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ANFIS technique for handling vibration characteristics of a diesel engine fueled by hybrid biodiesel-Natural Gas

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Abstract

Pollution derived from the use of Diesel fuels led to finding a low emission alternative resource like biodiesel. The use of biodiesel has to improve engine performance and reduce emissions. Using dual-fuel technology (NG and pilot fuel) in compression ignition engines can be considered as another way to improve engine performance as well as reduce engine emissions by the use of alternative fuels. Otherwise, there is no justification for using alternative fuels. The vibration characteristics of an engine caused by the combustion process can be considered as one of the main factors for considering the engine's durability. In the present study, vibration characteristics of a diesel engine fueled by Diesel+NG and B5+NG have been studied. Also, the ANFIS technique has been employed for modeling and estimation of the total engine vibration value. Based on the results, B5 provided a lower vibration compared with Diesel fuel, especially in the dual-fuel systems. This indicated that biodiesel makes more compatible fuel samples for dual combustion systems. Also, ANFIS could successfully cope with the modeling task with high accuracy and a low deviation from target values. According to the results, the capability of the Gaussian MF type for providing the testing phase data was considerably higher than that for the Tri. (about 3.5 %), Trap (about 69.66%) and Gbell (about 65.37%).

Keywords: Biodiesel; Diesel Engine; ANFIS; Vibration, Natural Gas

1. Introduction

The importance of energy and its role in economics and politics in today's world is quite clear. This subject is important for both the advanced industrialized countries which are the major energy consumer and the oil-producing countries [1]. Nowadays, the most important source of energy in the transportation, industry, agriculture, and household sectors is fossil fuels and their derivatives [2]. Based on reports from the U.S. Energy Information, the transportation sector is one of the major consumers of diesel fuel in the world which can emit a significant volume of pollutants. These concerns led to the production of low-emission alternative fuels with pollution and environmental damage. A few years after the invention of spark-ignition engines, in 1893 Rudolf Christian Karl

Diesel Invented an engine in which the combustion of fuel was carried out by the high temperature of the compressed air. The fuel used by this engine was initially coal powder. After years of research by scientists and the invention of the injector pump by Robert Bush in 1923, the evolved types of these engines were made which were working with diesel fuel, and in honor of Rudolf Diesel they were named Diesel engines [3]. Nowadays, these engines have many applications in various fields such as agriculture, transportation, and industry [4]. Diesel engines are more efficient and more cost-effective compared to spark-ignition engines. They are also safer, as diesel fuel is less volatile than other fuels such as gasoline and natural gas which are used in spark-ignition engines, and also its steam is less explosive. Unlike gasoline engines, especially for heavy duties, diesel engines operate well and efficiently compared with that spark-ignition engines, so they are ideal for the use of ships, trucks, buses, railroads, and locomotives [5].Diesel engines have a higher compression ratio compared with spark-ignition engines. A higher compression ratio means that parts of a diesel engine must be very resistant to impacts, corrosion, and pressures. Because of this, diesel engines need to be stronger and heavier, so for a long time, they were used to move large vehicles and machinery. Although this may sound like a weakness, it means that diesel engines are usually more powerful and they have longer durability compared with that spark-ignition engines [3].Pollution is also one of the biggest weaknesses of diesel engines. They are noisy and produce soot and smoke that are both dangerous to health. Theoretically, diesel engines are more efficient, so they consume less fuel and produce less carbon dioxide which is the most important GHG, therefore it can be claimed that they contribute to reducing GHG emissions [6].

