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Vibration analysis diagnostics by continuous-time models: A case study

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ABSTRACT

In this paper a forecasting system in condition monitoring is developed based on vibration signals in order to improve the diagnosis of a certain critical equipment at an industrial plant. The system is based on statistical models capable of forecasting the state of the equipment combined with a cost model consisting of defining the time of preventive replacement when the minimum of the expected cost per unit of time is reached in the future. The most relevant features of the system are that (i) it is developed for bivariate signals; (ii) the statistical models are set up in a continuous-time framework, due to the specific nature of the data; and (iii) it has been developed from scratch for a real case study and may be generalised to other pieces of equipment. The system is thoroughly tested on the equipment available, showing its correctness with the data in a statistical sense and its capability of producing sensible results for the condition monitoring programme.

1. Introduction

Condition monitoring consists of selecting “a measurable parameter on the machines which will change as the health or condition of a machine or other production asset deteriorates. We then regularly monitor that parameter, and look for this change. Once that change is detected we can make a more detailed analysis of the measurements to determine what the problem is, can hence arrive at a diagnosis of the problem” [1]. There are a large number of techniques in condition monitoring [2], though vibration analysis is considered the most widely used in general, due to its high capacity of diagnosis [3].

In this paper a forecasting system in condition monitoring is developed based on vibration data in order to improve the diagnosis of a certain critical equipment. The system is based on statistical models capable of forecasting the state of the equipment combined with a cost model proposed by Christer et al. [4] and generalised to a bivariate signal case by Pedregal and Carnero [5]. The statistical models are set up in a state space (SS) framework, mainly due to its advantages, for which the Kalman filter (KF) and associated fixed interval smoother produce the optimal state estimation. Diagnosis, cost models and the use of SS models are common in the field of condition monitoring, as is usually found in the literature; see comments below.

The number of contributions regarding diagnosis based on a wide range of techniques applied to vibration data of different kinds in condition monitoring is immense. The shock pulse method has been used since 1970 and International Research and Development (IRD) set up spike energy applied to bearings diagnosis; Bently Nevada [6], Bently [7] and www.bently.com describe a new method for diagnosis in bearings based on eddy current proximity probe; Jantunen et al. [8], within the Vision project (Brite Project BE95-1313), propose the use of statistical methods (envelope, spectral, cepstrum, etc.) with the aim of obtaining a diagnosis based on several techniques; Varde et al. [9] develop a system based on an artificial neural network and a rule-based system for diagnosis and emergency procedure generation; artificial neural networks applied to mechanical equipment was proposed by Jardine et al. [10]; Knapp et al. [11] present a condition monitoring programme based on vibration monitoring by statistical analysis; Al-Najjar [12] presents a discussion for a paper company; fuzzy logic is applied by García et al. [13] to air-generators; Saranga and Knezevic [14] use Markov models for reliability prediction; Li et al. [15] analyses industrial gearbox vibration signals by principal components; Al-Bedoor et al. [16] present experimental results that examine the validity of extracting blade vibration signatures from the shaft torsional vibration signals; Al-Qaisia et al. [17] analyse the damage and crack detection in structural components; etc.

In an application known as ISPMAT (Intelligent System for Predictive Maintenance Applied to Trains), Sanz et al. [18] use a multi-channel system (up to 32 signals) for the acquisition of vibration and electrical current data, and other channels for the acquisition of temperature and process variables. All these data are analysed by an anomalies module, in which each model of

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behaviour has its own output variable related to the state of the component. The value of each output variable is related to the inputs to the model, which depends on the working conditions of the machinery. The diagnosis is issued by a decision rule-based expert system with factors of certainty.

There are a number of contributions that integrate the SS framework with condition monitoring. Such contributions are found in a wide range of applications, demonstrating the flexibility and versatility of the approach. One of the oldest applications was the monitoring of aircraft engines by Pau [19]. More recently, these methods have been applied to power systems for planning their short-term maintenance [20]; to calculate the probability of inductor erosion in an induction furnace [4]; to monitor DC motors [21,22]; to the remote condition monitoring of the mechanisms used in railway turnouts, integrating reliability-centered maintenance and remote condition monitoring to the management of switch and crossing maintenance [23–25]; to the prediction of the remaining lifetime of components with fatigue crack growth processes [26]; to the state detection of gearboxes [27]; etc.

