Control Engineering Practice 57 (2016) 29–38

Contents lists available at ScienceDirect

Control Engineering Practice

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

Fan mill state estimation based on acoustic signature analysis

Sanja Vujnovic*, Zeljko Djurovic, Goran Kvascev

School of Electrical Engineering, University of Belgrade, Bulevar kralja Aleksandra 73, 11000 Belgrade, Serbia

ARTICLE INFO

Article history:
Received 1 March 2016
Received in revised form
23 August 2016
Accepted 23 August 2016

Keywords:
Acoustic signals
Fault detection
Condition-based maintenance
Thermal power plant
Feature extraction
Discriminant analysis

ABSTRACT

Two new, real time, noninvasive techniques for the detection of states of impact plates in fan mills at thermal power plants, using acoustic transducers as sensor elements, are proposed in this paper. Both methods rely on analysis of recorded acoustic signals in the time and frequency domains. One method uses a linear dimension reduction procedure and the state of the impellers is assessed by analyzing statistical distance as a metric. The second method uses a subtractive clustering technique to determine the cluster centers in multidimensional space and introduces the Euclidean distance ratio as a metric to estimate the amount of wear of the impellers. These data-driven methods are tested on real acoustic signals recorded at the thermal power plant TEKO Kostolac A1 in Serbia and shown to be effective in an extremely noisy environment. A comparison of the methods is made bearing in mind the efficiency and computational complexity of the algorithms.

1. Introduction

In recent years in modern industry great emphasis has been placed on the development of cost-effective approaches to machine maintenance and timely fault detection. This is not so surprising if one takes into account the estimate that one third of the maintenance costs of an average industrial plant are due to excessive or inefficient upkeep (Mobley, 2002). Standard strategies began with breakdown maintenance and advanced to preventive maintenance, which is the most common approach in industry today. Breakdown maintenance assumes that equipment should be fixed only after a failure has occurred, whereas preventive maintenance is based on the assumption that the performance of a system will degrade over time, so inspection and replacement of equipment is scheduled periodically. In this way the risk of sudden failures and degradation of system performance due to wear is significantly reduced, at the expense of more frequent checks. Such checks cause additional spending, which tends to be proportional to the initial cost of the equipment (Jardine, Lin, & Banjevic, 2006). This is precisely the motivation for the development of modern techniques such as condition-based maintenance (CBM), which uses measured data in the form of vibration signals, thermographic images or other parameters to evaluate the state of the machine (i.e. to decide whether it is necessary to perform maintenance or not; Vachtsevanos, Lewis, Roemer, Hess, & Wu, 2006). In this paper two CBM algorithms are developed which, using signals acquired by acoustic sensors, estimate whether it is necessary to replace fan mill impellers in thermal power plants. The main contribution of this research lies in the feasibility and practical applicability of the algorithms in real industrial surroundings, using acoustic transducers as sensor elements.

It is widely known that vibration and acoustic signals hold useful information about the condition of a machine and that they can be used for fault detection and state estimation (Tafreshi, 2005). The use of vibration signals for feature extraction and subsequent diagnostics of the state of the device is well established in the literature and tested on different types of machines, including industrial mills (Su, Wang, Yu, & Lv, 2008). However, over the past ten years increasing emphasis has been placed on the use of acoustic signals in fault detection. It has been shown that they can be as informative as vibration signals (Henriquez, Alonso, Ferrer, & Travieso, 2014) and that, due to their high sensitivity to environmental changes, they can detect certain faults sooner. Also, the sensors used to detect sound are less expensive, contactless, and can be installed externally, while the device is in operation. This technique has been very effective, both independently (Albarbar, Gu, Ball, & Starr, 2010; Wang, Ma, Zhu, Liu, & Zhao, 2014) and in combination with other signals (Loutas, Roulias, Pauly, & Kostopoulos, 2011). One major problem with the use of acoustic signals for fault detection is that they are extremely sensitive to ambient noise, especially if recording is made in a noisy environment. The algorithms proposed in this study manage to overcome this issue and are capable of state estimation in a real, noisy, industrial environment, using only information obtained from acoustic sensors. The basic approach to signal analysis amounts to selecting the appropriate pre-processing method, extracting the

* Corresponding author.
E-mail address: svujnovic@etf.bg.ac.rs (S. Vujnovic).

http://dx.doi.org/10.1016/j.conengprac.2016.08.013
0967-0661/

characteristic features of the signal and choosing a pattern recognition algorithm to diagnose the condition of the machine.

Signal pre-processing is applied to transform recorded signals into feature vectors, which are more suitable for mathematical analysis. There are many methods used in the literature: from simple analysis in the time and frequency domains, to more complex presentations of non-stationary signals, such as Wigner–Ville Distribution (WVD; Albarbar et al., 2010), Wavelet Transform (Su et al., 2008), and Hilbert–Huang Transform (HHT; Wang et al., 2014). WVD provides a time–frequency representation of the signal with a very high resolution, but it also introduces interference between different parts of the spectrum. Time-scale representation in the form of Wavelet Transform has a variable time–frequency resolution that can be extremely useful when several faults of different duration are observed, or when it is not known with certainty which resolution is needed for a successful signal analysis. The HHT method has been gaining popularity in recent years; it is purely empirical and can be used to analyze nonlinear non-stationary signals by separating them into intrinsic mode functions in order to obtain instantaneous frequency. All of these methods are applied in practice; however, they are very computationally demanding and often reduced to analysis of a two dimensional figure, which is either visual or uses a complex image processing and feature extraction method. To preserve computational simplicity and facilitate implementation of the developed algorithms in a hardware device, a simpler analysis of the acquired signal is implemented in this paper. The algorithm is based on observing the characteristics of the signal in the time and frequency domains, and extracting the features using knowledge of the physical characteristics of the process (Stepanic, Latinovic, & Djurovic, 2009; Sun, Chen, & Li, 2007).

