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Research Article

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Determination of Combined Vibrational and Exhaust Emission Signatures of Vehicle Bi-fuel Petrol Engine Condition Diagnosis

Shawki A. Abouel-seoud, Mohamed N. Mansy*, Mohamed I. Khalil, Ahmed A. Abdel-hamed

Automotive Engineering Department, Helwan University, Cairo, Egypt

Abstract Vehicle bi-fuel petrol engine condition diagnosis is very important for reducing the downtime, maintenance cost; and improving the safety, reliability, and lifespan of the engines. The present work reports the results concluded by long term experiments to a defected vehicle bi-fuel petrol engine system, with the reduction of the lubricant oil level of 50 % is considered as a fault. . For 100% and 50% lubricant oil levels, recordings every 30.0 min were acquired and a total of 7 recordings (~ 3.0 h of test duration) were resulted until the termination of the test. 50% lubricant oil levels fault is assured by increasing the test period to the point of where the engine condition has enough wear and friction to be in the plastic deformation region. An experimental procedure is developed to assess the severity of the bi-engine condition fault. The bi-engine in its two fuel phases with lubricant oil level of 50% (fault) was tested under accelerated fault conditions, where a comparative analysis of condition monitoring indicators for various faults detection has been done. The experimental localized fault residual (difference between 100% and 50%) signals (vibration acceleration and emission components signals) in the two phases were subjected to the same diagnostic indicators such as RMS, spectral kurtosis, skewness and crest factor. The results look promising, where the RMS value analysis could be a good indicator when compared with the other indicators in terms of early detection and characterization of faults.

Keywords Vehicle bi-fuel engine, exhaust emission components, fault diagnosis, vibration response, condition monitoring indicators

1. Introduction

Various techniques in machinery diagnostics, models and algorithms have been presented and maintenance decision-making, with emphasis on the last two steps. Different techniques for multiple sensor data fusion have also been discussed. Although advanced maintenance techniques have been available in the literature. There are still two common extremes in current industry [1]. One extreme is to always adopt a run-to-failure (breakdown) policy. The other extreme is to always apply an as-frequent-as-possible maintenance policy. Of course, the two conventional maintenance policies, namely the run-to-failure policy and the time-based preventive maintenance can be applied to some special cases with satisfactory results. However, in many situations, especially when both maintenance and failure are very costly, CBM is absolutely a better choice than the conventional ones

A set-membership condition monitoring framework has defined for dual fuel engines based on simultaneous input and parameter estimation techniques. In an approach, a priori aging/degradation (health) parameter bounds, onboard collected data, measurement noise level estimates and dynamic relationships based on the model equations are fused to estimate health parameter plausible ranges [2]. The estimators is demonstrated may need to be organized in a cascade with the results from an upper level estimator feeding to the lower level estimator. Finally, given that the use of transient data improves parameter identify ability, a specific opportunity is demonstrated in dual fuel engines to exploit data from diesel to gas mode transitions.

The use of intelligent algorithms is useful for developing a CBM of vessels in operation have proved. ANN has been used previously for this purpose: nevertheless, all previous models were based upon laboratory tests, under controlled conditions [3]. In contrast to the laboratory-based tests engine models in which faults have been induced in commercial vessels have to be detected from registered data. The fault diagnosis has been established on the four main areas of the engine, which can generate an increase in the instantaneous fuel consumption: (1) clogged turbine; (2) clogged air filter/compressor; (3) clogged air cooler; and (4) bad fuel injection. A computing tool has been developed in LabVIEW. The tool will permit ship-owners and chief engineers to control the maintenance of the engine; likewise, optimize the engine, based upon energy efficiency. The failure modes should be refined for the future CBM of such engines

Recent advances in automatic vibration- and audio-based fault diagnosis in machinery using condition monitoring strategies have reviewed. It presents the most valuable techniques and results in this field and highlights the most profitable directions of research to present [4]. Automatic fault diagnosis systems provide greater security in surveillance of strategic infrastructures, such as electrical substations and industrial scenarios, reduce downtime of machines, decrease maintenance costs, and avoid accidents which may have devastating consequences. Automatic fault diagnosis systems include signal acquisition, signal processing, decision support, and fault diagnosis

The use of measurements of acoustic emission, vibration and dynamic pressure transducers for a range of flows and two pump speeds on a double-suction centrifugal pump have presented. These show that acoustic emission (AE) signals are more sensitive to change in flow condition away from the pump's best-efficiency point than either vibration or dynamic pressure measurement [5]. Results indicate that AE monitoring may therefore be appropriate for determining the location of best efficiency and for detecting the onset of undesirable hydraulic conditions such as recirculation and cavitation.

The results of vehicle exhaust measurements that were used to establish emission standards for an inspection/maintenance I/M program have presented. For this purpose, a total number of 100 private autos distributed across model years ranging between 1972 and 2002 were tested under idling conditions [6]. The monitored indicators included air to fuel ratio %, CO %, CO_2 %, HC parts per million, ppm, NOx ppm, and O_2 %. Private autos with model years greater than 1994 were found to be compliant with international standards and are relatively well maintained. Emissions from older models increased significantly with a lack of engine maintenance. They have concluded with criteria for proposing I/M emission standards based on exhaust measurements taking country specific socioeconomic characteristics into consideration.

An investigation of the fault diagnosis technique in internal combustion engines based on the visual dot pattern of acoustic and vibration signals have presented most of the conventional methods for fault diagnosis using acoustic and vibration signals are primarily based on observing the amplitude differences in the time or frequency domain [7]. Unfortunately, the signals caused by damaged elements, such as those buried in broadband background noise or from smearing problems arising in practical applications, particularly at low revolution, are not always available. And they have proposed a visual dot pattern technique to identify the acoustic emission and vibration signals for fault diagnosis in an internal combustion engine and drive axle shaft. Experiments are carried out to evaluate the proposed system for fault diagnosis under various fault conditions.

