Vibration Signal Pre-processing For Spall Size Estimation in Rolling Element Bearings Using Autoregressive Inverse Filtration

Nader Sawalhi[1], Wenyi Wang[2], Andrew Becker[2]
[1]*Prince Mahammad Bin Fahd University, Saudi Arabia*
[2]*Aerospace Division, Defence Science and Technology Group,*
506 Lorimer Street, Fishermans Bend, Victoria, 3207, Australia

Abstract

Vibration responses from spalled races of rolling element bearing are composed of two parts. The first (step response-low frequency event) originates when the rolling element moves into the spall, while the second (impulse response-high frequency) results from the impact of the rolling element with the trailing edge. The estimation of the spall size (entry-impact spacing) is often a challenging task due to the need of providing a signal processing algorithm to equally balance both events. In this paper, a signal processing algorithm to aid fault size estimation is proposed. The algorithm involves the enhancement of the step response through using autoregressive inverse filtration, which has the effect of removing deterministic components including the sinusoidal ringing effect of resonances, thus providing a much needed enhancement to the weak entry event and better localization to the impulse event. Results from a naturally grown inner race spall are presented to demonstrate the effectiveness of the proposed processing algorithm and compare it to a previously utilized autoregressive whitening algorithm.

Keywords: Spall size, Autoregressive inverse filtration, step response, entry-impact

Introduction

A main challenging area of rolling element bearing health monitoring, which still needs more research, is the quantifying of the fault size using vibration data. This is very crucial in maintenance planning and decisions. A key fundamental work in understanding the nature of the vibration signal as the rolling element passes over the spalled area is the work of Epps [1]. In his thorough investigation of the vibrations of defective rolling element bearings, Epps established the presence of two main parts of the vibration response resulting from the passage of a rolling element over a spalled area in one of the races. The first part originates as the rolling element rolls into the spall. Due to a change of curvature at the instance of rolling, a step response in the acceleration signal arises. This is characterized by low frequency content with a negative slope. The second part of the vibration signal results from the impact of the rolling element with the trailing edge. This causes a sudden change of the rolling direction, which gives a step response in velocity and results in an impulse response in acceleration. It is often the second part of the vibration signal that dominates the response and gets detected using envelope analysis [2]. Epps showed that the time between the rolling in (step response) and the impact (impulse response) is proportional to the size of the spall and can be used to measure the spall width. A typical example from Epp's thesis showing the two parts of the vibration signal is shown in figure 1.

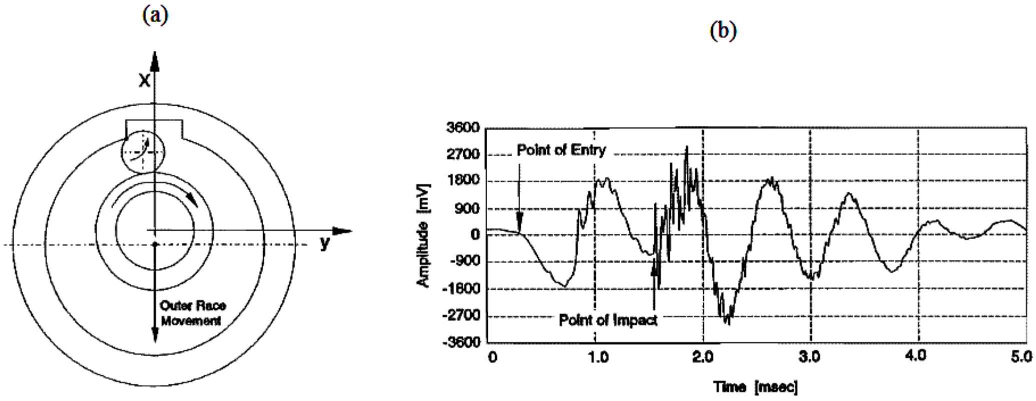

Figure 1 (a) Model of rolling element travelling into a fault (b) A typical measured response [1]

