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Combination of process and vibration data for improved condition monitoring of industrial systems working under variable operating conditions

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ABSTRACT

The detection and diagnosis of faults in industrial processes is a very active field of research due to the reduction in maintenance costs achieved by the implementation of process monitoring algorithms such as Principal Component Analysis, Partial Least Squares or more recently Canonical Variate Analysis (CVA). Typically the condition of rotating machinery is monitored separately using vibration analysis or other specific techniques. Conventional vibration-based condition monitoring techniques are based on the tracking of key features observed in the measured signal. Typically steady-state loading conditions are required to ensure consistency between measurements.

In this paper, a technique based on merging process and vibration data is proposed with the objective of improving the detection of mechanical faults in industrial systems working under variable operating conditions. The capabilities of CVA for detection and diagnosis of faults were tested using experimental data acquired from a compressor test rig where different process faults were introduced. Results suggest that the combination of process and vibration data can effectively improve the detectability of mechanical faults in systems working under variable operating conditions.

1. Introduction

The detection and diagnosis of faults in industrial systems is a very active field of research due to the reduction in maintenance costs achieved through the implementation of improved condition monitoring methods. A reduction in the number of unplanned shutdowns, increased system availability, the potential to pre-order spare parts as needed, increased safety in plant operations and the increase of the process efficiency are some of the main benefits of condition based maintenance. Modern industrial facilities are heavily automated and instrumented; consequently there is a lot of process data available which can be used to monitor the condition of the system. The difficulties attached to the development of accurate and reliable first-principle models of large and complex industrial facilities have motivated the development of data driven monitoring algorithms such as Principal Component Analysis (PCA), Partial Least Squares (PLS) or Canonical Variate Analysis (CVA) [1]. Literature gives examples of extensive application of these methods for detection and diagnosis

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of faults using computer simulated data [2–5] or real data obtained from industrial facilities or experimental test rigs [6–12]. Despite their success, PCA and PLS (and their corresponding dynamic approaches known as Dynamic PCA and Dynamic PLS [13,14]) have been reported not to be as efficient as other state-space based methodologies such as Canonical Variate Analysis (CVA). The benefits of CVA are especially relevant when applied to systems working under variable loading conditions, principally due to the representation of the system dynamics [2,15,16].

Despite the success of the aforementioned methods in the detection and diagnosis of process faults, these methodologies can be insensitive to incipient mechanical faults if only process variables are analysed, as typical faults such as misalignment or unbalance have a minor effect on the performance of the machine during the early stages of degradation. However, this kind of fault can have a disastrous effect on the machines, causing catastrophic failures if the malfunction is not corrected due to the dynamic effects of the additional loads generated by the faulty condition. Vibration-based monitoring is probably the most common method for detection and diagnosis of mechanical faults in rotating machinery due to its advantages relative to other methods.

The simplest and most commonly used method for detecting the presence of faults using vibration analysis involves the comparison of different signal features (such as RMS value, Kurtosis or peak amplitude) in the measured signal against a machine working under healthy conditions. Assuming that the initial status of the machine was healthy, any changes in the measured feature response may be assumed to be due to the deterioration of the machine condition. However, this assumption is only valid if all the measurements are taken under the same loading conditions, as different levels of load will generate different vibration levels [17]. It is possible to find in literature some examples of techniques used to monitor the condition of machines working under variable loading conditions using vibration data. McFadden [18,19] proposed a method based on band pass filtered time-domain synchronous averaging (TSA) and the Hilbert transform, with Kurtosis being used as an indicator of fault severity. However there are some disadvantages in this technique due to the requirement of the user to configure the bandwidth for the band-pass filter [20]. Other methods are based on the examination of time-frequency maps where the instantaneous power spectrum is represented [21], but this method does not produce a single indicator of the machine condition that can be tracked in time. Parker Jr. et al. [22] proposed a method based on change detection in the bispectral domain which produced severity indicators which are independent of the loading conditions. However, the method requires long computational times. The work presented by Zhan et al. [23] proposes a technique based on motion residuals, which are calculated as the difference between the TSA of a signal and the average vibration observed in the healthy state under different loading conditions. This area has gained importance in the last years and Braun [24] reviewed the state of the art of vibration diagnostics using TSA in 2011. Other methodologies presented recently are based on capturing the correlation between features extracted from the vibration signal and the operating conditions. This kind of approach has been applied successfully for diagnostics of planetary gearboxes in a bucket wheel excavator [25] and wind turbine bearing diagnostics [26].

There are several examples in industry where machines are working under severe changes in loading conditions, such as wind turbines. Industrial needs are evolving towards more flexible production schemes in order to promote efficiency and maintain their competitiveness in a market where the demand, the price of raw materials and even the price of the energy can be very volatile. For this reason it is important to develop condition monitoring tools that can detect and diagnose faults in industrial systems working under variable operating conditions. These improved methods should be able to deal with both process and mechanical faults in order to ensure the quality of the product and the safe and economical operation of the plant.

In light of these challenges, this paper proposes a method to analyse a combination of process, electric and vibration measurements to provide a more robust and reliable condition monitoring tool. The methodology presented here takes advantage of CVA capabilities to reveal the correlation between the analyzed measurements even under varying operating conditions, with the aim of improving the detection and diagnosis of both, process and mechanical faults. Due to the different characteristics and sampling rates of fast oscillating measurements such as current or vibration, and typical process measurements such as flow rate, pressure or temperature, a feature extraction procedure is proposed in the first instance to allow the combination of both types of data. The objective of the investigation is to demonstrate that the addition of time and frequency domain features from current and vibration can enhance the performance of the CVA for diagnostic purposes. Evidently, including such signals will increase the sensitivity of the method to mechanical faults, an aspect which to date has not been studied in previous investigations on CVA. Additionally, due to the dynamic interactions between components in a system, it is possible that certain faults may be observed as changes in signals recorded by sensors which were not specifically designed to monitor that fault (for example a process oscillation may be observed in a vibration measurement). As a result, by incorporating data from multiple sources throughout an industrial system, the overall fault detection sensitivity of CVA may be increased. The validity of the method was tested using experimental data acquired from an air compressor test rig. The capabilities of the proposed technique were tested initially by seeding simulated mechanical faults in the acquired vibration signals, and these results were validated in a real case study about compressor surge. The results suggest that it is possible to improve the performance of the CVA method in a real system by adding other sources of data such as current or vibration into the analysis.

2. Methodology

2.1. CVA for fault detection in industrial processes

The main objective of the most popular multivariate algorithms for process monitoring is to convert the high-dimensional data acquired from a system into a single health indicator that provides information about the condition of the