VIBRATION MONITORING FOR FAULT DIAGNOSIS OF HELICOPTER PLANETRY GEARS

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Abstract: In this paper, vibration data analysis techniques are investigated for fault diagnosis of helicopter planetary gears. A data pre-processing technique is introduced that achieves the same result as the commonly used Time Synchronous Averaging with much lower computational complexity since interpolation is not required. A notion of using raw vibration data instead of the Time Synchronous Averaged data is also presented that is more suitable for the analysis of vibration data produced by planetary gearboxes and for the purposes of detecting carrier plate crack fault. Based on this notion, features such as the Harmonic Index in the frequency domain and the Intra-Revolution Energy Variance in the wavelet domain are derived. The features are used as inputs to fault classifiers and are shown to detect the fault successfully based on the test data that is available.

Keywords: Fault Diagnosis, Vibration Measurement and Data Analysis, Time Synchronous Averaging, Planetary Gear Carrier Plate Crack, Feature Extraction.

1. INTRODUCTION

Measurement and analysis of vibration data produced by a gearbox is important, either with a view to reducing the noise level of a gearbox or to assessing its mechanical condition. The majority of the available data analysis techniques for transmission systems are based on the Time Synchronous Averaging (TSA) of vibration signals (McClintic, *et al*., 2000; McFadden, 1987, 1989, 1991). It is assumed that a pulse signal synchronized to the rotation of a gear indicating the start of an individual revolution is available. Numerous revolutions are ensemble averaged resulting in an averaged data with a length corresponding to a single revolution. The TSA technique is intended to enhance the vibration frequencies that are multiples of the shaft frequency, which in many cases are mainly vibration related to the meshing of the gear teeth, while averaging out other components such as random vibrations and external disturbances. The resulting averaged data shows vibration characteristics of a gear in the time domain over one complete revolution, and differences in the vibration produced by individual gear teeth can be seen. Advanced local damage to gear teeth can often be detected by direct inspection of the time averaged data (McFadden, 1991).

Since the rotational speed of a transmission typically varies slightly during normal operation, the numbers of the data samples per revolution are different for a given sampling frequency. Interpolation is required to make the sample numbers per revolution the same before ensemble averaging can be carried out. Interpolation transforms the vibration signal from the time domain to the angle domain, and redefines the sampling frequency to be a function of angular position rather than time.

In this paper, the TSA technique is compared with other vibration data pre-processing techniques in the frequency domain. Since interpolation, as required by the TSA, is computationally demanding and time-consuming, it is undesirable especially for on-line real-time vibration monitoring. A simple technique is introduced that achieves the same result as the TSA with much lower computational complexity since interpolation is not required. The analysis and comparison between these different preprocessing techniques are presented in Section 2.

While time domain averaging has proved its superior performance for the analysis of fixed-axis gear vibration signals, problems arise when it is applied to the vibration produced by epicyclic gearboxes. The problems are mainly due to the motion of the planet gears and the multiplicity of contact regions between the planet gears and the annulus gear, and between the planet gears and the sun gear (Keller and Grabill, 2003; McFadden and Smith, 1985). In (McFadden, 1991), a technique for vibration separation (or mapping) of each individual planet within one revolution was used before time averages for the individual planet gears were calculated. However, the technique introduces additional complexity and requires detailed geometrical knowledge of a planetary transmission system (Forrester, 1998; Howard, 1991; McFadden, 1994; Samuel and Pines, 2000). Its usefulness is limited to planetary gearboxes with certain geometric properties, and to the detection of gear tooth faults.

In this paper novel signal processing and feature extraction techniques are proposed for analysis of vibration produced by epicyclic gearboxes that are based on raw vibration data instead of time synchronous averaged data. The techniques were motivated by a crack that was recently found in the planetary carrier of the main transmission gear of a U.S. Army's UH-60A Blackhawk helicopter (Keller and Grabill, 2003). Work has been carried out to develop a simple, cost-effective test capable of diagnosing this fault based on vibration data analysis techniques. Various Condition Indicators (features of the vibration data) of the carrier plate crack fault were presented in (Keller and Grabill, 2003) with the TSA technique. Of these features, only the Sideband Index (SI) and Sideband Level Factors (SLF) were consistently successful at detecting the presence of a fault under test cell conditions. None of the features were able to detect a crack under on-aircraft conditions at the low torque levels tested.

