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Response Surface Optimization of Vibration Level in Diesel Engine with Biodiesel Usage: A Performance Enhancement Study

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ABSTRACT

In this study, a single-cylinder direct-injection (DI) diesel engine was fueled by biodiesel. The Palm Oil Methyl Ester (POME), blended in amounts up to 20%, is tested at various engine speeds and loads to measure vibration level. Then, mathematical modeling was developed to relate the engine vibration level's responses to variables, including engine speed, load, and biodiesel blending percentage. Finally, all the numerical factors were calibrated using the proposed models. The significance of all factors in this study was demonstrated by the second peak of the engine's vibration, which contains a wealth of information about the excitations. Modeling results had previously shown that the significance of factors could vary according to the corresponding peaks of vibration in the engine. Meanwhile, the adjusted R^2 *of the developed model for vibration responses were 0.98, 0.87, 0.76, and 0.79, respectively. Further, the optimization results highlighted that utilizing a B20 fuel blend—a mixture of 20% biodiesel and 80% diesel fuel by volume—run at 2160 rpm with no load condition produced the best solution with the highest desirability value to satisfy all the responses. In summary, the study's findings showed that optimization should be considered while developing a new policy for using biofuel in internal combustion engines.*

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Introduction

According to current estimations, global energy demand will increase by 50% in the next few years. Diesel is now the second largest energy source in the transport sector and accounts for more than a third of global energy production as developing countries increasingly use internal combustion engines [1]. To address the depletion of fossil fuels and the significant exhaust emissions of internal combustion engines, environmentally friendly alternative fuels are being developed primarily to meet the world's expanding energy needs, reducing reliance on fossil fuels and reducing pollution compared to conventional fuels [2]-[3]. Those biofuels mixed directly with conventional diesel without further processing are considered primary biofuels and have a significant cost advantage in production, initial investment, and transportation [4]. Due to the recent increase in demand and decrease in the availability of fossil fuels caused by the growth of cities and the rise in the number of vehicles, research into the use of renewable energy sources, particularly oxygenated biofuel/biodiesel as a diesel substitute, has dramatically intensified [5]-[6].

Despite the superior power density, high thermal efficiency, high reliability, durability, low fuel consumption, and specific costs of diesel engines [7], they are reported to generate a higher noise level due to piston slap [8]. The vibration of the vehicle's body is observed to be larger than that of a petrol engine because of its higher compression ratio, which owes to the engine's rougher combustion process, which generates higher structural dynamics [9]. This phenomenon has made a significant contribution to the engine's noise production. Interestingly, biodiesel-diesel blend development is claimed to lessen the vibrations due to the better combustion process [10]-[11]. The change, however, could advance with higher compression ratios due to a higher cylinder pressure that increases the vibration generation [12]. With the significant benefits of biofuels, which may be produced from numerous feedstocks of both edible and non-edible oil categories, renewable sources, and conveniently accessible [13], the researchers' efforts to assess the engine's noise and vibration characteristics have been boosted.

A few years ago, Sarıdemir and Ağbulut [14] analyzed the effects of cottonseed methyl ester as a substitute fuel in diesel engines operated at varying engine loads and constant engine speeds. Since the maximum increased pressure, cylinder pressure, and rate of heat release are the parameters that relate to the generation of noise and vibration, lowering them by reducing the ignition delay time might reduce both noise and vibration simultaneously. Aside from that, using the B20 fuel blend produced the least vibration of all the tested fuels due to the biodiesel's better fuel qualities. In a different study, Karagöz et al. [15], who used the waste tire biodiesel, found that the engine vibration amplitude increased as a result of the increasing pyrolytic fuel content in blends and engine loads. This indicates that the highest blending percentage at the highest load conditions produced the maximum amplitude. It is safe to conclude that the higher in-cylinder pressure values and longer ignition delays should be what caused this. Conversely, a study by Velmurugan et al. [16] showed that adding 30% palm oil biodiesel to diesel improved the vibration level at 50% and full load. This illustrates how different fuel qualities, such as cetane number, viscosity, density, calorific value, and others, may influence the decrease in vibration level. Recently, Jaikumar et al. [17] evaluated the vibration characteristics of a diesel engine running on several biodiesel blends made from moringa oleifera under varied load levels. They discovered that using biodiesel mixes should lessen the potential for knocking because they burn fuel more completely and smoothly than regular diesel. However, they also noted that the vibration was exacerbated toward greater loads due to the significant force created on the piston because of increasing cylinder pressure. As a result, stronger vibrations were observed at higher loads. Nevertheless, the Root Mean Square (RMS) velocity was recorded as lowest by the B20 usage.

With several analyses performed in the engine, improvements in the results can be made through optimization. The best combination of parameters can be obtained by numerically imitating how the engine could lead to a certain output level. Many of the parameters (known as "calibration parameters") can be quickly modified on a real engine in a lab to evaluate the characteristics. However, this method needs to give the complete information required to comprehend why such a change in the analysis is observed. Therefore, it is imperative to develop a reliable model for calibrating the relevant parameters [18]. In a work by Deb et al. [19], using multi-linear response methods, the performance and emission characteristics of the hydrogen-diesel dual fuel strategy have been estimated. Equations for the response function were also employed to implement the optimization using a genetic algorithm. Similarly, Percy and Edwin [20] used the Response Surface Methodology (RSM) to simulate how a dual-fuel engine would function and what emissions it would produce under various load circumstances and compression ratios. According to the model analysis, the quadratic model is significant for all six responses, and the predicted quadratic equations are appropriate for the prediction. In different work, Uslu and Celik [21] chose RSM to simulate engine performance and emission responses in various engine loads and addition rates of cerium dioxide (CeO_2) to diesel fuel. Results revealed that engine load considerably influenced all responses, while the addition of CeO_2 had no significant impact on the Brake-Specific Fuel Consumption (BSFC) and Exhaust Gas Temperature (EGT) responses. Additionally, all R^2 values in this study are higher than 98%, demonstrating the model's effectiveness.

