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Signal Patterns of Piston Slap of a Four-Cylinder Diesel Engine

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Abstract

This paper presents an experimental study on the vibration signal patterns associated with a simulated piston slap test of a four-cylinder diesel engine. It is found that a simulated worn-off piston results in an increase in vibration RMS peak amplitudes associated with the major mechanical events of the corresponding cylinder (i.e., inlet and exhaust valve closing and combustion of Cylinder 1). This then led to an increase of overall vibration amplitude of the time domain statistical features such as RMS, Crest Factor, Skewness and Kurtosis in all loading conditions. The simulated worn-off piston not only increased the impact amplitude of piston slap during the engine combustion, it also produced a distinct impulse response during the air induction stroke of the cylinder attributing to an increase of lateral impact force as a result of piston reciprocating motion and the increased clearance between the worn-off piston and the cylinder. The unique signal patterns of piston slap disclosed in this paper can be utilized to assist in the development of condition monitoring tools for automated diagnosis of similar diesel engine faults in practical applications.

1. Introduction

As part of a broader project being undertaken by the CRC for Infrastructure and Engineering Asset Management, an online diesel engine monitoring system is being developed in collaboration with ASC Pty Ltd. The application of this system is initially focused on its application to a Collins Class Submarine test engine, however such a system and its associated technologies has the potential for a much broader application. An experimental study on the vibration signal patterns associated with a simulated piston slap test of a four-cylinder diesel engine is one of several research elements undertaken by the CRC to support the development of the diagnostic and prognostic tools for this system.

Fuel efficiency, exhaust emission and reliability are the main concerns in modern diesel engine operation. Unpredicted diesel engine faults, particularly combustion related faults not only produces unwanted radiated noise, reduces fuel efficiency and reliability, but can also increase exhaust emission of an engine which can pose an environment hazard to human health. The damage caused by particle emission of a diesel engine to human health can be even worse in enclosed spaces such as in an underground mine. It is thus essential to mitigate the impacts of unpredicted engine faults through early detection to ensure optimum engine performance and to lessen exhaust emission. To minimize or to prevent the occurrence of unpredicted engine faults, the health state of a diesel engine needs to be monitored continually so that a fault symptom and its root cause can be diagnosed and dealt with at the first instance before it deteriorates further and causes damage.

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Piston slap is one of the most common combustion related diesel engine faults, which is caused by excessive clearance between the piston and the cylinder wall or liner due to wear or inappropriate operation of an engine. Excessive piston slap can induce severe engine damage such as scuffing on the piston and cylinder wall/liners. Vibration and noise radiation from diesel engines due to piston slap has been studied for several decades. Ungar and Ross [1] presented a theoretical model to estimate the vibration and noise power induced by piston slap of reciprocating machinery with a particular focus on diesel engines. Cuschieri and Richards [2] studied the noise radiated by combustion and piston slap of a diesel engine by considering single impacts. A method was also proposed in their study to reduce the noise due to piston slap. Nakashima et al [3] presented a numerical simulation study to reduce piston slap noise of a diesel engine by optimising the piston centre of gravity and piston pin offset design. Piston slap noise was separated from the combustion noise of a 4-stroke 4-cylinder diesel engine by Badaoui et al [4] by utilising a cyclic Wiener filter. In their approach, the filtered pressure signal measured inside a cylinder of the engine was used to evaluate the combustion power component on accelerometers mounted on locations close to the cylinder. The result was used to estimate the contribution of combustion noise on the overall vibration signal, which was then subtracted from the vibration signal to obtain the specific vibration component due to piston slap. A blind source separation model was further developed in an accompanying work to separate the piston slap and combustion noise of the diesel engine by using the vibration signals detected by the accelerometers attached close to one of the cylinders [5]. Zheng et al [6] investigated piston slap induced ship hull vibration by using finite element and boundary element analysis. They found that the excitation due to piston slap can induce higher level ship hull vibration and sound radiation than vibration induced by the vertical inertial force of the reciprocating masses of the engine.

