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Automotive Diesel Engine Performance and Condition Monitoring using Downpipe Acoustic Waveform Analysis

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ABSTRACT

It would seem logical that acoustic signals measured from within a diesel engine's exhaust pipe would contain useful information for engine monitoring. Preliminary experimental results, however, are found to be influenced significantly by changes in sensor positions and silencer configurations due to acoustic reflections inside the exhaust pipe. In order to suppress the contamination of reflection, this paper develops an effective acoustic method using two sensors mounted along the exhaust pipe. In addition to simulation modelling and theoretical study, experimental investigations are conducted to verify the reliability of this method. The experimental results show that using peak and shape indices of the incident waveforms, derived from measurements of the two sensors, accurate and reliable detection and diagnosis results are obtained for a range of realistic incipient faults under different operating conditions.

Key words: Exhaust Acoustics, Reflection Suppression, Diesel Engine; Combustion Diagnosis, Condition Monitoring

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1 INTRODUCTION

To maintain internal combustion engines running at optimized conditions, many condition monitoring techniques have been investigated for early fault detection and diagnosis [1]. The exhaust stream is directly related to the combustion process and contains rich information about combustion conditions [2]. For these reasons, several recent publications have concentrated on exhaust measurements for combustion monitoring [3, 4 and 5].

Exhaust gas temperature techniques measure the temperature pulsation associated with the exhaust gas pulses in each cylinder port using fast response thermocouples and correlation with burned fuel mass. Using this method, thermo-dynamic properties can be determined and dispersion between the injectors can be obtained [2].

Turbocharger speed has been used in conjunction with exhaust gas pulsation in the exhaust manifold for the diagnosis of abnormal fuel injector operation and the control of fuel supply [6 and 7]. The results demonstrate a good fault detection capability using this method. In addition, this approach benefits from the fact that the measurement of the speed signal is very simple.

Exhaust pressure fluctuation based methods have also been investigated for engine monitoring in several publications [3, 8 and 9]. Authors have used pressure fluctuation measured at a single position for the fault detection of engine misfires and manifold leakage in spark ignition engines. However, Markus [3] also mentions in his paper that the pressure pulsations and the resulting spectral amplitudes are strongly influenced by the standing pressure waves caused by reflections. He concludes that the measurement position must be carefully chosen by taking into account reflection, propagation and attenuation. Although this work performed experiments for a misfire fault only, it showed the potential of exhaust pressure fluctuation for fault detection. This method has also been studied in [5] for valve fault detection in diesel engines. It has been found that the capability of this method is effective but it too suffers adversely from wave reflections in the exhaust systems.

In addition to the use of exhaust information, airborne acoustic measurements have also been investigated in recent years for monitoring engine condition. Authors in [10, 11 and 12] have used advanced signal processing methods to reduce the background noise from airborne acoustic measurements, whilst targeting faults within the fuel injection and valve systems. The monitoring results are impressive but the authors acknowledge that performance will likely be degraded when the signal to noise ratio is low because of strong reverberations inside engine rooms of power stations and ships.

To improve the usability and performance of an exhaust acoustic measurement approach to the condition and performance monitoring of diesel engines, this paper investigates a reflection suppression method based on the understanding of the theoretical characteristics of acoustic waveforms from the engine exhaust system. It models the engine and its exhaust system as a linear time-variant source and simulates the acoustic wave behaviour under a wide range of realistic operating conditions and reflection circumstances. From these understandings, a two-sensor method is investigated to suppress reflected waves. An experimental investigation is then conducted on a four cylinder diesel engine for the detection and diagnosis of common combustion faults from valve and fuel injection systems to evaluate the usability of the developed method.

2 ACOUSTIC CHARACTERISTICS OF EXHAUST SYSTEMS

Pressure fluctuations in the exhaust system should contain rich information about engine combustion and exhaust processes. Conceptually, from the characteristics of the source it should be possible to monitor the condition of the engine. The problem is how to retain and thereafter extract the useful information in the signal whilst suppressing the contaminating components at the same time. A source modelling and simulation study were hence conducted first to gain an understanding of how the pressure waveform could be used as a detection signal. This understanding is then used to develop measurement and signal processing methods for monitoring information extraction.

2.1 CHARACTERISTICS OF THE PRESSURE WAVEFORM

Many advanced acoustic models have been developed for engine exhaust systems to predict noise radiation and hence to design more effective exhaust components [13, 14, 15, 16 and 17]. An equivalent acoustic one-port source is often the basis for the description of the exhaust source in terms of impedance and strength in the frequency domain. This one-port source method allows the acoustic generation of the engine valve system and the wave propagation inside exhaust ducts to be combined together and it produces good results validated by experimental investigations.

However, such models have only been developed for the examination of the acoustics when the engine is operating under healthy conditions. Little information about the waveforms under abnormal conditions can be obtained with these models. For condition monitoring based upon exhaust pressure measurement, it is important to understand the waveforms for a variety of conditions both when processing the measured signals and when developing fault detection and diagnosis features. An acoustic model has to be developed so that the variations of the pressure waveforms can be investigated over different operating conditions including those of abnormal combustions. Rather than combining the acoustic generation with the wave propagation, this study deals with this two issues separately to highlight the details of the acoustics generation process (including various valve motions and combustion variations). Furthermore, the analysis of pressure is focused on the time domain because it provides more interpretable information for the diagnosis of abnormal combusting cylinders compared to frequency domain analysis.

Based on the studies in [16 and 17], the acoustic process of the engine exhaust can be modelled as a time-variant source. For a typical four-cylinder diesel engine exhaust system, illustrated in Figure 1, the volumetric velocity of the flow of a particular cylinder $V_i(t)$ through a discharge valve during the period of a discharge stroke can be expressed [16]

$$\rho_i(t)c_i(t)V_i(t) = C_i A_i(t)[P_{ci}(t) - P_e(t)] \quad (1)$$

where subscript i is the cylinder number; P_c is the pressure in cylinder number i; P_e is the pressure inside the exhaust pipe; C is the discharge coefficient of the valve; A is the effective flow area of the valve; and ρ_i and c_i are the density and speed of sound of the gas flow through the valve respectively.

