Journal of Sound and Vibration 337 (2015) 321–341

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Development of a generic rotating machinery fault diagnosis approach insensitive to machine speed and support type

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ARTICLE INFO

Article history:
Received 14 April 2014
Received in revised form
22 September 2014
Accepted 22 October 2014
Handling Editor: K. Shin
Available online 14 November 2014

ABSTRACT

Despite numerous difficulties that can be encountered when using trend monitoring of harmonic components from the simple amplitude spectra to aid diagnosis of rotor related faults on large multi-stage multi-bearing rotating machines, the technique continues to be the mainstay in industry. This is due in part to factors including a lack of adequate experimental validation of newly proposed techniques aimed at improving or replacing this traditional practice. Nevertheless, in recent studies, simple but robust Individual Speed Individual Foundation (ISIF) and Multi-Speed Individual Foundation (MSIF) fault diagnosis (FD) methods that both used a single vibration sensor per bearing without the use of phase information was applied with good results to fixed and variable speed machines respectively. A similar Individual Speed Multi-Foundation (ISMF) technique later enabled FD by direct comparison of vibration data between similarly configured machines with different dynamic characteristics operating at the same steady-state speed. However, the efficacy of these techniques was questioned as they were all applied to experimental rigs with the same few rotor related faults. Thus, the objective of this study is to test the transferability of these said techniques on a wider range of rotor related faults on different machines. A new Multi-Speed Multi-Foundation (MSMF) method which facilitates FD by the direct comparison of vibration data from similarly configured machines with different dynamic characteristics operating at different steady-state speeds is also proposed. It is observed that the previously proposed methods are indeed able to separate the range of conditions tested on machines with different dynamic characteristics. Analysis done with newly proposed MSMF approach gives improved isolation of fault conditions tested compared to the previously proposed techniques.

1. Introduction

Vibration-based diagnosis of rotor related faults using the simple amplitude spectra is widely used in practice; owing to factors including its range of fault sensitivity, relative computational simplicity and flexibility for application to different types of machines. Despite its versatility, challenges can be encountered when considering fault diagnosis (FD) of a large rotating machine with multiple bearings; say a multi-stage steam turbine. A number of vibration sensors and measurements

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http://dx.doi.org/10.1016/j.jsv.2014.10.033
0022-460X/

(including phase information) are required at each bearing location [1]; which results in the acquisition of large volumes of data. The measured data then becomes a computational burden to process and extract useful information (features) which best represent the health (condition) of the machine [2,3]. Even after successful extraction, fault features may be indistinguishable and misleading. Consequently, in traditional practice, it has been accepted that the simple spectra on its own may not be adequate for confident FD and might require support from additional techniques; such as the Orbit plot [4]. Because of such difficulties in processing and interpretation of the data, the FD process can be lengthy, subjective and inconsistent; all of which could prove costly.

Consequently, ongoing research has focused on improving vibration-based FD. Such efforts can be divided into two broad categories: the improvement or development of traditional techniques and alternatively the development of new techniques [5]. The works done can be further divided into different or a combination of different focus groups [6]: data input, data manipulation, health assessment and prognostic assessment. Data input deals with sensors, transducers and methods of data entry, while data manipulation addresses signal processing and feature (descriptor) extraction. The British Standards Institution [6] states that health assessment "utilises expertise from human or automated agent to determine the current health of the equipment and to diagnose existing fault conditions". Prognostics deal with predicting the future state of monitored equipment using various models and their algorithms. Some recent experimental works aimed at developing new approaches in the mentioned focus groups have been succinctly reviewed.

Hashemian [7] demonstrated the usefulness of wireless vibration sensors for remote condition monitoring of rotating equipment on a research nuclear facility. The biggest benefit was of course remote access to equipment which would have otherwise been unsafe for manual data collection. Similarly, Arebi et al. [8] compared wireless sensors with three commonly used sensors; a laser vibrometer, an accelerometer and an encoder. These were used to measure and compare their respective responses in the time and frequency domain on a misalignment condition to test the performance a wireless measurement scheme. It was found, amongst other things, that "the wireless sensor produces a full separation of levels and shows a unique increasing trend with speed." Though, useful for remote access of machinery with clear benefits for increased safety condition monitoring technicians, the use of wireless sensors does not mitigate the aforementioned difficulties associated with the traditional practice in vibration-based fault diagnosis. That being said, Elnady et al. [9] proposed the use of the on-shaft vibration (OSV) measurement technique using a MEMS wireless accelerometer and found that it requires special arrangement of the measurement instrumentation that currently may not be applicable in a practical sense.

Numerous studies have focused on developing relatively new data manipulation techniques such as time–frequency analyses [10–12]. Even with over 20 years of development and promising results thus far, there still exist various complexities, with the practical application of the widely studied time–frequency analysis methods to machine FD [10,12]. Qin et al. [13] proposed a technique which focused on multicomponent vibration signal separation. The objective was to introduce a method that could accurately extract features that would be useful for FD. Though it was opined that the proposed method had better accuracy than some established time frequency techniques, it was noted that the method is slow and in need of future development.

Other researchers have directed efforts that address combined improvements in data input, data manipulation and health assessment. That said, Sinha and Elbhbah [14] suggested fusion of data from all sensors in the frequency domain for the extraction of useful diagnostic features, while avoiding the complexity of traditional techniques. The Higher Order Spectra (HOS), namely bispectrum, which is derived from a composite spectrum, was demonstrated. It was postulated that the HOS would facilitate: sensor reduction (as only one sensor per bearing was required), utilisation of computational power in current signal processing to compensate for sensor reduction and data fusion. By exploring the relations of different harmonics of the same signal measured at a bearing pedestal, the authors were able to obtain unique features for the conditions tested. Elbhbah and Sinha [15] later explored the usefulness of the coherent and non-coherent composite spectra for data fusion of on-bearing vibration data for fault discrimination and observed that the coherent composite spectra were better able to discriminate between the faults tested. In both studies, it was similarly concluded that the suggested methods had the potential for practical application, but the methods were complex.

Jiang et al. [16] proposed a multi-sensor feature-level fusion methodology with subsequent Support Vector Machine (SVM) classification of time domain vibration features for the diagnosis of rotating machinery faults including rotor crack. The authors opined that for a complex system, a single sensor is incapable of collecting data requisite for accurate fault diagnosis, and as such, "multiple sensors "needed in order to do a better job" when applied simultaneously are better able to comprehensively describe a machine state. The technique was demonstrated on a small laboratory rig with crack fault amongst others. Though promising, since there is no standard method for choosing the kernel function [17], which is the key process for SVM, the choice of the kernel function used here, and by extension the results obtained, is questionable.

Nembhard et al. [18] introduced a novel processing method for the diagnosis of rotor related faults on a machine operating at an individual steady-state speed, while Nembhard and Sinha [19] later developed this technique for the diagnosis of faults on machines that can operate at different steady-state speeds called a "Unified Multi-Speed Analysis". The salient common objectives in both studies were the development of a simple but robust diagnostic method that could process data from a reduced number of sensors per bearing. The former technique was based on recognition of patterns in temperature and vibration-based features extracted from each bearing for a given condition, while the latter was based on feature-level fusion of purely vibration features extracted at different steady-state speeds from a given machine with a given rotor fault. Both studies similarly produced easily interpreted graphical representations that negated the need for a skilled and highly experienced vibration analyst. Although the results presented in both studies were seemingly practicable, both