Biodiesel is the most promising plant-based biofuel which is considered an alternative fuel for diesel fuel. Biodiesel is mono alkyl of fatty acid ethyl or methyl esters which is produced from waste animal or planet resources through the trans-esterification process [7] and can be blended with diesel fuel. Biodiesel benefits some advantages a low volume of emissions compared with diesel fuel. Biodiesel also contains 10 to 12 % oxygen content which can reduce soot emissions and improve the combustion process [8]. Biodiesel is considered a renewable and sustainable energy source that can significantly affect the environment and economic concerns. In contrast to the various benefits, this fuel also has disadvantages like reducing the engine BP, increasing the BSFC, and increasing NOx emission [9]. In recent years, various studies have been developed to discuss the production and effect of biodiesel on combustion characteristics including the performance and emission of diesel engines [10-12]. Based on reports, there are differences between the physical properties of diesel and biodiesel fuels which make differences in combustion and emission characteristics of fuel samples. Biodiesel benefits from higher viscosity and density and lower calorific value compared with diesel fuel. A low calorific value reduces BP and increases BSFC. Aydin and Bayindir [13] studied the effect of biodiesel fuel on BSFC and found that the BSFC for B100 fuel is about 18% more than that for diesel fuel. In another study by Armas et al [14] the effect of soybean oil biodiesel on BSFC was compared with that for the ultra-low sulfur diesel fuel in direct injection, naturally aspired diesel engine at 2400rpm. Based on results, the BSFC for B100 fuel was about 12% more than that for diesel fuel. In the study by ghazanfari et al [15], the reduction of BP and attempts to compensate for it, was expressed as the main reason for the increase of BSFC. Ramalingam et al [16]studied the effect of biodiesel on NOx emission in comparison with diesel fuel. Based on the results biodiesel fuel emits NOx emissions higher than diesel fuel. The oxygen content of biodiesel fuel increases the NOx emission in the diesel engine. The use of biodiesel has to improve the engine performance and reduce emissions, otherwise, there is no justification for using alternative fuels [17]. This led researchers to apply fuel additives to improve the disadvantages of biodiesel and diesel fuels. Some additives including metal-based additives [18-20], ethanol and methanol as alcohol [21, 22], CN improvers [23], and emulsifiers [24] have been employed to improve the NOx emission in a diesel engine fueled with biodiesel.

According to the progress in the use of alternative fuels in CI engines, the need for introducing and using sustainable fuels seems to be necessary. Dual fuel technology which uses NG and pilot fuel is considered one of the sustainable ways for employing alternative fuels by researchers. In dual fuel technology systems, NG-air pre-mixture takes into the combustion chamber and starts the combustion process by the injection of pilot fuel. NG benefits a higher compared with that diesel fuel. This protects NG from self-ignition which needs a comparison ratio higher than 1:40 [25]. Biodiesel as pilot fuel helps for improving the pilot fuel condition. Otherwise, there is no justification for using alternative fuels. Among the common tests, the engine durability test can be a more comprehensive issue. The performance and reliability of a diesel engine depend on its durability in addition to its performance and emission characteristics. The durability of the engine is one of the most important phenomena which is somehow associated with fuel properties. Vibration characteristics of an engine caused by the combustion process can be considered as one of the main factors for considering engine durability.

Table 1, briefly presents studies that considered the vibration characteristics of a CI engine.

Table 1. the characteristics of studies developed in line with the corrosion and lubrication characteristics of biodiesel

Ref.	Fuel type	year	Engine	Finding
Nag et al. [26]	Hydrogen-Diesel dual fuel	2019	Kirloskar, Model TV1 Single-cylinder, 4-stroke, water-cooled CI diesel engine	Hydrogen-diesel improved vibration characteristics at part load condition
Lei et al [27]	Diesel–Methanol dual fuel	2016	Turbocharged, inter-cooled, and in-line six-cylinder diesel engine	Vibration is a function of peak pressure and injection timing as well as engine load
Javed et al [28]	Hydrogen-Diesel dual fuel in the presence of Zinc Oxide particles	2016	Kirloskar, Model TV1 Single-cylinder, 4-stroke, water-cooled CI diesel engine	The presence of hydrogen by 0.5, 1, and 1.5 l/min including 40 nm of ZnO successfully reduced vibration
Omar et al [29]	LPG-Diesel dual fuel	2017	Ricardo E6, naturally aspired, single-cylinder diesel engine	LPG could effectively reduce the engine vibration compared with that of the Diesel
Satsangi et al [30]	Diesel-n-butanol dual fuel	2018	Kirloskar, Model TV1 Single-cylinder, 4-stroke, water-cooled CI diesel engine	n-butanol increased the vibration in comparison with diesel fuel especially at higher engine loads

Recently, machine learning (ML) techniques have been successfully employed for considering and handling the vibration characteristics of CI engines in prediction and modeling tasks. Hosseini et al [31] employed the ANN technique for the prediction of performance, emission, and vibration characteristics of a single-cylinder, air-cooled Lombardini Model 3LD510 CI engine. Based on the results ANN could successfully cope with the task. Recently, ML techniques have considerable progress in taking sustainable and more accurate techniques for different tasks and fields of science. The present study wants to look into the effects of engine load, NG fraction, and biodiesel blends in dual-fuel combustion in the presence of NG, diesel, and biodiesel on engine vibration. This trend also wants to employ the ANFIS technique as a hybrid ML technique for the prediction of total engine vibration. To the best of our knowledge, this study can be the first study for the employment of the ANFIS for handling a CI engine vibration fueled by Diesel-biodiesel-NG which the results could be interesting for researchers who are studying for finding the best fuel sample for reaching a sustainable and proper engine performance.

