GEAR AND BEARING FAULT DETECTION USING WAVELET PACKET AND HILBERT METHOD VIA ACOUSTIC SIGNALS

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Abstract

Detection of gearing and bearing faults using vibration signals has been widely used for decades. A lot of methods of vibration signal processing for fault detection have been used, such as fast Fourier transform, Hilbert transform, wavelet and wavelet packet transform. In recent years, a new method for vibration signal processing, combining Hilbert transform and wavelet packet appeared, and has become an effective method to extract modulating signal and help to detect the early gearing and bearing faults. The article deals with the use of the combination of wavelet packet method and Hilbert transform for processing acoustic signals to identify bearing and gearing faults in a two-stage gearbox test rig. Three simultaneous faults are made: a chipped tooth on the input pinion, a pitting tooth on the output gear and a pitting (spall) on the outer race of a rolling bearing on output shaft. By comparison of the processed acoustic signals of normal and faulty gearbox, these three faults can be exactly detected.

Keywords: Acoustic signal, Bearing, Fault detection, Gear, Hilbert transform, Wavelet packet

Introduction

Gearboxes play an important role in industrial applications. Early diagnosis and detection of defects in gearboxes could reduce the cost of maintenance process. Typical faults of gears include pitting, chipping, and more seriously, crack. Typical ones of bearings are pitting in the inner or outer races.

Detection of gearing and bearing faults using vibration signals has been widely used for decades. Plenty of methods of vibration signal processing for fault detection have been used, such as Fourier transform, Hilbert transform (HT), wavelet and wavelet packet transform (WPT) [1], [2]. N. G. Nikolaou, I. A. Antoniadis [1] has used the wavelet packet transform and vibration signals to detect the localized defects in bearings. In [2] by Zarei and Poshtan, incipient bearing failures is detected by using wavelet packet analysis via stator current analysis. In recent years, new method for vibration signal processing combining Hilbert transform and wavelet packet has become an effective method to extract modulating vibration signal and help to detect the early faults in gearing [3].

Vibration signal analysis is the most widely used technique in fault diagnosis, whereas in some cases vibration-based diagnosis is restrained because of its contact measurement. Acoustic-based diagnosis with non-contact measurement has received little attention, although sound field may contain abundant information related to fault patterns [4]. Tian Hao et al. [5] have proved that the sound pressure contains many kinds of frequency vibration information of gearbox, and the characteristic parameters of gearbox can be extracted by analysing the acoustic signal to diagnose the faults. When analysing the acoustic signal of fault gear, cepstrum analysis is an effective method [5]. Some researchers have proved the advantage of the acoustic emission method over vibration method, when applying to bearing

faults detection [6]. Xiaoqin Liu, Xing Wu, Chang Liu have used envelope detection and spectrum analysis of vibration and acoustic emission for diagnosing bearing faults. They compared the vibration and acoustic method on bearing diagnosis and showed that the quality of acoustic emission signal decreases more significantly than the vibration signal when speed slows down. Of the same fault condition, with higher rotary speed, the acoustic method is superior to vibration method, while at lower speed, the acoustic may be taken by the latter [6]. Satish Mohanty et al. [7] predicted the faults on ball bearing under different states using acoustic and vibration signatures without knowing complete bearing information. The study showed that fast Fourier transform fails to analyse the signals of transient and non-stationary nature, extraction and analysis of transient signal can be better done using empirical mode decomposition [7].

In gearing fault diagnosis technique, demodulation is an effective technique to extract the fault frequency. Hilbert transform has been shown useful for demodulation, to detect the envelope of the vibration signal. With the fast Fourier transform (FFT), the fault frequency can be extracted. However, the FFT is not appropriate to the transitory signal issued from defects in multi-stage gearbox that may contain several fault frequency components. The wavelet transform helps resolving the problem of transitory signals, but with an unsatisfactory resolution in low frequency band. Non-stationary envelope signals can be analyzed by WPT, since WPT is the perfect tool for analysis of non-stationary signals. Therefore, the combination of wavelet packet with Hilbert transform would be more effective for fault detection than using WPT alone.

This paper focuses on the combination of wavelet packet method and Hilbert transform [3] via acoustic signal to detect faults in a two-stage gearbox test rig. Three simultaneous faults are made: a chipped tooth on input pinion, a pitting tooth on output gear surface and a pitting (spall) on outer race of a bearing on output shaft. By the comparison of the processed acoustic signals of normal gearbox and faulty one, we could identify exactly these three faults. The analysed results also show that acoustic signals could be used in gearing and bearing fault detection.

