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Medición de las vibraciones del motor utilizando mezclas de combustible de aceite vegetal reciclado y diesel. Un análisis matemático y computacional

Measurement of engine vibrations using fuel blends of recycled vegetable oil and diesel. A mathematical and computational analysis

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Resumen: Las vibraciones del motor de combustión interna son un indicador de su estabilidad y condición mecánica. Las vibraciones del motor que resultan del movimiento alternativo y giratorio de sus partes también dependen de la calidad del proceso de combustión y las propiedades del combustible. La presente investigación se centra en el efecto de las propiedades y la concentración de la mezcla de combustible de diesel y aceite vegetal reciclado en el nivel de vibración del motor debido al proceso de combustión. Las vibraciones del motor se recopilaron con los acelerómetros de un dispositivo de comunicación móvil, para luego determinar el nivel de vibración resultante del motor y su espectro de frecuencia mediante transformadas de Fourier rápidas. En este procedimiento llevado a cabo con cada uno de los combustibles probados, las propiedades como el número de cetano y el punto de inflamación se encontraron como aquellas que tienen influencia en el nivel de vibración del motor. El propósito de la presente investigación es cuantificar el nivel de vibración producido por diferentes concentraciones de la mezcla de combustible de diesel y aceite vegetal reciclado, dependiendo de sus propiedades y en comparación con el diesel puro. De esto, se concluye que la estabilidad del motor con respecto a su nivel de vibración debido al proceso de combustión, puede controlarse de acuerdo con las propiedades del combustible.
Palabras clave: diésel; aceite vegetal reciclado; número de cetano; punto de inflamación; vibraciones del motor

Abstract: Vibrations of the internal combustion engine are an indicator of its stability and mechanical condition. The vibrations of the engine resulting from reciprocating and rotating movement of its parts also depend on quality of combustion process and properties of the fuel. The present research focuses on the effect of the properties and concentration of the fuel blend of diesel and recycled vegetable oil on the vibration level of the engine due to the combustion process. The vibrations of the engine were collected with accelerometers of a mobile communication device, to then determine the resulting vibration level of the engine and its frequency spectrum by means of fast Fourier transforms. In this procedure carried out with each of the tested fuels, the properties such as the cetane number and the flash point were found as those that have influence on the vibration level of the engine. The purpose of the present investigation is to quantify the level of vibration produced by different concentrations of the fuel blend of diesel and recycled vegetable oil, depending on their properties and compared to pure diesel. From this, it is concluded that the stability of the engine in regard to its level of vibration due to the combustion process, can be controlled according to the properties of the fuel.
Key words: diesel; vegetable recycled oil; cetane number; flash point; engine vibrations

Introduction

The study of alternative and ecological fuel blends, mainly aims to reduce the pollutant emissions compared with the use of neat diesel. At the same time, for sustainable use of a fuel blend as an energy source for internal combustion engines, it must have properties and characteristics that keep or improve the engine parameters such as performance, fuel consumption, durability and stability. As the quality of the combustion is conditioned by the cetane number and flash point of the fuel, the present research focuses on determining of the effect of these properties on the engine vibration level.

The vibrations on the internal combustion engine are the result of unbalanced forces of the rotational and reciprocating parts; as well as cyclic variations of pressure inside of the engine cylinders, which depend on the rotation velocity, fuel supply and quality of the combustion process [1]. There are identified two types of engines vibrations: torsional and longitudinal. The torsional vibrations have an effect over the engine crankshaft, because of the pressure fluctuation coming from the fuel combustion and engine loads; while the longitudinal ones, have an effect over the engine block and mountings, because of the rotary and alternating components [2]. The present research considers the effect of the fuel properties and the quality of the combustion on the total end engine vibration resulting from the torsional and longitudinal engine vibrations.