Since the exhaust flow is restricted by downstream components such as the changes in pipe shape and joint and the resistance effects of the silencers and catalytic converters, the manifold and its down pipe can be treated as a flow-in/flow-out chamber of volume V_e [18]. Without considering the effects of acoustic wave propagation (mainly the effect of reflections from downstream), the exhaust pressure P_e in the chamber can be derived from the first law of thermodynamics as

$$P_e = \frac{1}{V_e}\int \left[\sum_i^n \rho_i(t)c_i^2(t)V_i(t) - \rho_e(t)c_e^2(t)V_e(t)\right]dt \qquad (2)$$

As the discharge coefficient and the effective flow area are controlled by the nonlinear process of the valve lift, the volumetric velocity and the exhaust pressure will vary accordingly and hence it is difficult to produce an analytic solution for the analysis of the exhaust pressure over a wide range operating conditions. A numerical study therefore, has been adapted for the analysis.

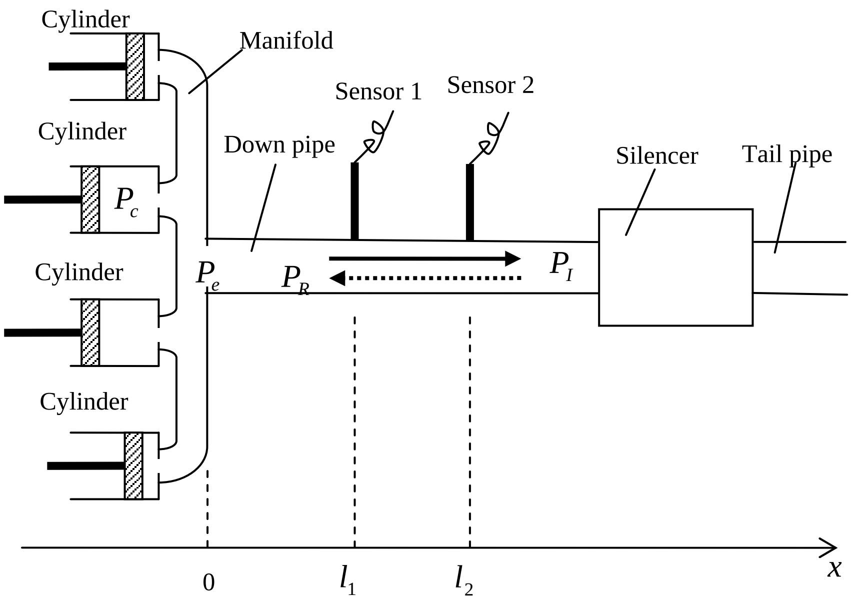

Figure 1 Schematic of a typical exhaust system for a four cylinder diesel engine

Using equations (1) and (2) together with piston motion dynamics, combustion thermodynamics and valve motion behaviour[18] the exhaust pressure can be calculated numerically at different conditions including when experiencing different forms of faulty combustion. To simulate the combustion process this study introduces a cylinder pressure rise process, with a controlled amplitude and duration, around the top dead centre (TDC) position of the crankshaft. Based on previous study[5], the pressure rise is adjusted to correspond to different engine loads, with a half-sinusoidal profile being used to represent the valve opening and closing processes. These simplicities will inevitably detract the accuracy of the predicted waveforms, however, they will nevertheless incorporate the critical features of the engine combustion and exhaust process, allowing the fundamental features of exhaust pressure to be studied with low computational overhead.

Figure 2 shows the exhaust pressure characteristics from a four cylinder diesel engine, detailed in section 4, with a firing order: 1-2-4-3. The predicted exhaust pressures were obtained under two engine speeds: 1500rpm for low speed and 3000rpm for high speed, and three different engine loads, represented by cylinder pressure rises of 5bar, 10bar and 20bar. To emphasise the oscillatory feature of the pressure waveform, the mean value is firstly removed and then each waveform is normalised by the largest peak value from the case when the combustion pressure rise is 5bar at high speed; illustrated by the solid line in Figure 2(b). In addition, the exhaust pressure waveforms are presented for a complete engine cycle, which starts at TDC of the combustion occurring in the first cylinder, corresponding to a crankshaft angle of 0°.