Fundamentals of Wavelet Packet and Hilbert Transform

Wavelet Packet Method

The wavelet packet transform is a generalization of wavelet transform [1], [3]. The wavelet packet function is defined as followings:

$$W_{j,k}^m(t) = 2^{j/2} W^m \left(2^j t - k \right) \tag{1}$$

Where: j is the scale parameter (frequency localization) and k is the translation parameter (time localization) ($j, k \in Z$), m is the oscillation parameter ($m \in N$), $W^m(t)$ denotes $W_{j,k}^m(t)$ for the case of $j = k = 0$.

The first two wavelet packet functions (m=0, 1; j=k=0) are called the scaling function $\varphi(t)$ and the mother wavelet $\psi(t)$:

$$W^0(t) = \varphi(t) \tag{2}$$

$$W^1(t) = \psi(t) \tag{3}$$

The other wavelet packet functions for m=2, 3…, are defined by the following relations:

$$W^{2m}(t) = \sqrt{2} \sum_k h(k) W^m \left(2t - k \right) \tag{4}$$

$$W^{2m+1}(t) = \sqrt{2}\sum_{k} g(k)W^m(2t-k) \tag{5}$$

Where $h(k)$ is the low-pass (scaling) filter and $g(k)$ is the high-pass (wavelet) filter. The function $h(k)$ is related to the scaling function and $g(k)$ is associated with the mother wavelet function [3].

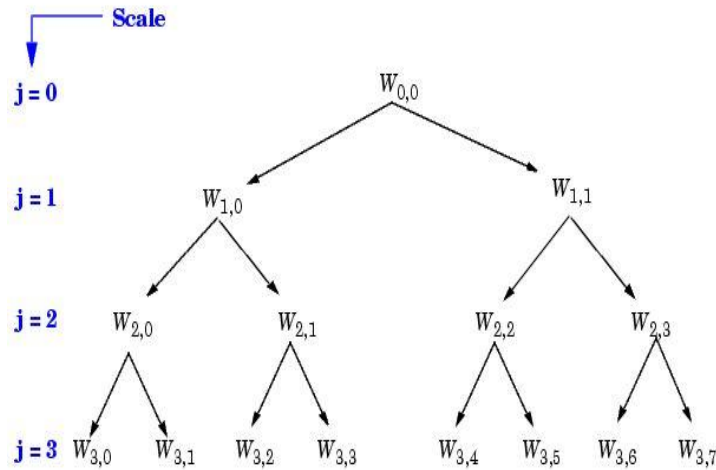In Figure 1, an example of a wavelet packet decomposition tree of three levels is illustrated.

Figure 1. Three-level wavelet packet decomposition tree

Wavelet packet coefficients of the signal $x(t)$ are as follows [3]:

$$P_j^m(k) = \left\langle x, W_{j,k}^m \right\rangle = \int_{-\infty}^{+\infty} x(t)W_{j,k}^m(t)dt \tag{6}$$

Where $P_j^m(k)$ denotes the mth set of wavelet packet decomposition coefficients at the jth scale parameter and k is the translation parameter. The signal $x(t)$ must be in the discrete format: $x(t) = \left\{ P_0^1(k) \,|\, k = 1, 2, ..., N \right\}$, where N is the length of the signal. $\left\{ P_0^1(k) \,|\, k = 1, 2, ..., N \right\}$ can be then decomposed into different time-frequency space with the Eq. (6).

In this paper, we use the DB10 Daubechies mother wavelet for analysis the signal.

Hilbert Transform

Hilbert transform is a time-domain convolution that maps one real-valued time-history into another. It is defined by [3]:

$$H[x(t)] = \frac{1}{\pi} \cdot \int_{-\infty}^{+\infty} \frac{x(t)}{t - \tau} \cdot d\tau \tag{7}$$

where t is time, $x(t)$ is a time domain signal, and $H[x(t)]$ is the Hilbert transform of $x(t)$.

