Vibration Signal Processing Using Cepstrum Editing Technique to Enhance Spall-related Vibration Features in Rolling Element Bearings

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Abstract— **This paper proposes the use of cepstrum editing technique as a signal pre-processing algorithm to enhance spall related vibration features in rolling element bearings for the purpose of size quantification and fault prognosis. Cepstrum editing technique has been proposed and utilized in a number of contexts which include: signal separation; bearing diagnosis enhancement through pre-whitening and operation modal analysis through extracting the forcing function. In this paper, the cepstrum editing technique is utilized to enhance the weak step response event originating from the entry of the rolling element into the spall region. The cepstrum editing technique is used to remove the transfer path effect (high quefrency liftering). The effectiveness of the cepstrum editing technique is demonstrated on two sizes of a naturally originated and propagated inner race spalls from a high-speed test rig. The use of the proposed technique helps in clarifying the entry event at a number of locations when visually examining the time domain signal. The further processing of the signal using bearing synchronous averaging for instance will give a definite measure for the size of the spall. In addition, features extracted with the aid of the cepstrum editing can be applied effectively in neural networks (NNW) and artificial intelligence (AI) algorithms to quantify spall**

Index Terms—**rolling element bearings, spall, step response, impulse response, cepstrum editing**

I. Introduction

Rolling element bearing fault diagnosis has been the focus of research and industry for decades. A number of signal processing algorithms have been developed and implemented successfully to diagnose bearing faults. The common most widely used original technique in this field is envelope analysis or the high frequency resonance technique (HFRT) [1]. This technique works by amplitude demodulating a frequency band (often chosen in the high frequency region, i.e. away from the dominance of other components in the low frequency region) and analyzing the spectrum of the enveloped signal.

A more challenging area is quantifying the spall size in bearings using vibration signals. This is very crucial for maintenance planning and decision making. The work of Epps [2] established the existence of two main parts for the vibration response of spalled rolling element bearings. The first comes as the rolling element rolls into the spall, where the change of curvature causes a step response in acceleration. The second event results from the impact of the rolling element with the trailing edge, which causes a sudden change of the rolling direction and results in an impulse response in acceleration. The time between the rolling in and the impact (denoted as the time to impact (TTI)) is proportional to the size of the spall. This can be used to measure the spall width and quantify the spall size.

The nature of the entry event and the impact was found to be a function of mainly the spall width, the rotational speed of the shaft and to some extent the load applied. Sawalhi and Randall [3] investigated the entry-exit vibration features, provided an analytical model and proposed a number of signal processing algorithms to enhance the weak entry event and estimate the size of the spall. Further work was conducted by researchers, e.g. [4-8] with the focus of enhancing the step response (often buried in noise, very weak and excites low frequency) and estimating the size of the spall.

In this paper, a signal pre-processing algorithm based on cepstrum editing is proposed to enhance the weak entry step response in the vibration signal of defective inner race. The pre-processing serves in enhancing the detectability of the entry event and thus improving the confidence and accuracy of estimating the spall size. The result of the pre-processing can be utilized to further process the vibration signal and also in training sets used

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in neural networks and other artificial intelligence algorithms to aid bearing prognosis.

II. Vibration Data Pre-Processing To Enhance Spall Features Using Cepstrum Editing

A. Cepstrum Analysis

Cepstrum analysis [9] is a nonlinear signal processing technique with a variety of applications in areas such as speech and image processing. It is very useful for signals containing families of harmonics and sidebands (of uniform spacing). Bearing faults and localized faults in gears are typical examples for the benefits of cepstrum analysis. The cepstrum is defined as the inverse Fourier transform of a logarithmic (amplitude) spectrum. The logarithmic conversion enhances periodic spectrum structures in the same way as spectrum analysis highlights periodicity in time signals.

