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Vibration Based Health Monitoring for Automotive Engine

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Monitoring

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Abstract: In this study of vibration signature is investigated and discussed. The vibration signature of different fault is then compared to the normal engine condition. Eleven selected faults have been selected and tested one at a time so that the outcome of the vibration signature can be predicted. The vibration levels are recorded at one point through three different axes of the engine, the axial direction along the crankshaft axis (x-axis), the transverse direction in the horizontal plane and normal to the crankshaft axis (y-axis) and the vertical direction along the cylinder axis (z-axis). In addition to that, the effect of each fault induced on the engine power and torque also is measure and discuss. All the testing is tested on two different load, no load and full load. The results have shown that every fault that applied to the engine will clearly give a higher vibration level compared to the normal condition. Thus, it can be concluded that the monitoring of the engine health can be done through vibration monitoring technique.

1 Introduction

Modern internal combustion (IC) engine systems have grown significantly progress in producing a better fuel consumption, emission and driveability. It is progressing from fuel carbureted system to fuel injection system. Other innovations, including advance ignition system plus with some variables valve timing system, the combustion process have become more complicated and complex. Therefore, fault detection and diagnosis method is not easily done and need to be improved. So, an advance engine predictive maintenance programs need to be developed. The programs or methods for monitoring the engine parts failure can detect malfunction and interruptions of normal engine operations.

An internal combustion engine will create a vibration or excitation while it is running. This source of vibration may be a free moment or a guide force moment produced by the engine or the influence on chassis frame and engine structure arising from the torsional vibration of the shaft system. A guide force moment is the transverse reaction forces that occur when the engine crossheads are acting on the engine upper structure. Modern vehicle on-board diagnosis system are mainly based on simple limit or plausibility check of some measured signals and on simple signal based methods like frequency analysis of the speed signal [1]. By measuring the corresponding output signal for symptoms such as worn crankshaft, malfunction of oil pump or heavy knocking derive from abnormal combustion, etc, it becomes possible to detect the problem and localize the fault.

With the emerging of various systems on the IC engine, it is hard to figure out when the parts or the system is failing out. The method that commonly used by the user to determined the failure on the IC engine is by using a vehicle diagnostic scanner. This type of equipment only deals with the electrical voltage signals coming from the various types of sensors attached to the system. If the failures come from the mechanical parts such as spark plug faulty, it will not be registered in the vehicle diagnostic fault. This type of failure will create its own vibration pattern. In order to rectify and solve the problem, vibration based analysis methods need to be developed. In this paper, the focus has been given to study and apply vibration monitoring system to detect engine failure.

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2 Approach and Methods

The aim of the research is to compare the vibration signature between the faulty engine conditions to the normal engine condition at part load. The first step is to setup the engine on the engine dynamometer and the accelerometer is attached to the engine block using industrial adhesive. The location of the accelerometer is described in the experimental setup chapter. Then the engine is tested for performance result according to the engine manufacturer specification. On each the vibration signature will be recorded and tabled for discussion. For the vibration signature table, there are two domains will be recorded, i.e. engine speed domain and frequency domain. The next step is to apply the engine with selected faults and test it at part load. During this testing, each vibration signature from different faults will be collected and compared with the normal engine condition. Power and torque curve also will be collected for each test. Finally, all the result for the testing will be discussed in the result and discussion section.

2.1 Previous Works

Vibration signature analysis is used to determine the operating and mechanical condition of equipment. It can identify problems before they become too serious and cause unscheduled downtime or a poor maintenance practices, such as improper bearing installation or replacement. Vibration measurement is an effective, non-intrusive method to monitor machine condition during start-ups, shutdowns and normal operation. It's primarily used on rotating equipment such as steam and gas turbines, pumps, motors, compressors, paper machines, rolling mills, machine tools and gearboxes. Several studies had shown the suitability of vibration analysis for application to rotary and reciprocating machines, which can be considered to be the most widely used in general, in addition to its high capacity of diagnosis, make it the most versatile predictive technique. This technique consists of measuring the vibration levels from a certain machine and analyzing these measurements to predict any failure in the machine. The presence of a fault in industrial equipment will be accompanied by a detectable increase or modification of vibratory signal, this is the main reason behind using vibration monitoring to detect machine failure [2].