Meanwhile, Said et al. [22] modeled the performance, combustion, and emissions based on engine load, fuel injection timing, and oxyhydrogen flow rate. They discovered that the engine load and flow rate significantly impact all the responses, but the fuel injection timing only impacts the carbon monoxide (CO) responses. Considering the adjusted R^2 for each response, a high degree of correlation can be noticed, with the combustion response variable having the highest value at 0.9973. Consequently, it demonstrates that the RSM can effectively forecast the engine responses.

In addition to modeling, numerous research has shown that the RSM may be one of the best optimization methods for carrying out the optimization. This includes the work of Sahu and Sharma [23] that optimizes Brake Thermal Efficiency (BTE) and nitrogen oxides (NOx) according to the load, compression ratio, and mixture. The RSM gave both solutions equal weightage, and the acceptable solution was reported based on the desirability value. To optimize the smoke opacity, BTE, BSFC, EGT, hydrocarbon (HC), NOx, CO, and Carbon Dioxide ($CO_{2)}$ with Trichosanthes Cucumerina Biodiesel (TCB) blend, engine load, and compression ratio as the input factors, Manimaran et al. [24] used the RSM. The combination of 45% TCB blend, 17.5:1 compression ratio, and 1.5 kW of engine load was found to have the maximum desirability at 0.9741. The output responses' lowest and highest error percentages were 1.27% for BSFC (kg/kWh) and 6.22% for NOx (ppm). Similarly, Kumar et al. [25] have identified the optimal value for the input parameters to achieve the highest energy-exergy efficiency and the lowest levels of BSFC, CO, HC, and NOx emissions. For the highest desirability value (0.9003), the test engine operates best with input settings of 4.571 kg load, 18 compression ratio, and 18.56% fuel blend. Meanwhile, Kocakulak et al. [26] have carried out RSM optimization with input parameters including naphtha ratio, engine speed, and lambda value; output parameters include effective torque, indicated thermal efficiency, BSFC, crank angles at 10% and 50% of completion of heat release ATDC, combustion duration, cyclical differences, maximum pressure rise rate, unburned hydrocarbon, and CO values. The best input parameter values were 75% naphtha ratio, 1166.75 rpm engine speed, and 2.12 lambda value. Post-optimization solutions showed that the highest desirability value was attained at 0.925.

According to the literature review, using biodiesel results in less vibration production. However, some findings contradict each other. The fuel's properties substantially influence the vibration response. The optimum blending ratio must be discovered, and optimization is required. Therefore, this study uses RSM to calibrate the design parameters to minimize the vibration level of a single-cylinder DI diesel engine using POME biodiesel.

Material and Methodology

The steps of the research are:

1. Preparing the biodiesel mixture.
2. Measure the vibration level generated by the engine powered by POME biodiesel.
3. Proposing a mathematical model to correlate the engine vibration to the engine working condition.
4. Calibration of the engine working condition to minimize engine vibration level.

Properties of the fuel

Felda Global Ventures (FGV) Holdings Berhad provided the palm oil methyl ester used in this study, produced using the transesterification process. Pure diesel is used as the reference fuel. Table 1 displays the characteristics of pure diesel and biodiesel mixtures. The table shows that biodiesel fuel has greater viscosity, density, and cetane number than pure diesel fuel.

Table 1: Properties of the fuel tested

Property	D100	POME5	POME10	POME20
Acid value (mg KOH/g)	0.16	0.17	0.18	0.22
Viscosity at 40 °C (mm^2/s)	3.8	3.83	3.86	3.91
Density (kg/m^3)	847	848.5	850	853
Cloud point (°C)	-8	-6.5	-5	-2
Pour point (°C)	-14	-12.5	-11	-8
Heating value (MJ/kg)	45.21	44.72	44.23	44.12
Cetane number	50.5	50.83	51.15	51.8
Calorific value (MJ kg^{-1})	45.89	45.67	45.45	45.01

Test engine specifications

This work used a horizontal single-cylinder, direct-injection diesel engine (YANMAR TF 120M). It was connected to an eddy current dynamometer to supply load for the engine. Three engine speeds—low, medium, and high—with an increase of 480 rpm from 1200 rpm to 2160 rpm were used in the experiment. It's crucial to note that resonance is an important phenomenon in vibration analysis. It may be influenced by additional factors, including excitation characteristics, system parameters, and measurement constraints [27]. Therefore, once the natural frequency of the engine structure is ascertained, the engine speed can be carefully selected based on the rule of thumb to avoid resonance effects in the responses. Thus leaving purely the excitation from the combustion and mechanical operation. For load application, the eddy current dynamometer can provide up to 28 Nm of load to the engine. Therefore, to set the load at 0%, 50%, and 100%, as done by Suhaimi et al. [28], the configuration for the load will be 0 Nm, 14 Nm, and 28 Nm. Figure 1 depicts the test engine's schematic diagram, and Table 2 contains its specs.

