

Signal Processing Parameters for Estimation of the Diesel Engine Combustion Signature

2011-01-1649

Published
05/17/2011

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doi:10.4271/2011-01-1649

ABSTRACT

Research into the estimation of diesel engine combustion metrics via non-intrusive means, typically referred to as “remote combustion sensing” has become an increasingly active area of combustion research. Success in accurately estimating combustion metrics with low-cost non-intrusive transducers has been proven and documented by multiple sources on small scale diesel engines (2-4 cylinders, maximum outputs of 67 Kw, 210 N-m). This paper investigates the application of remote combustion sensing technology to a larger displacement inline 6-cylinder diesel with substantially higher power output (280 kW, 1645 N-m) than previously explored.

An in-depth frequency analysis has been performed with the goal of optimizing the estimated combustion signature which has been computed based upon the direct relationship between the combustion event measured via a pressure transducer, and block vibration measured via accelerometers. The goal of this paper is to explore the signal processing parameters involved in this process and to introduce the idea of the use of the singular value decomposition (SVD) to identify frequency content required to accurately and robustly estimate the combustion signature which may be otherwise unidentifiable in standard frequency domain measurements such as coherence and frequency response.

In addition to the singular value decomposition other signal processing techniques are employed with the goal of optimizing the estimated combustion signature, including optimization of the time-domain windowing process and the application of various filtering regimes.

INTRODUCTION

With increasingly more stringent emissions regulations, the ability to detect combustion characteristics has spawned a great deal of research in combustion ignition engines specifically in the areas of condition monitoring and in a closed loop feedback control system as a means to optimize engine performance and minimize nitrous oxide (NO_x) and particulate matter (PM) emissions. In conjunction with ongoing research into effective methods of condition monitoring is the investigation of an externally mounted transducer, such as an accelerometer, whose response could be used in a closed-loop feedback system to estimate in-cylinder combustion properties. Multiple methods to relate accelerometer response to the combustion process have been published, however these results have typically been limited by engine size.

Based on the frequency response function computed between measured in-cylinder pressure and block vibration, methods to estimate the in-cylinder pressure and rate of heat release directly from the response of an external transducer, such as an accelerometer have been demonstrated by several sources [1,2,3]. Efforts to improve the combustion metrics estimated using this method are the primary focus of this paper.

Additional results have shown that in an explicit frequency band, a unique relationship between a combustion event and the response of an accelerometer due to this event exists. In a time domain analysis, this relationship can be used to estimate the start of combustion as well as the location of the maximum cylinder pressure and the beginning of the diffusive combustion phase exclusively from the accelerometer signal. With regard to frequency domain analysis, it has been demonstrated that an accelerometer signal filtered in an explicit frequency band can also be used to quantify the in-cylinder pressure development through

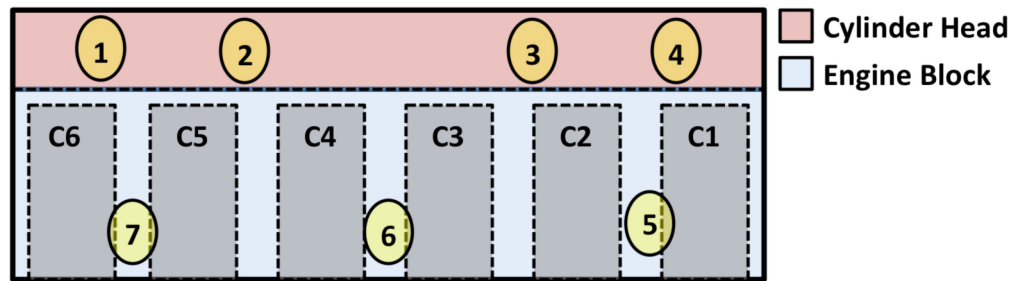


Figure 1. Triaxial accelerometer locations on 9L diesel engine

evaluation of the pressure gradient and peak value. It was also shown that proportionality exists between the maximum value of the cylinder pressure and the absolute value of the minimum of the filtered vibration response corresponding to the same crank angle value [3].

With regard to condition monitoring of compression ignition engines two metrics which have been of particular interest are misfire detection and torque estimation. Misfires can be directly correlated to degradation in engine performance and to an increase in hydrocarbon emissions. Torque estimation is also of interest as it links directly to the fueling in a CI engine, particularly injection timing and duration. Several methods of torque estimation and misfire detection have been proposed including utilization of the crankshaft and engine block's angular acceleration, use of the crankshaft position sensor signal which can be correlated to the angular acceleration of the engine, and measurement of block vibration to both directly monitor the combustion process and in the recreation of the cylinder pressure [1,2,4,5].

