An Ergodic Method with Harmonic Signal-to-Noise Ratio in the Squared Envelope Spectrum Matrix for Planetary Gearbox Fault Diagnosis

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Abstract—**Vibration signal of planetary gearbox contains plenty of amplitude modulated and frequency modulated (AM-FM) components, which carry much information about the operation status of planetary gearbox. In the process of fault diagnosis, it is necessary to decompose its vibration signal into mono-components and then use demodulation algorithm to extract fault features. In this paper, variational mode decomposition (VMD), harmonic L2/L1 norm (HL21N) based method, and harmonic signal-to-noise ratio (HSNR) are utilized to form a new method that can take their advantages. VMD can decompose AM-FMs signal into mono-components and it is robust against noise. HL21N, proposed recently, can reduce influence of outliers. In addition, HSNR, proposed in this paper, can screen out the best diagnosis result among all the squared envelope spectrums given by VMD-HL21N method. For the purpose of validating the proposed method, vibration signal collected from a planetary gearbox with ring gear tooth crack and planet gear tooth broken are investigated, respectively. In comparison study, fast kurtogram and HL21N-based methods are also used to analyze the same data. Finally, in the abovementioned two experiments, the proposed method is doing better than fast kurtogram and HL21N-based method.**

Keywords — Planetary gearbox, fault diagnosis, variational mode decomposition, harmonic L2/L1 norm, harmonic signal-to-noise ratio.

I. Introduction

Gearbox, especially planetary gearbox, is an essential part of mechanical systems. Due to its large transmission ratio, high carrying capacity, and small volume, planetary gearboxes play a vital role in many machines, e.g., wind turbine, helicopter excavator. Therefore, planetary gearbox faults might cause serious consequences. For example, as for wind turbines, the fault rate and the downtime of planetary gearbox are relatively higher than those other components. In a study of wind turbines, the failures caused by planetary gearbox are 12% of all failures [1]. As for helicopter, when a planetary gearbox fault happens, staffs in helicopter would be in danger. Hence it is necessary to carry out condition monitoring and fault diagnosis of planetary gearbox. Vibration analysis is a useful method for rotating machinery monitoring and fault diagnosis, mainly because vibration signal is easy to obtain and contains abundant information of machine operation status. To perform this method, a key step is to extract fault characteristics from the signal, which is gathered by acceleration sensor or displacement sensor installed on a house of planetary gearbox. If fault characteristic frequency (FCF) and their harmonics (FCFHs) can be found, there may be some faults happening in the planetary gearbox. The calculation formula of FCF is given in [2]. However, planetary gearbox vibration signal is very complex since it contains many amplitude modulated and frequency modulated (AM-FM) components and much noise caused by multiple and time-varying transmission paths [1]. Therefore, it is not easy to extract fault characteristics from planetary gearbox vibration signal.

For the aforementioned reasons, vibration signal is usually decomposed into a series of mono-components at first [1]. At this moment, many signal processing methods are available to deal with complicated signals like vibration signal of planetary gearbox. For example, the empirical mode decomposition is used to decompose real vibration signal into several intrinsic mode functions (IMFs) [3]. In [4], several product functions are given through the method of local mean decomposition algorithm. In [5], variational mode decomposition (VMD), which is known for its robustness against noise, is used to decompose raw vibration signal into a set of IMFs. Next, with some demodulation algorithm, the FCFHs are demodulated from the spectrum. However, there is no a certain index or criteria that can screen out the component containing the richest fault information from all component [1].

With that in mind, the spectral kurtosis (SK) [6] is a good index to identify which resonance band in raw signal spectral is full of local fault induced impulses. For example, SK-based method is used to detect tooth crack of wind turbine planetary gearbox [7], and to detect the planet bearing fault [8]. However, the SK is sensitive to strong non-Gaussian noise (outliers). Hence, the harmonic L2/L1 norm (HL21N) based method was proposed to diagnosis bearing fault [9].

