




Article

Study on the Variable Speed Diesel Generator and Effects on Structure Vibration Behavior in the DC Grid

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Featured Application: This research provides the methods to improve the fuel combustion efficiency of the variable speed diesel generator in the DC grid. However, this also results in higher structure vibrations. The causes and solutions for that problem are discussed.

Abstract: Global warming and air pollutants are in general major worldwide concerns including for the marine shipping industry. Equipped with new technologies, the onboard DC grid has proven several advantages, including up to 27% reduction in specific fuel consumption with reduced emissions. That can be achieved by installing an optimized variable speed diesel generator. The engine speed is adjusted according to the required power, which allows to always keep the best efficiency of the combustion process. However, it also exposes some changes in the behavior of the structure vibrations. Measurements on an experimental variable speed diesel generator show that vibration increases when trying to slow down the engine for the same load. This behavior is closely related to the resonance in low rev range that usually occurs with general gensets. In other words, we can conclude that the DC grid's variable speed generator may be beneficial for fuel efficiency, but not for mechanical life and safety. Several measures had been given, of which the alternation of the natural frequency is presented as an economical and efficient solution. The ultimate goal is to maintain operational safety while respecting reduced fuel consumption.

Keywords: structure vibration; variable speed diesel generator; DC grid; fuel consumption; emissions



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1. Introduction

In the maritime industry, the DC grid is becoming increasingly more popular and has shown several advantages. It allows for simple, flexible, and functional integration of energy sources such as variable speed generator sets, shaft generators, batteries, and fuel cells. There is no need to use AC to DC transformers; many components can be reduced as well as less power transmission loss and harmonic distortion [1]. It is possible to distribute high voltage power, which represents a saving of up to 40% of the cabling. An additional generator for port usage is not required. These minimizations can save the carbon footprint up to 30% [2]. The benefits of the DC network are also expressed through the best-in-class fault-tolerance. It provides a highly controllable power plant suitable for advanced operation and optimization by overriding control. The audible noise is drastically reduced by more than 5 dB. Up to 30% lower maintenance costs are due to reduced engine wear [1–9]. In case the full advantages of all these features are exploited, the specific fuel oil consumption (SFOC) can be improved by up to 27% with reduced emissions [10]. With these high hands, the DC network is gaining ground in a wide range of vessels.

This article focuses on the variable speed diesel engine generator set in DC grid. Understanding its characteristics would help us optimize the operation of genset. The advantages, as mentioned above, are obtained by assuming that the best combustion phenomenon is maintained for entire speeds. However, in the case of conventional engines with camshaft, the combustion efficiency depends on injection which is affected by rotating speed. This matter does not happen with a general genset that always operates with constant synchronized speed. In variable speed engines, the injection angles are fixed but varying speeds can change the injection pressure as well as injection duration. Many previous studies have helped to clarify this. In this regard, a series of measurements were carried out by Bolt and Henein in an experimental single-cylinder engine [11,12]. The injection timing was set manually, so the injection would start at a constant crankshaft angle at all engine speeds. The measurement results indicate that the ignition retardation in degrees of crankshaft angle increases with speed. In the time-domain, the observed ignition delay decreases with speed. But in the correction at the same temperature, it increases with speed. The heat transfer time to the cylinder wall is reduced as the engine speed decreases. This results in a higher temperature of the air-fuel mixture and subsequently reduces the ignition delay time. Finally, increasing engine speed results in an increase in the ignition delay. To maintain the ignition time, the injection timing must be adjusted earlier.

In another research, Rahman et al. evaluated the effects of engine speed on injection timing and engine performance [13]. On this basis, the same amount of fuel was injected into the cylinder in one cycle in all tests while varying engine speed and injection timing. The observed performance increased as the engine speed decreased. The indicated efficiency dropped earlier at higher rates due to the interaction between injection timing and ignition delay. Therefore, it can be concluded that the engine performance corresponding to optimum injection timing is highly dependent on engine speed. The injection timing should be adjusted to maintain the ignition at substantially top dead center (TDC). Lower speed requires optimal injection timing closer to engine TDC [14].

Those experiments showed that the conventional engines with camshaft cannot keep the combustion at best performance over the entire rev range. The fuel injection process is strongly influenced by the variation in speed. It is necessary to be equipped with a fuel injection control system capable of self-calibrating at specific speeds. Furthermore, for each specific combustion chamber size, there is only a small range of optimal amount of fuel injected. Outside of this range, the SFOC is higher. Therefore, each engine has an optimum performance range. To always maximize the combustion efficiency, the amount of fuel injected in each cycle is maintained within an optimized range while the speed varies with the load. It may be difficult to do with a diesel engine that serves as a main engine because the torque is closely related to the rpm. But in case of a diesel genset, the required torque can be easier to control by generator. Prior studies on energy performance and maximization of DC-grid efficiency with variable speed power generation are limited. In this study, two procedures of operating for the best combustion efficiency have been recommended for specific diesel generator sets. This was achieved by a series of power performance measurements under various operating conditions. However, this also causes the vibration characteristics of the system to vary, which can result in stronger vibrations at certain specific speeds. There were no experimental studies yet on the effect of variable speed power generation on vibrations. This should be carefully considered when designing a new generator set as well as when converting an existing one. In this study, the mechanical vibration of the whole generator system was evaluated by actual measurements to detect and prevent problems in advance. The vibration measurement procedure followed the requirements of ISO 8528-9:2017. This research presents the novelty in the improvement of the variable speed diesel generator through a new approach in terms of vibration and deriving the optimal operating procedures in terms of fuel consumption.

2. Combustion Performance Optimization in Variable Speed Genset

2.1. Methodology

The combustion performance in a general engine is demonstrated in Figure 1 with the best efficiency at around 70% of the nominal torque corresponding to 70% of the nominal fuel injected per engine cycle. For example, the required engine power is 50% load. In a range of 100 to 65% of the maximum rated revolution (MCR), decreasing the operating speed can increase the combustion efficiency. The best combustion performance is gained at 65% of the MCR. Lower than that operating point, the decrease in speed leads to a decrease in combustion performance. Likewise, to generate 75% load, the optimized speed is 100% of MCR. This solution provides an easy tool to determine the appropriate speed.