After feature extraction, pattern recognition and classification steps are usually followed to obtain necessary information about the state of the machine from the separated features. Various classification methods have so far been tested and implemented in real processes, among which the most commonly used are neural networks (Wu, Tian, & Chen, 2013), fuzzy logic (Sims, Manson, & Mann, 2010) and genetic algorithms (Lu, Yan, & de Silva, 2015). All have been shown as able to process complex input data and successfully diagnose a fault in rotating elements. In this research, however, classification into two or more discrete sets is not applicable because the goal is not to detect a fault, but rather to monitor the condition of the mill and the state of its impact plates. The transition from healthy to worn impact plates is gradual, so during their life cycle they will find themselves in each of the states between the two extremes.

Two new approaches are proposed in this paper, which can estimate the level of wear of the plates inside the mill using acoustic signals recorded in a very noisy environment. The two algorithms have to go through a training procedure in which the recordings of both healthy impact plates (right after maintenance) and worn plates (when maintenance is necessary) are used. The first method relies on discriminant analysis to perform dimension reduction, after which the statistical distance of the measured samples from the training set of the healthy plates is used as a measure of wear of the plates. The second method, however, applies discriminant analysis simply to discard uninformative features, and uses multidimensional space for subtractive clustering. In this case, the level of wear is represented as a ratio of Euclidean distances of the recorded signal from the obtained cluster centers.

It is very difficult to generalize the results of this research due to the fact that each rotating mechanical object used in industry generates a sound signal which is, to greater or lesser extent, specific to that element. However, the authors of this paper are convinced that the proposed concept is largely applicable to entire classes of objects in thermo-energetics. Specifically, the authors have gained positive experience in the application of this methodology to evaluate the operating mode of feed-water pumps, as well as compressors that generate a pressurized fluid.

Two methods for condition based maintenance of fan mills in thermal power plants are proposed. Both use acoustic signals recorded in the vicinity of the mill while it is in operation. These algorithms have been successfully tested on real signals recorded in the thermal power plant TEKO Kostolac A1 in Serbia over a period of several months. The ultimate goal of this research was to develop a simple computer algorithm that can be inexpensively implemented in a commercial hardware device for detecting the states of impact plates. The suggested algorithms consist of several steps. First, acoustic signals need to be recorded in the vicinity of the mill. More information about the fan mill itself and the way in which these signals were recorded is provided in Section 2. Then significant features are extracted from the recordings, analyzed and the wear of the fan mill grinding plates estimated using the methods described in Section 3. The results and discussion are presented in Section 4.

2. Fan mills and signal acquisition

Acoustic signals were recorded on a fan mill at the thermal power plant TEKO Kostolac A1 (Serbia), in a 110 MW block. The impact plates rotate around the center of the mill and, using friction, they grind the coal into a fine powder. When the powder is sufficiently ground, it moves into a heater system that consists of four levels. Since the load of these mills is low, their base rotating frequency is around 12.5 Hz. Within the mill there are 10 impact plates resulting in an expected high energy component at 125 Hz.

2.1. Fan mills

In coal-fired thermal power plants, fan mills are used to dry and pulverize coal which, in the form of finely ground powder, is transported to a mill separator. Insufficiently pulverized particles return back to the mill, while the air mixture is transported to the burners. Mills used to grind coal lose their productivity over time and must be periodically serviced. The impact plates become worn and need to be replaced every 8–10 working weeks (about 1500 working hours), on average. If maintenance is not performed on time, the grinding performance of the mill becomes poor and more time is needed to achieve the optimal size of the ground particles. This, in turn, causes frequent congestion and sporadic loss of mill capacity. Naturally, the time after which it is necessary to carry out maintenance can vary considerably, depending on many factors including the quality of the plates, the granulation of coal, and the presence of other materials inside the mill such as sand, stones, etc. Fig. 1 (a) shows the fan mill on which acoustic signals were recorded. Fig. 1(b) and (c) shows a healthy and a worn impact plate, respectively.

One way of estimating the efficiency of a mill would be a model-based approach which consists of constructing a mathematical model which describes the relation of these and other parameters and the state of the grinding plates. In the literature, there are various attempts to derive a model of a coal grinding mill. Some of these models are deployed in control systems to maintain desired states (Agrawal, Panigrahi, & Subbarao, 2015), while other models are implemented to monitor the states (Wang, Wei, & Guo, 2010). Regardless of their purpose, all these models are extremely complex. Specifically, models that take into account all the relevant data, such as heat, mass and power, are nonlinear models of a very high order and cannot be significantly simplified even with linearization. Therefore, in this paper, instead of