

Slew Bearings Damage Detection using Hilbert Huang Transformation and Acoustic Methods

P. Nikolakopoulos^a, A. Zavos^a

^a University of Patras/Department of Mechanical and Aeronautics Engineering/Machine Design Laboratory, Greece.

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ABSTRACT

Slow speed slew bearings are widely used in many applications such as radar, aviation and aerospace units, bogie bearings for vehicles, harbor and shipyard cranes. Slew bearings are designed to carry out high axial and radial loads, they have high tilting rigidity and they are lubricated with grease. Slew bearings consist of the rollers, the inner and the outer ring and the gear in general. One of the most common problems arising in such equipments is the vibration levels due to wear of either regarding the rollers or the other components. Actually, it is very critical for his safe operation and reliability to know from where the vibrations come from, and how much severe are. In this article, the acoustic emission method is used in order to excite slew bearings either for laboratory tests or real naval application receiving the sound waves in the time domain. The Hilbert Huang Transformation (HHT) with the empirical mode decomposition (EMD) is used in order to detect the possible defect and to estimate the healthy state from the measured sound signals of the bearing, through to investigation of the statistical index kurtosis.

Corresponding author:

*Pantelis Nikolakopoulos
University of Patras,
Department of Mechanical and
Aeronautics Engineering,
Machine Design Laboratory,
Greece.
E-mail: pnikolak@mech.upatras.gr*

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1. INTRODUCTION

Condition monitoring due to vibrations of low-speed rotational slewing bearings is significant, since it is become necessary for a proper maintenance program that replaces the slewing bearings installed in massive machinery in the steel and naval industry, among other applications. Further, acoustic emission (AE) is still the main technique used in terms of low-speed bearings. The majority of the literature on the slew bearings field are commonly concerned with using the finite element method for analysis[1-3]; there is also a small amount of works done in oil analysis [4,5], and even less in

vibration monitoring techniques using the Hilbert Huang Transformation [6-12]. A detailed review regarding the development and the application of HHT in the field of structural health monitoring in the last two decades are presented in [9]. The basic principle of the HHT method, which contains the extraction of the intrinsic mode function (IMF), mechanism of the Empirical Mode Decomposition (EMD), and the features of HT; shows the application of HHT in the system fault identification. Moreover, the two basic bearing frequencies, called ball spinning frequency (BSF) and outer race passing frequency (BPFO), that do not identified in the usual Fast Fourier Transform (FFT) are identified using the EMD method [10].

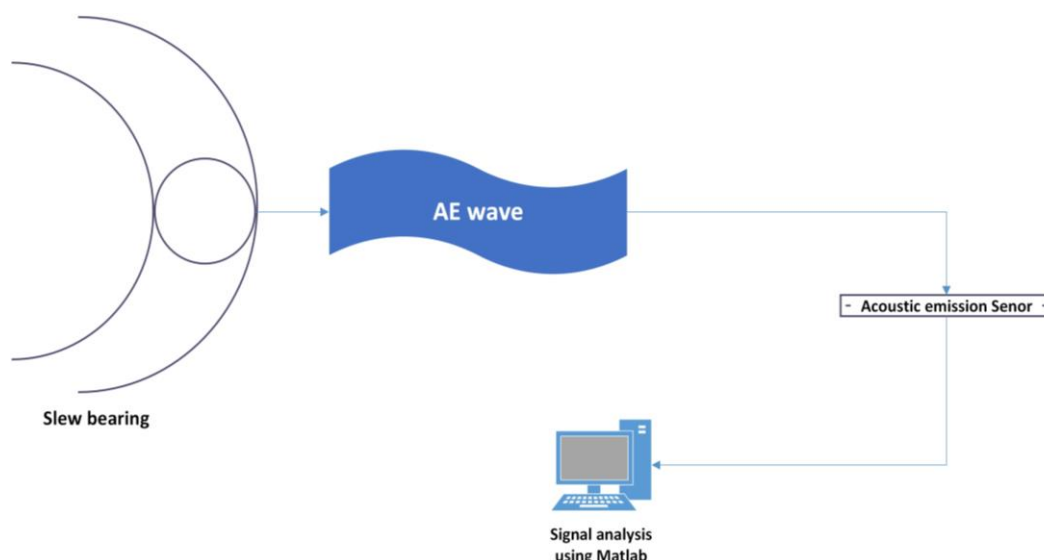


Fig. 1. A schematic procedure of acoustic signals.

