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Improved multi-order Vold-Kalman filter for order tracking analysis using split cosine and sine terms

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ABSTRACT

Order tracking analysis is an effective tool for the analysis of non-stationary vibration and acoustical signals for the purposes of machinery fault diagnosis and operational modal analysis. The second-generation Vold-Kalman filter is widely used for order tracking analysis; however, the formulation of the data equation is based on incomplete complex kernels, which introduce an imaginary part error in the cost function. In this work, the data equation of the second generation Vold-Kalman filter is re-formulated using separated cosine and sine kernels that necessarily provide a real-valued sum. Doing so will minimize the error in the data equation and offer better optimization scheme to reduce the error in the structural equation and; hence, provide smooth envelopes. Unlike Vold-Kalman method which requires high filter weighting factors to suppress envelope artifacts, the proposed method can achieve high accuracy even when using small weighting factor as deduced from the simulation and experimental investigations. The proposed method can be used to measure the envelopes of close and crossing orders, as well as orders experiencing resonance conditions or orders with high slew rate due to lower filter decay time.

1. Introduction

In vibration analysis terminology, order tracking refers to extracting the amplitude and phase of individual components that constitute vibration or acoustic signals. Each component is termed "order" because when order tracking was first introduced, it was used to track the components with frequencies that are related to the rotating speed of the machine. For example, the first order represents the speed of the machine and is denoted by "1x". Other orders are denoted by "*n*x" where *n* is a real positive multiplier which can be less than 1 for sub-synchronous frequencies and more than 1 for other harmonics. Many mechanical anomalies produce vibration or sound at frequencies that are integer multiples of the rotating speed. Some other faults produce non-integer harmonics, such as rolling element bearings and electrical faults. Some faults produce orders that are close to each other in frequency. For example, coupling misalignment in a 2-pole induction motor produces 2× the running speed, while stator eccentricity produces 2× the supply frequency. On the other hand, complex machines may have more than one rotating shaft. These shafts produce crossing orders when, for example, one of the shafts is rotating at some fixed speed while the other shaft is speeding up or slowing down.

The process of order tracking analysis (OTA) has a special importance when the machine undergoes start-up or shutdown, where common analysis techniques, such as the Fourier transform, cannot be used [1]. In such cases, vibrational or acoustic signals are classified as non-stationary signals. Vold and Leuridan introduced the first generation Vold-Kalman order tracking (VKOT) scheme in 1993 [1]. In the first generation Vold-Kalman method, the objective was to obtain reconstructed versions of the orders that satisfy both the structural and data equations. The structural equation indicates that the orders have slowly varying amplitudes, while the data equation implies that the sum of the orders approximates the observed signal. Later, Vold et al. [2] proposed the second generation VKOT method, in which the objective was to obtain the envelopes of the orders, and the signal can be reconstructed by multiplying the obtained envelopes by the corresponding rotating vectors.

Other order tracking techniques include the work of Qian [3] who proposed the discrete Gabor expansion for order tracking (GOT) method. Blough [4] introduced order tracking using the Time Variant Discrete Fourier Transform (TVDFT), which is an alternative to computed or resampling order tracking. However, the TVDFT method suffers from a number of limitations, such as the inability to track signals with a high slew rate due to the fact that it processes successive subdivisions of the signal (block-wise processing). Bai et al. [5] developed an intelligent diagnostic system by exploiting the recursive least squares algorithm and Kalman filter. The method of Bai et al. is computationally very expensive and does not address the issue of crossing orders. Pan and Chiu [6] proposed an enhanced GOT method to handle crossing orders/frequency components. Li [7] presented the order bi-spectrum technique to detect gear crack faults in a gearbox under non-stationary run-up condition. His method combines computed order tracking technique and

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