The present study follows two main steps:

- To describe the vibration characteristics of a CI engine fueled by Diesel-Biodiesel-NG
- To evaluate the ANFIS technique for the prediction of total engine vibration

2. Materials and Methods

2.1. Fuel samples

The trans-esterification process, as one of the most applied methods in biodiesel production, is performed in presence of NaOH or KOH as the catalyst and alcohol (methanol or ethanol as a common type of alcohol) at a certain temperature during a certain processing time. In this study, Biodiesel was produced through a trans-esterification process from WCO as an available and low-cost source. Differences in the values of the impact Factors like the amount and type of catalyst and alcohol and processing time and temperature strongly affect the production yield. The amount and type of factors were selected from the study by Faizollahzadeh et al [9] which the maximum biodiesel production yield (98.46%) was obtained in the case of using methanol as the alcohol at 67.62 °C, in presence of NaOH as the catalyst by 1.1 wt. %, mixing intensity of 709.42 rpm and the alcohol to oil ratio of 6.09.The thermophysical properties of biodiesel are considered as the important factors which can affect the performance of the fuel these factors include density, viscosity, calorific value, and flashpoint. In this study, the mentioned factors were measured during the instructions of ASTM standards. ASTM defines a measuring standard and a range for each factor. Table 1 presents the measuring standards and range for each factor. Fuel samples were prepared with Diesel and B5 samples in the presence of pilot to gaseous fuel ratios of 50, 60, 70, and 80 %. The ratio of the pilot to gaseous was prepared by the use of Eq. 1 which prepares samples by the percentage of alternative energy.

$$Z = \frac{(\dot{v}) \times density_p \times LHV_p}{(\dot{v}_{NG}) \times density_{NG} \times LHV_{NG} + (\dot{v}) \times density_p \times LHV_p} \qquad (1)$$

Where $\dot{v}_p$ refers to the vol. the ratio of the pilot fuel $\dot{v}_{NG}$ refers to the vol. the ratio of the natural gas and Z indicates the pilot to gaseous fuel ratio.

2.2. Experiments

Experiments were performed using a 0.948 L, naturally aspirated, direct injection, four-stroke, single-cylinder, water-cooled diesel engine manufactured by Kirloskar Oil Engines Ltd., India. The engine benefits a displacement of 948 cc which was loaded by a jb/t-200 electricity generator which was suspended to the test engine using a shaft. The generator was connected to a 200 kN load cell through a 30 cm arm. The engine was loaded by a variable resistance TDGC2-5KVA. The fuel consumption is also measured by calibrated cylinder method. The tests were conducted at a constant speed of 1500 rpm and full load. The specifications of the employed engine were presented in table 2.

Table 1. The measuring standards for the thermo-physical properties [32]

Properties	Measuring method	Unit	Standard range
density	Weighting method	Kg/Lit	-
viscosity	D445	second	1.9-6
calorific value	D240	Mj/Kg	41.3
flash point	D93	°C	>130

Table 2. Engine Specifications
Manufacturer: Kirloskar Oil Engines Ltd., India
Engine type: Vertical, four-stroke, single-cylinder
constant speed, direct injection CI engine
Rated power: 7.4 kW @ 1500 rpm`
Bore/stroke: 102 mm/116mm
Displacement volume: 0.948 l
Compression ratio: 17.5
Start of fuel injection timing: 26° bTDC
Nozzle opening pressure: 200 bar
Cooling type: Water Cooling
Length/width/height: 685/532/850mm
BMEP at 1500 rpm 6.21 bar

The vibration was measured by VIBRO-Rack 1000-8 in three directions x, y, and z which is indicated in Fig. 1.