It was not until recently that there was another major study into the topic by Sawalhi and Randall [3], who further investigated the entry-exit vibration features. In addition to providing an analytical model for the two parts (see figure 2), Sawalhi and Randall proposed a number of signal processing alternatives to enhance the weak entry event and estimate the size of the spall. In particular, they proposed the use of signal pre-whitening using autoregressive modeling (AR) [4] for enhancing the entry event, Morlet wavelet analysis [5] to balance the energy of the entry and exit events and the cepstrum [6] to estimate the spacing between the two events. For verifications of the simulation results and the proposed enhancement processing algorithms, seeded notched inner race and outer race faults were tested using a fan bladed test rig at different speeds. This resulted in good correspondence and reasonable fault size estimation.

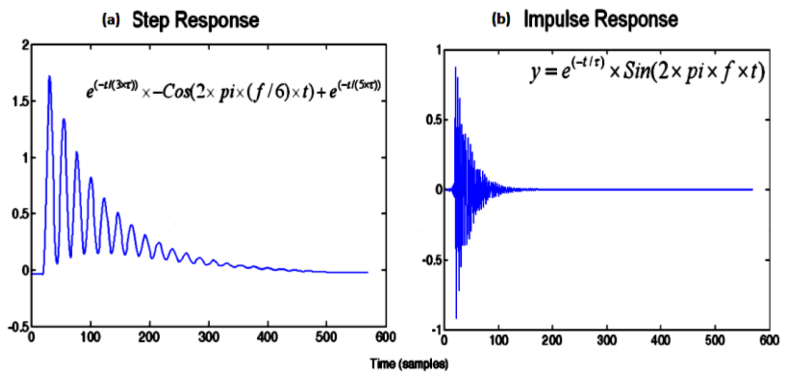

Figure 2 Figure 2 Analytical models of the step (a) and impulse(b) responses

In this paper, a processing signal algorithm to enhance the weak entry step response from the vibration signal of defective inner/outer races is proposed and verified using signals from naturally originated and propagated inner race spall. The proposed algorithm is compared to the pre-processing algorithm proposed by Sawalhi and Randall [3].

Autoregressive Modelling and Pre-whitening

Sawalhi and Randall [3] used signal pre-whitening using autoregressive modeling (AR) to enhance the step response. The whitening was achieved based on deriving an AR filter coefficients using the raw vibration signal itself. The residual signal (difference between the raw signal and an estimated version of it using the AR model) is white in the sense of containing noise and impulses, which has a relatively flat spectrum. This helps in lifting the energy of low events and thus results in gaining some enhancement. In an autoregressive model (AR), a value at time t is based upon a linear combination of prior values (forward prediction), upon a combination of subsequent values (backward prediction), or both (forward-backward prediction). If x is a data series (zero mean stationary process) of length N and a is the autoregressive parameter array of order p, an AR model Y can then be defined in equation (1) as follows [7] :

$$Y_k = \sum_{i=1}^{p} a_i x_{i+k} + \varepsilon_k \qquad (1)$$

where p is the order of the model, i =1,2,…p are weighting coefficients. The error term ε_k (pre-whitened signal) is a white noise process, with a variance σ_p^2 , which represents the difference between the actual and linearly predicted values. It contains additive white noise and non-stationary in the form of impulses, both of which are delta correlated, with a white spectrum. The Pre-whitening approach was attempted successfully on both simulated and seeded signals with a reported enhancement [3]. A typical result from ref [3] is presented in figure 3.

