Engine Diagnosis Based on Vibration Analysis Using Different Fuel Blends

Jairo A. Grajales, Héctor F. Quintero, Carlos A. Romero and Edison Henao

Abstract Fault diagnosis of an internal combustion engine is proposed herein by means of vibration analysis; in order to show the reliability of it, this paper presents a comparative study of normal and faulty scenarios. An engine test bench was used to acquire the vibration signals. For this study, the fault considered on the bench was misfire, which was induced by removing the spark plug wire of a cylinder. Fast Fourier Transform was used to obtain the frequency domain of the signal as a preliminary step to the subsequent identification process based on statistical characteristics extraction. In order to validate previous works on misfire with pure gasoline, measurements included tests performed with ethanol-gasoline fuel blends, namely E30, E20 and commercially available E8 at three different speeds. A simpler classification process was obtained with the extraction of several statistical characteristics from several frequency bands, based on the excited frequency components. The presence of three peaks (at 0.75, 1.25, and 1.5 of the combustion frequency) in the vibration signal of the engine block in the transversal direction for the induced misfire condition, provided differentiation between normal and faulty conditions with all tested fuel blends. According to results, changes in the fuel mix seem to have little impact on the performance and behavior of the engine vibration signals.

Keywords Engine diagnosis · Vibration analysis · Frequency analysis

1 Introduction

Given the importance of internal combustion engines within the modern industry, many manufacturing plants depend on predictive maintenance for these machines. Due to its relevance, approaches like condition monitoring have gained growing interest. The main measurement used for this purpose is cylinder pressure [1], since

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it shows a great deal of information concerning the internal combustion process. However, it is an invasive and expensive procedure due to additional costs of sensors and engine modifications.

In an attempt of finding more affordable options, the use of less specific type of sensors has reported good performance in techniques such as angular speed measurement [2], oil analysis [3], surface temperature and exhaust emissions. But, great interest has been placed on the study of acceleration measurement using sensors, such as accelerometers [4], acoustic sensors [5] and knock sensors [6], with satisfactory results and widespread deployments in condition monitoring of rotating machinery [7]. However, they have been found to present problems when using conventional analysis methods for assessment in the particular conditions of internal combustion engines, since the measured signals are non-stationary.

The identification of diverse causes to engine block vibration from single point measuring in [6] was achieved based on short time Fourier transform on the signal, collected with a commercial knock sensor. A determination of combustion parameters by means of neural networks reported in [2] was supported on angular velocity measuring. Both indicated and load torques were estimated in [8] using the variations in motor speed. An assessment of the influence of the shape variations of the piston bowl on the combustion process was given in [9], for this purpose vibration data from the engine block was analyzed. According to [10], results from studies with only gasoline in faulty operations, such as a misfire, reported changes in the spectral composition of the vibratory signal of an engine and the presence of peaks different from the combustion frequency.

Nevertheless, these researches did not take into account the influence of alcohol-gasoline fuel blends on the vibration features. [11] used a chassis dynamometer to report on engine performance at different speeds and loads of a vehicle driven by fuel blends consisting of gasoline and alcohol derivatives like ethanol and methanol (E5, E10, M5 and M10). Their results showed that alcohol-gasoline blends increased brake specific fuel consumption and delayed cylinder gas pressure.

The present study was conducted to assess the effects of using different blends of gasoline and ethanol as fuel on the spectral composition of the vibration signal of the engine, in the presence of a fault, in this case a simulated misfire on cylinder 4. Additional sensors were used during the experiments to consolidate a robust database. This work showed that the same characteristic frequencies and peaks reported on pure gasoline are present on gasoline-ethanol blends of commercial fuel (E8), E20 and E30, when testing under misfire conditions. And that some statistical characteristics can be extracted from the frequency domain signals, on certain frequency bands, to simplify the identification process. This article describes in detail the experimental setup, test procedure and a comparative analysis of measurements under normal conditions and induced misfire.

2 Experimental Setup

The experimental test bench for this study consisted of a four cylinder, four stroke spark ignited internal combustion engine from a truck with a capacity of 2 l, and mounted on a movable structure that allowed access to the components of the motor as well as better control of temperatures and leaks which in turn simplified condition monitoring.