The vibrations are mainly understood as mechanical effects, which can be controlled by attenuators [3]; for this reason, another methods and researches are carried out, in order to analyze this phenomenon in a more detailed way. One of the investigations in special determined that the irregular torque on the engine cylinders are produced by unequal fuel injection in each cylinder. The control of the fuel injection improves the exactitude of the delivered fuel quantity, allowed to reduce the level of vibration up to 92% [4].

One of the applied techniques is non-intrusive, which allows measuring of the engine vibrations without interrupting functionalities of either process [5]. With this technique, the data of the vibrations measurements, can be collected during the combustion process. It allows also distinguishing and analyzing of the effects of different fuel types.

The method to construct the frequencies spectrum and evaluate the vibration level of the engine was performed by means of the fast Fourier Transforms (FFT) [6]. This method consists of discomposing the resulting signal of the acceleration spectrum in individual components of a sinusoidal wave in order to get a frequency spectrum [7]. In this way it is possible to visualize the value of the dominant frequencies corresponding to rotation and ignition process of the engine. The relationship between the frequencies of these two processes is expressed as a function of the engine rotation speed and the number of cylinders [8, 9]. It means that in case of a four-cylinder and four-stroke engine the frequency values corresponding to the ignition are equal to the double of the rotation frequency of the engine. Any additional excitation source, for example the effect of the concentration of the fuel blend, is evidenced with the apparition of addition dominant frequencies in the spectrum.

The studies of engine vibrations with different types and concentrations of biodiesel, beside of valuation of engine stability, show also the capacity of a determined type of biodiesel to be burned, and its ability to keep or improve the engine performance [6, 10]. Engine measurements, regarding engine performance and vibrations using biodiesel based on animal fat [11], show that with increase of biodiesel in the fuel blend there is an increase in the cylinder pressure, with the consequently growing engine vibrations.

Other investigations testing different concentrations of biodiesel based on recycled vegetable palm oil blended with neat diesel, affirm that the engine vibration level decreases when the biodiesel concentration is higher in the blend, because of a higher combustion capacity [10]. While in the investigation, where the fuel blend was preheated [12, 13], the vibrations were reduced, because of the solved issues regarding the higher viscosity, improving the performance of a process like pumping, atomization or combustion.

The biodiesel of the present research, based on recycled vegetable palm oil, was obtained by means of transesterification with methanol and heterogeneous catalysators like calcium oxide (CaO). This kind of catalysators was selected because of their reusability, lower water requirement during the process and easier separation of methyl esters from glycerol [14]. Furthermore, the resulting methyl esters are more volatile compared with the esters resulting from the transesterification with ethanol. The choice of ethanol obeys to the fact that the methanol is more reactive and economic; however, it is more toxic and comes from non-renewable sources, in comparison with ethanol, which comes from starch or sucrose components [15].

The problems to solve in order to produce and implement alternative ecological fuels are not limited to reduce pollutant emissions and fuel consumption; for this reason, in the present research, it is considered that the engine stability can be controlled, by managing the fuel properties, which influence the combustion quality, such as the cetane number and the flash point. A higher cetane number reduces the ignition delay avoiding the combustion in later stages and sudden pressure rises; while a lower flash point allows the combustion process at lower cylinder pressure and temperature. The goal is to determine the effect of these properties of the fuel blend from recycled vegetable palm oil biodiesel for the engine vibration level, compared with neat diesel. In this way it is possible to control engine stability with a more ecological fuel.

Materials and Methods

Material and Equipment

Five types of fuels were characterized. The first one consists of neat diesel, and the other four consist of a blend with the 5, 10, 15 and 20% concentration of recycled vegetal palm oil with 95, 90, 85 and 80% of neat diesel respectively. The oil was processed by means of transesterification with calcium oxide, because of more environmentally friendly process [14]. The blend with diesel was carried out by agitation, without any additional reactive, equipment or processes.

Table 1.Fuel properties.