Experimental tests to determine the performance and exhaust emission characteristics of an automotive direct injection dual-fuelled diesel engine have conducted. Natural gas was used such that 65 per cent of engine. Brake power was supplied from compressed natural gas and the rest was supplied from diesel fuel. The possibility of decreasing exhaust emission is investigated with the lowest performance sacrifice. At part loads, a dual-fuelled engine inevitably suffers from lower thermal efficiency and higher carbon monoxide (CO) emission [8]. This is mainly due to leaner mixture and incomplete combustion, which is a consequence of the smaller amount of pilot fuel. To resolve these problems, the effects of cooled exhaust gas recirculation (EGR) were investigated. The experimental results show that the application of EGR, at higher loads with 10 per cent EGR and at part loads with 15 per cent EGR, can considerably reduce NOx and other exhaust emissions such as unburned hydrocarbons, CO and soot. Results show that the performance parameters almost remain at the baseline engine level.

A dynamic model for a single cylinder diesel engine that can simulate engine performance under both transient and steady state operating conditions has presented. The model has been implemented in SIMULINK. Validation has been performed for two types of diesel engine, one for transient response and the other for steady state. Predicted profiles of the instantaneous engine speeds through the transient and steady state are in excellent agreement with measurements. The model includes all the engine friction components, namely the piston assembly, the crankshaft bearings, the valve train, the pumping losses and the pumps [9]. A dynamic dynamometer model is also included, which enables a variety of engine tests to be carried out The model has been developed with the aim of investigating different strategies for transient fuel control. Work was also ongoing to include modeling of operation from cold start.

The maintenance strategies for replacing units or components that are subject to failures and can be replaced with either new or overhauled units of the same type have described. Current practices in maintenance range from breakdown maintenance through preventive maintenance, all the way to condition-based maintenance (CBM). Breakdown maintenance (replacement only at failure strategy) waits until failure and then a replacement is made [10]. This may be an appropriate strategy for maintenance in some cases, such as when the hazard rate is constant. And also have brought together theoretical issues associated with the potential role of proportional hazards modeling (PHM) to assist in the interpretation of signals emanating from a condition-based maintenance program, such as oil analysis.

In this paper a comparative analysis of condition monitoring indicators for a defected bi-fuel vehicle engine, where a reduction of engine lubricant oil to be 50% has been done and considered to be a fault. The experimental methodology is briefly introduced and the information about the experimental investigation is tested under accelerated fault conditions at speed of 2000 r/min and torque load of 30 Nm, where recordings every 30.0 min were acquired and a total of 7 recordings (~ 3.0 h of test duration). Moreover, an experimental procedure is developed to assess the severity of the engine components fault. The experimental localized fault signals (exhaust emission and vibration acceleration signals) were subjected to the same diagnostic techniques such as RMS, spectral kurtosis analysis, skewness analysis and crest factor analysis. Finally the present work reports the results concluded by long term (~ 3.0 h) experiments to a defected engine system.

2. Condition Monitoring Indicators

2.1. Background

Bi-fuel petrol engine components condition indices process the exhaust emission vibration acceleration of the engine to return a single value indicating its overall health. This signal could be either increasing or decreasing as the engine fault increases. The exhaust emission and vibration spectrum signals of a faulty engine usually consider being amplitude modulated at characteristic fault frequency. Matching the exhaust emission and the measured vibration spectrum with the fault characteristic frequency enables the detection of the presence of a fault and determines where the fault is.

2.2. Root mean square (RMS)

It signifies the energy content within a signal with respected to time. The root mean squared (rms) is defined as the square root of the mean of the sum of the squares of signal samples [9]. It measures the magnitude of a discretized signal and is given by

$$RMS_x = \sqrt{\frac{1}{N}[\sum_{i=1}^{N}(x_i)^2]} \quad (1)$$

where, x is the original sampled time signal, N is the number of samples and i is the sample index.

2.3. Skewness (SK)

SK (xIN): measures the asymmetry of the data about its mean value. A negative SK value and positive SK value imply the data has a longer or fatter left tail and the data has a longer or fatter right tail, respectively.

$$SK(x_{IN}) = \frac{\frac{1}{N}\sum_{i=1}^{N}\left(x_i - \bar{x}\right)^3}{\left[\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(x_i - \bar{x}\right)^2}\right]^3} \quad (2)$$

2.4. Kurtosis (KT)

It is the fourth order moment normalized by the square of variance of a signal and gives a measure of the peakedness of the signal. It measures the peakedness, smoothness, and the heaviness of tail in a data set and given by

$$KT(x_{IN}) = \frac{N\sum_{i=1}^{N}\left(x_i - \bar{x}\right)^4}{\left[\sum_{i=1}^{N}\left(x_i - \bar{x}\right)^2\right]^2} \quad (3)$$

2.5. Crest Factor (CF)

The crest factor is defined as the ratio of the peak value to the RMS of a signal and in other term is equal to the peak amplitude of a waveform divided by the RMS value. The purpose of the crest factor calculation is to give an analyst a quick idea of how much impacting is occurring in a waveform.

