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Numerical simulation and experimental study of a two-stage reciprocating compressor for condition monitoring

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Abstract

A numerical simulation of a two-stage reciprocating compressor has replicated the operations of the compressor under various conditions for the development of diagnostic features for predictive condition monitoring. The simulation involves the development of a mathematical model of five different physical processes: speed–torque characteristics of an induction motor, cylinder pressure variation, crankshaft rotational motion, flow characteristics through valves and vibration of the valve plates. Modelling both valve leakage and valve spring deterioration has also been achieved. The simulation was implemented in a MATLAB environment for an efficient numerical solution and ease of result presentation. For normal operating conditions, the simulated results are in good agreement with the test results for cylinder pressure waveforms and crankshaft instantaneous angular speed (IAS). It has been found that both the IAS fluctuation and pressure waveform are sensitive detection features for compressor faults such as valve leakage and valve spring deterioration. However, IAS is preferred because of its non-intrusive measurement nature. Further studies using the model and experiments are being undertaken in order to develop fault detection features for compressor driving motors and transmission systems.

Keywords: Reciprocating compressor; Numerical simulation; Instantaneous angular speed; Cylinder pressure; Condition monitoring

1. Introduction

Reciprocating compressors are one of the most popular machines in use in industry. The effective and accurate diagnosis of possible faults which degrade compressor performances are required to help in both reducing maintenance costs and increasing the plant efficiency. For these requirements, a large amount of research work has been conducted with state of the art technologies in detecting and diagnosing various faults in reciprocating compressors. Liang et al. [1] developed a procedure for the detection and diagnosis of valve faults using vibration in the time domain, frequency domain and smoothed-pseudo-Wigner–Ville-distribution. Gu et al. [2] studied automating the diagnosis of valve faults in reciprocating compressors. In 1984, Imaichi et al. [3] studied vibration sources in reciprocating compressors and how to minimise vibration generation.

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Daniel et al. [4] focused on vibration and dynamic pressure methods, including the *P–V* diagram, for fault diagnosis and condition monitoring of reciprocating compressors. Elhaj et al. [5] developed a new method for the monitoring and diagnosis of valve faults in reciprocating compressors using the features obtained from the time domain, frequency domain and continuous wavelet transform of the airborne sound signals.

To develop more accurate fault detection methods, many investigations have been carried out on developing mathematic models of compressors. Costagliola [6] developed the first mathematical model of a reciprocating compressor. The main concern in this model was the dynamics of the valves. The modelled valves were reed type and only one degree of freedom was presumed. Wambasganss [7] worked with a similar model, a high-speed hermetically sealed compressor fitted with reed valves. As with Costagliola's model, Wambasganss paid special attention to the dynamics of the valves; however, several degrees of freedom were allowed. Manepatil et al. [8] studied the modelling and computer simulation of reciprocating compressors with various faults incorporated, as to determine the influence of the faults on performance parameters, using pressure signals to detect and quantify the faults.

There are two significant advantages of employing a mathematical model and a simulation study. One is that with their help less time and equipment are needed to obtain effective fault signatures, especially for the faults, which cannot be induced to a real machine for test studies. The other one is that it permits the researchers to examine the performance of different compressors over the same operating conditions [9,10]. Because of these advantages, this study uses them to develop the detection features for reciprocating compressors. In addition to studying the features from pressure measurement, this paper also investigates crankshaft instantaneous angular speed (IAS) for fault detection. One of the merits of IAS measurement is that it is non-intrusive, compared with the pressure measurement. IAS also has less noise contamination and is more directly related to machine dynamics, compared with conventional structural vibration and airborne acoustics. Therefore, it is easier to interpret IAS results and produce more accurate diagnoses. In addition, the encoder used for IAS measurement is not only cheaper, but also does not need periodic calibration. This allows for the accurate comparison of measurements in different periods and different IAS sensors. For these merits, IAS measurement-based monitoring has studied widely in recent years [17].

Therefore, this paper develops a mathematical model for a two-stage reciprocating compressor to simulate different operations including normal and faulty compressor conditions. It models the working process with a number of non-linear, coupled with differential equations describing the crank mechanism, valve movement, and discharge processes for both the low- and high-pressure compressor cylinders. Simulations are then conducted under different operating and fault conditions including the effects of load change due to change in discharge pressure, and valve faults such as leaking valves. To identify the fault features from both cylinder pressures and crankshaft IAS the simulated and measured results are represented in the angular domain so that they can be explored in association with the typical events in a compressor working cycle. In addition, a test system is also developed to evaluate the model and the simulated results through waveform comparisons between the measured and the predicted pressures and IAS.

2. Dynamic modelling of a two-stage reciprocating compressor

A reciprocating compressor driven by an electric motor converts electric energy into potential energy of the compressed air through the reciprocation motion of a piston in. The working of the compressor thus consists of three different physical processes: an electromagnetic process for the electrical torque generation; a mechanical process for the dynamic movement of the crank shaft, piston and valve; and a fluid flow process for the pressure build up in the cylinders and air flow through the valve. The modelling of the compressor, therefore, focuses on these three processes, respectively.

2.1. Mechanical motion

Based on the construction and working process, a two-stage reciprocating compressor can be represented as in Fig. 1. It consists of three parts: an electric motor, a compressor unit and the compressed air storage tank.