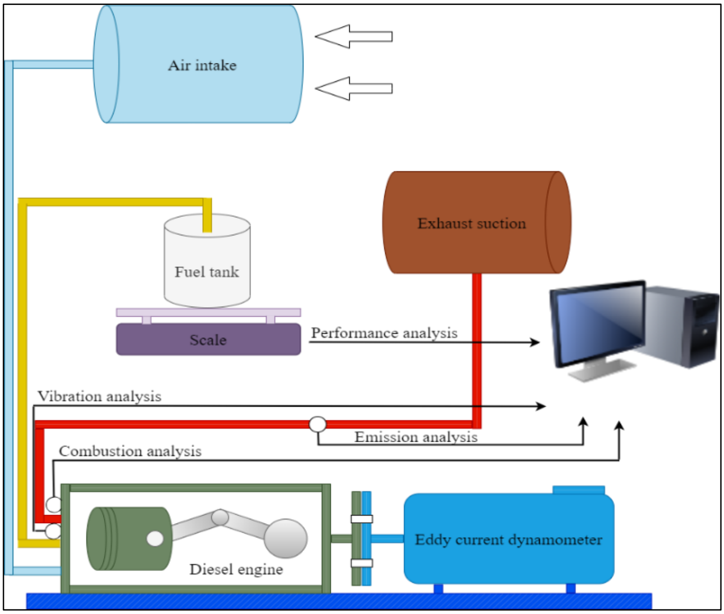


Figure 1: Schematic drawing of test bed engine

Table 2: Specifications of the evaluated engine

Model	**YANMAR TF 120M**
Number of cylinders	1
Cylinder bore x stroke, mm	92 x 96
Displacement, cc	0.638
Cooling system	Hopper/radiator
Dimensions: length x width x height, mm	695 x 348.5 x 530
Compression ratio	17.7

Design of experiments

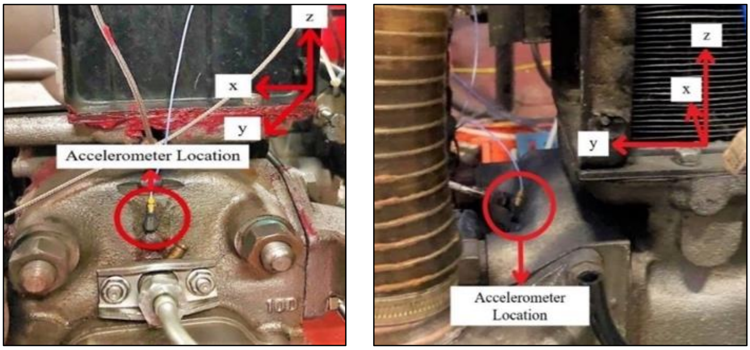
Table 3 lists the factors considered for this analysis and their levels. The multilevel factorial design was selected for the experiment's design (DoE), and the engine's vibration characteristics were evaluated in the frequency domain analysis to provide a better understanding.

Table 3: Matrix of experiments (factors)

Factor	Level 1	Level 2	Level 3	Level 4
Biodiesel percent (%)	0	5	10	20
Engine speed (rpm)	1200	1680	2160	-
Engine load (Nm)	0	14	28	-

Vibration analysis

A data logger, data storage unit, and uniaxial accelerometer are utilized to measure the vibration level. An accelerometer was attached to the top of the cylinder head using adhesive glue to assess the amount of vibration brought on by combustion activity. Of the three axes—vertical, longitudinal, and lateral—the vertical and longitudinal axes often exhibit a higher peak than the lateral. This situation will change based on the type of engine used since different engines operate on different operating principles. In normal occasions, vibrations with high longitudinal and high vertical axis detonations were seen. The upward and downward motion of the piston, as well as its left and right motion, caused the vibration. Meanwhile, to prevent adhesive-related damage to the accelerometer, which could affect the accelerometer's sensitivity, the accelerometer was only ever mounted to the engine once during the study. Figures 2(a) and 2(b) depict the location of the accelerometer from the front and side, respectively.



(a) (b)

Figure 2: Uni-axial accelerometer location; (a) front view and (b) side view

It is essential to note that the waveform in the diesel engine study is intricate and challenging due to the multiple excitations. Thus, the Fast Fourier Transform (FFT) was employed in this work to convert the time waveform into a frequency spectrum and display the waveform peaks associated with specific frequencies.

Vibration is often detected in terms of acceleration using an electromechanical device known as an accelerometer. However, vibration measurement using acceleration is favorable for the high-frequency region, affecting the extraction of information in the low-frequency region. Thus, the measured data was integrated into velocity units to display the information accurately, and it will be evaluated using the RMS method. Hanning windowing was also used since it can lessen the effects of leakage in this frequency spectrum analysis. Figure 3 shows a sample frequency response spectrum for an analyzed engine setting.

