Journal of Sound and Vibration 368 (2016) 191–201

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Smoothing localized directional cyclic autocorrelation and application in oil-film instability analysis

Xiaofeng Liu*, Lin Bo, Honglin Luo

The State Key Laboratory of Mechanical Transmission, Chongqing University, Chongqing 400044, PR China

A R T I C L E I N F O

Article history:
Received 22 September 2014
Received in revised form
18 November 2015
Accepted 9 January 2016
Handling Editor: K. Shin
Available online 25 January 2016

Keywords:
Localized optimal radially Gaussian kernel
Smoothing directional cyclic autocorrelation
Rotor-bearing system
Oil film instability

A B S T R A C T

In this paper, smoothing localized directional cyclic autocorrelation (SLDCA) is proposed as a novel time–frequency distribution to analyze the vibration signal of rotor-bearing system in oil-film instability. Based on the cyclostationarity of real-valued signal, directional cyclic autocorrelation (DCA) is defined for the complex-valued signal. In order to suppress the cross-term interferences, the DCA is localized and filtered with two-dimensional time–frequency window which allows the smoothing kernel function to adapt to the signal time–frequency-varying characteristics. And then the localized DCA is smoothed by the localized optimal radially Gaussian kernel and cascaded to produce the SLDCA with high time–frequency resolution and less susceptibility to cross-term interferences. The application of SLDCA in the oil-film instability analysis verifies that the SLDCA can not only precisely detect the instantaneous frequency information in the time–frequency distribution with high resolution and robustness to the noises and cross-terms, but also provide the phase coupling information of rotor instantaneous planar motion by which the directivity and shape of the planar motion can be determined.

1. Introduction

Oil-film instability is a common nonlinear fault in a rotor-bearing system, which may bring a serious hazard to rotary machines. Causes of oil-film instability can be rotor/stator relative motion, fluid-dynamic forces producing instabilities and self-excited vibration [1,2]. For the practical rotor-bearing system under many circumstances, the oil-film instability is usually combined with other secondary phenomenon such as rub-impact, crack, pedestal looseness etc. [3,4]. Accordingly, the vibration signal collected from a rotor-bearing system consists of random, periodic, non-stationary and nonlinear components because of the nonlinear transfers. Especially in oil-film instability, the rotor vibration signal exhibits the nonlinear modulation and phase/frequency coupling features which are difficult to be completely and precisely extracted with the traditional single data analysis methods currently used, such as orbit portrait, FFT spectra, cepstra and time–frequency or time-scale analysis, etc.

The analysis of complex-valued signal derived from two orthogonally installed proximity sensors can overcome the problem of information loss of rotor rotation direction or relative phase in conventional spectrum analysis. The classic complex-valued analysis method for rotor-bearing system was the full spectrum from which the orbit ellipticity and vibration precession could be determined without being affected by probe orientation [5,6]. However, the full spectrum has

* Corresponding author.
E-mail address: liuxfeng0080@126.com (X. Liu).

http://dx.doi.org/10.1016/j.jsv.2016.01.013

the limitations in revealing local or instantaneous rotor vibration information and distinguishing the first critical frequency resonance from oil whip [7]. The directional Wigner–Ville distribution (DWVD) was proposed to identify the shape, directivity, and inclination angle of the time-varying complex-valued signal representing instantaneous planar motion [8,9]. But the DWVD has the problems of intense cross-term interferences so as to lose some important effective information.

Cyclic spectral analysis can be an effective tool for rotating machinery diagnostics practice, which has been shown to be a powerful tool to give insight into the underlying periodic time-varying characteristics through nonlinear transformation [10]. Considering multi-source information on the same section of a rotor and nonlinear feature of oil-film instability, directional cyclic autocorrelation (DCA) is developed to provide the multi-channel fusion information of rotor vibration. However, it is noteworthy that DCA is a bilinear transformation which could cause intense cross-term interferences when the signal contains multiple components. How to effectively separate the auto-terms and restrain the cross-terms is very important for the improvement of signal characteristics interpretability. The problem of cross-terms motives researchers to design new and effective kernels since the solution to cross-term elimination or "artifact" is a well designed kernel, such as hyperbolic wavelet kernel [11,12], Choi–Williams kernel [13], high-order hyperbolic kernel [14]. These efforts have been considerably made to keep the tradeoff between the effect of cross-term interferences and time–frequency resolution. This led to the signal-independent kernels and adaptive time–frequency representation in which the kernel function varies with the signal [15,16]. However, the signal-dependent representation uses one kernel to adapt the entire signal, which forces the compromises in the kernel design for multi-components signals.