Vibrations analyzed herein correspond to three different measured accelerations. These accelerometers were installed on three different areas (the first one vertically positioned at the top of the engine, the second one longitudinally positioned in respect to the crankshaft axis and mounted close to cylinder one, and the last one mounted in the middle of cylinders two and three with a normal direction to the crankshaft axis). Respective data acquisition resorted to two equipments mounted on a NI cDAQ 9174 four-slot chassis (NI 9232, 3 channel ±30 V analogue input module and a NI 9234, 4 channel ±5 V analogue input module).

In order to determinate stable speeds of the engine for measurement and reliable conditions for the running periods of testing, a preliminary test was run.

Since the test bench allowed easy access to the engine components, it was possible to test two different operational conditions with no load. (1) Normal: with four cylinders running and (2) Misfiring Piston: Induced misfire of a piston by disconnecting the spark plug from cylinder four. The comparative analysis between normal and faulty operations of the engine was based on an experimental testing that focused on different variables of speed and fuel blend. Three fuels were used during the tests:

(i) E8: Blend of gasoline with 8% ethanol.
(ii) E20: Blend of gasoline with 20% ethanol.
(iii) E30: Blend of gasoline with 30% ethanol.

Data was collected at three different speeds: 1500, 1700 and 2000 rpm, for each condition, running on each fuel previously presented, and recording the data from the eight instruments at the same time. Three sets of data were collected for each condition on each constant speed. Making use of the available data acquisition setup the sampling frequency was set to 51.2 kHz/channel, and measurements were recorded for 2 s, for each set of data.

The process of differentiation between normal and faulty conditions was based on data obtained from signals in time domain and frequency domain transformation of the signal, namely full spectrum of acceleration vibrations and subsequent focus on areas/zones of special interest due to the presence of excited frequencies. This study also resorted to the extraction of the following eight statistical features applied to all the data obtained from the aforementioned signals: Root mean square (RMS), Arithmetical mean, Kurtosis, Standard deviation, Skewness, Energy, Maximum value, Minimum value.

3 Results

Measuring started after installing the pressure sensor on the engine, which was previously heated and set up to maintain a stable operation. Firstly, the normal condition was tested for the E8 fuel blend; three different measurements were taken for each one of the speeds selected. Afterwards, misfire is induced by disconnecting the spark plug of the fourth cylinder, and the measuring process is repeated for each speed. After completing the tests for E8, remaining fuel was removed from the tank before introducing the next fuel blend. The same measuring procedure described above was repeated until obtaining complete data from the remaining fuel blends (E20 and E30). Figure 1 depicts the measurements with the vertical accelerometer.

To analyze the signals in the frequency domain, the fast Fourier transform was applied. With all these new signals, a comparison was performed to identify differences in the frequency components of the signal in the different operating conditions, and see if the differences are still present when the different fuels are used. Frequency domain signals for the three fuel blends under both normal and faulty conditions at 1500 rpm can be seen in Fig. 2. In the graphic, two tendencies are recurrent in both conditions for all the fuel blends. Firstly, from 400 to 700 Hz,

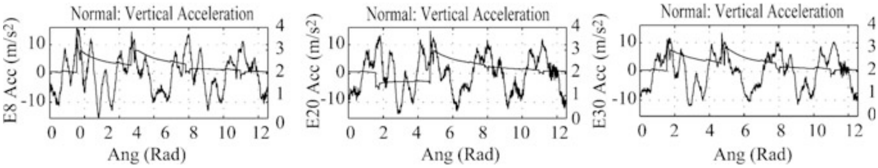

Fig. 1 Vertical acceleration, normal operating conditions on three fuels, second axis, spark detection

