Estimating Bearing Fault Size using Vibration Analysis

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Abstract

Rolling element bearing failure forms one of the most critical categories of machine failures. The size estimation for bearing raceway spalls can provide very crucial information for bearing fault prognosis. Vibration analysis has been used for bearing fault detection and diagnosis for many years. However, the estimation of bearing fault size using vibration analysis has only been found in dealing with simulated or notched ideal bearing faults. It is a great challenge for vibration analysis to estimate the size of naturally occurring bearing faults. The objective of this research at DSTO is to define some feasible vibration signal processing methodologies in dealing with size estimation for naturally generated and propagated faults. In this paper, we present a technique based on time synchronous averaging with the bearing fault characteristic frequency. The averaged signal presents the vibration characteristics within one period of impact produced by the bearing faults. When the fault size is smaller than the pitch spacing of the balls, the features associated with the balls entry into and exit from the fault may be extracted and the fault size may be derived. The technique is validated using the vibration data from a bearing test rig at DSTO. The results show that the technique is capable of revealing the entry and exit features needed for the size estimation of naturally generated bearing faults.

Keywords: bearing fault prognosis, fault size estimation, vibration analysis, times synchronous averaging.

1. Introduction

Bearing fault prognosis often requires the very crucial information about the current size of bearing raceway spalls. The objective of this research is to define some feasible vibration signal processing methodologies dealing with size estimation for naturally generated and propagated faults. Vibration analysis has been used for bearing fault detection and diagnosis for many years. However, the estimation of bearing fault size using vibration analysis has only dealt with simulated or notched ideal bearing faults. It would be much more difficult to estimate the size of naturally occurred bearing faults via vibration analysis.

The earliest research of bearing fault characterisation and quantification using vibration analysis was the PhD study by Epps in 1991 [1]. He reported that the vibration characteristics associated with ball passage over a raceway spall could consist of a step response for the ball entry into the spall and an impulse response for the ball impact on the trailing edge of the spall. The step response is associated with lower frequency content than the impulse response in which broad frequency content including high frequency resonance oscillations can be evident. Work carried out later by Sawalhi and Randall [2] further investigated the Epps' observation with both simulated and seeded faults. In the simulations, the entry into the spall was modelled by a step response and the exit from the spall was modelled by an impulse response. Seeded faults with clearly defined sizes were created by electric discharge machining (EDM). Sawalhi and Randall employed some advanced signal processing techniques, such as pre-whitening filtering, wavelet and cepstrum analyses, to enhance and extract the entry and exit features for fault size estimation. In naturally generated faults, the entry features are expected to be much weaker than in seeded faults, as the rolling in event may not happen in a very definite instant, and in most cases these features could be submerged in other dominating signal components and noise.

Time synchronous averaging (TSA) method has been widely used in gear fault diagnosis. It is a powerful technique in extracting weak fault signal features. However, for bearing fault diagnosis the tachometer reference signals from both the shaft and the cage of the bearing are needed, which is impractical for most machine configurations [3]. There was a breakthrough in doing TSA without any tachometer reference in 2007 using the vibration signal's instantaneous phase information at a dominant shaft order [4]. A few researchers have applied this method to the detection and diagnosis of bearing faults [5, 6].

The possible use of the TSA for bearing fault size estimation was briefly discussed in Epps thesis [1] but never attempted. In this paper, we present a technique based on time synchronous averaging with the bearing fault characteristic frequency obtained from raw vibration signatures. The averaged signal represents the vibration characteristics within one period of impact produced by the bearing fault. When the fault size is smaller than the pitch spacing of the balls, the features associated with the ball's entry into and exit from the fault may be extracted and the fault size may be derived. The technique is validated using the vibration data from a bearing test rig at DSTO.

