

Psychoacoustic Analysis of Gear Noise with Gear Faults

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ABSTRACT

Gear drives are widely used in the transmission of many types of vehicles and various gear faults were reported to have different effects on the performance of transmission systems. The psychoacoustics metrics, which are used to represent the human hearing property, are objective indicators of product sound quality performance. Therefore, psychoacoustic analysis of gear noise with gear faults needs to be conducted. In this paper, different types of gear faults are summarized, and two of them, including wear and misalignment, are studied separately in the psychoacoustic analysis of the synthesized noise signal of an example gearbox. The gear noise spectra for the cases with different gear faults are synthesized based on the findings of previous publications, where it shows that the two gear faults can either increase the amplitude at the harmonics of the gear mesh frequency or cause the sideband responses. Five psychoacoustics metrics, including loudness, sharpness, tonality, spectral centroid and Kurtosis, are analyzed for the cases with various gear faults. The analysis results indicate that the psychoacoustic analysis provides more gear faults information, and it can be used in gear health monitoring and troubleshooting. In addition, the psychoacoustic metrics can also be used as design targets in the early stage of the gear design.

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INTRODUCTION

Helical gear drives are widely used in the transmission of automotive, wind turbine, helicopters and other gear reducers. One of the main reasons of the transmission system breakdown was reported to be the gear failure [1], and a lot of efforts have been applied to the gear fault detection and diagnosis in the past few decades [2, 3, 4, 5, 6, 7, 8, 9, 10]. Various signal processing methods were developed and proved to be effective tools for gear condition monitoring and troubleshooting, including the time-domain [2, 3], frequency-domain [4, 5, 6] and time-frequency domain approaches [7, 8, 9, 10]. However, these signal processing methods mostly focus on using the objective metrics to detect gear faults, such as the magnitude variations of the noise and vibration signals [3, 8, 10].

Psychoacoustic analysis of noise becomes more and more important, and some standard psychoacoustics metrics, developed in the past few decades, are widely used in the automotive industry to evaluate the sound quality of an entire car or its components [11, 12, 13, 14]. This is mainly because that the calculated psychoacoustic metrics are the direct measurements of human perceptions of the noise [15, 16]. On the other hand, there are only a few publications talking about the psychoacoustic analysis of the gear noise. Brecher, et.al [17, 18] investigated the effect of the system geometry parameters and the gear tooth profile on the human perception of the gear noise. Kim, et. al [19] developed a new tonality psychoacoustic metric to evaluate

the sound quality of a special axle-gear whine noise, which is a non-stationary signal. Later on, they also correlated the subjective and objective evaluation results for the same axle-gear whine noise through using the Artificial Neural Network (ANN) method [20, 21]. Becker [22] developed an objective method for the analysis of the invehicle gear whine noise, which was shown to be an effective approach for evaluating the gear whine noise by performing a statistical analysis of the physical data. However, most of these psychoacoustic analyses of the gear noise were performed for the sound quality evaluation purpose, and there is no publication dealing with the diagnosis of gear faults using the psychoacoustic analysis of the gear noise, to the best knowledge of the authors.

Therefore, one primary purpose of this study is to diagnose gear faults through performing psychoacoustic analysis of the noise radiated by geared system with different type of gear faults. To do so, different types of gear faults are summarized, and two of them, including wear and misalignment, are studied separately in the psychoacoustic analysis of the synthesized noise signal of an example helical gear box. The gear noise spectra for the cases with different gear faults are synthesized based on the findings of previous publications, where it shows that the three gear faults can either increase the amplitude at the harmonics of the gear mesh frequency or cause the sideband responses. Five subjective metrics, including loudness, sharpness, tonality, spectral centroid and Kurtosis, are

analyzed for the cases with various gear faults. The analysis results indicate that the psychoacoustic analysis provides more information for detecting gear faults, and it can be used in gear health monitoring and troubleshooting.

