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Normalization and source separation of acoustic emission signals for condition monitoring and fault detection of multi-cylinder diesel engines

Weiliang Wu [a], Tian Ran Lin [b], Andy C.C. Tan [a,*]

[a] School of Chemistry, Physics and Mechanical Engineering, Queensland University of Technology, 2 George St, Brisbane 4001, QLD, Australia
[b] School of Mechanical Engineering, Qingdao Technological University, 11 Fushun Road Qingdao 266520, P.R. China

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ABSTRACT

A signal processing technique is presented in this paper to normalize and separate the source of non-linear acoustic emission (AE) signals of a multi-cylinder diesel engine for condition monitoring applications and fault detection. The normalization technique presented in the paper overcomes the long-existing non-linearity problem of AE sensors so that responses measured by different AE sensors can be quantitatively analysed and compared. A source separation algorithm is also developed in the paper to separate the mixture of the normalized AE signals produced by a multi-cylinder diesel engine by utilising the system parameters (i.e., wave attenuation constant and the arrival time delay) of AE wave propagation determined by a standard pencil lead break test on the engine cylinder head. It is shown that the source separation algorithm is able to separate the signal interference of adjacent cylinders from the monitored cylinder once the wave attenuation constant and the arrival time delay along the propagation path are known. The algorithm is particularly useful in the application of AE technique for condition monitoring of small-size diesel engines where signal interference from the neighbouring cylinders is strong.

1. Introduction

Acoustic emissions are transient elastic waves produced by the rapid release of energy caused by dislocations or surface displacements in material. The phenomenon was first discovered in the early 1950s by Kaiser [1] who observed that a material under load emits ultrasonic waves when the previous maximum applied stress is exceeded. Since then, AE techniques have been adopted in many engineering applications, particularly in Non-Destructive-Testing (NDT) and Condition Monitoring (CM). For example, AE technique has been successfully employed to detect crack, fracture and property change in engineering materials [2,3], wear or leak of oil/gas in pipelines and high pressure vessels integrity evaluation [4,5]. The technique has also been applied in bearing defect detection [6,7]. It was found that AE technique is not only more effective than the conventional vibration technique in early bearing defect detection, it can also provide indications of the defected size and thus enable the monitoring of degradation rate of a damaged bearing [6]. Recently, AE

* Corresponding author.
E-mail address: a.tan@qut.edu.au (A.C.C. Tan).

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technique has been successfully employed for CM and fault detection of reciprocating machinery [8–11]. For instance, AE signals were used to identify the mechanical events such as valve movements, fuel injection and combustion in multi-cylinder diesel engines [8,12]. Nevertheless, the nonlinear frequency response of AE sensors remains a challenge in sensor calibration to provide a meaningful measurement. It also poses a problem in AE data analysis when multiple sensors are needed in a multi-cylinder diesel engine such as in Refs. [13–15]. Under such circumstances, extensive expert knowledge is needed to correctly interpret the information conveyed in the AE signals and the analysis of AE data can only be carried out in a qualitative manner. The drawbacks of AE technique often attract criticism from practitioners in the field which motivates the first half of the work presented in this paper.

The accuracy of results obtained for direct comparison of AE signals from different (un-calibrated) sensors is always questionable since each AE sensor has the inherently unique nonlinear frequency response during the manufacturing process [16]. To overcome this problem, a simple signal processing technique is presented in this work where the nonlinear responses of AE sensors are normalized in the frequency domain based on the sensor calibration chart provided by the manufacturer. The signal processing approach normalizes the AE signals by linearizing their responses in the frequency domain. This process can be related to channel equalization in digital telecommunications. After this procedure, it not only enables the quantitative analysis of AE signals from different sensors but also enables a direct comparison of the signal amplitude in different frequency bands of a single AE sensor. The technique is thus particularly useful for source identification and separation of a complex system response where multiple AE events are present and several AE sensors are needed.

AE root-mean-square (RMS) energy was successfully employed in the analysis of the AE signals for condition monitoring and fault detection of multi-cylinder diesel engines [10,17,18]. Comparing to raw AE data, AE RMS energy (termed as AEE in the later analysis) data is smaller in size and thus, requires less computer storage space and offers a faster data processing. Nevertheless, it was found that the AE signal produced by mechanical events of a cylinder of a small multi-cylinder diesel engine is often corrupted by signals generated from the adjacent cylinders due to the short time interval between sequential mechanical events and the small spatial distance between cylinders [18]. For instance, an AE sensor used to monitor AE events of a cylinder can also detect AE signals from the adjacent cylinders. The problem needs to be resolved for a better application of AE technique in condition monitoring of multi-cylinder diesel engines. To this end, a source separation algorithm is developed in the second half of this paper to minimize the signal interference of adjacent cylinders so that condition of a particular cylinder can be effectively monitored by an AE sensor mounted close to it.

Blind source separation (BSS) algorithm is often employed to restore a set of hidden source signals from a set of observed signals. The word ‘blind’ implies that both source and the mixing process are unknown and only recordings of the mixtures are available [19]. However, it is impossible to uniquely estimate the original source signals without a prior knowledge of both sources and mixing process [20]. Furthermore, BSS algorithm also suffers from both scaling ambiguity and permutation indeterminacy after separation [21,22]. The drawbacks of BSS algorithm have thus far limited its application for CM and fault diagnosis of reciprocating machinery. The main challenges of applying BSS algorithms to AE signals of multi-cylinder diesel engines are three-folds: (1) the number and location of AE sources are undetermined during engine operation; (2) the propagation properties of AE waves along the engine structure are largely undetermined; and (3) the statistically independency of AE signals associated with different mechanical events of a diesel engine has not been studied. To overcome these challenges, a practical source separation algorithm analogically to the BSS process is presented in the second half of this paper to separate the mixture of AE signals from a multiple-cylinder diesel engine. Instead of restoring all the sources in the diesel engine, the proposed technique groups the sources within each cylinder as one source. Thus, the number of AE sensors required in a CM application equals to the number of cylinders, and if the condition changes or fault occurs in a particular cylinder it can be identified. A standard Pencil Lead Break (PLB) test is used to determine the parameters (i.e., the attenuation constant and arrival time delay) of AE wave propagation in the cylinder head required by the Source Separation (SS) algorithm.

The layout for the rest of the paper is arranged as follows: Section 2 describes the diesel engine test rig and the experimental setup. Section 3 presents an elaboration of the signal normalization technique to normalize the AE data acquired from the diesel engine test rig. Effects of normalizing the AE signals and its implication on the signal analysis are also discussed in the section. A PLB test is conducted on the cylinder head of the diesel engine to determine the system parameters of AE wave propagation in Section 4. Section 5 describes the SS algorithm to separate the normalized AEE signals of the diesel engine for condition monitoring and engine fault detection. An error analysis is also presented in Section 5. The main findings of this study are summarized in Section 6.

2. A description of the diesel engine test rig

An in-line four-cylinder diesel engine as shown in Fig. 1 was used in the experimental work presented in this paper. The engine generates a 15 kW of nominal power output at full load condition. The output shaft of the engine is coupled to an Olympian three-phase alternator. A three-phase, 15 kW industrial fan heater was connected to the generator to dissipate the power output of the diesel engine in the experiment. The fan heater has three heat settings, which can be adjusted for various engine loadings during the experiment.

Four resonant-type, micro-30D AE sensors from Physical Acoustic Corporation (PAC) are mounted on the engine head close to each of the four cylinders to monitor the condition of the diesel engine as shown in Fig. 1. The AE signals are pre-