2. Bearing signal TSA without tachometer

McFadden and Toothy [3] carried out the work of doing TSA for bearing vibration signals with tachometer references from both the rotating shaft and the bearing cage. The fundamentals of the work are based on the following commonly utilized bearing kinematics (fault frequencies) equations:

$$
\begin{aligned}
f_{irf} &= \frac{N}{2} f_r \left(1 + \frac{D_b}{D_p} \cos\beta \right) \\
f_{orf} &= \frac{N}{2} f_r \left(1 - \frac{D_b}{D_p} \cos\beta \right) \\
f_{cage} &= \frac{1}{2} f_r \left(1 - \frac{D_b}{D_p} \cos\beta \right)
\end{aligned} \tag{1}
$$

where f_{irf} and f_{orf} are the inner race and outer race fault frequencies, f_{cage} and f_r are the cage and shaft rotational frequencies. N is the number of balls, D_b and D_p are the ball and pitch diameters. Parameter β is the contact angle (load angle) between the raceway and balls. By re-arranging these equations we have

$$
\begin{aligned}
f_{irf} &= N \cdot \left(f_r - f_{cage} \right) \\
f_{orf} &= N \cdot f_{cage}
\end{aligned} \tag{2}
$$

Therefore, doing TSA for inner race fault would need the differential speed reference between the shaft and the cage, whereas TSA for outer race fault only requires the cage speed reference. TSA without any tachometer reference has been made possible based on the work of Bonnardot *et al* [4] in 2005 using vibration signal's instantaneous phase information at a dominant shaft order. In the spectrum of bearing vibration signal, if a dominant component at the fault characteristic frequency or its harmonics can be identified, the unwrapped instantaneous phase could be derived and used as the basis to resample the vibration data at equal phase angles. This would result in the TSA with respect to the bearing fault frequency.

3. DSTO bearing test rig and vibration data

For this research, a DSTO bearing test rig was used to generate bearing vibration data acquired by a high bandwidth data acquisition system. The vibration data were sampled at 200 kHz. The test rig is shown in Figure 1 and the details of the test bearing are listed in Table 1. The naturally propagated spalls for two test bearings (labelled as AC8 and AC3) are shown in Figure 2. The spalls were initiated from the EDM notch of 2×0.25×0.1 mm (width×length×depth) across the middle of the inner race, and propagated along the raceway circumference (i.e. the length direction of the spalls) in accelerated endurance tests. The final lengths of the spalls are about 4.2mm and 6.2mm for AC8 and AC3 respectively, by counting the number of grids on the pictures in Figure 2.

Table 1. Test bearing parameters

Parameter	Value
Number of rolling elements	15
Contact angle	15 degrees
Inner ring bore	30 mm
Diameter of outer raceway	50.19 mm
Diameter of inner raceway	35.80 mm
Inner race groove diameter	7.55 mm
Ball diameter	7.14 mm
Pitch diameter	42.93 mm
Raceway & Ball material	AISI 52100
Modulus of elasticity (AISI 52100)	210 GPa
Poissons ratio	0.3
Maximum radial load	9450 N (static)
Maximum axial load	4000 N