Demodulation is accomplished by Hilbert transform forming a complex-valued time domain signal called the analytic signal $A[x(t)]$ which is defined as:

$$A[x(t)] = x(t) + i \cdot H[x(t)] = a(t) \cdot e^{i\phi(t)} \tag{8}$$

Where: $i = \sqrt{-1}$

The resulting complex time-domain signal can be converted from the real/imaginary format to the magnitude/phase format given below:

$$a(t) = \sqrt{x^2(t) + H^2[x(t)]} \tag{9}$$

$$\phi(t) = \arctan\frac{H[x(t)]}{x(t)} \tag{10}$$

Hilbert transform removes carrier signals, while retaining modulating signals, from that are extracted the frequencies related to gearbox faults.

Algorithm For Acoustic Signal Analysis

The algorithm for acoustic signal analysis using wavelet packet and Hilbert method is presented as below [3]:

- Load the original vibration signal $x(t)$
- Pre-processing the signal $x(t)$, and get a new signal represented as $\left\{P_0^1(k), k = 1, 2, ..., N\right\}$
- Let $\left\{P_0^1(k)\right\} = \sqrt{\left(P_0^1(k)\right)^2 + H^2\left[P_0^1(k)\right]}$
- WP decomposition of $P_0^1(k)$ at the level j_{max}
- Coefficients of the node (j_{max}, m), $(m=1,2...,2^{jmax})$ will be re-array again
- Shrinkage WP decomposition coefficients based on the threshold $\sigma\sqrt{2\log(n)}$
- Set coefficients of all the other sets at level j_{max} to zero except the set of node (j_{max}, m) $(m=1,2, ...,2^{jmax})$
- Reconstruct signal $\left\{P_0^1(k)m \mid m = 1, 2, ..., 2^{j\max}\right\}$ which contains frequency component in the interval of $\left[(m-1)F_S / 2^{j\max+1}, mF_S / 2^{j\max+1}\right]$
- Fault feature extraction

In order to eliminate the influence from the noise over the received data, the vibration signal is pre-processed with the following relation: $x'(t) = x(t) - \frac{1}{N}\sum_t x(t)$, with $x(t)$ is the original signal, $x'(t)$ is the pre-processed signal, $t=1,2,..., N$, N is length of the signal (step a).

F_s is the sampling frequency (step h).

To de-noising in all frequency bands, a threshold equal to $\sigma\sqrt{2\log(n)}$ is used, where n is the number of wavelet packet coefficients points in all frequency bands of the level j_{max}, σ stands for the minimum noise standard deviation of wavelet packet decomposition coefficients in all frequency bands of the level j_{max} (step f).

Experimental Setup

Test Rig and Fault Simulation

The experimental setup is shown in Figure 2. The apparatus consists of an electric motor, a belt driver, a two-stage gearbox, an accelerometer ICP 603C11 PCB PIEZOTRONICS for acquisition of vibration signals, a microphone MI-1235 together with a pre-amplifier MI-3111 ONO-SOKKI and an amplifier SR-2200 to receive acoustic signals, a signal receiver set cDAQ917 and NI9233 of National Instrument, a PC computer with LabVIEW Sound and Vibration software and Matlab tool, a generator to simulate the external load on the end shaft of the gearbox. Motor speed can be measured by SKF GX Series Microlog equipment.

Figure 2. Experimental setup

The gearing pitting (spall) was made by punching three holes on gear surface with diameter of 1mm and depth of about 0.6mm (Figure 3a). For simulating a broken tooth, a gear tooth has been cut down about 20% of its volume by a small handy grinding machine (Figure 3b).
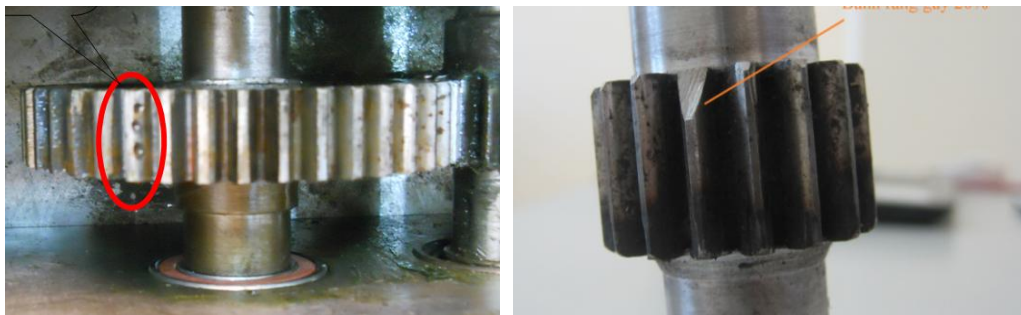

Figure 3a, b. Simulation of gear pitting and chipped gear tooth

Figure 4. Spall on bearing outer race

The bearing defect was produced by punching a small hole (depth and diameter of 0.8mm) on the outer race surface with a hardened boring tool (Figure 4).

