CONDITION MONITORING IN DIESEL ENGINES FOR COLD TEST APPLICATIONS. PART I: VIBRATION ANALYSIS FOR PASS/FAIL DECISION

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ABSTRACT
In this paper the characteristics of the cold test technology will be described and a monitoring method for quality tests of diesel engines at the end of assembly line will be considered. A variety of different techniques for processing vibration signals has been proposed by many researchers but only a few applications in cold test monitoring exist.
The determination of reliable threshold values for pass/fail decision through the calculation of global parameters which describe the PDF (Probability Density Function) of the vibration signal in the time domain is the goal of this work. Experiments on normal and faulty engines were carried out in order to develop this approach. In particular, eight different faults were artificially introduced and the influence of the operational speed during tests is investigated. Furthermore, a comparison between measurements concerning vibrations, pressure and torque is shown and discussed.

KEYWORDS
Condition monitoring, diesel engines, cold test, vibrations.

1. INTRODUCTION
Nowadays, the main part of engine manufacturers test their engines by means of a “hot test”, i.e. a test in which the engine is firing. On the other hand, recently, some companies have introduced a “cold test” instead of the hot test, but this method has to be further improved. The essential difference between these two methods is that the hot test aims to verify the engine performance, whilst the cold test aims to verify the anomalies by means of torque, pressure and vibration measurements. Although in the hot test the main
anomalies could be detected, in the cold test the fault detection is more simple and effective because the engine is driven by an electrical motor, so that no noise and vibration due to the firing are added. In the “hot test”, each engine must be connected to a test bench which includes a brake and provides the cooling (water, oil and possibly turbo compression air) and the connection with the other auxiliary services in working condition as fuel, gas and air. For this reason, the cost in time for a complete hot test procedure is more than ten minutes. At present, the hot test technology only indicates to the manufacturer which engines are not good for customers, but does not give any more information regarding the causes of the fault producing the malfunction. Moreover, hot tests also give auxiliary costs for oil and fuel consumption, need of trained personal in order to set up the test, auxiliary costs of bench’s maintenance, and as said above difficulty of detecting the causes of the faults. On the other hand, the cold test reduces oil and combustible consumption, emissions of CO – SO\textsubscript{2} – CO\textsubscript{2} and test time until about 3 minutes. In addition, the introduction of this technology decreases the noise produced during the test as well as the number of personal involved giving reduced costs of testing and fast detection of faults and of their causes. Mechanical faults in engines often show their presence through abnormal vibration signals compared with the normal ones. Techniques for machine condition monitoring based on the analysis of vibration signals are being used widely [1-4]. However, most of the studies have been carried out on simple mechanical parts, such as gears, rolling bearings [5-7] and cam mechanism for automatic packaging machines [8]. The analysis of vibration signals associated with internal combustion engines is complicated due to the complexity of the engine. About the monitoring of i.c. engines [9-16] and other rotating machines [17, 18], most of the works are related to new signal processing techniques. Among these new techniques, cyclostationarity and time-frequency analysis take into account the non-stationarity nature of the vibration signals acquired from the engine block. In addition, these techniques are often applied for tests on engines in firing conditions. All these methods, based on standard and advanced techniques, are effective for the manual analysis based on meaningful comparisons among vibration signatures or patterns obtained from these signatures. Accurate comparisons require extensive experience usually acquired at the cost of less production efficiency. Moreover, a degraded product quality may be obtained due to mistakes in judgments.

The use of vibration measurements for the purpose of condition monitoring in end-testing is most commonly practiced by gearbox manufacturers. Usually, as said before, the measurements are shown graphically and analysed manually by a technician. On the other hand, the engine industrial manufacturing testing requires an automatic analysis: vibration is measured and some features have to be set in order to classify a condition as pass/failure.

In this work some monitoring features characterizing the time domain vibration signal are evaluated after numerous experiments in order to find which is more sensitive for the detection of the common types of mechanical maladjustments in engine assembly. The present study examines several fault conditions which are not common in literature. The paper is organised as follows. Section 2 describes the experimental apparatus, the test conditions and the data acquisition system; the artificially introduced faults are then presented in Section 3. Finally, Section 4 shows the comparisons between several features and the results achieved.