Nevertheless, because excessive piston slap can be easily detected from the emitted audible noise, not much effort has been directed toward an automated detection of such faults in diesel engine monitoring. Furthermore, piston slap normally occurs only after a long lifespan of diesel engine operation since excessive wear of piston and cylinder wall/liner usually takes a long period to develop. Simulation of such faults in a controlled manner is thus vital to understand the signal patterns for automated engine monitoring and fault diagnosis. As part of a program to develop a comprehensive engine condition monitoring and fault diagnostic tool for online condition monitoring of the Hedemora diesel engine of ASC Pty Ltd [7], several common diesel engine faults such as injector fault, inlet and exhaust valve faults, piston blow-by and piston slap were simulated in a diesel engine test rig in the laboratory. Signal patterns associated with each fault were studied by using various condition monitoring techniques in the investigation.

The signal patterns from the baseline test of a diesel engine test rig at different loading conditions have been investigated and reported by Lin and Tan [8] using acoustic emission and vibration techniques. They showed that the major combustion-related events such as inlet valve opening and closing, combustion, exhaust valve opening and closing produced specific Acoustic Emission (AE) Root Mean Square (RMS) peaks. A near-period decaying piston rocking motion (essentially, piston slaps) during the engine combustion process was also detected in the measured acoustic emission signals. It was found that the mechanical process and operation condition of the diesel engine were more stable under higher loads (e.g., full load) for a healthy engine. Lin et al [9] further illustrated that the loading condition of a diesel engine can be estimated from the instantaneous angular speed (IAS) analysis. Moreover, it was found that the IAS technique can be employed to detect the leaking of an exhaust valve. Leakage of the exhaust valve will result in reduced combustion power output of a cylinder and thus lead to the reduced amplitude of the order component of the IAS waveform corresponding to the engine firing frequency. The amplitude reduction of the order component of the IAS waveform increased for higher engine loads attributing to the increased combustion power loss by the leaking exhaust valve. The result and finding for this part of work is summarized in a separate paper to be submitted for consideration of a journal publication. Signal patterns (the time and frequency domain features) of a simulated injector fault of the diesel engine were reported in another study [10] in which both acoustic emission and in-cylinder pressure techniques were employed.

Since piston slap can be detected in the audible frequency range, vibration data will be used in the analysis presented in this study. Typical signal patterns and features associated with piston slap of a four-cylinder diesel engine are studied. A description of the diesel engine test rig and the experimental setup is given in the next section. Section 3 presents the analysis of vibration signals to extract the signal patterns and features induced by piston slap. A general discussion of the result is also included in the section. Section 4 provides a summary of the main findings from this study and is followed by a general conclusion.

2. A description of the diesel engine test rig and the experimental setup

The diesel engine test rig as shown in Fig. 1 was employed in a range of engine fault simulations in the experimental study. The engine is an in-line 4-stroke, 4-cylinder diesel engine, which is commonly used for power generation in remote construction sites or an emergency power generator in hospitals. The engine generates about 15kW of nominal power output at full load condition. During the experiment, the power outlet of the diesel engine generator set was connected to a three-phase 15kW industrial fan heater. The fan heater has three heat settings at 5kW, 10kW and 15kW, which can be adjusted during the experiment for different engine loadings. The engine specification is shown in Table 1.

A PCB ICP industrial type piezoelectric accelerometer was stud mounted on the non-drive end of the engine block close to Cylinder 1 as shown in Fig. 1 for vibration detection of piston slap and other engine operation noise. The accelerometer mounting location was chosen to minimize the effect of high amplitude low frequency engine rocking motion (i.e., swinging of the engine block on the flexible engine mounts) on the measured acceleration signal during engine operation. Other sensors installed on the test rig include four resonance type acoustic emission (AE) sensors, one high temperature pressure sensor and a combined encoder and Top Dead Centre (TDC) recorder unit. The signals acquired from these sensors are not used in this paper but used in the analysis presented in Refs [7-10].

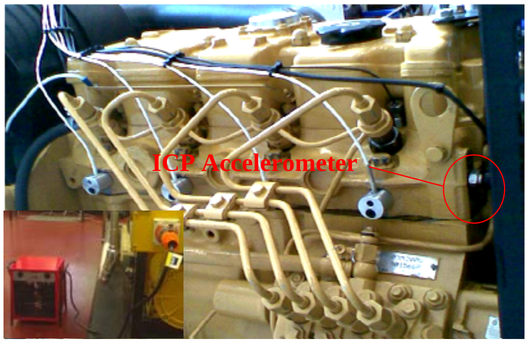

Fig. 1. A graphical illustration of the 4-stroke 4-cylinder diesel engine test rig and the attached sensors.