The fundamental definition of the cepstrum (real cepstrum) is the inverse Fourier transform of a logarithmic spectrum as in equation (1).

$$C(\tau) = \Im^{-1}\{\log(F(f))\} \qquad (1)$$

The cepstrum can also be obtained from the forward Fourier transform of a time signal, in which case it will be complex. If the phase is retained, the logarithmic spectrum has log amplitude as real part, and phase as imaginary part, and the so-called “complex cepstrum” is obtained as shown in equation (2):

$$C_c(\tau) = \Im^{-1}\{\ln(A(f) + j\phi(f)\} \qquad (2)$$

In order to calculate the complex cepstrum, the phase must be a continuous function of frequency. This is possible for analytic functions such as FRFs, but not in general for forcing functions or response functions where the forcing function is modified by a transfer function. Forcing functions often consist of a mixture of deterministic discrete frequency components, where phase is undefined between these components, and noise, whose phase is discontinuous with frequency. Note that despite its name, the complex cepstrum is actually real, since the log amplitude is even, while the phase is odd. If the phase is disregarded, as in equation (3), the so-called “real cepstrum” is obtained.

$$C_r(\tau) = \Im^{-1}\{\ln(A(f))\} \qquad (3)$$

This has the advantage that the phase does not have to be unwrapped, and it can be applied to forcing and response signals. On the other hand it is only reversible to the spectrum, rather than a time signal. It can also be applied to smoothed auto spectra, which will generally reduce noise

B. Cepstrum Editing Technique

Sawalhi and Randall [10, 11] proposed the use of the cepstrum to remove selected families of harmonics and sidebands using the signal itself (i.e. without the need of a tachometer of the use of a delayed version of the signal) and with minimum disruption to the signal. The core base of the cepstrum editing algorithm is the transformation of the signal into the cepstrum domain. In this domain, a family of harmonics and sidebands becomes localized in discrete components called rahmonics. These are eliminated (lifterd) by setting them to zeros and the signal is transformed back into the logarithmic domain, where initial phase is restored and then processed further and transferred back to the time domain. The end result is a filtered time domain signal that does not have the targeted family of harmonics and sidebands. The process is schematically illustrated in Fig.1. The cepstrum editing method is currently the latest and up to date innovative approach proposed in this area and a number of usages and case studies have been presented in number of papers, e.g. [12-13].

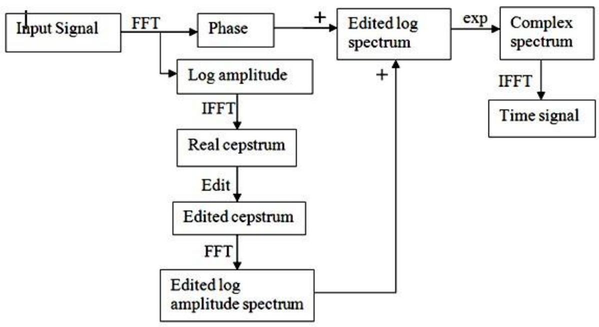

Figure 1. Schematic diagram of the cepstrum editing method for removing selected families of harmonics and/or sidebands from time signals [10, 11].

C. Cepstrum Editing to Remove the Transfer Path Effect

A flow chart of the proposed cepstrum editing method (after being modified) for the spall feature entry enhancement is presented in Fig.2. In this current utilization of the cepstrum editing method for enhancing the step response associated with the ball entry into the spall, the effect of the transfer path is removed in the cepstrum domain by setting the low quefrency part (first N samples [except the first sample which is kept for scaling]) to zero and inverse transforming back to the time domain after restoring the phase. The number N is determined visually by examining the cepstrum domain, but can be selected automatically by curve fitting the low quefrency part using an exponential function

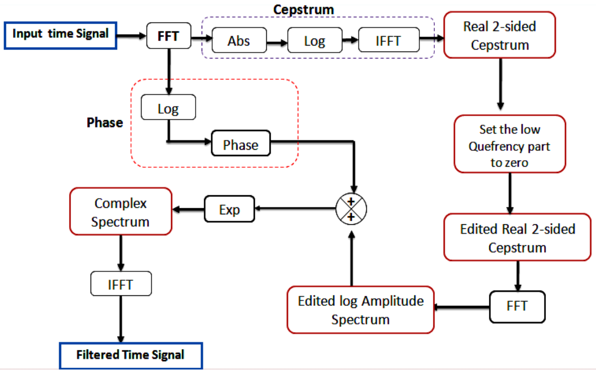

Figure 2. Proposed Cepstrum editing algorithm to remove transfer path effect and enhance spall entry feature

III. Vibration Test Rig and Data Acquisition

The vibration test rig used to generate the data for this work is pictured in Fig.3. 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 minute (rpm). The test rig is 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). Two main fault sizes (AC8 and AC3) were used in the testing are shown in Fig.4.