2. EXPERIMENTAL APPARATUS

The experimental investigations are carried out on a 2.8 l engine produced by VM Motori, 4-cylinder 4-stroke with eight valves, turbocharged with an exhaust-driven turbo-compressor (Figure 1). The cold test bench prototype has been designed by Apicom (Cento, Italy) and it is equipped with a data acquisition system produced by Sciemetric and controlled by the QWX software: in this paper all the data were processed and analysed by means of this software. The cold test cycle under consideration is composed by three consecutive speed phases at 60, 1000 and 120 rpm. The results presented in this paper concern two specific speed phases: 120 and 1000 rpm. For quality control purposes all the compared vibration signals are picked up exactly at the same operating conditions. In the cold test the engine is driven by an electric motor via a coupling unit and it is maintained in a non-combustion state. During the test cycle, that is controlled automatically, measurements of torque,
vibration, and pressure are simultaneously acquired. The data acquisition system, shown in Figure 2 (b), collects and processes data through dedicated test algorithms and compares them to threshold value in order to take a pass/fail decision. Moreover, Figure 2 (a) shows the accelerometer locations for the two test investigations: for the second test investigation the accelerometer position is slightly changed. However, the accelerometer is mounted close to a bearing support of the crankshaft in both experimental investigations.

The exhaust pressure and torque signal acquisitions are based on an engine synchronous data recording, thus on externally triggered measurements. The information about the rotational position of the engine is generated using signals picked up by a crank sensor. The crank signal is decoded into a 360° periodical reference signal. The exhaust pressure and torque data are triggered, collected and referenced to the crankshaft position. The exhaust pressure, measured through a piezoresistive pressure sensor at 120 rpm, is triggered and carried out with an external clock at 360 pulse/rev. The torque signal, which is measured by a torsiometer mounted between the electric motor shaft and the engine shaft, is triggered and carried out with an external clock of 720 pulse/rev. The oil pressure data are collected on a time-based basis at the sampling speed of 100 Hz; the torque and the oil pressure data are recorded at both test speed phases. The vibration signal is measured by means of a piezoelectric general purpose accelerometer (MTN 1020; frequency range: 2-13 kHz) mounted on the engine block (turbocharger size) close to the bearing support of the crankshaft in two different positions as said above. In the whole cold test the vibration signal acquired at two different constant operation speeds of the engine (120 and 1000 rpm) is processed using the Sciemetric acquisition system. The sample frequency was 14 kHz in all the presented cases. The duration of the vibration signal acquisition is 2 s.
3. ENGINE FAULTY CONDITIONS

Experiments were performed over engines in sound and faulty conditions. In particular, eight engines in faulty conditions with assembly faults, artificially introduced one by one in the engines, are considered. A photograph of the mechanical devices involved in faulty conditions is presented in Figure 3. Here below the faults are listed and described:

- **Inverted piston** – Figure 3(a). The piston may be assembled inverted with a non correct positioning of the valve sites. This wrong assembly does not permit the correspondence between the valve plates and the valve sites. Since the exhaust valve site area is larger than the intake valve site one, the exhaust valves hit their non-correspondent intake valve sites.

- **Counter-rotating masses mounted with a phase lag** – Figure 3(b). The correct phase position of the counter rotating weights is necessary for the correct balance of the inertial forces due to the motion of the piston.

- **Exhaust equalizer out of housing** – Figure 3(c). The assembly of the cylinder head may cause the displacement of the equalizer out of the contact with the corresponding valve spring.

Figure 3 – Mechanical devices involved in faulty conditions: (a) piston, (b) counter rotating masses, (c) equalizer, (d) rod half-bushes, (e) oil pump, (f) rod, (g) oil jet, (h) overpressure oil valve.
• Rod without a half-bush (Fig. 3(d)) or tight with a pre-load of only 3 kgm and not with the correct, higher pre-load of 9 kgm – Fig. 3(f). These kinds of fault cause an irregular rotation of the rod and, consequently, an incorrect stroke of the piston, this affecting the engine operation.
• One of the oil pump screws is not properly tight – Figure 3(e). The oil internal gear pump is mounted on the accessory side of the engine near the vacuum pump.
• One of the four oil jets is not properly tight – Figure 3(g). The oil jet, i.e. the piston oilier, is mounted on the block under his corresponding piston.
• Overpressure valve mounted inverted – Figure 3(h). The incorrect assembling of the overpressure valve does not permit to properly limit the maximum oil pressure value in the oil circuit within the engine block.