$$Crest\ Factor = \frac{Peak}{RMS} = \frac{Crest\ Value}{RMS\ Value}$$

$$CF\ (x_{\mathrm{iN}}) = \frac{Sup|x(i)|}{\sqrt{\frac{1}{N}\sum_{i=1}^{N}[x(t)]^2}} \quad (4)$$

$$Peak = Crest\ \ Value = \frac{1}{2}\left[\max(x(t)) - \min(x(t))\right]$$

2.6. Higher Order Statistics Indices

From the previous discussion, descriptive and higher order statistics (HOS) indices have been generating intensive interest. The RMS, average crest factor and kurtosis values calculated from the measured signal have nearly similar trend, where the RMS value is found to be a better indicator as compared to either average crest factor or kurtosis. However, the RMS values of rotational vibration acceleration used to evaluate the wind turbine gearbox components faults severity assessment. Component fault health level (CFHL) can be calculated based on the following equation:

$$RFR = \frac{(RMS)_{Faulty} - (RMS)_{Healthy}}{(RMS)_{Healthy}} = \frac{(RMS)_{\mathrm{Residual}}}{(RMS)_{Healthy}} \quad (5)$$

where:

RFR = **Residual over Full Oil Level Ratio**

$(RMS)_{Healthy}$ = RMS value for healthy condition

$(RMS)_{Faulty}$ = RMS value for faulty condition

$(RMS)_{\mathrm{Residual}}$= RMS value for the residual value for faulty condition

3. Experimental Methodology

3.1 Background

The measurement methodolgy used a separately-excited brake that is coupled to the vehicle bi-fuel SI engine output shaft and connected brake paddle to apply or remove load into the engine. In order to measure the vibration responses and emission components of the engine on real condition monitoring signals. The established test rig was utilized to provide data on a commercial transmission as its health progresses from healthy to faulty. The vehicle engine type VAZ 2103 1.5 is used in this work. The speed variation can be accomplished by varying the amount of fuel (gasoline or CNG)/air ratio. The mechanical and electrical losses are sustained by a small fraction of whole power. The established test rig has the capability of testing most of vehicle engines. The system is sized to provide the maximum versatility to speed and load settings. The use of different speed ratios and load values other than those listed in this study is possible if appropriate consideration to system operation is given. The engine and hydraulic disc brake are hard-mounted and aligned on a bedplate. The bedplate is mounted using isolation feet to prevent vibration transmission to the floor. The shafts are connected with both flexible and rigid couplings.

3.2. Experimental Setup

The bi-fuel engine speed allows tested operation at 2000 r/min. The load is provided by a hydraulic brake connected to the load engine at 30 Nm. The faults were made by decreasing the engine lubrication oil level typically 50%. Smart phone sensors was used for the vibration acceleration signals record mounted upon the engine valve cover. The sampling frequency used was 6.0 kHz and signals of 22.0 sec duration were recorded. The ICM-20608-G is the latest 6-axis device offered by InvenSense for the mass market. Measures the acceleration force in m/s^2 that is applied to a device on all three physical axes (x, y, and z), including the force of gravity. The ICM-20608-G is a 6-axis Motion Tracking device that combines a 3-axis gyroscope, and a 3-axis accelerometer in a small, 3 mm x 3 mm x 0.75 mm (16-pin LGA) package. The gyroscope has a programmable full-scale range of ±250, ±500, ±1000, and ±2000 degrees/sec. The accelerometer has a user-programmable accelerometer full-scale range of ±2*g*, ±4*g*, ±8*g*, and ±16*g*. Factory-calibrated initial sensitivity of both sensors reduces production line calibration requirements. Figure 2 shows vibration sensor position AGE-200 gas analyzer is infrared rays exhaust gas analysis module, to be connected to the serial port of any personal computer with the integrated software type OMNIBUS-800. The analyzer and software are belong Brain Bee. The small size and the 12V DC- power supply allows using it as portable tool wherever required used during the experimental work. The gas analyzer is equipped with gas sampling probe to collect the exhaust gas from the muffler. The gas is then filtered and dried before entering the analyzer. The speed is measured by a photo electric probe. Recordings were carried out at constant speed condition. Figure 3 shows Emission measurement system. Recordings were carried out at constant speed. After acquiring the measured vibration signals in the time domain as described above, it is processed to obtain feature vectors

3.3. Experimental Procedure

One non-destructive technique has been employed to test the vehicle bi-fuel engine during operation, namely vibration acceleration generation and exhaust emission components. One fault has been made artificially on the engine, namely reduce the lubricant oil by 50% to create a wear which eventually led to a propagating failure. For 50% oil level, a recordings every 30 min were acquired and a total of 7 recordings (0-3 hr of test duration) were resulted until the termination of the test. This type of test was preferred in order to have the opportunity to monitor path fault modes, i.e., the natural fault propagation. Failure is assured by increasing the test period to the point of where the remaining metal in the contact components have enough wear to be in the plastic deformation region. Since the engine is not new, the residual signals of vibration acceleration and the exhaust emission components measured between the signal at lubricant oil 100% and 50% is considered Figures 1 and 2 show vibration sensor position and Emission measurement system respectively.

