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Diagnostic features for the condition monitoring of hypoid gear utilizing the wavelet transform

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ABSTRACT

The present paper contributes to the development of new efficient solutions aimed at improving vehicle functional safety through the implementation of new transmission diagnostic methods. The study focuses on a new perspective of the diagnostic frequency range for hypoid gear condition monitoring, using acoustic emission and vibro-acoustic signal measurements and the Discrete Wavelet Transform for data analysis. The identification of the most sensitive diagnostic parameters and determination of frequency intervals using the Discrete Wavelet Transform, in which the most significant increase in the values of diagnostic parameters can be seen, has been presented. In addition, the identification of the sensitivity of the above-introduced non-destructive methods is presented. Diagnostic results in the extended frequency range were compared with the results of the classical method, and it was found that the selected parameter in the proposed measuring range could better characterize the condition of the gear unit.

1. Introduction

The improvement of vehicle functional safety is a very important task for engineers working in the automotive industry. Faults of separate transmission elements, such as bearings, gears, and shafts, may cause changes in the dynamic characteristics of the whole transmission. To prevent serious damage, transmission condition monitoring must be applied. Many investigations have been carried out in this field, and most attention has been given to spur gears and ball bearings. There are many nonlinear mathematical models for the abovementioned elements; thus, experimental investigations can be checked theoretically. However, most loaded gears in vehicles are hypoid gears, whose probability of fault occurrence is very high. Because of the complexity of hypoid gears, the efficiency of the classical methods used for diagnostics of other gears is low. In the present paper, an experimental investigation of a defective hypoid gear is carried out.

To identify the condition of a gear, various methods could be used: measurement of the vibro-acoustic signal (VS), oil debris method, sound measurement, acoustic emission (AE) method, temperature measurement, etc. VS and AE methods enable not only variations of the condition to be identified but also the type of fault. VS is a well-known method used for rotor system diagnostics and is widely described by Taylor and Kirkland [1] among others. AE was originally developed for non-destructive testing of static structures; however, over the years, its application has been extended to health monitoring of rotating machines and bearings [2]. The AE method is promising, and researchers [3] have identified that in some cases, this method enables detection of faults earlier than using VS. When performing diagnostics, it is important to consider rotation speed, torque, oil temperature and other parameters. Tan and Mba [4] investigated gear dynamics and determined the relationship among temperature, oil film thickness and AE activity. The preliminary data presented in the article showed that seeded fault identification with AE using the Root Mean Square (RMS) parameter was unsatisfactory. Tests with constant temperature have revealed far-reaching consequences that may alter the approach of applying the AE technique to gear fault diagnosis and monitoring. The impact of temperature on AE signals was shown in [5].

To register VS, a piezoelectric accelerometer can be used, and the primary signal in millivolts can be replaced by acceleration. The AE sensor is used to measure millivolts without transmission to another physical parameter. All data processing methods could be divided into three main domains [6]: time, frequency, and time–frequency. The simplest representation of the time domain is graphical in which the dependency of the measured signal is on time. Such a data analysis technique requires a highly qualified staff and time expenses, and the error probability is high.

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Diagnostic parameters that can be used to process signals are presented in Table 1.

The RMS parameter (X3) is the measure of the power content in the vibration signature [19] and is widely used in diagnostics; some researchers have used RMS parameter change (delta RMS). Diagnostic parameters, such as Peak (X1), Peak to Peak (X2) or Crest Factor (X10), also could be used for the identification of changes in the condition. Parameters from X15 to X24 presented in Table 1 were created for gear diagnostics, and additional signal processing is required for their use. First, Time Synchronous Averaging of a signal is required; then, Residual or Difference signals could be used. Residual signals can be applied by removing the shaft components and the gear meshing frequency with their harmonics [18]. Difference signals can be applied by removing the shaft frequency and its harmonics; the primary gear meshing frequency and the first-order sidebands and its harmonics are the main elements of the regular gear meshing signal [18]. More information on the presented diagnostic parameters can be found in the literature presented in Table 1.

When analysing the signal in the frequency domain, it is easy to detect not only the fault itself but also its type. Skrickij and Bogdevičius [20] investigated the variance of the centre distance on spur gear dynamics. It was found that when the centre distance is increasing, odd gear mesh frequencies in the spectra are increasing, even frequencies are decreasing, and the change in the first gear mesh frequency is negligible. Fast Fourier Transform (FFT) and Cepstrum can be used for data processing in the frequency domain; the parameters used in the frequency domain are presented in Table 2.

Signal analysis in the time–frequency domain is a convenient tool that can be used to investigate a signal not only according to frequencies but on the time scale as well. It could be useful when a mechanism works at non-stationary modes. There are a few algorithms that can be used to process a signal in time–frequency scales: Short Time Fourier Transform (STFT), Wigner–Ville distribution, Choi–Williams distribution and Wavelet transform, which is not a direct time–frequency representation but rather time-scale.

