COMPARISON OF SQUARE AND HILBERT BASED ENVELOPE ANALYSIS BASED ON BACKGROUND NOISE

[1]MD SAIFUL ISLAM, [2]FARHANA SHIRIN CHOWDHURY, [3]JUNG-CHUL LEE, [4]UIPIL CHONG

[1,3,4]University of Ulsan Ulsan, South Korea
[2]Premier University Chittagong, Bangladesh
E-mail: [1]Saiful05eee@yahoo.com, [2]fshirin2007@gmail.com, [3]jungclee@ulsan.ac.kr, [4]upchong@ulsan.ac.kr

Abstract- The bearing fault is the most common in the rotating machines faults. Envelope analysis for rolling element bearing diagnostics has gained in the last years a leading role among the different digital signal processing techniques. This paper deals with the use of a simple and effective signal processing technique of square and Hilbert-based envelope analysis for detecting rolling element bearing faults. This paper also compares the bearing fault detection capability obtained with square and Hilbert-based envelope analysis. For this purpose additional white Gaussian noise (AWGN) and random noise are used with different SNR. Simulation results show that the noise sensitivity of the Hilbert-based envelope is higher than that of the square envelope. Square envelope shows steady in response to both AWGN and random noise.

Keywords- Hilbert transform, squared envelope, bearing faults, Noise analysis, SNR

I. INTRODUCTION

Rolling element bearings in the rotating machinery consist one of the most widely used industrial machine elements, being the interface between the stationary and the rotating part of the machine. Due to the internal geometry of the bearing and the magnitude of the external load, the charge distribution of the rolling elements is unequal. As a result, there is huge chance of failure in the rolling elements. Its unexpected failures will result in economic loss and even human casualty. In order to prevent daily accidents/shutdowns, bearing early fault detection is especially valuable.

The failures of bearings will produce inimitable frequency components in the vibration of the machine. Distributed and localized faults are two categories of bearing faults. This paper only focused on localized faults for rolling elements bearings. When there is a single point occurs on the rolling surface, which caused localized faults As a result, opposing and tearing off of material can rapidly accelerate the wear of a bearing which finally generated-strong vibrations. At each time one of the balls rolls the excitation and response generate over the flaw. So the fundamental frequency of the response waveforms is the rate at which the elements roll over the flaw. The unique bearing characteristic frequencies are named as ball pass frequency of inner race (BPFI), ball pass frequency of outer race (BPFO) and ball spin frequency (BSF).

In order to keep machinery operating at its best, several bearing fault diagnosis techniques have been developed. For detection and diagnosis of rolling element bearing defects [2], vibration or acoustic measurement is the most widely used method. Various approaches for bearing fault diagnosis have been developed based on vibration analysis. Many authors already proposed various methods such as multi-wavelet analysis [3], kurtogram [4], independent component analysis [5], the improved Hilbert-Huang transform [6] and ensemble empirical mode decomposition [7], for bearing fault detection. Generally, these methods are classified as time domain, frequency domain and time-frequency domain. Time domain includes statistical parameters where frequency domain includes Fourier spectra analysis and envelope spectra analysis. The time-frequency domain includes the Short Time Fourier Transform, the Wigner-Ville Distribution, and the Wavelet Packet Transform. There is also some non-stationary signal processing methods like artificial intelligence (AI) methods include artificial neural networks (ANN), support vector machine (SVM) and fuzzy logic, etc. Since the background noise can be involved easily to rotating machine signals, incipient bearing faults can be mask due to this noise. Therefore, in this paper, the comparison between square and Hilbert-based envelope is performed in term of the noise. For this purpose, additional white Gaussian noise (AWGN) and random noise are used in the simulation. The rest of the paper is organized as follows. In Section II, the literature of Hilbert transform regarding bearing fault analysis is presented briefly. In Section III, we describe the envelope analysis technique and Section IV is devoted to the performance assessment of this work. The performances have been presented on computer-based simulation. Finally, some conclusions are given in Section V.