Fuel properties	Diesel	95% diesel with 5% recycled vegetable palm oil	90% diesel with 10% recycled vegetable palm oil	85% diesel with 15% recycled vegetable palm oil	80% diesel with 20% recycled vegetable palm oil
Density API 60°F	35.3	34.5	34.5	33.7	33.9
Flash point [°C]	62.3	65.4	67.4	69.5	70.1
Kinematic viscosity [cSt]	4.02	4.35	4.55	4.75	5.03
Cetane Number [-]	51.8	51.98	51.25	50.37	50.20
Lower heating value [MJ /kg]	42.7817	42.6389	42.2469	42.5648	42.5632

Characterization of neat diesel and different concentrations of biodiesel. Source: Authors

The vibration measurement was performed with neat diesel and with each of the characterized fuel blends on an engine equipped with a common rail system. The goal is to find the concentration and the properties of the biodiesel, that provides the same or a better engine performance and stability, compared with the use of neat diesel.

Table 2. Engine specification.

Displacement	2999 cc
Fuel injection system	Common rail direct injection
Fuel type	Diesel
Number of cylinders	4
Number of valves	16
Power	134 hp @ 3600 rpm
Torque	294 Nm @ 1400-3000 rpm

Specification of the test engine. Note

The vibrations were registered with accelerometers of a communication mobile device, by means of a non-intrusive measurement. The collected data is the result of the individual accelerations in each orthogonal axis, X, Y and Z; afterward the resulting acceleration is calculated. The data were registered in format *.txt, in order to be exported into a spreadsheet for the construction of the frequencies spectrum by fast Fourier transforms (FFT).

Table 3. Linear accelerometers specification.

Resolution	0.009575196 [m/s^2]
Accuracy	±1.1%
Measurement range max.	19.61 [m/s^2]
Power	0.13 mW

Specification of the linear accelerometers of the mobile communication device. Note

Experimental procedure

The vibrations measurement was registered over the valves cover on the top of the engine (see Fig. 1), at different speeds without load, with each of the characterized fuels. As for the conditions under load, more fuel needs to be burned, and as a consequence the vibration level of the engine increases, it is necessary, firstly, to determine the possible level of vibration that can be obtained under conditions that are not too severe to engine, avoiding to put it in risk of damage. Secondly, it is necessary to guarantee, that the fuel blends of this research will not compromise the safety and durability of the engine, by means of corrosion effects and lubricity ability of the fuel injection components.

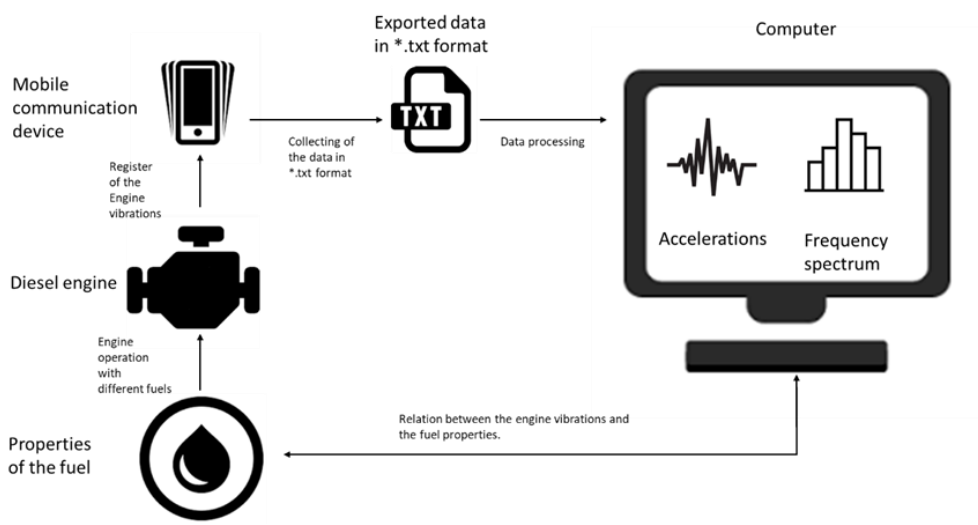

Figure 1. Measurement process and data processing of the engine vibrations.

