Mechanical Systems and Signal Processing 83 (2017) 356–370

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Sinusoidal synthesis based adaptive tracking for rotating machinery fault detection ☆

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A R T I C L E I N F O

Article history:
Received 5 April 2015
Received in revised form 28 April 2016
Accepted 13 June 2016
Available online 24 June 2016

Keywords:
Sinusoidal synthesis
Time series modeling
Adaptive
Vibration signal
Fault detection

A B S T R A C T

This paper presents a novel Sinusoidal Synthesis Based Adaptive Tracking (SSBAT) technique for vibration-based rotating machinery fault detection. The proposed SSBAT algorithm is an adaptive time series technique that makes use of both frequency and time domain information of vibration signals. Such information is incorporated in a time varying dynamic model. Signal tracking is then realized by applying adaptive sinusoidal synthesis to the vibration signal. A modified Least-Squares (LS) method is adopted to estimate the model parameters. In addition to tracking, the proposed vibration synthesis model is mainly used as a linear time-varying predictor. The health condition of the rotating machine is monitored by checking the residual between the predicted and measured signal. The SSBAT method takes advantage of the sinusoidal nature of vibration signals and transfers the nonlinear problem into a linear adaptive problem in the time domain based on a state-space realization. It has low computation burden and does not need a priori knowledge of the machine under the no-fault condition which makes the algorithm ideal for on-line fault detection. The method is validated using both numerical simulation and practical application data. Meanwhile, the fault detection results are compared with the commonly adopted autoregressive (AR) and autoregressive Minimum Entropy Deconvolution (ARMED) method to verify the feasibility and performance of the SSBAT method.

1. Introduction

In rotating machines, component failures can lead to costly downtime and they can even be catastrophic. Specifically, rolling element bearings and gears are among the most critical components in rotating machinery, and their faults can cause severe damage to the entire machine. Fault detection of rotating machinery has broad applications in many industrial and engineering systems, such as power plants, turbines [1] and helicopter transmissions [2]. Generally, fault detection methods can be either signal-based or model-based. The vibration signal-based technique provides a unique solution for in-situ, non-intrusive fault detection for rotating machines, and numerous vibration based fault detection approaches, ranging from

☆ This work is supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) and Syncrude Canada Ltd (NSERC CRDJ 447546-13).

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http://dx.doi.org/10.1016/j.ymssp.2016.06.019
0888-3270/

frequency domain to time domain ones, have been developed and successfully applied [3].

Frequency domain or spectral analysis of vibration signals is commonly used for rotating machinery fault detection. Cyclostationary analysis [4] can take advantage of the stochastic process nature of the vibration signal. Cepstrum analysis [5] is another common technique in this field. In this method the cepstrum magnitude is used to detect the side-bands associated with time varying components or to quantify harmonics. Spectral Kurtosis (SK) was proposed for fault detection based on rotating machine vibration data in [6]. SK is a method in which a bandpass filter is selected to maximize the Kurtosis of the resulting filtered signal. The SK method is shown to be effective in rotating machine monitoring and has been receiving wide research attention in the last few years.

In contrast to frequency analysis, time-domain analysis is fast and easy to implement. There have already been a great amount of schemes developed for time-domain analysis. Most methods are applied to the raw signals directly such as Root Mean Square (RMS), Crest Factor (CF), Energy Ration (ER), Kurtosis and Energy Operator (EO) [7]. Among the many commonly used time-domain methods the Time Synchronous Average Signal (TSA) based method is deemed to be powerful. TSA can be used to remove any signal components that are not synchronous with the rotating bearings or gears. Therefore, random background noises and disturbances can be easily removed. To filter out asynchronous vibration and noise, speed or tachometer information is combined with angular re-sampling. TSA method has found successful applications in bearing and gear fault detection [2]. A major drawback of TSA is the significant loss of information contained in the distribution or autocorrelation function, which may contain important information related to possible faults [8].