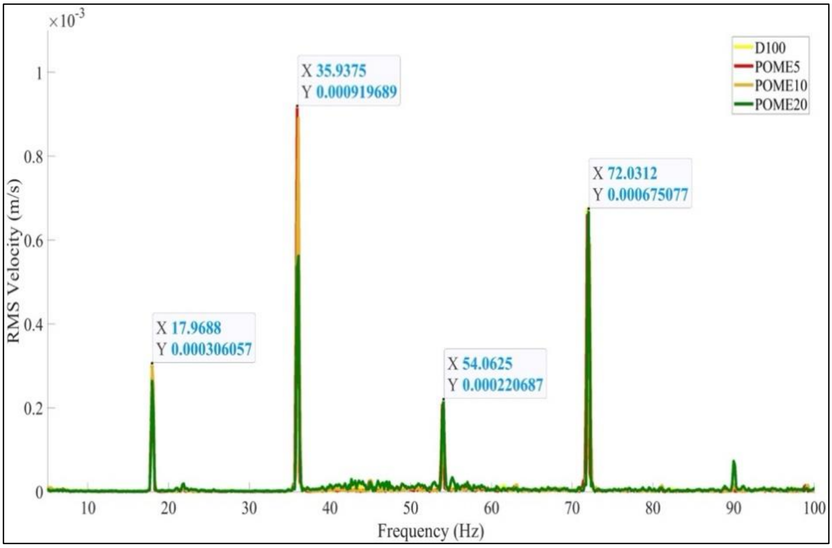


Figure 3: Frequency response spectrum

RSM approach

Response Surface Methodology (RSM), which integrates statistical and mathematical methodologies, can improve and optimize operations in several engineering applications [29]. Using RSM, the impact of important design parameters on the sub-objectives might be understood more clearly. The SS-ANOVA algorithm discovered the most critical design parameters before developing RSM functions [30]. The DoE and RSM also offer detailed results with fewer tests, save time, and utilize fewer resources to predict the best outcomes [31].

Empirical statistical models will be developed to explore the factor space. These models reflect the correlation between the variables [32]. In other words, statistical models resembling Equation (1) will be created to predict response *y* in accordance with variables x_1, x_2, ..., x_k.

$$y = f(x_1, x_{2,} \dots, x_k) + \varepsilon \tag{1}$$

The form of function *f* is not specified and may be very complex, and the ε is a representation of the variables that the f function might not have taken into account. Generally, ε is the result of the impact of unaccounted-for variables, background noise, and measurement error of the response [33]. The variables or independent factors in this study are the biodiesel blend (%), engine speed (rpm), and engine load (Nm). While the responses are the peak-to-peak value of vibration velocity obtained from the spectrum analysis. The models generally take the following form:

$$\begin{bmatrix} R_1 \\ R_2 \\ R_3 \\ R_4 \end{bmatrix} = f\begin{pmatrix} biodiesel\ blend\ (\%), engine\ speed\ (rpm), \\ engine\ load\ (Nm) \end{pmatrix} + \varepsilon \tag{2}$$

The next stage, optimization, also known as maximizing or minimization, is selecting the best input parameter values from the targeted response parameter values [34]. Typically, the optimization process via RSM entails three basic steps: statistically designed experiments, establishing the coefficients of a mathematical model, and finally, predicting the response and assessing the model's adequacy [35].

To assess the quality of the solution as the model is found adequate, desirability function, a helpful statistical technique for optimizing a given function may be used. It can enhance one or more responses by maximizing or minimizing the inspected item and transforming the response values into desirability function values between 0 and 1. Values are assigned a value of 0 when they may not have the desired effect and a value of 1 when they do, indicating that the test factor is functioning optimally [36].

In the current study, the process parameters that will be calibrated to reduce the vibration level at each peak concurrently are the biodiesel percentage, engine speed, and engine load. However, since the vibration data obtained is usually relatively small, there are some limitations in determining the optimization results due to the fixed decimal places. Therefore, a global normalization method will be used to bring all the responses onto a comparable scale [37], which improves the response accuracy of the model and facilitates more effective convergence of optimization methods by reducing the impacts of discrepancies in the range of variables [38]-[39]. The standardization method has been chosen to perform the normalization, transforming the data to have a mean of 0 and a standard deviation of 1 [40]. This scaling method is beneficial if the data's distribution is only sometimes Gaussian or if any outliers information wants to be preserved [41]. The equation for the standardization is listed in Equation (3). As the optimal solution is obtained, the results will revert to their original scale by applying the inverse transformation using the original mean and standard deviation. The equation for the inverse transformation is listed in Equation (4). All the optimization processes will be carried out using Design Expert 13 software. Tables 4 and 5 show the parameters calibration range and the optimization goal.

$$X_{normalized} = \frac{X - X_{mean}}{X_{std}} \quad (3)$$

Here, X represents an individual data point, X_{mean} is the mean of the dataset, and X_{std} is the standard deviation of the dataset.

$$(Normalized\ value\ \times standard\ deviation) + mean \quad (4)$$

Table 4: Variables to be calibrated

Factor	Unit	Range
Biodiesel percent	%	[0 - 20]
Engine speed	rpm	[1200 - 2160]
Engine load	Nm	[0 - 28]

Table 5: Optimization goal for the responses

Response	Goal
R1	Minimize
R2	Minimize
R3	Minimize
R4	Minimize

Results and Discussion

Vibration analysis

Various facts can be highlighted from the vibration results that were provided. An in-depth analysis was carried out as the second response typically indicates a higher level. Figures 4 to 6 show a consistent trend that persisted throughout the engine speed increment, showing that the vibration intensity decreased as engine speed increased. This decrease can be ascribed to several things, including the improved engine balance. Due to the fact that uneven rotating and reciprocating components cause engine vibration [42], the rapid movement of components at greater engine speeds has reduced the vibration from uneven forces since smoother and more balanced movement takes place. Additionally, engine manufacturers use various balancing strategies to minimize vibration for specific goals, such as improving dynamic balance.

