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Development of a gear vibration indicator and its application in gear wear monitoring

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ABSTRACT

Gear tooth wear is an inevitable phenomenon and has a significant influence on gear dynamic features. Although vibration analysis has been widely used to diagnose localised gear tooth faults, its techniques for gear wear monitoring have not been well-established. This paper aims at developing a vibration indicator to evaluate the effects of wear on gear performance. For this purpose, a gear state vector is extracted from time synchronous averaged gear signals to describe the gear state. This gear state vector consists of the sideband ratios obtained from a number of tooth meshing harmonics and their sidebands. Then, two averaged logarithmic ratios, *ALR* and *mALR*, are defined with fixed and moving references, respectively, to provide complementary information for gear wear monitoring. Since a fixed reference is utilised in the definition of *ALR*, it reflects the cumulated wear effects on the gear state. An increase in the *ALR* value indicates that the gear state deviates further from its reference condition. With the use of a moving reference, the indicator *mALR* shows changes in the gear state within short time intervals, making it suitable for wear process monitoring. The efficiency of these vibration indicators is demonstrated using experimental results from two sets of tests, in which the gears experienced different wear processes. In addition to gear wear monitoring, the proposed indicators can be used as general parameters to detect the occurrence of other faults, such as a tooth crack or shaft misalignment, because these faults would also change the gear vibrations.

1. Introduction

Gear wear refers to the progressive material loss from contacting tooth surfaces due to the combined rolling and sliding motion under mixed or boundary lubrication conditions. It is one of the major failure modes of gears. The direct results of gear wear include dynamic transmission error, power transmission losses, and high vibration and noise levels [1–3]. Severe wear can also cause uneven load distributions, which could lead to the occurrence of other types of gear failure, such as broken teeth. For these reasons, the topic of gear wear monitoring is receiving considerable attention in the condition monitoring community.

In practice, wear particle analysis has been popularly used for gear wear monitoring, while vibration analysis techniques have been employed for gear fault diagnosis and monitoring, but generally not for wear analysis. For instance, numerous instruments have been made to capture and analyse wear particles contained in the lubricating oil, and it has been established that: wear particle concentration is an indicator of the overall wear condition of a machine, and a significant change in the concentrate reflects

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a change in the wear rate; particle size and size distribution show the wear intensity; and, particle shape and surface morphologies reveal the wear mechanism [4,5]. Nevertheless, wear debris analysis, usually carried out off-line, can be time consuming and costly. Moreover, wear particles cannot directly reveal changes in gear dynamic features, which can be used to check if a gear pair still works properly. In contrast, gear vibration signals are the reflection of gear dynamic features at the moment they are measured, and thus could be suitable for efficient real-time assessment of the effects of wear on gears. Relevant existing works are summarised below.

The influence of wear on gear dynamic features has been investigated theoretically. It has been recognised that tooth surface wear has significant effects on the dynamic load and its distribution. Because of the changes in the tooth working surface caused by wear, the gear transmission ratio would no longer be static [2], especially for the case of spur gears, whose transmission errors are highly sensitive to wear [3]. Meanwhile, the gear dynamic features could also affect the wear process, so there is a two-way relationship between them [6]. Thus it can be concluded that the effects of gear wear would manifest themselves as changes in vibration features, and so it should be possible to develop an approach to gear wear monitoring based on vibration analysis.

Unfortunately, studies on vibration-based gear wear monitoring are rather sparse. This may be attributed to the fact that the response of vibration signals to gear wear is rather complex, which will be further described in Section 2. Existing studies have revealed that uniform tooth wear would lead to increases in the amplitude of tooth meshing harmonics, and the amplitudes of higher order meshing harmonics are a reliable way of detecting uniform wear at its early stage [7,8]. Recently, spectrum and cepstrum analysis were applied together to identify the wear state for high contact ratio gear pairs [9]. It was found that gear pitting and scuffing can be detected by trending the amplitudes of the meshing harmonics or rahmonics (which, as outlined in the discussion below, would only apply to the uniformly distributed part). A simple parameter, named matched filtered RMS, was reported to monitor the gear wear process in [10]. This parameter was defined to be the logarithmic value (expressed in dB) of the averaged power ratio between components of the current vibration signal and those of the reference signal. It is more sensitive and reliable in detecting gear damage than classic parameters such as RMS and peak values, and is easy to trend. However, matched filtered RMS still focuses on the changes in the signal power, and thus may not be able to reflect the changes in the signal spectral distribution, which is also closely related to gear condition. In addition to monitoring the variation in signal power, cyclostationary analysis was also successfully applied to monitor tooth spalling [11]. In the presence of tooth spalling, the meshing process would generally vary from tooth to tooth, and these transient meshing processes would give rise to an increase in the cyclostationarity of vibration signals. As known, wear is inevitable in the lifetime of gears, and it could significantly change the tooth profiles by abrasive wear before the occurrence of evident faults, such as pitting or spalling. Therefore, it is desirable to develop a vibration analysis technique that is able to monitor the wear process of gears and further to indicate changes in the process.

This paper aims at developing a dimensionless, vibration-based parameter to evaluate the effects of wear on the gear state. The proposed parameter is based on the vibration signals pertaining to individual gears, which can easily be separated from one another and from background noise using techniques such as phase demodulation based order tracking [12] and time synchronous averaging [13]. The features extracted from those separated signals could thus give a reliable description of the state of the individual gears. As described in Section 2, tooth wear will change the transmission error of a gear pair, making gear vibration features deviate from their initial values accordingly. This deviation of gear vibration features from their initial values is utilised in this study to evaluate the influence of tooth wear.

2. Effects of wear on gear vibration signals

It is well accepted that transmission error (TE) is the main vibratory excitation of gear systems. The TE consists of geometric deviations of the unloaded working surfaces from equi-spaced ideal involute profiles, and tooth elastic deformations (elastic deformation in the contact area and elastic bending of the whole tooth) under loaded conditions. For a gear with N teeth, all teeth may deviate from the perfect tooth profile in different ways, giving rise to variations of TE according to the rotational angle. As described in [14,15], the arithmetic average of these N working surface deviations is the average working surface deviation from a perfect involute surface. For a meshing gear pair, there are two such average working surface deviations, and their superposition contributes to the tooth meshing harmonics in the spectrum of the vibration signals. For each gear, the differences between individual tooth working surface deviations and the average working surface deviation constitute its tooth-to-tooth differences, which contribute to the sidebands spaced around the tooth meshing harmonics at the rotational speed of that gear. If the gears of a meshing pair have different numbers of teeth, there would be two sets of sidebands in the vibration spectrum, one for each gear.

The effects of gear wear on vibration signals can be explained in terms of its influence on TE. Assuming the gear supporting system and the gear operating conditions are invariant, gear wear will be the main source of changes in TE and vibration signals. Depending on the wear pattern, the average working surface deviation and/or the tooth-to-tooth differences will be changed.

Generally, there are two types of wear: uniform and non-uniform. Uniform wear refers to the case where all teeth are worn identically, which is an ideal wear pattern. This kind of gear wear results in an increase in the average working surface deviation, and will manifest in increases in the amplitudes of tooth meshing harmonics. Note that the relative changes in these tooth meshing harmonics depend on the way in which the average working surface deviation is changed. For example, the typical double-scalloped wear pattern will mainly lead to an increase in the second harmonic of tooth meshing frequency [16].