EXPERIMENTAL SETUP

Testing was conducted on an inline 6-cylinder 9-liter turbo-charged, common rail diesel engine. For each of the test conditions recorded, a total of 29 channels of data were acquired: 6 cylinder pressure measurements, 21 acceleration measurements, and 2 crank angle encoder signal measurements (N & Z type). Data was captured using a Hewlett-Packard VXI mainframe configured to simultaneously record up to 64 channels of acquisition. LMS CADA-X software was used to configure and control the data acquisition hardware. The data was acquired on a temporal basis, which resulted in approximately 465 data points per engine cycle per cylinder. The sampling parameters used are displayed in [table 1](#) below.

Table 1. 9L Diesel Data Acquisition Parameters

Sample Frequency	51,200 Hz.
Measurement Period	40 seconds
Number of Samples	2,048,000

The acceleration response of the engine structure was acquired using PCB model HT356A63 sensors. The HT356A63 is a high-temperature piezoelectric tri-axial ceramic shear accelerometer with a nominal sensitivity of 10 mV/g and frequency response range of 2-4,000 hertz.

Six piezoelectric cylinder pressure transducers were mounted in the cylinder head, positioned such that the response of each transducer responded to the pressure fluctuations of a single cylinder only. The response measurements were made using accelerometers mounted at seven structural locations on the engine, four on the cylinder head and three on the engine block. The schematic in [Figure 1](#) displays the general location of the accelerometers. The axes of the accelerometers were all oriented in the same direction, such that their x-axis sensed parallel to piston travel, z-axis parallel to the length of the crankshaft, and y-axis normal to the aforementioned directions. Accelerometers were mounted via a stud and base which were coupled to structural engine members with epoxy to ensure a rigid connection.

TEST CONDITIONS

Because diesel combustion, specifically power output and emissions are highly dependent upon injection parameters the analysis presented is focused on test conditions operating at a constant speed of 2200 RPM and engine load of 725 N-m with variation in injection timings. The injection characteristics for the conditions analyzed are displayed in [table 2](#) below.

RESULTS

The theory supporting the method used in estimating in-cylinder combustion metrics is based on the existence of a linear relationship between the combustion phenomena and block vibration. In order to evaluate this linearity, extensive frequency domain processing of the signals was done.

Prior to transforming the time domain data to the frequency domain, the raw pressure and accelerometer traces were segmented based on a single combustion event for each cylinder. In order to maximize the angular and frequency resolution of the signals, a 120 degree combustion window

Table 2. 9L diesel injection parameters

Test Number	Start of Injection (°BTDC)	Injection Duration (CAD)
1	11.4	12.5
2	12.4	12.1
3	13.4	12.3
4	14.4	12.4
5	15.4	12.0

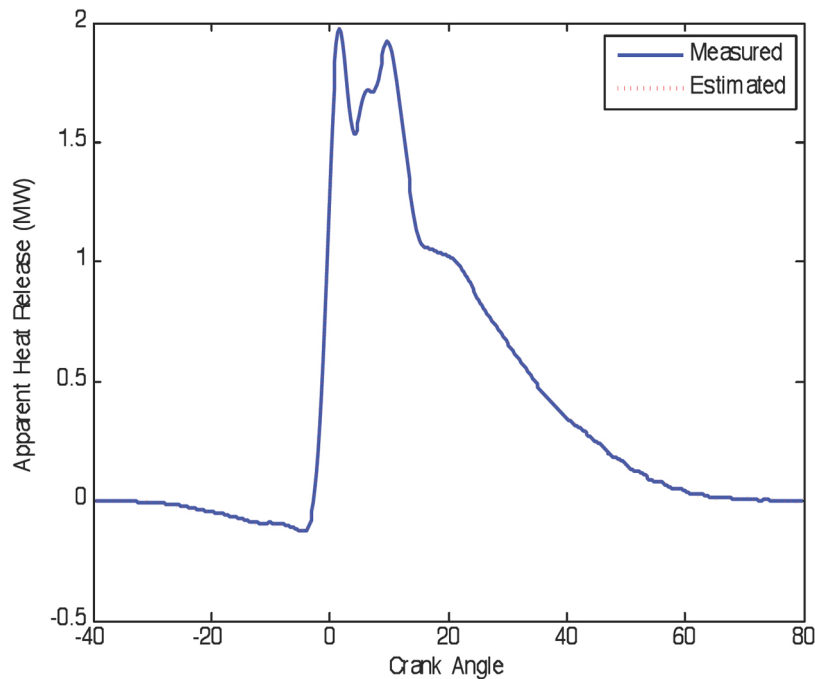


Figure 2. Operating condition 1 Measured v. estimated apparent heat release

was used around each combustion event when separating the raw signals. 120 degrees was determined to be the maximum amount of combustion data that could be used without using overlapping data from the accelerometer signals. The length of the combustion window was computed based on the basic operating principles of a 4-stroke engine, from which it can be ascertained that 720 crank angle degrees correspond to 6 combustion events.