STFT is a classic time–frequency analysis technique that could be used in gear diagnostics [23]. The Wigner–Ville distribution was created in the first half of the XXth century. Twenty years ago, this method was first used for gear diagnostics [18]. The Cho–Williams distribution provides better resolution than the smoothed Wigner–Ville distribution, but it is still insensitive to the time-scale of signal components [24]. If compared to STFT, Wavelet uses narrow time windows at high frequencies and wide time windows at low frequencies [23]; by using the Wavelet transform, computing time can be reduced. The usage of the Wavelet transform to analyse gear vibro-acoustic signals and detect different faults was investigated by Wang and McFadden in [25]. Table 3 provides the diagnostic parameters in the time–frequency domain.

In addition to the parameters presented in Table 3, other parameters such as X1–X14 presented for the time domain (Table 1) could be used as well.

In practice, diagnostics of rotational equipment are performed using the vibro-acoustic method and are regulated by ISO standards. During the initial phase of the diagnostic process, the most commonly used diagnostic parameter is the RMS parameter of the vibro-acoustic signal in frequency intervals from 10 to 1000 Hz. In this paper, different combinations of the diagnostic parameters and frequency intervals were investigated with the aim to determine a combination of the most sensitive to the occurring fault.

2. Theoretical approach

To investigate the influence of hypoid gear fault on its dynamical characteristics, non-destructive vibro-acoustic and acoustic emission diagnostic methods were used. AE signals were measured in the range of 0–102,400 Hz, and VS signals were measured in the range of 0–25,600 Hz; data were then decomposed into frequency intervals and selected by considering characteristics of measuring equipment and sensors. Multilevel Wavelet Decomposition was used for signal processing. Unlike the STFT and other time–frequency distributions, which combine a constant time and frequency resolution, the Wavelet transform simultaneously displays both the large and small sizes in a signal, enabling the detection of distributed and local faults [25]. In addition, this feature minimizes computational time, which is a very important factor to adapt the proposed diagnostic method in the industry. Because ISO standards require measurements in low frequencies, Daubechies Wavelet (db5) was selected to conduct signal processing, as it has good resolution in the domain of low frequencies. The AE signal was decomposed into 11 intervals (Fig. 1b), VS into 9 intervals (Fig. 1c).

The first step of a multilevel Wavelet decomposition produces two sets of coefficients (Fig. 1a). These vectors are obtained by convolving the original signal s with the low-pass filter for approximation coefficients cA_1 and with the high-pass filter for detail coefficients cD_1, followed by dyadic decimation (downsampling) [28]. The next step splits the approximation coefficients into two parts using the same scheme, replacing the original signal with approximation coefficients and producing approximation coefficients cA_2 and detail coefficients cD_2 of the higher level, and so on (Fig. 1).

Equation that governs this decomposition [29]:

$$s = \sum_{j=J_0}^{J-1} cD_j + cA_j = \sum_{j=J_0}^{J-1}\sum_k \gamma_{j,k}\psi_{j,k}(t) + \sum_k \lambda_{J0}\phi_{J0,k}(t) \quad (1)$$

where s is the original signal, $\sum_{j=J_0}^{J-1}\sum_k \gamma_{j,k}\psi_{j,k}(t)$ are the detail coefficients, $\sum_k \lambda_{J0}\phi_{J0,k}(t)$ are the approximation coefficients, j is the level, k is the data translation, $(J - J_0)$ is the number of decomposition levels, $\psi_{j,k}(t)$ is the Wavelet function, $\phi_{J0,k}$ is the scale function, and γ and λ are the respective coefficients of the functions.

After all operations, the vector of the reconstructed coefficients, based on the Wavelet decomposition structure, is computed, and the values of diagnostic parameters are established. For result comparison, diagnostic parameters X1–X14 were applied. The usage of these parameters was proved by other studies; they can be used for diagnostics of different types of gears and bearings. Other diagnostic parameters presented in Table 1 require additional signal analysis to obtain Residual and Difference signals and can be used mostly for gear diagnostics.

3. Test rig description and experimental procedure

In this section, the results of the experimental investigation are presented. This investigation involves experimental testing of a hypoid gear to obtain its dynamic characteristics under different conditions. For this purpose, a series of tests were carried out using the test rig presented in Fig. 2a. Motor 1 (Fig. 2a and b) was operated under motor mode, whereas motors 2 and 3 were employed for carrying a load. A vehicle hypoid gear (Fig. 3a and b) with a transmission ratio of 3.38 (44:13, module 4364) shown in Figs. 3 and 2b (red body)[1], was used in the study. The main characteristics of the test rig are presented in Table 4. In similar investigations, other researchers usually connect acoustic emission sensors directly to the faulty element, increasing the sensitivity of the method, reducing noise level and reducing the practical application of this method; in this research, not only VS but also AE sensors were

[1] For interpretation of color in Fig. 2, the reader is referred to the web version of this article.