Some studies also have shown that the most important technique in engine health monitoring is vibration analysis as it gives clear indications regarding the condition of the machine [3][4][5]. In addition the level of vibrations and the frequency at which these vibrations occur can serve in determining the exact location of the defect and possibly severity of such defect [2]. Vibration analysis, properly applied, allows the technician to detect small developing mechanical defects long before they become a threat to the integrity of the machine and thus provides the necessary lead-time to schedule maintenance to suit the needs of the plant management. In this way, plant management has control over the machines. The vibrations in a reciprocating internal combustion engine are caused by unidirectional combustion force and mechanically induced structural resonance [6]. With a sufficient database about the machine's operating order, its components and history of malfunctions, the vibration monitoring technique can provide early information about progressing malfunctions, the sources of these malfunctions and in some cases an estimation of the time period before the problems become serious [5]. The concept behind the vibration analysis method is that any machines with moving parts vibrate in response to the excitations employed on its components. Variation in the excitation forces, the machine's components or its integrity will affect the vibration pattern. The correlation between the measured vibrations of an engine and its components as a source for the excitations, and concluded that the source of the vibration can be definitely be identified by employing the vibration analysis method [7].

It is possible to examine the same vibration signal in terms of acceleration, velocity or displacement. It is seen that velocity at any frequency is proportional to the displacement times the frequency and the acceleration at any frequency is proportional to velocity times frequency, which means it is also equal to displacement times frequency squared. Vibration displacement strongly emphasizes the lowest frequencies and acceleration strongly emphasizes the highest frequencies. When looking at the vibration spectrum of a given machine, it is desirable to display the parameter that has the most uniform level over the frequency range. This will maximize the dynamic range of the measured signal. For most rotating equipment of medium size, it will be found that vibration velocity produces the most uniform spectrum, and for this reason it is usually chosen as the default parameter for machine monitoring.

Trend analysis has also been established to be a reasonable technique in condition monitoring [6]. Internal combustion engines normally operate across a wide spectrum of speed and load. Time domain averaging of signals under varying speed conditions would lead to erroneous results. In an environment where fault detection has to be instant, it would be desirable to have a system with minimal computational requirements which could evaluate the machine condition on a per sample basis. The criterion for the selection of the best features for fault classification is a

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vital issue. In modern fuel injection systems of IC engines, non-uniform cylinder-wise torque contribution is a common problem, causing increased torsional vibration levels of the crankshaft and also stress of mechanical components. Each moving component of an engine usually produces a vibration signature on some points of the engine body. Engine block side is the most sensitive location for collecting data and the direction transverse to the piston's movement plane is the most informative one [5]. Typically, the main sources of excitation that are likely to be observable from the vibration signal are associated with the following subjects [4] [7]:

i. rocking and twisting of the engine block on its supports, due to the action of internal forces
ii. impacts due to clearances at links, those at the crankshaft bearings and the so-called piston slap being extremely noisy
iii. closures and opening of valves
iv. high-pressure fuel injection in diesel engines
v. Rapid rising of gas pressure in the cylinders during the combustion, especially in diesel engines where it is compared with a hammer blow.

Any point measured on the internal combustion engine structure, the vibratory signal is composed of a very complex superposition of the contributions of different vibratory sources modified by their respective transmission paths [4]. These sources originate from several internal phenomenons in the engine and excite the natural modes of the engine. The vibration is amplified at the natural frequencies of the engine. Therefore, the produced vibration and the noise radiated from the engine result from the combination of the excitations and the dynamic response of the structure. The measurements were taken at four points (see Figure 1), two points were on opposing side of the engine block between cylinder 2 and 3 a few cm above the crankcase [5]. The other two points were in the vicinity of the rear crankshaft bearing at 70^{o} and 240^{o} relative to each cylinder axis. At each point's measurement were taken in three principal directions, the vertical along the cylinder axis, the axial direction along the crankshaft axis and the transverse direction in the horizontal plane and normal to the crankshaft axis.