Mathematical formulation

The registered accelerations in each orthogonal axis X, Y and Z were used to calculate the resulting accelerations, in order to analyze and to determine the effect of the properties of each fuel type on the vibration level of the engine.

$$R = \sqrt{{a_x}^2 + {a_y}^2 + {a_z}^2} \qquad (1)$$

R: Resulting acceleration
a_x, a_y, a_z: Acceleration values in the orthogonal axis

To calculate the engine vibration level and to represent it as a function of a unique amplitude value, the root mean square acceleration was calculated with each calculated resulting acceleration.

$$R_{RMS} = \sqrt{\frac{{R_1}^2+{R_2}^2+\cdots+{R_n}^2}{n}} \qquad (2)$$

A_{RMS}: Root mean square acceleration
R_1, R_2, R_n: Resulting accelerations in the selected measured range
n: Number of data in the selected measurement range

Finally, the frequency spectrum was calculated by means of fast Fourier transforms on a spreadsheet, according to the following mathematical formulation:

$$C_j = \frac{1}{\sqrt{n}} \sum_{k=0}^{n-1} v_k e^{2\pi i\left(\frac{j}{n}\right)k} \qquad (3)$$

C_j: Vector of the FFT function
k: Additive index from 0 to n-1
v: Output vector
i: Imaginary unit
j: Harmonic number from 0 to n/2

Measurements and Evaluation

The performed measurements were carried for about 10 seconds at four different engine rotation speeds and with each of the five characterized fuels. From the 20000 registered measurement points, the range with the higher stability at the measured regime was selected. From this selection, only 256 points were used to calculate the root mean square accelerations; while by means of the fast Fourier transforms, the frequency spectrums were obtained. As the lowest engine frequency at 1000 rpm is equal to 16.6 Hz, there is no necessity that the frequency spectrum has a resolution higher than the 256 selected points.

The resulting root mean square acceleration and the frequency spectrum with the use of the neat diesel in each one of the engine velocities during the test, determines the engine condition and becomes the reference point to compare the effect that have the fuel properties on the base of recycled vegetable palm oil. Once the frequency spectrum of the engine running with neat diesel is obtained and excluding the frequencies and amplitude values from the rotation and ignition of the engine, it is considered that every variation with reference to this reference point, is an effect of the concentration and properties of the tested fuel blend.

Results

The figure 2 shows the development of the engine vibrations at different engine speeds. At each engine speed and with each of the fuel types 256 measured points are represented. It is observed, that higher peak values take place at 3000 rpm and particularly with the fuel blend of 20% recycled vegetable palm oil and 80% neat diesel.