Table 3. Specifications of VIBRO-Rack 1000-8

Signal conditioner	Amplifier/Integrator to obtain velocity or displacement
Supply voltage	110/220 VAC
Current output	4-20 mA
Buffered output	For connection to portable data collector
Resolution	12 bit
No. of channels	8 channels
No. of samples	From 1000 to 100000 per channel
Communication	R-485, RS-232, with Modbus protocol
Accuracy	Input: 0~2.5 V, accuracy (%FSR) ±1LSB: 0.05
Dynamic range	0, 6, 14, 20 dB

Table 3 presents the specification of VIBRO-Rack 1000-8. The related sensors and equipment were bonded to the engine block in 3 directional axes (x-longitudinal axis, y-lateral axis, z-vertical axis). Vibration results were collected as RMS values calculated by the use of Eq. 2 [33]:

$$a_w = \sqrt{(\frac{1}{T}\int_0^T a_w^2(t)dt)} \tag{2}$$

Where a_w refers to acceleration (m^2/s) and T is the whole time. After measuring a_x, a_y and a_z the total acceleration can be calculated by Eq. 3:

$$a_t = \sqrt{(a_x{}^2 + a_y{}^2 + a_z{}^2)} \tag{3}$$

Errors in experimental measurements have been categorized into two groups including errors related to operators and devices. Device errors occur due to the nonlinear behavior of devices as well as wrong calibration. These errors lead to uncertainty in the measurements obtained and the results of the tests appear to be inaccurate. This makes it possible to use some statistical and mathematical methods to minimize errors. In general, the reduction of the effect of errors on the final results can be performed by the duplicate measurements as well as the calculation of the minimum error rate [34].

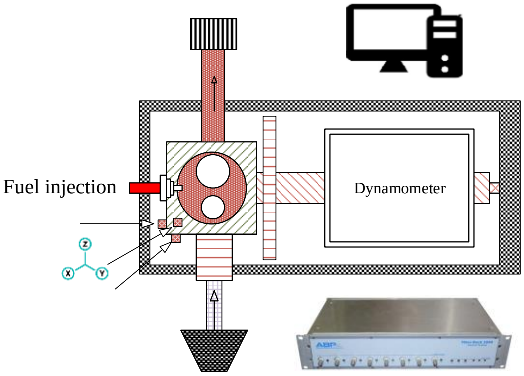


Fig. 1. The schematic of the engine test setup

2.3. Adaptive neuro-fuzzy inference system (ANFIS)

In the present study, ANFIS was employed as a modeling platform for the estimation of the total vibration value. Additional description about ANFIS is available in our previous study in [35]. As is clear from the architecture of ANFIS in Fig. 2, biodiesel portion, NG ratio, and engine load are three inputs for generating the only output value (total vibration). The modeling phase for ANFIS was started using three MFs of Tri., Trap, Gbell for choosing the best function. These MFs are four types of the most popular membership functions for developing the ANFIS technique in the training phase. The training phase was performed using 70% of the total data. ANFIS was developed using the hybrid optimum method with linear type for the output membership function.Evaluation of results of the ANFIS was performed by RMSE and correlation coefficient described in Eq. 3 and 4.

$$RMSE = \sqrt{\frac{1}{n}\sum (Targets - Outputs)^2} \qquad (3)$$

$$CC = \sqrt{1 - \frac{\sum (Targets - Outputs)^2}{\sum (Targets)^2}} \qquad (4)$$

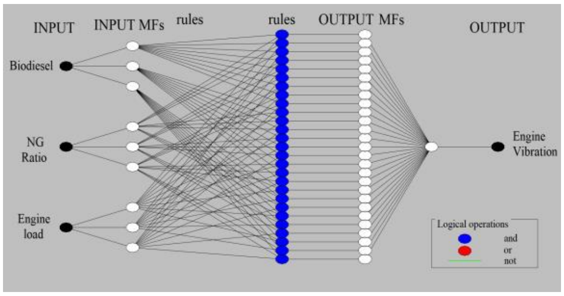


Fig. 2. ANFIS architecture

3. Results

Fuel samples have been prepared using B5 and Diesel fuel has been considered as the control fuel. NG was premixed by air and imported to the combustion chamber after the filtration process. These fuel samples also provide the studying of the individual and mutual effects of NG+Pilot in comparison with single Pilot fuel. These comparisons can lead and orientate the study towards the effect of hybrid Diesel-Biodiesel-NG on vibration characteristics of a diesel engine.

3.1. Fuel Samples

This section presents results related to the measuring of fuel samples’ properties (Table 4). Measuring each property was performed by the related standard which was prepared by ASTM standards according to Table 1. Based on table 4, the density and flash point of B5 is more than those for the diesel fuel. increasing the portion of biodiesel in fuel samples can significantly increase the density value but reduces the calorific and flash point values. Fuel properties can be the most effective factor in the behavior of fuel in the combustion chamber of a diesel engine [36]. Density and calorific value are two factors that have a significant effect on the combustion characteristics of fuels [37].