The engine is subject to complex vibration effects, which may produce six different free motions or degrees of freedom and combinations of the same. These motions can generate what are termed 'bounce' and 'yaw' about a vertical axis, fore-and-aft movement and roll about a horizontal longitudinal axis, and sideways shake and pitch about a horizontal lateral axis. The three inertia axes intersect at the centre of gravity of the engine (Figure 2). Reciprocating machines (gas and diesel engines, steam engines, compressors, and pumps) all have one thing in common - a piston that moves in a reciprocating manner.

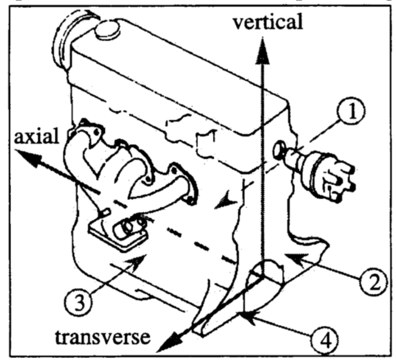

Figure 1: Location and direction of vibration measurement [5].

These machines generally have high overall vibration levels and particularly strong responses at 1X and harmonics, even when in good condition. The vibrations are caused by compressed gas pressure forces and unbalance. Vibrations at 1/2 X may be presented in four-stroke engines because the camshaft rotates at one half the crankshaft speed [8]. Many engines operate at variable speeds, which will allow the strong forcing functions to excite resonances of the components and the mounting structure, if it is not designed in a robust manner. Excessive vibrations in reciprocating machines usually occur due to operational problems such as misfiring, piston slap, compression leaks, and faulty fuel injection [8]. These problems result in elevated 1/2 X vibrations, if only one cylinder is affected, and a decrease in efficiency and power output. Gear and bearing problems may also occur in reciprocating machines, but the characteristic defect frequencies for these faults are significantly higher.

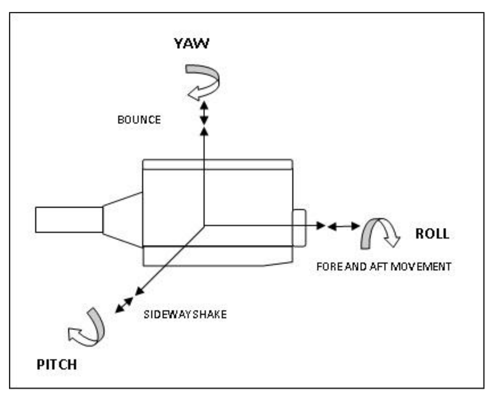

Figure 2: Vibratory motion of an engine

The vibrations of an engine block are related to the instantaneous crankshaft torque [5] [9]. Large vibration

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levels occur at crank angles integer-multiple of 120^o, when the piston of each cylinder reaches the top dead position and immediately afterward during combustion [4]. The rotational shafts which have anisotropic characteristics throughout the longitudinal axis cause the self excited force to be increased [7]. Nevertheless such factors are usually considered as asymmetric distribution of mass. The crankshaft cannot be made perfectly rigid, and during engine operation it can be subjected to three modes of vibration which is torsional, axial and bending. Meanwhile, a crankshaft is subjected to many periodical dynamic loads, generating vibrations and consequently stresses that shall be quantified to ensure the structural integrity of the component [10]. Crankshaft torsional vibrations occur on internal combustion engines due to the periodical nature of the actuating torque.

The preceding statement is not completely true for modern car engines, which drives a number of accessories (air conditioner, a large alternator, etc.) through belts. When torsional vibrations are excited, they exert forces that are variable in time on the supports of the accessories, and the resulting vibration can be detrimental to the acoustic and vibrational comfort of the vehicle and to structural safety. Recently, torsional vibration dampers, which were limited to diesel engines, started to be used on many spark ignition engines and complicated types aimed to reduce the transmission of vibrations to the accessories appeared [11]. If the frequency of the disturbing vibrations should coincide with one of the natural frequencies of crankshaft vibration, then a condition known as *resonance* will occur. A danger of resonant vibration is that the energy of the disturbing vibrations may be greater than that lost by the twisting and untwisting of the crankshaft, so that the amplitude of torsional vibration builds up to such a degree that the crankshaft can be over-stressed and eventually suffer a fatigue fracture. Axial vibration of a crankshaft is of lesser significance than torsional and bending vibration and is generally regarded as being a by-product of the former. That is, the twisting and untwisting of the crankshaft are accompanied by alternate decreases and restorations in length, which would of course apply to any other body subjected to the same treatment.

