Adaptive wavelet based signal processing scheme for detecting localized defects in rolling element of taper roller bearing

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Abstract

The vibration signal due to defect on roller of a bearing is superimposed by signal from other elements of a bearing such as inner race, outer race and cage. Background noise also gets superimposed on the vibration signal. These make diagnosis of fault in roller of a bearing a complicated task. In this communication, a signal processing scheme is proposed for detection of fault in roller of a taper roller bearing. To achieve this; in the first stage of processing, Un-decimated wavelet transform (UWT) is applied to the raw vibration signal. The UWT is applied as it has translation invariant property. In the second stage of processing, impulsiveness of selected decomposed signal is enhanced by Minimum Entropy Deconvolution (MED) filtering. The above two stages of signal processing extract hidden impulse which are buried in the presence of noise. Finally, continuous wavelet transformation (CWT) using adaptive wavelet is applied. The adaptive wavelet for CWT is designed from the impulse extracted from the signal obtained after second stage of signal processing using least squares optimization under given constraints. It results in higher coefficient in the region of impulse produced due to the defect. Study has been made for three different cases; i) single groove defect on a roller ii) two similar defects at orientation 0˚ and 90˚ on the same roller and iii) single groove defect each at roller number 1 and 5. Result for defect frequencies for the above cases obtained from the proposed scheme were compared from the theoretical one. The accuracy of result of defect frequency is 97.85%. Position of defects has been measured with accuracy of 94%.

1 Introduction

Rolling element bearings are essential components of rotating machinery and are primary cause of breakdowns in machines [1]. The vibration signal of a defective bearing is an amplitude modulated signal at the characteristic defect frequency. The spectrum of defective bearing consists of a harmonic present at the bearing defect frequency with the highest amplitude around the resonance frequency [2]. The vibrations resulted from the faulty bearings get masked easily by higher energy vibrations generated by other components of the same machine or another machine. Due to weak defective bearing signals, the defect frequency of bearing may not be clearly visible in the conventional FFT spectrum. Therefore a signal processing technique is required to provide more evident information for incipient defect detection in rolling element bearings. Enveloping technique is utilized by many researchers to find out the repeated impulse in the signals [3-6]. It consists of applying a band-pass filter, which removes the large low-frequency components as well as the high frequency noise. Only the burst of high frequency vibrations remains and afterward envelope is detected using Hilbert transform. The result obtained using envelope detection is satisfactory however envelope technique can't enhance the weak signature from a noisy signal and doesn't detect early stage defect. Applications of binary discrete wavelet transform and wavelet package transform lead to quick computing speed. Both of them employ orthogonal wavelet-base function which makes the scale partition presenting the jumping characteristic owing to the binary partition. Compared with binary wavelet the continuous wavelet has finer time-scale partition and the selection of wavelet base only need to satisfy the admission condition. Hence it is quite suitable for the rolling bearing fault diagnosis [7]. Further, the result of wavelet based decomposition also depends greatly on the relative energy level of the signal coefficients and noise coefficients. In case of smooth signal there are few high coefficients which can be separated from low noisy coefficient. Result obtained by it is satisfactory for smooth signal but are not satisfactory for impact signal where coefficient are not concentrated [8].

In order to analyse non stationary signal many researchers utilize and enhanced the wavelet transform [7-15]. Kankar et al. presented mother wavelet selection based upon the ratio of maximum energy to Shannon entropy or to the maximum relative wavelet energy in fault diagnosis of rolling element bearings [9]. Chen et al. implemented the adaptive wavelet transform for vibration signal modelling for investigating the faults in water hydraulic motor [10]. Kumar and Singh [13] measured groove defect width in the outer race of bearing using discrete wavelet transform.

The study of the above literature reveal that during the last few years, a significant progress in wavelet transform have made possible to examine defect like outer race and inner race defect in bearing, however rolling element defect detection is still a challenge. Highly impulsiveness nature of burst produced due to impact between roller and bearing structure and also presence of high noise further add difficulty in impulse detection.