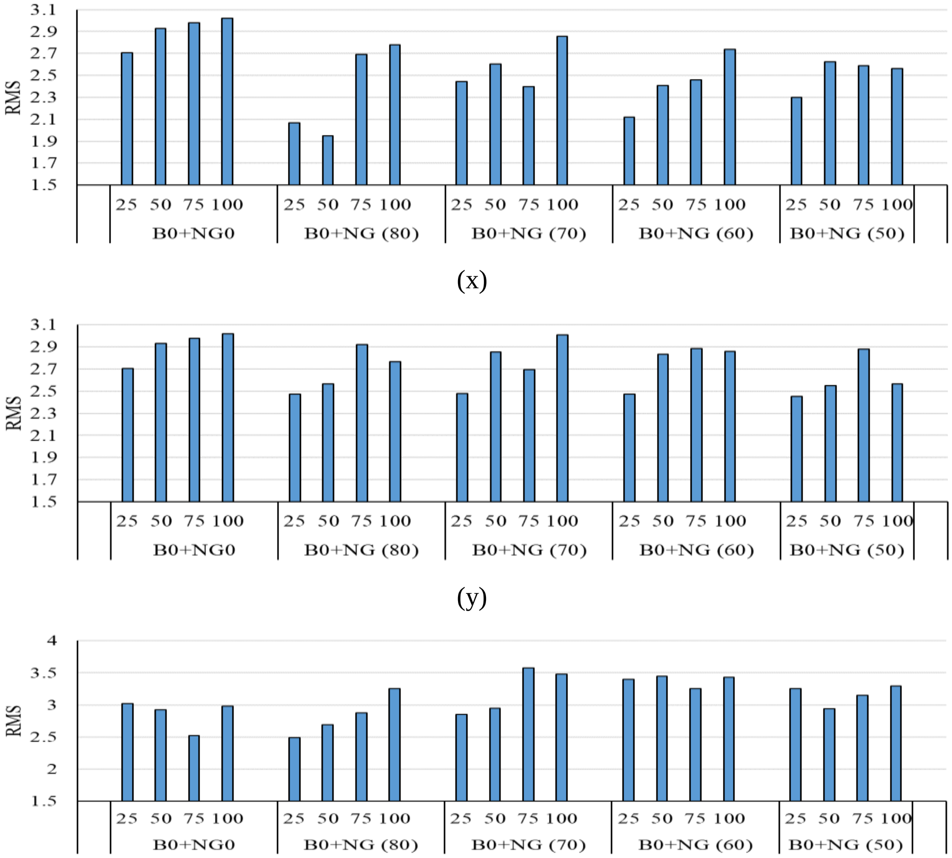
3.1. The effect of Diesel samples on Engine vibration

Fig. 3 presents the effect of Diesel fuel samples on engine vibration in the presence and absence of NG in three directions x, y, and z. As is clear, in longitudinal and lateral axis the presence of NG in the combustion chamber reduces the engine vibration. Also in all the cases except NG 50, the increase of engine load increases the engine vibration such that the full load condition has a higher vibration compared with the part-load condition. This can be due to the higher cetane number of NG compared with Diesel fuel. The higher cetane number can effectively reduce the ignition delay and accordingly reduce the engine vibration.

Table 4. Properties of fuel samples

Fuel sample	Density (kg/m3)	Calorific value (kj/kg)	Flash point (°C)	Surface tension mN/m
D	0.869	45700.368	86	26.7
B5	0.8702	45294.9462	89	27.1
NG	0.9	47100	-	-

But on the vertical axis, the vibration trend is a little different. Such that, the presence of NG in the combustion chamber increases the vertical vibration. This can be due to the increase of peak pressure in the combustion chamber in the presence of NG which increases the piston force in the vertical direction because of its higher calorific value (kJ/kg) compared with Diesel and B5.



(x)