II. HILBERT TRANSFORM

The German Mathematician David Hilbert first introduced the well-known tool is called Hilbert transform (HT) [8]. After that it has been widely used in many areas, such as theory of modulation [8], edge detection [9], [10], and so on. It is a linear operator connecting the real and imaginary parts of an analytic function. In an analytical signal, the imaginary part is

the Hilbert transform of the real part. In signal processing and communication theory the Hilbert transform is an important tool in constructing analytic signals for various purposes, such as obtaining the envelope of a signal in instantaneous frequency analysis, amplitude modulation, signal demodulation, and many other domains.

There are many ways to define the Hilbert transform meaningfully. Suppose we have a signal $x(t)$, the conventional Hilbert transform of a continuous signal $x(t)$ is computed as [8]

$$\hat{x}(t) = \frac{1}{\pi} PV \int_{-\infty}^{\infty} \frac{x(\tau)}{t-\tau} d\tau \qquad (1)$$

Where $\hat{x}(t)$ is the Hilbert transform and the Cauchy principle Value, PV is taken in the integral.

The continuous Hilbert transform consists of a $\pi/2$ radian phase shift (for positive frequencies only) in the frequency domain [13].The Fourier transform of the Hilbert transform is given by [11]

$$\hat{X}(\omega) = -jsgn(\omega)X(\omega) \qquad (2)$$

Where

$$-jsgn(\omega) = \begin{cases} j, & \text{for } \omega > 0 \\ 0, & \text{for } \omega = 0 \\ -j, & \text{for } \omega < 0 \end{cases} \qquad (3)$$

And $X(\omega)$ is the Fourier transform of $x(t)$.

The discrete Hilbert transform is developed as an exact equivalent of the Hilbert transform for discrete domain sequences and is defined as [11]

$$\hat{x}(n) = x(n) * h(n) \qquad (4)$$

Where $h(n)$ is the impulse response of the discrete Hilbert transformer.

$$h(n) = \begin{cases} \frac{2\sin^2(\pi n/2)}{\pi n} & n \neq 0 \\ 0 & n = 0 \end{cases}$$

The transfer function of the discrete Hilbert transform is defined as [12]

$$H(\omega) = \begin{cases} j, & 0 < \omega < \pi \\ 0, & \omega = 0 \ \& \ \omega = \pi \\ -j, & -\pi < \omega < o \end{cases} \qquad (5)$$

The procedure to identify the components in the vibration signal spectrum related to the bearing faults relying on Hilbert transformation is as follows [13]

Step 1:	Compute the Fourier Transformation of the vibration signal in time domain to isolate the resonances of the system, and to identify the largest harmonic component.
Step 2:	The vibration signal in time domain is band-pass filtered in order to obtain a reduced spectrum around the largest harmonic component
Step 3:	Compute the Hilbert transformation of the band-pass filtered signal.
Step 4:	Compute the Fourier Transformation of the analytic signal obtained through Hilbert transformation.

III. ENVELOPE ANALYSIS

Envelope analysis is another approach to separate modulation signals from the carrier. For rolling element bearing fault detection, Envelope analysis has been successfully used for decades [13, 14].Basically, it is used in rolling element bearing diagnostics to justify cyclostationary analysis. This method can be used to obtain with high accuracy the modulating signals for increasing the signal to noise ratio of results [15].

Figure 1 shows the example of envelope analysis where the red line and the green line indicates the upper envelope (E_{upp}) and lower envelope (E_{low}), respectively. If the modulation index is lower than 1 for amplitude modulation, the carrier signal, and the modulating signal is computed by $m(t) = E_{upp} - E_{low}$ and $C(t) = E_{upp} + E_{low}$, respectively.