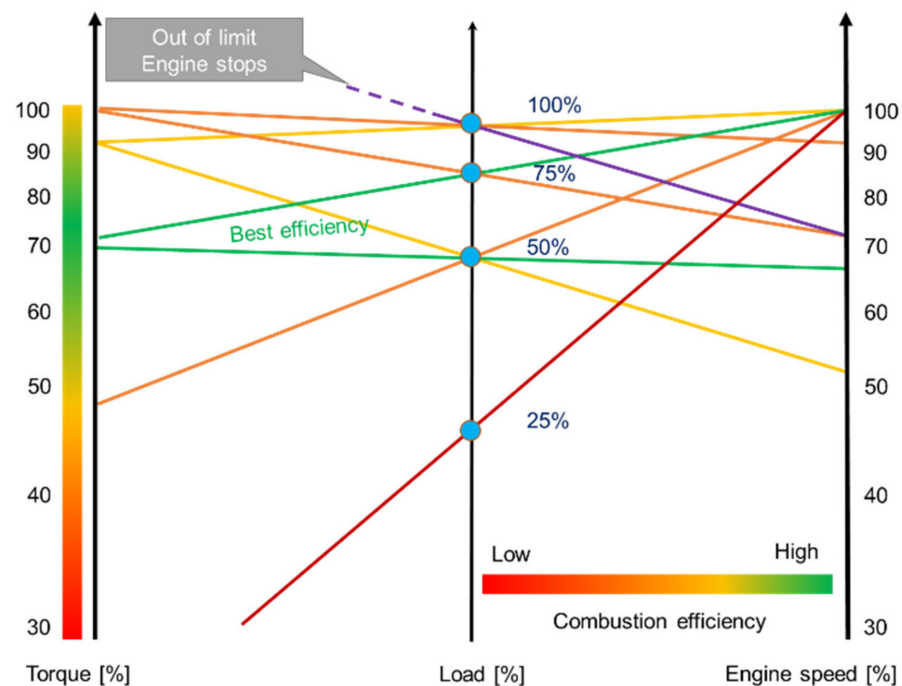


Figure 1. Combustion performance of variable speed engine.

In another way, while following the same principle, engine speed can be calculated by following:

$$n = \frac{60P}{2\pi T} \quad (1)$$

Here, n is the engine speed [rpm], P is the required power [W] and T is the generated torque [N·m] corresponding to optimized fuel injected. The engine speed cannot be set too low compared to the power required. This leads to too much torque needed, the required amount of fuel injected in 1 cycle is out of the limit, then the engine stops (see Figure 1—purple line: 70% MCR + 100% load).

2.2. Experiment and Result

A series of measurements were performed with an experimental variable speed diesel generator set under various operating conditions. The specifications of the diesel engine and generator can be seen in Appendix A. The engine was designed for constant speed operation, but the parameters of genset can be manually adjusted to determine the effects of variable speed on combustion performance. The schematic minimalistic diagram of the experiment system is described in Figure 2. The Coriolis type fuel mass flow meters were installed on both fuel supply and fuel return pipes. The flow rate measurement accuracy is $\pm 0.2\%$. By comparing the difference between the amount of fuel in and out, the fuel consumption was obtained, and is depicted in Figure 3. The effective torque is determined

from generator load and engine speed using Equation (1). The red circles describe an approximation of the constant specific fuel oil consumption. In which, the smaller circle represents better fuel consumption. The best performance operation point is defined by the intersection of the constant load curve and the smallest possible SFOC circle. As a result, reducing engine speed at low load can improve fuel efficiency, better than constant speed operation.

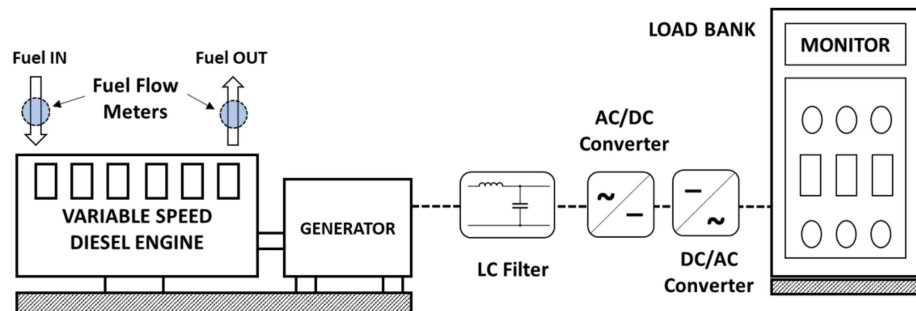


Figure 2. Schematic diagram of experimental variable speed diesel generator set.

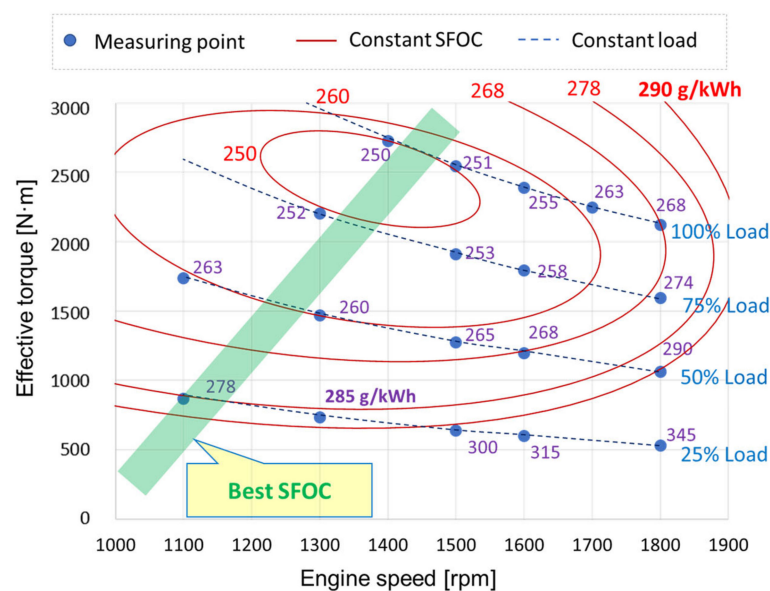


Figure 3. The measured specific fuel consumption of experimental variable speed diesel generator set under various operating conditions.

2.3. Discussion

We expected that the constant specific fuel oil consumption (or constant combustion efficiency) circles would be flatter and wider horizontally, as shown in Figure 4. Accordingly, the combustion efficiency does not change much for constant torque. The best SFOC operating line is almost horizontal as a fixed torque line. But in case of the diesel engine in this experiment, there are differences in the measurement result due to the following limitations:

- Like any other engine equipped with turbocharger, lower engine speed reduces the pressure of the scavenging air.
- The injection pump is driven by camshaft, the injection quality varies with speed.
- The injection timing is not variable.