In this research works, a new fault detection scheme is proposed which consists of applying Un-decimated wavelet transform to the raw signal in the first stage. In the second stage, impulsiveness enhancement of the selected detail signal is done using MED technique. Detail signal is selected out of other approximate and detail signal according to maximum kurtosis criteria. Finally, CWT using adaptive wavelet is applied for measurement of roller defect frequency and its location in a taper roller bearing.

2 Underlying Theory

2.1 Un-decimated wavelet transform (UWT)

Un-decimated wavelet Transform (UWT) provides a time-scale decomposition of the signal on a sample-by-sample basis and is well-suited for fault diagnosis. The un-decimated wavelet transform (UWT) is shift invariant and linear in nature. This feature makes it helpful in feature extraction, pattern detection, better de-noising and peak detection. It also provides a better approximation to the continuous wavelet transform than the approximation provided by discrete wavelet transform.

UWT is explained with the help of Fig. 1. The original signal x is passed through low pass filter (L) and high pass filter (H) as shown in Fig. 1. As a result approximate signal A(1) and detail signal D(1) are produced at the first level of transform. In this figure H and L are same as in the discrete orthogonal wavelet transform, $H\uparrow$ and $L\uparrow$ indicate dyadic up sampling of H and L by 2. As a result, the approximation coefficients and detail coefficients at each level are the same length as that of original signal [16].

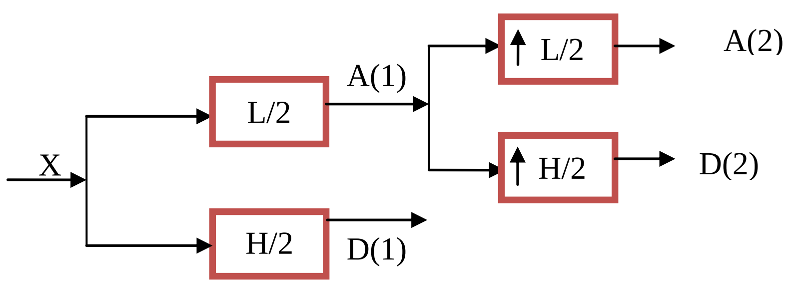


Figure 1: Un-decimated wavelet transform

2.2 Minimum Entropy Deconvolution (MED)

The MED technique was originated by Ralph Wiggins [17] and has shown its effectiveness in deconvolving the impulsive excitations from a mixture of response signals [18,19]. It was used effectively by Endo and Randall [20] to enhance the impulses arising from spalls and cracks in gears. The objective function of MED is to search for an optimum set of filter coefficients f that gives the output signal x[n], which has the maximum value of kurtosis. The Kurtosis is an indicator which is related to impulsiveness and expressed below as [21].

$$O_k(f) = \frac{\left[\sum_{n=1}^{N} x^4[n]\right]}{\left[\sum_{n=1}^{N} x^2[n]\right]^2} \tag{1}$$

Maximum value of kurtosis is found by finding the values of f for which the derivative of the objective function is zero, i.e.

$$\frac{\partial O_k(f)}{\partial f} = 0 \tag{2}$$

2.3 Continuous wavelet transform

The vibration signals from faulty bearings are non-stationary in nature. To achieve time frequency resolution, the signals are processed through the continuous wavelet transform to generate the two dimensional map of CWT coefficients. Mathematically, the continuous wavelet transform of x(t) is defined as its integral transform with a family of wavelet functions, ψ (a, b) described as [14].

$$CWT(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} x(t)\psi^*\left(\frac{t-b}{a}\right)dt \tag{3}$$

Where ψ^* is the complex conjugate of the mother wavelet, ψ. The notation a is for scale factor, b is for time location and $\frac{1}{\sqrt{a}}$ is used to ensure energy preservation. In the present work CWT is carried out using adaptive wavelet. The adaptive wavelet is used because wavelet follow matching mechanism i.e. result of CWT is better when wavelet matches with the impulse. Since adaptive wavelet is designed from the sample burst of a vibration signal from a defective bearing. Result of CWT is better when CWT is carried with adaptive wavelet.