Figure 1: Vibration sensor position overview

Figure 2: Emission measurement system overview

4. Results and Discussion

4.1. Engine Exhaust Emission Results

Since the engine used in this work is in-used engine, so the residual was established and defined by the difference between the signals measured when the lubricant oil is complete (100%) and those when the lubricant oil reduced to be 50% level (0.5). The reduction of the oil level is considered as a fault and the diagnosis procedure carried out. **Figures 3 to 6** illustrate the residual engine exhaust emission components signals of oxides nitrogen (NOx), carbon monoxide (CO), carbon dioxide (CO2) and total hydrocarbon (THC) at 45 s when the engine works in gasoline phase and CNG phase in terms of time domain and at engine speed of 2000 r/min with torque load of 30 Nm. For 50% oil level, a recordings every 30 min were acquired and a total of 7 recordings (0-3 hr of test duration) were resulted until the termination of the test. Based on the experimental methodology which presented in earlier section. This is done to display the difference between the engine signal in its gasoline phase and that for the CNG one in clear way. It is observed that the signals in the CNG are lower than that for the gasoline particularly for the NOx and CO

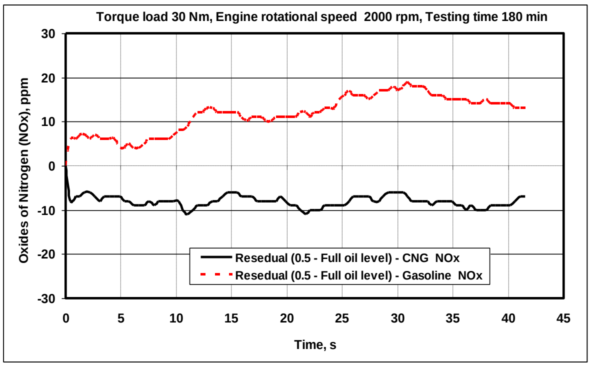

Figure 3: Residual values of oxides nitrogen (NOx) for gasoline and CNG

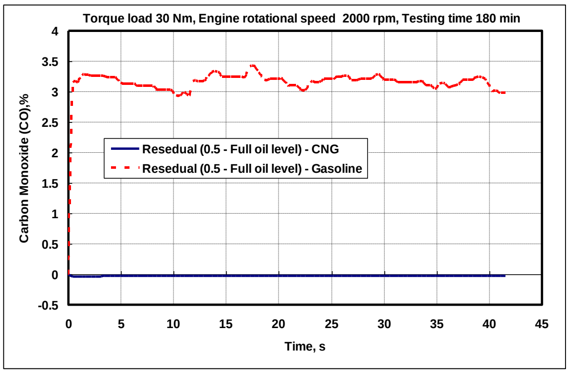

Figure 4: Residual values of carbon monoxide (CO) for gasoline and CNG

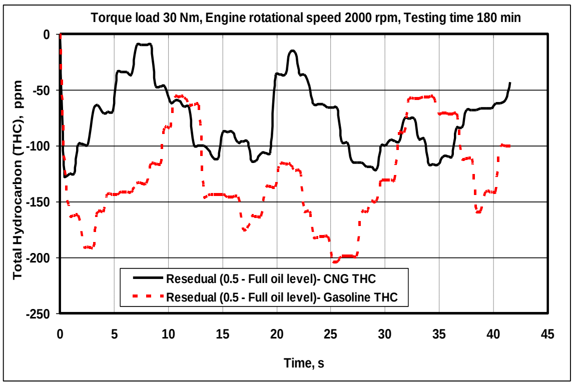

Figure 5: Residual values of carbon dioxide (CO2) for gasoline and CNG

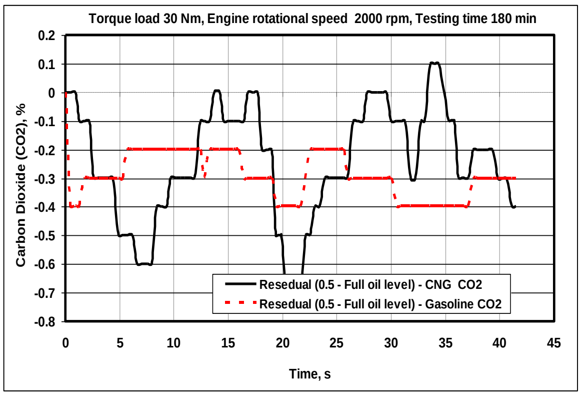

Figure 6: Residual values of total hydrocarbon (THC) for gasoline and CNG

Referring to **Tables 1 and 2**, the bi-engine in gasoline phase and CNG phase emission components condition monitoring indicator values computed based on equations (1) to (4) and presented for speed of 2000 r/min and torque load of 30 Nm. For 50% oil level, a recordings every 30 min were acquired and a total of 7 recordings (0-3 hr of test duration) were resulted until the termination of the test respectively. The reduction of the oil level is considered as a fault. For gasoline phase and NOx component (**Table 1**), the value of RMS varies from 12.944 ppm to 38.72 ppm. The normal distribution of the indicators values are for kurtosis varies from 45.92 to 141.2, for crest factor value varies from 1.0523 to 1.412. Moreover and at the same conditions, the skewness values indicate that the experimental results data has fatter left trail.. The same observations are applied on the rest of engine emission components of CO, CO2 and THC (**Table 1**). For CNG phase and NOx component (**Table 2**), the value of RMS varies from 8.183 ppm to 30.44 ppm. The normal distribution of the indicators values are for kurtosis varies from 41.19 to 154.2, for crest factor value varies from 1.0808 to 3.793. Moreover and at the same conditions, the skewness values indicate that the experimental results data has fatter left trail.. The same observations are applied on the rest of engine emission components of CO, CO2 and THC (**Table 2**).