The effects of the internal combustion engines variable inertia due to unexpected large angular displacements in multiples of the engine speed occur due to the variable inertia characteristics of the crank-mechanism can be extremely dangerous for the crankshafts [12]. Bending vibration of the crankshaft when considered as a beam are also resulted from the pulsating gas and inertia forces imposed upon it via the piston and connecting rod assemblies. As might be expected, this form of vibration is strongly reacted against at the main bearings. In high-compression-ratio engines, the maximum rate of pressure rise during combustion can be such as to cause undesirable vibration of the engine structure and mechanism, especially bending vibration of the crankshaft if it and its bearing supports are not rigid enough. The axial vibration can be dangerous because of the possibility of excitation by gas pressures and inertia forces of reciprocating parts due to the coupling of the various modes [11]. In the past, axial vibrations were an actual danger only in a few cases, mainly linked with slow large internal-combustion engines, but the modern tendency toward higher stress levels, speed, and power/mass ratio caused them to become an important factor in the design of a wider class of reciprocating machines.

2.2 Experimental Setup

The experiment begins with assembly the engine to the engine dynamometer. For this purpose the PROTON CAMPRO IAFM engine is used. Before the engine can be started, the accelerometer transducer had to be mounted to engine block using an industrial adhesive. When the engine is well prepared and all related connections from the dynamometer have been connected accordingly to the engine had achieve, then the engine is left running at idle speed at several moment until the engine temperature reaches the running temperature which is 85 ^{0}C and above. This is similar to the temperature of these thermostat when it is open as well as to radiator fan when is switched on. Then only the engine will be tested for various fault and all the data received will be recorded in the ETAS Software for engine performance and LMS Test.Xpress for vibration.

Data was collected accordingly based on the fault's induce the engine. There two type of data that been measured. The data that had been collected are vibration and engine performance. For vibration data, the measurement are taken from the accelerometer transducer and the result are plotted in RPM vs. Acceleration graph. A frequency vs. acceleration graph also will be plotted. For engine performance data, the measurements are taken using dynometer software (ETAS) which record all the performance parameter such as power, torque, temperature and pressure coming from the engine during testing. All the performance data that being collected then are tabled for each experiment and will be discussed on the next section. Both data was collected simultaneously.

A number of common faulty conditions have been considered in this experiment. Each vibration signal that coming from each faults then will be compared to normal operating engine conditions. Each symptoms and cause of the faults are carefully monitored and reported in Table 1.

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Table 1: List of fault apply to the engine

No.	Problem	Symptoms	Cause
1.	Misfire.	• Engine vibrates • High lambda values during idle > 1.1 • Black deposits around spark plug	• Due to faulty ignition coil • Due to clogged spark plug
3.	Combustion limit.	• Engine vibrates at very low engine speed	• ECU malfunction • Low throttle opening • Less fuel into the engine • High ignition retard
5.	Mild & Severe Knocking.	• Engine knocking sound • Low exhaust temperature	• High ignition advance
6.	Engine backfires.	• Engine vibrates • Sometime exploding sounds comes from intake system • Small fire can be seen inside plenum	• Exhaust system doesn't flow well • Some exhaust gas reverted back into the combustion chamber
7.	Loose engine components	• Engine parameters ok • Noisy sound comes from engine	• Detached engine components • Loose components such as: • Heat shields
8.	Detached breather hose	• Engine ramps up to high speed after cranking • Engine speed fluctuates during idle	• Disconnected breather hose to plenum. • ECU cannot control idle as it depends on plenum pressure.
9.	Lambda sensor detached	• Engine cannot run in close loop during idle and part load • Engine fueling will run richer	• Faulty connection of oxygen sensor to ECU • Faulty sensor • Lambda heater not functioning, so element cannot be heated up.
10.	Faulty Vim Actuator	• Low Performance > 4000 rpm • Engine Vibrates > 6500 rpm	• Faulty Wiring Connection

3 Results and Discussion

In this section, each set of data from the experiments will be compared and analyzed to normal engine condition (no fault). The data consist of two plotted graph from the experiments. The first graph is acceleration (m/s^2) vs. engine speed (RPM) and followed by acceleration (m/s^2) vs. frequency (Hz). On each graph, the measurement were taken in three principle directions, the axial direction along the crankshaft axis (x-axis), the transverse direction in the horizontal plane and normal to the crankshaft axis (y-axis) and the vertical direction along the cylinder axis (z-axis). For every experiment, each engine parameter will be table and plotted graph of a power and torque curve will be shown to represent to effect of faulty condition of the engine.