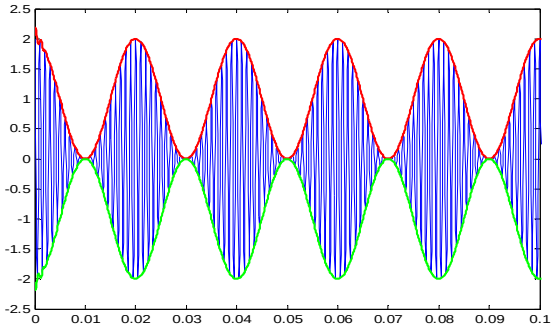


Figure 1. Example of envelope analysis

The general way of performing an envelope analysis contains two steps.

Step 1: The vibration signal is filtered using band-pass filter around the mechanical resonance of the machine, which serves as a carrier for the bearing signal.

Step 2: To extract the characteristic frequency of defect from the carrier frequency, the band-pass filtered signal is demodulated by an amplitude demodulation technique to extract the characteristics frequency of defect from the carrier frequency.

Analogue band-pass filter and rectifier are normally used for demodulation, even when the final analysis was done digitally with an FFT analyzer. To obtain high accuracy, the envelope detectors have to select a resonant frequency band in which the impulsive components excited by defects are dominant. But in the practical case, it is very challenging to specify which resonant modes of neighboring structures will be excited. Envelope analysis has a few advantages over Hilbert transformation like the computational cost is lower, bandpass filtering is not required and the method is effective even without a carrier. However, square envelope provides greater benefits than the envelope itself.

IV. SIMULATION AND RESULTS ANALYSIS

Simulation results are presented in this section to demonstrate the performance of square and Hilbert-based envelope analysis for detecting the incipient bearing faults under heavy surrounding noise. Here

only bearing outer race fault is considered and these simulation results show the close relation between noise and magnitude of outer race fault. The noise samples used in the simulation are modeled as additional white Gaussian noise and random noise with different SNR. The simulations are carried out 360 rpm for SNR values ranging from 10 dB to 40 dB.

Table 1: outer race fault values of rolling element bearing at 360 rpm

SNR	AWGN		Random noises	
	Squared envelope	Hilbert transform	Squared envelope	Hilbert transform
10 dB	0.2972	0.2974	0.2975	0.2455
20 dB	0.2992	0.3312	0.3005	0.3129
30 dB	0.3014	0.3442	0.3021	0.3356
40 dB	0.3043	0.3471	0.3055	0.3426

Vibration signal of rolling elements is shown in figure 2(a). The corresponding frequency spectrum of the vibration signal is shown in figure 2(b) and it contains no diagnostic information. After applying square and Hilbert-based envelope analysis, the frequency spectrums of the vibration signal is presented in figure 3. This figure illustrates the benefits achieving diagnostic information (circle with magenta color) by envelope analysis. Hilbert-based envelope shown in Figure 3(b) provides higher fault magnitude in compare to square envelope shown in figure 3(a).

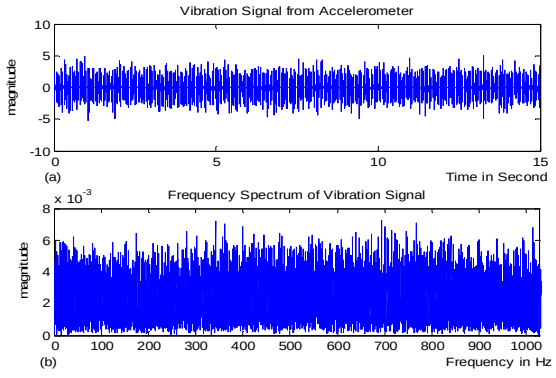


Figure 2. (a) Vibration signal of rolling elements from accelerometer, (b) Corresponding frequency spectrum of vibration signal