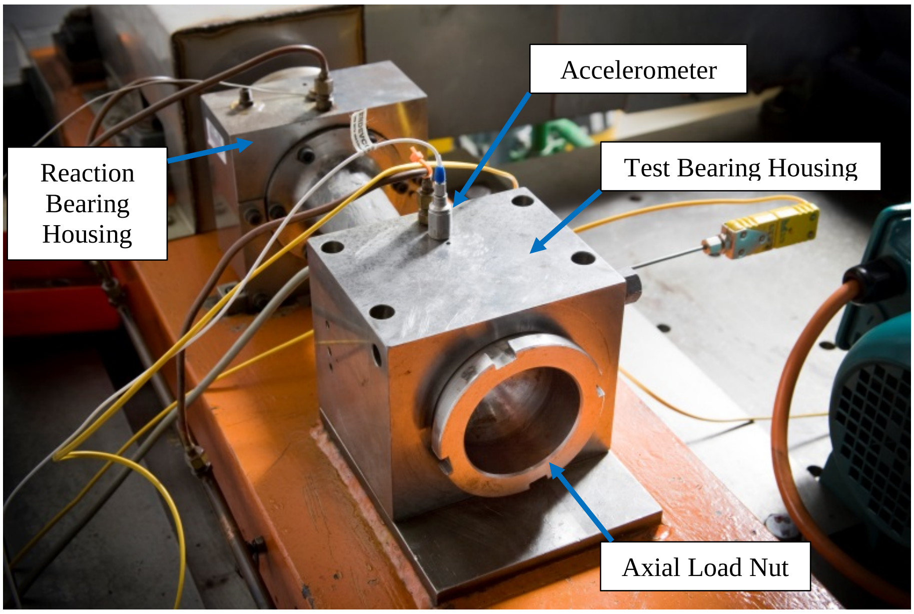

Figure 1. DSTO Bearing test rig

(*a*) Bearing AC8: spall is 4.2mm long (*b*) Bearing AC3: spall is 6.2mm long

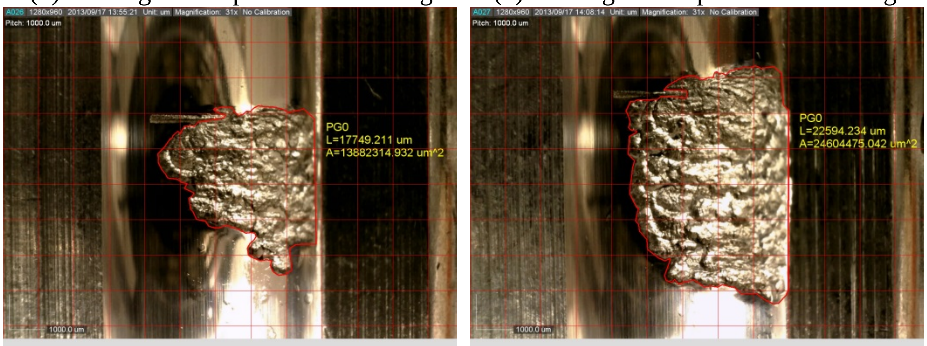

Figure 2. Pictures of the spalls on the inner race of Bearings AC8 & AC3

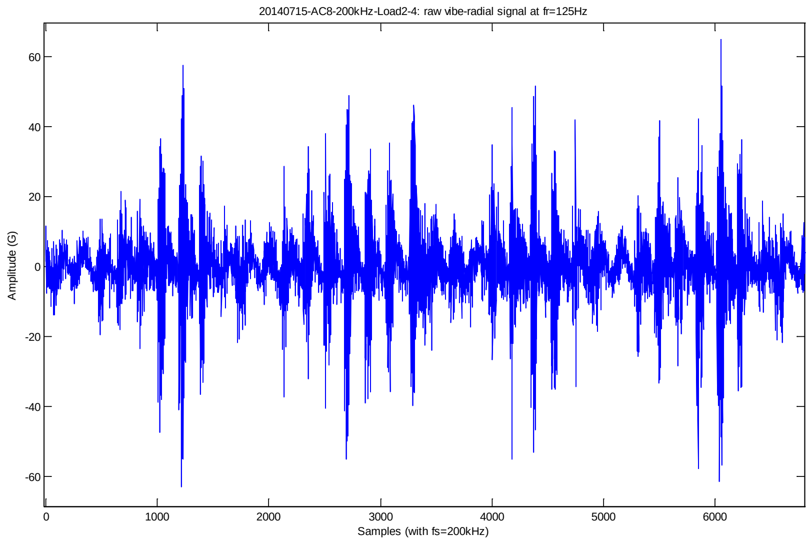

Figure 3. Raw vibration signal with Bearing AC8

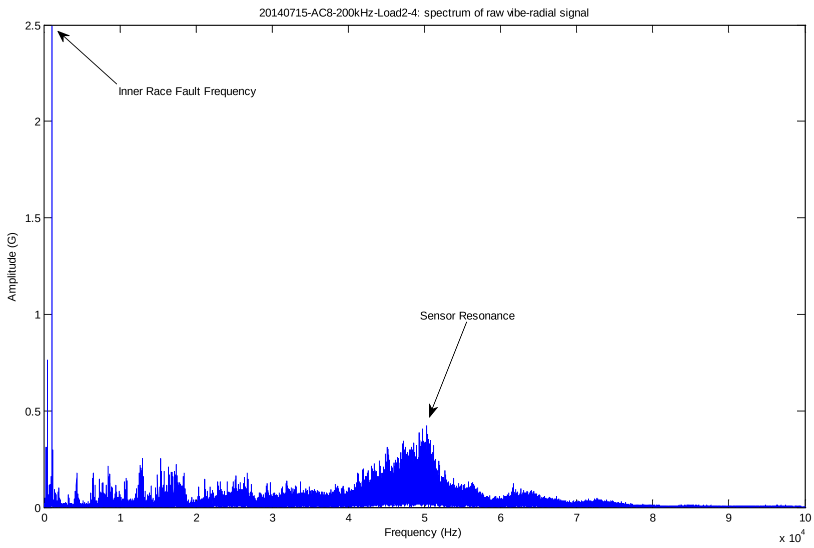

Figure 4. Spectrum of raw vibration signal shown in Figure 3

For the test with the AC8 bearing, the test rig was running at a nominal speed of 7500 rpm, which is the same as inner race rotational speed (f_r). The nominal inner race characteristic fault frequency is therefore calculated to be $8.51 \times f_r = 1063.75$ Hz, which corresponds to an impact period of about 188 samples (i.e. 200000/1063.75). A raw vibration signal from the AC8 bearing is shown in Figure 3, where the impacts generated by the passage of balls over the spall can be seen clearly. The amplitude spectrum is shown in Figure 4 with the inner race fault frequency absolutely dominating. The sensor's resonance frequency around the 50 kHz is also visible.

4. Bearing fault size estimation using vibration TSA with fault frequency

Because there is a lot of noise and interferences in the raw signal between two impacts, it is impossible to extract features with the balls entry into and exit from the spalled area on the inner raceway. Due to the high speed of the test rig, even with the high sampling frequency used the number of samples between two consecutive impacts is still quite small (around 190 samples). This could create an overlap between the entry and exit features because the entry-related response doesn't