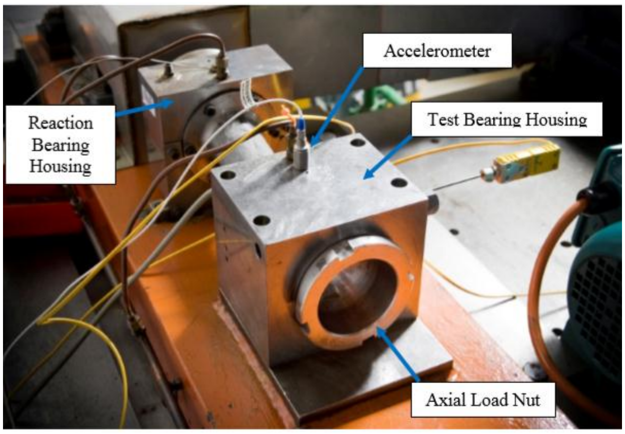

Figure 3. Bearing prognosis test rig.

IV. Results and Discussion

Fig.5 shows the acceleration signals measured for the two spalls, with the highlighting of one shaft rotation. The ball pass frequency of the inner race (BPFI) is estimated at 8.7 times the shaft speed and thus it is clear that there is around 8 to 9 impacts each shaft rotation. Due to the high speed of the shaft (around 7700 rpm) it is very hard to separate the entry and impact events. The latter is seen to dominate the vibration signal. The examination of the cepstrum of the vibration signal for the two spalls is presented in Fig.6, which clearly reflects the periodicity noticed in the time domain signals for both faults. The 8th and 9th ball passage periods (rahmonics) and their multiples can be observed in the cepstrum. Note the difference in the speed between the AC8 data and the AC3 data, where the AC3 signal shown here was acquired at a speed of about 100 Hz while the AC8 data was capture at 125 Hz. Thus for the AC8, the first ball pass rahmonic is seen at 183 samples, while it is 229 samples for the AC3 data. The effect of the transfer path (Transfer function) can be seen in the low quefrency part (100 samples).

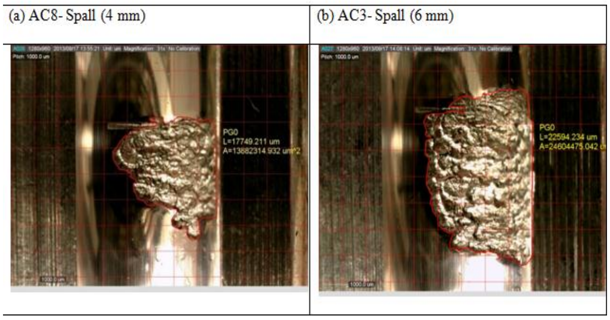

Figure 4. Two spall sizes (a) AC8-Spall (4 mm) (b) AC3-Spall (6 mm).

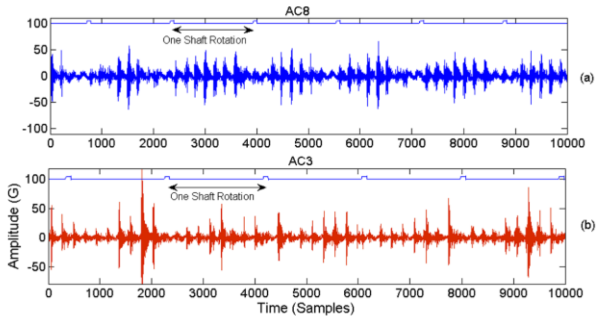

Figure 5. Raw vibration signal of (a) AC8-Spall and (b) AC3-Spall.

