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Bearing fault diagnosis under unknown variable speed via gear noise cancellation and rotational order sideband identification

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A B S T R A C T

The interfering vibration signals of a gearbox often represent a challenging issue in rolling bearing fault detection and diagnosis, particularly under unknown variable rotational speed conditions. Though some methods have been proposed to remove the gearbox interfering signals based on their discrete frequency nature, such methods may not work well under unknown variable speed conditions. As such, we propose a new approach to address this issue. The new approach consists of three main steps: (a) adaptive gear interference removal, (b) fault characteristic order (FCO) based fault detection, and (c) rotational-order-sideband (ROS) based fault type identification. For gear interference removal, an enhanced adaptive noise cancellation (ANC) algorithm has been developed in this study. The new ANC algorithm does not require an additional accelerometer to provide reference input. Instead, the reference signal is adaptively constructed from signal maxima and instantaneous dominant meshing multiple (IDMM) trend. Key ANC parameters such as filter length and step size have also been tailored to suit the variable speed conditions, The main advantage of using ROS for fault type diagnosis is that it is insusceptible to confusion caused by the co-existence of bearing and gear rotational frequency peaks in the identification of the bearing fault characteristic frequency in the FCO sub-order region. The effectiveness of the proposed method has been demonstrated using both simulation and experimental data. Our experimental study also indicates that the proposed method is applicable regardless whether the bearing and gear rotational speeds are proportional to each other or not.

1. Introduction

Vibration signal is one of the most important sources of information for monitoring conditions of rolling element bearings. However, such vibration signals are often contaminated by various noises and interfering vibrations in particular the strong vibrations from the gearbox when the vibration sensor cannot be mounted in the near vicinity of the bearing

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Acronyms

ANC	adaptive noise cancellation
BRF	bearing rotational frequency
BRO	bearing rotational order
DRS	discrete random separation
FCF	(bearing) fault characteristic frequency
FCO	fault characteristic order
GRF	gear rotational frequency
GRO	gear rotational order
IDMM	instantaneous dominant meshing multiple
IFCF	instantaneous (bearing) fault characteristic frequency
IMF	instantaneous meshing frequency
IRF	instantaneous rotational frequency
ROS	rotational order sideband
SANC	self adaptive noise cancellation
SK	spectral kurtosis
STFT	short-time Fourier transform
TFR	time–frequency representation
TSA	time synchronous average

being monitored. Among these interferences, those generated by the gear meshing vibrations are particularly disturbing and have attracted much attention of researchers. In the previous studies, the gear noise has been generally classified as discrete frequency noise. In this way, the algorithms designed for eliminating the time-invariant components, such as linear prediction [1,2], self-adaptive noise cancellation (SANC) [3], discrete random separation (DRS) [4] and time synchronous averaging (TSA) [5], can be used to deal with this kind of noise. However, if the corresponding rotational speed varies with time, which is common in real applications [6], it is no longer appropriate to treat the gear vibration as the time-invariant. This obviously undermines the usefulness of some of these existing methods.

For this reason, the method reported in Ref. [7] recovers the capability of existing gear noise removing algorithms with the help of the order tracking algorithm. Specifically, angular resampling is first used together with the SANC algorithm to remove the gear noise in the gear angular domain and then it is jointly applied with the envelope analysis for the final bearing fault diagnosis. By means of the tachometer reference signal, Wang [8] proposed an autoregressive model-based method to diagnose gear and bearing faults influenced by gear noise under time-varying rotational speed conditions. These studies are important contributions to the literature. Nevertheless, its success heavily relies on the availability of the accurately measured gear and bearing rotational speeds. However, the installation of speed sensor for each and every machine component is not always technically feasible due to the limited space and accessibility, and not always economically viable because of the costs incurred in investment, operation and maintenance of such sensors. Hence another type of the order tracking in which the instantaneous rotational frequency (IRF) is estimated based on the TFR instead of the speed device is proposed to fill this gap [9]. Among this type of important tracking methods, Urbanek et al. [10] presents a notable method to extract the instantaneous rotational speed trend even in the presence of closely spaced sidebands.

For the gear vibration, there exists extractable trend in its TFR which could be used as the substitute of the gear IRF. In general, the spectrum of gear vibration under a constant rotational speed should contain several prominent peaks at the gear meshing frequency and its multiples. The highest peak should be located at an integer multiple of meshing frequency (usually a small integer including one). If the rotational speed changes with time, this multiple frequency will change with it and forms a trend which is named in this paper the instantaneous dominant meshing multiple (IDMM) trend. The IDMM can be defined as an instantaneous meshing frequency harmonic that has the highest amplitude among all harmonics (including the fundamental meshing frequency) of the instantaneous meshing frequency (IMF). It is necessary to mention that this characteristic may not be applicable if the gear noise comes from planetary gearboxes. The reasons lie in that the corresponding spectrum has distinct characteristics and is much more complicated comparing to the one of a gearbox with fixed shafts. In the case of rolling bearings, the instantaneous fault characteristic frequency (IFCF) trend can be extracted from the TFR of the filtered bearing envelope signal [11] and then be used to substitute the corresponding IRF trend.

In the context of this study, the raw signal contains the gear noise with larger amplitude and the target rolling bearing signal component with relatively weaker one. Hence, the IDMM trend can be directly extracted from the TFR of the raw vibration signal using a peak searching algorithm. As the IDMM changes proportionally with the gear IRF, it seemingly could be used to convert the gear signal component under time-varying rotational speed into the deterministic (i.e., time-invariant) one and then one of the existing gear noise elimination algorithms could be applied. However, in fact the existing algorithms cannot be used in the context of this research because the process of applying one of the existing gear noise elimination algorithms will have a side-effect on the bearing signal components due to the possible distortion of the bearing signal components in the raw signal mixture. This obviously adversively affects the extraction of the IFCF trend which is key to the final bearing fault diagnosis. As such, an effective gear noise removing algorithm should *not only remove the gear noise, but preserve the integrity of the bearing signal component in the signal mixture as much as possible*. Based on the analysis mentioned before, order tracking based on the IDMM trend may not always be adequate.

The traditional adaptive noise cancellation (ANC) [12] might be suitable for the elimination of gear noise under varying rotational speed without the speed information because it does not need the characteristic information of discrete frequency but nevertheless requires an additional accelerometer collect only the gear related vibration signal to be used as the ANC reference input. In doing so, the gear noise could be reduced without much distortion of the bearing signal content