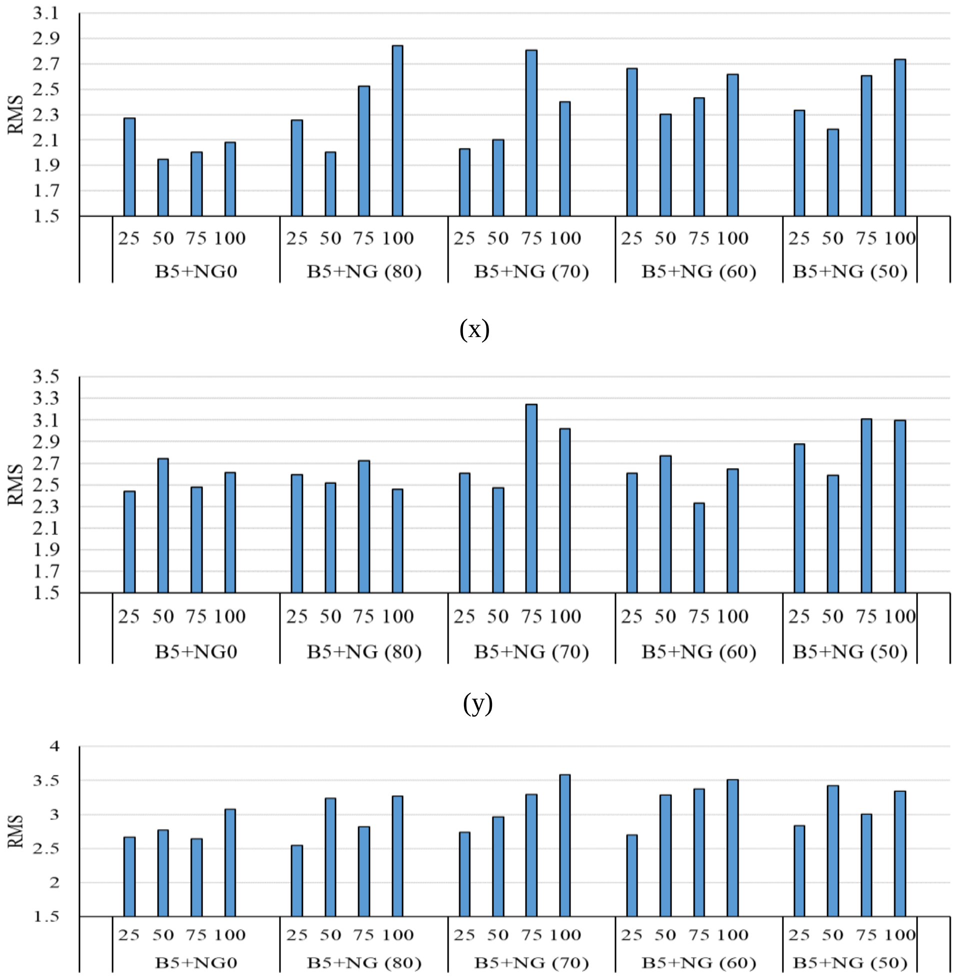
(y)

(z)

Fig. 3. The effect of Diesel (B0) fuel on diesel engine vibration

3.2. The effect of B5 fuel samples on Engine vibration

Fig. 4 presents the effect of B5 on diesel engine vibration. As is clear, B5 provides lower engine vibration compared with B5+NG. in this case, the part-load condition provides the lower engine vibration compared with full load same as diesel fuel. In the case of using B5+NG, it seems that increasing the NG ratio reduces the engine vibration. So, it can be claimed that the presence of biodiesel is more compatible with NG from the viewpoint of engine vibration compared with Diesel+NG.



(x)

(y)

(z)

Fig. 4. The effect of B5 fuel on diesel engine vibration

Fig. 5 compares the engine vibration among diesel fuel and B5 from the viewpoint of total RMS. Based on the results, B5 provides lower vibration compared with diesel fuel. Also, in the case of using B5, increasing the NG ratio can effectively reduce the engine vibration compared with Diesel fuel. Therefore, it can be concluded that, for dual fuel technology, B5 can be a more effective and suitable fuel sample compared with diesel fuel. This is due to the presence of oxygen in the biodiesel structure that successfully reduces the ignition delay and helps for reaching complete combustion compared with Diesel fuel and makes a lower engine vibration.

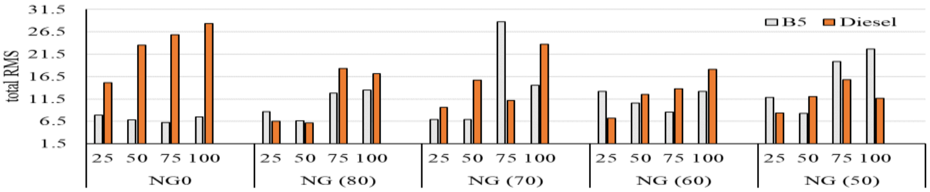


Fig. 5. Comparison of engine vibration in case of using Diesel and B5 fuel samples