Typical results using the cepstrum editing method on the AC8 and AC3 data are presented in Figs 7.b and 8.b respectively. These are compared to the raw vibration signals in 7.a and 8.a. The removal of the transfer path (i.e. setting the 1st 100 samples in the quefrency domain to zero) has the effect of enhancing the ball pass periodicity and the entry events at a number of locations. The entry features (step responses) are enhanced and become visually recognized at few locations in the processed signals. The clarity of the events are seen in two consecutive ball passages every revolutions.

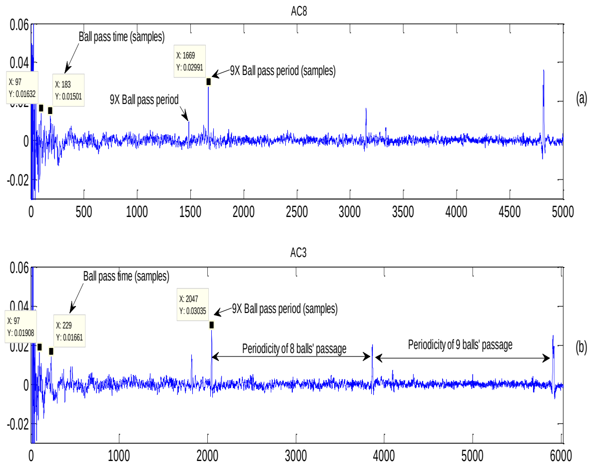

Figure 6. Figure 1 (a) Cepstrum analysis for the AC8 vibration data (b) Cepstrum analysis for the AC8 vibration data.

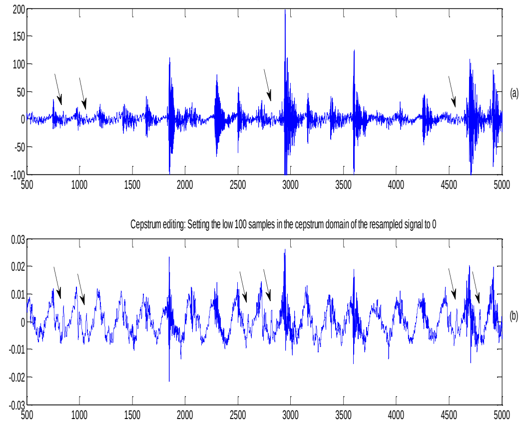

Figure 7. (a) Raw vibration signal with Ac-8 Spall (b) Pre-processed signal using Cepstrum editing.

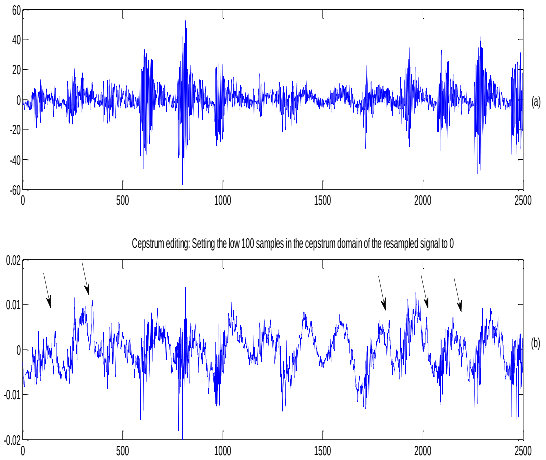

Figure 8. (a) Raw vibration signal with Ac-3 Spall (b) Pre-processed signal using Cepstrum editing.

V. Summary and Conclusion

A signal pre-processing algorithm to enhance the spall entry feature of defective rolling element bearings has been presented. The algorithm is based on removing the effect of the transfer path through cepstrum editing. The low quefrency part is set to zeros in the cepstrum domain and the signal is transferred back to the time domain. The effectiveness of the pre-processing was tested on the vibration signals from two spalled bearing with large spall sizes. The removal of the transfer path using cepstrum editing has the effect of enhancing the ball pass periodicity and the entry events at a number of locations. The entry features have been enhanced and become visually recognized at few locations in the processed signals.

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