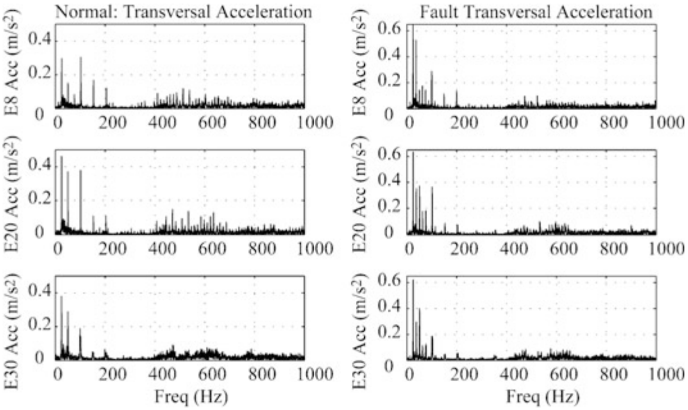

Fig. 2 Transversal acceleration, normal and fault operating conditions on three fuels, 1500 rpm

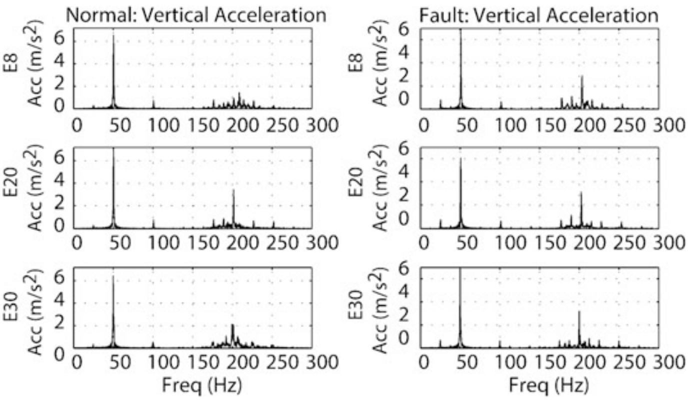

Fig. 3 Vertical acceleration, normal and fault operating conditions on three fuels, 1500 rpm

several smaller peaks can be seen, which may be resonant responses from the supporting structure due to their repetitive presence in almost every measurement. And secondly, the prominence of three particular peaks is recurrent: namely at 25, 50, and 100 Hz. As expected for the engine used, under normal conditions at 1500 rpm combustion frequency (CF) was reported at 50 Hz but oddly the peak at 25 Hz corresponding to revolution or speed frequency (RF) also appeared in CF peak is the only one expected to appear and the peak at 100 Hz may be considered its harmonic, hence the presence of RF peak should have stemmed from some unbalance and differences in the support of the mounting.

From faulty conditions, the two tendencies described above kept taking place, however a couple of new facts provided enough distinction between faulty and normal conditions. Firstly, RF peak at 25 Hz is reported to be the highest. And secondly, under faulty conditions there was a constant presence of another three peaks at 37.5, 62.5 and 75 Hz. Such frequencies may also be considered as 0.5 CF, 0.75 CF, 1.25 CF and 1.5 CF respectively. It is worth of noting that these distinctive and discrepant tendencies of normal and faulty conditions took place with all fuel blends. Results with similar behaviors were obtained for tests run at 1700 and 2000 rpm.

Neither the longitudinal nor the vertical acceleration measurements reveal any significant discrepancy between faulty and normal conditions. The results obtained with vertical accelerometers reported in Fig. 3 are in accordance with [10]: On both operational modes, CF peaks took place very clearly and the only differentiating elements are minor increases of the small RF peaks for the instances of induced misfire. Just like in the previous measurements, all the tested fuel blends repeatedly shared tendencies.

Since the first comparisons based on frequency domain transformations revealed that distinguishing elements between operating modes exhibited greater salience at frequencies below each one of the CF peaks, the analysis of statistical characteristics focused on such lower frequencies. The first frequency band selected for statistical

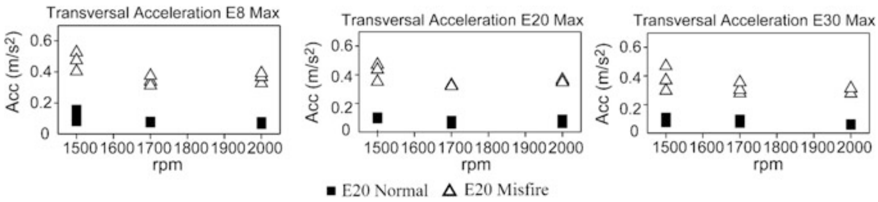

Fig. 4 Transversal acceleration, normal and fault operating conditions on three fuels, maximum value, 0.6–0.9 CF