The statistical indicator Kurtosis is a result of mathematical algorithm on a fixed frequency band of the time signal. It shows the impulsive shape of the signal in the time domain [11]. Without impulsive phenomena in time domain the value of Kurtosis is 3 and some higher values could be an indication of shocks.

In this paper, the acoustic emission method is used in order to excited slew bearings with and with out defects getting the sound waves in the time domain. The Hilbert Huang Transformation with the Empirical Mode Decomposition is used in order to detect the possible defect and estimate from the measured sound signals how severe is the situation for the bearing. A laboratory tests in damage slew bearing is prepared and a fault detection is achieved. Therefore, the statistical indicator kurtosis is also calculated showing the fault magnitude of the slew bearing.

2. ACOUSTIC EMISSIONS

Acoustic Emission (AE) is defined as transient elastic waves produced from rapid release of strain energy caused by deformation or damage within or on the surface of a material. AE differs from ultrasonic testing [10]. In particular, the frequency of acoustic emissions varies between 30 kHz and 2 MHz. Acoustic emissions is described for the emissions from active defects and is very sensitive to detect any activity when a structure is loaded. Boundary, liquid friction and break noise in automobiles generate

acoustic emission in the ultrasonic area. To detect AE it is important to have an AE-piezoelectric transducer, which transforms the elastic waves into an electrical signal. These transducers have a piezoelectric disk transforming the mechanical wave into the corresponding electrical signal. Each transducer has its own characteristic e.g. resonate or wideband transducer. Later in the procedure, the extracted electrical signal must be filtered and computed. In practical terms, the identification methods to investigate a measured AE-signal are usually Root-Mean-Square-Value, Fast Fourier Transformation, Wavelet and Hilbert Huang Transformation. As follows, from Fig. 1 the procedure of acoustic wave transferred from a slew bearing surface to a sensor and then to a computer unit are illustrated. In this study, the signal analysis is performed using the Matlab software.

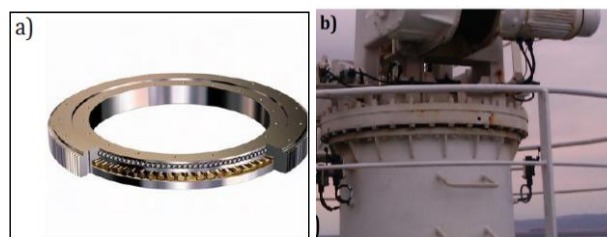


Fig. 2. (a) A typical slew bearing, (b) Real naval application.

In Fig. 2 a typical slew bearing and the slew bearing from a naval application are presented. Actually the acoustic signal of the above slow speed large slew bearing is analyzed and discussed.

3. HILBERT HUANG TRANSFORM

Hilbert - Huang Transform (HHT) is a time-frequency analysis technique introduced by Huang to process non-stationary signals [6]. It combines the Hilbert transform and the Empirical Mode Decomposition (EMD). The main interest of the EMD is to consider the features of the analyzed signal, which are oscillations on determining the IMFs by using an iterative process (see Fig. 3). This explains that the time-scale of the decomposition will automatically be adapted to the dynamic of the analyzed signal.

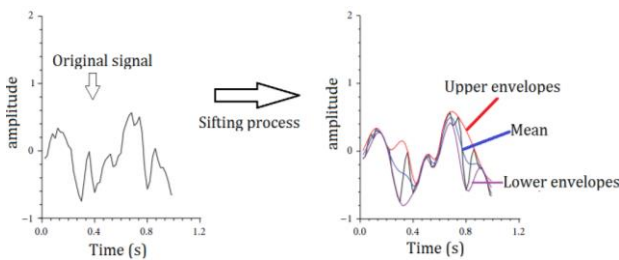


Fig. 3. Signal sifting process.

The below procedure for a signal $x(t)$ and their mean value $m_1(t)$ is followed:

$$h(t) = x(t) - m(t) \quad (1)$$

$$x(t) - c_1 = r \quad (2)$$

Setting r as new $x(t)$, repeat above steps and then obtain the 2nd IMF c_2 , the 3rd IMF c_3 ..., until n c or r satisfies the stopping criterion. Then $x(t)$ can be decomposed into:

$$x(t) = \sum_{i=1}^N c_i + r \quad (3)$$

For each IMF, the Hilbert transform is defined as:

$$H[c(t)] = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{c(\tau)}{1 - \tau} d\tau \quad (4)$$