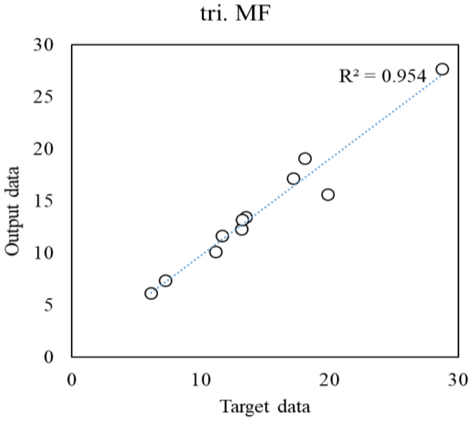
3.3. Results of ANFIS

This section describes the modeling results using the ANFIS technique. Results were evaluated using RMSE and correlation coefficient values. Table 5 presents the comparison results for the training phase.

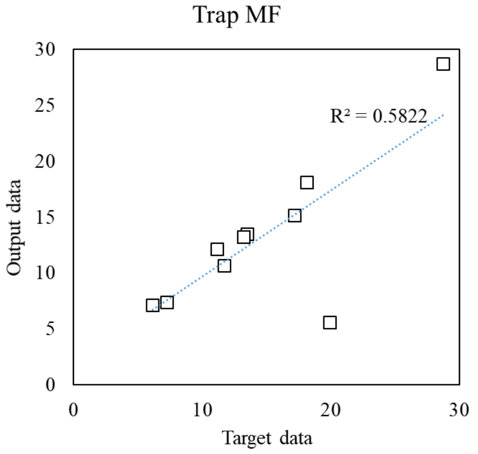
Table 5. Results of the training phase for developing a proper ANFIS technique

MF type	No. of MFs	Run time	Epoch No.	RMSE	CC
Tri.	3	112 s	3158	3.710	0.6966
Trap	3	54 s	1286	1.691	0.9423
Gbell	3	34 s	785	3.698	0.7
Gaussian	3	82 s	2218	0.687	0.9832

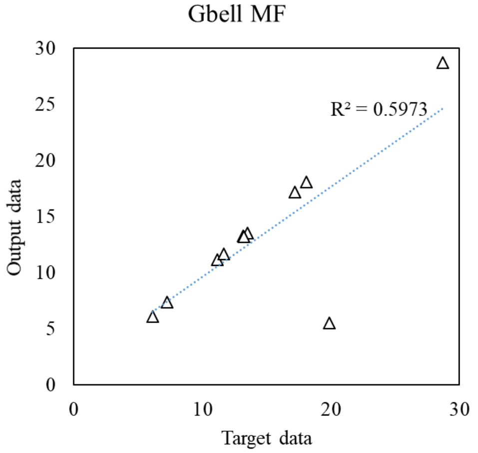
Based on Table 5, Gaussian MF followed by Trap MF provided a higher training accuracy compared with Tri. And Trap MF types. Trap type by lower run time compared with Gaussian MF provided higher sustainability due to its lower Epoch No.Gaussian increased the prediction accuracy by about 80 and 81% compared with Gbell and Tri. MF types, respectively. Fig. 6 presents the determination coefficient as well as the plot diagram for the testing phase for each MF type, separately.



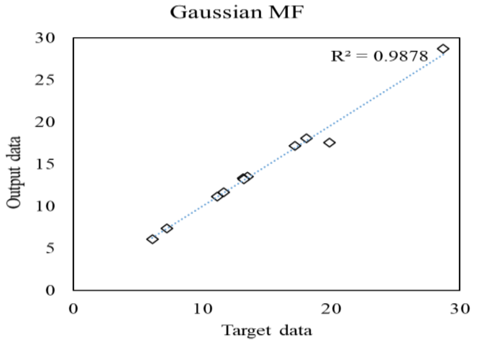
(a)



(b)



(c)



(d)

Fig. 6. CC for testing phase related to four MFs. a) Tri. MF. b) Trap MF. c) Gbell MF and d) Gaussian MF

As is clear from Fig. 6, the capability of the Gaussian MF type for providing the testing phase data is considerably higher than that for the Tri. (about 3.5 %), Trap (about

69.66%) and Gbell (about 65.37%). Accordingly, Fig. 7 indicates the 3D surface generated by ANFIS for Gaussian MF. based on Fig. 8, an NG fraction of 60 to 70% at engine part loads can be considered an effective and important range from a total vibration point of view.