Table 1. Specification of the diesel engine

Perkins 404C-22 engine data	
Number of cylinders	4
Arrangement	In-line
Running speed	1500 rpm
Bore	84.0mm
Stroke	100.0mm
Displacement	2.216 litres
Compression ratio	23.3:1
Firing order	1-3-4-2
Injection timing (estimated)	15 degrees (+/- 1 degree) before TDC
Exhaust valve open (measured)	143 degrees after TDC
Exhaust valve close (measured)	370 degrees after TDC
Inlet valve open (measured)	354 degrees after TDC
Inlet valve close (measured)	584 degrees after TDC

The setup of vibration measurement is schematically illustrated in Fig. 2. A National Instrument data acquisition card (NI DAQ 6062E), which has a maximum sampling frequency of 500 kHz and can acquire data synchronously for up to 16 channels, was used for the data acquisition. A sampling frequency of 30 kHz was used in the experiment with a low pass filter set at 10 kHz for vibration measurement.

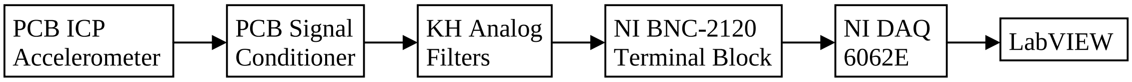

Fig. 2. A schematic illustration of the data acquisition setup in the experiment.

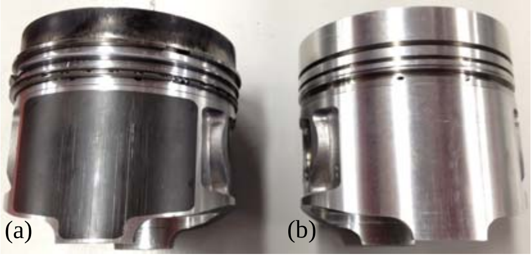

Fig. 3. A graphical illustration of the piston; (a) Healthy piston, and (b) Faulty piston (the piston skirt was milled off by 0.1 mm).

After completing the baseline measurement of the diesel engine at various loading conditions, a simulated faulty piston (see Fig. 3(b)) was used to replace the healthy piston (see Fig. 3(a)) in Cylinder 1 to simulate piston slap during the engine operation. In this simulation, the skirt of the piston was milled off by 0.1mm around the surface (i.e., the upper service limit according to the engine service manual) as shown in Fig. 3(b). Signal characteristics of the simulated piston slap are analyzed in the next section to extract the useful features associated with piston slap to assist the development of automated condition monitoring applications for diesel engines.

3. Analysis of vibration signals from the simulated piston slap test

Vibration Signal Patterns

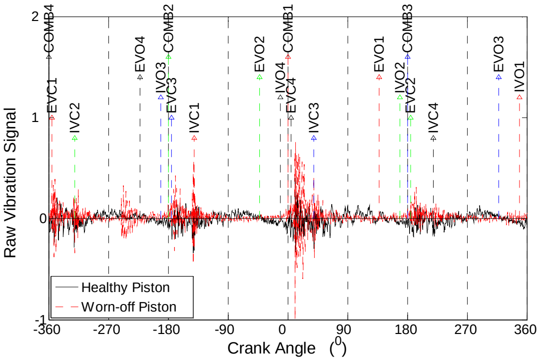

Fig. 4. Comparison of the measured raw vibration signals for the healthy and worn off piston cases.

Fig. 4 compares the measured raw vibration signals for the healthy and the worn-off piston cases of the engine at the unload condition. It is observed that there is a noticeable increase in vibration amplitudes during the combustion of cylinder 1 when the simulated worn-off piston was used. In Fig. 4, COMB denotes the combustion, EVC stands for exhaust valve closing, EVO represents exhaust valve opening, IVC denotes inlet valve closing and IVO indicates inlet valve opening. The number following these acronyms represents the corresponding cylinder number.