Construct the analytic signal,

$$z(t) = c(t) + jH[c(t)] = a(t)e^{j\theta(t)} \quad (5)$$

The amplitude function is given as:

$$a(t) = \sqrt{c^2(t) + H^2[c(t)]} \quad (6)$$

Instantaneous frequency of the IMF component is defined as:

$$f(t) = \frac{1}{2\pi} \frac{d\theta(t)}{dt} \quad (7)$$

Then after applying the Hilbert transform in each IMF, it is obtained:

$$s(t) = \text{Re} \sum_{i=1}^N a_i(t) e^{j\theta_i(t)} \quad (8)$$

Finally, the Hilbert spectrum (9) and the Marginal spectrum (10) are expressed as:

$$H(\omega, t) = \text{Re} \sum_{i=1}^N a_i(t) e^{j \int \omega(t) dt} \quad (9)$$

$$h(\omega) = \int_0^T H(\omega, t) dt \quad (10)$$

4. KURTOSIS

Kurtosis is a statistical indicator used in the time domain, which defines the impulsive nature of a signal. It is defined as the fourth statistics moment of the distribution [11] of the time domain data. Kurtosis compares the distribution of the data with the Gaussian distribution. The Kurtosis factor is given as:

$$KURTOSIS = K = \frac{M_4}{M_2^2} = \frac{\left(\frac{1}{N} \sum_{n=1}^N (x(n) - \bar{x})^4 \right)}{\left[\left(\frac{1}{N} \sum_{n=1}^N (x(n) - \bar{x})^2 \right)^2 \right]} \quad (11)$$

where M_4 is the fourth order statistic moment, M_2 is the second order statistic moment, $x(n)$ is the amplitude of signal, N is the number of samples and \bar{x} is the mean value of the amplitudes. In practical terms, a signal with Gaussian distribution has Kurtosis value ($K = 3$), while the impulsive signals has Kurtosis factors ($K > 3$).

5. SLEW BEARING COMPONENTS FREQUENCIES

The laboratory setup was prepared consists of a slew bearing type 12NPPB G0403. In this experimental study, the bearing was operated at 100 rpm without lubricant oil having a fault on inner ring of the slew bearing. Therefore, the expressions of the rotational defect frequencies of the slew bearing are presented:

Outer race passing frequency:

$$BPFO = \frac{N}{2} \left(1 - \frac{d}{Dt} \cos \alpha \right) fn \quad (12)$$

Inner race passing frequency:

$$BPFI = \frac{N}{2} \left(1 + \frac{d}{Dt} \cos a\right) fn \quad (13)$$

Ball Spinning frequency:

$$BSF = \frac{Dt}{2d} \left(1 - \left(\frac{d}{Dt} \cos a\right)^2\right) fn \quad (14)$$

Fundamental train frequency:

$$FTF = \frac{1}{2} \left(1 - \frac{d}{Dt} \cos a\right) fn \quad (15)$$

where N = number of balls, a = contact angle, fn = rotational frequency, d = ball diameter and Dt = pitch diameter of balls. Regarding the current test bearing, the frequencies of components are calculated as: $BPFO = 14$ Hz, $BPFI = 99$ Hz, $BSF = 3.39$ Hz and $FTF = 1.93$ Hz.

6. RESULTS AND DISCUSSION

6.1 Noise Measurement and Analysis of Naval application

In this section, the results concerning the measurements of a real naval slew bearing application are analyzed. In Fig. 4 the original noise signal and the Spectrum of Hilbert-Huang Transformation are presented.

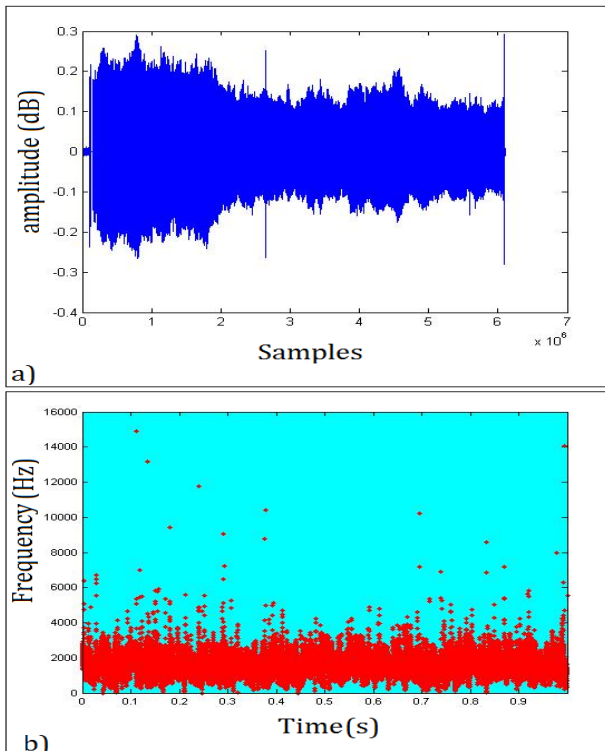


Fig. 4. (a) Measured noise signal and (b) Hilbert-Huang Spectrum for naval application.