This includes using flywheel and crankshaft counterweights and deliberately designing and positioning all engine components. Reduced vibration results from these balancing systems becoming more effective at greater engine speeds [43]. In addition, greater rpm range optimization techniques may be applied. Engine designs frequently focus on maximizing performance over a narrow rpm range. This implies that when the user approaches the engine's maximum rpm range, it runs more smoothly because it is closer to its intended design parameters [44]. Meanwhile, developing engine manufacturing techniques and materials may also help reduce vibration. Modern engines commonly use lighter, more robust materials, like composites or aluminum, to better reduce vibrations [45]. However, it's essential to note that while greater engine speeds often lessen vibrations, severe or irregular vibrations might still be a sign of mechanical problems or imbalances in the engine or other components [46]. Regular maintenance and inspection ensure the engine runs smoothly and efficiently.

In contrast to engine speed, engine load exhibits a linear relationship with the vibration intensity. This can be observed as the vibration level rises along with the increase in engine load. This level can be affected by various factors, including higher combustion forces. When working under a heavier load, the engine must produce more power to meet the demand. As a result, the cylinders experience stronger combustion forces, including higher pressures and temperatures. If the load exceeds the engine's design parameters, the increased forces may cause the engine to vibrate more. Secondly, when an engine runs, uneven forces are exerted on parts like the crankshaft, connecting rods, and pistons. Usually, the engine design includes balancing systems to offset these forces. However, the uneven forces may be more evident under heavy load conditions and result in additional vibrations [47]. Besides that, the higher engine loads could impose more mechanical stress on the engine components, including crankshaft, bearings, and pistons. As a result of the additional stress, parts may deform or wear unevenly, which can enhance vibration while the engine is running [48].

Meanwhile, as can be seen from the findings, the B20 consistently displays the lowest amount among all tested fuels as the engine speed is increased. Biodiesel's greater lubricity might explain this. Compared to regular diesel fuel, biodiesel offers better lubricating characteristics that reduce friction and wear between moving engine parts, resulting in smoother operation and reduced vibration. It can be found in the work by Satsangi and Tiwari [49] that as the viscosity and density of a fuel decrease, higher noise and vibration are generated at the high load. Also, biodiesel typically has a higher cetane number than regular diesel fuel. This higher cetane number improves combustion efficiency, leading to a cleaner and more complete fuel burning. This results in a lower amplitude of vibrations [50]. Moreover, biodiesel has a lower carbon content and more oxygen than petroleum-based diesel fuel [51]. This may assist in reducing the amount of carbon buildup on the fuel injectors, valves, and combustion chamber, which may enhance airflow, fuel atomization, and combustion efficiency, resulting in smoother engine operation and less vibrations [52].

