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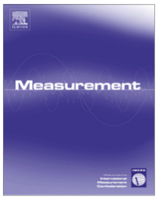

Spur gear tooth root crack detection using time synchronous averaging under fluctuating speed

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ABSTRACT

Filtering techniques are used to improve the signal to noise ratio (SNR) for better feature extraction. The time synchronous averaging (TSA) is one of such method that is based on averaging periodic sections. However, it fails to give significant results for an asynchronous or fluctuating speed condition. Moreover, most of the real life applications of gear are in asynchronous conditions. The aim of this paper is to develop a methodology which is robust for fault detection of gears under fluctuating load and speed conditions. A multiple-pulse individually rescaled-time synchronous averaging (MIR-TSA) technique in conjunction with conventional time synchronous averaging has been proposed. A 2-D finite element methodology based on principal or linear elastic fracture mechanics is adopted for predicting the crack propagation path at the root of gear tooth. The crack has been introduced using wire electrode discharge machining (WEDM). The vibration signals were recorded using drivetrain dynamic simulator (DDS) setup for various combination of load and crack length both for constant as well as fluctuating speed. Various time domain features such as root mean square, crest factor and kurtosis have been calculated using classical TSA and proposed MIR-TSA. A comparison of different extracted features between the proposed method and classic TSA has also been outlined. It has been observed that the proposed method enhances the fault detection under fluctuating speed conditions.

1. Introduction

Gear box condition monitoring and fault diagnosis of gears has been carried out for decades and a great amount of research has been performed for automated processing and analysis of the recorded vibration data. The most common gear diagnosis method is to analyze the vibration signals obtained from the machinery, specifically the shafts containing the gears. These vibration data also undergo a number of filtering techniques before features are extracted from them. Synchronous averaging, to extract the periodic components and commonly implemented as a time domain (filtering) averaging technique, is one of the most powerful and effective signal processing technique for the extraction of periodic signals from a composite signal applied to rotating machinery [1–5]. McFadden [6] proposed a technique for crack detection in geared system using the synchronous time averaging with phase demodulation. Boulahbal et al. [7] used synchronous time averaging and wavelet transform for the detection of cracks in geared systems. Lin et al. [8–10] proposed wavelet based filters for mechanical fault diagnosis using, Morlet and adoptive wavelets. They have assumed a constant shaft rotation rate constant and introduced the idea of time-averaged wavelet spectrum. Zeng et al. [11] used continuous wavelet transform for gear fault diagnosis. The time-averaging methods, proposed until now, are limited to synchronous signals, while gearbox signal are

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not synchronous in practical cases. Jafarizadeh et al. [12] proposed a new noise canceling method based on time-averaging method for asynchronous input followed by complex Morlet wavelet implemented for feature extraction and diagnosis of different kind of local gear damages.

In this paper the aforementioned limitation is overcome with a proposed multiple-pulse individually rescaled-time synchronous averaging (MIR-TSA) technique to effectively remove noises from periodic signals and suppressing signals that are not periodic within the averaging period. It is also a de-noising filter, which extracts feature components of the signal by capturing the mesh frequency and filtering out the other frequencies in every noise background.

There have been number of studies in predicting gear tooth crack propagation by various researchers using FE analysis using principles of Linear Elastic Fracture Mechanics (LEFM) to predict the crack propagation paths for variety of gear tooth and rim configuration. The studies show that a tooth root crack typically starts at the point of the largest stress [13–15]. In the present study, the crack propagation path at a pinion tooth root has been predicted using finite element analysis followed by the generation of crack trajectory on actual pinion under investigation. The drivetrain diagnostic simulator experimental setup is introduced and the details about the experimental investigation for the cracked pinion under different load, speed and crack length has been demonstrated. A time-averaging method for de-noising asynchronous signal is described for analysis of the signals obtained. A method has been proposed and its comparison the classical TSA using different time domain statistical features have been quantified. At the end results of the present study have been outlined. The scheme of the investigation discussed above has been outlined as shown in Fig. 1.

2. Vibration analysis using classical and proposed TSA technique

2.1. Synchronous speed condition

The first step in experimental verification was to incorporate classic synchronous TSA into the setup. For this purpose, the single stage spur gear arrangement described in Section 3 is utilized in which the gear in consideration was a 32-teeth pinion meshed with an 80-teeth gear. The rotating speed was maintained at a constant 5 Hz. The sampling rate of the signal was 3.2 kHz. The figures below depict the raw signal and the TSA signal.

2.2. Asynchronous speed condition

To simulate real life conditions of asynchronous (or varying) shaft rotation speed, the motor was programmed to run with a speed profile as depicted in the Fig. 2. The profile is chosen in such a way that the average speed of the shaft is around 5 Hz and maximum and minimum speeds are 6.5 Hz and 3.5 Hz (±30%) respectively.

2.3. Proposed multiple-pulse individually resampled TSA (MIR-TSA)

The proposed method utilizes an n-pulse per revolution tachometer to account for speed fluctuations within a single rotation along with rescaling the obtained data to rectify the asynchronous nature of the signal as shown in Fig. 3(b).

2.3.1. Speed estimation

A tachometer is used to estimate the speed of rotation of the gear shaft. Standard electrical tachometer is an electrical apparatus in which a single pulse is generated for every revolution. This pulse is generated due to the presence of a single strip of reflector on the gear shaft which reflects the light emitted by an emitter placed next to the shaft. A sensor, also placed next to the shaft, records the reflected light. The information recorded is pulse vs. time, which can be used to calculate the rotating speed or rotations per minute (RPM) of the shaft. In case of TSA, the time of zero crossing is used as a trigger. The following Fig. 3a depicts classical TSA graphically.

The proposed design uses an '*n*' pulse per revolution tachometer, which enables us to actually measure the variation in shaft speed even within a single revolution. Increase in pulse rate would directly mean a better filtering technique. Thus the decision on pulse rate is majorly dependent on the hardware limitations. The maximum pulse rate that can be chosen should be one at which the tachometer can distinctly record two consecutive pulses at the maximum operating speed of the shaft in reference. This includes the maximum speed it would attain due to speed fluctuations.

For the pulse generation, '*n*' equally spaced reflectors should be placed on the shaft in consideration. Thus the recorded signal will have a corresponding tachometer pulse, with the pulse generated at every $360/n$ degrees.

2.3.2. Rescaling

The obtained vibration signal should be cut at every point of tachometer pulse. This will give us n signal parts for every revolution. Each part can be linearly interpolated and rescaled to a time T corresponding to $T = T_b/n$, where T_b – time period of base signal.

Let the sampling rate be 'm' Hz (corresponds to m steps per second or $1/m$ seconds between two consecutive steps) and time gap between the any two tachometer pulses be t_{g1}. Thus the corrected time between two steps will be

$$t'_{s1} = \frac{T}{m\ t_{g1}} \tag{1}$$

or the re-sampled rate will be '$m\ t_{g1}/T$' Hz for the same data. A linear interpolation method can be used for the re-sampling as shown in Fig. 3b.

Following this, the first '*n*' consecutive part signals which have already been resampled to a time '*T*', should be added in series and merged to form the re-scaled signal corresponding to one revolution. The same process is to be repeated for the next '*n*' consecutive part signals to obtain the re-scaled signal for second revolution and so on. Thus,