In rotor dynamics analysis, over the past two decades, the order-tracking (OT) technique has been actively researched. The conventional order tracking approaches use orders (i.e. multiples of the rotating speed) as the frequency base [9], which are mainly based on Fourier analysis, such as windowed Fourier transform (WFT) and the resampling methods [9,10]. They have limited resolution in some situations and suffer from a number of shortcomings. In particular, they are ineffective when there exist multiple components rotating at independent speeds. For performance improvement, model-based methods have been proposed, where OT problems are formulated based on state space models. A well-known scheme is Vold–Kalman-filter(VKF) OT [11–13], in which the order amplitudes are calculated off-line by using a least-squares approach. Therefore, the VKF OT method is generally implemented as a post-processing scheme. Adaptive model-based OT methods were recently proposed based on a recursive least-squares [14] and adaptive VKF approach [15]. Online real-time process monitoring has been performed using the adaptive VKF OT techniques [16]. Both the conventional OT and the model based OT methods require information of shaft speed. Gabor OT is another technique which can extract specific order components in addition to characterizing the processed signal in rpm-frequency domain [17]. The Gabor OT can be used for applications where rotational speed information is not available. When applying order tracking to rotating machinery fault diagnosis, order amplitudes, as a function of harmonic order and shaft speed, are calculated and analyzed for fault diagnosis purpose. Therefore, this method can be referred to as order domain fault diagnosis. Human experience or intelligent expert system may be needed in OT based fault diagnosis [18,19].

With the development of miniature sensors, wireless communication, and high-efficiency computing techniques, time-series methods become more popular and applicable in machine fault detection applications [20]. Autoregressive (AR) model is commonly used in time-series analysis, in which the model parameters carry important information of the system condition, and an accurate AR model can reflect the characteristics of a dynamic system [2,21,22]. An AR model is usually a linear model identified from the signal under no-fault condition. The model is then used to predict the future sample to be compared with the measured value. This error in prediction, also called the residual, is well-suited to extracting features associated with a vibration fault. AR models are data driven in nature so that faults can be detected or even isolated without knowledge about the physical model of the system. On the other hand, AR models may be of high dimensions. For a vibration signal composed of M sinusoids, at least a $2M$ order model is shown to be suitable [2]. In addition, the AR method normally requires a priori knowledge of the vibration under no-fault conditions for data-fitting. Minimum Entropy Deconvolution (MED), originally proposed by Wiggins for applications on seismic recordings in 1978 [23], has been recently applied to gear fault detection together with the AR method by Endo et al. [21]. It was shown that the ARMED resulted in improved performance over the traditional AR method. The MED algorithm prefers a solution with the fewest number of impulses to maximize the Kurtosis. This can sometimes result in deconvolution solutions of fewer-than-desired impulses. Moreover, in this method, a filter needs to be designed to maximize the signal Kurtosis, which may lead to increased false alarm rate in the normal condition. Recently, a new Maximum Correlated Kurtosis Deconvolution method was proposed and shown to be effective in detecting periodic faults [24]. However, it needs the periodicity information of the vibration signals.

It is known that the vibration feature of a rotating machine usually consists of three major components: a sinusoidal component, an impact caused broad-band frequency component and random noise [25]. Therefore, detection of impact-faults such as rotor rubbing, rolling element bearing inner or outer-race faults, and gear tooth faults can be improved through prediction based on a sinusoidal restriction [26]. These impact faults are among the most damaging machine faults and it is crucial to detect them before they cause more catastrophic failures. Impact faults are known to periodically excite the rotating machine dynamics with time-localized disturbances. Analysis based on sinusoidal synthesis is well established as a method for synthesizing accurate replicas of musical tones [27]. Sinusoidal expansion and parameter identification methods were also developed and applied to bearing and gear fault detection and prognosis [28]. Recently, adaptive filtering and estimation theory have been utilized for estimation of sinusoidal frequencies and amplitudes [29–31]. A discrete-time version of the frequency estimator model was given in [32] and it was adopted for gear crack fault detection.

As indicated in [7], for a vibration signal, its trend represented by the sinusoidal components is more obvious in