

Engine Diagnostics Using Acoustic Emissions Sensors

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ABSTRACT

Engine acoustics measured by microphones near the engine have been used in controlled laboratory settings for combustion feedback and even combustion phasing control, but the use of these techniques in a vehicle where many other noise sources exist is problematic. In this study, surface-mounted acoustic emissions sensors are embedded in the block of a 2.0L turbocharged GDI engine, and the signal is analyzed to identify useful feedback features. The use of acoustic emissions sensors, which have a very high frequency response and are commonly used for detecting material failures for health monitoring, including detecting gear pitting and ring scuffing on test stands, enables detection of acoustics both within the range of human hearing and in the ultrasonic spectrum. The high-speed acoustic time-domain data are synchronized with the crank-angle-domain combustion data to investigate the acoustic emissions response caused by various engine events.

Combustion can clearly be identified as a high energy event in the acoustic emissions data with the frequency of the response corresponding to a resonant mode of the combustion chamber. Additionally, both the start and end of fuel injection result in short-duration, high energy, frequency-independent acoustic bands. Some valve closing events can be identified as well. Hardware configuration changes to the piston ring pack resulted in different acoustic emissions signatures indicating the ability of acoustic emissions sensors to detect ring-liner interactions. A change of 25° C to the coolant (and thus liner) temperatures displayed distinct changes in the observed acoustic emissions. Finally, these sensors and this technique were highly sensitive to end-gas knock with a significant response to even very light end-gas knock.

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INTRODUCTION AND BACKGROUND

As modern engines become more advanced and complex, additional diagnostic and sensing approaches are necessary for both control and development purposes. One non-conventional approach that has shown some promise in recent years is the analysis of engine acoustics. Cavina, et al. [1] used several microphones placed around the engine to determine a correlation between the acoustics in several frequency bands and pressure rise rate and knocking intensity, with a focus on frequencies near the resonant modes of the cylinder. Massey and Drallmeier [2] evaluated the combustion metrics contributing to the noise signature of HCCI combustion, and Massey, et al. [3] also explored the use of accelerometers for sensing combustion phasing in advanced combustion. Ponti, et al. demonstrated the use of microphone-based acoustic measurements for combustion phasing control in a diesel engine [4], and Cavina, et al. [5] also correlated

such measurements to turbocharger speed and knock for GDI engine applications. All of these approaches largely focus on acoustics in the audible spectrum transmitted through the air surrounding the engine.

Ultrasonic acoustic emissions within materials have also been used in other industries for non-destructive and non-intrusive testing and health monitoring applications, e.g. gear pitting [6] and sliding wear [7]. A limited number of offline engine-related applications have been noted, including measurement of piston ring/cylinder liner scuffing on a bench rig by Shuster, et al. [8].

The acoustic emissions (AE) measured in this technique are transient elastic stress waves within a material caused by the rapid release of localized strain energy, i.e. pressure waves within a material. Acoustic emissions are generally studied in the 1 kHz to 100 MHz range, although most of the energy is in the lower frequency range (1 kHz to 1 MHz). The most common application for acoustic emissions

sensing is material health monitoring for detecting the initiation and propagation of a crack, as in the examples above. However, acoustic emissions can also be generated from sources not involving material failure including friction, cavitation, and impact [8,9,10]. In this paper, we investigate AE on-engine, with a goal of identifying the causes of acoustic emissions that are observed. Specific signatures of the beginning and end of fuel injection events, valve closing events, and overall response changes showing differences in ring-liner interactions at various conditions are observed. Additionally, these directly-measured AE signals are found to have a very sensitive response to even light knocking conditions.

METHODOLOGY

Experimental Hardware Configuration

A four cylinder, 2.0L, turbocharged, spark ignited (SI) General Motors LTG engine was instrumented with acoustic emissions sensors mounted on the engine block at the outer surface of the cylinder liner, as shown in [Figure 1](#). The sensors were positioned with the mindset of determining whether AE-based approaches to measuring ring/liner interaction would give useful information in an operating engine. The engine is instrumented for in-cylinder pressure with AVL GH14DK pressure transducers. The cylinder pressure is recorded in a NI/LabVIEW-based data acquisition system triggered by a crank angle encoder with 0.2° resolution.

