Mechanical Systems and Signal Processing 70-71 (2016) 104–119

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Fault detection in reciprocating compressor valves under varying load conditions

Kurt Pichler [a,*], Edwin Lughofer [b], Markus Pichler [a], Thomas Buchegger [a], Erich Peter Klement [b], Matthias Huschenbett [c]

[a] Linz Center of Mechatronics GmbH, Altenberger Str. 69, 4040 Linz, Austria
[b] Johannes Kepler University Linz, Altenberger Str. 69, 4040 Linz, Austria
[c] Hoerbiger Service America, Inc., 5613 DTC Parkway – Suite 1050, Greenwood Village, CO 80111, USA

ARTICLE INFO

Article history:
Received 27 April 2015
Received in revised form
18 August 2015
Accepted 1 September 2015
Available online 28 September 2015

Keywords:
Fault detection
Compressor valves
Varying load conditions
Time–frequency analysis
Feature extraction
Feature engineering

ABSTRACT

This paper presents a novel approach for detecting cracked or broken reciprocating compressor valves under varying load conditions. The main idea is that the time frequency representation of vibration measurement data will show typical patterns depending on the fault state. The problem is to detect these patterns reliably. For the detection task, we make a detour via the two dimensional autocorrelation. The autocorrelation emphasizes the patterns and reduces noise effects. This makes it easier to define appropriate features. After feature extraction, classification is done using logistic regression and support vector machines. The method's performance is validated by analyzing real world measurement data. The results will show a very high detection accuracy while keeping the false alarm rates at a very low level for different compressor loads, thus achieving a load-independent method. The proposed approach is, to our best knowledge, the first automated method for reciprocating compressor valve fault detection that can handle varying load conditions.

1. Introduction

Reciprocating compressors are heavily used in modern industry, for instance in chemical industry, refinery, gas transportation and gas storage. Economic demands of the last decades have also affected the operation of reciprocating compressors. In many cases, compressors run at full capacity without backup. Reliable performance is thus a key issue and becoming more important than ever. Costumers expect reduction or even elimination of unscheduled shutdowns as well as extended maintenance intervals. These challenges are addressed by the development of advanced materials and designs. However, fatigue and wear cannot be avoided.

There is also an economic trend towards saving on labor costs by reducing the frequency of on-site inspections. Such considerations mean that modern gas storage facilities are run by remote control stations and the compressors are monitored by automated technical systems. In this case, the system must be able to retrieve and evaluate relevant information automatically to detect faulty behavior.

* Corresponding author. Tel.: +43 732 2468 6237; fax: +43 732 2468 6005.
E-mail addresses: kurt.pichler@lcm.at (K. Pichler), edwin.lughofer@jku.at (E. Lughofer), markus.pichler@lcm.at (M. Pichler), thomas.buchegger@lcm.at (T. Buchegger), ep.klement@jku.at (E.P. Klement), matthias.huschenbett@hoerbiger.com (M. Huschenbett).

http://dx.doi.org/10.1016/j.ymssp.2015.09.005

For these reasons, monitoring and diagnostics are almost an economical and technical necessity. Firstly, monitoring systems enable condition-based maintenance. Secondly, improved understanding of compressor behavior allows evaluation and recommendations regarding efficient compressor operation.

Condition monitoring can be based on measurements of various physical states, for instance, vibrations, flow rate, power, position, temperature, and pressure. The data required for diagnostic evaluation depend mainly on the types of faults expected and observed. Broken valves, with a percentage of about 36%, are the most common reason for unscheduled shutdowns [1], followed by faulty pressure packings (about 18%) and piston rings (about 7%). The objective of this paper is the *early detection* of cracked or broken (i.e. leaking) valves by analyzing vibration measurements, which reflect upcoming problems in the form of abnormal, changing patterns. This reduces the number of expensive in-cylinder pressure sensors required, and thereby the cost. Furthermore, detecting a crack as early as possible prevents debris of the broken valve to be sucked into the compression chamber and cause severe secondary damage.