Considering the merits of HL21N and VMD, a method combining VMD and HL21N-based method can be established. However, the mode number of VMD has a large impact on the decomposition results. In case an inappropriate mode number is selected for VMD, the HL21N-based method may not obtain

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a good resonance band to identify FCFHs. Because of that, an ergodic method with harmonic signal-to-noise ratio (HSNR) index is proposed, which is used to screen out the squared envelope spectrum (SES) with the most obvious FCFHs in the SES matrix given by the above VMD-HL21N method. Finally, the method, which combines VMD, HL21N-based method, and HSNR, is proposed in this paper and is named an ergodic method with harmonic signal-to-noise ratio in the squared envelope spectrum matrix (EMHSNR).

The subsequence of this paper is as follows. Section II presents a brief introduction of VMD and HL21N-based method, which are the basis of the proposed method in this paper. Section III details the new method EMHSNR. Section IV validates the new method by using the experimental data of planetary gearbox with ring gear tooth crack and planetary gear tooth broken, respectively. Finally, conclusions are made in Section V.

II. Theory Background

A. Variational Mode Decomposition

VMD was first proposed by Dragomiretskiy and Zosso in 2014 [10]. It is a new and useful method for signal decomposition. The main idea of VMD is to decompose a signal into several IMFs with limited bandwidths and under the constraint that their sum is equal to the original signal. The mode of VMD refers to the finite bandwidth AM-FM signals or IMF.

$$u_k(t) = A_k(t)\cos(\phi_k(t)) \tag{1}$$

where $u_k(t)$ stands for the IMFs, $A_k(t)$ is the envelope of $u_k(t)$, and $\phi_k(t)$ is the non-decremental phase.

The process of VMD decomposition is described as:

Firstly, the analytical signal of original signal can be obtained by Hilbert transform, and the unilateral spectrum is calculated as follows.

$$\left(\delta(t) + \frac{j}{\pi t}\right)*u_k(t) \tag{2}$$

where * stands for the convolution operator. $\delta(t)$ is the Dirac delta function. j is the imaginary unit. $k = 1, 2, 3, ..., N$ and N is the predefined mode number.

Secondly, shift the spectrum of $u_k(t)$ to its fundamental frequency.

$$\left(\left(\delta(t) + \frac{j}{\pi t}\right)*u_k(t)\right)*e^{-jw_k t} \tag{3}$$

where w_k is the center frequency of $u_k(t)$.

Thirdly, estimate the bandwidth of $u_k(t)$ by calculating the squared L2 norm of the gradient of the above-mentioned demodulated signal. In the end, an optimization problem is obtained as below [9].

$$\min_{\{u_k\},\{w_k\}} \left\{ \sum_k \left\| \partial_t \left[\left(\delta(t) + \frac{j}{\pi t}\right)*u_k(t) \right] e^{-jw_k t} \right\|_2^2 \right\} \\ s.t. \sum_k u_k = f \tag{4}$$

where f stands for the original signal.

The above-mentioned problem is a constrained optimization problem which can be solved by using a quadratic penalty term and Lagrangian multipliers, and alternating direction method of multipliers. After that, we can get a set of $u_k(t)$ which stand for the modes.

However, the modes might have no practical physical meanings if the number of modes is set too small or too large. This is very unfavorable for signal processing since it is hard to extract useful information from such kind of modes. Therefore, it is necessary to set a proper number of modes before starting VMD. In order to deal with this problem, a method that can select an appropriate number of VMD modes for rotating machine fault diagnosis is proposed in this paper, which will be introduced in Section III.