In this case, a signal of 22 kHz was emitted in the slew bearing and the noise signal of Fig. 4 (a) was obtained. After that, the frequency versus time (see Fig. 4(b)) using the expression (9) of HHT was calculated. It is observed that the amplitudes of the calculated frequencies are high enough, and this is due to the existing noise of the real application. Also, it can be observed that in lower frequencies (eg. 2-100 Hz) there are not data. This means that there are not expected faults in this case. The application concerning low speed slew bearings (revolution of 1.5 rpm).

Further, it could be observed from the extracted IMFs, that there is not any high peak, which is compatible with above conclusion regarding the spectrum.

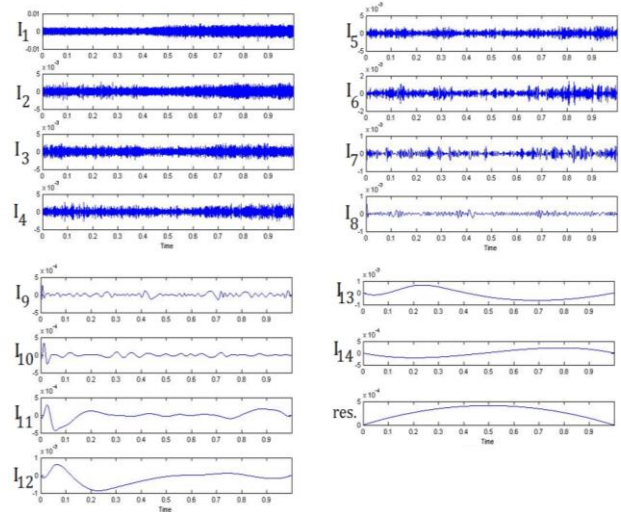


Fig. 5. IMFs extraction after EMD method for naval application.

Simultaneously, it is easily to conclude that all Kurtosis value is below than the value three ($K=2.84$). To this end, it is obvious that there is not any fault in the bearing.

6.2 Noise Measurement and Analysis of a laboratory test application

The laboratory test setup was prepared consists of a bearing type 12NPPB G0403. In this particular set up, the bearing was operated without lubricant having a fault on inner ring of the slew bearing at 100 rpm's. Ultra probe UE systems 2000 was used for the measurements with frequency adjust possibility 20-100 kHz and sensitivity control precision 10-turn adjustment dial with numerically calibrated

sensitivity increments for finite gain adjustment. It is observed that the received noise signal is illustrated in Fig. 6 (a). In this case the emitted signal was at 30 kHz.

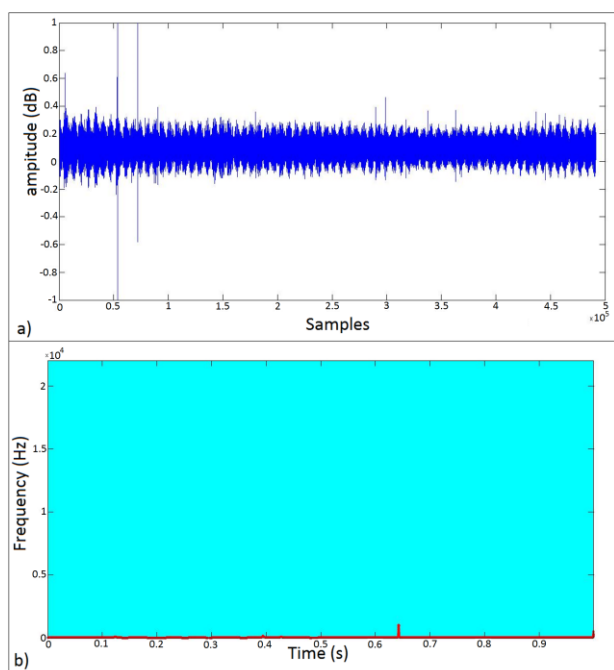


Fig. 6. Measured noise signal and (b) Hilbert-Huang Spectrum for laboratory test.