Several papers have been published about valve fault detection in reciprocating compressors. In [2], pattern recognition techniques are applied to time–frequency representations and non-stationary auto-regressive models of vibration measurements. Lin et al. [3] combined time–frequency analysis of vibration data and an artificial neural network, which enabled them to differentiate between new and worn valves. Applying their approach to extended test scenarios with 15 seeded faults [4] did not lead to satisfactory validation results. However, by reducing the number of fault cases to 7, they finally achieved good classification results. Cyclostationary modeling of reciprocating compressors is introduced in [5,6]. Zouari et al. [5] decompose the vibrations into periodic and random parts and use the random part to construct an angular frequency map of the vibration energy. This allows to extract indicators for detecting fault signatures. Tiwari and Yadav [7] analyzed pressure pulsation with a back-propagation neural network. The pressure pulsation (peak to peak) is modeled in relation to the leak percentage. In [8], a method using support vector machines was presented. The first four zero-lag sums of sub-band signals of the intrinsic mode functions are extracted from vibration measurements and used as features. Then, typical patterns are classified using support vector machines. Drewes [9] described the effect of a valve fault on the p–V diagram. Additionally, the effects of some other faults such as piston ring wear and damages to crank gears and pistons were discussed. Several different fault detection methods were introduced in [10]. They are divided into four main categories: time domain analysis, frequency domain analysis, orbit analysis, and trend analysis. Yang et al. [11] focus particularly on small reciprocating compressors for refrigerators at constant operation conditions. They use wavelet transform to extract features from raw noise and vibration data and classify them using neural networks and support vector machines. The changes in cylinder pressures and instantaneous angular speed for various leakage percentages were analyzed visually in [12]. Based on the results, a decision table for valve faults is built. Wang et al. [13] introduce an automated evaluation of the p–V diagram. They determine 7 invariant moments of the p–V diagram and classify them using support vector machines. In [14], the valve motion is monitored using acoustic emission signals and simulated valve motion. As the authors state in the paper, the method can easily distinguish between normal valve, valve flutter and delayed closing, but it is not sensitive to leaks.

Some of the approaches are basically similar to the one proposed in this paper in the way that they analyze time–frequency representations of vibration measurements, for instance [2,4,5]. However, none of the methods above, which are sensitive to valve leaks, are designed explicitly for varying compressor load. Since modern reciprocating compressors are controlled by reverse flow load control systems, load changes are not unusual. For some applications, changing the load is even a necessity. Hence, an automated monitoring system has to cope with this fact.

In this paper, we propose a data-driven method based on time–frequency analysis of vibration data. In fact, it is an extension of the approach presented in [15]. Therefore, we compare a spectrogram to a reference spectrogram by computing the point-wise difference. In case of faults, this difference shows certain distinct patterns, indeed not appearing in the case of fault-free states, but depending on the load levels of the spectrograms and on the fault state of the valve. The main task is to identify these patterns on-line. However, due to some uncertainties, for instance noise levels and varying positions of the patterns within the spectrogram, identifying the patterns directly did not lead to satisfying results. Taking a detour via two-dimensional autocorrelation centers the patterns and reduces noise effects. This makes it easier to determine appropriate features for valve fault detection. Once the features are extracted, a classifier is built up based on some pre-collected training samples including different 'fault' and 'no fault' states with the usage of two machine learning techniques (logistic regression and support vector machines). This is an important step in order to extract optimal decision boundaries between the classes 'fault' and 'no fault', which are applied for classifying new on-line data. The big advantage of this approach is that it is independent of the load levels of the two spectrograms involved in the analysis. Whatever the load is, the features will indicate the fault state as showing the same trend over different loads. Furthermore, there is no need to scale or normalize according to other measured values, which helps to avoid the risk of error propagation. The proposed method is, according to our best knowledge, the first method for reciprocating compressor valve fault detection that can deal with changing load levels. Another strong characteristics of our method is that classifiers can be established fully automatically (without any manual redesign phases) on new scenarios or machines, once new training samples have been gathered there, thus opening a wide range of applicability. The main novelty of the paper is the characterization of a leaking valve in the space of spectrogram differences and the subsequent feature extraction.