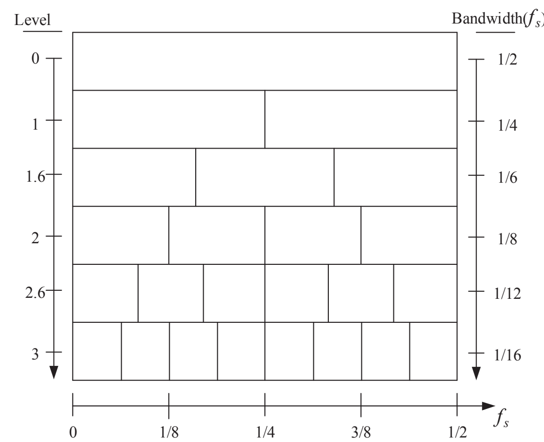

Figure 1. 1/3-binary decomposition tree of filter banks. fs is the sampling frequency [9].

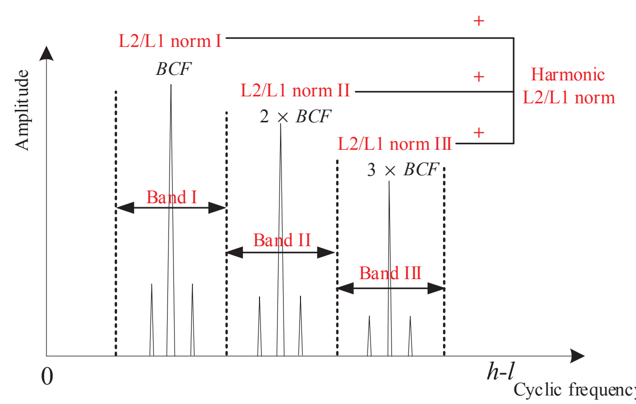

Figure 2. Harmonic L2/L1 norm [9].

B. Harmonic L2/L1 Norms-based Method

Impulse signal usually implies a fault in rotating machine, such as pitting in bearing or gear tooth. However, the energy of impulse signal is so weak that it can hardly be extracted from background noise. Fortunately, impulses always come with modulation in rotating machine, which can be extracted through demodulation. However, before demodulation, it is necessary to search the resonance band that contains abundant fault information in raw signal spectral. HL21N can do that and can also reduce the influence of outliers. The procedure of HL21N-based method is as follows.

Firstly, as shown in Fig. 1, the 1/3-binary tree [9] is used to process raw signal. In this method, a one-into-two and a one-into-three filters are used to decompose a raw signal into 2^k banks, where k=1, 1.6, 2, 2.6, 3, 3.6… In general, the bandwidth of subband in the last layer should be large than triple of FCF.

Secondly, search the frequency band that can maximize HL21N. As shown in Fig. 2, HL21N index is the L2/L1 norms of SES of a specific band obtained from the 1/3-binary tree. Instead of calculating all the L2/L1 norms of squared envelope signal, HL21N only considers the band related to FCFHs in SES. The definition of HL21N index is as follows [9]:

$$H_{L1/L2}(l,h,M,B)=\sum_{k=1}^{M}\frac{\|SES_{l,h}^{i,j}(k)\,[n]\|_2}{\|SES_{l,h}^{i,j}(k)\,[n]\|_1} \tag{5}$$

and the k-th harmonic band $SES_{l,h}^{i,j}(k)\,[n]$ are defined in (6).

$$\begin{cases} i\leqslant n\leqslant j \\ i=FCF(k)-B \\ j=FCF(k)+B \\ FCF(k)=k\times FCF(1) \\ k=1,2,3,\ldots,M \end{cases} \tag{6}$$

where l and h are the lower and the upper cutoff frequencies in raw signal spectrum, respectively. i and j are also the same as l and h but they belong to the SES, as shown in Fig. 2. As for the parameters M and B, Ref. [9] advise to set them as $M=3$ and $B=FCF(1)/2$, where $FCF(1)$ is the FCF.

III. The Proposed Diagnosis Method

This section will detail the proposed EMHSNR that take advantage of the merit of VMD, HL21N and HSNR. A complex AM-FM signal can be decomposed into several mono-component IMFs by VMD. HL21N can indicate which band contains abundant impulses of machine fault. HSNR is used to choose a good result in the SES-matrix. The details are given as follows.