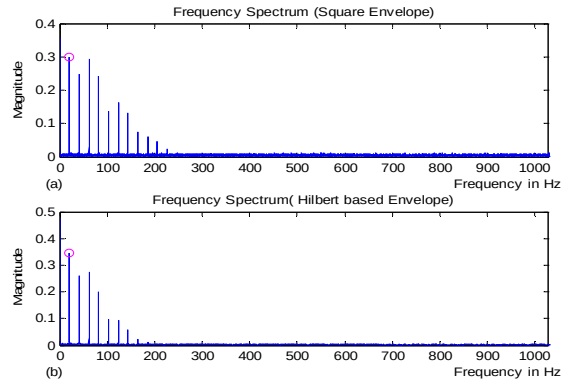


Figure 3. The frequency spectrum of figure. 2(a). (a) Square envelope (b) Hilbert transform

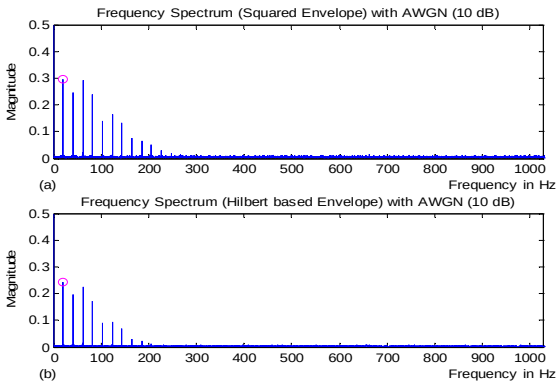


Figure 4. Frequency spectrum of vibration signal which is contaminated by AWGN with 10 dB. (a) Square envelope (b) Hilbert transform

The response of this two methods is verified by adding additional noises in the vibration signal. Figure 4, figure 5, figure 6 and figure 7 displays frequency spectrum of vibration signal which is contaminated by AWGN with different SNR. As can be seen, the variation of outer race fault value with respect to SNR value is totally different for the square and Hilbert-based envelope. Hilbert-based envelope shows a wide range of variation with respect to AWGN with different SNR while square envelope provides less variation shown in figure 12. Here it is worth to mention that Hilbert-based envelope is more sensitive to AWGN than the square envelope.

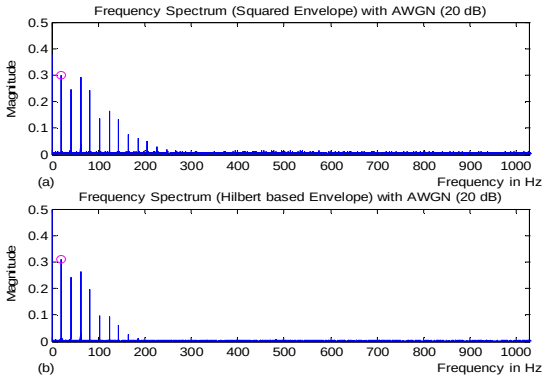


Figure 5. Frequency spectrum of vibration signal which is contaminated by AWGN with 20 dB. (a) Square envelope (b) Hilbert transform

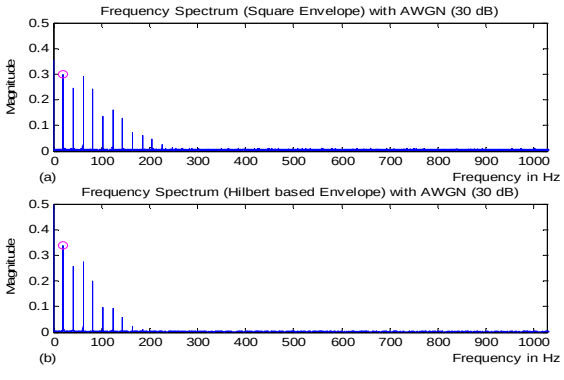


Figure 6. Frequency spectrum of vibration signal which is contaminated by AWGN with 30 dB. (a) Square envelope (b) Hilbert transform