The helicopter transmission planetary gear system and vibration data recordings are briefly described in Section 3, while Section 4 presents the proposed signal processing and feature extraction techniques. Features that are able to differentiate under various testing conditions the faulted and unfaulted planetary gears of the UH-60A Blackhawk helicopters include the Harmonic Index in the frequency domain and the Intra-Revolution Energy Variance in the wavelet domain. The Harmonic Index feature is defined as the amplitude sum of all apparent sidebands of a specific gear meshing harmonic of the raw data, and the Intra-Revolution Energy Variance feature is defined as the variance of the vibration energy around a specific gear meshing harmonic within an individual revolution.

The raw vibration data instead of the TSA data is used to extract the features since the former provide better results. Note that the fault on the planetary gear is a crack in the carrier plate, and it is different from the usual tooth crack or breakage or from faults in a fixed-axis gear, in which case various features based on the TSA signal are sufficient to detect and identify the fault (McClintic, *et al.*, 2000). It is possible that the resonance frequency of the planetary gear, which may indicate the plate crack fault, is averaged out, since the TSA tends to average out external disturbances and noise that are not in sync with the carrier rotation. Even some meshing harmonics and their sidebands may also be averaged out or reduced if their initial phases at the start of each carrier rotation are different. Further evidence of the validity of these features based on raw data is still required and a Finite Element analysis method is actively pursued in an effort to discover the changes in the resonance frequency. Nevertheless, data analysis techniques based on the TSA are not excluded if new data acquired from the test cell or on-aircraft become available.

2. VIBRATION DATA PREPROCESSING

The data segment $x_m(n)$, for $n = 0, 1, ..., N-1$, is defined as the vibration data of revolution $\#m$ of a total number of M revolutions after interpolation, and $\bar{x}(n)$ for $n = 0, 1, ..., N-1$ as the time averaged data. The Discrete Fourier Transform (DFT) of the time averaged data is given by:

$$
\begin{aligned}
X(k) &= \sum_{n=0}^{N-1} \bar{x}(n) e^{-j2p\frac{kn}{N}}, \quad k = 0,1,..., N-1 \\
&= \frac{1}{M} \sum_{n=0}^{N-1} \sum_{m=1}^{M} x_m(n) e^{-j2p\frac{kn}{N}}.
\end{aligned} \tag{1}
$$

A new data preprocessing technique involves taking the DFT of each revolution of the vibration data (no interpolation required) and then ensemble averaging the complex numbers (including the amplitude and phase information) of the corresponding indices. The rationale behind this technique is described as follows. The frequency resolution of the DFT is given by $\Delta f = \frac{1}{T_{shaft}} = f_{shaft}$, where T_{shaft} is the time length of each individual revolution and may vary slightly from one revolution to another. If the period of the gear shaft rotation, T_{shaft}, is longer, the data volume sampled in a revolution is greater. The frequency resolution is then finer while the sampling frequency is the same, resulting in a higher number of frequency indices. However, the index of the meshing frequencies and their sidebands does not change. We can average the frequencies with common and corresponding indices and discard the extra frequencies of higher indices.

The result obtained using this preprocessing technique is equivalent to the DFT of the time synchronous averaged (TSA) data (which will be explained in the following paragraphs), while the interpolation and resampling as required in time averaging is not needed. In some sense we obtain the TSA data in the frequency domain. This processing step reduces the computational complexity since, in most cases, the DFT (FFT) is simpler and faster than resampling the vibration data, especially when the sampling frequency is high.

Since the DFT operation is linear, the DFT of the ensemble averaging of the interpolated data is equivalent to the ensemble averaging of the DFT of the interpolated data, as shown below:

$$
\begin{aligned}
X(k) &= \sum_{n=0}^{N-1} \bar{x}(n) e^{-j2p\frac{kn}{N}}, \quad k = 0,1,..., N-1 \\
&= \frac{1}{M} \sum_{n=0}^{N-1} \sum_{m=1}^{M} x_m(n) e^{-j2p\frac{kn}{N}} \\
&= \frac{1}{M} \sum_{m=1}^{M} \sum_{n=0}^{N-1} x_m(n) e^{-j2p\frac{kn}{N}}
\end{aligned} \tag{2}
$$

Fig. 1 illustrates the DFT of a TSA data set, which can be calculated by averaging the DFT as shown in the right part of the figure. In the figure, the data points connected by the dashed lines are to be averaged. Since the time length of each individual revolution varies, the frequency resolution of the DFT of each individual revolution varies as well.

