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Perceptual study of the evolution of gear defects

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ABSTRACT

The objective of this work is to apply the sound perception approach to study and diagnose gear defects. Simple and multiple defects of different levels of severity are artificially simulated on the gear teeth. The corresponding sounds are then acquired to perform a sound base representative of the diversity of gear defects. Acoustic sounds are generated using the processing software DynamX V.7. These sounds are analyzed with the paired comparison method to find a correlation between the sound perception and the scalar indicators. The results show that perception tests allow classifying gear defect sounds by order of degradation. The relation between the vibratory indicators and sound perception enabled us to obtain applicable mathematical models for the other sounds not included in the listening tests. These models can be used to monitor the evolution of gear degradation without repeating perceptions tests.

1. Introduction

Gears are used to transmit and change the rate of machinery shaft rotation. They can also change the direction of the rotation axis and rotary motion to linear motion, and they have existed since the invention of rotating machinery. Because of their force-multiplying properties, early engineers used them for hoisting heavy loads such as building materials. However, when dedicated to high-speed machinery such as automobile transmissions, gears are the optimal technological solution for low energy loss, high accuracy and low play. There are several categories of gears and they can be combined in a multitude of ways.

Vibration based methods for gear fault analyses have been established for a long time; they have been widely used for monitoring rotating machine conditions and for fault diagnostics. Regarding gearbox fault diagnosis, many signal processing tools have been used recently, such as the time–frequency method [1], spectral analysis [2], cepstral analysis [3], empirical mode decomposition and the Hilbert spectrum [4], and wavelet multi-resolution analysis [5].

In addition, noise signals, which are closely correlated to vibrations, have also been actively investigated for gearbox condition monitoring and fault diagnosis over the last two decades [6,7]. Nevertheless, both vibration and acoustic signals can be contaminated by different background noises. Therefore specific analysis with more advanced tools should be carried out to obtain reliable measures for fault diagnosis.

As vibration and acoustics have the same generation mechanism, acoustic noise can also be used for machinery condition monitoring when combined with effective signal processing methods, such as the sound perception method. Perceptual tests can be used to analyze various sound characteristics, and to discover the perceptive dimensions used by listeners to differentiate these audio stimuli. These measures of relative differences allow creating a similarity matrix perceived between stimuli. The dimensions are obtained from the similarity matrix using the Multi-Dimensional Scaling (MDS) method [8], which allows representing the dissimilarity perceived by listeners between stimuli in a multidimensional space. The paired comparison method is mainly recommended as the standard method for making judgments of dissimilarity directly between audio stimuli [9,10]. Auditors have to assess the overall dissimilarity of pairs, for example, by recording their estimate on a linear scale ranging from "very similar" to "very dissimilar". Individual dissimilarity matrices are filled with auditor's estimates and lead to an average matrix adapted to the MDS.

The perceptive approach to sounds has been used in several domains, for example in automobiles for the study of the sounds produced by air conditioning systems, and in railways for the perception of interior noises in a high-speed train to improve comfort and satisfy consumers' expectations [11,12]. Many researchers have investigated the comparison of listening tests and explained the benefits of the paired comparison method [13]. Other researchers have studied a serious problem in the paired comparison method: that of the considerable duration of listening tests in the case of a high number of stimuli, as it leads to auditive fatigue. The search for a test allowing the evaluation of a high number of

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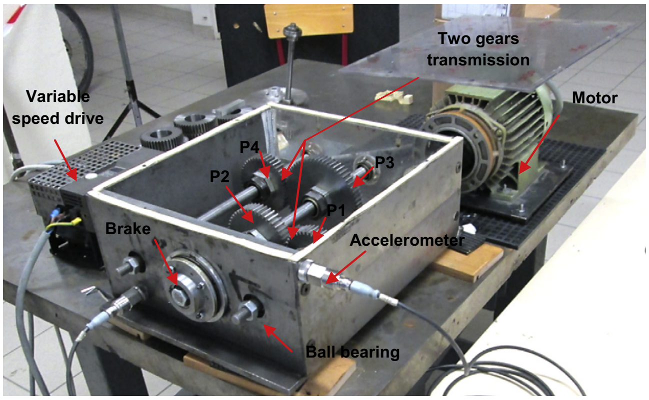

Fig. 1. Experimental setup.

stimuli led to the adaptation of a new method based on visual perception, called comparison with reference method. The task consists in assessing the similarity of a group of stimuli compared to a Ref. [14].

