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# Identification of fault size of rolling element bearing on outer race from vibration signature analysis

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Abstract: Prognostics deals with the estimation of the remaining useful life (RUL) of machine, which is predicated based on their present condition and their future operating condition. Rolling element bearing failure is one of the commonly explained reason for machine breakdown. At the point when machine is in running condition and fault occur in bearing, it is extremely difficult to identify fault size in bearing. Thus, for safety of machine it is necessary to change bearing before fault size increases to a significant level. Further, the replacement of bearing might be extremely costly and on other hand chances can't be taken with safety aspects. Therefore, it is necessary to find the RUL of bearing by identifying the spall size of fault from vibration signal. Fault size estimation can be done by decomposition of vibration signal by using discrete wavelet transform and also introducing the autoregressive method, minimum entropy deconvolution and Hilbert transform. The decomposed signal is divided into peak corresponding to the ball enter into the fault and exit from the fault. Experiment conducted for various size of faults present on the 25 mm inner diameter polyamide cage deep groove ball bearing. The minimum size of 0.3 mm is detected in the present work for outer race defect with only radial load. Further, fault size estimation is investigated for 1mm defect present at outer race subjected to both radial and axial load

## **1. INTRODUCTION**

For estimating the spall size, vibration analysis based fault diagnosis is mostly preferred for identification faults in the components of bearings [1]. Khanam et al. [2] investigated the vibration signal obtained for the faulty bearings. From the signal analysis, the first peak generated due to entry of the rotating element into the fault, and the second peak generated due to the rotating element as it strikes the trailing edge of the fault is obtained. As the size of the fault increases, entry and exit events can be successfully extracted from the vibration signal [2]. Sawalhi and Randall [3] studied the vibration signal to estimate fault size from the vibration signal of ball enter into the fault and exit from the defect using two distinct methodologies. The first methodology is called joint treatment and second is separate treatments of ball enter into the fault and exit from the fault [3]. Wade Smith et al. [4] implemented discrete random signal separation, spectral kurtosis and minimum entropy deconvolution for tracking spall size of 1.6 mm. David and Reuben [5] used switching Kalman filters for detection of fault and to determine RUL of AH64D helicopter tail rotor gearbox bearing. Qiu et al. [6] used wavelet filter for weak signal detection for bearing prognostics and test was peroformed for 35 days until considerable amount of metal trash was found on the magnetic plug of the test bearing. Sawalhi et al. [7] used autoregressive and minimum entropy deconvolution method with special kurtosis for bearing diagnosis. To the best of author's knowledge, it is observed from the literature review that fault size detection is carried out for fault size for pure radial loading only and hence in

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the present work fault size estimation is carried out with radial and axial combined load condition as in practice bearing are mostly subjected to combined load in practical situation.

#### **2. FAULT SIZE DETECTION**

For fault detection various signal processing techniques are used such as, discrete wavelet transform, auto-regressive process and minimum entropy deconvolution. These techniques are explained in brief in this section.

#### 2.1. Discrete wavelet transform (DWT)

The DWT has been used for fault detection of bearings and gears. DWT can be expressed using the equation (1) [2],

$$DWT(j,k) = \frac{1}{\sqrt{2^{j}}} \int_{-\infty}^{\infty} s(t)\varphi^{*}(\frac{t-2^{j}k}{2^{j}})dt$$
(1)

Two frequency filters one low-pass frequency filter and second high-pass frequency filter are used for dividing the original signal. One part is approximation, and another one is detail respectively. For next level, only the approximation signal passes through the filters. Repetition of this process gives a wavelet decomposition tree (multi-level decomposition) as shows in Fig. 1. So, signal S = A3+D3+D2+D1.



Figure 1. First level decomposition and multi-level decomposition [8]

#### 2.2. Autoregressive method and Minimum entropy deconvolution (AR+MED) filter

In the autoregressive model, the output values linearly depends upon its own previous values and also depend upon an imperfectly predictable term (a Stochastics term). Autoregressive filter can remove the deterministic noises in linear prediction and at the same time gives a pre-whitening signal of the time signal. The Minimum entropy deconvolution technique is used to get a linear signal that maximized the characteristics of spike pulse and maximum kurtosis. DWT cannot give information related to estimated size, because smaller size of defects produce low impulse and it is very difficult to extract the data from low impulse. Therefore, it is required to use first AR+MED filter, than use DWT for decomposition of vibration signal. Using the decomposed signal, calculate the time duration between the ball entered into the fault and exit from the fault. The defect size l can be expressed by equation (2) as follows [2]

$$l = r_{b} \times w_{b} \times \Delta t = \frac{D_{p} w_{s}}{4} (1 - \frac{d_{b}^{2}}{D_{p}^{2}} (\cos \phi)^{2}) \Delta t$$
(2)

Where, r\_b is the radius of ball, w\_b is the speed of ball, w\_s is the rotational speed of shaft, D\_p is the bearing pitch diameter, d\_b is the diameter of ball,  $\emptyset$  is the contact angle.  $\Delta t$  is the duration between the ball entered into the fault and exit from the fault.