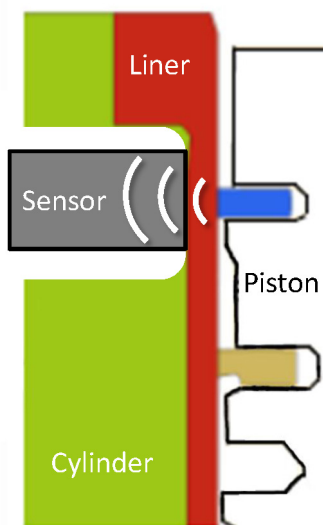


Figure 1. Graphic depiction of the acoustic emissions sensor embedded in the engine block behind the cylinder liner to sense vibrations imparted in the cylinder liner by piston ring dynamics

Five acoustic emissions sensors were machined into the engine block in different locations to measure the acoustic emissions in the cylinder liner of two of the four cylinders. [Figure 2](#) shows the location and variety of each of the five acoustic emissions sensors embedded in the engine block behind the cylinder liner. Note that the mounting locations for all of the small acoustic emissions sensors with a high frequency response curve are located at the top of the cylinder liner, above the water jacket, whereas the large, lower-

frequency sensors are located at the bottom of the cylinder, below the water jacket. [Figure 3](#) is a photograph of the large AE sensor mounted at the base of cylinder 4.

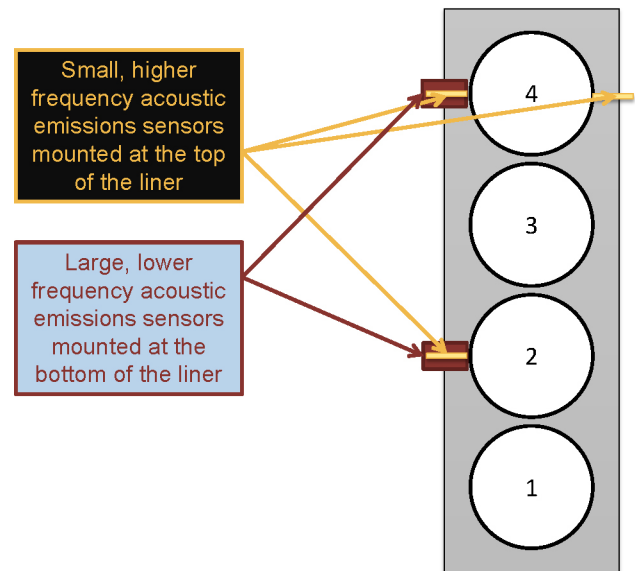


Figure 2. Graphic depiction of the location and variety of each of the six acoustic emissions sensors embedded in the engine block behind the cylinder liner

While the AE system is capable of measuring much higher frequencies, the data presented here were sampled at 200 kHz. The maximum frequency component that can be determined from the data (the Nyquist frequency) is 100 kHz and therefore an antialiasing filter at 100 kHz was used when collecting the data. Higher frequencies were tested (up to 500 kHz), but it was found that extending to a sample rate higher than 200 kHz did not yield additional information for this application, although it did result in much larger data files. The acoustic emissions sensors and data acquisition system used in this study were supplied by MISTRAS.



Figure 3. Photograph of the large acoustic emissions sensor mounted at the base of cylinder 4

In a separate data acquisition system, the cylinder pressure is collected at evenly spaced crank angle increments of 0.2° . The two data acquisition systems, one time-based and one crank angle based, are synchronized in time by generating an analog sine wave and

sending the signal to both data acquisition systems. When post-processing the data, the sine wave signals in both data sets are aligned at the beginning and at every zero-crossing, and the time- and crank-angle-based data sets are thus aligned with each other. By synchronizing the time-based acoustic emissions data with the crank-angle-based cylinder pressure data, the specific signatures in the acoustic emissions data can be correlated to the timings of distinct engine cycle events (e.g. combustion, valves closing, etc.).

For all experiments, the inlet air was conditioned to supply a constant temperature and humidity, and engine coolant, oil, and charge air coolers were maintained within 1°C of steady-state set points. The engine was operated at a steady speed using a motoring dynamometer.

Signal Processing Technique

Acoustic emissions signals, when used for health monitoring, are often processed by counting high-energy-level events within a certain frequency band, with the output metric of interest being “counts”. This approach is useful for monitoring the formation and propagation of cracks or pitting on steadily operating machinery, but not well-suited for the repeated discrete events occurring in an operating engine: if every combustion event, valve closing, etc. is counted, then the AE events of real interest will be lost in the noise. Therefore, instead of counting and logging only the high energy events, the acoustic emissions signal was continuously collected and the signal processed using Fourier transforms.

A discrete Fourier transform (DFT) can be very helpful for decomposing a measured acoustic signal into its constituent frequencies. In [Figure 4](#), the raw acoustic emissions signal for one engine cycle from one of the sensors is shown with its Fourier transform.