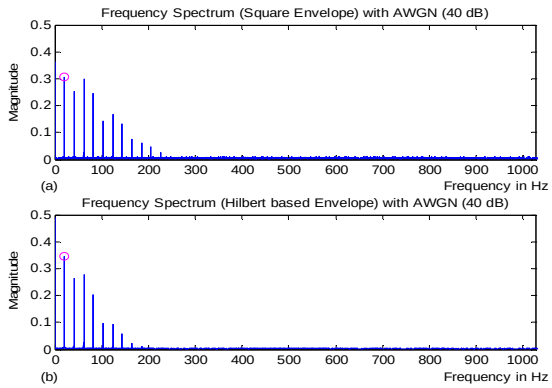


Figure 7. Frequency spectrum of vibration signal which is contaminated by AWGN with 40 dB. (a) Square envelope (b) Hilbert transform

Frequency spectrums of vibration signal which is contaminated by random noise with different SNR are shown in figure 8, figure 9, figure 10 and figure 11. Like the AGWN, the variation of outer race fault value with respect to SNR value is not similar for square and Hilbert-based envelope. In this case also, Hilbert-based envelope shows a wide range of variation with respect to different SNR while square envelope provides less variation shown in figure 13.

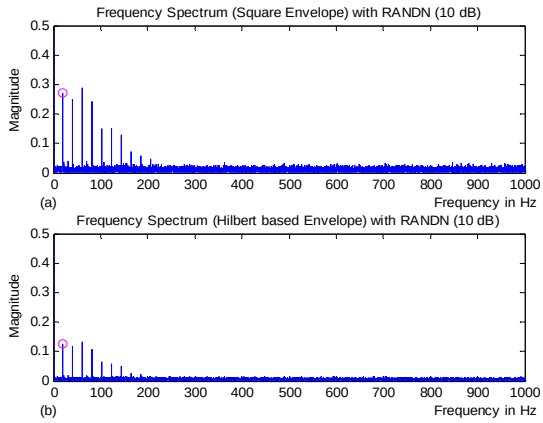


Figure 8. Frequency spectrum of vibration signal which is contaminated by Random noise with 10 dB. (a) Square envelope (b) Hilbert transform

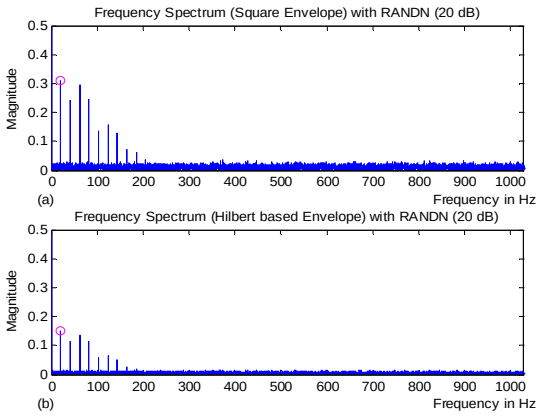


Figure 9. Frequency spectrum of vibration signal which is contaminated by Random noise with 20 dB. (a) Square envelope (b) Hilbert transform

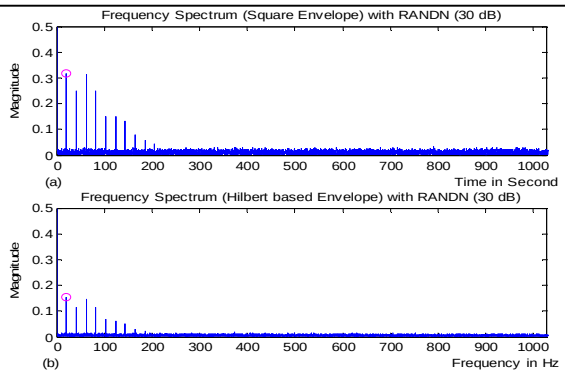


Figure 10. Frequency spectrum of vibration signal which is contaminated by Random noise with 30 dB. (a) Square envelope (b) Hilbert transform