The averaged vibration Root Mean Square (RMS) data (averaged over 192 engine cycles) calculated from the measured vibration signals for both health and faulty piston cases at the unload condition are shown in Fig. 5. It is shown that every valve closing event produces a corresponding vibration RMS peak. The simulated worn-off piston has led to a substantial amplitude increase for vibration RMS peaks associated with the major mechanical events of Cylinder 1 (i.e., COMB1, EVC1, IVC1) attributing to the increasing piston slap. The slight mismatch between some mechanical events and the corresponding vibration RMS peaks in the figure is caused by the engine speed variation and the error between the static measured valve timing and the actual valve timing while the engine is in operation. A vibration RMS peak due to piston slap can be clearly identified during the air induction stroke of Cylinder 1 as shown in Fig. 5. The peak is present in the vibration signals for all loading conditions as shown in Fig. 6 but was absent in the vibration signals when the healthy piston was used in the experiment. The vibration signal produced by piston slap during engine combustion process overlapped with the engine combustion noise [4] which is difficult to differentiate from the low frequency vibration signal. However, impacts produced by piston slap during engine combustion were clearly detected by using high frequency acoustic emission technique in the experiment [8] where piston slap was termed as piston rocking motion. Piston slap induced by the direction change of the lateral force of the crank-rod-piston system for other piston strokes as disclosed by Geng and Chen [11] was not detected by the vibration sensor. This could be either due to the overlapping of piston slap induced vibration and those generated by other mechanical events of the engine or due to the energy attenuation of the impact signal when it propagated from the cylinder wall to the engine block.

In order to extract the useful frequency features of the signal, power spectra of the raw vibration data for the healthy and the worn-off piston cases at the unload condition (see Fig. 4) are presented in Figs. 7 and 8 respectively. It is shown that the spectra of the vibration signal in both cases are largely contaminated by the electric frequency (50 Hz) and its higher harmonics of the output power generated by the diesel engine operation. These electric frequency components can be clearly identified and isolated from the spectra using the order analysis as shown in Figs. 7 and 8. However, care has to be taken when the frequency of the major order components are close to the electric frequency and its higher harmonics such as that in the full load case, which is to be discussed in the subsequent analysis.

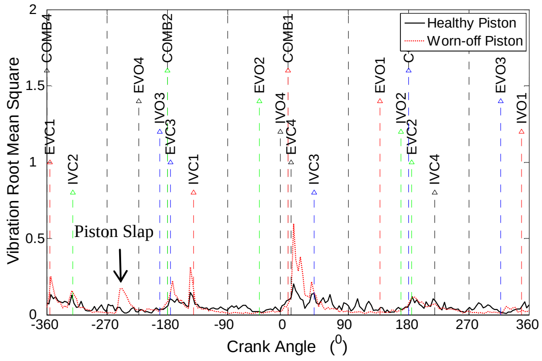

Fig. 5. Comparison of vibration RMS amplitude for the healthy and worn-off piston cases.

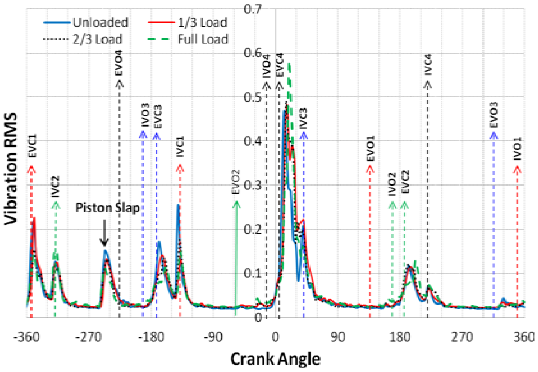

Fig. 6. Comparison of vibration RMS amplitude for the worn-off piston case at different loading condition.

The major order components of the power spectra in both cases contain the orders of 2, 4, 6 and 8 times of the crankshaft rotating frequency. This is typical for a 4-stroke, 4-cylinder diesel engine. Other order components (the less dominant) such as 0.5, 1, 1.5, 2.5, 3 and so on can also be identified in the spectra although these order components have smaller amplitudes. For a better fault characterization, the major order components at different engine loading conditions were extracted from the spectra. The extracted order components at each loading condition were averaged across 10 data files to minimize the effect of amplitude variation of the diesel engine on the interpretation of the result.