Table 1: Bi-fuel engine gasoline fuel phase-exhaust emission components

No.	Emission Component	Condition monitoring indicators	Testing Time, min						
			0.0	30.0	60.0	90.0	120.0	150.0	180.0
0	Residual (Full-0. 50) oil level, engine speed 2000 rpm, Torque load 30 Nm								
1	Oxides of Nitrogen (NOx)	RMS, ppm	12.944	21.94	20.10	38.72	30.21	36.45	25.41
2		Crest Factor (CF)	1.0523	1.412	1.097	1.344	1.220	1.217	1.530
3		Kurtosis (KT)	55.092	54.82	45.92	141.2	54.24	55.12	48.67
4		Skewness (SK)	0.0510	-0.06	0.240	-0.57	0.094	-0.038	-0.055
1	Carbon Monoxide (CO)	RMS, ppm	20958	30140	31740	29460	25050	27020	35490
2		Crest Factor (CF)	1.0470	2.010	1.080	1.082	1.117	1.124	1.082
3		Kurtosis (KT)	73.053	276.5	55.64	52.23	68.20	99.72	68.72
4		Skewness (SK)	1.5829	-3.09	0.577	0.582	0.514	1.308	0.682
1	Carbon Dioxide (CO 2)	RMS,%	2.839	0.8356	0.776	0.457	0.866	0.971	0.301
2		Crest Factor (CF)	-1.20	-2.393	1.287	-1.31	-1.153	-1.235	-1.32
3		Kurtosis (KT)	38.44	40.324	47.52	48.90	48.94	53.52	41.71
4		Skewness (SK)	-0.48	-0.975	0.043	0.283	0.252	0.114	0.233
1	Total Hydrocarbon (THC)	RMS, ppm	259.43	300.1	260.3	351.7	324.0	394.0	323.6
2		Crest Factor (CF)	1.3064	1.368	1.496	1.601	1.633	1.641	1.488
3		Kurtosis (KT)	63.193	174.2	55.41	96.77	53.24	52.06	53.74
4		Skewness (SK)	-0.264	0.770	0.189	-0.41	-0.204	-0.195	0.088

Table 2: Bi-fuel engine CNG fuel phase-exhaust emission components

No.	Emission Component	Condition monitoring indicators	Testing Time, min						
			0.0	30.0	60.0	90.0	120.0	150.0	180.0
0	Residual (Full-0. 5) oil level, engine speed 2000 rpm, Torque load 30 Nm								
1	Oxides of Nitrogen (NOx), ppm	RMS, ppm	13.00	30.44	23.647	24.980	19.95	12.12	8.183
2		Crest Factor (CF)	1.307	1.149	1.1417	1.0808	2.505	3.793	1.344
3		Kurtosis (KT)	74.84	154.2	68.938	71.645	56.41	41.19	62.96
4		Skewness (SK)	0.340	-1.359	-0.091	-0.413	-0.15	-0.08	-0.25
1	Carbon Monoxide (CO), ppm	RMS) ppm	23.06	272.3	206.79	246.68	256.1	283.4	268.5
2		Crest Factor (CF)	4.335	1.101	1.4506	1.2161	1.170	1.411	1.489
3		Kurtosis (KT)	409.3	37.91	75.993	28.163	24.51	52.78	59.75
4		Skewness (SK)	3.985	-0.678	0.1128	0.4396	0.054	0.482	0.658
1	Carbon Dioxide (CO2), %	RMS, %	1.205	0.408	1.2429	2.0086	1.403	1.961	1.309
2		Crest Factor (CF)	1.914	1.480	2.0577	2.0216	1.968	1.809	2.259
3		Kurtosis (KT)	53.30	56.29	59.074	100.37	70.45	62.03	63.79
4		Skewness (SK)	-0.276	-0.141	0.0643	0.7155	0.674	0.008	-0.56
1	Total Hydrocarb on (THC), ppm	RMS, ppm	37.78	55.63	89.074	107.44	94.30	73.74	84.35
2		Crest Factor (CF)	1.852	1.671	1.3584	1.6194	1.463	1.613	1.505
3		Kurtosis (KT)	91.40	73.49	41.553	96.179	52.67	47.32	55.57
4		Skewness (SK)	-0.208	0.134	-0.006	-0.139	-0.15	-0.11	0.139

4.2. Engine Valve Cover Vibration Acceleration Results

Figures 7 to 9 show the residual vibration acceleration measured over the engine valve cover in the three directions (X, Y, Z) in terms of frequency-domain up to 800 Hz and at a speed of 2000 r/min with torque load of 30 Nm. For 50% oil level, a recordings every 30 min were acquired and a total of 7 recordings (0-3 hr of test duration) were resulted until the termination of the test. For the engine in its phases (gasoline and CNG) and based on the experimental methodology presented in the previous section is considered, where the signals in these figures are normally dominated by the firing order harmonics modulation with the rotation of the engine crankshaft when the lubricant oil level reduced to be 50% (0.5) as described previously. In most cases, the modulation waveforms are also sinusoids with lower shaft orders, i.e. one time and/or two times the shaft frequency. At 500 Hz, the vibration acceleration signal measured in CNG phase is positive and negative in 600 HZ, while for the gasoline phase at 500 Hz is negative. This is due to the natural of combustion process for both fuels in all the three directions (X, Y, Z). The operation of the engine with half lubricant oil level will induce an impulsive change with comparatively low energy to the engine vibration signal. This can produce some higher engine order modulations and may excite engine structure resonance