4. RESULTS AND DISCUSSION

Most of the common techniques concerning mechanical systems work in time and frequency domains. In any case, quality control applications need low computational costs. In this work this requirement is considered and the goal is to obtain suitable features with upper threshold values, as shown in Figure 4.

As said in Section 2, two experimental investigations are carried out in order to evaluate the accelerometer position: in the first one 20 tests were performed on several normal engines and 6 faulty engines. Concerning the second one, 3 tests are carried out over one normal engines and two faulty ones after the accelerometer location changing. It is worth noting that only one test is available for all the tested faulty conditions. The features obtained in the first investigation from torque, exhaust pressure and oil pressure signals are good options for quality control purposes in three of the eight faulty cases under consideration, namely engines with counter rotating masses not in phase, the exhaust equalizer out of housing and with overpressure oil valve mounted not in the right sense. Figures 5, 6, 7 show the signals in the case of engine in normal and faulty conditions.

![Upper Threshold](image)

**Figure 4 – Example of an upper threshold of the feature values for different engines.**

Regarding the counter rotating masses, the effect of the lag is very clearly observable from the torque trend (Figure 5 (b)). In cold test applications, in which the engine is not in firing, the only torque born during the motion is due to the inertial forces. In this study case the masses are unable to balancing the inertia forces; in addition, because of the 180 degrees phase lag, the inertia torque increases.

Analogous results were obtained for the valve mounted in the wrong sense (Figure 6): the peak value of the oil pressure in faulty condition is greater than in normal condition. The valve does not permit to overcome a defined pressure limit and when it is correctly mounted high pressure values are achieved.
Figure 5 – Torque curves (1000 rpm). (a) Normal engine; (b) engine with counter rotating masses with a phase lag of 180 degrees.

Figure 6 – Oil pressure curves (1000 rpm). (a) Normal engine; (b) engine with overpressure oil valve mounted not in the right sense.

Figure 7 – Exhaust Pressure curves of the third cylinder (120 rpm). (a) Normal engine; (b) engine with one exhaust equalizer out of housing.
The effect of the wrong position of the exhaust equalizer is very slight in the exhaust pressure signal (Figure 7): there are not clear differences between the two pressure signatures in normal and faulty conditions. On the other hand, the angle location of the first angular derivative minimum of the pressure signal is rather different between normal and faulty conditions (Figure 8). The first angular derivative of the pressure represents the pressure variation within the exhaust manifold. In the case of the engine with exhaust equalizer out of housing, one of the two exhaust valves remains closed and the section for the exit of combustion exhaust gas is consequently reduced. This section reduction causes slower pressure variation in the faulty engine manifold. These facts are confirmed by observing the results about the trend of the first derivative and precisely, the angle location of its minimum. Table 1 shows the reliable features from pressure and torque signals which are extracted from only three of the eight faults introduced.

<table>
<thead>
<tr>
<th>Fault</th>
<th>Signal</th>
<th>Features</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Counter-rotating masses</td>
<td>Inertial Torque</td>
<td>Peak to peak value</td>
<td>40.8</td>
</tr>
<tr>
<td>with a phase lag</td>
<td></td>
<td>Peak value</td>
<td>3.6</td>
</tr>
<tr>
<td>Overpressure valve</td>
<td>Oil Pressure</td>
<td>Angle location of the minimum of the 1st angular derivative</td>
<td>643°</td>
</tr>
<tr>
<td>Exhaust equalizer out of housing</td>
<td>Exhaust Pressure</td>
<td></td>
<td>652°</td>
</tr>
</tbody>
</table>

Table 1 – Feature extraction from torque and pressure signals.

Since it was desirable to extract reliable features for all the studied cases, the engine block acceleration is analysed. Figure 9 compares the engine block acceleration measured in the first experimental investigation for one normal and three faulty conditions: inverted piston, one oil jet improperly tight and equalizer out of housing. A number of statistical parameters are evaluated from the PDF (Probability Density Function) in order to characterise the signal amplitude. An energy parameter (RMS value) and two dispersion parameters (skewness and kurtosis coefficient values) of the acceleration signal are calculated for normal and faulty engines.
Table 2 shows the results regarding the first test investigation: for each parameter, the values concerning the faulty engines are compared to a reference value for the normal engines, obtained computing the mean value and the standard deviation (Sigma) over a set of 20 acceleration time histories relative to normal engines; the reference value for establishing an upper threshold is considered the mean value incremented of three times the standard deviation (Mean + 3 Sigma). The RMS value and the kurtosis coefficient can be considered as a monitoring features for all six faults introduced and used to obtain a reliable upper threshold. One can notice that the influence of the operational speed during tests has to be considered.