A burst can be considered suitable for the formation of wavelet function if it is finite in time and frequency. The wavelet function ψ(t) should also satisfy the following properties [14]:

a) The average of the function is zero, that is ψ (t) = 0

b) The amplitude | ψ (t)| must decay rapidly to zero when | t | approaches infinity.

Fulfilling the above criteria, adaptive wavelet is designed for the purpose.

The adaptive wavelet for CWT in the present work is designed from the impulse extracted from the signal obtained after second stage of signal processing i.e. after applying UWT and MED filtering using least squares optimization under given constraints. The corresponding adaptive wavelet is shown in Fig. 2. The generated adaptive wavelet is used as the mother wavelet in CWT to compute the scalogram.

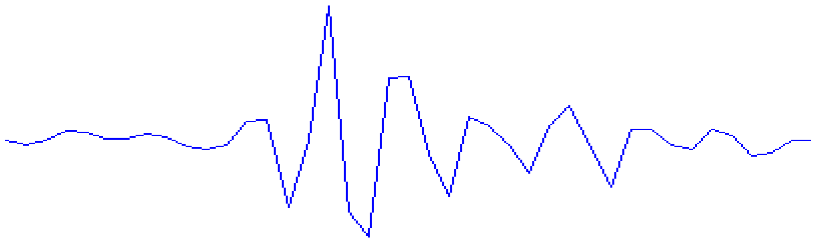
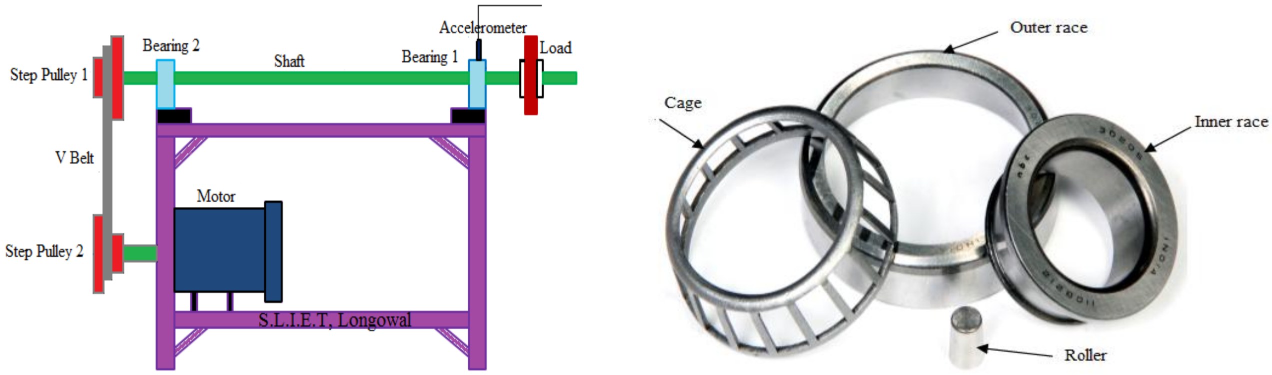


Figure 2: Adaptive wavelet extracted from the signal obtained after UWT and MED filtering

3 Experiment and Result

In the present study, experiment for measurement of bearing defect frequency is performed on a test rig as shown in Fig. 3(a). The test bearing has groove defect on the roller. The bearing used in the experiment is a taper roller (Make: NBC, bearing number: 30205) having number of rollers as 17. Mean diameter of roller is 6.39 mm and pitch diameter of bearing is 38.5 mm. The angle between two rollers is 21.18˚. A typical photograph of the test bearing is shown in Fig. 3(b).