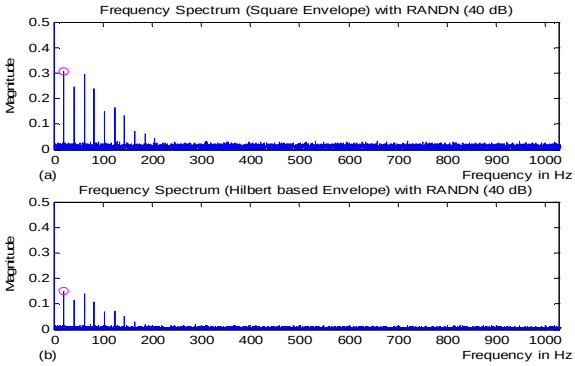


Figure 11. Frequency spectrum of vibration signal which is contaminated by Random noise with 40 dB. (a) Square envelope (b) Hilbert transform

Figure 12 and figure 13 show the comparison results of the square and Hilbert-based envelope for AWGN and random noise respectively. It can be noticed that the sensitivity of the Hilbert-based envelope is higher to the noise than that of the square envelope. Square envelope shows steady in response to both AWGN and random noise shown in table 1. Here, Fault values and variation in the fault values are almost same for the both type of noise. For the random noise fault values are slightly increased. This implies squared envelope is less sensitive to noises. On the other hand, the Hilbert-based envelope is very sensitive to both noises. Both cases variation in the fault values are higher. With the low SNR, Hilbert-based envelope shows poor performance for the outer race fault value. This implies that when the bearing signal is merged under severe noise, the Hilbert-based envelope would not be able to provide the fault signature properly without denoising the raw signal.

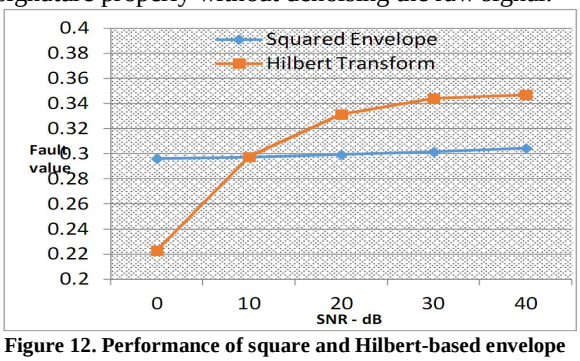


Figure 12. Performance of square and Hilbert-based envelope to AWGN

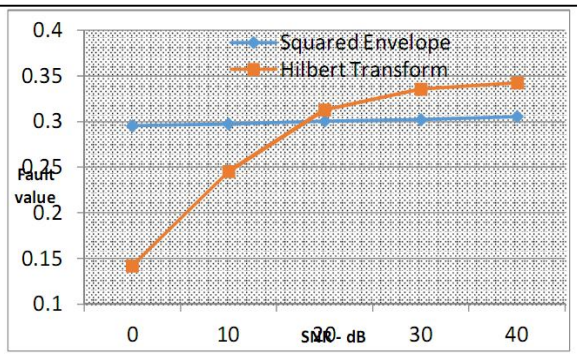


Figure 13. Performance of square and Hilbert-based envelope to random noise

Upon the results are shown in figure 12, figure 13 and Table 1, between the AWGN and random noise, bearing signal is more affected by random noise. Hilbert-based envelope provides the lower fault value for random noise with lots of variation. Square envelope provides good diagnosis information for random noise. However, Hilbert-based envelope provides higher fault magnitude in compare to the square envelope is reported in figure 3 where the bearing signal is noiseless.

CONCLUSION

This paper has described the use of a simple and effective signal processing technique of square and Hilbert-based envelope analysis for detecting rolling element bearing faults. A theoretical analysis is presented on Hilbert transform and squared envelope analysis and a comparison between them also given for incipient rolling element bearing fault detection. Computer simulation results are presented to demonstrate the performance of the Incipient rolling element bearing fault detection capability under heavy surrounding noise (to both AWGN and random noise). The results presented in this paper indicate that the sensitivity of the Hilbert transform is higher to the noise than that of the squared envelope. The square envelope shows steady in response to both AWGN and random noise.

