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Compound faults detection in gearbox via meshing resonance and spectral kurtosis methods

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ABSTRACT

Kurtosis-based impulsive component identification is one of the most effective algorithms in detecting localized faults in both gearboxes and rolling bearings. However, if localized faults exist in both gear tooth and rolling bearing simultaneously it is difficult to tell the differences between the two types of defects. As such, this study proposes a new method to solve the problem by using the meshing resonance and spectral kurtosis (SK) algorithms together. In specific, the raw signal is first decomposed into different frequency bands and levels, and then the corresponding Kurtogram and MRgram are calculated via the fault SK analysis and the meshing index. Furthermore, the resonance frequency bands induced by localized faults of the gear tooth and rolling bearing are separately identified by comparing the Kurtogram and the MRgram. Finally, the compound faults are respectively detected using envelope analysis. The effectiveness of the proposed method has been validated via both simulated and experimental gearboxes vibration signals with compound faults.

1. Introduction

Localized faults appear in the main components of machinery because of severe and long-term working conditions. For the rotating machinery, localized defects always result in a series of impulses with certain repeated frequencies, such as the ball pass frequency of the rolling bearing, and the rotational frequency of the faulty gear, which can be used as fault characteristic frequencies to realize further diagnosis of faults. In fact, detecting localized faults in the rolling bearings and gearboxes has always been an important topic in both academia and industry [1,2]. The condition of rotating machinery can be reflected via measuring vibration [3,4], acoustic emission (AE) [5,6], temperature [7,8], and debris [9,10]. Among those techniques, a widely used technique for fault detection is the vibration-based signature analysis, including time-domain statistics [11,12], spectrum based analysis [13,14], and time-frequency representation [15,16].

Among the vibration signal based fault diagnosis algorithms, the kurtosis based method [17] is one of the most powerful techniques for localized fault diagnosis. In specific, the resonance frequency band due to local defects related impulse series is firstly located. And the band-pass filtering and envelope analysis methods are then used together to obtain the envelope spectrum with prominent fault related frequency to achieve the final fault detection. During this strategy, the determination of frequency band plays a key role, and several algorithms [18–22] has been proposed to accomplish this step. However, most of the algorithms are proposed to detect mono-fault.

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Nomenclature

$x_{gearmeshing}$ Gear meshing signal
$x_{bearingfault}$ Rolling bearing fault related signal
$f_{r,driving}$ Rotational frequency of the driving gear
A_{gear} Magnitudes of the AM in gear meshing signal
$A_{meshing}$ Amplitude of the impulses due to the meshing behavior
$\varphi_{meshing}$ Resonance frequency excited by the meshing behavior
n Serial number of the impulses induced by the meshing behavior
$f_{r,gearfault}$ Rotational frequency of the faulty gear
$B_{gearfault}$ Magnitudes of the FM in gear faulty signal
$\beta_{gearfault}$ Structural damping characteristic frequency of gear fault
$t_{m,gearfault}$ The occurrence time of the m^{th} impulse due to the gear fault
M Total number of the impulses induced by the gear fault
$\beta_{bearingfault}$ Structural damping characteristic frequency of bearing fault
τ_j random slippage
I Total number of impulses induced by the bearing fault
$x_{gearfault}$ Gear fault related signal
$f_{meshing}$ Meshing frequency
$f_{r,driven}$ Rotational frequency of the driven gear
B_{gear} Magnitudes of the FM in gear meshing signal
$\beta_{meshing}$ Structural damping characteristic frequency of meshing behavior
$t_{n,meshing}$ The occurrence time of the n^{th} impulse due to the meshing behavior
N Total number of impulses induced by the meshing behavior
$A_{gearfault}$ Magnitudes of the AM in gear faulty signal
$A_{m,gearfault}$ Amplitude of the impulses due to the gear fault
$\omega_{gearfault}$ Resonance frequency excited by the gear fault
m Serial number of the impulses induced by the gear fault induced
$A_{bearingfault}$ Amplitude of the impulses due to the bearing fault
$\omega_{bearingfault}$ Resonance frequency excited by the bearing fault
i Serial number of the impulses induced by the bearing fault
$n(t)$ White noise

Compound faults indicate that several faults appear simultaneously, or that one fault leads to the following fault. Comparing with the traditional algorithms designed for the mono-fault condition, the methods for compound faults detection are relatively fewer. Moreover, this compound faults are common in real application and may cause severe disruption. Towards this topic, McFadden et al. [23] proposed a model for the high-frequency vibration produced by multi-point defects. Li et al. [24,25] employed principal component analysis and fuzzy k-nearest neighbor (FKNN) algorithms to extract multi-fault feature in rotating machinery, respectively. Purushotham et al. [26] and Lei et al. [27] separately used hidden Markov model (HMM) classifiers and hybrid intelligent method to determine multi-faults. Wang et al. [28] designed an adaptive spectral kurtosis (SK) algorithm to identify multiple transient faults in the rolling bearings. Several wavelet transform based algorithm [29–31] have been proposed for compound faults detection with good performance. Zhao et al. [32] made use of a generalized demodulation algorithm to accomplish compound fault detection under time-varying rotational speed. Some of the algorithms, [24–28,31,32] were proposed to detect faults that exist in a single component, such as a rolling bearing or gearbox, and algorithms mentioned in [29,30] can deal with faults existing in different components based on the approved multiwavelet transform. These contributions have significantly enriched the literature for the compound faults diagnosis.

According to the algorithms summarized previously, a typical compound faults diagnosis strategy distinguishes the faults and then locates the corresponding fault features, particular when multi-faults appear in different components. This study proposes a new algorithm to detect compound faults that happen in the gear and the rolling bearing of a gearbox simultaneously. This algorithm can distinguish the resonance frequency bands induced by the gear and bearing faults by taking full advantage of a commonly overlooked meshing resonance phenomenon [33,34], which indicates that the meshing behaviors will generate resonance even without the present of a fault. ***The underlying principle*** of the proposed algorithm is that the characteristics of the resonance frequency bands induced by the gear and rolling bearing faults are different from each other. The *proposed algorithm* mainly consists of the following four steps: (a) decomposing the raw signal with quasianalytic filters, (b) obtaining the kurtogram using the fault SK analysis, (c) calculating the MRgram based on the meshing index, (d) detecting the compound faults by comparing the Kurtogram and the MRgram.

The rest of the paper are structured as follows: Section 2 describes the specific compound faults detection algorithm based on meshing resonance and spectral kurtosis methods. The effectiveness of the proposed algorithm is separately testified with simulated and experimental data in Sections 3 and 4. And the conclusions are drawn in Section 5.

2. Compound faults diagnosis algorithm based on meshing resonance and spectral kurtosis methods

As mentioned above, the key step of compound faults diagnosis is distinguishing the faults from each other. When localized faults appear in both the gear tooth and the rolling bearing, the contacts between these two defects and their