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Fault detection in non-Gaussian vibration systems using dynamic statistical-based approaches

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ABSTRACT

This article develops and contrasts two different statistical-based techniques for monitoring mechanical systems that produce stochastic, non-Gaussian, and correlated vibration signals. Existing work in this area relies on the assumption that the recorded signals follow a multinormal distribution and/or the data model is static, i.e. the signals are assumed to possess no serial correlation. The developed approaches rely on (i) recent work on independent component analysis and support vector data description that is applied to a dynamic data structure and (ii) the incorporation of the statistical local approach into a dynamic data representation. The analysis of experimental data from a gearbox system confirms (i) significant auto- and cross-correlation within and among these signals and (ii) that they cannot be assumed to follow Gaussian distributions. The application of both approaches showed that they are more sensitive to incipient faults than conventional multivariate statistical methods.

1. Introduction

The early detection of incipient fault conditions is of fundamental importance for the operation of mechanical systems, such as aerospace, civil, and general mechanical systems. The consequences of not being able to detect such faults at early stages can, for example, include reduced productivity in manufacturing processes, reduced efficiency of engines, equipment damage or even failure. Early detection of such faults can therefore provide significant improvements in the reduction of operational and maintenance costs, system down-time, and lead to increased levels of safety, which is of ever-growing importance. An incipiently developing fault in a mechanical system usually affects certain parameters, such as vibration, noise and temperature. The analysis of these "external variables" therefore allows the monitoring of internal components, such as gears, which are usually inaccessible without the dismantling of the system. It is consequently essential to extract relevant information from the recorded signals for the aim of detecting any irregularities that could be caused by such faults.

The work described in this paper relates to the signal analysis of a set of vibration sensors to detect incipient tooth defects in a gearbox. If running speed and loading conditions are kept constant, the vibration signals are influenced by defects, such as deformation, breakage or fracture of the teeth. Over the last few decades, various techniques have been proposed, including averaged vibration signal, spectrum and time-frequency techniques, as well as amplitude and phase techniques. Recent work in these areas includes [1–10]. Due to the conceptual simplicity, Fugate et al. [11] recently showed

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that applying statistical process control technique in conjunction with auto-regressive filters could detect a progressive damage of a concrete bridge. Since vibration information may be available from more than one sensor, Baydar et al. [12,13] introduced the application of multivariate statistical process control (MSPC) to successfully detect tooth defects. In a comprehensive comparison, Baydar et al. [13] showed that multivariate statistical techniques are equally as sensitive in detecting tooth defects as signal-based approaches but easier to implement in practice. More recent application of MSPC methods in monitoring mechanical systems have been reported in Refs. [14–16].

Despite the reported success of MSPC-based work in detecting faults by analyzing recorded vibration signals, the research literature has not considered data structures that can represent correlation among and between these signals. Moreover, the MSPC monitoring scheme assumes that the vibration signals follow a Gaussian distribution. The analysis of experimental data in this article, however, shows that readings from vibration sensors may not possess such statistical properties. To address these issues, this paper proposes two approaches that can monitor correlated vibration signals which are non-Gaussian. Proposed work on dynamic MSPC [17,18] showed that an incorrect data model can affect the number of Type I and II errors, whilst the same effect is noticeable for assuming an incorrect distribution function for the vibration signals [19–21].

Although a number of research studies have been carried out on these two aspects separately, such as dynamic PCA (DPCA) [17,18,22], improved dynamic PCA [23], subspace model identification (SMI) [18,24,25] for the dynamic issue, and independent component analysis (ICA) [17,19,20], support vector machine (SVM) [21], support vector data description (SVDD) [26] for the non-Gaussian issue, the research literature has not offered a comprehensive treatment that considered both dynamic and non-Gaussian behavior.

1.1. *First proposed method*

The first technique is based on a dynamic ICA formulation [27] to produce source signals that, in turn, generate correlated and non-Gaussian vibration signals. Utilizing the SVDD method then allows performing a statistical inference to determine whether the recorded signals correspond to an in-statistical or out-of-statistical-control situation. With the latter scenario being indicative of a fault condition, this method represents a dynamic extension of the recent work in Ref. [26].

1.2. *Second proposed method*

The second algorithm relies on the utilization of the statistical local approach [28,29] to monitor changes in parameters for computing the state sequences. The underlying data model, describing the correlated vibration signals, is of Kalman innovation form and represents a state space model. The statistical local approach has been proposed as a method for detecting abrupt changes [28], and overcomes the effects of non-Gaussian process data [30]. This technique has been applied in many areas, such as bridge damage detection and mechanical vibration monitoring [29,31,32]. A recent study in Ref. [33] proposed the integration of statistical local in an MSPC framework to detect incipient changes in the variable covariance structure. This second approach incorporates the statistical local approach into the dynamic monitoring framework which is based on SMI and therefore represents a dynamic extension of the work in [30,33].

2. Gearbox application study

This section describes the specification of the gearbox system used in this study and discusses how fault conditions of various magnitudes were injected into this system. This is an important research area, given that a gearbox is an arrangement involving a train of gears by which power is transmitted from the engine to the axle of a car for example.

2.1. *Description of the gearbox system*

A schematic diagram of the two-stage helical gearbox system, used in this study, is given in the left plot and a similar gearbox is shown in the right plot of Fig. 1. A tooth breakage in a gearbox, which is a serious localized fault, was simulated by removing a certain percentage of one tooth in the pinion gear. This tooth removal enables the experimental representation of gradual fault advancement to test the statistical-based fault detection schemes developed in this article. Each experiment was performed under the full-load condition of 260 N m. Further specifications of the gearbox are summarized in Table 1.

Similar to previous research [2,13], which studied the same problem, 4 accelerometers, whose locations are depicted in the left plot of Fig. 1, recorded the vibration of the gearbox under full-load conditions. The vibration signals were simultaneously sampled at a frequency of 6.4 kHz. Each recorded data set contained 2620 samples, which corresponded to 7.81 revolutions of the pinion.