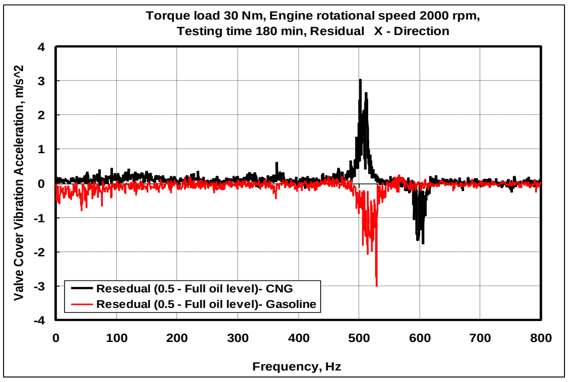

Figure 7: Residual vibration acceleration for gasoline and CNG in X-direction

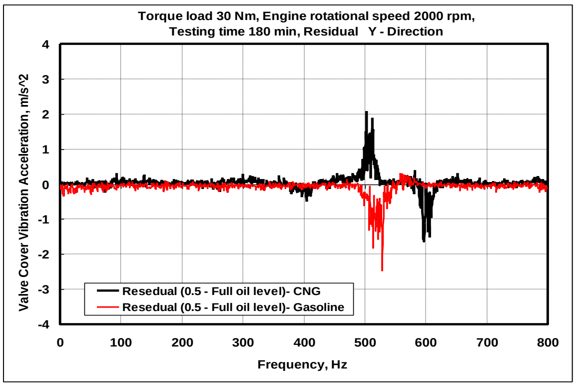

Figure 8: Residual vibration acceleration for gasoline and CNG in Y-direction

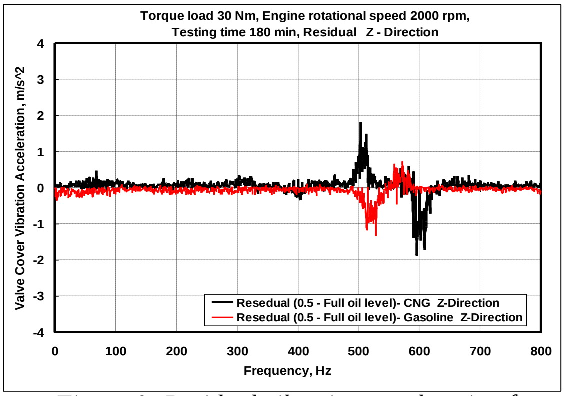

Figure 9: Residual vibration acceleration for gasoline and CNG in Z-direction

Tables 3 and 4 tabulate the bi-engine condition monitoring indicators values calculated based on equations (1) to (4) of RMS, SK, KT, and CF for the testing time ranging from 0.0 to 3.0 h (every 30 min) for the engine phases (gasoline and CNG) at 2000 r/min with torque load 30 Nm when the lubricant oil level was reduced to 50%. For gasoline phase and X-direction (**Table 3**), the value of RMS varies from 0.161 m/s^2 to 0.377 m/s^2. The normal distribution of the indicators values are for kurtosis varies from 28.462 to 211.9, for crest factor value varies from 4.972 to 14.90. Moreover and at the same conditions, the skewness values indicate that the experimental results data has fatter right trail. The same observations are applied on the rest of engine valve cover vibration acceleration of Y-direction and Z-direction (Table 3). For CNG phase and X-direction component (**Table 4**), the value of RMS varies from 0.201 m/s^2 to 0.322m/s^2. For more accurate observation of these values through the range of the testing time, the RMS value is nearly increased with the increase in the testing time. A magnification is obtained, which is important and possesses diagnostic value as they can be used to define and characterize the critical changes of the engine wear accumulation and evaluation. The values of the remaining indicator parameters are scattering. In summary, it can be seen that for the bi-engine vibration from ther accelerometer mounted on the valve cover, the RMS and KT show good fault detection potential, while SK and CF of the accelerometers work in most cases but are not stable. The vibration signals are highly affected by the background noise or mechanical resonance, making their performance unstable.

Table 3: Bi-fuel engine gasoline fuel phase -vibration acceleration

.No .	Vibration Component	Condition monitoring indicators	Testing Time, min						
			0.0	**30.0**	**60.0**	**90.0**	**120.0**	**150.0**	**180.0**
0	**Residual (Full-0. 50) oil level, engine speed 2000 rpm, Torque load 30 Nm**								
1	**Vibration Acceleration, X-Direction**	RMS) , m/s2	0.161	0.225	0.168	0.377	0.317	0.323	0.337
2		Crest Factor (CF)	4.972	14.90	11.45	11.23	9.632	8.787	9.791
3		Kurtosis (KT)	28.46	211.9	152.60	130.5	109.6	99.81	115.8
4		Skewness (SK)	2.665	8.003	6.7212	6.324	6.118	5.841	6.368
1	**Vibration Acceleration, Y-Direction**	RMS) , m/s2	0.233	0.289	0.138	0.286	0.270	0.267	0.259
2		Crest Factor (CF)	9.602	12.76	13.10	11.24	9.797	9.709	9.435
3		**Kurtosis (KT)**	105.1	162.9	199.5	131.4	106.1	117.1	106.4
4		**Skewness (SK)**	5.608	7.823	8.045	6.376	5.880	6.507	5.930
1	**Vibration Acceleration, Z-Direction**	RMS) , m/s2	0.283	0.451	0.349	0.705	0.336	0.335	0.360
2		Crest Factor (CF)	9.474	12.07	12.25	8.631	7.416	7.647	8.068
3		**Kurtosis (KT)**	94.43	151.4	152.4	77.70	65.36	63.06	64.93
4		**Skewness (SK)**	5.452	7.518	6.722	4.506	4.368	4.344	4.180