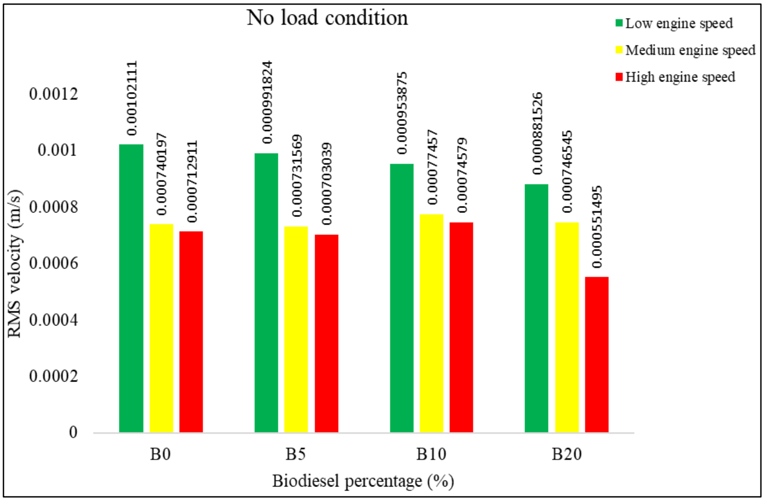


Figure 4: Second vibration response during no-load conditions

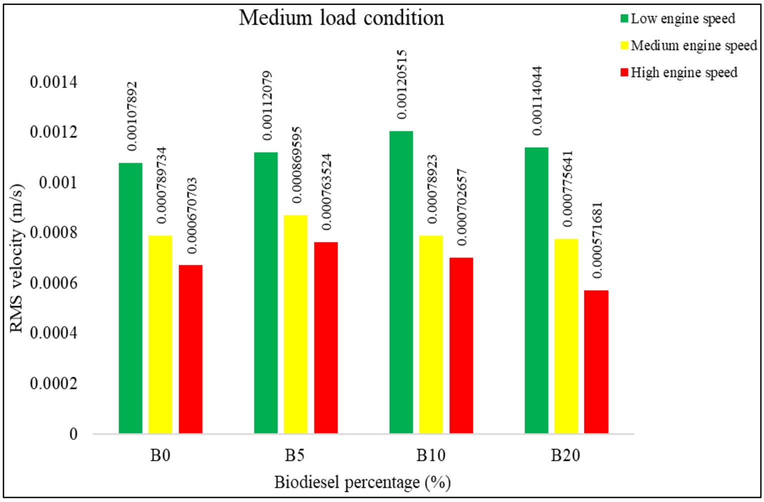


Figure 5: Second vibration response during medium load conditions

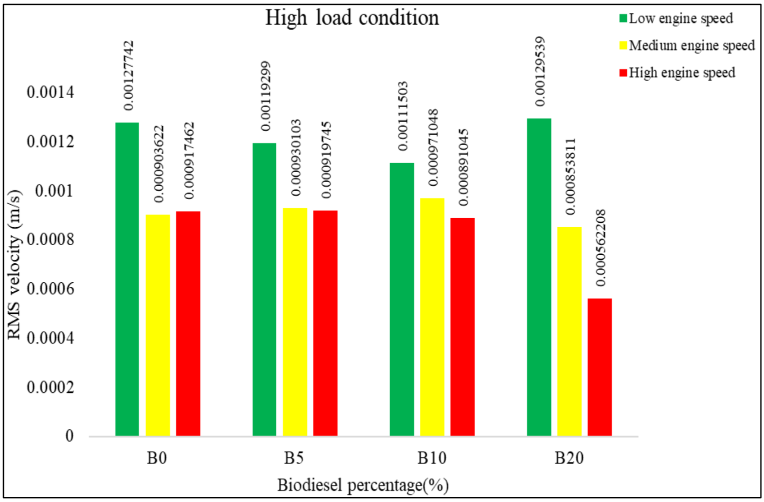


Figure 6: Second vibration response during high load conditions

Model and data analysis

Table 6 shows the importance of the model terms based on the analysis of variance (ANOVA) of the quadratic model for responses. A brief look at the table reveals that, aside from the second peak, the vibration responses are not significantly influenced by the amount of biodiesel. On the other hand, the engine load is found to be exceptionally irrelevant in the fourth peak response, whereas the engine speed considerably impacts all responses. On top of that, the second peak also shows that every model term is significant, demonstrating how much information is contained in the response.

Table 6: Significance of model terms based on ANOVA

Response	A	B	C	AB	AC	BC	A^2	B^2	C^2
R1	x	✓	✓	x	x	✓	x	✓	✓
R2	✓	✓	✓	✓	x	x	x	✓	x
R3	x	✓	✓	x	x	x	x	x	x
R4	x	✓	x	x	x	x	x	✓	x

✓ – significant at 95% confidence interval, x – not significant at 95% confidence interval

A – Biodiesel percent

B – Engine speed

C – Engine load

The statistical characteristics of the developed models are shown in Table 7. As shown in the table, all F-values indicated that the models are statistically significant. On the other hand, the correlation coefficient (R^2) and adjusted correlation coefficient are greater than 0.50 and fall within the range suitable for all models. These parameters show the model's ability to predict the parameter's actual value and how successfully it accomplished it [53]. The models are adequate if there are minimal discrepancies between the R^2 and the adjusted R^2. The table shows that the first vibration response has the highest adjusted correlation coefficient (R^2 = 0.98). Various models were tested to estimate the engine parameters, and the software automatically selected a quadratic model based on the correlation coefficient values for each model.

Table 7: ANOVA for the response model

Response	**Sum of squares**	**df**	**Mean square**	**F-value**	**R^2**	**Adjusted R^2**
R1	34.39	5	6.88	340.18*	0.9827	0.9798
R2	31.16	5	6.23	48.67*	0.8903	0.8720
R3	26.92	2	13.46	55.01*	0.7693	0.7553
R4	28.04	2	14.02	66.43*	0.8010	0.7890

* - model is significant

The mathematical models for the vibration responses are presented in Equations (5) – (8), respectively. The values in these equations for variables are as their units.

$$R1 = 4.14287 + (-0.00731017 * ES) + (-0.0706139 * EL) + 4.90696e\text{-}05 * ES * EL + 2.58184e\text{-}06 * ES^2 + 0.000885113 * EL^2 \quad (5)$$

$$R2 = 7.73117 + 0.0675448 * BP + (-0.00838478 * ES) + 0.0341691 * EL + (-5.33571e\text{-}05 * BP * ES) + 2.03972e\text{-}06 * ES^2 \quad (6)$$

$$R3 = 2.97412 + (-0.00202245 * ES) + 0.0302568 * EL \quad (7)$$

$$R4 = -15.8322 + 0.0179037 * ES + (-4.787e\text{-}06 * ES^2) \quad (8)$$

Figure 7 shows the correlation between the predicted and actual values for the parameters. As seen in the Figure, most of the data are close to the 45-degree line, which shows a significant correlation between the actual and predicted values. Based on the correlation coefficient values for various factors, it can be inferred that the proposed model can be utilized to estimate the engine vibration responses.