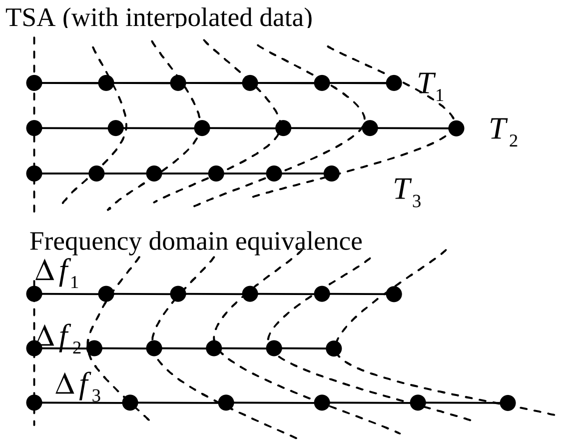

Fig. 1 DFT of a TSA data set

Fig. 2 shows the averaging of the DFT for multiple revolutions without interpolation. From the illustrations in the frequency domain, it can be seen that the results are equivalent at the common indices to the DFT of the TSA data shown in Fig. 1. Since the variation in the rotational speed of a rotor shaft is very small (usually the difference in the sample numbers between two revolutions of raw data is about 0.05%), the difference between the DFT of the TSA data and the averaging of the DFT of the raw data (without interpolation) is at the end of the spectrum axis and is negligible when the sampling rate is very high (for example 100 kHz).

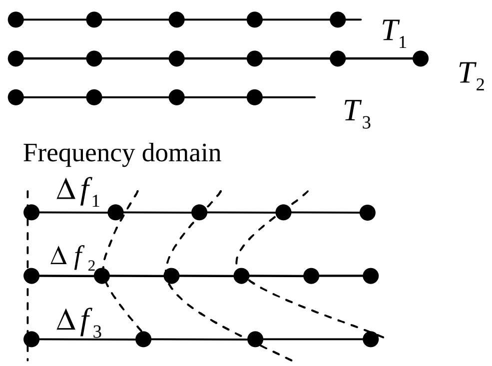

Fig. 2 Multiple revolution data without interpolation in the time and frequency domains

Another perspective is provided by viewing the sampling of individual revolutions in the angle domain. The frequency in this case is defined in the angle domain, instead of the time domain. It has a unit of "rotor shaft frequency" instead of Hz, that is, the frequencies are multiples of the shaft frequency. It is a very useful representation since the tooth frequency is always a specific multiple of the shaft frequency no matter how the rotational speed of the shaft changes. True frequency values may change with the shaft rotational speed, however the frequency values as multiples of the shaft frequency may not change. This allows invariant characteristics of the vibration data across multiple revolutions to be extract and enhanced. Fig. 3 shows the data samples in the angle domain and the corresponding frequency domain of the interpolated data, as in the TSA. Fig. 4 shows the data samples in the angle domain and the corresponding frequency domain of the data without interpolation. Again, we can see that in the frequency domain the two techniques are equivalent at the nontrivial frequencies.

An attractive data processing technique, different from the ones described above, is obtained by averaging the amplitudes of the DFT of multiple revolutions of the raw data (without interpolation). The phase information in this case is discarded, since the phases of different revolutions may be different, in fact, they may vary more than the signal amplitudes. This technique will be used in Section 4 to derive useful features such as the Harmonic Index.

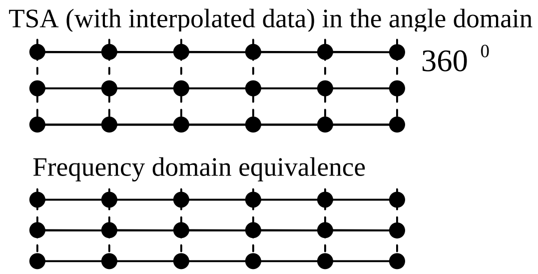

Fig. 3 TSA data samples in the angle domain and the corresponding frequency domain