characteristics extraction corresponded to the zone 0.6–0.9 CF. Analyzing this frequency from transversal measurements, only one (minimum value) out of the eight statistical properties did not report discrepancies that allowed to differentiate between normal and faulty conditions. The constant tendency of the seven differentiating properties was higher values under faulty conditions. Maximum values and Standard Deviations were the ones that provided a better distinction, i.e. a greater gap between values of the two conditions tested. Maximum values (Fig. 4) serve as an example to illustrate the satisfactory distinction obtained by means of statistical characteristics extraction from transversal acceleration measurements at the aforementioned frequency band for all the speed and fuel blends variables of this study.

Further analysis on transversal acceleration at the wider frequency band 0–0.9 CF reported that five statistical characteristics (maximum value, RMS, mean value, standard deviation and energy) allowed clear distinction between conditions for the three fuel blends at 1500 and 1700 rpm, however differentiation didn't took place at all from measurements at 2000 rpm. The remaining three characteristics (Kurtosis, Skewness, and Minimum value) exhibited inconsistency in their results, whether they didn't report differences whatsoever or only for isolated conditions.

Despite full spectrum readings of vertical vibrations reported an overall similarity unpromising for signs of differentiating elements between operational modes, the corresponding statistical characteristics surprisingly allowed some distinctions. Maximum value was the only statistical characteristic capable of differentiating normal and faulty conditions at the 0–0.9 CF frequency band from vertical vibrations. Such a distinction was present for all the speed and fuel blends variables of the study as shown on Fig. 5. It is plain to see that considerably lower maximum

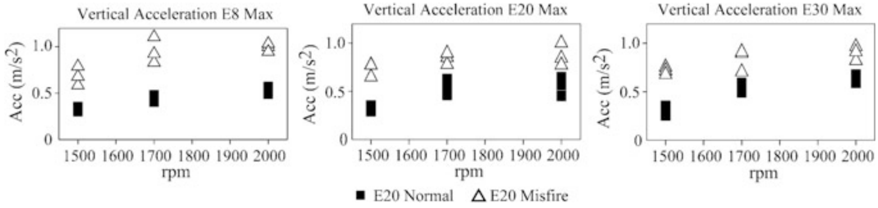

Fig. 5 Vertical acceleration, normal and fault operating conditions on three fuels, maximum value, 0–0.9 CF

values took place in normal conditions in comparison to those for conditions with induced misfire. None of the other statistical characteristics provided results as reliable as those from maximum values to assist in the differentiation process between operation conditions. Yet again, longitudinal vibrations signal didn't yield any statistical characteristic capable of providing constant and reliable distinction between the operation modes tested herein.

Frequency domain analysis reported some excited frequencies during normal operation, most of them correspond to the combustion frequency (CF) and its harmonics, a foreseen fact due to typical characteristics of a spark ignited internal combustion engine. The equipment used herein was a four-cylinder engine, whose CF is known to be two times the revolution frequency (RF). The latter also appeared in the analysis. As opposed to literature reporting the largest magnitudes for CF peaks on normal conditions, normal conditions tested at 1500 rpm (Fig. 3) revealed RF peaks to be the highest, which in turn can be explained with a test bench problem stemmed from unbalance of the pieces. Specially, the inertia added to the system by the dynamometer attached to the engine.

In parallel with the above analysis, the non-harmonic nature of readings from faulty conditions was confirmed with the presence of 0.75, 1.25 and 1.5 CF peaks for all the speed and fuel blend variables of the study, such peaks never appeared on normal conditions measurements. That anharmonicity was also a foreseen fact due to one idle cylinder leading to three combustions in a two cycle period.

This work extends the scope of previous studies by including different fuel blends and thus more scenarios for assessment. Extra amount of oxygen provided by the addition of ethanol changes the characteristics of the combustion process particularly in respect to speed and power of the combustion. However, the same excited frequencies reported in literature with only gasoline operations were also found in the three ethanol-gasoline blends tested herein, despite that the carburetor used was not the appropriate for the new conditions of the combustion.