On the contrary of the aforementioned naval case of Fig. 4, the calculated frequencies from Hilbert spectrum are very low and the relevant extracted IMFs have high peaks. Fig. 7 shows the extracted IMFs of the test slew bearing with damage on the external ring.

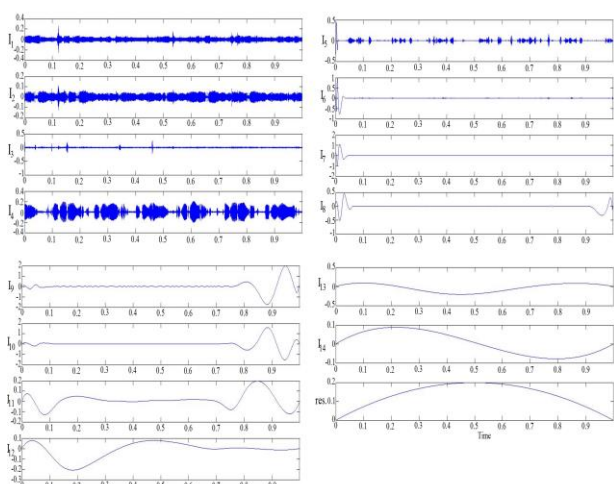


Fig. 7. IMFs extraction after EMD method for laboratory test.

This observation is in line with the kurtosis factor. The Kurtosis value is higher than 3,

shown that there is a fault in the bearing ($K=3.57$). This is also validated for the increased amplitude in the first IMFs signal. As follows from Fig. 8, the magnitude of extracted IMFs shows the difference between the two examined cases. For example, near to 0.05, 0.1 and 0.15 seconds it is observed that the amplitude has been increased drastically for the tested slew bearing at it is illustrated in positions A, B and C. According to naval slew bearing the amplitude of IMFs is normal without shocks.

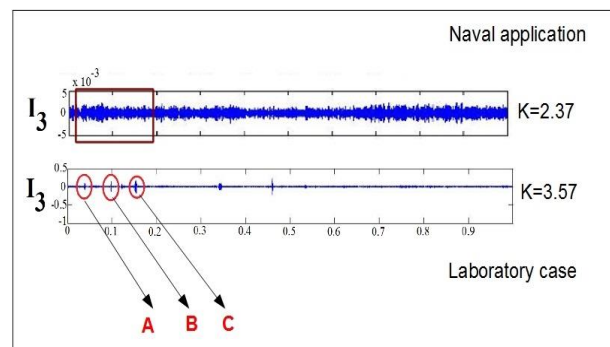


Fig. 8. Comparison of IMFs and Kurtosis factors.

Finally, the Marginal spectrum of IMF 3 shows the inner racing passing frequency $BPFI = 99$ Hz, since the detection of the inner ring fault achieved as it is illustrated in Fig. 9.

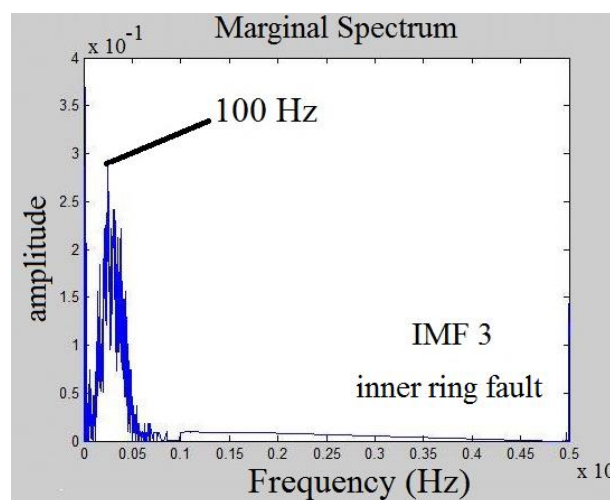


Fig. 9 Marginal Spectrum for test slew bearing and the inner ring fault detection.

7. CONCLUSION

Hilbert Huang Transformation is a time-frequency signal decomposition technique, and in combination with the Kurtosis approach, provides an effective tool for the analysis of

transient vibration signals and fault detections in slew bearings.

The Hilbert Huang Transform using the Empirical Mode Decomposition (EMD) shows clearly the kind of damage in laboratory tests. However, the noise measurement of big slew bearings in a real naval application needs more detailed analysis in order to get the detection in fault conditions. The reason is that in this particular real world application the existing noise was observed in high levels.

Comparisons between Wavelet and Hilbert Huang methods are for future investigation, regarding the slew bearings application.

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