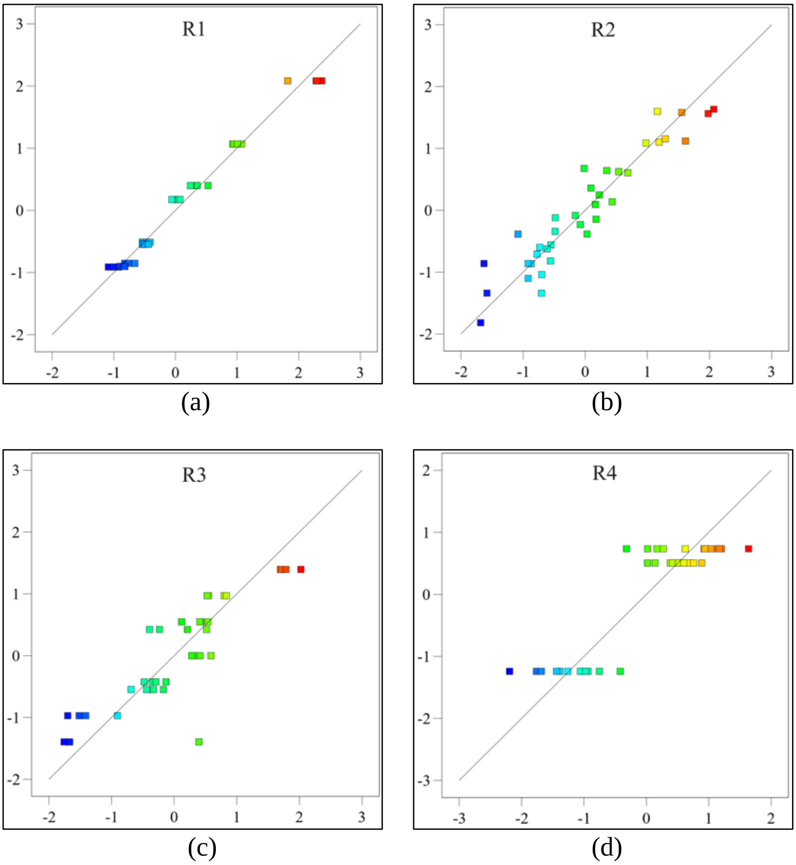
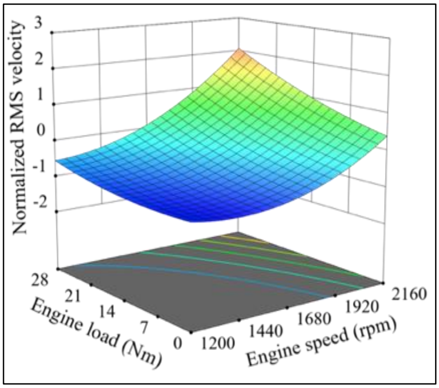


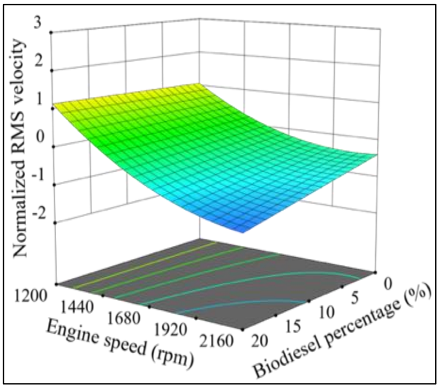
Figure 7: Experimental vs. predicted values of different responses; (a) predicted R1, (b) predicted R2, (c) actual R3, and (d) actual R4

The optimization was carried out using the above-mentioned proposed models. It is essential to discuss how the responses differ depending on the factors considered. To do this, 3D surface graphs can be used to comprehend how the variables may affect the response's vibration generation. As can be noted in Table 6, the second response is further addressed because it contains all significant model terms.

Figure 8(a) demonstrates that the engine speed and load increase in the first response tend to increase the vibration level as the biodiesel proportion in the fuel blend does not significantly contribute. Concerning the engine load application, a direct correlation can be noticed as the increment in engine load led to higher vibration levels. This was attributable to an increase in engine-related forces. The engine should produce more power to keep up with the demand while operating under a heavier load. As a result, the combustion forces within the cylinders have increased, leading to higher pressures and temperatures and a higher vibration level [54]. On the other hand, engine components, such as pistons, connecting rods, and crankshafts, experience imbalanced forces during the operation. These forces are typically counteracted by balancing mechanisms in the engine design. However, the imbalanced forces may be more prominent because of the greater inertia forces associated with the operation under heavy load [55]. Hence, this leads to an increment in vibration generated by the engine.



(a)



(b)

Figure 8: Variation of vibration level in first and second response vs. effective factor (statistically significant effect); (a) R1 and (b) R2

However, in the second response indicated in Figure 8(b), the interaction effect of engine speed with biodiesel percentage shows a reduction in trend as the engine speed increases and a larger biodiesel proportion is used in the fuel blend. This can be expected through improving the combustion process, which could later increase engine balance. Ahirrao et al. [56] state that vibrations can be minimized by eliminating the unbalanced forces and supporting the engine at proper mounts. Since higher engine speeds will increase the balance of an engine, a reduction can be expected. Apart from that, proper design of the engine components and balancing procedures like counterweights on the flywheel and crankshaft could also help the reduction. These balancing systems may function more effectively at certain high engine speeds, which would lessen vibration [57]. Meanwhile, considering that biodiesel possesses high lubricating properties compared to conventional diesel fuel, the ability to reduce friction and wear between moving engine parts is visible as the lower vibration level could be obtained in a higher biodiesel percentage in the fuel blend [58]. Moreover, the vibration signature was typically noticed less for biodiesel fuel blends than regular diesel fuel due to the combustion effectiveness of biodiesel blends, which resulted in greater cetane number and higher oxygen content. Thus, complete combustion results in a lesser knock tendency [59].