<table>
<thead>
<tr>
<th>Engine</th>
<th>Kurtosis coefficient</th>
<th>Skewness coefficient</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean + 3 Sigma for normal engines</td>
<td>21.19</td>
<td>9.02</td>
<td>0.75</td>
</tr>
<tr>
<td>Inverted piston</td>
<td>46.38</td>
<td>71.90</td>
<td>-0.09</td>
</tr>
<tr>
<td>Overpressure valve</td>
<td>4.98</td>
<td>9.98</td>
<td>-0.04</td>
</tr>
<tr>
<td>Exhaust equalizer out of housing</td>
<td>5.01</td>
<td>32.20</td>
<td>0.12</td>
</tr>
<tr>
<td>Oil pump screw improperly tight</td>
<td>4.27</td>
<td>19.06</td>
<td>0.02</td>
</tr>
<tr>
<td>One connecting rod tight with 3 kgm</td>
<td>5.81</td>
<td>12.22</td>
<td>-0.03</td>
</tr>
<tr>
<td>Oil jet improperly tight</td>
<td>4.71</td>
<td>25.77</td>
<td>-0.02</td>
</tr>
</tbody>
</table>

Table 2 – First experimental investigation: parameters characterising the vibration signal.
As a matter of fact it is possible to achieve an upper threshold value, distinguishing the faulty conditions from the normal one, through calculation of the RMS value at 120 rpm and the kurtosis coefficient at 1000 rpm. The skewness coefficient values are not able to obtain a reliable upper threshold and to clearly recognize the faults at both operational speeds (only the piston inverted condition shows the skewness coefficients higher than the normal one at 1000 rpm). Thus kurtosis coefficient and RMS values permit to establish an upper threshold for the decision procedure. As stated above, to evaluate the influence of the accelerometer location a second investigation is carried out: during the iterative cold test procedure an operator may slightly change the position of the transducer.

By observing the results relating to the second test investigation which was based on the comparison between two faulty conditions and only one normal engine (Table 3), the influence of the different location of accelerometer is clearly evident from the kurtosis coefficient and RMS values at 120 rpm. On the contrary, the skewness coefficient seems to be insensitive to the location of the accelerometer. However, the kurtosis coefficient and RMS values can be assumed as threshold parameters to establish the faulty condition at 120 rpm (counter rotating masses) and at 1000 rpm (rod without bush): these parameters are not able to discriminate a faulty condition for an unique operational speed as well as in the previous test investigation in which a parameter (e.g kurtosis coefficient) may be used as a threshold parameter for the six faults at the same velocity (1000 rpm). Concerning the capability of the skewness coefficients the results are the same obtained for the first experimental acquisition: a little difference is shown by the comparison between the skewness coefficient of the normal engine and the faulty one with counter rotating masses with a phase lag.

5. CONCLUSIONS

This work concerns a new approach for the evaluation of the engine condition at the end of assembly line based on the analysis of vibration signals during cold test. The traditional features obtained from torque, exhaust pressure and oil pressure signals are good options for quality control purposes but for cold test applications seem to be unable to recognize some kinds of assembly malfunctions; according to the presented results, these features are able to detect only three of the eight introduced faults.

On the other hand, the test results show that the kurtosis coefficient and the RMS value of the vibration signal in the time domain can be considered as monitoring features and they are sensitive for the detection of all the introduced faults. Therefore, the decision procedure can be applied using a proper upper threshold of this parameters.

Two experimental investigations are led in order to evaluate the effects of the location of accelerometer: the kurtosis coefficient and the RMS value are dependent on the location for the tests carried out at 120 rpm. Moreover the influence of the operational speed is evaluated to give information about the possibility of each parameter to recognize all the faults introduced at the same operational speed.

In conclusion, a great number of experiments were carried out on faulty and normal engines, in order to assess the correct threshold value. Good results are obtained in the detection of faults based on vibration measurements.

The future direction is to improve this method for a higher number of experiments and to evaluate several techniques for the diagnostic of the faults analysed in the present work.
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