In first step, the VMD is used to decompose a raw machine vibration signal into IMF matrix with multiple modal number groups in (7). In IMF matrix, the Mi-j is the j-th IMF, which comes from raw signal through VMD with the mode number k equal to i. In other words, the row number of IMF matrix is the overall mode number defined before operating each VMD. The number of columns of IMF matrix is the sequence number of IMFs in each decomposition. The maximum mode number n in (7) can be set flexibly according to different situations.

$$\begin{bmatrix} M1-1 & 0 & 0 & \cdots\cdots & 0 \\ M2-1 & M2-2 & 0 & \cdots\cdots & 0 \\ M3-1 & M3-2 & M3-3 & \cdots\cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ Mn-1 & Mn-2 & Mn-3 & \cdots & Mn-n \end{bmatrix} \tag{7}$$

In the second step, the HL21N-based method is used to select a band which can maximize the HL21N index in each IMFs in the IMF matrix. After this step, an SES matrix is given such that obvious FCFHs can be found. However, it is not necessary that every SES in SES matrix is good enough and then the good result needs to be recognized with HSNR.

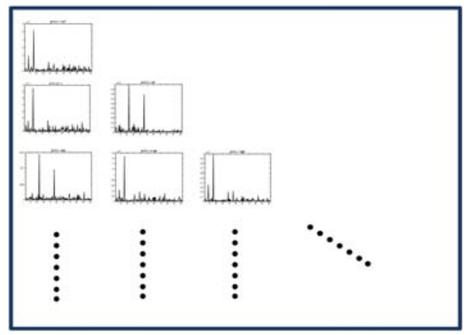

Figure 3. The SES matrix transfer from IMF matrix with HL21N-based method.

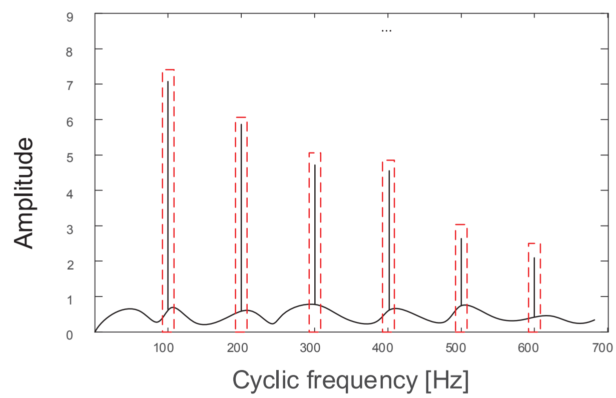

Figure 4. One of the SES in the SES matrix presented to describe the definition of HSNR.

In the third step, the HSNR is used to search the SES in the SES matrix, which can maximize HSNR index. HSNR is defined as:

$$HSNR=10\log\Big(\sum(\|UFF_i\|_\infty^2)/\sum(\|ULF_j\|_\infty^2)\Big) \tag{8}$$

where UFF_i (useful frequency) are the bands in the red rectangles in Fig. 4 and ULF_j (useless frequency) are the bands in the background frequency with the SES subtracted by UFF_j. The rectangles are symmetrical with each FCFH and its bandwidth is empirically defined as 0.02*FCF.