(a) **(b)**

Figure 3: (a) Schematic diagram of experimental set up for measuring defect frequency and (b) A typical photograph of taper roller bearing (Bearing no: NBC 30205)

The shaft operating speed is set at 2050 rpm (34.16Hz). A PCB® make uni-axial accelerometer having sensitivity 100 mV/g is placed right above the bearing casing perpendicular to the axis of the rotation of the shaft so that it can acquire vertical acceleration. Position of accelerometer on the bearing casing is shown in Fig. 3(a). A personal computer based data acquisition system (Make: National Instrument, SCXI-1000 chassis along with SCXI-1530 module having 4 channel input) is used to acquire the vibration data obtained from accelerometer. Formula of defect frequency and its numerical value obtained theoretically is shown in Table 1. Study has been made for measurement of defect frequency for three different cases; i) single groove defect on a roller (referred as (defect type-I), ii) two similar groove defects at orientation 0˚ and 90˚ on the same roller (referred as defect type-II), and iii) single defect each at roller number 1 and 5 (referred as defect type-III). The proposed methodology for measurement of defect frequency is shown in Fig. 4.

Type of Frequency	Formula	Theoretical value of frequency in Hz (for NBC 30205)
Roller Spin frequency (Fs)	$\frac{D}{2d} \times F\left[1-\left(\frac{d}{D}\cos\alpha\right)^2\right]$	100.09
Cage Frequency	$\frac{F}{2}\left[1-\left(\frac{d}{D}\cos\alpha\right)\right]$	14.24
Roller Defect Frequency (Single groove on a roller)	$2 \times F_s$	200.18
Roller Defect Frequency (Two groove on a roller)	$2 \times (2 \times F_s)$	400.36
Roller defect frequency (Two defective roller at 1st and 5th position)	$2 \times F_s$	200.18

Table 1: Theoretical bearing frequencies

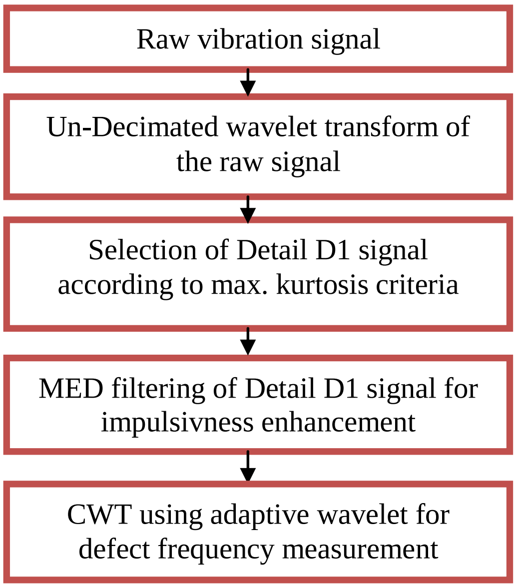


Figure 4: Scheme of the proposed processing technique

There is no distinct pulse in the raw signal of defect free bearing. Vibration signal acquired from defective bearing has higher amplitude with some pulses. A typical vibration signal of 0.1 sec duration captured for the bearing with type-I defect is presented in Fig. 5(a). Un-decimated wavelet transform is applied up-to 4th level of the raw vibration signal. Out of the detail and approximation at four levels, detail at 1st level has maximum kurtosis value and presented in Fig. 5(b). It has been taken for further processing by MED technique. The filtered signal so obtained by MED technique is shown in Fig. 5(c). The above stages of signal processing increase the kurtosis of signal and extract the hidden impulse buried in the noise. The kurtosis value of the signal at different stages of signal processing is shown in Table 2.

CWT scalogram signal using adaptive wavelet applied on processed signal is shown in Fig. 6(a). High coefficient is observed in this scalogram. These high coefficients correspond to burst due to defective roller.