X -Axis

For the part load test, the faults graphs are compared to the normal engine condition. The three principle direction (x-y-z) will be tabled separately. Each principle direction will be tabled accordingly to engine speed (RPM) domain and frequency (Hz) domain.

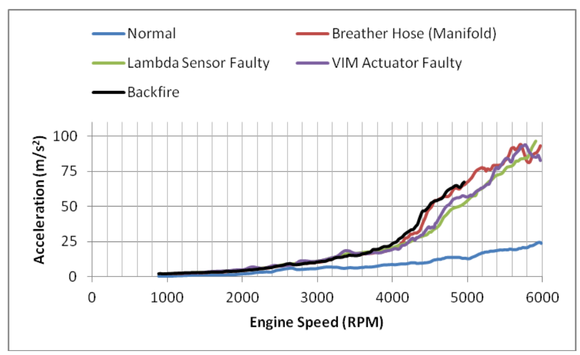

Figure 3: Comparison of vibration signature based on engine speed during part load at the axial direction along the crankshaft axis (X-axis).

Considering Figure 3 characteristic it is found that the vibration signatures of the axial direction along the crankshaft axis based on engine speed (RPM) are increased slightly when the engine speed is above 2700 rpm. The maximum value recorded for the acceleration is 96 m/s^2 and it is happened during lambda sensor faulty. It is found that the vibration signatures from various faulty applied to the engine increase abruptly from about 4400 rpm onwards as the engine speed increase compared to the normal engine condition which the vibration signature increases

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linearly and it records maximum acceleration at 24 m/s^2. From Figure 4, the maximum value of acceleration occurs at around 200 Hz during lambda sensor faulty conditions. It is predicted that the faulty condition applied to the engine are significantly affected by the acceleration. At the highest value faulty, the acceleration will increase. It may be happened because of the Electronic Control Unit (ECU) cannot detect the amount of fuel injected during the operation. During this stage, the ECU will implement a correction to prevent the engine from damaged which in turns it will inject the fuel in rich mixture. It is assumed that the combustion will take a longer time to burn all the fuel and therefore, the expansion of the hot gas are at higher rate.

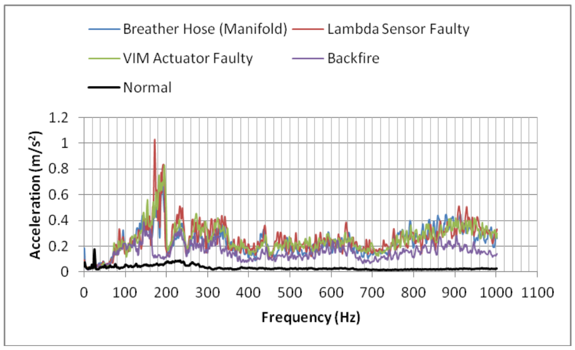

Figure 4: Comparison of vibration signature based on frequency during part load at the axial direction along the crankshaft axis (X-axis).

Y-Axis

Figure 5 shows the characteristics of vibration signatures of difference engine conditions to acceleration. The result shows that the increasing of engine speed will increase vibration level. The maximum value of acceleration was found at 5000 to 6000 rpm. The maximum acceleration of 290 m/s^2 was found during breather hose (intake manifold side) faulty conditions. This condition should be predicted as the increasing of mass air flow rate in the manifold forms a turbulences flow. The turbulence will affect the vibration. Compared to the normal engine condition, it is found that every faulty that being applied to the engine will affect the vibration.

In Figure 6, it shows the vibration level of various frequencies from different engine conditions at part load. Considering this figure, the highest vibrations levels of normal engine condition occur at frequency of 25 Hz and at 0.7 m/s^2. The acceleration is similar for other level of frequencies. The maximum frequency recorded is found during the lambda sensor faulty condition. The maximum value of acceleration recorded is 0.9 m/s^2 and found at frequency of 171 Hz.

