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Dense framelets with two generators and their application in mechanical fault diagnosis

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ABSTRACT

Wavelet analysis has been widely applied to mechanical fault diagnosis. Aiming at the problems of current wavelet basis, such as low time–frequency sampling, asymmetry and poor shift-invariance, this paper develops a new family of dense framelets with two generators and some desirable properties. To perform the corresponding framelet transform, three-channel iterated filterbank should be used, where the first and the third channel is decimated while the second channel is undecimated. This arrangement is very helpful for extracting the fault feature of the mid and low frequency band signal components and obtaining some symmetric framelets. To obtain framelets with high symmetry and a specified number of vanishing moments, B-spline and maximally flat linear FIR filter are, respectively, used to design filterbank. Three symmetric framelets and one framelets with symmetric low-pass filter and high-pass filter are constructed. Compared with the higher density framelets and orthonormal wavelets, the proposed framelets have better shift-invariance and denoising performance. Finally, the proposed framelets are applied to fault diagnosis of two gearboxes. The results show that the proposed framelets can be effectively applied to mechanical fault diagnosis and is superior to other commonly-used framelets/wavelets.

1. Introduction

Fault diagnosis of large and complex machines has got great attention in recent decades, in order to keep machines run steadily and prevent economic loss. The mechanical vibration signals usually contain abundant status information of machines. However, due to the harsh working conditions and complex structure, the important fault feature may be embedded in background noise and other normal vibration contents. In many cases, it is very difficult to directly obtain the fault information from the original vibration signals. Especially for low signal-to-noise ratio (SNR) vibration signals, it is greatly necessary for us to develop various effective signal processing methods for different applications.

Currently, the two most commonly used approaches for fault extraction are, respectively, wavelet analysis and empirical mode decomposition (EMD). EMD is a data-driven analyzing approach and possesses wavelet-like filtering characteristic [1,2]. The outstanding merit of EMD is its adaptivity, but it often encounters such problems as mode mixing and ending

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effect, and is very sensitive to noise [3]. Due to its good time–frequency localization and "zoom-in" property [4], wavelet analysis does well in signal denoising, singularity detection, weak feature extraction and so on [5]. Thus wavelet analysis is more suitable for processing low SNR vibration signals and extracting transient vibration feature than EMD.

The most widely used wavelet analysis approach may be the discrete wavelet transform (DWT). Daubechies has well established a systematic approach to construct orthonormal wavelets for DWT. To improve the computational efficiency, Sweldens proposed the lifting scheme to construct second generation wavelets [6,7]. DWT and lifting wavelet transform have been well applied to mechanical fault diagnosis [8,9]. Orthonormal wavelets do not have symmetry except for the Harr wavelet, and lack shift-invariance [10]. Besides, DWT has low frequency resolution and energy leakage [11]. These drawbacks limit its effectiveness in some fault extraction applications. Hence, redundant wavelet frames are developed for obtaining such desirable properties as wavelet smoothness, symmetry, high vanishing moments and approximation orders, shift invariance, desirable support, etc. By increasing the number of mother wavelets (generators), more degrees of freedom in the wavelet design can be obtained, and the tight wavelet frames (framelets) with several generators can be constructed by a compactly supported function and oversampled filter bank [12,13]. Daubechies has given the definition of framelets in [12]. The wavelets in overcomplete wavelet transform or frames can be regarded as framelets. Let $\boldsymbol{\Psi}$ be a finite subset of $L^2(\mathbf{R}^d)$, the dyadic wavelet system $X(\boldsymbol{\Psi})$ generated by the mother wavelets $\boldsymbol{\Psi}$ is given by $\{\psi_{j,k},\ \psi\in\boldsymbol{\Psi},\ j\in\mathbf{Z}, k\in\mathbf{Z}^d\}$. If $X(\boldsymbol{\Psi})$ is derived from a multiresolution analysis and is a frame, its elements are named as framelets. To obtain a finer frequency resolution, rational dilation wavelets [14] and overcomplete rational dilation wavelets [15] are proposed. Unfortunately, it is very difficult to design symmetric rational dilation wavelets with FIR filter bank. Using frequency domain method, symmetric overcomplete rational dilation wavelets can be obtained, however the obtained filters without rational transfer functions are less computationally efficient. Ref. [16] has used overcomplete rational dilation discrete wavelets to extract fault feature of gearbox.

Most of the previously developed framelets just offer a redundant representation in the wavelet domain for one signal with respect to time or scale [17–20]. To achieve an oversampling with respect to both time and scale, Selesnick [21] proposes a higher-density discrete wavelet transform. In succession, [22] develops another family of higher-density wavelet frames and apply them to mechanical fault diagnosis. Using the filter structure designed by [21], it is very difficult to obtain symmetric framelets. In order to obtain more symmetric framelets and improve shift-invariance, this paper develops a new family of framelets with dense time–frequency sampling. This type of framelets also consists of two mother wavelets, of which the combined filters are band-pass and high-pass, respectively. Obviously, the proposed framelets also have intermediate scales. However, the wavelet corresponding to the band-pass wavelet filter in this paper is half-integer translated while the wavelet corresponding to the high-pass wavelet filter in [21] is half-integer translated. Obviously, the way in which the proposed wavelet frames here sample the time–frequency plane is different from that in [21]. This arrangement is very helpful for extracting the feature of the mid and low frequency band signal components, because the second channel is undecimated. Since the proposed framelets increase the sampling of time–frequency grid, the proposed framelets are named as dense framelets. Moreover, the new filterbank structure contributes to obtaining more symmetric framelets and increasing the vanishing moments of the second wavelet. Especially, compared to the framelets constructed in [22], the structure forms of band-pass filter and high-pass filter are totally different, thus the new design procedure can lead to constructing three completely symmetric framelets and increasing the vanishing moments of the second wavelet. It is well known that symmetry and shift-invariance are beneficial to signal denoising. The proposed dense framelets have been employed to analyze the faulty gear vibration signal, and the results show that they have better performance on fault feature extraction than Selesnick's framelets and Daubechies wavelets.

2. New dense framelets construction

2.1. Preliminaries

In this paper, the proposed dense framelets sample the time–frequency plane as illustrated in Fig. 1. This arrangement leads to a new filterbank structure which can help us obtain more symmetric framelets and increase the vanishing moments

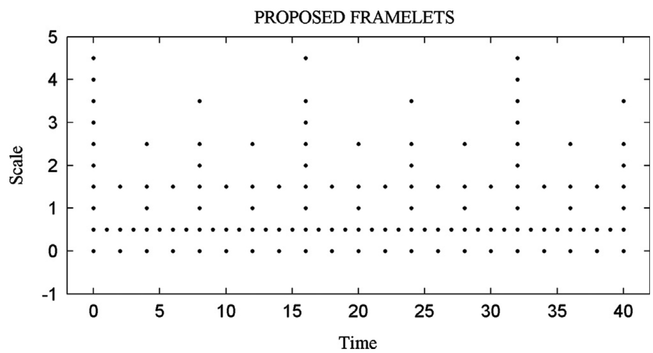

Fig. 1. Sampling of time–frequency plane by the proposed framelets.