Characteristic parameters of the two-stage gearbox: Motor rotational speed: about 1570 (rpm); Pinion: $Z_1 = 17$; Gear: $Z_2 = 43$; Meshing frequency of the first gear stage: 444.8Hz; Meshing frequency of the second gear stage: 175.8Hz; Input shaft frequency: 26.1Hz; Intermediate shaft frequency: 10.3Hz; Output shaft frequency: 4.08Hz. Based on geometric parameters of one-row bearing on output shaft, ball pass frequency of outer race (BPFO) is calculated as 16,6Hz.

The chipped tooth is on the pinion of the input shaft, the pitting tooth is on the gear of the output shaft, the spall is on the bearing outer race of the output shaft. The fault frequencies relative to these three faults are 26.1Hz, 4.08Hz, 16.6Hz respectively.

Results and Discussion

First of all, the acoustic signals issued from the gearbox with only one fault (pitting on the pinion of the output shaft) are received and processed. The meshing frequency of this second gear stage is 175.8Hz. The frequency of the output shaft (which carries the gear of pitting tooth) is 4.08Hz (this frequency is also the modulating frequency of the signals, which reflects the gearing fault).
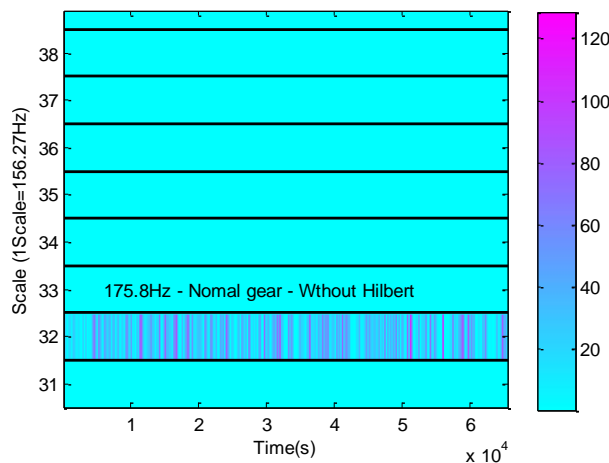

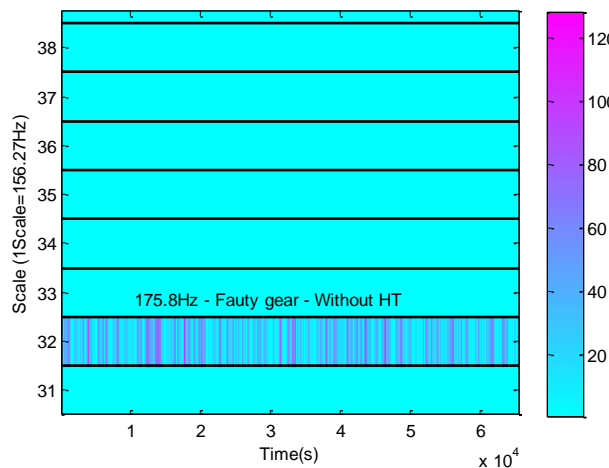Figure 5. WPT (without HT) of acoustic signal for normal gearing at 5th level