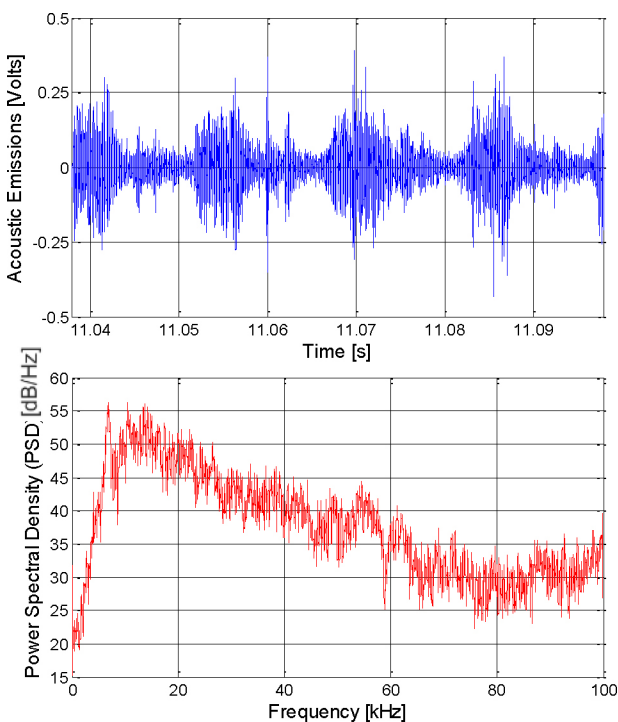


Figure 4. Example raw acoustic emissions data with the power spectral density (PSD) calculated from the discrete Fourier transform (DFT)

The Fourier transform has been converted into power spectral density (PSD) in decibels per hertz [dB/Hz]. From the PSD, it can be seen that the acoustic emissions has peaks in power content at approximately 8, 11, and 13 kHz. The power then decreases as frequency increases.

While the DFT is an invaluable tool for determining the frequency components in an acoustic emissions waveform, the time dependency is removed when the signal is converted to the frequency domain through the Fourier transform. Fortunately, however, there are signal processing techniques that maintain the time variable in the data while decomposing the signal into its frequency components known as *joint time-frequency analyses*. There are several *joint time-frequency analyses* including Short-Time Fourier Transform (STFT), Wavelet transforms, and others. The STFT and the Wavelet transform provide very similar results, although there are differences that cause advantages and disadvantages for each technique. The STFT is easier to implement and understand, but has an inherent trade-off between time and frequency resolutions. The Wavelet transform is able to solve this trade-off to some extent and provide better frequency resolution. In this work, the STFT was chosen because the sampling frequency (200 kHz) was sufficiently high to ensure that the trade-off between time and frequency resolutions was not restrictive. However, results from using a Wavelet transform, instead of an STFT, would be very interesting as well, and could be implemented in the future. In fact, the results presented later in this paper suggest that if the sampling frequency is 100 kHz or below, a Wavelet transform would be better suited; whereas sampling frequencies above 100 kHz can use either the Wavelet or the STFT. This conclusion is drawn from the fact that there is a large amount of acoustic activity below 50 kHz; however, between 50 kHz and 100 kHz, there is not a significant amount of additional information to be gained.

In an STFT, the signal is subdivided into time segments and a DFT is performed on each “short” time segment. The results from each DFT are then merged together in a time-frequency map, called a spectrogram. [Figure 5](#) is an example of a spectrogram for the same acoustic emissions data shown in [Figure 4](#). [Figure 5](#) also shows each of the cylinder pressures for reference with the pressure of the cylinder nearest this particular sensor shown as a solid green line. The operating condition at which these data were collected was 2000 rpm, a brake mean effective pressure (BMEP) of 19 bar, and a spark timing of 2 degrees after top dead center (TDC). The spectrogram allows each distinct event in time to be decomposed into its constituent frequencies and the events in time can then be studied in the context of the cylinder pressure and engine cycle events. One of the many strengths of these spectrograms is that they are simultaneously qualitative and quantitative. Note that this spectrogram shows the data for one engine cycle for one of the five sensors at a specific operating condition. For all data collected herein, the sampling frequency of the acoustic emissions data was 200 kHz. For the STFT analysis, the data were divided in time using Hamming windows with a width of 3°CA (0.25ms) overlapped by 50%, and the number of DFT points resulted in a frequency resolution of 12 Hz from 0-100kHz.