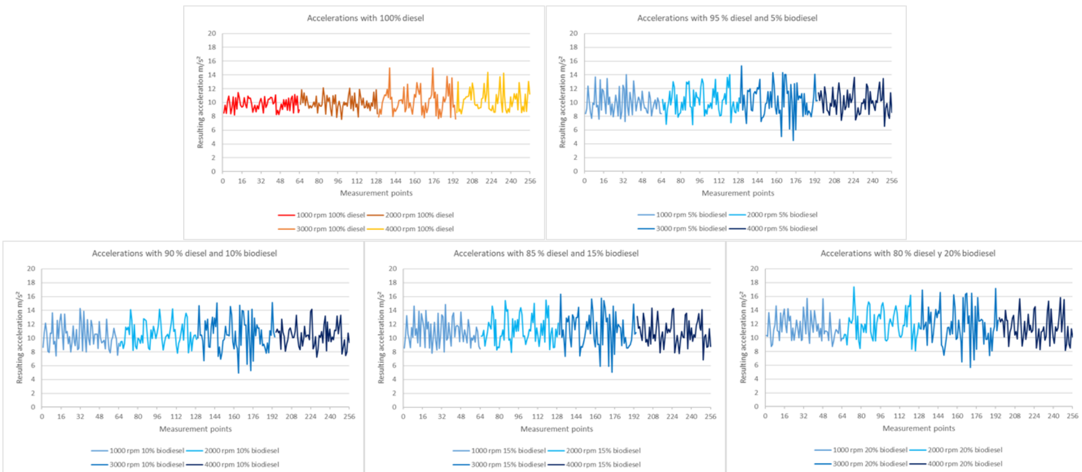

Figure 2. Development of the engine vibrations with each fuel type at different engine speeds.

The resulting vibration level, expressed as a function of the root mean square accelerations (see Fig. 3), determine that the engine stability depends on the concentration of biodiesel in the blend and on the engine rotation speed; in the present research the higher vibration level corresponds to the blend with 20% recycled vegetable palm oil at 3000 rpm. However, from the 3000 upwards, with the blend of 5% oil and 95% neat diesel, the engine vibration level is lower, even compared with the values corresponding to use of neat diesel. The fuel blend that shows a more stable vibration level along the whole engine rotation speed range, is the blend of 15% oil and 85% neat diesel.

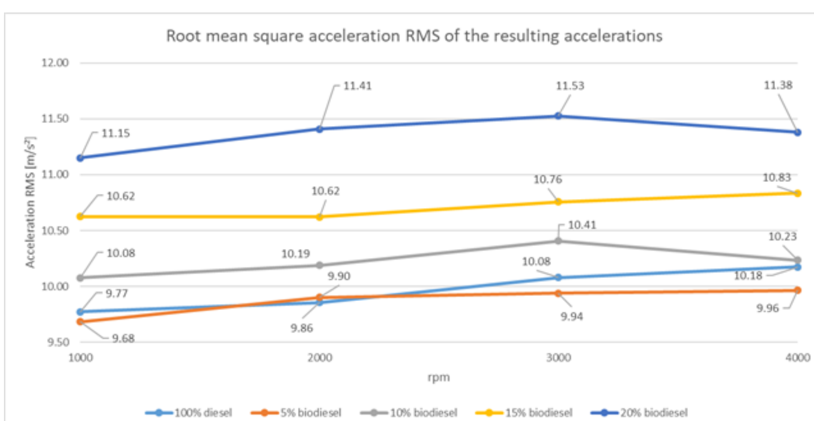

Figure 3. Root mean square accelerations at different engine speeds with each characterized fuel type.

In each frequency spectrum the frequencies corresponding to the engine rotation and fuel ignition are identified. The resulting spectrum when using neat diesel is the reference and any additional amplitude in the spectrum, a range equal or higher to the ignition frequency, it is considered as the effect of the cetane number and the flash point of the fuel blend. The variations of amplitudes in a frequencies range lower than the frequencies of the ignition and rotation speed of the engine, must be considered as a mechanical instability.

Table 4. Engine Frequencies.

Engine rotation speed [rpm]	Frequency of rotation [Hz]	Frequency of ignition [Hz]
1000	16.6	33.3
2000	33.3	66.6
3000	50	100
4000	66.6	133.3

Frequencies corresponding to the rotation and ignition of a 4-cylinder and 4-stroke engine.