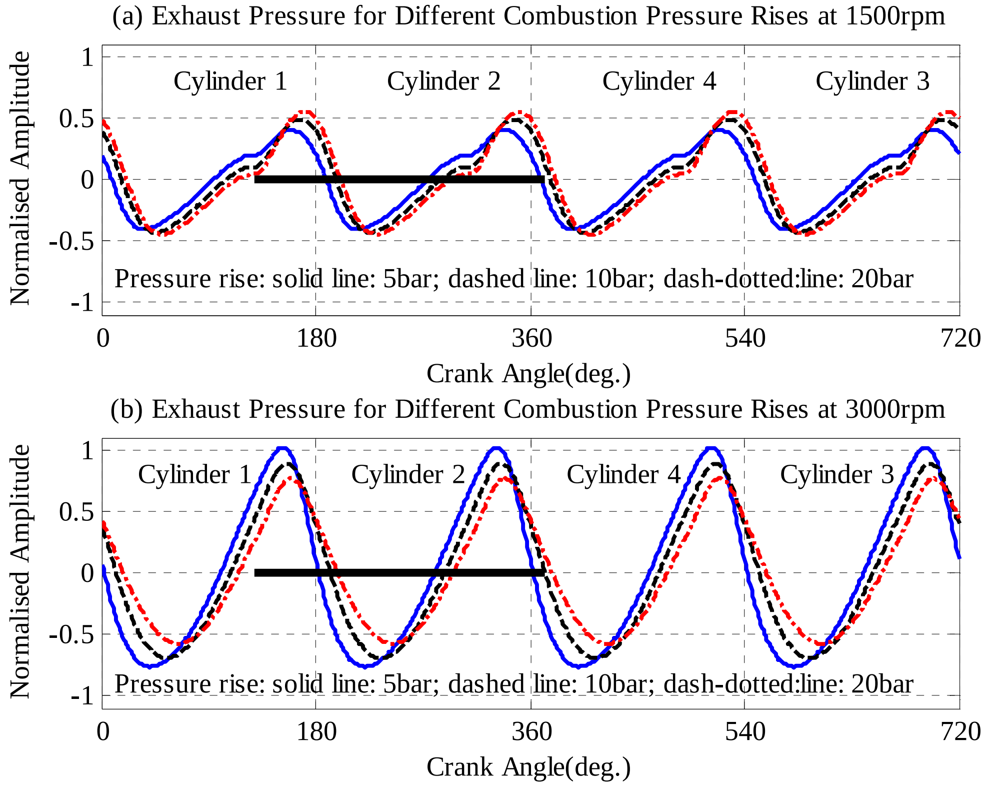

Figure 2 Simulated exhaust pressures for healthy engine condition

It can be seen from Figure 2(a) that the exhaust pressure waveform has four distinctive peaks in a complete engine cycle, each of them indicating the exhaust stroke for a particular cylinder of the four cylinder engine. Each peak appears just after the onset of each exhaust process, illustrated for the first cylinder by a bold line in Figure 2. These peak features are each formed by the superposition of the exhaust pressures from two characteristic exhaust effects. The first is the exhaust flow driven by the cylinder residual pressure at the moment of exhaust valve opening and the second is the exhaust flow forced by the upward piston motion. Because the exhaust valve opens in advance of BDC and closes beyond TDC the exhaust pressure from the first characteristic effect adds to the pressure from the second effect. The first exhaust effect, resulting from residual expansion upon the exhaust valve first opening, causes a burst of pressure in the exhaust pipe and a peak in the waveform within around 40° (referring to the bold line) of crank rotation. This is followed by a steady decrease in pressure as the residual pressure pulse dissipates, before the second exhaust effect associated with the upwards movement of the piston starts to take effect. As a result the pressure waveform rises to a second peak at around 30° before the exhaust valve closes.

. At low engine speeds, the exhaust flow driven by the residual pressure is more pronounced. It leads to a clear sharp pressure rise before the peak pressure. In addition, the peak value also becomes higher and shifts later as the cylinder pressure rise increases. This is understandable because at higher engine load the residual pressure is higher and hence it results in a higher exhaust peak. In contrast, at high engine speed, the exhaust flow forced by the piston motion upwards is more pronounced and hence the sharp pressure rise cannot be seen. Interestingly, the peak value becomes lower with increase in engine load, resulting from the phase delay of the pressure waveform from the first exhaust effect.

Moreover, the exhaust pressure waveforms are uniform over the four cylinders at different peak pressure rises and speeds. It is upon these features that combustion condition monitoring can be based for a multiple cylinder engine, without the extra requirement for baseline signatures, which is often difficult for engine user to be obtained.

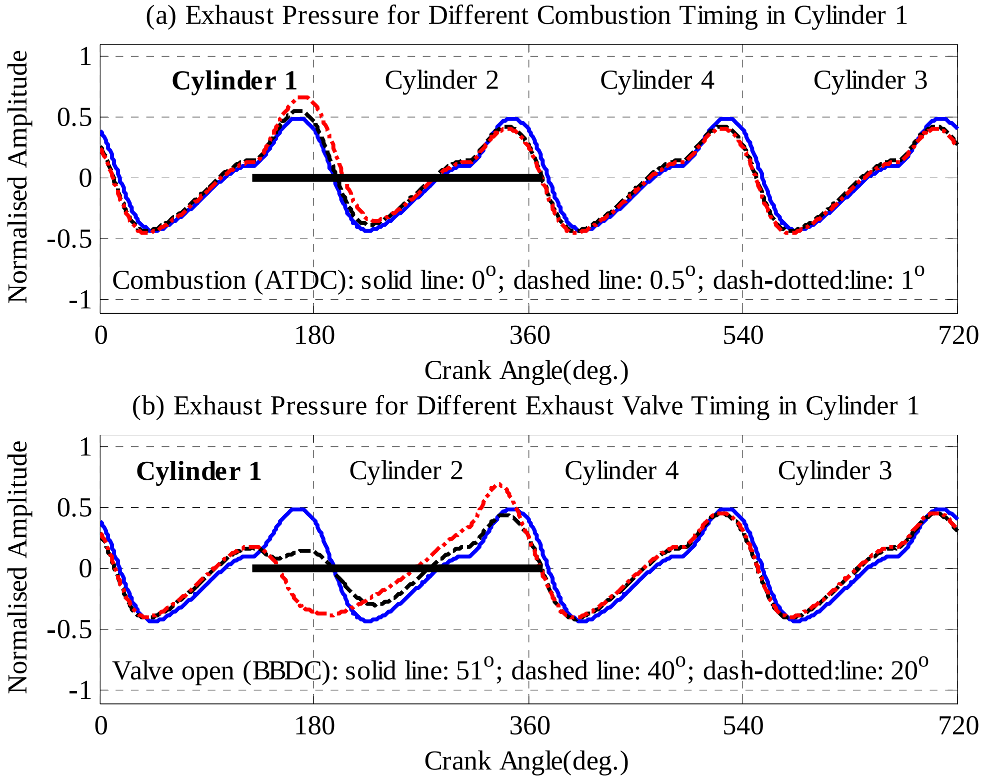

Figure 3 Simulated exhaust pressures for faulty engine conditions at 1500 rpm and 10bar pressure rise

Figure 3 shows the simulation results when cylinder 1 has different fault conditions including retarded combustion and erroneous exhaust valve timing. It is clear that there are distinctive differences between the normally combusting cylinders and the faulty one. One of the features, shown in Figure 3(a), is that the peak value corresponding to the faulty cylinder is higher than others and becomes larger as the severity of the fault increases. Another feature is that the overall waveform profile also changes significantly, shown in Figure 3(b). In addition, the valve faults cause more distortion to the waveforms than the faults of retarded combustion. From these observations it would be seen that the differences in peak values and waveform profiles between cylinders can be used for engine fault detection and diagnosis. Potentially a useful scheme based on waveform uniformity evaluation can be developed for fault detection without the baseline signature, a situation which is a rare luxury in the field of condition monitoring.