Ideally, the response from each of the accelerometers would be due only to the vibration of the engine structure due to a combustion event. For each of the operating conditions listed in Table 2, a linear relationship was established between the apparent heat release, derived from measured cylinder pressure and volume, and the corresponding accelerometer response segment. As shown in Figure 2, this method yielded excellent results for individual test conditions, however due to uncertainty in the relationship between channels and across test conditions, utilizing a single linear relationship to quantify combustion across several operating conditions proved extremely difficult.

The following procedures and techniques have been devised with the goal of improving the combustion estimation results across operating conditions from a single linear relationship. An initial investigation was performed to see if the accelerometer data could be filtered to remove non-combustion related frequencies that were detrimental to the estimation of the cylinder pressure and apparent heat release. Although the accelerometer data has been segmented to ensure no overlap of the signals, due to the nature and location of the accelerometer it was not possible to ensure that non-combustion related activity was not captured by the accelerometer response. Figure 3 displays an autopower spectrum computed from the measured cylinder pressure for a single cylinder. The peaks in amplitude occur at exactly one-sixth at the firing frequency of the engine and its harmonics, indicating that only this frequency content is present during combustion.

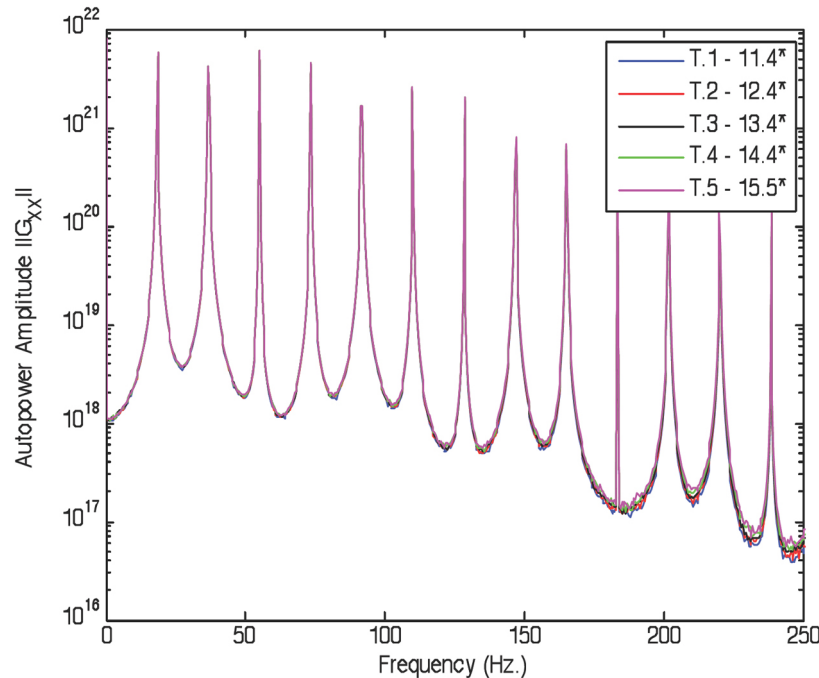


Figure 3. Measured cylinder pressure autopower spectra

Additionally, the frequency content of the accelerometer signals was analyzed to see if there was a correlation with the combustion frequency content. As observed from [Figure 4](#), the frequency content of the signals captured by the accelerometers also occurs only at one-sixth the engine firing frequency. The relationship between the apparent heat release and accelerometer response was quantified with respect to frequency through computation of a coherence function between the two, displayed in [figure 5](#). From [Figure 5](#) it can be observed that the highest coherence values occur at one-sixth the engine firing frequency and its harmonics, indicating that the firing frequency and its harmonics dominate the response of the engine structure and the response captured by both the cylinder pressure transducers and accelerometers.

Despite the fact that the accelerometer's response was principally due to combustion, difficulties still existed in reconstructing the cylinder pressure or apparent heat release across test conditions with a single linear relationship. It was hypothesized, that although the response of the accelerometer was principally due to combustion, the possibility still existed that the accelerometer signal may still contain response due to combustion on cylinders other than the one of interest. This hypothesis was investigated in two ways.

The first method of evaluating the hypothesis was through the computation of the singular value decomposition (SVD) on the raw cylinder pressure and accelerometer signals. If the response of the structure was principally due to combustion,

peaks in the SVD should only occur at one-sixth the firing frequency of the engine (18.8 Hz).

The power spectrum matrix containing the auto and cross powers computed between each of the signals was computed (27 total signals) and the singular value decomposition was then performed at each frequency. [Figures 6](#) and [7](#) display the SVD's computed for a single test condition.