completely disappear before the exit event starts. TSA may prove very useful here in order to attenuate the noise and interferences and provide a clearer picture about the events associated with ball passages over the spalled region. Because of impracticality it was not attempted to acquire the cage tachometer signal for TSA with f_{irf}. The phase reference from the raw vibration signal was obtained for calculating the TSA. The procedure of obtaining the TSA without a tachometer reference can be found in [4].

Through zooming-in around the dominant spectral component at f_{irf}, as shown in Figure 5, a band with no interference components mixed with the peak at f_{irf} can be identified. Note that the peak is a little smeared due to some small speed fluctuation and ball skidding between the raceways. By band pass filtering around the peak and calculating the unwrapped instantaneous phase, an equally angular-spaced 256 samples (i.e. equally spaced instantaneous phase angles) are obtained through interpolation, where 256 is the next power of two of the estimated number of samples between impact (i.e. 188 here). In this way, the TSA of the AC8 bearing vibration signal in Figure 3 was obtained and is shown in Figure 6. Obviously, the TSA is dominated by the inner race fault characteristic period of $1/f_{irf}$. There are some lower frequency features in the first half of the TSA signature, and on top of that, there are some higher frequency features in the second half of the TSA. However, the entry and exit features characterised by Epps [1] are still not evident. To further enhance these features in the TSA, the squared envelope from the TSA was derived, as shown in Figure 7.