Optimization result

Using multi-objective optimization, the mathematical models previously mentioned are employed to optimize the vibration intensity in various peaks. As the optimization was run numerically, 41 solutions were discovered. With different values for different variables, there are many optimal solutions. This is because when the software tries to optimize one variable, the values of other variables will also change. Consequently, the desirability function can be employed as a quality indicator to assess the solutions. The best option is recommended since its attractiveness value is close to 1. In this case, the highest desirability value for the ideal solution is 0.935. It was discovered that the engine vibrated the least while running at 2160 rpm with a B20 fuel blend under no load. Figures 9(a) and 9(b) highlight the fluctuation of the solution's desirability vs. factors.

As previously discussed, it was shown that increasing engine speed and adding more biodiesel might reduce engine vibration due to the improved biodiesel fuel qualities and improved engine balance. Thus, for the same reason, the optimal solution suggested that the highest engine speed and biodiesel proportion should be utilized to reduce excessive vibration. However, since the engine load is proportionally related to the vibration level, the lower value of the engine load applied is supposed to reduce the vibration level. Therefore, the optimal solution also recommends that no load be applied to minimize vibration. Similarly, all the explanations are also applicable to enlighten the results illustrated in the graph of the solution’s desirability.

Since the rotational frequency primarily occurs in the second peak and its harmonic, the first and third peaks present lower vibration levels regarding the optimal solution's vibration level. The results before optimization show a comparable trend. Therefore, we recommend the experimental verification of the optimal solution parameter.

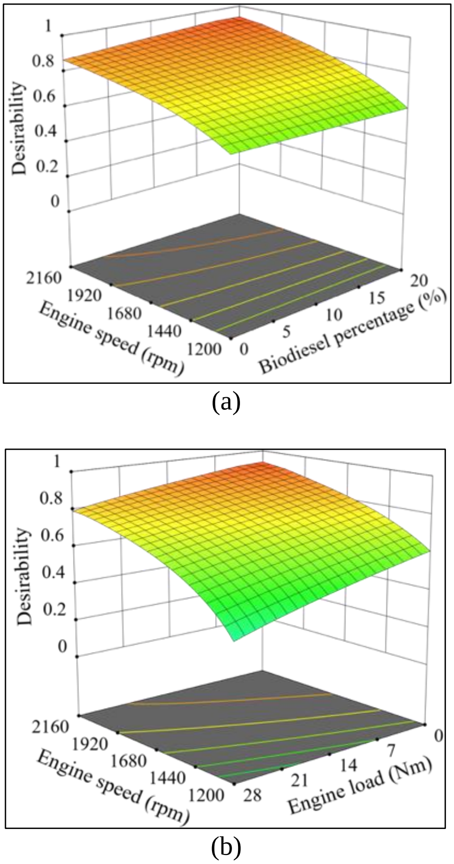


Figure 9: Variation of the solution desirability vs. factors, (a) AB and (b) BC

The responses' experimental outcomes were recorded using the suggested values for the optimal engine operating condition point. Then, in Table 8, these experimental and numerical data are compared. The table shows that the largest and minimum deviations between experimental data and predicted values are 4.97% and 2.25%, respectively. Since the RSM does not provide a particular error percentage range, the results can be described in terms of how closely the predicted and experimental data agree. As the importance level of the second peak is essential, it may be noted that the error percentage may vary according to the trade-off between each response.

Nevertheless, the error percentage for each response indicated that the optimization is able to minimize the engine's vibration level.

Table 8: Optimized conditions by RSM

Response	Experimental value	Predicted value	Error percent
R1	0.000149981	0.000155	3.24
R2	0.000546846	0.000525	4.16
R3	0.000260339	0.000248	4.97
R4	0.000570851	0.000584	2.25

Conclusion

This study used a small single-cylinder engine on biodiesel as an alternative fuel. Different test conditions were applied to operate the engine using different biodiesel blend percentages, speeds, and loads. A multi-objective optimization employing RSM has been used to obtain the optimum combination of parameters to produce the lowest possible vibration level. The study's findings allow for the following conclusions to be made:

i. The ANOVA shows that the biodiesel proportion has an insignificant effect on the responses except for the second response.
ii. Meanwhile, both engine speed and load significantly contributed to all responses, except for engine load, which does not effectively influence the fourth response.
iii. Using the quadratic model, the adjusted R^2 for all models is within the acceptable range, with the highest of 0.98 in the first response, indicating the model can be used to predict the response.
iv. The optimization suggested that the minimum vibration level can be obtained by using B20 run at RPM 2160 without any load conditions, which produces 0.000155 m/s, 0.000525 m/s, 0.000248 m/s, and 0.000584 m/s of RMS velocity for the first, second, third, and fourth responses, respectively.
v. Validation using the optimal operating point indicated the closeness between the experimental and predicted results, with the lowest percentage error of 2.25% and the highest percentage error of 4.97%.
vi. The optimization shows an excellent capability to optimize the responses. Therefore, this method can be utilized to optimize the other engine responses.

Contributions of Authors

The authors confirm the equal contribution in each part of this work. All authors reviewed and approved the final version of this work.

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Conflict of Interests

All authors declare that they have no conflicts of interest.

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