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Rotating machine fault diagnosis based on intrinsic characteristic-scale decomposition

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ABSTRACT

A new method called intrinsic characteristic-scale decomposition (ICD) is proposed in this paper, which is particularly suitable for processing the nonlinear and non-stationary time series. When fault occurs in gearbox and rolling bearing, the measured vibration signals would exactly present non-stationary characteristics. ICD, a new self-adaptive time-frequency analysis method, can decompose the non-stationary signal into a series of product components (PCs). Therefore, it is possible to diagnose gearbox and rolling bearing fault. In this paper, the ICD method is introduced and the decomposition performance is compared with LMD method. The results demonstrate that ICD has the advantages at least in running time, alleviating the mode mixing problem and restraining the end effect. The ICD method is applied to the practical gear and rolling bearing fault diagnosis. The results demonstrate that the proposed method is effective in the fault signature analysis of the rotating machinery.

1. Introduction

Rotating machines are playing an important role in the industry filed and widely used in automations, helicopters, railways transportation, etc. Since gear and rolling bearing are the most common and easy to be damaged parts in the rotating machinery, more and more attention has been paid to the gear and rolling bearing fault diagnosis techniques in recent years [1–3]. Due to the direct relationship between the vibration and the structure of the rotating machine, the vibration analysis method has been widely applied in the diagnostic field. The vibration of the gear and rolling bearing with localized defect has the nature of non-liner and non-stationary. Gear and rolling bearing with localized defect would excite the resonance frequency modulated by the transient impulse with defect characteristic frequency [3]. So, the demodulated method is required and the defect induced frequency can be gained by using the envelope spectral analysis. Generally, vibration analysis method can be summarized into three steps: data acquisition, fault feature extraction and fault classification. For the non-stationary vibration signal, the key step is to extract the fault information. There are many signal processing techniques which can extract the fault information from the response signal. Such as envelope spectrum, wavelet transform, demodulation analysis and so on [4,5]. However, traditional signal processing methods have their own limits. Envelope spectrum can identify the defect-induced frequency through demodulating impulsive vibrations and performing spectral analysis. The drawbacks of the envelope spectral analysis are that the exact structural resonance frequency should be identified. Wavelet transform (WT) can decompose multi-scales into several-scales time–frequency components, which has ability of processing the non-stationary and nonlinear signals. WT has been widely applied to diagnostic rotating machine. In fact, WT is essentially an adjustable window Fourier transform, which doesn't have the nature of self-adaptive feature [6,7].

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Empirical mode decomposition method (EMD) can self-adaptively decompose a complicated signal into a series of simple components defined as intrinsic mode functions (IMFs), which indicate the natural oscillations embedded in the vibration signal [8]. However, the traditional EMD method uses cubic spline to interpolate the local extrema of the signal which has outstanding over- and undershoot problems [9,10]. Furthermore, EMD also has the end effect and mode mixing problem. Local mean decomposition (LMD) is an improvement of EMD, which can decompose a complicated signal into a number of product functions (PFs) [11–13]. However, LMD method also suffers from the mode mixing, distorted components and time-consuming decomposition. Recently, Frei and Osorio proposed a new self-adaptive time–frequency approach, intrinsic time-scale decomposition (ITD), which can decompose the non-stationary signal into a sum of proper rotations (PRs) [14]. In the proposer's view, ITD method can overcome the drawbacks of EMD due to its special formulation and decomposition process, such as the error produced by the envelope interpolation and iterative sifting process [14]. Also the end effect has been restrained in ITD method. But due to the fact that there is no definition for PR, the PRs obtained by ITD are not real mono-components, which may cause erroneous instantaneous characteristics.

From above discussion, LMD and ITD are both self-adaptive signal processing methods. The similarities and differences of the two methods are as follows. To begin with, they can both self-adaptively decompose a complicated signal into a sum of single components, whose instantaneous frequency has physical sense. Secondly, according to the difference of the definition of the single component signal, the decomposition process varies from each other. Compared with EMD, the main advantages of LMD are efficient iteration process and Hilbert transform-avoidance. At the same time, ITD has the priority of fast computation and better bound effect. In summary, LMD and ITD can be seen as an improvement of EMD.

Inspired by LMD sifting process, a new self-adaptive time–frequency analysis approach called intrinsic character-scale decomposition (ICD) is proposed, which integrates the advantages of LMD and ITD. Just like the LMD method, by using ICD, a multi-component AM–FM signal could be decomposed into several product components (PCs) and a residue which reflects the trend of the signal, In fact, each PC(t) is a mono-component AM–FM signal. When the fault occurs in the gearbox and rolling bearing, in the generally case, the vibration signals picked up by sensor would show AM–FM characteristics, which need demodulation technique to analyze such signal. Since the ICD decomposition process is extract the demodulation process, therefore it can be used to demodulate the feature and extract the fault signature of the gearbox and rolling bearing vibration signal [15,16]. Moreover, the envelope spectrum analysis of the first few PCs can identify the fault frequency of the gearbox and rolling bearing effectively.

The rest of this paper is organized as follows: Section 2 describes the main steps of ICD method. The comparisons of simulation signal analysis between ICD and LMD are discussed. In addition, the three performance assessing indicators are introduced in Section 3. The experiment data analysis of the gearbox and rolling bearing vibration signal with fault are given in Section 4. Finally, the conclusions about the diagnostic capability of the proposed method are drawn in Section 5.

2. ICD method and the assessing indicators

LMD is originally developed to decompose multi-component signals into a small set of product functions (PFs), each of which is the product of an amplitude envelope signal and a purely frequency modulated signal. Furthermore, the instantaneous amplitude (IA) can be got from the envelope signal and well-defined instantaneous frequency (IF) could be calculated from the frequency modulated signal. Due to its special iteration process, LMD has less sifting times of each component and the better decomposition results compared with EMD algorithm. However, the problems of the mode mixing, end effect and low calculation efficiency also restrict its applications. What's more, MA approach is applied to construct the local mean and envelope functions in the sifting process, which may pose a major problem for LMD, because unsuitable sliding step sizes of MA has an adverse impact on the final calculation of IA and IF in the end. Therefore, the selection of the sliding step is also a problem [17].

ITD was proposed by Frei and Osorio in 2007 [14], the main innovation of ITD is that it introduced the symmetry point of the extreme (maxima or minima) to construct the baseline. Due to ITD's special formulation, the end effect has been restricted in ITD method, and the computation efficiency has been improved compared with EMD algorithm. However, the major problem of ITD is that the definition of PR has looser constraints, which lead to that the decomposition results are not a series of precise mono-components and the instantaneous frequency may distort heavily [18].

Considering the advantages of LMD and ITD, a new algorithm called ICD is put forward whose sifting process is similar to LMD's and the local mean and envelope function formation are constructed based on ITD's baseline formula. Therefore, ICD method has the advantages of LMD and ITD. In ICD method, a complicated signal can be decomposed into a series of product components (PCs) adaptively. Each PC(t) is the combined of an envelope signal and a purely frequency modulated signal. Namely, each PC(t) is a mono-component AM–FM signal and the physically meaningful instantaneous frequencies can be calculated from the FM signal.

Theorem. Given a signal $x(t)$, for a successive extrema (τ_{k-1}, X_{k-1}), (τ_k, X_k),and $(\tau_{k+1}, X_{k+1})(k = 2, 3 \cdots N)$, the geometrical local middle points and envelope points can be defined as follows:

$$\begin{cases} M_k^t = \tau_k \\ M_k^X = \dfrac{X_k + A_k}{2} \end{cases} \tag{1}$$