2.2 REFLECTION CONTAMINATION

For the majority of instances, pressure measurements are influenced by acoustic reflections inside the exhaust pipe. This will make the raw signal, which is obtained from the sensor and used as the detection evidence traditionally, vary with position. This difference makes it difficult to choose the position of measurement using a single sensor method [3]. The influence would be obvious when the reflection coefficient at the end of the exhaust pipe is large and thus the measurement result is not reliable.

Figure 4 shows the simulation results of the pressure measurements in three different positions when a reflection coefficient value of 0.5 is used to simulate the reflection for the third of the successive waveforms in Figure 3(b) i.e. for the case of 20° of shift in valve timing. The waveforms in Figure 4 show the three typical waveforms obtained at different measurement positions. Waveform (a) displays a clear difference between the first wave and the other three, allowing the faulty valve to be identified. However, the measured waveforms at two other positions, shown in (b) and (c) of Figure 4 respectively, have very different characteristics from the original wave. The Waveform (b) is comprised of only three distinctive major waves with very different amplitudes. The Waveform (c) exhibits two large peaks of similar amplitudes, together with two small waves of different amplitudes. Obviously, it is not possible to use waveforms (b) and (c) to identify the abnormal combustion cylinder.

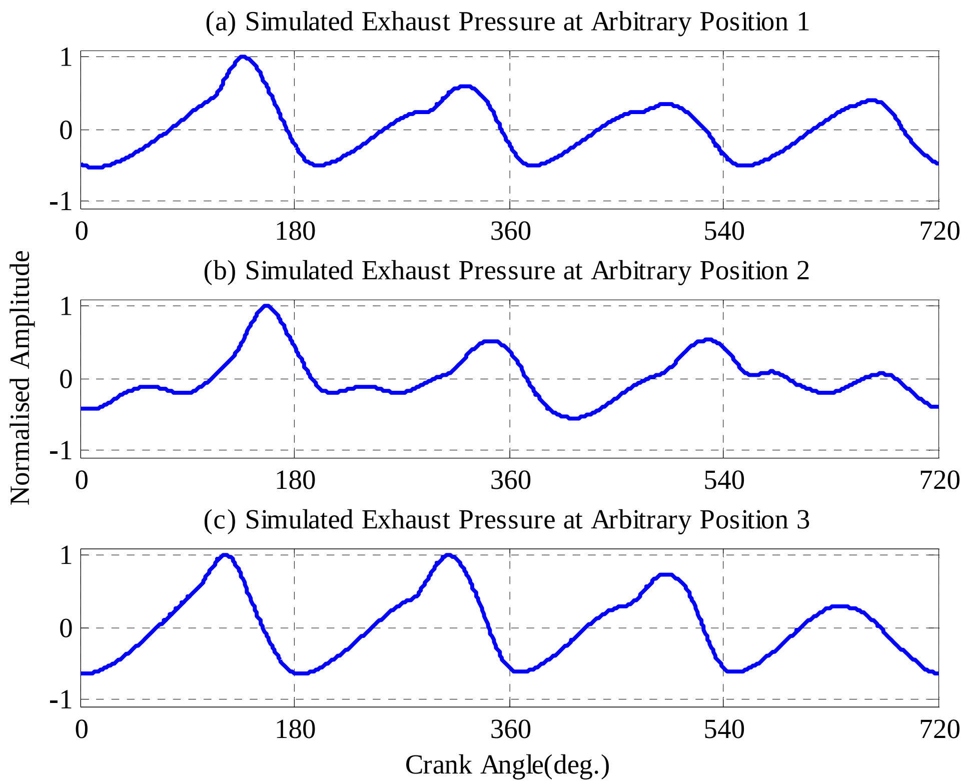

Figure 4 Influences of reflection on measurements

This simulation analysis demonstrates that the use of one sensor measurement for fault detection is neither reliable nor accurate due to the reflections. Therefore, effective methods for reflection reduction have to be investigated to use the exhaust acoustic information for engine diagnosis.

3 REFLECTION SUPPRESSION

The two-microphone scheme has been used widely for the measurement of the one-dimensional acoustics properties in a duct. In particular, it has been studied to determine the characteristics of acoustic sources experimentally when it was relied on to predict the noise radiation from the exhaust system of an I.C. engine [19, 20 and 21]. As this scheme has the potential for easy on-line implementations, it is re-examined in time domain to gain more understandings of the acoustic field inside a duct and hence to develop an effective noise suppression method.

3.1 In-Duct Acoustic Field

To analyse the acoustic field in the exhaust pipeline more accurately, an in-duct wave propagation model is used as shown in Figure 5. Defining P_R as the reflection wave, P_I as the incident wave consisting of P_S, the source wave, and P_{R2}, the reflection of P_R at the source end, P_I can be expressed as:

$$P_I = P_S + P_{R2} \tag{3}$$

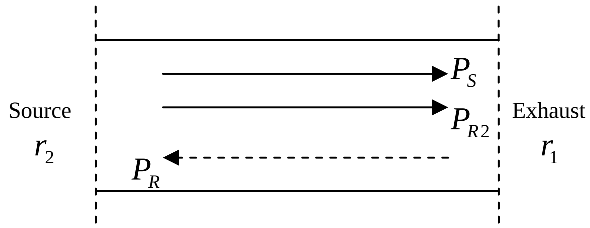

Figure 5 Waves propagating in the exhaust pipe

Defining the reflection coefficients at the exhaust end and the source end as r_1 and r_2 respectively, the following can be derived

$$P_R = r_1 P_I = r_1 (P_S + P_{R2}) \tag{4}$$

$$P_{R2} = r_2 P_R \tag{5}$$

Take into account (4) and (5), the source pressure is

$$P_S = (\frac{1}{r_1} - r_2) P_R = (1 - r_1 r_2) P_I \tag{6}$$

In equation (6), r_1 is easily obtained by an off-line test or empirical calculations, however, r_2 is much more difficult to determine by calculation because of nonlinearity of flow at exhaust port. There are two unknowns in equation (6), P_S and r_2. In order to determine them, two equations may be formed based on experimental data obtained with a special test procedure. This test can be achieved by changing the acoustic loads at the exhaust end. Assuming that the two loads conditions are A and B respectively, P_S and r_2 can be calculated by using equation (7).