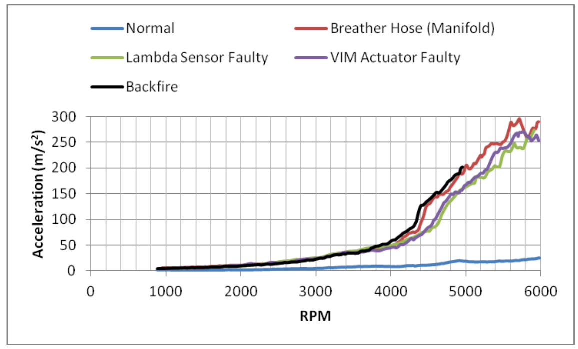

Figure 5: Comparison of vibration signature based on engine speed during part load at the transverse direction in the horizontal plane and normal to the crankshaft axis (Y-axis).

It can be predicted that the rotation of crankshaft during the process will affect the value of the acceleration. It is assumed that at the highest crankshaft rotational speed, the acceleration will be maximum level (Figure 6).

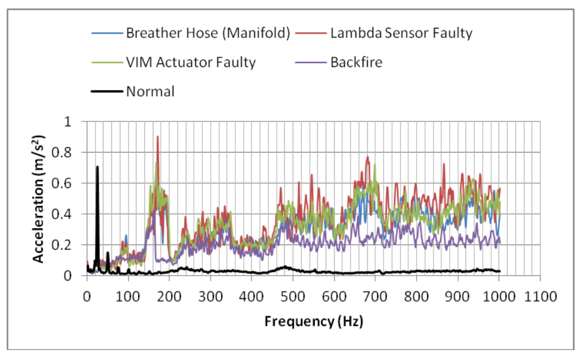

Figure 6: Comparison of vibration signature based on frequency during part load at the transverse direction in the horizontal plane and normal to the crankshaft axis (Y-axis).

Z-Axis

Figure 7 shows characteristics of vibration signatures of acceleration for difference engine conditions based on engine speed at part load. The result shows that the increasing of engine speed will increase vibration level. The maximum value of acceleration found at 5000 to 6000 rpm. The maximum acceleration recorded is 338 m/s^2 found during breather hose (intake manifold side) faulty condition. This condition should be predicted as the increasing of mass air flow rate in the manifold forms a turbulences flow. The turbulence will affect the vibration.

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Compared to the normal engine condition, it is found that every faulty that being applied to the engine will affect the vibration.

Figure 8 shows the acceleration of vibration affect on different engine condition based on frequency at part load. Considering this figure, the normal engine vibrations occur at frequency of 1.318 m/s^2. The condition acceleration becomes similar for all level of frequency. The maximum acceleration for normal engine condition is found at frequency of 25 Hz. When comparing the entire applied fault to the normal engine condition it is found that the maximum acceleration occurs at 173 Hz during lambda sensor faulty condition. The value of recorded acceleration is 2.4 m/s^2. After 200 Hz the increasing of acceleration is not significant. From the Figure 7 and Figure 8, it was predicted that the increasing of acceleration because of transitional movement of the piston. It is also considered by the affect of expand of the gasses during the combustion process.

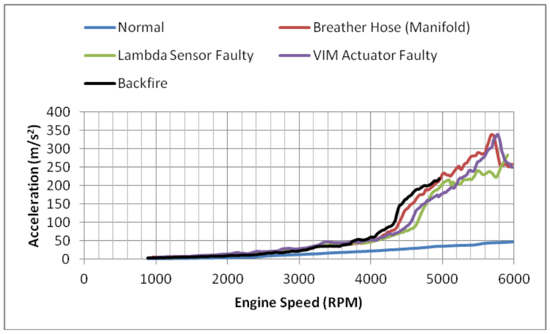

Figure 7: Comparison of vibration signature based on engine speed during part load at the vertical direction along the cylinder axis (Z-axis)

Considering Figure 9, it is found that around 1500 rpm to 3000 rpm, the power drop a few for breather hose faulty. The normal engine condition will give a maximum power output of 27 kW. The power curve is almost identical for all fault tests to normal engine condition at part load. There is slightly dropped of peak power during breather hose faulty condition and VIM actuator faulty condition starting at the speed of 5000 rpm onwards. Figure 10 shows the characteristics of torque at part load for all engine conditions. The torque curve started at different value for each fault compare to normal engine. The curve is almost identical for all faults at the engine speed between 2000 rpm to 6000 rpm except for VIM actuator faulty where its start to drop when the engine speed reaching 4000 rpm onwards. The maximum torque recorded is 58 Nm at engine speed of 1000 rpm.

