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Instantaneous fault frequencies estimation in roller bearings via wavelet structures

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ABSTRACT

The main target of the current paper is the effective application of the method proposed in "Antoniadis et al. (2014) [17], in roller bearings under variable speed. For this reason, roller bearing model with slip and real data coming from a test rig has been used. The method extracts useful information from a complicated signal where the overlap among the harmonics can raise up to 30%. According to the proposed method, a set of wavelet transforms of the signal is first obtained, using a structure of Complex Shifted Morlet Wavelets. The center frequencies and the bandwidths of the individual wavelets, as well as the number of wavelets used, are associated with the characteristic fault frequency and its harmonic components. In this way, a set of complex signals result in the time domain, equal to the number of the wavelets used. Then, the instantaneous frequencies of the signals are estimated by applying an appropriate subspace algorithm (as for e.g. ESPRIT), to the entire set of the resulting complex wavelet transforms, exploiting the corresponding subspace rotational invariance property of this set of complex signals. The iterative procedure brings up accurate results from complicated signals, separating the fault associated signal components. Also, the spectrograms of the processed signals confirm the ability to match excited areas with specific faults.

1. Introduction

In many applications, the roller bearing, a vital component of rotary machines, faces an increasingly complex working environment. In order to satisfy production requirement, roller bearing fault diagnosis is essential to ensure that roller bearings work in good state. Unexpected failures would cause fatal breakdown of machines. Therefore, it is extremely important that the fault feature is correctly and efficiently extracted from the original signal, which also directly affects the classification results and diagnostic accuracy. In roller bearing fault diagnosis, the variation of working conditions frequently leads to the change of most feature vital parameters and even the entire diagnostic method. Adjusting the feature parameter or the diagnostic method according to the working condition is particularly labor intensive and time consuming. Thus, it is essential to find a roller bearing diagnostic method that is applicable to different working conditions.

The vibration signal of roller bearings is characterized by nonstationarity, which makes the Fourier Transform unsuitable for extracting this feature of the signal. Many methods have been developed to cope with this feature. As time-frequency

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analysis methods, the short-time Fourier Transform [1] (enhanced formula), the Wigner–Ville distribution [2], and the wavelet transform [3] can process the nonstationary signal. However, they all have respective limitations. Due to Heisenberg's uncertainty principle, the finest time location and the best frequency resolution cannot be reached simultaneously [4], which restricts the application of the short-time Fourier Transform.

More specifically, some researchers have paid more attention to the study of the roller bearing fault diagnosis under variable working conditions. An approach with important and precise results can be found in the promising method [5], where the variable speed should vary linearly with time, a major compromise for diagnosis. Other practical implementations lead to qualitative identification and separation [6], but the unsteady conditions do not include cases with overlap among the signal harmonics. Also, there are some successful efforts that require a 'health' signal as a reference for diagnosis as shown in [7]. At the end, an experiment was performed in [8] where signal fault orders are correctly recreated - with the obligatory presence of an accurate encoder.

Concerning the field of wavelet transforms, recently a sequence of papers with the last one [9] which concentrates on roller bearing faults concludes in an accurate demodulation of the signal. The Empirical Wavelet Transform is also used [10] offering enhanced results also in comparison with other methods [11]. As for applications with unsteady conditions similar to those that are implemented in the current paper, much less applications can be found. Interesting results appear in [12] via discrete wavelet transform in roller bearing defects. The case where the harmonics overlap is not investigated something that is further examined in [13] with Hilbert Transform. Two types of bearing errors are distinguished in spectra but also other irrelevant edges do exist.

In order to overcome some inabilities of the wavelet transform such as energy leakage effects, [14] introduce contrary to the classical concept of "scaling" the wavelet in the time or frequency domain, just "shifting". The method presents the optimal resolution simultaneously in the time and in the frequency domain. Compared to the Discrete Wavelet Transform (DWT), allows the continuous (and thus more accurate) approximation in both time and frequency domains. However, contrary to the classical subspace methods which are applied to the signal itself, the method proposes the application of the method after the signal has been appropriately transformed by an appropriate wavelet structure. In this way, the performance of the subspace based approach is increased, since the desired time-frequency features of the signal are enhanced, while simultaneously, the undesired frequency components, as well as the noise, are suppressed.

Another interesting point appears, when multiple frequencies may coexist in the frequency band of a single wavelet, or equivalently, a time dependent instantaneous frequency may coexist in different wavelet bands during the time. The task of effectively separating the individual instantaneous frequencies emerges. This is possible due to the subspace rotational invariance property of the entire set of the resulting complex signals, a property quite similar with the rotation invariance property of the signal itself [15]. Also a brief comparison with one of the most stable methods such as Hilbert Transform has been executed in [16]. After some enhancements [17] in signals with significant overlap, the method is further examined in the present paper, where the main concern is the implementation in faulty roller bearings.

The rest of the paper is organized as follows. The theoretical background of the method and the model simulating a roller bearing with an outer race fault is presented in Section 2. Applications in synthetic signals of the previews model under variable speed are presented in Section 3. Finally, applications to instantaneous fault frequency estimation in experimental measurements are presented in Section 4.

2. Theoretical backgrounds

2.1. Theoretical background of the estimation method

The complex Morlet wavelet is defined in the time domain as a harmonic wave with a frequency f_c multiplied by a Gaussian time domain window:

$$Y(t) = c e^{-\sigma^2 t^2} e^{-j2\pi f_c t} \tag{1a}$$

where c is a positive integer. If the parameter is chosen as:

$$c = 2\sigma/\sqrt{\pi} \tag{1b}$$

the Fourier Transform of the Morlet wavelet becomes:

$$\hat{Y}(f) = \hat{Y}*(f) = 2e^{-\frac{\pi^2}{\sigma^2}(f-f_c)^2} \tag{2}$$

where $\hat{Y}(f)$ is the complex conjugate of $\hat{Y}(f)$ and $\hat{Y}(f) = \hat{Y}*(f)$, since $\hat{Y}(f)$ is real. In view of Eq. (2), f_c denotes the center frequency of the wavelet and $f_b = c$ presents a measure of its bandwidth. This wavelet has the shape of a Gaussian window in the frequency domain. The center frequency of the window is defined by the frequency f_c of the harmonic component and the bandwidth of the window is determined by the parameter σ.

The scaling of the mother wavelet, simultaneously shifts the location of the window, affects the height of the window and modifies the bandwidth as well. In this way, the bandwidth of the wavelet cannot be chosen independently from the central frequency. For this reason, instead of scaling, just shifting has been proposed [14,18].