5.87	5.74	6.78
	4.6	5.05	4.14	4.67
Average		6.11	6.97	10.34

Table 4. Broadband r.m.s values of vibration velocity in the frequency range from 2 Hz to 1000 Hz recorded on engine foundation

Foundation				
RPM	Torque [kNm]	Butanol 0%	Butanol 15 %	Butanol 30 %
		The average value in the frequency range 2–1000 Hz [mm/s]		
600	1	2.70	2.60	2.64
	2.8	3.39	3.11	3.25
	4.6	3.76	3.70	3.72
675	1	4.14	4.10	4.30
	2.8	4.73	4.83	5.09
	4.6	6.14	5.69	5.88
750	1	2.37	2.33	2.70
	2.8	2.95	2.84	3.16
	4.6	3.83	3.79	3.84
Average		3.78	3.67	3.84

Table 5. Broadband r.m.s values of vibration velocity in the frequency range from 2 Hz to 1000 Hz recorded on engine turbocharger

Turbocharger				
RPM	Torque [kNm]	Butanol 0%	Butanol 15%	Butanol 30%
		The average value in the frequency range 2–1000 Hz [mm/s]		
600	1	5.42	5.66	5.42
	2.8	9.49	9.18	8.72
	4.6	13.50	12.16	13.21
675	1	9.62	9.56	9.95
	2.8	10.86	10.21	10.58
	4.6	14.92	14.53	13.21
750	1	7.22	6.85	7.36
	2.8	16.82	13.05	10.71
	4.6	13.54	12.94	11.10
Average		11.27	10.46	10.03

environmental protection, particularly in light of the increasing significance of marine environment noise pollution in recent times.

The most reliable results are obtained from measurements taken at a point located on the engine foundation. This point provides insights into the resultant vibrations of all moving components associated with engine operation and directly informs about the amplitude values transmitted to the engine's foundation. It is worth noting that most main drive engines of large commercial vessels are rigidly mounted on foundations without any vibration-absorbing elements. Results obtained from this measurement point indicate only a slight increase in average vibration velocity amplitudes (averaged for all measurements of a given fuel type) when the engine is fueled with a mixture containing 30% butanol. Measurements on the turbocharger bearing indicate a decrease in vibroactivity with an increase in butanol content in the diesel oil, likely due to the decrease in maximum combustion pressure as described in the literature. Measurements recorded on cylinders 1 and 6 indicate an increase in vibration parameters with increasing butanol content; however, this is not confirmed by measurements taken at the engine foundation.

The research conducted in this study confirms the feasibility of safely using butanol additives in diesel oil, maintaining vibration parameters at levels similar to those obtained when the engine is fueled solely by diesel oil. Further research is necessary to explore the effects of higher butanol content in the fuel, which the author intends to undertake in the near future.

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