From [Figure 7](#) it can be seen that at approximately 445 hertz there is a spike in the SVD, however this does not correspond to a harmonic of 18.8 hertz. It is unknown which mechanical operation of the engine this corresponds to, however because it was not combustion related it was filtered out of the raw data in an attempt to improve the estimated apparent heat release.

In order to filter this single frequency out, a Vold-Kalman order tracking filter was used to extract this information from the data. [Figure 8](#) displays the estimated result before and after the filtering of the data. The raw data was filtered with both a first and second order Vold-Kalman filters with neither having a significant effect.

The concern with these results is that the oscillation prior to and following the combustion event still remains. The conclusions drawn from this analysis led to an extensive investigation into the geometry of the time-domain window used to truncate the cycle-segmented cylinder pressure and accelerometer signals.

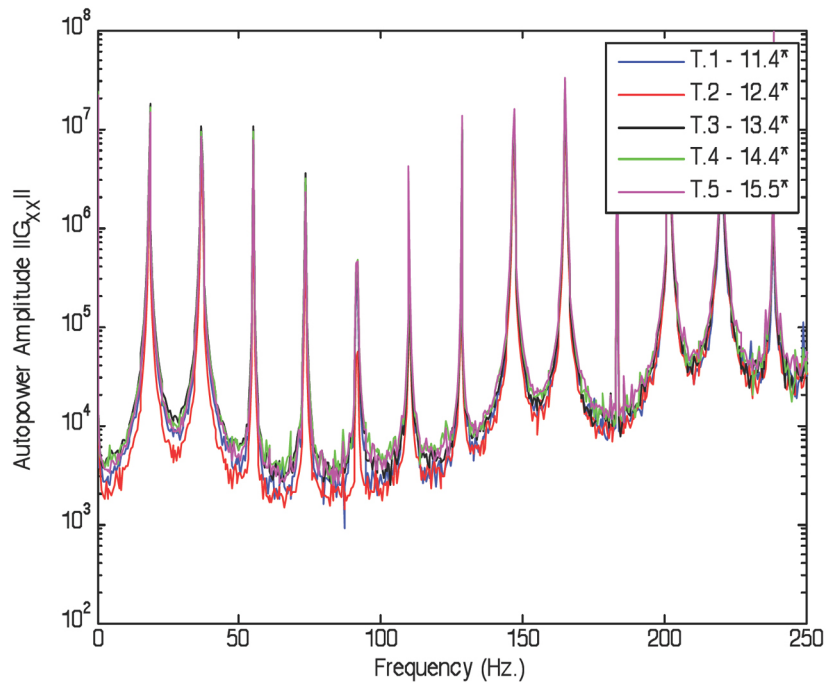


Figure 4. Accelerometer autopower spectra

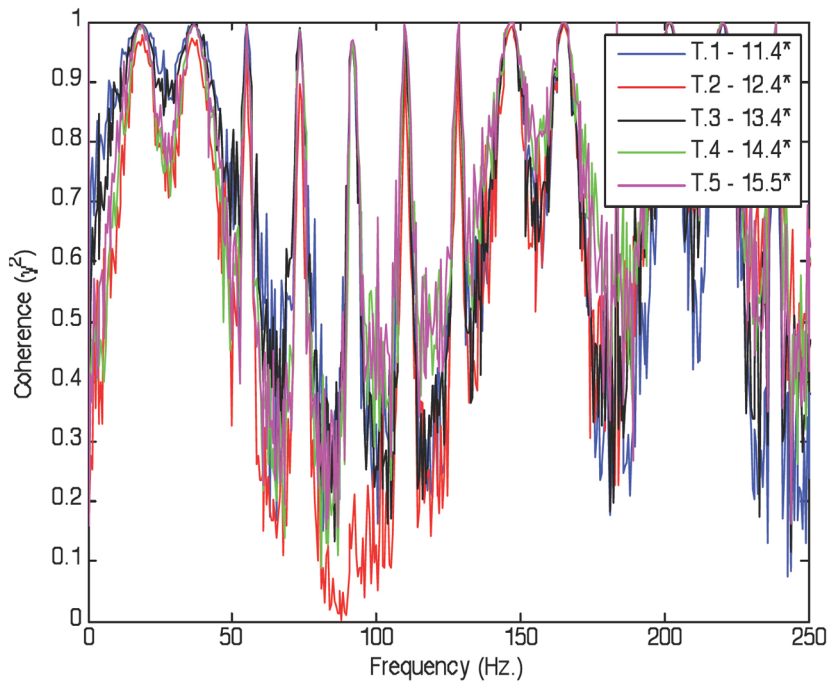


Figure 5. Coherence computed between measured apparent heat release and accelerometer response