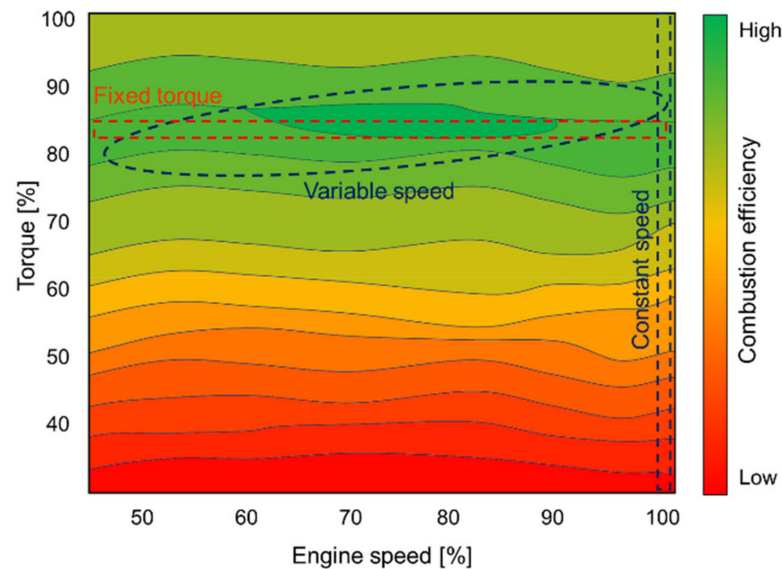


Figure 4. Illustration of torque-speed operating characteristics comparison between constant speed and variable speed generators (courtesy of ABB [10]).

To achieve much more improved combustion efficiency at low speeds, an auxiliary blower installation is essentially required to provide sufficient air at low engine speeds. Besides, it is needed to equip an electronically controlled system, which can fully control the fuel injection. For the engine with mechanical control as in this experiment, an effective solution consists in equipping the system of variable injection timing (VIT). The VIT injection pump elements are interchangeable with the existing injection pump elements and can be installed during maintenance without any further modifications [15–17]. Moreover, the amount of fuel injected in each cycle is necessary to remain within the optimized range corresponding to the specific size of combustion chamber despite the variable speed with load. The best performance is always obtained. The engine can achieve maximum combustion pressure at a lower load to improve the fuel consumption. In addition, it reduces the engine's energy expenditure, and therefore more efficient combustion.

In fact, it is difficult to keep all the combustion factors unchanged. To hold the compatibility between all the operating factors, easy to control and not to overload the other systems, the torque for variable speed is not barely fixed but maintained in the optimal range. The torque-speed operating line of the engine is slightly inclined rather than horizontal as in the case where the torque is hardly fixed. After all, in case of the full optimized engine as illustrated in Figure 4, the following operating procedure is recommended for the best combustion efficiency:

1. Maintain the generator torque corresponding to the optimized range of combustion performance (this is the key point).
2. Determine the appropriate engine speed corresponding to the required generator power using Equation (1).
3. Adjust the engine speed with the governor. The amount of fuel injected will be in the optimized range.

In the case of the system, such as the experimental genset, it is necessary to establish the best SFOC operation line as shown in Figure 3. Therefore, the following operating procedure is recommended:

1. From required load, determine the operating point, including torque and speed, for the best fuel efficiency.
2. Adjust the generator torque.
3. Adjust the engine speed by the governor. The amount of fuel injected will be in the optimized range for the best combustion efficiency.

3. Effects of Variable Speed on the Structure Vibration

3.1. Materials and Methods

The experiment diagram and sensors installation are shown in Figures 5 and 6 following the requirement of ISO 8528-9. All vibration channels were recorded simultaneously with a sampling rate of 8192 samples/second using the Vibration Monitoring software developed by Green Ship Technology Laboratory of Korea Maritime and Ocean University. Sensors in both types of acceleration and velocity were used to measure the vibrations of the structure. The nonlinearity of sensors is $\pm 1\%$. Vibration data from accelerometers were converted to velocity using integration. The diesel engine excites vibrations with frequencies mainly between 2 and 300 Hz. However, when considering the overall genset structure and components, a range of 2 to 1000 Hz is required to evaluate the vibration [18]. In the general case of any vibration in the time-domain, the vibration level is given by the root mean square (RMS) value as known as effective value of vibration. It is defined as square root of the arithmetic mean of the squares of the values. In the case of a set of N velocity values $\{v_1, v_2, \dots, v_N\}$, the RMS value is defined by:

$$v_{RMS} = \sqrt{\frac{1}{N}(v_1^2 + v_2^2 + \dots + v_N^2)} \quad (2)$$

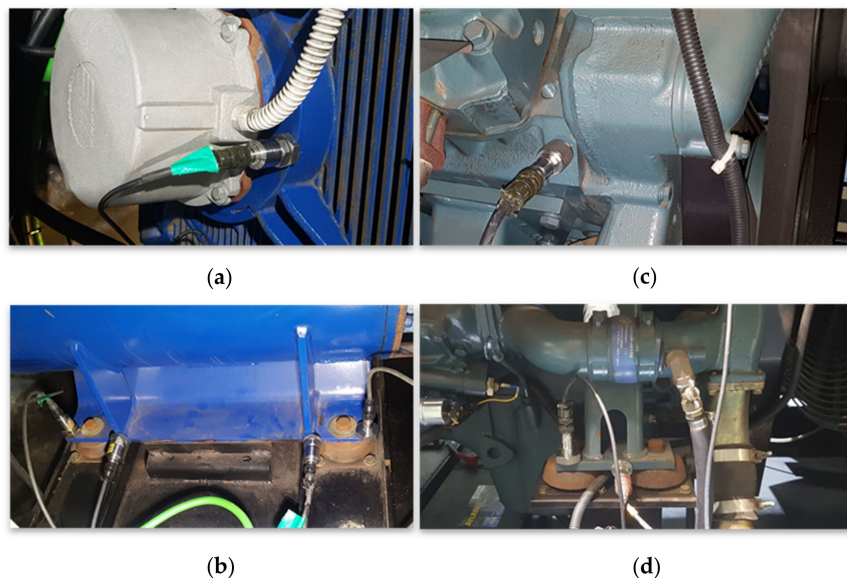


Figure 5. Sensors installation for structure vibration measurement based on ISO 8528-9. (a) Generator main bearing housing; (b) Generator base; (c) Engine top girder; (d) Engine base.