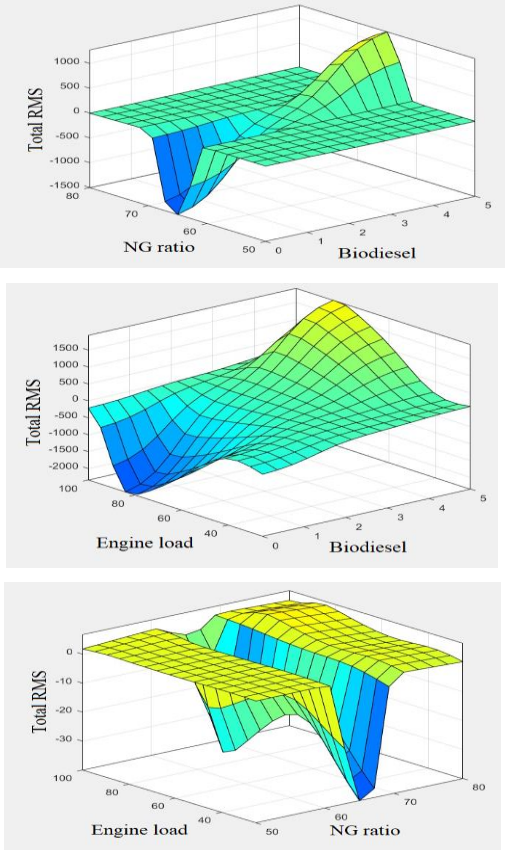


Fig. 7. 3D surface for ANFIS modeling

Finally, Fig. 9 is painted by calculating the deviation values for each MF type from the target values. As is graphically clear, the lowest deviation from target values is related to Gaussian MF followed by Trap type.

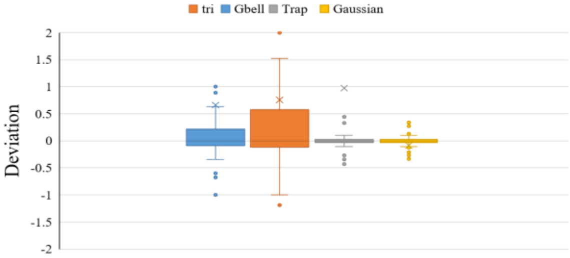


Fig. 8. Comparison of four membership functions

Therefore, these two MFs can be selected as the best MF types for the estimation of engine vibration.

4. Conclusion

The present study discussed the effect of NG (at 50, 60, 70, and 80%), engine load (at 25, 50, 75, and 100%), and Biodiesel (B5) on the Vibration characteristics of a single-cylinder diesel engine. This study can be helpful study for policymakers in the field of using a sustainable additive and alternative fuel for diesel-fueled engines. Based on the results the following conclusions could be derived:

- Increasing the engine load from 25 to 100 increased the engine vibration, especially in the Diesel cycle. Accordingly, in all the cases, the increase of engine load increased the engine vibration such that the full load condition had a higher vibration compared with the part load condition. This can be due to the higher CN of NG compared with Diesel fuel.
- In the vertical axis the vibration trend was different. The presence of NG in the combustion chamber increased the vertical vibration. This could be due to the increase of peak pressure in the combustion chamber in the presence of NG which increases the piston force in the vertical direction because of its higher calorific value (kJ/kg) compared with Diesel and B5. This point requires more studies about the relation between vertical vibration and piston peak pressure that can be a considerable future perspective for further studies.
- B5 provided lower vibration compared with that diesel fuel. Also, in the case of using B5, increasing the NG ratio

could effectively reduce the engine vibration compared with Diesel fuel.

- ANFIS could successfully predict the total engine vibration with high accuracy. This makes ANFIS a robust tool for future studies. ANFIS also has the capability of staying on as a controlling unit for control purposes. Results of the present study can successfully cover the operations of intelligence systems for the reduction of engine vibrations.

In general, it can be concluded that biodiesel can be more compatible with the dual cycle compared with diesel fuel, especially in higher NG ratios, and makes the combustion process more effective and suitable compared with diesel fuel from the viewpoint of engine vibration. This also can affect the engine's durability and can successfully prevent unwanted failures in the engine. This point also needs more related experimental works for future studies. On the other hand, using hybrid ML-based techniques such as ANFIS can effectively help in developing predictive models. Predictive models can be successfully employed for system optimization and for choosing the effective parameters for the system performance.

Notations	
BP	Brake power
NG	Natural gas
MF	Membership function
NOx	Nitrogen oxides
CI	Compression ignition
ASTM	American Society for Testing and Materials
CO	Carbon monoxide
CO2	Carbon dioxide
CN	Cetane number

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