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Semi-supervised vibration-based classification and condition monitoring of compressors

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ABSTRACT

Semi-supervised vibration-based classification and condition monitoring of the reciprocating compressors installed in refrigeration appliances is proposed in this paper. The method addresses the problem of industrial condition monitoring where prior class definitions are often not available or difficult to obtain from local experts. The proposed method combines feature extraction, principal component analysis, and statistical analysis for the extraction of initial class representatives, and compares the capability of various classification methods, including discriminant analysis (DA), neural networks (NN), support vector machines (SVM), and extreme learning machines (ELM). The use of the method is demonstrated on a case study which was based on industrially acquired vibration measurements of reciprocating compressors during the production of refrigeration appliances. The paper presents a comparative qualitative analysis of the applied classifiers, confirming the good performance of several nonlinear classifiers. If the model parameters are properly selected, then very good classification performance can be obtained from NN trained by Bayesian regularization, SVM and ELM classifiers. The method can be effectively applied for the industrial condition monitoring of compressors.

1. Introduction

Condition monitoring (CM) of machines and products is an established and important part of successful modern industrial production. In order to manufacture fault-free products, various non-destructive, time series analysis based condition monitoring approaches can be applied during the production process. Vibration signal analysis [1,2] continues to be one of the most useful and popular CM methods, as well as other acoustic and acoustic emission based approaches [3,4]. Analysis of vibration signals usually requires and combines feature extraction and classification methods. Many feature extraction methods are known for various types of vibration signals, and the methods include statistical and spectral approaches, wavelets [5,6], psychoacoustic features [7], the Wigner-Vile distribution [8], empirical mode decomposition [9], chaotic vibration [10], and others. Classification methods include various statistical methods, neural and fuzzy logic based methods [11,12], and other modern machine learning methods, such as support vector machines [13,14] and, recently, deep learning approaches [15]. A broad overview of the numerous methods under the general title of natural computing, including neural networks, fuzzy logic, support vector machines, and other methods applicable to mechanical systems research, is provided in [16].

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In this paper, a vibration-based condition monitoring and fault detection approach for reciprocating compressors installed in refrigeration appliances is discussed. Various condition monitoring methods for different parts of reciprocating compressors have already been proposed. Yang et al. [17] applied neural networks (self-organising feature map and learning vector quantisation) and support vector machines to classify the conditions of reciprocating compressors based on wavelet features extracted from vibration and noise signals. Their results showed good reliability and flexibility in detecting faulty compressors. Elhaj et al. [18] introduced a method for monitoring the condition of reciprocating compressors and their valves using the crankshaft instantaneous angular speed and a cylinder pressure waveform. An experimental study confirmed the results obtained by using numerical simulation. Potočnik et al. [19] proposed a method for the detection of spring faults during the assembly of reciprocating compressors, which causes incorrect positioning of the compressor body on the supporting springs. The method combines analysis of force measurements performed on the manipulating system and statistical analysis by means of adaptive decision strategy. Qin et al. [20] introduced a scheme for the fault detection of compressor valves based on de-noising via basis pursuit, feature extraction via wave matching, and classification via a support vector machine. The core idea of these authors was to determine the underlying model of the vibration signal and to choose a suitable parameterized waveform to match the signal. The method can differentiate compressor valve faults with high accuracy and reliability. Lin [21] developed an automated vibration-based fault detection approach for the classification of reciprocating compressors. They applied a genetic algorithm in order to optimize the process, based on features extracted by time-frequency analysis, and a probabilistic neural network for classification. Wang et al. [22] described a method of diagnosing faults in reciprocating compressor valves using the acoustic emission signal coupled with the simulated valve motion, and considered that the proposed method could be used to easily distinguish between various valve conditions. Pichler et al. [23] proposed a novel approach for detecting cracked or broken reciprocating compressor valves under varying load conditions. The approach is based on a spectrogram representation of the vibration measurement data which shows typical patterns, depending on the fault state.

The existing approaches described in the literature are mostly based on supervised learning, where appropriate sets of samples representing classes of normal and faulty operation are available. Such a situation is difficult to find in industrial environments where prior class definitions are often not available. Labelling the condition monitoring data for supervised fault diagnosis and prognosis is expensive due to the use of field knowledge, whereas unlabelled data contain significant information about normal conditions or faults, which cannot be explored by supervised learning [24]. Consequently, statistical approaches, unsupervised learning, or various semi-supervised approaches, can be applied [25–27].

In this paper, novel a semi-supervised approach for condition monitoring and fault detection of reciprocating compressors is proposed, in which statistical evaluation of features is only applied to extract the initial class members, followed by the application of more advanced classification approaches in order to define class boundaries. The paper provides a comparative analysis of the various state-of-the-art classification approaches, including discriminant analysis (DA), neural networks (NN), and support vector machines (SVM), and also includes a novel technique, i.e. extreme learning machines (ELM). Various practical problems encountered in the application of advanced non-linear classifiers are addressed, and the paper also challenges the common logic of comparing various advanced classifiers in order to find the best one. The viewpoint expressed in this paper is that many modern machine learning classifiers offer more than enough expressive power to model almost any hard classification problem, so that a more appropriate question would be whether or not these classifiers are applied properly. The comparative qualitative results summarized in this paper illustrate this dilemma, and summarize suggestions on the best way of applying the described methods.

The main contributions of this paper are the following: (1) a novel semi-supervised approach specifically designed for industrial condition monitoring of reciprocating compressors is proposed, (2) the solution approach introduces a unique combination of various feature selection methods, statistical extraction of initial class representatives, principal component analysis, and the application of various advanced classifiers, and (3) extensive qualitative comparative analysis of various state-of-the-art classification approaches (including extreme learning machines) that are analysed with respect to efficient industrial condition monitoring application. The method is highly relevant for industrial application, and is demonstrated on a case study comprising 20,000 vibration measurements of compressors acquired during the industrial production of refrigeration appliances.

The paper is organized as follows: a description of the proposed solution approach is presented in the next section. Section 3 then introduces the vibration-based condition monitoring system that was applied for data acquisition of the vibration measurements. Extraction of the statistical and spectral features is described in Section 4, and the application of features to define the initial classes of compressors is explained in Section 5. The various classification methods applied in our study are described in Section 6, whereas Section 7 presents the classification procedure and summarizes the classification results. Discussion and conclusions are presented in Sections 8 and 9, respectively.

2. Solution approach

This study considers the problem of industrial vibration-based condition monitoring where large quantities of vibration measurements are available but labelled class information associated with each measurement is not provided. This situation is relatively common in industrial environments where prior class definitions are not available and are difficult to obtain from local experts. Possible product defects, failures or abnormal operation are not known in advance, so that a machine