REFERENCES

[1] S. A. McInerny and Y. Dai, "Basic Vibration Signal Processing for Bearing Fault Detection", IEEE Transactions on Education, Vol. 46, No. 1, pp 149-156, February 2003.

[2] M. J. Devaney and L. Eren, "Detecting motor bearing faults," IEEE Instrum. Meas. Mag., vol. 7, no. 4, pp. 30–50, Dec. 2004

[3] X. D. Wang, Y. Y. Zi and Z. J. He, "Multiwavelet construction via an adaptive symetric lifting scheme and its applications for rotating machinery fault diagnosis," Measurement Science and Technology, vol. 20, 045103, 2009.

[4] J. Antoni and R. B. Randall, "The spectral kurtosis: application to the vibratory surveillance and diagnostics of rotating machines," Mechanical Systems and Signal Processing, vol. 20, pp. 308-331, 2006.

[5] Q. Miao, D. Wang and M. Pecht, "Rolling element bearing fault feature extraction using EMD based independent component analysis," In Proceedings of IEEE PHM conference, pp. 1-6, 2011.

[6] Z. K. Peng, P. W. Tse and F. L. Chu, "A comparison study of improved Hilbert-Huang transform and wavelet transform: application to fault diagnosis for rolling element," Mechanical Systems and Signal Processing, vol. 19, pp. 974-988, 2005.

[7] W. Guo, P. W. Tse and A. Djordjevich, "Fault bearing fault recovery from large noise using a hybrid method based on spectral kurtosis and ensemble empirical mode decomposition," Measurement, vol. 45, pp. 1308-1322, 2012.

[8] D. S. Laila, M. Larsson, B. C. Pal, and P. Korba, "Nonlinear damping computation and envelope detection using Hilbert transform and its application to power systems wide area monitoring "Power & IEEE Energy Society General Meeting, Calgary, AB 2009. doi:10.1109/PES.2009.5275889

[9] G. M. Livadas and A. G. Constantinides, "Image edge detection and segmentation based on the Hilbert transform," in Proc. IEEE Int. Conf. Acoustics, Speech, and Signal Processing, 1988, pp. 1152–1155.

[10] K. Kohlmann, "Corner detection in natural images based on the 2-D Hilbert transform," Signal Processing, vol. 48, pp. 225–234, 1996.

[11] S.K.Padala K.M.M. Prabhu, "Systolic arrays for the discrete Hilbert transform", IEE Proc -Circuits Devices Syst., Vol. 144, No. 5, Octoher 1997

[12] Soo-Chang Pei and Min-Hung Yeh, "Discrete Fractional Hilbert Transform", IEEE Transactions on Circuits and Systems—II: Analog and Digital Signal Processing, Vol. 47, No. 11, November 2000

[13] Alberto Bellini, Fabio Immovilli, Riccardo Rubini, Carla Tassoni, "Diagnosis of bearing faults in induction machines by vibration or current signals: a critical comparison", IEEE Industry Applications Society Annual Meeting, 2008, Alberta, Canada.

[14] D. He, R. Li, and J. Zhu, "Plastic bearing fault diagnosis based on a two-step data mining approach," IEEE Trans. Ind. Electron., vol. 60, no. 8, pp. 3429–3440, Aug. 2013.

[15] R. B. Randall, J. Antoni, and S. Chobsaard, "A comparison of cyclostationary and envelope analysis in the diagnostics of rolling element bearings," in Acoustics, Speech, and Signal Processing, 2000. ICASSP '00. Proceedings. 2000 IEEE International Conference on, vol. 6, Istanbul, June 2000, pp. 3882–3885.

★★★