RMS value calculation using the general definition equation takes a long time. It is more complicated but less precise when using velocity integrated from acceleration data in time-domain, especially with a band-pass filter. The calculation method using frequency-domain can reduce work. In mathematics, Parseval's theorem [19,20] states that the sum (or integral) of the square of a function is equal to the sum (or integral) of the square of its transform. In this application, the Fourier transform is referred to. The theorem becomes [21]:

$$\sum_{i=1}^N |v_i|^2 = \frac{1}{n} \sum_{j=1}^N |V_j|^2 \quad (3)$$

Here, V_j is the discrete Fourier transform of v_i , both of length N . Substituting Equation (2) into Equation (3) results in:

$$v_{rms^2} = \frac{1}{n^2} \sum_{j=1}^N |V_j|^2 \quad (4)$$

or

$$v_{rms} = \sqrt{\frac{1}{2} \sum_{k=1}^{N/2} \hat{v}_k^2} \quad (5)$$

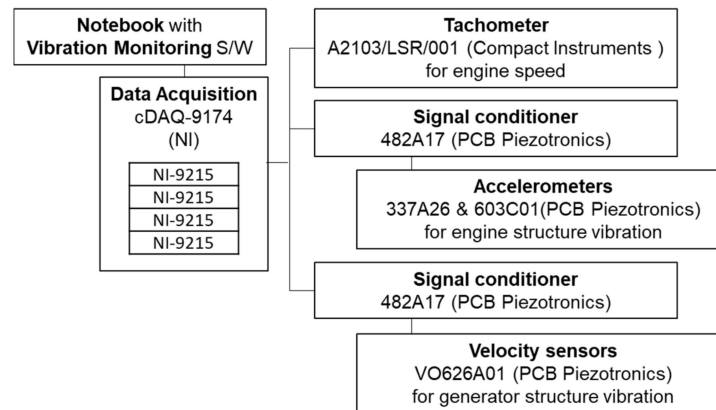


Figure 6. Schematic diagram for structure vibration measurement.

Here, \hat{v}_k is amplitude spectrum [22], also known as magnitude of velocity at each frequency amplitude in frequency-domain.

Time-domain signals are first analyzed using the fast Fourier transform (FFT), and then converted to a frequency-domain representation. From there, the magnitudes of all frequency components of the vibration are expressed. The interval of frequency in Hz is equal to the inverse of the recording time in seconds. In case of acceleration, it can be converted to velocity by:

$$\hat{v} = \frac{\hat{a}}{2\pi f} \quad (6)$$

Based on Equation (5), the RMS value can be obtained from the frequency-domain:

$$v_{RMS} = \sqrt{\frac{\hat{v}_1^2 + \hat{v}_2^2 + \dots + \hat{v}_k^2}{2}} \quad (7)$$

where, $\hat{v}_1, \hat{v}_2, \dots, \hat{v}_k$ are the peak velocity values of all frequencies in the range of 2 to 1000 Hz. This method is more precise and simpler than using the band-pass filter in the time-domain. The measurements were obtained in both constant maximum speed mode and variable speed operation mode with varying load.

3.2. Results and Discussion

To evaluate the vibration, the results of calculated RMS velocity vibration values are presented in Table 1 for the test at constant maximum speed of 1800 rpm and Table 2 for test at variable speed mode.

As described in the tables, the vibrations were measured in the axial direction, -x, transverse direction, -y, and vertical direction, -z. The acceptable vibration level for this experimental generator set refers to ISO 8528-9 requirements for the generator set with a speed below 2000 rpm and a power greater than 200 kW. Accordingly, the allowable vibration level for vibration on the diesel engine is 45 mm/s, and that on the generator is 20 and 28 mm/s. If the vibration level on the generator is less than 20 mm/s, it will be safe from damage. In cases where the vibration levels are between 20 and 28 mm/s, there must be a secure agreement between the generator manufacturer and the component supplier to ensure reliable operation. Compared to the results obtained, we found that all the vibration levels are below the limit in the test at constant maximum speed mode, but it is not preferable to be in variable speed mode. Under certain operating conditions,

the level of mechanical vibration on the generator exceeds the lower limit value as values marked in bold in Table 2.

Table 1. RMS values of velocity vibrations at constant maximum speed of 1800 rpm. Unit: mm/s.

Engine Speed [rpm]	1800	1800	1800	1800	1800	1800	1800
Engine Load [%]	0	10	25	50	75	90	100
Engine top aft -y	17.36	18.04	19.97	22.68	24.69	27.14	28.01
Engine top fore -y	12.27	13.93	14.65	15.47	15.54	15.34	15.27
Engine base -y	11.10	13.06	15.22	16.12	17.90	18.36	18.21
Engine base -z	16.02	24.46	29.17	24.57	25.40	27.04	30.75
Gen. bearing -x	4.21	5.04	5.65	7.02	8.80	10.37	10.55
Gen. base aft -y	8.28	9.15	10.58	11.76	13.33	13.80	14.11
Gen. base aft -z	7.47	8.44	9.57	11.40	13.61	14.87	14.97
Gen. base fore -y	8.23	9.87	12.02	14.18	16.64	17.46	17.63
Gen. base fore -z	10.25	12.25	15.41	15.99	16.07	16.68	17.49

Table 2. RMS values of velocity vibrations at variable speed. Unit: mm/s.

Engine Speed [rpm]	1100	1100	1100	1100	1300	1300	1500	1600	1800
Engine Load [%]	0	10	25	50	50	75	75	90	100
Engine top aft -y	12.21	13.55	14.34	15.08	17.96	19.84	21.70	29.97	28.17
Engine top fore -y	9.45	9.26	11.05	11.10	10.47	11.46	9.18	11.72	15.22
Engine base -y	9.49	11.45	12.72	13.91	12.70	15.81	18.16	20.79	17.35
Engine base -z	10.86	15.41	19.79	20.49	16.50	19.72	23.52	26.19	25.95
Gen. bearing -x	3.12	3.61	5.04	7.65	7.49	8.41	11.27	11.60	10.30
Gen. base aft -y	9.04	10.40	12.99	17.83	17.69	22.84	22.73	17.13	14.28
Gen. base aft -z	5.62	6.82	8.86	13.83	15.75	20.30	22.98	19.44	14.44
Gen. base fore -y	11.26	12.87	16.02	22.45	21.33	27.53	26.52	20.82	17.98
Gen. base fore -z	7.60	9.16	10.10	11.75	18.90	22.84	23.52	20.58	17.51

Effect of varying load on structure vibration. In the comparison between conditions at the same speed, the vibration levels increase with load. This state is clearly indicated in Table 1 at 1800 rpm and in Table 2 at 1100 and 1300 rpm with variable load. The results of vibration spectrums at generator base fore side in transverse direction are shown in Figure 7. The vibration became more intense at a higher load with the primary 4th order vibration caused by the combustion process of eight cylinders. It is usual and the same as other general diesel generator sets. At constant speed, creating more power requires generating greater torque. The torque reaction is a result of combustion impulse of each firing cylinder to twist the shaft with the strong rotational thrust and counter-reaction of stationary external parts; therefore, it produces structural vibrations. Additionally, vibration is caused by the pulsating force in piping systems, including liquids and gases. A heavier operating condition leads to higher vibration levels.