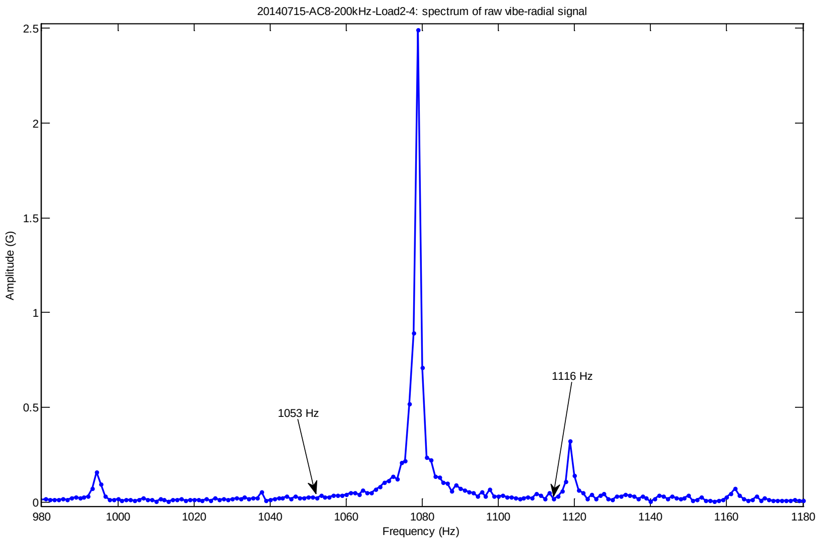

Figure 5. Identification of dominant bearing fault frequency in the spectrum of raw vibration signal

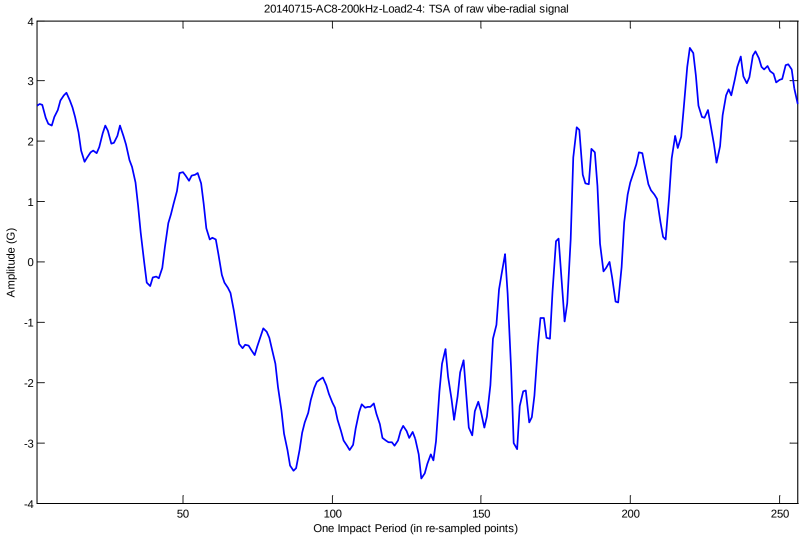

Figure 6. TSA of AC8

The entry and exit features appear to be much more evident in the squared envelope of the TSA, which are marked by 'data tips' in the plot, i.e. 38 at entry and 158 at exit. It must be emphasized that sample 38 was the moment when the ball's centre rolled off the leading edge of the spall, and sample 158 was when the ball hit the trailing edge of the spall yet the centre of the ball was still inside the spalled region. Therefore, a correction factor (x) [4] which depends on the ball diameter (D_b) and the depth of the spall (δ) must be considered:

$$x = \sqrt{D_b \delta + \delta^2} \tag{3}$$

which is estimated to be 1.2 mm in this case based on an estimated spall depth of 0.2 mm. A very intuitive approach was employed to calculate the spacing between the entry and the exit features. As the diameter of the inner raceway is 35.8 mm, the ball's pitch distance at the inner race is 35.8×π/15 = 7.498 mm, which corresponds to 256 re-sampling points. Therefore, the estimated spall length is 7.498×(158–38)/256 + x = 3.5+1.2 = 4.7 mm. In fact, this estimate is about 10 percent longer than the visual measurement of 4.2 mm.