4 Conclusions

A time frequency transformation was applied on three vibration signals (vertical, transversal and longitudinal accelerations) from an internal-combustion, spark-ignited engine; focusing on finding frequency components able to differentiate normal from induced misfired condition. Induced misfire was achieved by taking off spark plug number four. Besides the measurements at three different speeds, the study also expands the research scope by including three gasoline-ethanol fuel blends (E8, E20 and E30). Additional sensors were used for future investigations.

The results herein coincided with the literature. The expected presence of three peaks (referred to as 0.75, 1.25, and 1.5 CF) in the transversal vibration signal for the induced misfire condition, provided differentiation between the two operation conditions examined, in all tested fuel blends.

A subsequent extraction of eight statistical characteristics was performed on the signal in the time domain and on several frequency domain bands, aiming to simplify the differentiation process. Seven of the eight statistical characteristics extracted from transversal vibrations exploring the frequency band 0.6–0.9 CF, provided a clear distinction between operational conditions for all the variables tested.

In the case of vertical vibrations signals, the only statistical property capable of distinguishing operational conditions for all the variables tested was the maximum value in the frequency band 0–0.9 CF. Data from longitudinal vibrations only were able to provide isolated distinctions between conditions since inconsistency was reported throughout the variables of fuel blends and speed during the analysis.

References

1. Chandroth, G. O., Sharkey, A. J. C., & Sharkey, N. E. (1999). Cylinder pressures and vibration in internal combustion engine condition monitoring. In *Proceedings of Comadem, 99*.
2. Taglialatela, F., Lavorgna, M., Mancaruso, E., & Vaglieco, B. M. (2013). Determination of combustion parameters using engine crankshaft speed. *Mechanical Systems and Signal Processing, 38*(2), 628–633. doi:10.1016/j.ymssp.2012.12.009.
3. Jiang, R., & Yan, X. (2008). Condition monitoring of diesel engines. In *Complex System Maintenance Handbook [Electronic resource]*. Springer.
4. Gravalos, I., Loutridis, S., Moshou, D., Gialamas, T., Kateris, D., Tsiropoulos, Z., & Xyradakis, P. (2013). Detection of fuel type on a spark ignition engine from engine vibration behavior. *Applied Thermal Engineering, 54*, 171–175. doi:10.1016/j.applthermaleng.2013.02.003.
5. Arroyo, J., Muñoz, M., Moreno, F., Bernal, N., & Monné, C. (2013). Diagnostic method based on the analysis of the vibration and acoustic emission energy for emergency diesel generators in nuclear plants. *Applied Acoustics, 74*(4), 502–508. doi:10.1016//j.apacoust.2012.09.010.
6. Vulli, S., Dunne, J. F., Potenza, R., Richardson, D., & King, P. (2009). Time-frequency analysis of single-point engine-block vibration measurements for multiple excitation-event identification. *Journal of Sound and Vibration, 321*(3–5), 1129–1143. doi:10.1016/j.jsv.2008.10.011.
7. Li, Y., Tse, P. W., Yang, X., & Yang, J. (2010). EMD-based fault diagnosis for abnormal clearance between contacting components in a diesel engine. *Mechanical Systems and Signal Processing, 24*(1), 193–210. doi:10.1016/j.ymssp.2009.06.012.
8. Bengtsson, F. (2006). Estimation of indicated- and Load-torque from engine speed variations. *Master's Thesis*. Linkoping University.
9. Torregrosa, A., Broatch, A., Marant, V., & Beauge, Y. (2004). Analysis of combustion chamber resonance in DI automotive diesel engine. In *Thermo and Fluid Dynamic Processes in Diesel Engines 2*. Berlin Heidelberg: Springer.
10. Ben-Ari, J., de Botton, G., Itzhaki, R., & Sher, E. (1999). Fault detection in internal combustion engines by the vibration analysis method. SAE Technical Paper 1999-01-1223. doi:10.4271/1999-01-1223.
11. Eyidogan, M., Necati, A., Canakci, M., & Turkcan, A. (2010). Impact of alcohol–gasoline fuel blends on the performance and combustion characteristics of an SI engine. *Fuel, 89*(10), 2713–2720. doi:10.1016/j.fuel.2010.01.032.