Effect of varying speed on structure vibration. The main source of vibration is due to the movement and interaction of reciprocating (pistons, connecting rods) and rotating (rotating shafts, flywheel, rotor, etc.) parts. Higher speed generally produces stronger excitation forces leading to larger vibration. But synthetic vibration in a generator set as well as in any propulsion system is the sum and interference of many components. Sometimes they reinforce each other and sometimes they cancel each other out, it depends strongly on frequency as operating speed. It is well known that each mechanism generally has one or several natural frequencies. In the case that the excitation approaches the natural frequency then the resonance occurs, the resulting response vibration is amplified. Resonance is usually calculated during the designing stage to be away from the primary operating range. Most of the generator sets as well as this experimental genset have resonance at low speed. Generally, this resonance is only concerned during starting or speed accelerating, the engine always operates at a constant speed away from it. Changing operating speed may cause trouble. The measurement results in Table 2 indicate that excessive vibration

occurred at the base of the generator, with the worst case at the fore side in transverse direction. The vibration level is highest at 1300 rpm—50% load and gradually lower at 1500 rpm—75% load, 1100 rpm—50% load, and 1300 rpm—50% load. The vibration amplitudes in frequency-domain by spectrum analysis are shown in Figure 8. At this position, a lower speed results in increased vibration for the same power. This behavior is opposed to those at some other positions.

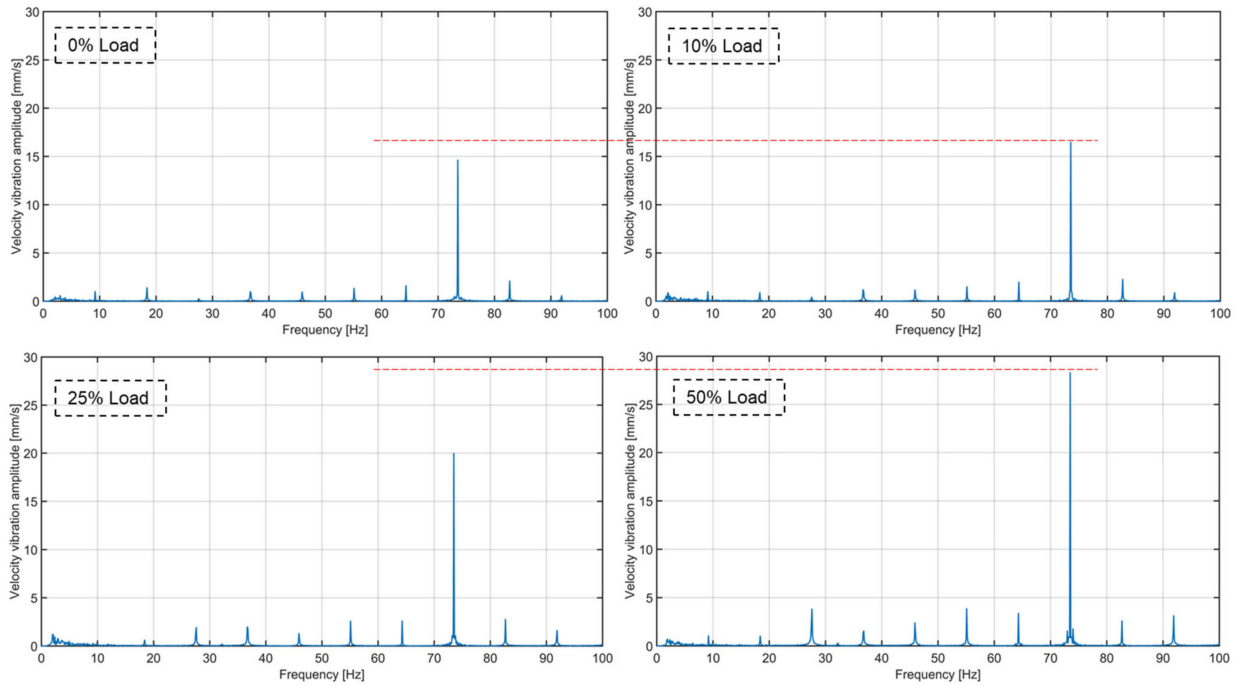


Figure 7. Vibration spectrums comparison of generator base fore side in transverse direction at the same 1100 rpm and varying loads.

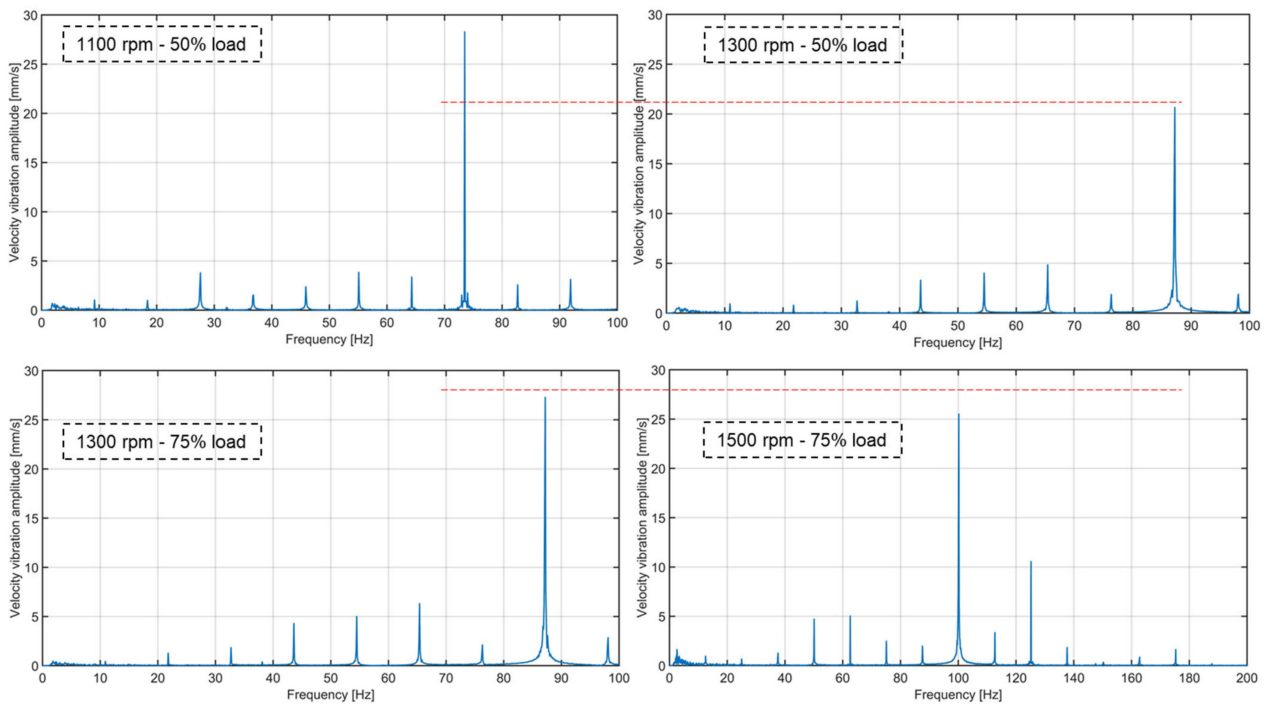


Figure 8. Vibration spectrums comparison of generator base fore side in transverse direction at the same loads and varying speeds.