Kanzari [15] carried out a vibro-acoustic analysis of sounds resulting from gear teeth defects. From the results obtained, she established a correlation with scalar indicators. These results showed that scalar indicators such as vibratory speed, the spectral center of gravity, and the peak to peak value clearly explain the dissimilarity judgments for gear sounds in rotating machines.

Although the main advantage of using acoustic condition monitoring is that acoustic signals can be acquired remotely, it is necessary to avoid safety hazards and eliminate the need for high temperature vibration sensors with their associated mounting problems. However, acoustic condition monitoring used for machinery has received very little attention. This is because the acoustics from nearby rotating machines tend to contaminate the airborne sound generated by the machine being monitored. The influence of the acoustic environment definitely plays an important role in machine condition monitoring, and these noise sources must be filtered out by advanced signal processing techniques. Also, regarding surface vibration measurement, sensors are sensitive to the direction of the vibration source, whereas for acoustic measurement the requirement for a microphone is that it should be pointed toward the machine.

In the case of closed transmissions solid-borne noise is the major component [16]. The vibration spectra produced by gearboxes appear to be complicated, but they can generally be broken down into: tooth meshing harmonics, ghost components, sidebands, low harmonics of shaft speed and intermodulation components. For a well-meshed set of gears, only the fundamental gear meshing frequencies are likely to be measured.

According to the literature study presented below, we found very few works on fault detection by sound perception. The objective of this work is to apply the sound perception approach to the study and diagnosis of gear defects. The paired comparison method is used for assessing various samples of gear defect sounds measured in different cases to find a relationship between scalar indicators and gear sounds.

By listening to vibratory signals of different defect configuration, we hope to construct a linear correlation between the defect aggravation and a combination of 2 scalar indicators used in monitoring. The advantage will therefore be to construct a model of defect detection with scalar indicators, from its birth to the aggravation stage. To conceive this type of model in a new real case, it will be necessary to constitute a signals' base of faulty and healthy configuration. This approach is rather similar to a method of artificial intelligence as neural networks, but does not require training stage for regulating optimization parameters. The originality of this article locates at the level of the contribution of subjective approach by human audition as a supplement to the actual physical methods.

The paper is structured as follows. Section 2 is devoted to the theoretical study of the MDS method. Section 3 contains the presentation of the experimental setup and the measurement chain. Sound perception tests are presented in Section 4. Finally, the results obtained from perceptive tests with the approach proposed are presented and discussed in Section 5.

2. Multidimensional scaling method

The multidimensional scaling method allows the representation of objects in a space starting from the proximity relationship existing between each couple of objects. Each object can then be represented in this space. A large number of algorithms can be used to determine the coordinates of objects in space, starting from the distances between them. Some of these algorithms allow taking into account the specificities of the various subjects or groups of subjects of the various stimuli, and even both of them simultaneously.

Multidimensional analysis is an iterative reduction process in which objects are placed in a space of several dimensions adjusted to similarity or dissimilarity measures between objects. In this space, the similar objects are placed close to each other, and the non-similar items are removed. Multidimensional analysis is used to find dimensional information common to a set of variables. The dissimilarity scores provided by the subjects are translated into distances in a comparison test of objects presented in pairs.

2.1. INDSCAL algorithm

The Multidimensional Scaling algorithms used in the literature are: EXSCAL [17]. CLASCAL [18], expanded CLASCAL expanded [19],

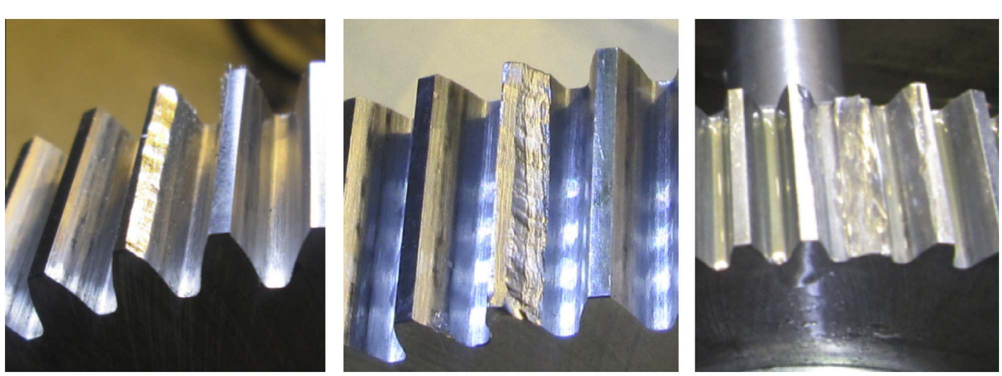

Fig. 2. Photos of various defects.