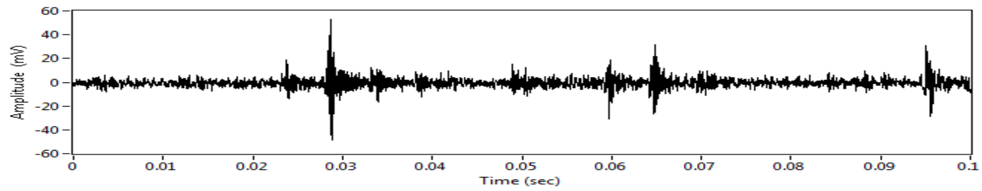
As roller spins as well as revolves, position of defect on it changes with respect to time. Accelerometer used for data acquisition is uni-directional and placed to acquire the vertical acceleration. It would not detect the burst in signal with sufficient amplitude when the defect was away from top and bottom positions because the component of vertical acceleration was less as well as inadequate for measuring the defect frequency. Relatively higher amplitude burst was selected in the signal as shown in 6(a). Average time interval between two bursts has been taken from 12 consecutive selected bursts. From this data defect frequency of the bearing is measured. The result of defect frequency is shown in Table 3.

For comparison purpose CWT using morlet wavelet has been applied to raw signal of the above said defective bearing and presented in Fig. 6(b). Due to ambiguity, roller defect frequency cannot be determined from this scalogram. It shows the limitation of conventional CWT scalogram and effectiveness of the proposed technique in defect frequency measurement.

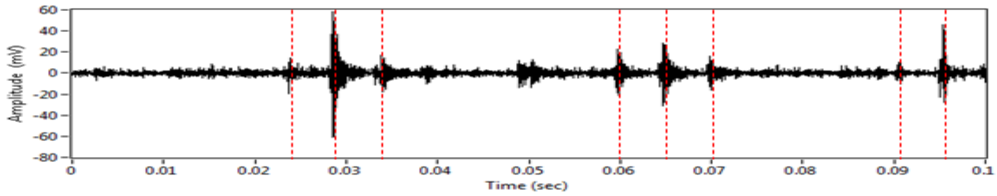
In the similar manner, vibration signal is acquired for bearing with type-II defect and type-III defect. For type-II defect, CWT scalogram of Detail signal at first level using Un-decimated wavelet transform filtered with MED technique is shown in Fig. 7(a). The corresponding diagram of bearing with type-III defect is shown in Fig. 7(b).

From Fig. 7(a) it is clear that defects on the same roller at 90˚ position reduce the time period of burst by half of the time period corresponding to the single defect. It results in defect frequency as twice to the defect frequency in case of single defect.

For defect type-III, as shown in Fig. 7(b), burst at A is of high magnitude which occurs due to burst produced by defective roller at vertical position. Burst magnitude progressively decrease as roller moves away from vertical position. At A' burst magnitude is modulated by burst produced from another defective roller at vertical position. From A to A' cages turn 79.7˚ as calculated from cage rotation frequency. Thus burst at A' is due to another defective in the roller which lies at angle of 79.7˚ relative to roller which produced burst at A. Angle between two rollers is 21.18˚. Angle of 79.7˚ is close to angle of 84.72˚ which is the angle between rollers at 1st and 5th. Hence, burst at A and A' is due to defective rollers at 1st and 5th position relative to each other. Thus an error of 5.909 % is incurred in measuring the position of roller. The error in the measurement of position occurs because roller revolves as well as rotates along with its own axis which creates difficulty in spotting the position of defective roller. Further slippage effect of roller also contributes error in measurement.