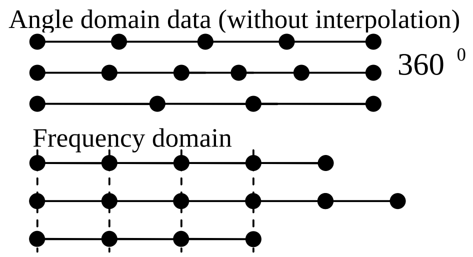

Fig. 4 Multiple revolution data without interpolation in the angle and frequency domains

3. PLANETARY GEAR PLATE CRACK

Epicyclic gears are important components for many rotorcraft transmission systems. An epicyclic gear system is defined by a sun/planet configuration, in which an inner "sun" gear is surrounded by two or more rotating "planets". Planetary systems are a subset of epicyclic gears defined by a stationary outer ring gear. Torque is transmitted through the sun gear to the planets, which ride on a planetary carrier. The planetary carrier, in turn, transmits torque to the main rotor shaft and blades.

If the transducer is placed in close proximity to the annulus, then the dominant vibration sensed at the transducer will originate from the meshing of the planet and the annulus, not the vibration generated by the meshing of the sun and the planet gears. Assuming that the ring gear has Z_a teeth, and the rotational speed of the planetary carrier is f_c, then the tooth meshing frequency of the vibration sensed by the transducer is $f_x = Z_a f_c$ (McFadden and Smith, 1985). Fig. 5 shows the carrier plate with a 3.25-inch crack of the main transmission gear. Since the planetary carrier is a flight critical part, a failure could cause an accident resulting in loss of life and/or aircraft. The discovery of the cracked plate resulted in flight restrictions on a significant number of the Army's UH-60A's. Manual inspection of all 1000 transmissions is not only costly in terms of labor, but also time prohibitive. There has been extensive work, therefore, to develop a simple, cost-effective test capable of diagnosing this fault based on vibration data analysis techniques.

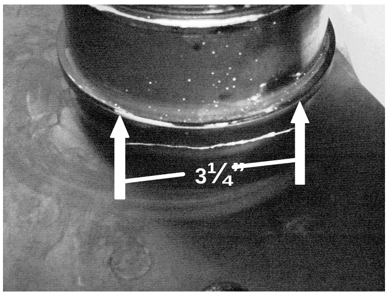

Fig. 5 Planetary Carrier Plate with a Crack

Vibration measurements of the main transmission gear were taken at the Helicopter Transmission Test Facility (HTTF) at Patuxant River NAS, MD. The data was acquired using an accelerometer sensor suite integrated into the Army's Vibration Management Enhancement Program (VMEP) system. Due to safety considerations, the transmission was not run for an extended period of time, and only small segments of data were taken at six torque settings ranging from 20% to 100% in the test cell, and two torque settings at 20% and 30% on-aircraft (Keller and Grabill, 2003). Each segment of the test cell data is 180 seconds long and was acquired at a rate of 100 kHz, and for the on-aircraft data each segment is 25 seconds long and was acquired at a rate of 48 kHz. A raw tachometer signal synchronized to the revolution of the planetary gear carrier plate and the main rotor is also included. The signal indicates the start of each individual revolution. The rotational frequency of the main rotor is slightly more than 4 Hz (it also varies a little over time), and, therefore, the segments of the test cell and on-aircraft data have 720 and 100 complete revolutions, respectively. Primarily, two signals from "PortRing" and "Input1" sensors (the accelerometers mounted on the left hand side of the ring gear of the main module and of the input module, respectively) provide important vibration signatures of the carrier plate crack fault.

4. FEATURE EXTRACTION

We extract a feature for each carrier revolution and average it over 10 revolutions. Since a sufficient number of experiments or data are not available to form a feature distribution for statistical evaluation purposes, we assume that a segment consisting of 10 revolutions constitutes an experiment providing a point in the distribution. The data length for every vibration signal is about 720 revolutions (180 seconds), and, therefore, there are 72 feature points in the distribution for each torque value. 10 feature data points, for each data segment, are available for on-aircraft data. Interesting features in the frequency and wavelet domains are described in the sequel.

4.1 The Frequency Domain: Harmonic Index

The fundamental and harmonic meshing frequencies (including their sidebands) of the planetary gear vibration signals are important components and are caused mainly by the meshing of the teeth of the ring gear and the planetary gears (McFadden and Smith, 1985). Their frequencies are related to the carrier plate rotational frequency and the tooth number of the ring gear. The planetary gear referred in this paper has 228 teeth, and therefore the 5th meshing frequency is $228 \times 5 \times f_c$ with f_c being the rotational frequency of the planet carrier.