Table 4: Bi-fuel engine CNG fuel phase-vibration acceleration,

No.	Vibration Component	Condition monitoring indicators	Testing Time, min						
			0.0	30.0	60.0	90.0	120.0	150.0	180.0
0	Residual (Full-0. 50) oil level, engine speed 2000 rpm, Torque load 30 Nm								
1	Vibration Acceleration, X-Direction	RMS, m/s^2	0.201	0.253	0.255	0.267	0.250	0.322	0.318
2		Crest Factor (CF)	10.42	10.27	11.95	10.695	8.260	11.54	13.90
3		Kurtosis (KT)	102.0	129.6	122.7	116.79	79.12	161.8	212.1
4		Skewness (SK)	5.820	6.741	6.192	6.259	5.387	7.474	8.327
1	Vibration Acceleration, Y-Direction	RMS) m/s^2	0.107	0.252	0.226	0.227	0.219	0.272	0.262
2		Crest Factor (CF)	11.22	11.02	12.75	11.604	8.891	11.62	14.96
3		Kurtosis (KT)	110.9	144.3	136.6	138.31	88.27	174.1	241.4
4		Skewness (SK)	6.211	7.231	6.655	6.9391	5.754	7.868	9.015
1	Vibration Acceleration, Z-Direction	RMS, m/s^2	0.127	0.202	0.187	0.167	0.172	0.176	0.171
2		Crest Factor (CF)	9.566	9.309	10.83	8.2792	8.042	8.313	10.33
3		Kurtosis (KT)	91.44	92.11	84.38	69.950	70.76	77.68	121.8
4		Skewness (SK)	5.716	5.647	4.725	4.6895	4.845	4.997	6.074

4.3. Engine Fault Severity Assessment Results

From the previous discussion, the condition monitoring indicators of RMS, skewness SK, KT, and CF have been generating intensive interest. They have nearly similar trend, where the RMS value is found to be a better indicator when compared to other ones. However, the RMS values of the engine emission components (NOx, CO, CO2, THC) and vibration accelerations of X-direction, Y-direction and Z-direction are used to evaluate the bi-engine faults severity assessment. Samples from these evaluations are depicted in **Figures 10 and 11** which have been achieved by the development of the experimental technique at 2000 r/min and torque load of 30 Nm. For 50% oil level, a recordings every 30 min were acquired and a total of 7 recordings (0-3 hr of test duration) were resulted until the termination of the test. Based on equation (5), the value of the **residual value over full oil level value ratio** (RFR) is calculated. **Figure 10** indicates the RFR value for the RMS of the engine exhaust emission THC component, while **Figure 11** indicates the RFR value for the RMS of the engine valve cover vibration acceleration in X-direction. In order to establish both the sensitivity and robustness of the engine condition indicator are clearly seen in the figures, where the RFR value is increased as the testing time is increased both in the bi-engine with gasoline and with CNG for the exhaust emission component of THC, while in the engine valve cover vibration acceleration still RFR increases for the CNG and gasoline. The use of RFR has shown that the fault on the bi-engine can be detected at its early stages, and symptoms of fault on vibration acceleration is not primarily caused by the reduction of components wear (which is the case for the detection of a localized fault), but mainly due to the deviations in component shape from its true component shape, where the deviations in component shape causes the original vibration acceleration and consequently causes the onset of the fault, whatever be the value of wear.

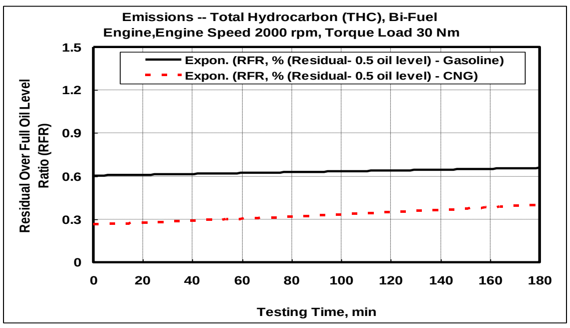

Figure 10: RFR exhaust emission for gasoline and CNG in THC component

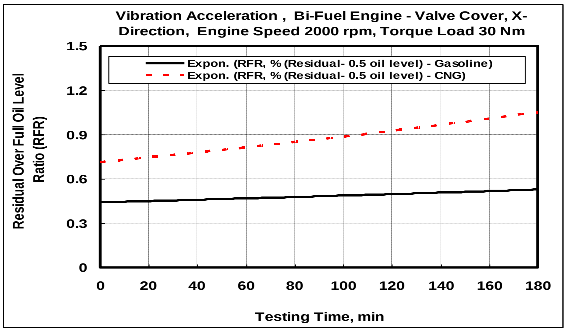

Figure 11: RFR vibration acceleration for gasoline and CNG in X-direction

4.4. Combined Engine Exhaust Emission and Vibration Signatures

No single condition monitoring technique is suitable to monitor all the aspects of a complex multi-component system likes the vehicle engine. Rather, several techniques may have to be employed. One may be dedicated to a specific area, but is not suitable to monitor some other features. Fault detection (diagnosis) through a single technique may lead to misjudgment, so that additional maintenance cost is caused. The application of the methods combined several techniques is necessary. Based on the combination of engine exhaust emission and vibrational techniques over testing time of 3.0 h and at 2000 r/min and torque load of 30 Nm is analyzed and presented in **Figures 12 to 17.** The analysis started by averaging the RFR values for each engine emission component with respect to gasoline and CNG phases over the testing time (**Figures 12 and 13**), while the RFR for vibration acceleration of the three directions modulus for each engine emission component with respect to gasoline and CNG phases over the testing time (**Figures 14 and 15**). The RFR data for the engine emission signatures in its two phases were add to each other and depicted in **Figure 16,** while the RFR data for the engine valve cover vibration acceleration signatures in its two phases were add to each other and depicted in **Figure 17.** It is observed from **Figures 16 and 17** that the severity of engine fault varies with the increase of the testing time. Moreover, the severity due to using the CNG in petrol engine is higher than that for the gasoline. On the other hand, It is recommended for the complex structure to consider the combined signatures from two or more signatures in order to detect the fault clearly.