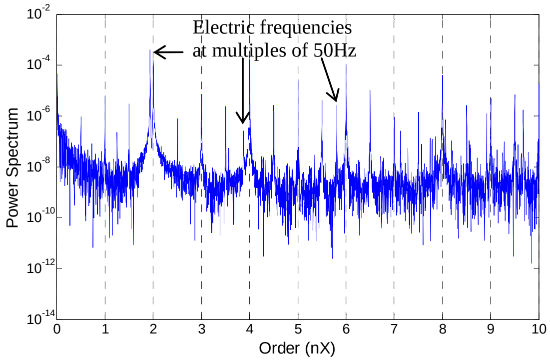

Fig. 7. Power Spectrum of the vibration signal at the unloaded condition for the healthy piston case.

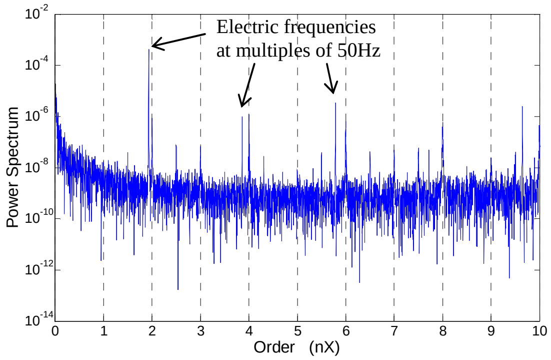

Fig. 8. Power Spectrum of the vibration signal at the unloaded condition for the worn-off piston case.

Frequency Domain Feature Extraction

Fig. 9 presents the (averaged) major order components of the vibration power spectrum at different engine loading conditions for the healthy piston case. It is shown that the spectrum is dominated by the order component associated with the engine firing frequency (i.e., the order of 2). The amplitude of this order component increases proportionally with the increase in engine load which indicates an increase in engine power output. Also presented in the figure is the linear trend line calculated based on the second order component as a function of engine loading conditions. Fig.10 shows the amplitude of the four order components (i.e., the orders of 2, 4, 6 and 8) at different engine loading conditions for the simulated worn-off piston case. Unlike that of the healthy piston case, the second order component does not have a dominant amplitude when compared with the other order components in all loading cases except for the full load condition (which is not shown in the figure due to the reason to be explained in the following paragraph). Since the impact time by piston slap is very short, the vibration response induced by piston slap is characterized by high frequency contents. This helps to explain why the amplitude of the low frequency order components in the simulated piston slap case (as shown in Fig. 8) does not increase from that of the healthy piston case (as shown in Fig.7) for all engine loading conditions. Instead, the amplitude of these order components decreases from that of the healthy piston case.

In the full load condition (i.e. the mean engine speed of approximately 1500 rpm), because the frequency of the second order component overlaps with the electric power frequency, and the amplitude of this electric frequency component is much higher than that of the second order component such as that shown in Fig. 8, the true amplitude of this order component is difficult to determine in this loading case. Although not uniformly, the sixth order component appears to have a higher response amplitude than the other order components in this case. The amplitude of this order component has a general increasing trend as the engine loading increased as shown in Fig. 10. Further investigation is required to improve the understanding of the frequency domain feature associating with the simulated piston slap.

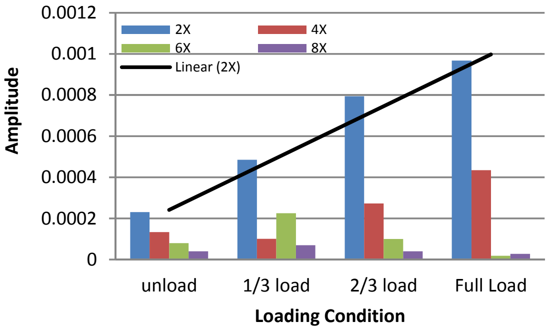

Fig. 9. The averaged amplitude of the four major order components at different engine loading conditions in the healthy piston case.

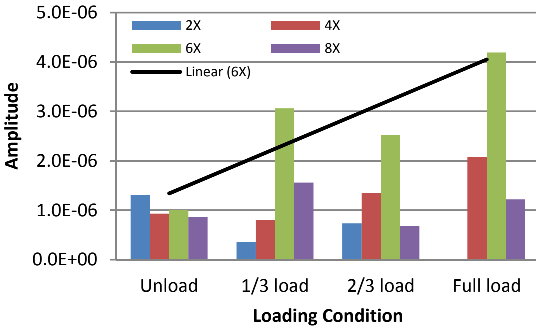

Fig. 10. The averaged amplitude of the four major order components at different engine loading conditions in the simulated worn-off piston case.