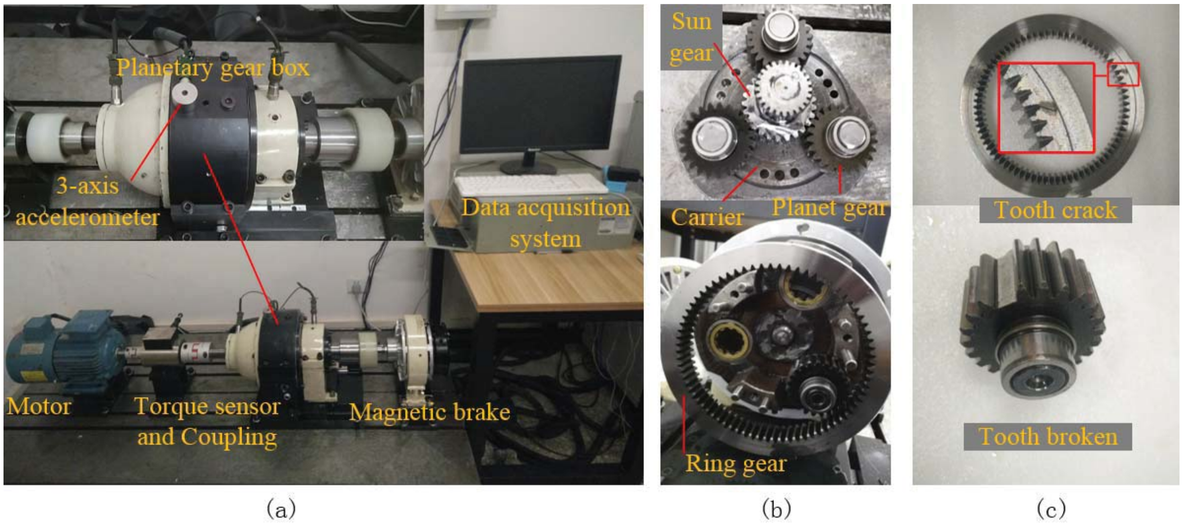

Figure 5. Test rig of planetary gearbox: (a) planetary gearbox test rig, (b) the inner structure of planetary gear box, (c) the ring gear and planet gear with tooth crack and tooth broken respectively

IV. CASE STUDY

Fig. 5 (a) is the planetary gearbox test rig in which some labels are given to describe it, and the inner structure of planetary gearbox is shown in Fig. 5 (b). In this section, two sets of real data which are collected from the test rig with ring gear tooth crack and planet gear tooth broken (see the Fig. 5 (c)) are used to validate the proposed method, respectively. For comparison, fast kurtogram and HL21N-based method are also used to analyze the data.

A. Planet Gear Tooth Broken Fault Diagnosis

1) Data Description: The data of planet gear tooth broken is the vertical vibration signal collected from the housing of the planet gearbox by a 3-axis accelerometer as shown in Fig. 5 (a). The planet gear with tooth broken is presented in Fig. 5 (c), which is made by wire cutting machine. The data sampling frequency is set to 5 kHz, and 10000 samples are involved in this analysis. Torque of the gearbox input-shaft is equal to 3N·m, which is given by the magnetic brake and measured by the torque sensor. The input-shaft speed is equal to 3000 rpm. The FCF is calculated by the following equation and it is equal to 40.62 Hz [2].

$$f_{cpd} = \frac{z_r z_s}{z_p (z_r + z_s)} \cdot f_s \tag{9}$$

where f_s is the input-shaft rotating frequency. z_s, z_p, z_r are the number of teeth of sun gear, planet gear, and ring gear respectively.

2) Data Analysis: Firstly, the trend term in the data is removed by the least squares algorithm. Then the data is analyzed by the EMHSNR, fast kurtogram, and HL21N-based method, respectively. In the VMD decomposition of EMHSNR, the maximum traveling mode number is set to 15 and other parameters are standard values. The results of EMHSNR, fast kurtogram, and HL21N-based method are presented in Fig. 6 (a), 6 (b), and 6 (c), respectively. The first, the second, the third, the fourth, and the sixth FCFHs can be recognized in Fig. 6 (a). In Fig. 6 (b) and 6 (c), FCFHs can also be recognized but the background noise is more than Fig. 6 (a). Additionally, there are some strong noise ahead of the first FCFH in Fig. 6 (c) and some strong noise between the first FCFH and the second FCFH in Fig. 6 (b), which may cause misleading conclusion in automatic diagnosis system. In general, in this case, the result of EMHSNR is slightly better than the others.