Figure 6. WPT (without HT) of acoustic signal for faulty gearing at 5th level

Figure 5 and 6 represent the WPT images of real signals at level 5 for the normal and faulty gear respectively. In these two figures, the meshing frequency 175.8Hz of the gear pair can be observed at scale 2 (156.27 to 312.54Hz). By comparing the shade of grey around the meshing frequency 175.8Hz of normal and faulty gearing images, we consider that the faulty signal has bolder color (higher energy), and we can predict that there is damage on the second gearing pair, but we cannot know exactly where the fault localizes (on pinion or on gear).
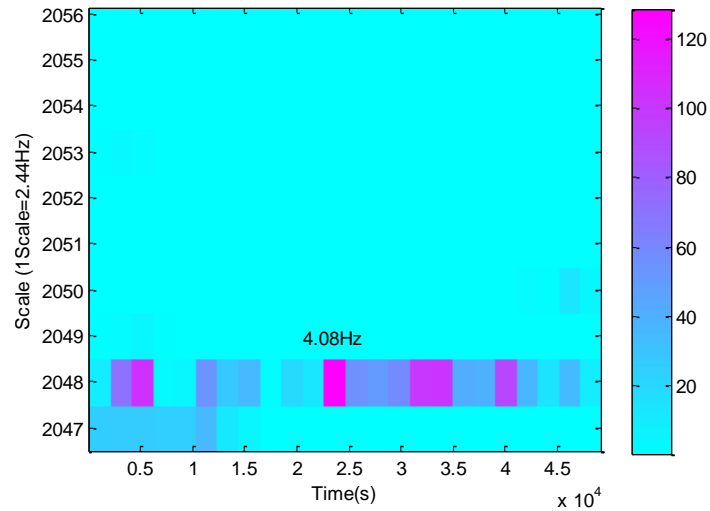
Figure 7. WPT (with HT) of acoustic signal for normal gearing at 11th level
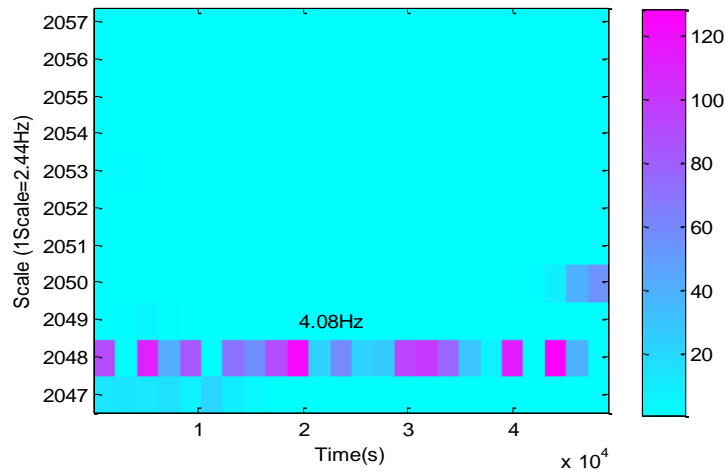

Figure 8. WPT (with HT) of acoustic signal for faulty gearing at 11th level

Then, using WPT in combination with Hilbert transform to process the acoustic signals for the same case to detect the demodulating frequency reflected the gearing fault. Since the frequency of the output shaft (on which located the pitting gear) is of 4.08Hz, the analyzed results in the frequency band by proposed method at 11th level are provided for both normal and faulty gearing acoustic signals in Figure 7 and 8. The frequency 4.08Hz related to the output shaft appeared at scale 2 (2.44→4.88Hz) in these two images. The energy of the faulty signal around 4.08Hz is higher than that of normal signal, this fact reflects that the pitting gear is located on the output shaft.

In the case of multiple faults in gearbox (chipped tooth on input pinion, pitting on output gear, spall on outer race of output shaft), the results obtained by the proposed method are presented in Figure 9 and 10. Since the interested demodulation frequencies indicating the three faults are 26.1Hz, 4.08Hz and 16.6Hz respectively, after having affected the HT on the real acoustic signals, we decompose the signals at 11th level. The frequency of 26.1Hz is located at 11th scale (24.4Hz to 26.84Hz), 4.08Hz at 2nd scale (2.44Hz to 4.88Hz), and 16.6Hz at 7th scale (14.64Hz to 17.08Hz).
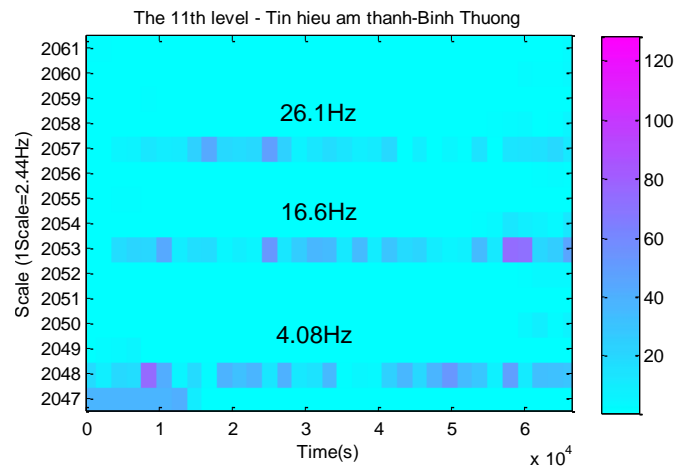
The 11th level - Tin hieu am thanh-Binh Thuong