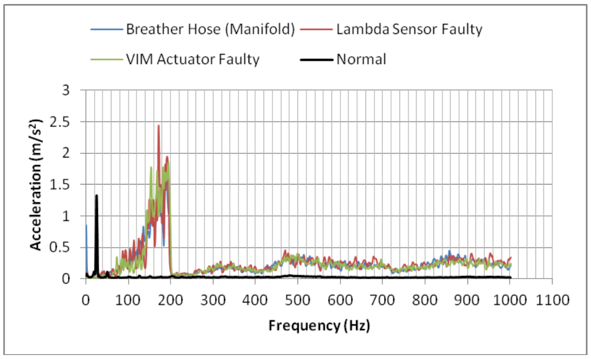

Figure 8: Comparison of vibration signature based on frequency during part load at the vertical direction along the cylinder axis (Z-axis)

Power And Torque at Part Load

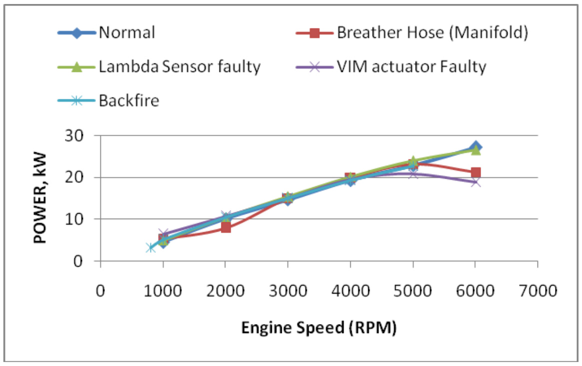

Figure 9: Comparison of engine power curve at part load.

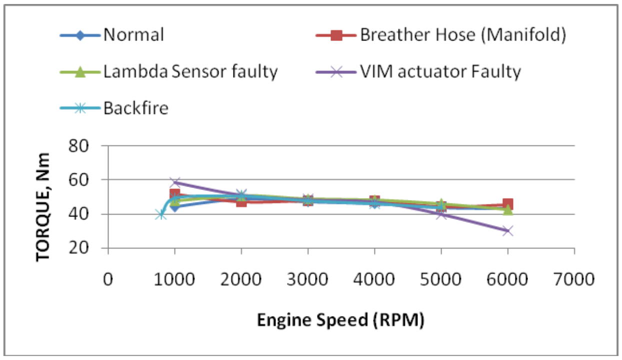

Figure 10: Comparison of torque curve at part load.

4 Conclusion

The objective of this paper has been carried out in order to see the vibration signature of 4 stroke cycle gasoline engine. The vibration based on frequency and engine speed was used to identify the signature for each fault applied. By considering the characteristics of various faults at part load based on engine speed, it's found that the entire fault signatures are indicative and different compared to the normal engine condition. The values of acceleration for each axis are different where the maximum values recorded are at 295 m/s^2. Referring the characteristics based on frequency, it is found that during part load test, the highest acceleration recorded is around 100 Hz to 200 Hz. For the entire fault applied to the engine, it is found that accelerations value for each frequencies also clearly different and indicative compare to the normal engine condition. In term of power and torque, it is found that there are a not much different between various faulty condition compare to normal engine condition. The objective gives ideas to observe the vibration signature obtained by varying the various engine conditions. By knowing the effects of various engine faults and compared it to normal engine condition, the vibrations can be monitored and engine health can be determined. The result of this test shows that a vibration level for each engine condition can be monitored and determined. However, there are some improvement can be made to make the result more accurate. The measurement point can be increase to two or three point. This will give more accurate data on where the malfunction or faulty components belong. The test can be set up at single speed for each fault applied so that the data can be clearly compared.

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