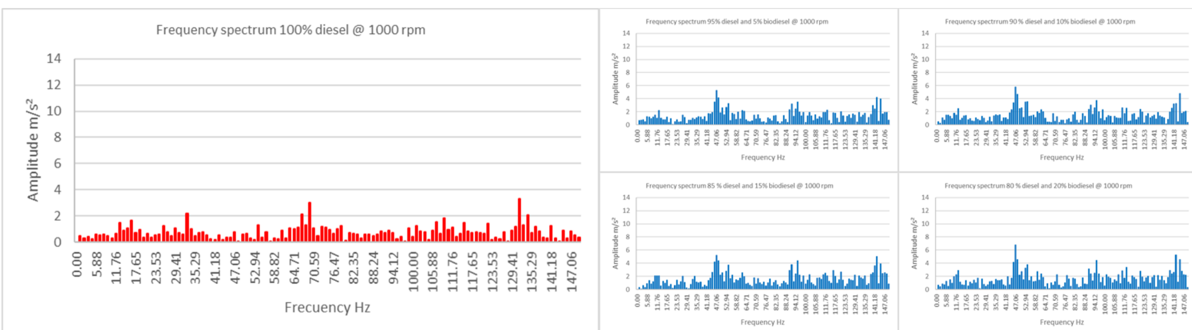

Figure 4. Frequency spectrum with each fuel type at 1000 rpm.

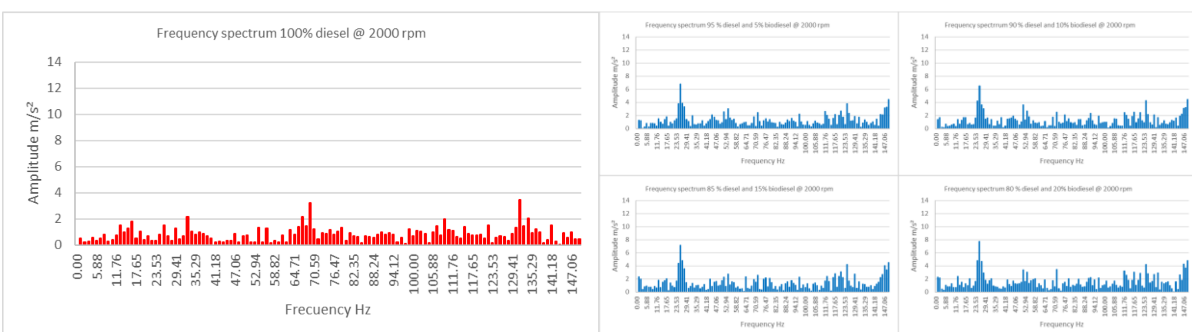

Figure 5. Frequency spectrum with each fuel type at 2000 rpm.

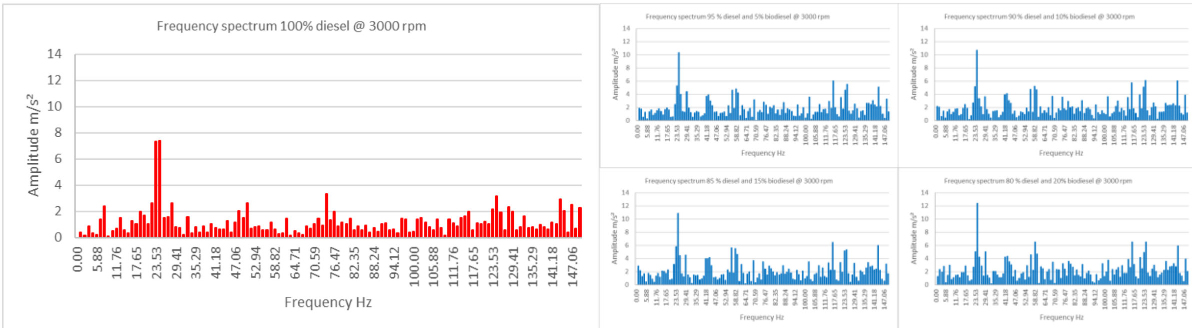

Figure 6. Frequency spectrum with each fuel type at 3000 rpm.