(a)



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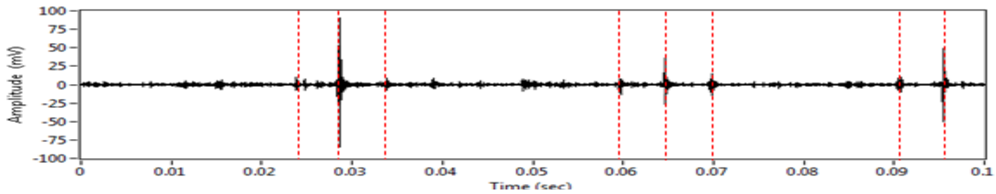
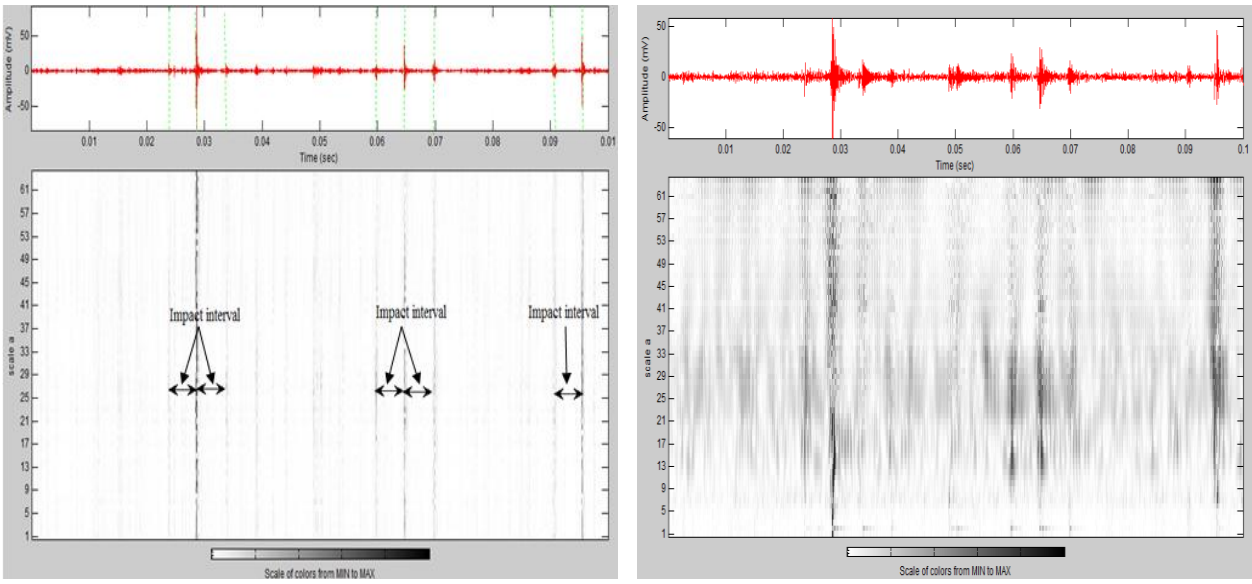


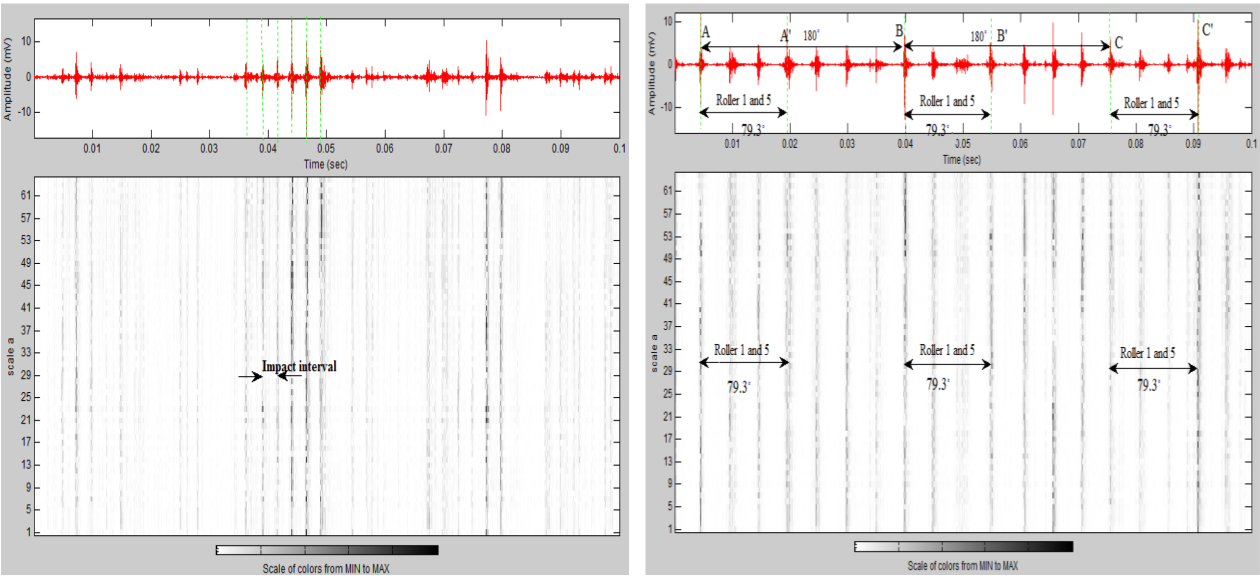
(c)