B. Ring Gear Tooth Crack Fault Diagnosis

1) Data Description: The sensors used for data sampling, the vibration position, direction, the torque of the gearbox input-shaft, and the sampling frequency are the same as the previous case. The ring gear with tooth crack is presented in Fig. 5 (c), which is also seeded by wire-electrode cutting. The input-shaft speed of input is equal to 1800 rpm. The data length is equal to 5000 samples. FCF is calculated by the following equation and is equal to 24.37hz [2].

$$f_{crl} = K \cdot \frac{z_s}{(z_r + z_s)} \cdot f_s \tag{10}$$

where K is the number of planet gear and equals to 3.

2) Data Analysis: Firstly, the trend term in the data is also removed by the least squares algorithm. Then the data was analyzed by the EHHSNR method, HL21N-based method, and fast kurtogram, respectively. In the VMD decomposition of EMHSNR, the parameters are the same as the first case. The result of EMHSNR, Fast kurtogram, and HL21N-based method are presented in Fig. 7 (a), 7 (b), and 7 (c), respectively. In Fig. 7 (a), the first to the fifth FCFHs are easy to be recognized. However, only first and second FCFHs can be recognized in Fig. 7 (b), and some misleading frequencies exist around them. In Fig. 7 (c), while the magnitude of FCFHs from first to fifth is large, there are a lot of noise in background, which may cause difficulty in identifying FCFHs.

In general, the EMHSNR is better than HL21N-based method and Fast kurtogram.

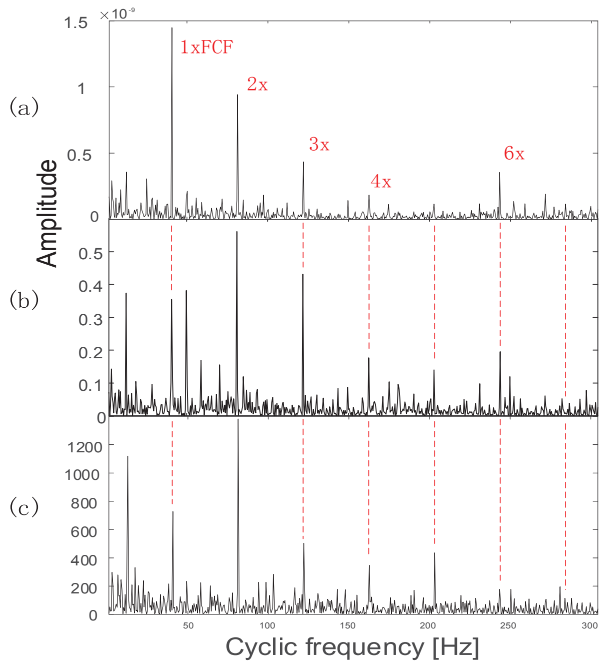

Figure 6. Diagnosis result of case 1: The SESs carried FCFHs of planet gear tooth broken given by (a) EMHSNR, (b) HL21N-based method, and (c) fast kurtogram respectively.