Figure 9. WPT with HT of gearbox acoustic signal of normal gearbox

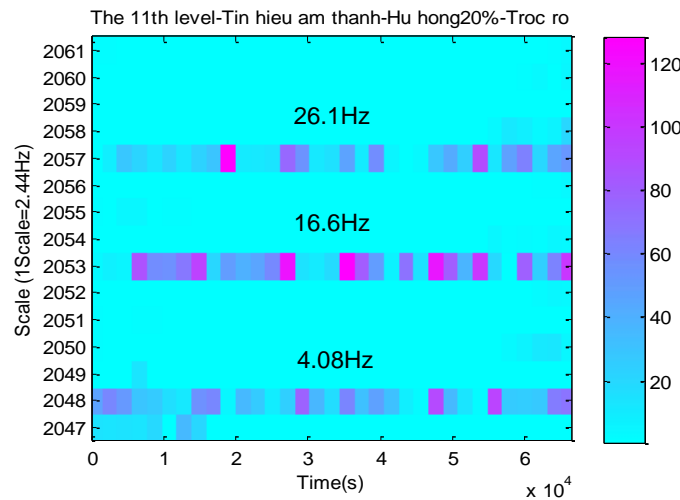The 11th level-Tin hieu am thanh-Hu hong20%-Troc ro

Figure 10. WPT with HT of gearbox acoustic signal of gearbox with three faults

By comparing the shade of grey of WPT images of normal and degrading gearbox around the respective fault frequency 26.6Hz, 4.08Hz and 16.6Hz, we consider that the faulty acoustic signal has bolder color (higher energy). Conclusion can be deduced: the location of the chipped tooth is on the input pinion, the pitting tooth on output gear, and on the outer race bearing of the output shaft exists severe failure. Furthermore, by observing the WPT images around an interested frequency along with the time domain, we can detect the time when the defects occurred in non-stationary signals.

Conclusions

The following conclusions are deduced from this study:

- Acoustic signals have a wide frequency bandwidth which include the vibration of many rotating machines and can be used for gearing and bearing fault detection in parallel with vibration signals.
- When using the method of Wavelet Packet transform in combination with Hilbert transform proposed in [3] to process the acoustic signals with some case studies mentioned in this paper, we have proved the efficiency of the method in gearing and bearing fault detection. We have considered that gearing and bearing faults can not

only be detected but can be exactly localized, whereas with the use of the Wavelet Packet transform, we can only detect the faults existed somewhere in the gearbox. The faults might also be exactly identified in case of multiple ones.

- By observing the WPT images around an interested frequency along with the time domain, we can detect when the defects occur in non-stationary signals.

References

[1] N.G. Nikolaou, and I.A. Antoniadis, "Rolling element bearing faults diagnosis using wavelet packets," *NDT&E International*, Vol. 35, No. 3, pp. 197-205, 2002.

[2] J. Zarei, and J. Poshtan, "Bearing fault detection using wavelet packet transform of induction motor stator current," *Tribology International*, Vol. 40, No. 5, pp. 763–769, 2007.

[3] X. Fan, and M.J. Zuo, "Gearbox fault detection using Hilbert and wavelet packet transform," *Mechanical Systems and Signal Processing*, Vol. 20, No. 4, pp. 966–982, 2006.

[4] W. Lu, W. Jiang, H. Wu, and J. Hou, "A fault diagnosis scheme of rolling element bearing based on near-field acoustic holography and gray level co-occurrence matrix," *Journal of Sound and Vibration*, Vol. 331, No. 15, pp. 3663–3674, 2012.

[5] H. Tian, L. Tang, and T. Yang, "Application of acoustic testing for gear wearing fault diagnosis," In: *The Eight International Conference on Electronic Measurement and Instruments*, pp. 3-635 - 3-638, 2007.

[6] X. Liu, X. Wu, and C. Liu, "A comparison of acoustic emission and vibration on bearing fault detection," In: *Proceedings 2011 International Conference on Transportation, Mechanical, and Electrical Engineering (TMEE)*, pp. 922-926, 2011.

[7] M. Satish, K.K. Gupta, K. S. Raju, S. Arvind, and S. Snigdha, "Vibro acoustic signal analysis in fault finding of bearing using empirical mode decomposition," *International Conference on Advanced Electronic Systems (ICAES)*, pp. 29-33, 2013.