$$\begin{cases} P_S = (1 - r_{1A} r_2) P_{IA} \\ P_S = (1 - r_{1B} r_2) P_{IB} \end{cases} \tag{7}$$

This method using two acoustic loads is referred as the multi-load method. The authors have investigated the use of this method for abnormal combustion detection and have achieved satisfactory results [4]. However, this method needs two acoustic loads which is inconvenient to set up for on-line monitoring because extra devices have to be installed in the exhaust system.

However, if the reflection coefficients satisfy a condition $r_1 r_2 << 1$, then source wave P_S may be approximated by the incident wave P_I only. In practice, r_1 is usually very small. The condition $r_1 r_2 << 1$ can be satisfied even if the value of r_2 is high. This is the common case for most practical engine exhaust systems. Therefore, the incident waveform P_I may be used to represent the source wave P_S.

3.2 Two-sensor Measurement

To find P_I from measurements of two sensors for the reflection suppression, a more simplified analysis is performed without considering the reflections at source end. As shown in Figure 1, P_I propagates from the engine to the silencer while P_R moves in the opposite direction. Ignoring influences of flow and its turbulence, taking $x = 0$ as the reference position, acoustic pressures at position 0, 1 and 2 can be expressed respectively as follows:

$$P_0(t) = P_I(t) + P_R(t) \tag{8}$$

$$P_1(t) = P_I(t - \frac{l_1}{c}) + P_R(t + \frac{l_1}{c}) \tag{9}$$

$$P_2(t) = P_I(t - \frac{l_2}{c}) + P_R(t + \frac{l_2}{c}) \tag{10}$$

In order to use the pressure waveform for condition monitoring, the influence of the reflection must be suppressed. Based on the previous discussion a two-sensor method is developed to achieve an on-line measurement.

If a two-sensor approach is used, the incident wave and reflected wave can be separated to a certain degree by a straightforward methodology. Based on equations (9) and (10), two equations sets can be obtained as:

$$\begin{cases} P_1(t + \frac{l_2}{c}) = P_I(t + \frac{l_2}{c} - \frac{l_1}{c}) + P_R(t + \frac{l_2}{c} + \frac{l_1}{c}) \\ P_2(t + \frac{l_1}{c}) = P_I(t - \frac{l_2}{c} + \frac{l_1}{c}) + P_R(t + \frac{l_2}{c} + \frac{l_1}{c}) \end{cases} \tag{11}$$

$$\begin{cases} P_1(t - \frac{l_2}{c}) = P_I(t - \frac{l_2}{c} - \frac{l_1}{c}) + P_R(t - \frac{l_2}{c} + \frac{l_1}{c}) \\ P_2(t - \frac{l_1}{c}) = P_I(t - \frac{l_2}{c} - \frac{l_1}{c}) + P_R(t + \frac{l_2}{c} - \frac{l_1}{c}) \end{cases} \tag{12}$$

By solving the equations sets (11) and (12), the two waves, P_I and P_R can be expressed by the measurements from the two sensors as

$$P_I = \int [\frac{P_1(t + \frac{l_2}{c}) - P_2(t + \frac{l_1}{c})}{\frac{2\Delta l}{c}}] dt \tag{13}$$

$$P_R = \int [\frac{-P_1(t - \frac{l_2}{c}) + P_2(t - \frac{l_1}{c})}{\frac{2\Delta l}{c}}] dt \tag{14}$$

where $\Delta l = l_2 - l_1$ is the distance between two sensors. Equation (13) means that the measurement from sensor 1 needs to shift backward by a time period $(l_2 - l_1)/c$ so that the reflected waves measured by sensor 1 are aligned with that of sensor 2 and hence they can be cancelled out by the subtraction, resulting in only the incident waves from the engine source. Similarly, if the measurement from sensor 1 shifts forward by a time period $(l_2 - l_1)/c$, the subtraction in equation (14) will yield the reflected wave only. This approach then produces two cleaner waveforms for fault detection.

The effective frequency range in reducing the reflection can be derived by standing wave analysis as follows

$$f \le \frac{c}{2\Delta l} \tag{15}$$

For the experimental study, a 0.32m distance was set between the two sensors, and this allowed waveforms with a frequency range up to 800Hz to be used in the analysis. This range covers up to the 10th order harmonics of the engine firing frequency and is sufficient to resolve the small changes in the waveform.

4 FAULT DETECTION AND DIAGNOSIS

4.1 EXPERIMENTAL SET-UP

To evaluate the theoretical analyses and benchmark the fault detection performance, experimentation was performed on a Ford FSD 425 four cylinder 2.5 litre direct injection diesel engine. A special exhaust system was fitted to the engine for the evaluation of the influence of reflections. As shown in Figure 6, the exhaust can flow out through two different exhaust systems via a 'Y' junction fitted with two throttle valves. This configuration allows the application of at least three different degrees of acoustic reflections achieved by adjusting the valves into three combinations of position: 1) both valves open; 2) valve A is open with valve B closed; and 3) valve B is open with valve A closed.

Two water-cooled pressure transducers and temperature sensors were mounted at different positions along the straight portion of the exhaust pipe as shown in Figure 6. The measured waves from these positions will have a minimising influence due to the difference in pipe shapes and random noise due to turbulences. As mentioned earlier, the distance between the two pressures sensors was 32cm to ensure that the calculation would be accurate in a frequency range of 20 to 800Hz.