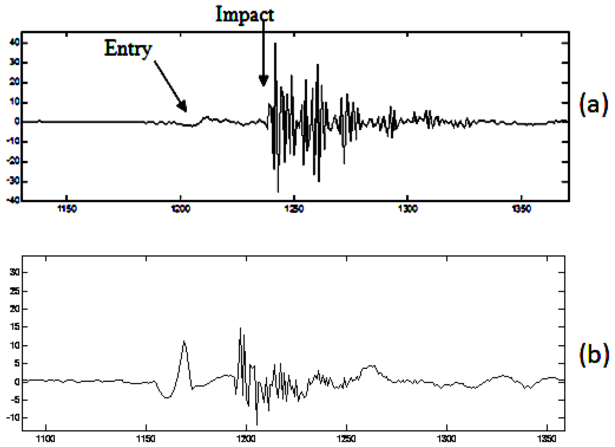

Figure 3 (a) Raw vibration signal of seeded inner race spall (b) AR whitened signal [3]

Autoregressive Inverse Filtration

Figure 4 describes schematically the new proposed AR inverse filtration process to enhance the step response. In this approach an AR model is derived from the shaft synchronous averaged signal rather than from the raw vibration signal.

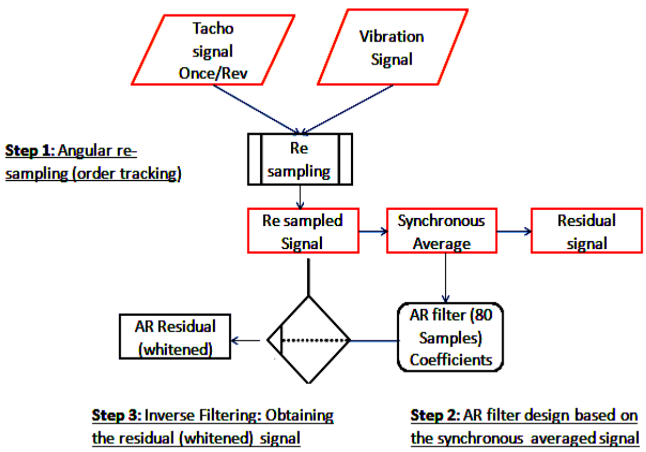

Figure 4 Order tracking and AR inverse filtration to enhance the step response

As illustrated in figure 4, the first step in the process includes using the tachometer signal to re-sample the vibration signal in the angular domain (order tracking) [8], thus removing any speed fluctuations. The synchronous averaged signal can then be estimated by an ensemble average over a number of rotations. The synchronous averaged signal contains all the harmonics of the shaft frequency and the ringing effects (sinusoidal components) of the structural resonances in the structure (see figure 2). This synchronous averaged signal is used to build an AR model using equation 1. The filter coefficients obtained through this model (a_i) are used to whiten the re-sampled signal (inverse filtration).

Note that unlike the AR whitening proposed in [3], the AR inverse whitening process ensures that a true AR model is derived for the signal and a more efficient removal of the masking deterministic components (shaft harmonics and resonance ringing sinusoidal components). Thus it is anticipated that the AR inverse whitening process will provide a better enhancement to the entry event and a better localization to the exit event. The limitation of the AR inverse whitening resides in the need of a tachometer signal for order tracking and synchronous average signal calculation. The choice of the filter length could be guided subjectively by the duration (length) of the impulse response in samples to capture the excited resonances within the model.

The results obtained from a naturally grown inner race spall using the Defence Science and Technology Group (DSTG) bearing test rig are used to test the effectiveness of the proposed processing algorithm and compare it to the one earlier developed and proposed in [3].

Experimental Setup and spall Sizes

The DSTG test rig used to generate the data for this work is pictured in figure 5. It consists of two bearing housings. One of these housings contains the test bearing (Angular contact bearing), which is loaded axially through screwing a large nut to the housing. The other bearing housing contains two angular contact bearings, arranged in tandem, which react to the test load. The test rig is driven by a constant speed motor through a belt -pulley system to give a running speed of around 7700 revolutions per second (rpm). The test rig was fitted with a vertical-radial accelerometer and a tachometer to get a speed reference. Data was acquired at a sampling rate of 200,000 samples/s (Hz). The naturally propagated spalls for two test bearings (AC8 and AC3) are shown in Figure 6. The spalls were initiated from a small EDM notch and grown to the final shown widths of 4.2mm and 6.2mm for AC8 and AC3 respectively. With the AC3 bearing test, the bearing shaft and the inner race were running at a speed of *fr* = 104.5 Hz. The nominal inner race characteristic fault frequency is therefore calculated to be $8.51\times fr = 889.3$ Hz, which corresponds to an impact period of about 225 samples (i.e. 200000/889.3). The AC8 bearing was running at a nominal speed of 7500 rpm, which was significantly higher than the AC3 bearing's running speed.