The order-tracking analysis shows that the primary vibration is still 4th order. In no-load condition, as described in Figure 9, the vibration of the diesel engine decreased when reducing the speed from 1800 rpm to 1500 rpm, but it increased from 1500 rpm to 1100 rpm. In the case of measured vibrations on the generator shown in Figure 10, there seems to be a resonance range at the lower speeds close to 1100 rpm in transverse direction. The vibrations there increased while the speed decreased. Generally, an increased torque reaction results in a higher vibration level when maintaining the same load but rotating at a lower rpm. In this experiment, the increasing torque effect is available but not as strongly as the effect of varying speed. The intense vibration observed on the diesel engine at lower speeds in the range below 1500 rpm was the result of resonance on genset.

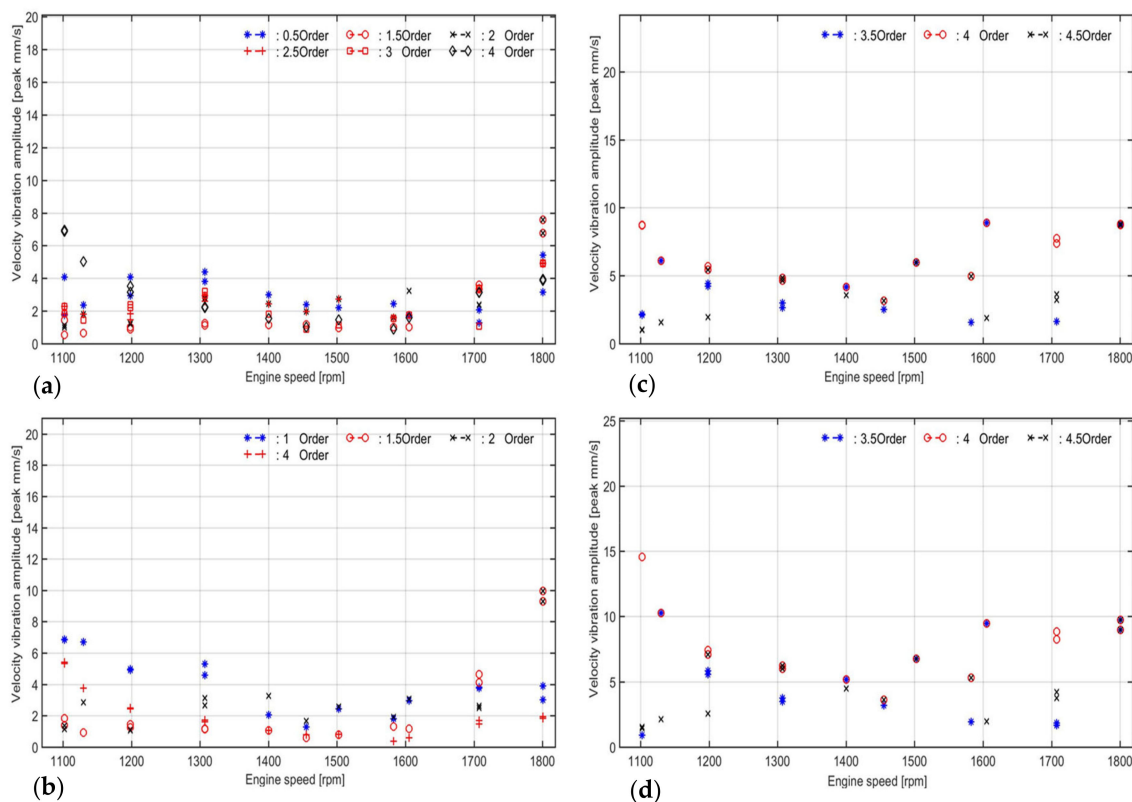


Figure 9. Vibration order-tracking of diesel engine in no-load condition. (a) Engine top aft side in transverse direction; (b) Engine top fore side in transverse direction; (c) Engine base in transverse direction; (d) Engine base in vertical direction.

It can be summarized that the effect of variable speed on the structure vibration is a combination of many influencing components, including the vibrational excitation of the moving part, the torque reaction, and the structural properties related to resonance. Decreasing the engine speed means that all moving parts become slower; therefore, the vibration is reduced. On the other hand, generating the same power at a lower rpm requires higher torque, resulting in a stronger torque reaction as well as increased vibration. The overwhelming effect belongs to the resonance. Once the engine is operating at a speed range close to resonance, the oscillation will be more intense despite weaker excitation. This is what happened with the experimental diesel generator set. To apply the variable speed operating mode to the existing generator set, it is necessary to verify the resonance of the vibrations throughout the operating range, firstly at varying speed in the no-load condition. If the vibration level at any position is above the limit, operation under these conditions should be avoided. The generator torque must be adjusted according to the new desired speed in order to maintain the required power generated. In case of operation under these conditions being necessary to improve SFOC, the vibration characteristic of the generator set should be changed.