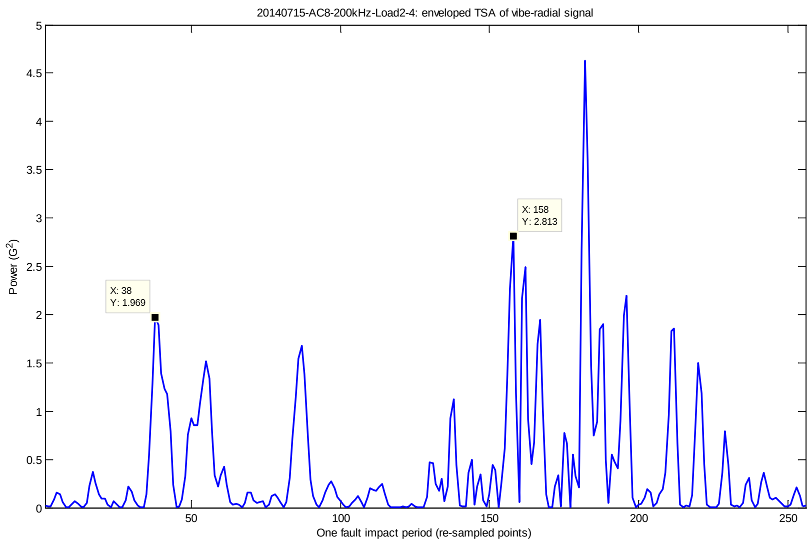

Figure 7. Enveloped TSA of AC8 (spall size estimate 4.7 mm)

Using the same approach, we obtained the squared envelope of TSA for the AC3 bearing and estimated the spall size to be 7.498×(217–56)/256 + x = 4.72+1.2 = 5.9 mm. This estimate is slightly shorter than the visual measurement of 6.2 mm. It is worth noting that the choice of exit point here may look somewhat ambiguous. The signal in Fig. 8 was divided into 3 different frequency bands and was processed by wavelet decomposition; this choice was obvious there.

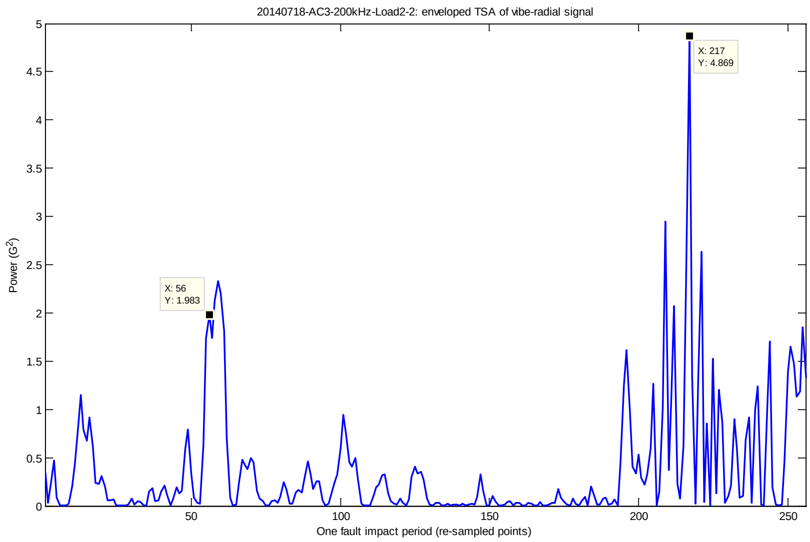

Figure 8. Enveloped TSA of AC3 (spall size estimate 5.9 mm)

5. Discussion and conclusion

From the above results, the square-enveloped TSA is believed to be capable of revealing the entry and exit features needed for the size estimation of naturally generated bearing faults. However, this capability may not produce an accurate spall size which is probably less important to know than whether or not the spall length has gone beyond the pitch distance. It has been reported that the pitch distance can be used as an upper limit for spalls on the bearing raceways, beyond which the spall's propagation is expected to accelerate [7]. An important observation here is that, for a naturally occurring spall, the entry and exit features may not be *distinctively* identifiable. It tends to have some kind of ambiguity associated with the identification of these features, which was the case for AC8 and AC3 bearing spalls presented in this paper. For this study, one of the difficulties experienced in the DSTO bearing rig was that the bearing speed was fixed and too high, which produced very noisy vibration signatures and reduced the time resolution (e.g. the number of samples) in each impact period making the subtle entry features less distinguishable.

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