Two types of fault, in several severities each, were introduced to the first cylinder of the engine. One was a changing of the fuel injector cracking pressure from 250bar to 150bar, 190bar and 280 bar, and the other was the changing of the exhaust valve open time from 51º BTDC (before top dead centre) to 40º and 20º. Both of these are common faults occurring in diesel engines and cause power losses and high pollutant emissions. Three different engine loads: 20Nm, 40Nm and 60Nm at three different engine speeds: 1500rpm, 1800rpm and 2100rpm were tested to check the fault detection and diagnosis capabilities.

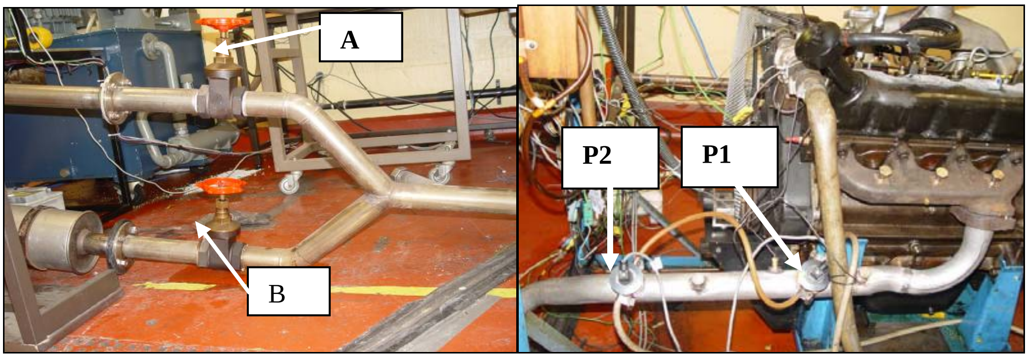

Figure 6: Photographs of the test facility showing valve and pressure transducer locations on the engine exhaust pipe.

4.2 RESULTS AND DISCUSSION

Figure 7(a) shows typical measured waveforms from the two sensors when the injection pressure in cylinder 1 is set at 280bar. The portion of the waveform due to the upward piston motion shows much higher amplitudes than that due to the residual pressure, and this is visibly inconsistent with the simulation waveforms shown in Figure 3(a). Moreover, the faulty cylinder, shown in the crankshaft angles between 0º and 180º, is difficult to isolate from both of the two waveforms.

However, the incident waveform obtained by equation (5), illustrated in Figure 7(b) using a solid line, exhibits a more consistent profile with that in Figure 3. Compared with the measured waveforms, the waveform portion due to the upward piston motion is reduced considerably. This then enhances the portion due to the residual pressure, providing a better rapid pressure rise. As shown in Figure 7, the peak value becomes the highest amplitude and the waveform shape also shows a clear difference from the other three. From these two features, the abnormality in cylinder 1 can be separated from the other cylinders. This demonstrates that the proposed method is effective in suppressing reflections and improving greatly the quality of the waveforms. Hence, in doing so, it will enhances the performance of fault detection and diagnosis significantly.

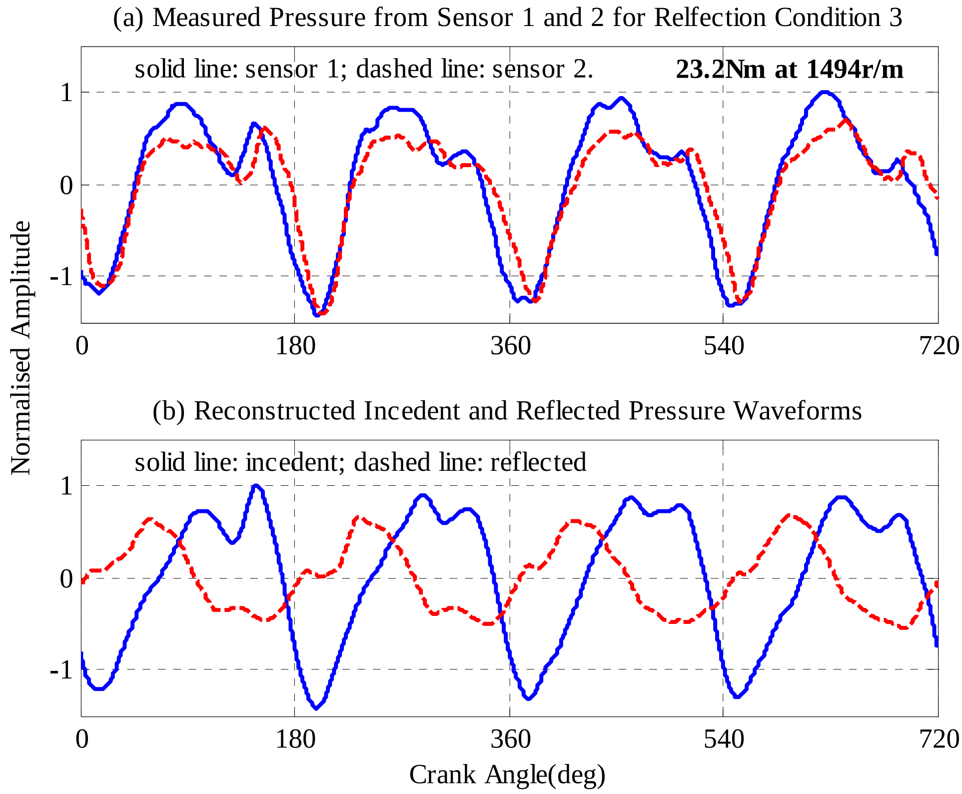

Figure 7 Measured and reconstructed signals from 280bar injection pressure

To produce more accurate detection results and subsequently to evaluate the performance of the detection method over different engine operating conditions, two key features can be derived based on the evaluation of the uniformity over the cylinders. If $\mathbf{x_n} = \{x_n(1), x_n(2), \ldots x_n(k)\}$ denotes the waveform portion for cylinder n, which corresponds to a crankshaft angle from $(TDC_n - 51°)$ to $(TDC_n + 129°)$, and is normalised to dimensionless unit Euclidean length, the peak value of this portion waveform is denoted as