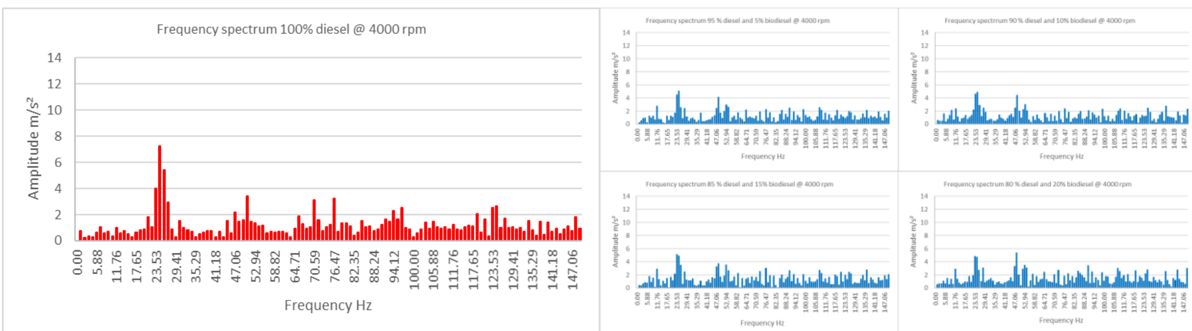

Figure 7. Frequency spectrum with each fuel type at 4000 rpm.

Discussion

The engine vibrations are the result of the lineal, rotational and reciprocating movement of its parts. The main indicator of vibrations at a determined frequency is an amplitude. In the vibrational analysis it is analyzed the natural and resonance frequency. The first one is the ability of an element to vibrate under the force action; while the second one occurs when an excitation source or an additional force influences on the system at a frequency equal to the natural one [16]. In the present research, are identified the frequencies and amplitudes corresponding to the engine rotation at fuel ignition, with use of neat diesel as a reference point, in order to analyze the effect of the values of the cetane number and flash point in each concentration of the fuel blend with recycled vegetable palm oil.

The changes in the amplitude values, corresponding to the frequency ranges of the ignition and subsequent processes, are analyzed separately in order to identify the effect of the fuel properties for the engine stability, considering the effects of an earlier ignition or any delay in the combustion process in the values that the amplitude can reach. The vibrations are more intensive during the ignition than during the combustion process, because the higher vibration amplitude is a result of the rapid pressure change inside the cylinder during the ignition [16]. Based on this information, it can be affirmed that a lower amplitude at the frequency corresponding to the fuel ignition, means a gradual, uniform and smoother combustion process, without sudden pressure rises in the cylinder.

Comparing the values of the flash point on the fuel characterization (see Tab. I), it is observed that this value increases with increase of the biodiesel concentration in the blend. It causes that the combustion process takes place at higher temperatures and pressures, which reflects the reached vibration levels (see Fig. 3).

Within the engine speed range from 3000 to 4000 rpm the fuel blend of 5% biodiesel and 95% neat diesel creates a lower vibration level even compared with neat diesel, which can be attributed to the higher cetane value for this type of the fuel blend. It reduces the ignition delay producing a more efficient combustion at higher engine rotation speeds.

A regular and uniform frequencies spectrum along the frequencies spectrum, demonstrate that there is a better energy conversion from the fuel into torque to the engine [6]. In the obtained results, it is observed at 4000 rpm with the blend consisting of 90% neat diesel and 10% recycled vegetable palm oil.

It was observed as well, that at around 23 Hz there is an amplitude that varies with the fuel blend concentration, which effects at 3000 rpm and higher. It is attributed to a mechanical effect and engine condition, because the 23 Hz are below the minimum ignition frequency of 33.3 Hz.

Conclusion

The engine vibrations are an indicator of mechanical failures, but they are also a factor that determines the performance and stability of the engine in function of the fuel properties.

In the present research, an experimental methodology was shown to evaluate the engine vibrations with a non-intrusive procedure, in function of the cetane number and flash point of the fuel blend based on recycled vegetable palm oil.

It is demonstrated that the characteristics that determine the engine stability, are associated to the properties of the fuel and engine operation condition.

The results of the tests with each fuel blends and with neat diesel, demonstrate that the vibration level depends on the engine rotation speed and the concentration of biodiesel on the fuel blend.

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