#### **3. EXPERIMENT SETUP**

For determining the spall size of defects in rotating element bearing under various operating condition, an experimental setup has been designed and fabricated (refer Fig. 2). AC motor (1440

## **1921** (2021) 012087 doi:10.1088/1742-6596/1921/1/012087

rpm) is connected to the rotating shaft with the help of flexible coupling. Rotating shaft is supported using plummer block. The bearing with defect is mounted in specially designed test bearing housing, in which load directly applied to bearing through hydraulic cylinders in both axial as well as radial direction. The applied load is measured using pan cake type load cell (maximum capacity 1 tonne) which is directly connected to hydraulic cylinder (maximum capacity 10 tonnes). For applying an axial load a housing is designed and fabricated in such a way that when shaft rotates the load cell remain stationary. This is done using a thrust bearing between the rotating shaft and load cell. The vibration signals are captured using single axis piezoelectric accelerometer (vibration sensor) having frequency range of 1-20 kHz. The vibration signal for various radial load, combine load (radial and axial load) for faulty as well as healthy bearing are taken and analysed using four channel FFT analyser.



Figure 2. Experimental setup



Figure 3. 1mm defect size on outer race

Table 1. Geometrical Properties of polyamide cage deep groove ball bearing.

	<u> </u>
Inner diameter	25 mm
Outer diameter	52 mm
Ball diameter	7.938 mm
Pitch diameter	39.1 mm
Dynamic load caring	14 8 kN
capacity	11.0 M
No. of ball	9

For identifying the spall size 2mm, 1mm and 0.3mm size of defects are generated on outer race of ball

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bearing using wire-cut EDM machine. These defects are measured with help of USB microscope (refer Fig. 3). Experiments are performed on 6205 polyamide cage deep groove ball bearing. Table 1 shows geometrical properties of bearing.

## 4. RESULT AND DISCUSSION

The vibration signal are captured for different loading condition and sampling rate using FFT analyser. Signal is recorded for 10 seconds. When ball passes through the fault on outer race, produce sudden high impulse in frequency signal. It is called a ball pass frequency for outer race (BPFO)[2]. The analytical expression for determination of **BPFO** is as follows,  $BPFO = \frac{N_b}{2} s(1 - \frac{b_d}{D_a}) \cos \phi = 87 Hz$  Where,  $N_b$  is number of ball, S is shaft speed (in sec.),  $b_d$  is ball diameter,  $D_P$  is pitch diameter and  $\emptyset$  is contact angle. The size of defect, load condition and sampling rate are shown in table 2.

	Table 2.	Faulty signal characteristics	
No.	Size of defect	Loading condition	Sampling rate
1	2 mm	400 Kg	25.6 kHz
2	1 mm	400 Kg	25.6 kHz
3	0.3 mm	700 Kg	25.6 kHz

4.1. Result for 2mm and 1mm defect size

25.6 kHz is sampling frequency therefore, 12.8 kHz  $F_{max} = \frac{F_s}{2}$  is the most extreme frequency of the signal. Decomposition is done using sym5 wavelet and up to  $5^{t_{\Box}}$  level (refer Fig. 4).



Figure 4 : Frequency bandwidth of wavelet decomposition

Back to back bursts and two events that is (i) ball enter in to the fault and (ii) when ball hit the trailing edge of the fault can be observed in detail  $5(d_5)$  (refer Fig. 5).



Figure 5: Enlarge view of detail level-5 (2mm fault on outer race).

Fault size is calculated from the data points between ball enter into fault and pass out from the fault in the decomposed signal and this data points helps in calculation of the time duration. Average of the data point between two events gives time duration between two events. The obtained time duration can be used in equation (2) for the estimating the fault size. The average data point (37.32) is finally

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**1921** (2021) 012087 doi:10.1088/1742-6596/1921/1/012087

converted in to time (0.00145 sec.). Estimated defect size is l = 2.05 mm. Similar step is followed for estimating 1mm defects size and estimated defect size is l = 0.99 mm.