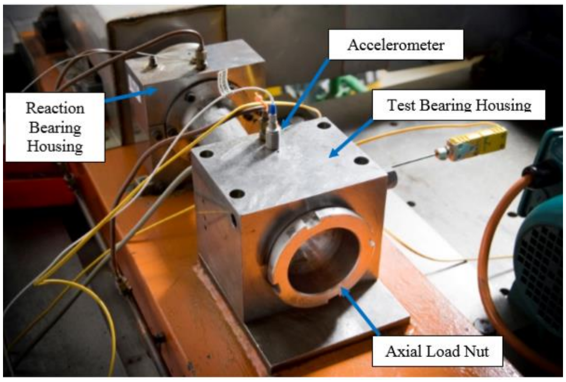

Figure 5 DSTG bearing test rig

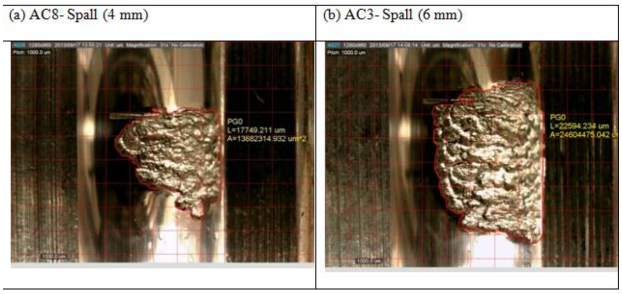

Figure 6 Images of the spalls on the inner race of Bearings AC8 & AC3

Results and discussions

Figures 7.a and 8.a show a zoom-in into a number of rolling element passages over the AC8 and AC8 spalls respectively. Through visual examination of the raw vibration responses, it is extremely difficult to locate the entry event (step response) preceding each of the impulses. The situation is not much improved after subtracting the synchronous averaged signal from the re-sampled signal (residual signal) as presented in figures 7.b and 8.b, as this only has the effect on removing the deterministic component related to the shaft harmonics. When using AR inverse filtration as described in figure 4, the entry event, which was not seen before can be now seen clearly in figures 7.c and 8.c for the two spall widths. The length of the AR filter has been selected as 80 samples in this study, guided mainly by the duration of the impulse response. The use of AR inverse filtration and whitening resulted in the removal of the dense areas noticed in the vicinity of the impulse response, which are sinusoidal components related mainly to structural resonances and in particular the accelerometer natural frequency at 50 kHz.

The performance of AR inverse whitening compared to the AR whitening [3] using the same filter order of 80 samples is presented in figures 9 and 10 for the small (AC8) and large (AC3) spalls respectively). Note that both methods enable the detection of the step response and provide a clear detection of the entry event.

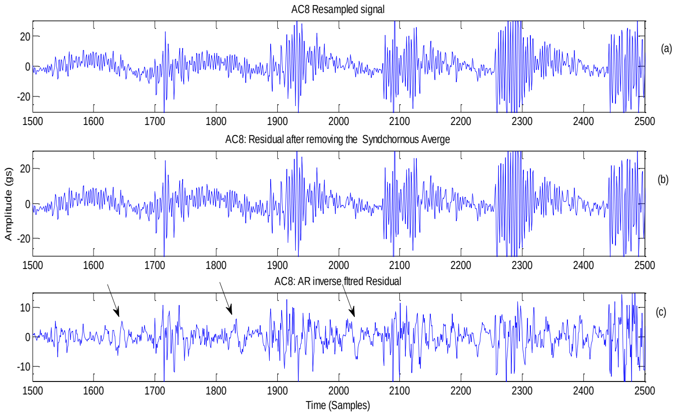

Figure 7 AC8 Processing using angular re-sampling and AR inverse filtration (a) Raw re-sampled signal (b) Residual after subtracting the synchronous average (c) AR inverse filtered signal