$$\alpha_n^{(p)} = \max(\mathbf{x_n}) \qquad (16)$$

A peak index is thus

$$I_n^{(p)} = abs\left(\frac{\alpha_n^{(p)}}{\alpha^{(p\max)}} - 1\right) \qquad n = 1, 2, 3, 4 \qquad (17)$$

where $\alpha^{p\max}$ is the maximum of the 4 peak values; and a shape index is calculated based on the Euclidean distance:

$$I_n^{(d)} = \sqrt{\sum_{i=1}^{k} [x^{(p\max)}(i) - x_n(i)]^2} \qquad n = 1, 2, 3, 4 \qquad (18)$$

where $\mathbf{x^{pmax}}$ is the waveform portion corresponding to the maximum peak value and *k* is the sample number covering the waveform portion of cylinder *n*.

As discussed above and in section 2, the peak value index measures the difference between the peak values corresponding to each cylinder. It will be close to 0 if the peak values close to each other. Otherwise it will be close to its maximum 1 if the difference between the peak values is very large. The shape index value is large when two portions of waveform is different and its maximum will be 2 when two portions of waveform are opposite in phase. Combining these two indices together can provide a quantitative measure on a two dimensional plane, which allows different types of faults under different operating conditions and different measurement configurations to be represented. Based on this presentation, accurate comparisons can be made to examine performance differences for different engine conditions.

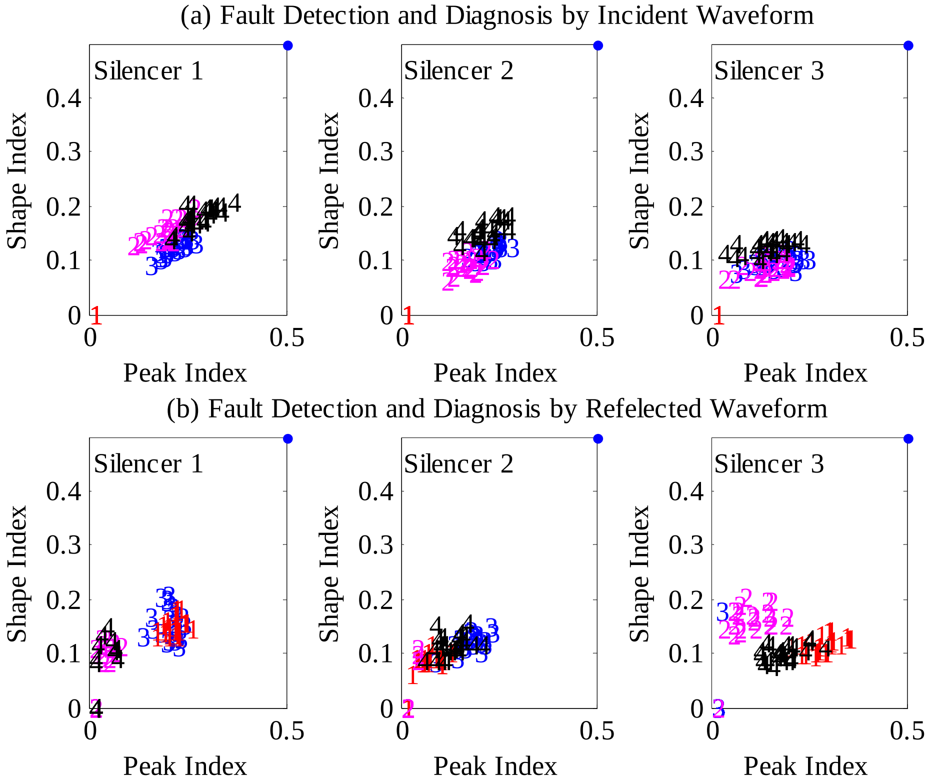

Figure 8 Detection and diagnosis results from reconstructed waveforms for three different silencers at 1500rpm and 20Nm

Figure 8 presents the detection and diagnosis results in the two dimensional plane for the same injector fault but with three different silencer characteristics i.e. three different degrees of reflections. The numbers: 1, 2, 3 and 4 in the plot denote the cylinder number. As shown in Figure 8(a), for the three different silencer configurations the index values for cylinders 2, 3 and 4 are similar but differ significantly from cylinder 1, indicating that the combustion in cylinder number 1 is abnormal. The top three plots also show that the index values extracted from the incident waveform are similar for all three different reflective conditions. This means that the incident waveforms are influenced slightly by the reflections and hence the results are consistent even if different silencers are used. However, the results are unable to distinguish cylinder 1 from the others when the reflective wave is used. This confirms that only the incident wave can be used to obtain reliable detection results.

To demonstrate the detection performance of the incident waveform, the index values from the raw waveform of each sensor are presented in Figure 9. Comparing the results with those obtained directly from the sensors, it is found that the results from the two sensors are not consistent with each other because the index value differences are significant between three different reflection conditions even if the fault case is the same. Especially, the results from the third silencer configuration where many wrong classifications have occurred. It can therefore be concluded that the use of individual sensors for monitoring is not reliable.

The proposed method was further explored to check if it was able to detect and diagnose all the different faults at various engine operating conditions. Figure 10 shows the results obtained for six cases: (a) normal exhaust valve setting, (b) a small degree retard; (c) a large degree of retard; (d) a small injection deviation, (e) a medium injection deviation and (f) a large injection deviation. It can be seen that the index values for cylinders 2, 3 and 4 are differ significantly from cylinder 1, This confirms that the method can separates all the faults successfully at different operating conditions. Importantly, it is also seen that the clusters drift gradually to the right top corner of each plot and become more spread out as the fault condition becomes larger, showing that the method also gives a clear indication of the fault severity.