The spectrum around the 5th meshing harmonic of the PortRing TSA data from the faulted as well as the unfaulted gears in the test cell experiments shows that the faulted data has higher vibration levels around the 5th harmonic for all torque levels except the 90% torque level. However, observing the amplitudes of the FFT of one revolution of the raw vibration data, whose spectral contents are obviously different from those of the TSA data, we can detect a consistent behavior between the faulted and unfaulted data. The spectrum around the 5th meshing harmonic of the PortRing raw data from the test cell experiments shows that the faulted data has a higher vibration level around the 5th harmonic for all torque values. Note that In order to obtain the spectra in this case, the FFT of one revolution of raw data is taken and the amplitudes of the corresponding index are averaged over 83 revolutions. The amplitude of a specific index corresponds to the amplitude of the frequency that is a multiple of the carrier shaft frequency, since the time length of the FFT is of one revolution long and the frequency resolution of the FFT is the carrier shaft frequency. For example, the component of index 1140 (228×5) is the 5th meshing harmonic for the FFT of every data segment with a length of one revolution, even though the carrier shaft frequency, f_c, may be slightly different for these individual revolutions and the real frequency of the 5th meshing harmonic may be, therefore, different. By aligning and averaging amplitudes of the same index, the meshing frequencies and their sidebands can be averaged and enhanced. The problem with this technique relates to the frequency leakage, that is, the frequencies that are not multiples of the carrier rotational frequency, f_c, show up in the surrounding frequencies that are multiples of f_c. So, it can only be used to describe a frequency band, such as in the Harmonic Index feature.

If, instead of the amplitudes, we average the complex numbers obtained from the FFT (including the amplitude and phase information), we arrive at results equivalent to those obtained from the FFT of the TSA data at multiples of the carrier rotational frequency, as was discussed in Section 2. The advantage of this technique is that it avoids the need for interpolation because of the variation in the carrier rotational frequency as in the TSA. The difference between amplitude averaging and FFT averaging or the FFT of the TSA data is that some components may be averaged out or reduced in the latter, and, thereby, the former is more efficient in distinguishing between faulted and unfaulted data. Based on these observations and the analysis carried out above, raw vibration data are preferred in the feature extraction process in an effort to diagnose the carrier crack fault in the planetary gears of the UH-60A Blackhawk helicopter.

To form the Harmonic Index feature, the Fourier Transform of the raw data of a time length equivalent to a carrier revolution is taken and the amplitudes of the 30 frequencies (with a resolution of the carrier frequency) to the left and to the right of a specific meshing harmonic are summed up. Fig. 6 shows the Harmonic Index around the 5th harmonic of the vibration data from the sensor at the Input1 location under test cell (upper part) and on-aircraft (lower part) conditions. In the figure, the feature values of the faulted carrier plate under various load conditions are in the contoured boundary. The faulted and unfaulted data points for each load condition should lie along lines vertical to the x-axis. However, for visualization purposes, the data points for each torque value are spread out along the x-axis based on the time sequence of the points. All subsequent feature distributions are plotted following this scheme. The distributions of the Harmonic Index show a clear separation of the feature values extracted for the faulted and unfaulted carrier plates.

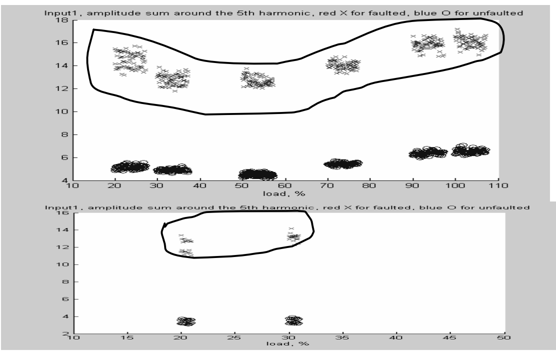

Fig. 6 Harmonic Index around the 5th harmonic of Input1 in test cell and on-aircraft

In a similar way, Fig. 7 shows the Harmonic Index around the 10th harmonic of PortRing. The points in the dashed line boundary represents the feature values from the additional data acquired from aircraft #5, which is an aircraft with a healthy main transmission planetary gear. The feature shows clear separation of the available data acquired from the faulted and unfaulted carrier plates as well. One concern about this feature is that the feature values from aircraft #2 and #5 are also quite apart, although both of them have healthy gears. The differences in the vibration levels may be due to the difference between the aircrafts.