Time Domain Feature Extraction

Four typical time domain features, RMS, Crest Factor, Skewness and Kurtosis were also calculated and are presented in Figs. 11-14 respectively. Each feature was calculated and averaged over ten data files. It is shown that all the time domain features chosen in this study provide a better indication than the order domain components for the detection of the simulated worn-off piston at all loading conditions. These time domain features can be utilized for condition monitoring and automated fault diagnosis of diesel engines in practical applications.

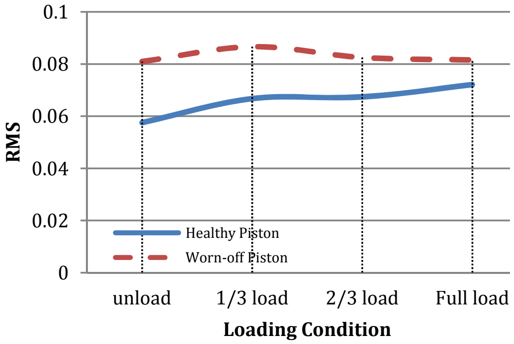

Fig. 11. The RMS value of vibration signals at different loading conditions.

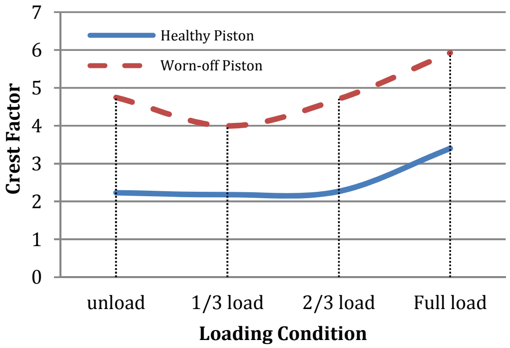

Fig. 12. The crest factor of vibration signals at different loading conditions.

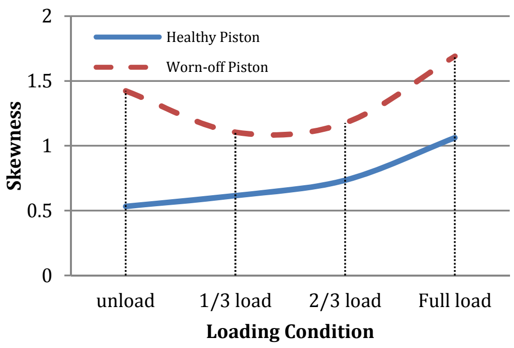

Fig. 13. The skewness feature of vibration signals at different loading conditions.

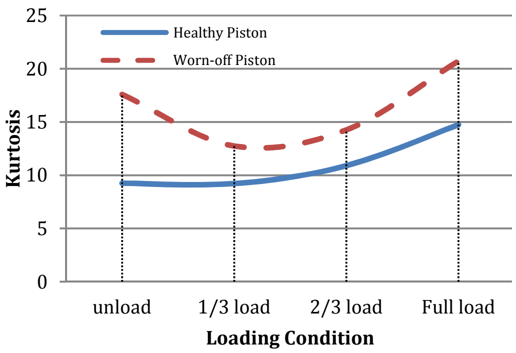

Fig. 14. The kurtosis value of vibration signals at different loading conditions.

4. Summary and Conclusion

In this paper, time and frequency domain features of vibration signals from a 4-stroke, 4-cylinder diesel engine due to a simulated piston fault were analyzed. Unique features associated with the simulated piston fault were extracted from the vibration signals for condition monitoring applications. It was found that the simulated worn-off piston resulted in increased vibration RMS peak amplitudes for major mechanical events of the corresponding cylinder (i.e., inlet and exhaust valve closing and combustion of Cylinder 1). This then led to the increase in overall amplitude of the time domain statistical features, i.e., RMS, Crest Factor, Skewness and Kurtosis in all loading conditions. The simulated worn-off piston not only increases the impact amplitude of piston slap during the combustion, it also produced a distinct impulse response soon after the compression stroke of the cylinder attributing to the increase in lateral impact force as a result of piston reciprocating motion and the increased clearance between the worn-off piston and the cylinder. These unique signal patterns of piston slap as disclosed in this paper can assist in the development of condition monitoring tools for automated diagnosis of similar diesel engine faults in practice.

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