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Automated valve fault detection based on acoustic emission parameters and support vector machine

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Abstract Reciprocating compressors are one of the most used types of compressors with wide applications in industry. The most common failure in reciprocating compressors is always related to the valves. Therefore, a reliable condition monitoring method is required to avoid the unplanned shutdown in this category of machines. Acoustic emission (AE) technique is one of the effective recent methods in the field of valve condition monitoring. However, a major challenge is related to the analysis of AE signal which perhaps only depends on the experience and knowledge of technicians. This paper proposes automated fault detection method using support vector machine (SVM) and AE parameters in an attempt to reduce human intervention in the process. Experiments were conducted on a single stage reciprocating air compressor by combining healthy and faulty valve conditions to acquire the AE signals. Valve functioning was identified through AE waveform analysis. SVM faults detection model was subsequently devised and validated based on training and testing samples respectively. The results demonstrated automatic valve fault detection model with accuracy exceeding 98%. It is believed that valve faults can be detected efficiently without human intervention by employing the proposed model for a single stage reciprocating compressor.

1. Introduction

Reciprocating compressors are often one of the most critical machines in gas transmission, petrochemical plants, refineries and many other industries which deserve special attention. The efficiency and the reliability of a particular reciprocating compressor highly depend on the performance of its valves. Therefore, valve design optimization and improving valve materials have been studied and proposed to extend valves lifetime [1]. Valve failures had been recognized as the most frequent malfunction in reciprocating compressor with high maintenance costs [2,3]. According to an industrial survey by Prognost Systems, 29% of unplanned shutdowns for reciprocating compressors were related to valve faults [4]. This issue drives the consideration of effective and accurate valves' fault diagnostic methodologies to ensure maximum productivity and minimize maintenance costs for reciprocating compressor.

Over the last past decade, various condition monitoring methods have been proposed to diagnose reciprocating compressor valves. For instance, Elhaj et al. [5,6] proposed a method based on the dynamic cylinder pressure and crankshaft instantaneous angular speed (IAS) to detect valve faults in reciprocating compressor. Zhenggang and Fengtao [7]

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proposed a method to monitor the valve condition using the variation of cylinder pressure. Pichler et al. [8] and Wang et al. [9] proposed pressure-volume (PV) measurements for valve condition monitoring in a reciprocating compressor. Then they used support vector machine (SVM) to classify the valve faults. However, the pressure curve is not the most direct way to show valve conditions [10]. Besides, intrusiveness into machine operation and required to fix the sensor into the compressor cylinder in a permanent way. Therefore, pressure measurement is not preferred in industry.

Vibration and acoustic emission based condition monitoring is often considered practical because both measurements are non-intrusive to machine operation. However, many scholars reported the effectiveness of the AE signal measurement compared to the conventional vibration signal analysis method for early fault detection in machinery condition monitoring [11–13]. In addition, AE signal could clearly describe the valve function when it employs for reciprocating compressor condition monitoring. Subsequently, many experimental studies have been carried out to investigate the use of AE for reciprocating compressor valve condition monitoring. For instance, Gill et al. [14] revealed the advantage of using the AE technique for valve faults detection in a reciprocating compressor. They further concluded that vibration analysis is less sensitive to the higher-frequency noise emitted by fluid-mechanical motion. El-Ghamry et al. [15] developed a technique based on AE statistical feature isolation to diagnose several reciprocating machinery faults. Wang et al. [10,16] proposed a diagnosis method for reciprocating compressor valve faults by comparing the AE waveforms for normal and faulty valves in simulated valve motion. Unfortunately, limited operational conditions have been used, and some faults could not be identified. Compared with the AE full waveform analysis, parameter analysis using simplified waveform parameters is a powerful method in the AE signal processing field [17,18]. However, few efforts have been published using AE parameters for reciprocating compressor valve fault detection. For example, Sim et al. [19] proposed a valve fault detection method by analysing the AE signal. The authors employed wavelet packet transform (WPT) to decompose the acquired AE signals to different frequency ranges. Then they used statistical analysis to detect the valve fault based on RMS value. Although the AE could detect the valve faults, the analysis was complicated and not practical to be used in the industry. Besides, wavelet transform (WT) has no standard rules for function selection with constant multi-resolution and adding more complexity.

Many analysis methods have been employed for machinery condition monitoring based on AE signals [20,21]. These methods have shown special advances in rapid signal processing due to the development of computers. For example, Phillips et al. [22] developed a condition classification model for heavy mining truck engines based on oil samples and binary logistic regression (LR). The study provides a comparison of the methods used with the SVM and ANN methods. The authors concluded that logistic regression performs better than other classification methods regarding prediction for healthy/not healthy engines. However, the analysis required additional effort to interpret the results of the LR model. Widodo et al. [23] used relevance vector machine (RVM) and SVM for low speed machine fault diagnosis. Despite the analysis revealed promising results and potential for use SVM in automated machinery fault diagnosis, no published work can be found employing this method to analyse AE parameters for reciprocating compressor valve condition monitoring. This paper will investigate the performance of support vector machine to detect valve condition in reciprocating compressor based on acoustic emission signal parameters. It should be noted that this work doesn't aim to generate an interface for valve fault detection but to employ the SVM for AE parameters analysis in an attempt to reduce human intervention in the analysis process. The paper structure is presented as follows. Section 1 reviews the state of the art methods used in valve fault detection. Section 2 briefly describes the theoretical background, including AE parameters and SVM. Section 3 explains the research methodology, including the research test rig, instrumentation and experimental procedure. Section 4 illustrates modelling results and validation. Section 5 concludes the paper.

2. Theoretical background

2.1. AE signal parameters

Acoustic emission refers to the generation of transient elastic waves produced by a rapid release of energy from a localized source within the surface of material, as reported by the American Society for Testing and Materials (ASTM) [24]. In this paper, AE is defined as transient elastic waves produced by the impact of one surface on another in a reciprocating motion. In other words, the transient elastic waves are produced by the impingement of the plates inside the valve with the upper and lower plate housing during the reciprocating compressor operation. AE hit has specific parameters related to the signal event. The interpretations of AE parameters are often related to the machine condition [25]. In this study, AE parameters have been extracted from the acquired AE hits include amplitude, counts, duration, energy, absolute energy, ASL and signal strength. See Fig. 1 and Table 1.

2.2. Support vector machine

Support vector machine is a supervised machine learning method that relies on statistical learning theory with an ability to handle high input features. This learning technique uses input vectors for pattern classification. During the training process, SVM creates a hyperplane that allocates the majority points of the same class in the same side, while maximizing the distance between the two classes to this hyperplane [2]. See Fig. 2. This hyperplane could be either linear or nonlinear, which is also relevant to the kernel function [23]. SVM training seeks a globally optimized solution and avoids over-fitting so that it can deal with a large number of features. A comprehensive description, limitations and drawbacks of SVM method are available in [26,27]. In the linearly separable case, there exists a separating hyperplane whose functions are:

$$\mathbf{w} \cdot \mathbf{x} + b = 0 \tag{1}$$

where
w: weight
x: input factor
b: bias