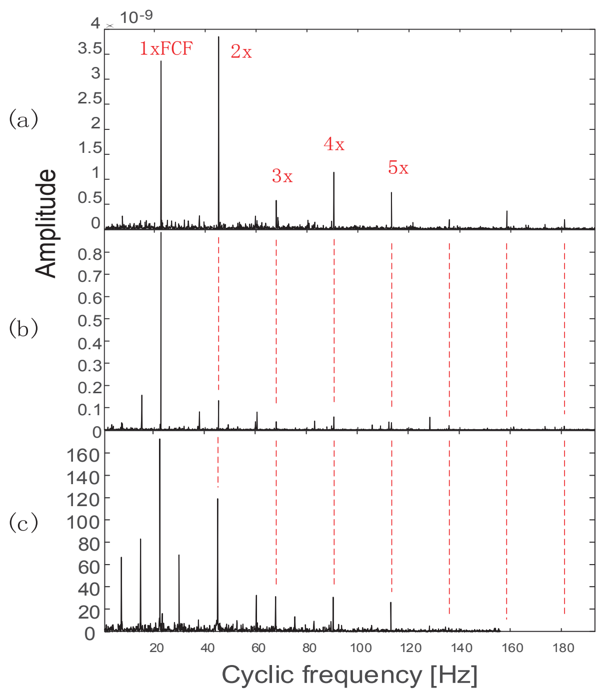

Figure 7. Diagnosis result of case 2: the SESs carried FCFHs of ring gear tooth crack given by (a) EMHSNR, (b) HL21N-based method, and (c) fast kurtogram respectively.

V. CONCLUSION

The proposed method takes the merits of VMD, HL21N, and HSNR. VMD can decompose a complicated signal containing multiple AM-FM components into mono-component and has robustness against noise. The HL21N is able to find a band which carries fault information in the signal and reduces influence of outliers. In order to screen out the best diagnosis result in the SES matrix given by the VMD-HL21N method, HSNR is proposed in this paper. Besides, the vibration signal of planetary gearbox is complicated because of the complicate machine structure. However, by virtue of the merits of VMD, HL21N and HSNR, EMHSNR can extract the fault information from the vibration signal. Moreover, the proposed method is better than fast kurtogram and HL21N-based method through the two cases. In general, EMHSNR is an effective and promising method for planetary gearbox fault diagnosis.

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REFERENCES

[1] T. Wang, Q. Han, F. Chu, and Z. Feng, “Vibration based condition monitoring and fault diagnosis of wind turbine planetary gearbox: A review,” *Mech. Syst. Signal Process.*, vol. 126, pp. 662–685, Jul. 2019.

[2] Q. Miao and Q. Zhou, “Planetary Gearbox Vibration Signal Characteristics Analysis and Fault Diagnosis,” *Shock Vib.*, vol. 2015, pp. 1–8, 2015.

[3] I. Antoniadou, G. Manson, W. J. Staszewski, T. Barszcz, and K. Worden, “A time–frequency analysis approach for condition monitoring of a wind turbine gearbox under varying load conditions,” *Mech. Syst. Signal Process.*, vol. 64–65, pp. 188–216, Dec. 2015.

[4] W. Y. Liu, W. H. Zhang, J. G. Han, and G. F. Wang, “A new wind turbine fault diagnosis method based on the local mean decomposition,” *Renew. Energy*, vol. 48, pp. 411–415, Dec. 2012.

[5] Z. Feng, D. Zhang, and M. J. Zuo, “Planetary Gearbox Fault diagnosis via Joint Amplitude and Frequency Demodulation Analysis Based on Variational Mode Decomposition,” *Appl. Sci.*, vol. 7, no. 8, p. 775, Aug. 2017.

[6] J. Antoni, “The spectral kurtosis: a useful tool for characterising non-stationary signals,” *Mech. Syst. Signal Process.*, vol. 20, no. 2, pp. 282–307, Feb. 2006.

[7] T. Barszcz and R. B. Randall, “Application of spectral kurtosis for detection of a tooth crack in the planetary gear of a wind turbine,” *Mech. Syst. Signal Process.*, vol. 23, no. 4, pp. 1352–1365, May 2009.

[8] T. Wang, Q. Han, F. Chu, and Z. Feng, “A new SKRgram based demodulation technique for planet bearing fault detection,” *J. Sound Vib.*, vol. 385, pp. 330–349, Dec. 2016.

[9] M. Wang, Z. Mo, H. Fu, H. Yu, and Q. Miao, “Harmonic L2/L1 Norm for bearing fault diagnosis,” *IEEE Access*, pp. 1–1, 2019.

[10] K. Dragomiretskiy and D. Zosso, “Variational Mode Decomposition,” *IEEE Trans. Signal Process.*, vol. 62, no. 3, pp. 531–544, Feb. 2014.