Based on the disadvantages of conventional methods, the localized smoothing directional cyclic autocorrelation (LSDCA) is proposed by using the time–frequency localized kernel to smooth the directional cyclic autocorrelation. It can not only provide the phase coupling information of rotor instantaneous planar motion by which the directivity and shape of the planar motion can be determined, but also reveal the instantaneous frequency information in the time–frequency distribution with high resolution and robustness to the noises and cross-terms. The effectiveness of the method is verified by the experiments performed on the rotor-bearing test rig with the oil-film instability faults. The structure of the paper is organized as follows. In Section 2, the theory of real-valued signal cyclostationarity is reviewed. Subsequently, combined with complex-valued signal notions the directional cyclic autocorrelation for complex-valued signal is represented. The method of smoothing directional cyclic autocorrelation is proposed in Section 3 and then the smoothing localized DCA is introduced in Section 4. In Section 5, the experiments conducted on a test bench are described and the results are obtained and discussed. In Section 6, the conclusions and the summary contributions of this paper are given.

2. Directional cyclic autocorrelation

2.1. Cyclic autocorrelation function of real-valued signal

For the journal bearing supported rotor system in oil-film instability, a number of harmonic components produced are nonlinearly transformed, and then the vibration produced contains spectral peaks at sum and difference frequencies, which are harmonically related. Accordingly, the vibration signals rotating machinery exhibits modulation and cyclostationarity character which generally are usually weak and buried in noises or other higher energy disturbances owing to the strong resonance in oil film instability. In this case, the cyclic autocorrelation shows its advantages in suppressing noise interferences and uncovering the underlying cyclic characteristics

A concise review of cyclostationarity and its applications have been presented in Refs. [17,18], respectively. A real-valued time series $x(t)$ is considered as cyclostationary if its first and second order moments are both periodic. In the engineering application, the interest generally focuses on the second order cyclostationary properties which deal with the auto-correlation function $R_x(t,\tau)$

$$R_x(t,\tau)=E\left\{x\left(t-\frac{\tau}{2}\right)x^*\left(t+\frac{\tau}{2}\right)\right\} \tag{1}$$

where $E\{\cdot\}$ is the mathematic expectation operator, $*$ denotes complex conjugation, τ is the time lag. For a cyclostationary signal, $x\left(t-\frac{\tau}{2}\right)x^*\left(t+\frac{\tau}{2}\right)$ has periodic statistics and $R_x(t,\tau)$ can be expressed as

$$R_x(t,\tau)=\sum_{\alpha} CR_x(\alpha,\tau)\mathrm{e}^{\mathrm{j}2\pi\alpha t} \tag{2}$$

where $\alpha=m/T\ \ (m\in Z)$ is cyclic frequency and $CR_x(\alpha,\tau)$ is the Fourier coefficient of $R_x(t,\tau)$. If $x(t)$ is modeled as cycloergodic (which excludes all-time-invariant random phases), then $CR_x(\alpha,\tau)$ can be obtained from the limiting time average, i.e.,

$$CR_x(\alpha,\tau)=\int_{-\infty}^{\infty} x\left(t-\frac{\tau}{2}\right)x^*\left(t+\frac{\tau}{2}\right)\mathrm{e}^{-\mathrm{j}2\pi\alpha t}\mathrm{d}t \tag{3}$$

$CR_x(\alpha,\tau)$ is also called as the cyclic autocorrelation function which is a function of τ for each cyclic frequency α. From Eq. (3), it can be clearly observed that $CR_x(\alpha,\tau)$ consists of the frequencies of the self conjugate terms and the harmonics of the cross correlation terms. The amplitude of function $CR_x(\alpha,\tau)$ represents the strength of the sinusoid in τ at cyclic frequency α.

The inherent advantage of cyclostationary theory is to reveal the underlying periodicity of signals through nonlinear transformations. Another advantage is being less susceptible to noises because the cyclic autocorrelation of noises is reduced