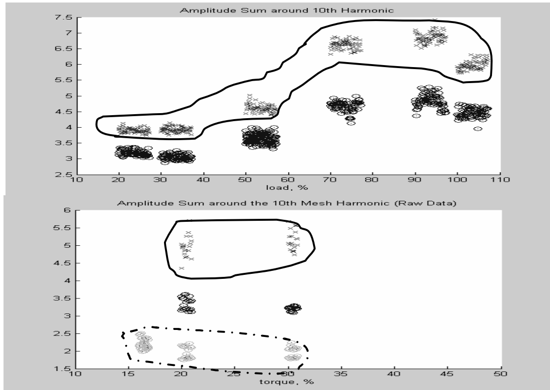

Fig. 7 Harmonic Index around the 10th harmonic of PortRing in test cell and on-aircraft

4.2 The Wavelet Domain: Intra-Revolution Energy Variance

The transducers that sense the vibration signals are braced on the housing of the gear box and are stationary relative to the rotating planetary gears and the carrier plate (McFadden and Smith, 1985). We expect to observe an increased non-uniformity during one revolution of the vibration data acquired from the gear system with a cracked carrier plate than from a healthy gear system. The Intra-Revolution Energy Variance feature attempts to describe this non-uniformity in the wavelet domain. To extract wavelet features, the Complex Morlet wavelet cmor70-1 was used to compute the wavelet map for the raw vibration data with a length of one revolution. Again, we focus on specific frequency bands and divide the wavelet map around the mth harmonic into 20 blocks in the temporal axis and the energy of each block is calculated. The Intra-Revolution Energy Variance feature is the energy variance of these 20 blocks and acts as an approximate indicator of the asymmetry or non-uniformity of the vibration in one carrier revolution. Fig. 8 shows the distributions of the values of the Intra-Revolution Energy Variance around the 5th meshing harmonic of the Input1 sensor data for the faulted and unfaulted carrier plates, respectively.

The features can be used as the inputs to a classifier to diagnose the planetary gear plate crack fault. The features of the Harmonic Index of the 5th harmonic of Input1 and that of the 10th harmonic of PortRing are provided as inputs to a Wavelet Neural Network (Vachtsevanos and Wang, 1998), which is accompanied with an appropriate decision logic that decided upon the particular fault class that the features (symptoms) belong to. It is found out that the features provide sufficient information for correct detection of the fault.

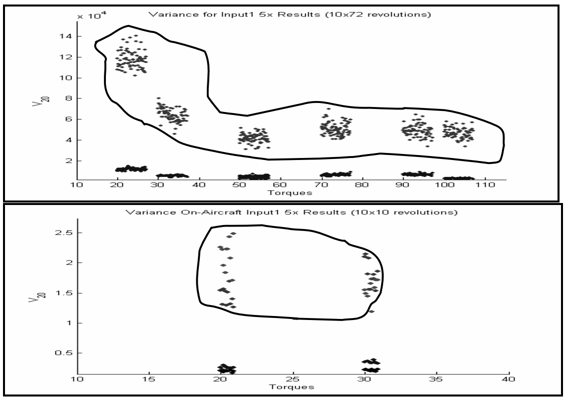

Fig. 8 Intra-Revolution Energy Variance of Input1 in test cell and on-aircraft conditions

5. CONCLUSIONS

Vibration data acquired from the main transmission planetary gears of the U.S. Army’s UH-60A Blackhawk helicopters in test cell and on-aircraft conditions were analyzed in an effort to detect the crack fault in planetary carrier plates. The plate crack is a new type of fault found in gear systems, and new feature extraction techniques, other than traditional ones that are used to detect tooth cracks or breakage or faults in fixed-axis gears, were investigated. It was found that the features labeled as Harmonic Index in the frequency domain and Intra-Revolution Energy Variance in the wavelet domain are able to differentiate the data acquired from the faulted and unfaulted planetary gears and, therefore, are potential candidates to detect the plate crack fault in the planetary gears under study.

6. ACKNOWLEDGEMENT

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