EFFECT OF GEAR FAULTS ON THE GEAR NOISE

The effects of the gear faults on the gear dynamics are widely studied, and a large number of publications can be found [29, 30, 31, 32, 33]. As a comparison, to the best knowledge of the authors, there is very few published paper directly studying the effect of the gear faults on the gear noise [24]. As a primary work, the noise signals for the cases with different gear faults are synthesized based on the previous findings about the effects of gear faults on the gear dynamics. In the following parts of this section, various gear faults are summarized and the effects of different gear faults on the gear dynamics are introduced to give the basis of synthesizing noise signals.

Summary of Various Gear Faults

Gear faults are more likely to occur in the modern geared transmission systems. This is mainly because that the geared transmission systems are designed to be lightweight, and usually work under very high speed and load conditions. Different gear faults are categorized into two groups in the ISO standard depending on how the gear faults occur [23]. Among all the different gear faults, the gear tooth wear and misalignment are two of the most frequent occurred gear faults. Wear is the gear fault which uniformly distributed over the gear tooth surface, and it is normally caused by the sliding motion between gear teeth. Misalignment is space errors, which come from the manufacture and assembly process. Therefore, in this study, psychoacoustic analyses of the noise generated by gears with wear and misalignment are performed independently.

Effect of Gear Faults on the Gear Dynamics

Gear dynamics has obtained extensive research and numerous gear models are established to study the dynamic behavior of all kinds of gears in the past decades. Among these models, the lumped parameter model of the contacting gear pair is mostly used. In this model, both pinion and gear are lumped as the mass of inertia that are coupled by mesh parameters such as mesh stiffness, damping and transmission error [24]. The occurrence of gear faults will directly affect those mesh parameters, hence the dynamic model for gear system with various gear faults can be simply formulated by changing these mesh parameters.

Dynamics of gears with different gear faults have already been widely studied and reported in previous literatures. For gear pairs with worn teeth, typically, the shaft frequency response, the gear mesh frequency and its harmonic responses can be observed in the vibration spectrum of the housing, which radiates noise into the environment. As wear increases, the magnitude of the responses at those harmonics increases gradually [29, 30]. For gear pairs with the eccentricity fault, the third gear mesh harmonic response is higher than its second harmonic response, and the responses having the gear body natural frequencies can also be observed in the spectrum [30].

Also, as eccentricity increase, the magnitudes of these frequency components increase gradually. For gear pairs with misalignment errors, the second gear mesh harmonic response is higher than the third harmonic response, and the amplitude of sidebands increases as the misalignment increases [30].

Psychoacoustic Parameters

Psychoacoustic metrics are widely used to represent human perceptions of various sounds, and actually some of the most used ones, for example the loudness and sharpness, have already been standardized for routine uses. Besides those standardized metrics, there are some other psychoacoustic metrics including the tonality, spectral centroid and Kurtosis, which are also very useful in revealing the features of the human perception of sound. In this study, five metrics are used to analyze gear noise to detect gear faults.

CASE STUDY

A one-stage helical gearbox is studied as an example to evaluate the capability of the psychoacoustic analysis for detecting gear faults, as shown in Fig.1. The parameters of the gear pair used in this model are listed in Table 1. To make an effective comparison of the cases with different gear faults, the gearbox for all the psychoacoustic analysis cases are assumed to operate in the same steady-state condition with the gear shaft rotating at 1200 round per minute (rpm). Hence, the basic frequency components, such as the gear shaft rotating frequency, fundamental gear mesh frequency and its harmonics, are all constant, and they are given in Table.2. The spectrum of the noise radiated by the helical gearbox with health gears is given as the baseline in Fig.2.

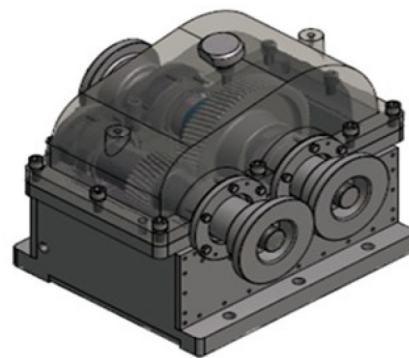


Figure 1. Example gearbox

Table 1. Parameters of a helical gearbox

Descriptions	gear	pinion
Tooth number	82	35
Module(mm)	2.75	2.75
Helical angle(deg)	10.00	10.00
Pressure angle(deg)	20.00	20.00
Teeth width(mm)	43.00	45.00