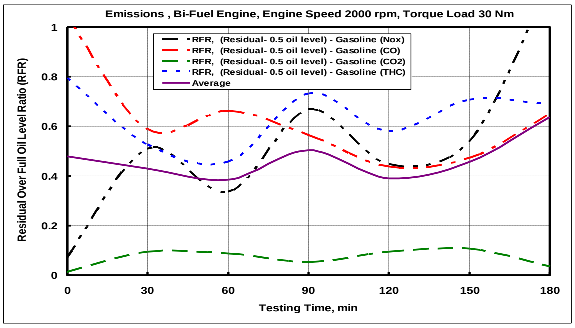

Figure 12: Average RFR exhaust emission component for gasoline phase

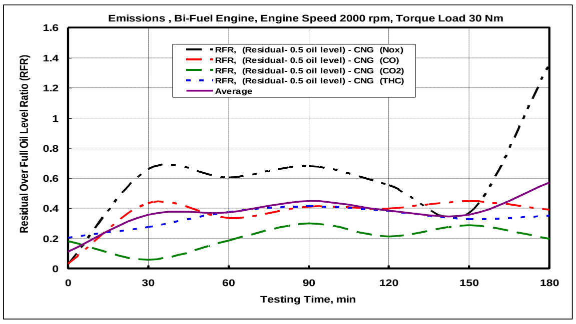

Figure 13: Average RFR exhaust emission component for CNG phase

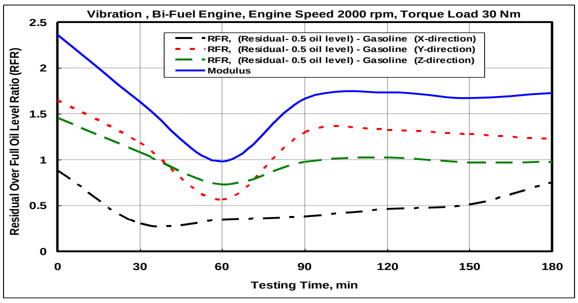

Figure 14: Modulus RFR engine vibration acceleration (X,Y,Z) for gasoline phase

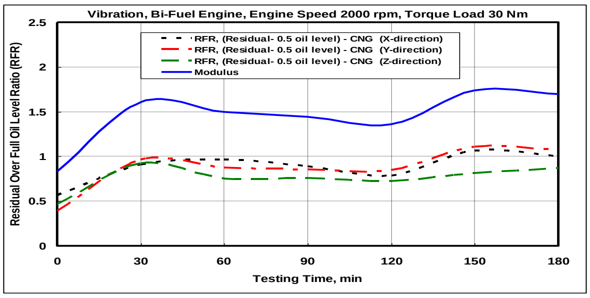

Figure 15: Modulus RFR engine vibration acceleration (X,Y,Z) for CNG phase

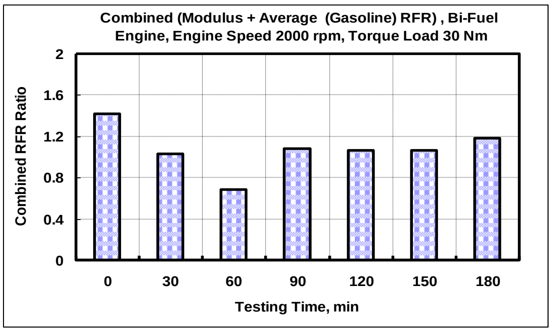

Figure 16: Combined RFR gasoline engine phase

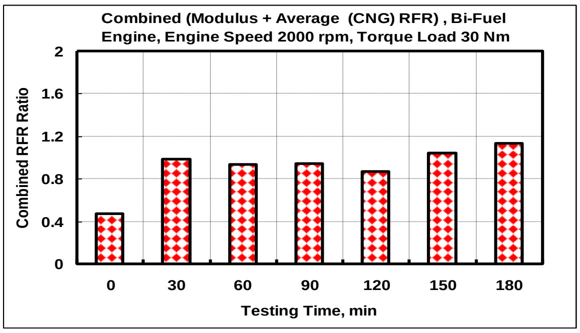

Figure 17: Combined RFR CNG engine phase

5. Conclusions

1- From this investigation, a new measurements technique based on vehicle bi-engine vibration acceleration and exhaust emission components fault diagnostic methodology was presented. The presented method was accomplished through the real time signals and condition indicators to extract diagnostic features. First, the smart phone and gas analyzer signals are band pass analyzed so as to retain the information related to the engine conditions. Then, time-domain and frequency-domain signals computed to obtain the periodically repeated waveform. The presented method was validated using data collected from seeded fault tests conducted on a vehicle bi-engine test rig in a laboratory. This carries diagnostic information which is of great importance for extracting features of the fault. Furthermore, Experimental results are revealed that the vehicle bi-engine components faults can be identified.

2- In order to extract the impulse feature of faulty vehicle bi-engine components for its two phases (gasoline and CNG), vibration acceleration and exhaust emission signals are used to analyze the signals of both healthy (100% oil) and faulty (50% oil) engine conditions.. The condition monitoring indicators of root mean square (RMS), skewness (SK), kurtosis (KT), crest factor (CF) and RFR reflect the condition of the engine. The results look promising, where the RMS value analysis could be a good indicator when compared with the other indicators considered for early detection and characterization of faults. Moreover, Multi-hour tests were conducted and recordings and were acquired using engine exhaust emission components and valve cover vibration acceleration monitoring.

3-The use of the residual value over full oil level value ratio (RFR) for the technique of combined signatures show that the fault on the vehicle bi-engine in its two phases (gasoline and CNG) can be detected at its early stages, and symptoms of fault on vibration and exhaust emission components are not primarily caused by the reduction components stiffness (which is the case for the detection of a localized fault), but mainly due to the deviations in component shape from the true component shape.

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