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Envelope calculation of the multi-component signal and its application to the deterministic component cancellation in bearing fault diagnosis

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ABSTRACT

Commonly presented as cyclic impulse responses with some degrees of randomness, the vibrations induced by bearing faults are multi-component signals and usually overwhelmed by other deterministic components, which may degrade the efficiency of the traditional envelope analysis used for bearing fault feature extraction. In this paper, the envelope of the multi-component signal, including both discrete frequency components and cyclic impulse responses, is theoretically calculated by the Hilbert transform in both time and frequency domains at first. Then, a novel deterministic component cancellation method is proposed based on the iterative calculation of the signal envelope. Finally, simulations and experiments are used to validate the theoretical calculation and the proposed deterministic component cancellation method. It is indicated that the oscillation part of the envelope is dominated by the cross-terms of the multi-component signal, and that the cross-terms between a discrete frequency component and cyclic impulse responses present as new cyclic impulse responses, which retain the cyclic feature of the original ones. Furthermore, the deterministic component can be canceled by iteratively subtracting the direct current (DC) offset of the envelope. Compared with the cepstrum pre-whiten (CPW) method, used to separate the deterministic (discrete frequency) component from the random component (vibration induced by the bearing fault), the proposed method is more efficient to the shifting of the cyclic impulse responses from the powerful deterministic component with little disruption, and is more suitable for the real time signal processing owing to the high efficient calculation of the Hilbert transform.

1. Introduction

Rolling element bearings, as critical support components, are widely used in rotating machines and their failure is one of the most common causes of the mechanical breakdowns in engineering applications. Therefore, the bearing condition monitoring techniques have attracted a great deal of attention in the past decades, and many fault diagnostic methods, involving the fault feature extraction [1], feature enhancement [2], fault classification [3], etc., have been proposed.

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The desire to detect the fault as early as possible, the feature extraction procedure whose result is the basis of the condition monitoring and the fault classification, has especially attracted the attention. Many signal processing methods, such as envelope analysis [1,4–18], cyclostationary analysis [19–25], squared envelope analysis [19,22,25] or spectrum autocorrelation analysis [26] are introduced to extract the fault characteristic frequency, an index that cannot only determine the occurrence but also the location of the fault.

Nevertheless, the vibrations induced by bearing faults and presented as cyclic impulse responses with some degrees of randomness are usually overwhelmed by some powerful deterministic (discrete frequency) components, caused by the eccentricity, bending, misalignment of the rotating shaft or gear meshing and so on. The effect of the aforementioned kinds of fault feature extraction or enhancement methodologies will be degraded owing to the interfusion of these deterministic components. For example, the kurtogram, if calculated on the analytical signal, can exactly match the sum of all peaks of the squared envelope spectrum (SES) only if the bearing fault is the only source of the second order cyclostationary signal component in the collected signal [27]. In 2004, Antoni and Randall [28] indicated that the vibration analysis of machines obtained much in efficiency if periodic vibrations could be separated from non-deterministic ones. Therefore, several deterministic component cancellation methods, including time synchronous averaging (TSA) [29], linear prediction [2], adaptive noise cancellation (ANC), self-adaptive noise cancellation (SANC) [28], discret/random separation (DRS) [30], and cepstrum pre-whiten (CPW) [31] are introduced to separate the bearing signals from the powerful discrete frequency noise. If there is a need to remove the discrete frequency components with minimum disruption of the residual signal, the TSA method can be one of the best candidates [29]. However, it requires a separate operation for every different set of harmonics, prior known, in the signal. Linear prediction is basically a way of obtaining a model of the deterministic part of a signal, based on a certain number of samples in the immediate past, and then using this model to predict the next value in the series. The residual signal, obtained by subtracting the deterministic (discrete frequency) components from the actual signal, includes the bearing signal because of the randomness. The autoregressive or AR model was usually used for linear prediction owing to its simplicity, efficiency and the low prior requirements for the application [2]. The model order was a key parameter for the AR model, and the optimal model order was recommended to be determined by maximizing the kurtosis of the residual signal and being less than the spacing between two consecutive impulses. However, it is known that the kurtosis decreases with the increase of the impulses and this method will be disturbed by the random transient impulse. The ANC was proposed many years ago as a means of extracting a faulty bearing signal in cases where the primary signal could for example be measured on the faulty bearing of a gearbox, and the reference signal on another remote bearing with no contamination from the faulty bearing signal. However, it does rely on being able to obtain an uncontaminated reference signal, which cannot be possible for example on a planetary gearbox, where all signals must be transmitted through the ring gear [28]. If one of the two components to be separated is deterministic (discrete frequency) and the other random, the reference signal can be made a delayed version of the primary signal. Thus, the separation can be achieved using one signal only, and the procedure is called SANC [28]. It is indicated that the adaptive filter will not recognize the random signal if the delay is longer than the correlation length of the random signal, and will find the transfer function between the deterministic part of the signal and the delayed version of itself. To adjust to small speed variations, the adaptive filter of the SANC may consume quite a long time for convergency, especially for filters with high orders. Further, if the components to be tracked are very stable in time or can be made so by order-tracking in a pre-processing step, the adaption is no longer needed and a much more efficient estimation of the filter can be achieved in the frequency domain by computing the frequency response function (FRF) between two blocks of the data [30]. This method can generally give similar results to SANC, but more efficient and without the possibility of divergence. Recently, another discrete frequency component cancellation method, named CPW [32], was proposed by setting a zero value for the whole real cepstrum (except possibly at zero quefrency). The proposed procedure is equivalent to a series of liftering operations around the quefrencies of the deterministic excitations, resulting in the almost complete deletion of their effect on the signal, as well as a removal of resonance effects. On the other hand, the second order cyclostationary component, not strictly periodic, will not present any strong peak in the absolute value of the cepstrum and will be left after the liftering. This procedure was further implemented in a very simple way, avoiding the transformation to the cepstral domain, just by dividing the Fourier transformed signal by its absolute value and transforming back to the time domain [31]. In practice, the CPW method usually eliminates the discrete frequency components with very high efficiency owing to the simple operation. However, this procedure may excessively weaken the impulse responses induced by the bearing fault, especially when the randomness of the impulse interval series is very weak.

Actually, even without involving the deterministic components, the cyclic impulse responses are multi-component signals. Figs. 1 and 2 illustrate the Wigner–Ville distribution (WVD) of the vibrations, collected in both the bearing center of Case Western Reserve University (CWRU) and the machine fault diagnosis laboratory of Tsinghua University. It can be seen that the cross-terms, which are the typical feature of the multi-component signal, appear clearly between every two adjacent impulse responses. Such phenomena indicate that every impulse response is a mono-component signal and the cyclic impulse responses are the cumulation of the impulse responses with different time shifts. Therefore, the discrete frequency components further increase the complexity of the collected vibration, and the assumption that the envelope analysis is traditionally applicable to the mono-component or narrow band signal should be relaxed. In this paper, the envelope of the multi-component signal, involving both deterministic components and cyclic impulse responses, is calculated by the Hilbert transform. Such investigation is the extension of the traditional Hilbert transform and the envelope feature of the multi-component signal is analytically exposed. Further, a novel deterministic component cancellation