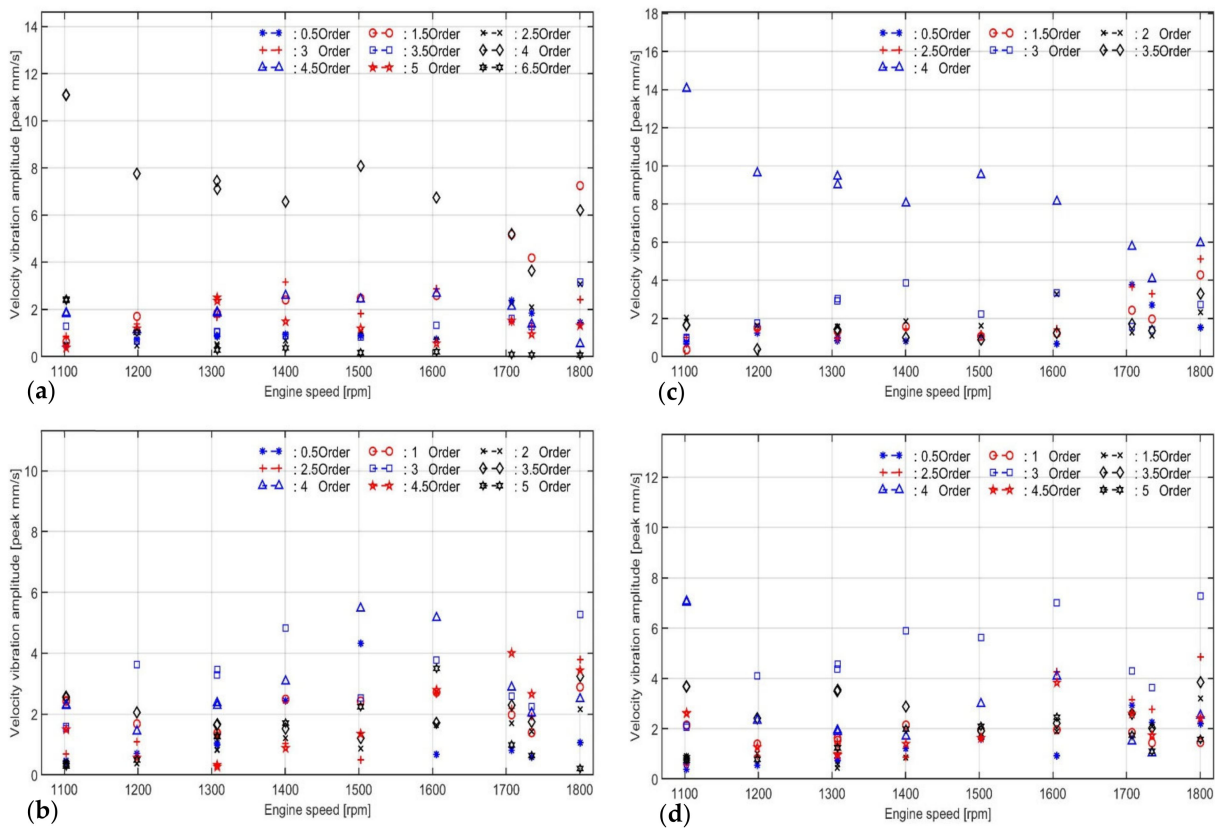


Figure 10. Vibration order-tracking of generator in no-load condition. (a) Generator base aft side in transverse direction; (b) Generator base aft side in vertical direction; (c) Generator base fore side in transverse direction; (d) Generator base fore side in vertical direction.

Solutions to improve the vibration behavior. There are several options to change the vibration characteristic of a diesel genset. It can be achieved by changing the design of system mechanism; hence, the new structure properties are adjusted to be optimum. The vibration can be prevented by changing the firing order, which considerably causes considerable side pressure leading to the transverse vibration of the engine frame. These solutions possibly work but are less executable due to their high cost and complexity. Altering the natural frequency by changing the rigidity of the frame is an economical and efficient solution for the diesel generator set, such as this experimental system. Furthermore, applying a better vibration isolator for the genset frame can result in considerable improvement of vibration behavior. Compared to the existing rubber vibration isolator (see Figure 11), a spring type vibration isolator is an excellent replacement. Besides changing the system resonance range, the spring isolator exposes many more advantages. Offering higher isolating efficiency, over 95% is much higher than below 90% of the rubber type, the spring isolator is applicable for high load capacity and bigger mass applications [23].

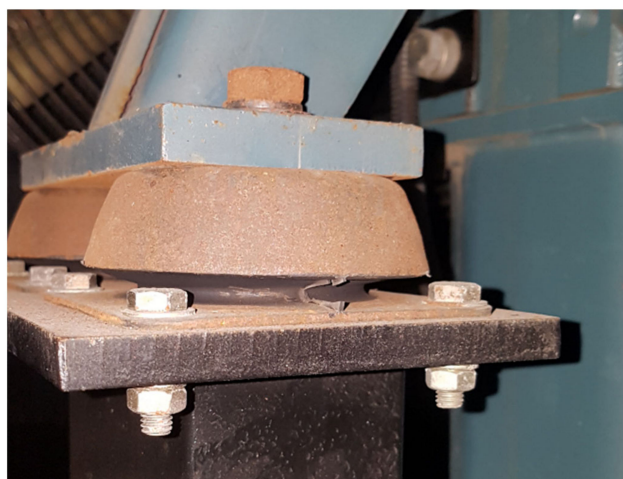


Figure 11. The rubber vibration isolator on this experimental genset.

4. Conclusions

In the current eco-friendly trend of the maritime industry, the DC network presents itself as a new way of distributing electricity onboard. The variable speed engine generator set as well as the energy storage are the heart of the DC grid system. This concept allows the engine to run at an appropriate speed corresponding to each specific load. This results in achieving the best combustion efficiency over the entire operating range, thus improving SFOC with reduced emissions. This study evaluated the effects of varying speed on engine performance and vibration behavior. The ultimate purpose is to maximize the benefit of variable speed engine while maintaining safety throughout the system against vibration. Our results can be summarized as follows:

1. Each engine has a fixed cylinder volume corresponding to a specific range of optimal fuel injected. In case the amount of fuel injected in each cycle is maintained in that range, the best combustion efficiency is always obtained. Outside this range, a higher SFOC is resulted. This fuel amount is closely related and can be controlled by adjusting the torque produced by the generator.
2. Variable speed operation requires a highly controllable fuel supply system, which can maintain the injection quality, including pressure, duration, and ignition time. The injection timing should be later, and an auxiliary air blower installation is essentially required to generate enough power at a lower speed.
3. At the same speed, the vibration increases with load. In addition, more torque generated at lower speed can produce larger vibration. This behavior is more serious once the engine is operating at a speed range close to resonance. Most generators have resonance at a lower speed, which is of little concern in fixed frequency generators that always operate at a constant speed. The vibration behavior should be confirmed to apply the variable speed genset. In case of operation under these conditions is necessary to improve SFOC, the vibration characteristic of the generator set should be changed.
4. Recalculating with a new design or changing the firing order is a possible solution to improve vibration behavior but has high cost and complexity. Altering the natural frequency by changing the rigidity of the frame is an economical and efficient solution for the diesel generator set. Replacing rubber vibration isolator with a spring type with many outstanding advantages is the best option for this experimental system.

The above findings should be of concern when applying a variable speed diesel generator. In the next study, the vibratory behavior should be confirmed after the replacement of the vibration isolator.

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Nomenclature

\hat{a}	Peak value of acceleration (mm/s ²)
f	Frequency (Hz)
n	Engine speed (rpm)
N	Length of data samples
P	Power (W)
T	Torque (N·m)
v	Velocity value (mm/s)
\hat{v}	Peak value of velocity (mm/s)
v_{RMS}	RMS value of velocity (mm/s)
V	Discrete Fourier transform of velocity (mm/s)

Appendix A

Table A1. Specifications of the experimental diesel generator set.