Figure 5: A typical vibration signal of 0.1 sec for bearing with type-I defect (a) Raw vibration signal (b) De-noised D1(detail signal at first level) signal using Un-Decimated wavelet Transform (c) D1 signal filtered using MED technique



(a) (b)

Figure 6: Scalogram of vibration signal for bearing with type-I defect (a) Scalogram using proposed scheme (b) Scalogram of raw signal using morlet wavelet



(a) (b)

Figure 7: Scalogram using proposed scheme for the defective bearing (a) Bearing with type-II defect (b) Bearing with type-III defect

Bearing	Kurtosis		
	Raw signal	D1 signal using UWT	D1 signal filtered using MED technique
Bearing with type-I defect	21.8139	49.7441	378.382
Bearing with type-II defect	6.2295	8.60645	97.5709
Bearing with type-III defect	7.11378	14.9669	61.6468

Table 2: Kurtosis value of signal at different stages of signal processing

Bearing	Time interval between two burst (in seconds)	Defect frequency obtained from experiment (Hz)	Theoretical defect Frequency (Hz)	Percentage deviation from theoretical frequency
Bearing with type-I defect	0.005012	199.50	200.18	-0.33
Bearing with type-II defect	0.002552	391.71	400.36	-2.15
Bearing with type-III defect	0.005103	195.96	200.18	-2.10

Table 3: Result of defect frequency

4 Conclusion

A signal processing scheme based on UWT, MED and CWT using adaptive wavelet has been found effective in identifying roller defect frequency. UWT is a suitable de-noising tool in detecting impulse in signal. Buried impulse in the noise is effectively extracted by MED filtering technique. CWT using adaptive wavelet is advantageous in measurement of roller defect frequency and defect position.

Roller defect frequency observed in case of bearing with two groove defects on a roller at orientation 0˚ and 90˚ is twice that of bearing with single groove defect on a roller. Defect frequency in case of bearing with two defective rollers at 1st and 5th position is almost equal to defect frequency in case of bearing with single groove defect on a roller. It is because, the two rollers are almost at 90˚ to each other and accelerometer can capture burst of sufficient magnitude only from one roller. However, defective rollers position can be measured, as burst strength is modulated after 79.3˚ of cage rotation, which indicate that defective rollers are at 1st and 5th position relative to each other. The maximum error observed in determining roller defect frequency is 2.15 % relative to theoretical defect frequency which occurs in case of bearing with two groove defect on a roller at orientation 0˚ and 90˚. Error observed in determining location of two defective rollers is 5.909 %. It has been observed that the simple application of Morlet wavelet on raw signal fails to detect buried impulse in the signal and making the defect frequency detection difficult. The experimental result indicates that the proposed adaptive wavelet based scalogram is advantageous in detection of roller defect in the bearing in comparison to conventional method of applying CWT with morlet wavelet.

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