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Acoustic emission characteristics of a single cylinder diesel generator at various loads and with a failing injector

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ABSTRACT

Acoustic emission sensing techniques have been applied in recent years to dynamic machinery with varying degrees of success in diagnosing various component faults and distinguishing between operating conditions. This work explores basic properties of acoustic emission signals measured on a small single cylinder diesel engine in a laboratory setting. As reported in other works in the open literature, the measured acoustic emission on the engine is mostly continuous mode and individual burst events are generally not readily identifiable. Therefore, the AE are processed into the local (instantaneous) root mean square (rms) value of the signal which is averaged over many cycles to obtain a mean rms AE in the crank angle domain. Crank-resolved spectral representation of the AE is also given but rigorous investigation of the AE spectral qualities is left to future study. Cycle-to-cycle statistical dispersion of the AE signal is considered to highlight highly variable engine processes. Engine speed was held constant but load conditions are varied to investigate AE signal sensitivity to operating condition. Furthermore, during the course of testing the fuel injector developed a fault and acoustic emission signals were captured and several signal attributes were successful in distinguishing this altered condition. The sampling and use of instantaneous rms acoustic emission signal demonstrated promise for non-intrusive and economical change detection of engine injection, combustion and valve events.

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1. Introduction

Scalable over a wide range of power levels and able to tolerate relatively low quality fuels, diesel engines are commonly found across many types of land and maritime transportation. They vary widely in their mechanical configuration based on output power, intended operation and other considerations. Military operators of small fleets containing several engine types may be challenged in their ability to apply flexible diagnostic technologies across their fleets, particularly for legacy propulsion systems. In addition to critical performance measures such as ignition and combustion processes, ascertaining the condition of the many mechanical components and interfaces is desirable to these operators.

A sensing technique exhibiting promise in the detection of both ignition-combustion and mechanical health characteristics is measurement of acoustic emission. Elastic waves originating and propagating within a material subjected to an external stimulus form the basis of acoustic emission (AE) phenomena [1], extensively studied for several decades especially in the monitoring of material health of engineering structures. These stress waves travel through solids, interacting with

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surfaces and many traveling along a surface as a Rayleigh wave which can be measured using a piezoelectric sensing element, usually lead zirconate titanate (PZT). These AE are produced in discrete packets released with the sudden movement of a group of atoms, often referred to as a "burst" emission. When the rate of occurrence of these bursts is sufficiently high and the individual bursts can no longer be distinguished, the AE is referred to as "continuous" mode. A very accessible primer on these and other principles of AE is given by Beattie [1].

The application of acoustic emission for diagnosis of machinery condition has only been active over about the past fifteen years. In precursor forms it dates back perhaps thirty years, with the first studies of AE to diagnose faults on bearings followed some of the initial techniques using high frequency vibration and structural resonance for detection of defects. Mba and Rao [2] describe the application of AE to an assortment of machinery applications, and Sikorska and Mba [3] highlight some of the practical aspects of measuring AE in these environments, which often differ greatly from structural health monitoring applications.

A wide variety of PZT AE sensors are available to suit many applications, although only a handful have been applied regularly to engine AE monitoring. Sensors for machinery monitoring usually have response ranges from 0.1 to 1 MHz, although sensors with ranges extending only up to 400–500 kHz are most common. Wideband sensors having a relatively flat frequency response are more regularly reported for engine applications, but resonant sensors are also viable options although little direct comparison of sensor influences on output is reported in the literature for machinery diagnostics. Inherent differences from sensor to sensor, nonlinear frequency response characteristics, and characteristics of sensor-to-surface coupling have until recently resulted in difficulty comparing AE signals directly with one another [3].

Fog et al. [4] conducted some of the first reported experimental studies of engine AE measuring an exhaust valve of a large marine diesel in an attempt to detect burn-through, applying principal component analysis on the AE data. Gill et al. [5] varied the fuel injector discharge pressure as a fault condition and noted changes in the raw acoustic emission signal. El-Ghamry et al. [6] considered the statistical properties of the local rms of the AE signals and found these to be sensitive to combustion behavior. Frances et al. [7] simulated injector faults by altering the injector shim and by simulating a manifold gasket leak, then measured the various characteristics of the AE response to the altered injection parameters and with the leak, yielding mixed results. El-Ghamry et al. [8] used cepstral methods with acoustic emission measurements to infer cylinder pressure waveforms from the measured AE signals, finding the cepstral analysis to perform well when the AE signal had lower energy content.

Pontoppidan et al. [9] applied a method of independent components analysis (ICA) to detect faults using rms AE, with a focus more on comparison of methods than specific description of the fault condition. ICA was also used by Wu et al. [10] to separate out the AE signal contributions of adjacent cylinders on a four-cylinder engine. Douglas et al. [11] and Douglas [12] measured AE related to the tribological interaction and blowby between piston rings and cylinder liners for large two stroke diesels, noting increased AE with increasing piston velocity. Lin and Tan [13] explored the AE characteristics of a small multicylinder diesel engine and compared this to vibration and pressure traces, and Lin et al. [14] attempted to create an injector fault by grinding down a pintle head, but could not conclusively measure altered combustion characteristics. Lowe et al. [15] induced diesel knock through ethanol fumigation of the fuel and found that while a head sensor could not detect the knock condition, a block sensor could. Later work by Lowe [16] also found that valve closure with excessive lash clearance to be readily observable in AE, but piston slap was only marginally detectable using a window of AE energy about the expected slap locations.

Sensor placement is important for measuring AE as the stress waves do not travel long distances. However, in the case of engine diagnostics this relieves the challenge of poor signal to noise ratio in vibration signals noted earlier where dynamic phenomena from other components and vehicle motion complicate vibration analysis. Characterization of the AE transmission characteristics through the engine block and representative structures was conducted in a series of papers by Robertson et al. [17] and Nivesrangsan et al. [18–20], which calculated wave speeds and attempted to determine the spatial location of the source based on the arrival times of AE events. Many of these engine AE diagnostic studies are listed in chronological order in Table 1.

Some studies of engine AE diagnostics have been done in rig tests rather than on a running engine. Nagata et al. [21] measured increased AE in a plain bearing when oil was interrupted, leading to increased asperity contact and bulk failure. Abdou et al. [22] measured AE on fuel injectors on a rig and compared this to measured pressure in the fuel line. Jafari et al. [23] measured AE from leakage flow in simulated cracked and notched valves of a cylinder head from a spark-ignited engine. Additionally, many works as summarized by Mba and Rao [2] have established feasibility and developed methods for fault monitoring of relevant components such as gears and bearings that may be applied to engines as well.

Finally, other works have characterized high frequency acoustic or vibration behavior of engines, but they have been concerned with spectral content under the roughly 100 kHz that we have considered to be the lower limit acoustic emission in this work. Those studies are relevant to the phenomena measured here and although an exhaustive review of all vibroacoustic approaches to engine diagnostics is beyond the scope of this work, a few are noted for reference. Using microphone measurements, Koike et al. [24] were able to detect the onset of scuffing when oil was interrupted to an engine bearing, Li et al. [25] applied independent component analysis to acoustic measurements to try to separate various process, and Jiang et al. [26] was able to detect injection pressure and valve timing faults. Arroyo et al. [27] compared simple signal rms of vibration and up to 62.5 kHz to detect a misfiring cylinder. These varied examples support that vibroacoustic methods for detecting and separating specific engine processes and phenomena can be accomplished with a range of instrumentation, although AE generally allows improved diagnosis with a higher signal to noise ratio [12].