## 4.2. Result for 0.3mm defect size subjected to radial load.

For 0.3 size of the defect, initially the same method as explained in previous section in implemented. However from the decomposed signal the balls events cannot be clearly identified (refer Fig. 6).

The impulse produced because of 0.3mm defect is comparatively low. For 0.3mm, first AR plus MED filter is used, and subsequently, discrete wavelet transform is performed. The obtained time signal after applying AR plus MED filter is shown in figure 7. Now Signal processing is carried out using db5 wavelet instead of sym5 wavelet considering the nature of fault signal. Hence, the filtered time signal is decomposed by using db5 mother wavelet. The decomposition level is up to 3<sup>rd</sup> level.



Figure 6. 5<sup>th</sup> level decomposition using sym5 wavelet (0.3mm fault on outer race).

Impulses due to fault are shown in Fig. 8 and which clearly indicates the balls events. The average data point (8.1) is finally converted in to time (0.000316 sec). From the equation (2) the calculated defect size is l = 0.44 mm.



Fig 7. Time signal obtained using AR plus MED filter (0.3mm fault on outer race).

**1921** (2021) 012087 doi:10.1088/1742-6596/1921/1/012087



Figure 8. Extended view of detail level-3 decomposed signal (0.3mm fault on outer race).

## 4.3. Result for 1mm defect size subjected to combine load.

In previous cases, only radial load is applied to bearing and under the radial loading condition spall size is obtained. Now, the bearing is subjected to combine loading condition. The vibration signal are for 500 kg radial load, 160 kg axial load and 25600 Hz sampling rate (refer Fig 9).



**Fig 9 :** Time signal of bearing subjected to combine load (1mm defect on outer race). The frequency signal shows the harmonics of BPFO. Due to axial load rolling element (ball) is shifted, therefore, harmonics of BPFO are not appearing clearly. The shifting of rolling element bearing is known as slip. The corresponding frequency signal is shows in Fig. 10(a). To get the harmonics frequencies the enveloping is performed using Hilbert transform. The output time signal using Hilbert transform is shown in Fig 10(b).



**Fig 10(a)** FFT spectra of time signal, **Fig 10(b)** FFT spectra of time signal using Hilbert transform.

Now, enveloped signal is used for fault detection process. First AR plus MED filter is applied and thereafter decomposition process is done using db5 mother wavelet. Decomposition is done up to 5<sup>th</sup> level. In detail 5 balls events are clearly identified (refer Fig 11). Thereafter calculating the data point and average data point (23.4) is finally converted in to time (0.000914 sec). The estimated defect size from equation (2) is l = 1.29 mm. The obtained data point and spall size is shows in table 3.



Fig 11: Extended view of detail level-4 decomposed signal at combine load (1mm fault on outer race)

Table 3 : shows the estimated value of the fault size and the actual measured size for defects	on the
hearing	

oburning.					
Loading	Actual spall	Average data points calculated from	Spall size calculating from		
condition	size	signal processing	data point		
Radial	1.975 mm	37.32	2.05 mm		
Radial Radial Radial + Axial	0.975 mm 0.325 mm 0.975 mm	17.95 8.1 23.4	0.99 mm 0.44 mm 1.29 m		

## **5. CONCLUSION**

In this work experiments conducted for outer race of 25 mm diameter deep groove ball bearing subjected to radial load as well as combine load. Initially, ball pass frequency for outer race (BPFO) is estimated theoretically from geometry of bearing as well as from vibration signal. Then, signal processing techniques are used for extracting the data related to spall size. The 2mm defect on outer race is detected using discrete wavelet transform. Decomposition is done using sym5 wavelet. From decomposition signal, it was possible directly to find the ball enter in to fault and exit from fault. Level of decomposition depends on different applications. When ball passes through fault, two peaks are generated. One peak is generated when ball enter in to fault and the other peak generated due to ball hit the trailing edge of the fault. From decomposition signal duration between the ball enter into fault and pass out from the fault can be measured. Similar method is applied to 1 mm defects size on outer race. Above describe method does not gives clear peak during ball event for 0.3mm size present in outer race of bearing subjected to radial load. For 0.3mm defect size AR plus MED filter is used, thereafter, discrete wavelet transform can be used for detection of fault in 0.3mm size defect on outer race. In combined loading condition, it is required to first eliminate the effect of axial load with help of enveloping. Thereafter, AR plus MED filter and subsequently, decomposition is performed using DWT for determining the fault size. It has observed that with the proposed method defect size up to 0.3 mm can also be estimated accurately for the combined loading condition.

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