The maintenance costs when condition monitoring is applied (alone or jointly with other maintenance policies) have been analysed extensively in the literature as well. Christer and Wang [28] propose a model that minimises the expected cost per unit time over the time interval between the current inspection and the next inspection in a component whose wear has been monitored. This was extended by Christer et al. [4] by adding a replacement cost model to balance at any time costly replacements with possible catastrophic failure. Thorstensen and Rasmussen [29] develop a model for condition monitoring of fatigue and corrosion where the expected cost of breakdown can be established in the same way as described for the efficiency deterioration. In [30] a model is developed to minimise the expected total system cost over a given mission time by means of Monte Carlo simulations. Grall et al. [31] develop an analytical model for a condition-based inspection/replacement policy for a stochastically and continuously deteriorating single-unit system to minimise the long-run expected maintenance cost per unit of time. The model developed by Castanier et al. [32] uses a cost function to coordinate the inspection and replacement of two components and minimise the long-run maintenance cost of the system [29,33,34].

The application of statistical tools to the diagnosis by means of vibration analysis can have great influence on the safety in big companies with a great amount of critical equipment, but also can improve the safety in small companies with a small amount of critical equipment, in which the implementation of a condition monitoring programme is in general more complex. Therefore, the main advantages of the present paper are:

- The forecasting system proposed here is on an area where the number of models proposed for solving real situations is still developing. In addition, validation of such models based on data collected at industrial plants is not very extensive yet [29,33,34].
- The statistical models on which the condition monitoring programme is based are set up in continuous time for bivariate signals. This represents a novel point of view regarding the diagnostic techniques exploited in condition monitoring and contributes to the application of these models to real cases. Using more than one signal implies a better diagnosis, since more information is used by the system. Continuous-time models are compulsory in this particular application from a formal point of view, since the data are irregularly sampled in time because of the data collection process.
- The statistical models are set up in a SS framework, because of its advantages and flexibility. A consequence of this fact is that the system can be generalised straight away to more than two signals.
- The system has been built for a real life case and the software has been developed by the authors from scratch. Therefore, a by-product of this research is a software package that implements the system. It has been developed with the help of the SSpace toolbox in Matlab® [35].
- Due to the previous item, the system may facilitate and speed up the equipment diagnosis, something rather difficult that requires trained staff, sometimes rather scarce. It also allows for the confirmation of the report issued by a human expert about the machine working conditions.

The outline of the paper is as follows. Section 2 is devoted to some important concepts about condition monitoring and vibration analysis. Section 3 presents the production process in which the critical equipment in the latter case study is installed. It also outlines the condition monitoring and the data acquisition process for the industrial equipment in the case study. In Section 4, the specific condition monitoring system is presented, emphasising the formal statistical set-up, the particular model used in this application and the cost model used in order to foresee when a preventive replacement should be carried out based on the point forecasts and their distributions (i.e. the output of the model). Section 5 exposes the main empirical findings. The final section extracts the main conclusions.

2. Condition monitoring

There are three main magnitudes usually employed to characterise the vibration amplitude: acceleration, velocity and displacement. They can be represented with respect to frequency (spectrum), or with respect to time. The use of one such measure instead of the others depends fundamentally on the working revolutions of the equipment under analysis. The main objective is to use the magnitude (i.e. acceleration, velocity or displacement) that provides a more uniform spectrum, since the necessary dynamic range is rather small [36].

According to [37], the presence of a failure in industrial equipment, even in its initial phase, produces increases or modifications of vibratory signals that can be detected. As a result, an extensive set of techniques has appeared that can be applied to the analysis of vibrations, in order to identify flaws in machinery. The number of methods is so large that it is necessary to investigate the most appropriate ones for the diagnosis of each particular piece of equipment. The main factors that may influence the method selection are diverse, like conditions of operation, the critical level of the machine and the means, the staff available for the control of the analysis, etc.

The diagnosis system generally used in industrial plants consists of obtaining an overall vibration amplitude [38], and of making a trend analysis. When an alarm value is reached, the spectral analysis is carried out. For example, in [39] the following sequence of action is recommended: (i) obtain the spectrum; (ii) control the state of the relevant harmonic frequencies; and (iii) make plots of trends of such harmonics.

There exist elementary condition monitoring techniques that detect failures only at a final state of evolution, whereas more complex ones are capable of confirming the presence of deficiencies from an early stage of development. In addition, different vibratory parameters under control present high variations that are not associated with alterations in the state of the equipment. It is necessary to distinguish between the variations