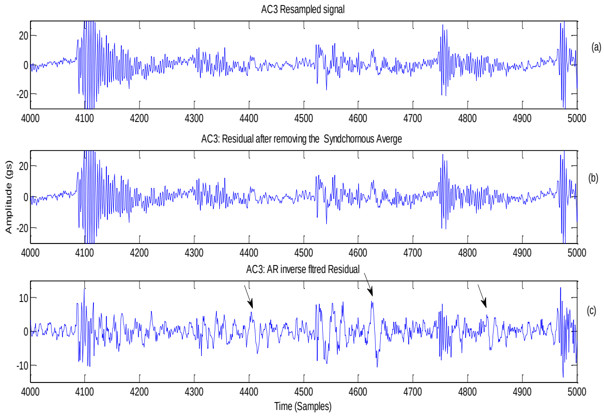

Figure 8 AC3 Processing using angular re-sampling and AR inverse filtration (a) Raw re-sampled signal (b) Residual after subtracting the synchronous average (c) AR inverse filtered signal

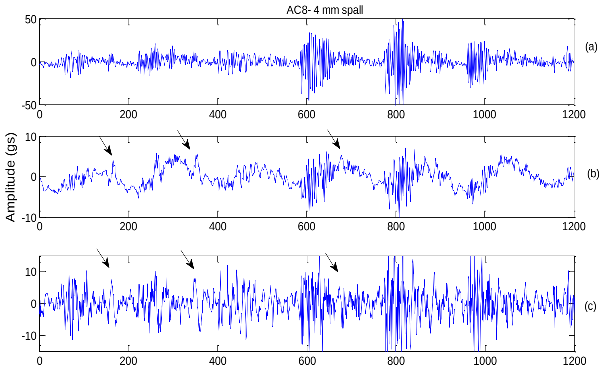

Figure 9 AC8 Comparisons of attempted processing to enhance the step response (a) Raw re-sampled signal (b) AR pre-whitened signal (c) AR inverse filtration

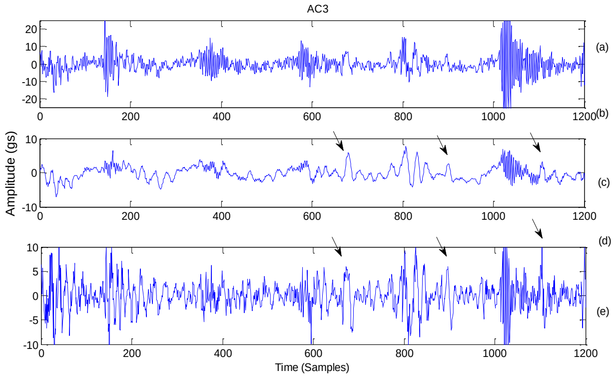

Figure 10 AC8 Comparisons of attempted processing to enhance the step response (a) Raw re-sampled signal (b) (b) AR pre-whitened signal (c) AR inverse filtration

Conclusions

This paper has proposed a signal processing algorithm to enhance the weak feature associated with the entry of a rolling element into a *spalled* region in inner/outer race of a ball bearing. The enhancement of the entry event, which is characterized by a step response in the acceleration signal is vital for the quantification of the spall size. The proposed algorithm is built on deriving an autoregressive model based on the synchronous averaged signal and applying it to whiten the angularly re-sampled (order tracked) signal. The algorithm has been tested on two naturally originated and propagated inner race spalls, which, unlike seeded faults, were very hard to detect visually in the raw vibration signal. The use of the AR inverse whitening filter shows promise and warrants further testing. Further work will involve establishing a criterion for selecting the AR model order and investigating alternatives [9] in the absence of a tachometer signal for performing the order tracking.

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