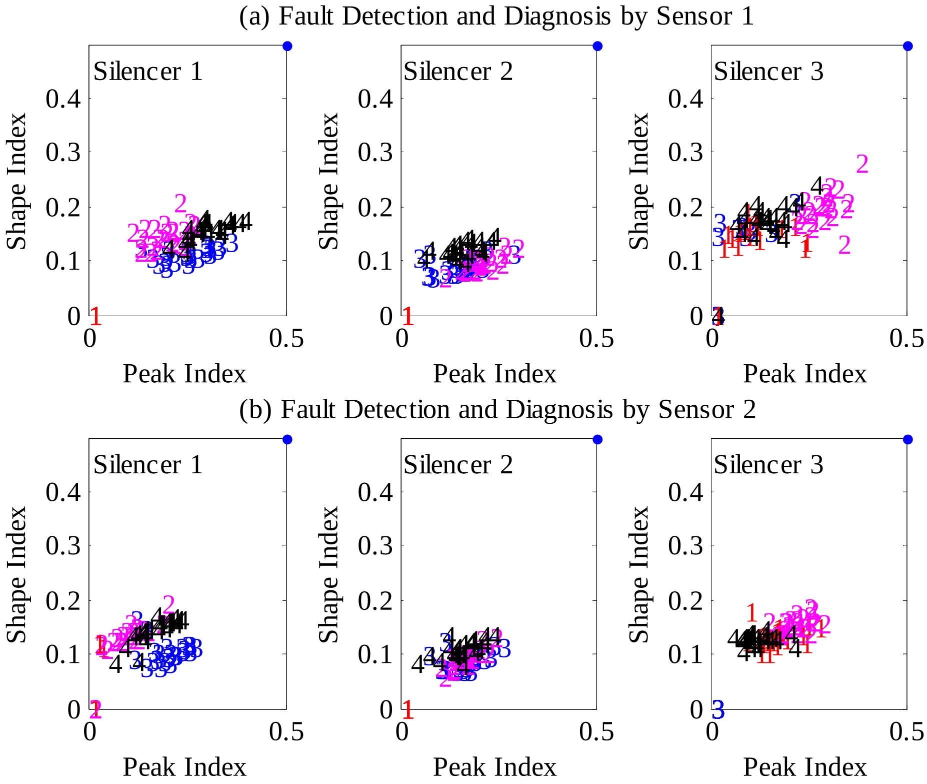

Figure 9 Detection and diagnosis results from raw waveforms for three different silencers at 1500rpm and 20Nm

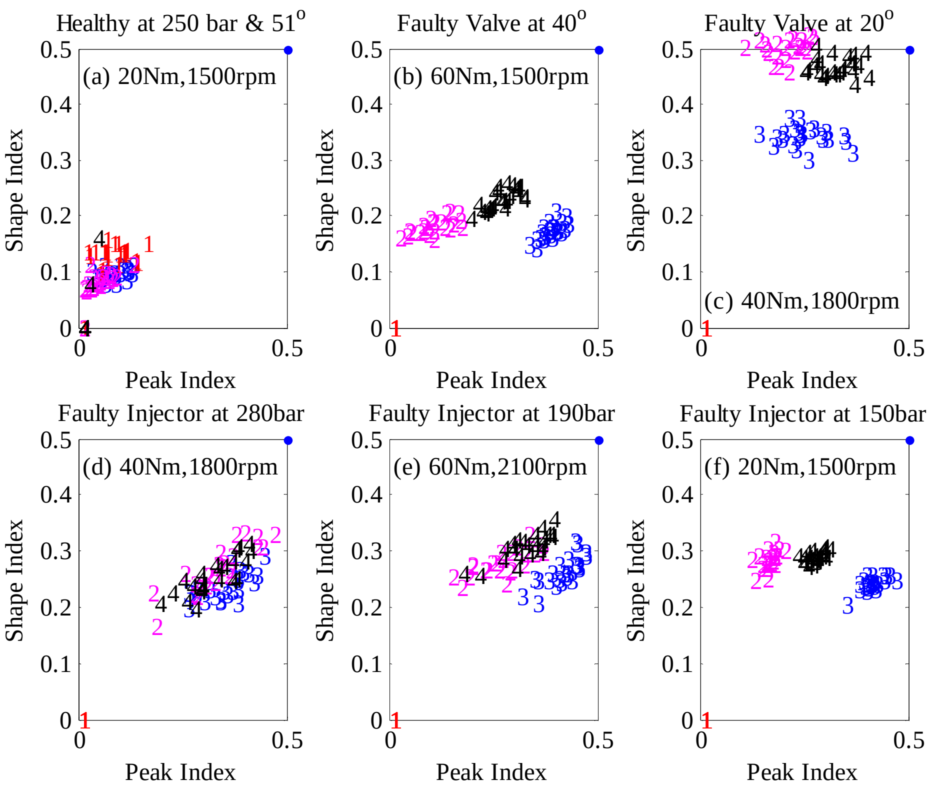

Figure 10 Detection and diagnosis results for different fault cases at different operating conditions

5 CONCLUSION

From a developed acoustic model it is straightforward to gain an understanding of the waveform characteristics inside exhaust pipes for both normal and abnormal conditions. A fault detection and diagnosis scheme can thus be developed based upon the evaluation of the uniformity over different waveform portion corresponding to different cylinders. In addition, the understanding also permits the development of a two-sensor reflection suppression method.

Experimental results have shown that the waveforms (incident waves) obtained from the measurements of two sensors correlate closely with simulated results. Using the peak and shape indices derived from the incident waveforms, accurate and reliable detection and diagnosis results are obtained in monitoring different types of faults under different operating conditions. As the method is developed by evaluating combustion uniformity over multiple cylinders, it can be implemented without the need of baseline data. In addition, the technique can be applied to different types of silencers, demonstrating that it forms a novel and yet reliable technique for engine condition monitoring using acoustic measurements of the exhaust system.

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