Diesel engine	Model	DOOSAN P158LE-III
	Type	4-Cycle, V-type, 8-Cylinder, Turbo charged & intercooled
	Rating	1800 rpm
	Standby Gross Output	508 kWm
	Standby Net Output	484 kWm
	Bore x stroke	128 × 142 mm
	Displacement	14.618 L
	Compression ratio	14.6:1
	Firing order	1-5-7-2-6-3-4-8
	Dry weight	961 kg
Dimension (LxWxH)	1389 × 1389 × 1216 mm	
Generator	Model	MARELLI MOTORI MJB 355 SB4
	Rating	570 kVA
	Power factor	0.80
	Number of poles	4
	Rated speed	1500 rpm
	Overspeed	2250 rpm
	Weight	Approx. 1550 kg
	Frequency	50 Hz
	Voltage	440 V
Rated current	822.7 A	

References

1. Prenc, R.; Cuculic, A.; Baumgartner, I. Advantages of using a DC power system on board ship. *J. Marit. Transp. Sci.* **2016**, *52*, 83–97. [CrossRef]
2. Onboard DC Grid—A System Platform at the Heart of Shipping 4.0. Available online: <https://new.abb.com/marine/generations/generations-2017/business-articles/onboard-dc-grid-a-system-platform-at-the-heart-of-shipping> (accessed on 2 September 2021).
3. Variable Speed Generators Sets Offer Advantages for Commercial Shipping. Available online: <https://www.mtu-solutions.com/cn/en/technical-articles/2020/variable-speed-generator-sets-offer-advantages-for-commercial-sh.html> (accessed on 2 September 2021).
4. Kim, K.; Park, K.; Roh, G.; Chun, K. DC-grid system for ships: A study of benefits and technical considerations. *J. Int. Marit. Saf. Environ. Aff. Shipp.* **2018**, *2*, 1–12. [CrossRef]
5. Jin, Z.; Sulligoi, G.; Cuzner, R.; Meng, L.; Vasquez, J.C.; Guerrero, J.M. Next-Generation Shipboard DC Power System: Introduction Smart Grid and dc Microgrid Technologies into Maritime Electrical Networks. *IEEE Electr. Mag.* **2016**, *4*, 45–57. [CrossRef]
6. Chai, M.; Reddy, B.D.; Lingeshwaren, S.; Panda, S.K.; Wu, D.; Chen, X. Progressing towards DC electrical systems for marine vessels. *Energy Procedia* **2017**, *143*, 27–32. [CrossRef]
7. Arcidiacono, V.; Monti, A.; Sulligoi, G. Generation control system for improving design and stability of medium-voltage DC power systems on ships. *IET Electr. Syst. Transp.* **2012**, *2*, 158–167. [CrossRef]
8. International Electrotechnical Commission. LVDC: Electricity for the 21st Century. Available online: https://storage-iecwebsite-prd-iec-ch.s3.eu-west-1.amazonaws.com/2019-09/content/media/files/tr_lvdc_en_2017_lr.pdf (accessed on 2 September 2021).
9. Geertsma, R.D.; Negenborn, R.R.; Visser, K.; Hopman, J.J. Design and control of hybrid power and propulsion systems for smart ships: A review of developments. *Appl. Energy* **2017**, *194*, 30–54. [CrossRef]
10. The Step Forward Onboard DC Grid the New Way with Onboard DC Grid. Available online: https://new.abb.com/docs/librariesprovider91/articles/lm00614-onboard-dc-grid-brochure_june2014_1.pdf. (accessed on 2 September 2021).
11. Bolt, J.A.; Henein, N.A. The Effect of Some Engine Variables on Ignition Delay and Other Combustion Phenomena in a Diesel Engine. *Proc. Inst. Mech. Eng. Conf. Proc.* **1969**, *184*, 130–136. [CrossRef]
12. Henein, N.A.; Bolt, J.A. Ignition Delay in Diesel Engines. *SAE Trans.* **1968**, *76*, 27–49. [CrossRef]
13. Rahman, M.; Kamil, M.; Bakar, R.A. Engine performance and optimum injection timing for 4-cylinder direct injection hydrogen fueled engine. *Simul. Model. Pract. Theory* **2011**, *19*, 734–751. [CrossRef]
14. Barnes, T.E.; Uhlenhake, B.E. Method of Determining the Fuel Injection Timing for an Internal Combustion Engine. U.S. Patent 6,367,456, 9 April 2002.
15. Hountalas, D.T.; Raptotiasos, S.; Antonopoulos, A.K.; Daniolos, S.; Dolaptzis, I.; Tsobanoglou, M. Two-Stroke Marine Diesel Engine Variable Injection Timing System Performance Evaluation and Optimum Setting for Minimum Fuel Consumption at Acceptable NOx Levels. In Proceedings of the ASME 2014 12th Biennial Conference on Engineering Systems Design and Analysis, Copenhagen, Denmark, 25–27 July 2014. [CrossRef]
16. Wärtsilä Variable Injection Timing. Available online: <https://www.wartsila.com/services-catalogue/engine-services-4-stroke/wartsila-variable-injection-timing> (accessed on 2 September 2021).
17. Variable Injection Timing (VIT): What Marine Engineers Must Know? Available online: <https://www.marineinsight.com/main-engine/vit-marineengineer-must-know/> (accessed on 2 September 2021).
18. ISO 8528-9:2017 Reciprocating Internal Combustion Engine Driven Alternating Current Generating Sets—Part 9: Measurement and Evaluation of Mechanical Vibrations; International Organization for Standardization: Geneva, Switzerland, 2017.
19. Antoine Parseval (1755–1836)—Biography—MacTutor History of Mathematics. Available online: <https://mathshistory.st-andrews.ac.uk/Biographies/Parseval/> (accessed on 2 September 2021).
20. Arfken, G.B.; Weber, H.J.; Harris, F.E. *Mathematical Methods for Physicists*; Elsevier Inc.: Amsterdam, The Netherlands, 2013. [CrossRef]
21. Parseval's Theorem. Available online: https://en.wikipedia.org/wiki/Parseval%27s_theorem (accessed on 2 September 2021).
22. Tan, L.; Jiang, J. *Digital Signal Processing: Fundamentals and Applications*; Elsevier: Amsterdam, The Netherlands, 2018.
23. Adeoye, O.S.; Adebayo, A.A.; Olofinjana, A.; Tafa, A.K. An Overview of Methods of Re-duction of Vibration for Diesel Generators. *J. Electr. Electron. Syst.* **2019**, *8*, 1–7. [CrossRef]