Localized fault detection and diagnosis in rolling element bearings: A collection of the state of art processing algorithms

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Abstract

This paper puts together a collection of a number of previously proposed signal processing techniques to detect and diagnose faults in rolling element bearings. The collection of previously proposed signal processing algorithms contains two main phases. Phase one includes a surveillance and diagnosis stage using time, frequency and an envelope analysis over the full frequency bandwidth. The second phase includes a more specific and impulsiveness-targeted analysis which starts by separating the signal into deterministic and random parts using time synchronous averaging (TSA) and/or discrete random separation (DRS). It then utilizes Spectral Kurtosis (SK) analysis (*Kurtogram*) for a more concise and automated envelope analysis. The SK-algorithm, encoded as AR-MED-SK analysis, includes pre-whitening using an autoregressive model (AR), Minimum entropy deconvolution (MED) and SK analysis. The two-phase setup hasn't been combined in a single algorithm previously and this paper points out a number of hints to produce a reliable diagnosis. The algorithm is explained using a signal from a helicopter gearbox that has a defective planetary bearing (both inner race and roller faults), with clear identification of the source of fault.

Keywords: Rolling element bearings, Pre-whitening, Spectral Kurtosis, Minimum entropy Deconvolution

Introduction

Vibration-based localized fault surveillance and diagnosis in rolling element bearings have been the focus of a number of researchers [1-9]. The authors [10-15] have provided a detailed analytical and dynamic modelling of the vibration signal of a localized fault and proposed a number of innovative and semi-automated signal analysis approaches.

On the aspect of modelling, it has been shown [14] that the acceleration response measured using an accelerometer in the proximity of the defective bearing is composed of two components. The first represents a step response (low frequency event), and happens at the instant the rolling element enters the spall, while the second part is an impulse response (high frequency event), which happens when the centre of the ball is in the middle of the spall. The impulse response excites the resonances of the structure. In practice, it is usually the impulse response that gets detected and used to diagnose the presence of the fault. The repetition frequency of the impulse responses varies randomly by1-2% of the mean ball passing rate as a result of ball slippage, which is a direct result of the variation of the load angle. This gives a smearing of the frequency spacing of the bearing defect frequencies in the high frequency region. In the low frequency region, the bearing defect frequencies are generally masked as a result of the presence of strong vibrations from other components in the system like, gears, bladed structures, electrical components etc.

To diagnose localized faults in rolling element bearings, the high frequency resonance technique [16, 17], also known as envelope analysis has been widely used as an effective tool for fault diagnosis. The essence of envelope analysis is the selection of a high frequency band (away from the masking components in the low frequency region)) and amplitude demodulating the signal in this band to extract the defect frequency. The band is selected where the signal to noise ratio is high (often determined by spectrum comparison between the good and faulty conditions). In recent developments, the use of spectral kurtosis (SK), the *Kurtogram* [4] and the *Protrugram* [9] has been proposed as a means of selecting the best band. The authors have shown that it is desirable to pre-process the signal prior to the SK analysis to maximize the fault detection. This pre-processing involves pre-whitening, deterministic/discrete signal removal and the removal of the transfer path effect. Pre-whitening using an autoregressive model (AR) [15] helps to equalize the low and high frequency content and enhance the impulsive part of the signal. The separation of deterministic and random signals [18] where order tracking, discrete/random separation or cepstrum technique could be used. Finally the minimum entropy deconvolution (MED) [10] was used to enhance the impulsiveness and remove the effect of the transfer path. A comprehensive tutorial on a number of the start of art techniques has been published recently by Antoni and Randall [19].

In this paper the packaging of the processing algorithms developed by the authors was implemented using MATLAB®. The developed software is interactive screen driven, which promotes the user to insert a number of parameters. There are two main phases of processing. The first phase involves plotting the time and frequency content of the signal for inspection by the analyst as well as a full band envelope spectrum (using the Hilbert transform) of the whitened signal. This phase gives a quick yet an effective, efficient way of inspecting the envelope spectrum for possible faults. The second phase involves removing the deterministic part of the signal and using the semi-automated approach (AR-MED-SK) earlier developed and discussed in [5].

The paper is organized as follows: after this introductory part, the two-phase handling approach is presented in section 2. Section 3 discusses and presents the processing of a helicopter gearbox case with an inner race fault. Finally section 4 presents the discussion and conclusions.

Algorithm and processing

Surveillance and Diagnosis

Time and Power Spectral Density

Vibration signal analysis should start by inspecting the time domain signal and observe any periodic components/events and impact events (high frequency content). This can be aided by plotting both the time domain signal along with the tachometer (if available). This is quite useful in general to give a sense of periodic components, modulations. It also provides a sense of what is being transformed into the frequency domain or processed later.

It is highly recommended next to Inspect the power spectral density of the signal and observe its contents. A logarithmic/dB scaled spectrum is preferred as a linear spectrum will in general show only high amplitude components, but much of the useful information will be hidden. As for the resolution, a coarse resolution will give an idea about the transfer function and resonances in the system. A finer resolution is required to observe the harmonic and side band patterns and families. Harmonic cursors are a good practice especially if they are fine-tuned to capture the different existing families. These families would be the shaft harmonics/synchronous components, gear mesh frequencies, blade pass frequencies, electrical components, etc. The sideband families around the harmonics will give an idea about the modulations occurring in the system. Usually there are two types of modulations, namely an amplitude modulation and a phase/frequency modulation. An example of an amplitude modulation is the case of rolling element bearing faults, while an example of phase modulation is the case of gears. The inspection of the power spectral density is quite advantageous; in particular when signals are captured using a low sampling frequency [20].

Pre-whitening/signal differencing for full frequency bandwidth envelope analysis

Pre-whitening for rolling element bearings was initially brought to attention by Sawalhi and Randall [21]. The main use then was to solve an anomaly in spectral kurtosis and was achieved by using the residual of an autoregressive model of an order *p*. The model order (*p*) was selected based on maximizing the kurtosis of the residual signal. Recently, pre-whitening has been realized by a much simpler approach through dividing the Fourier transformed spectrum by its absolute value and transforming back to the time domain; thus giving a uniform spectrum weighting [15].

This approach means that impulsive frequency bands dominate the time signals and an envelope analysis can be carried out on the full frequency bandwidth. This simple approach means that there is no need to search for an optimum frequency band for envelope analysis, and has the advantage of performing the envelope analysis over the full frequency bandwidth. Another simple means to perform full frequency bandwidth envelope analysis can also be facilitated by differentiating the raw measured vibration signal (possibly three or four times), taking its absolute value and then low pass filtering it by the aid of a smoothing filter before transforming that into the frequency domain. This approach has been recently proposed in [22], requires very minimal parameters to be set and is based on signal differencing which has been recently discussed in [7, 15] for enhancing fault detection in rolling element bearings. A comparison between the pre-whitening approach and the differencing approach is presented in the experimental section. These are compared to the SK selective approach explained next.

Order tracking/Time Synchronous averaging (TSA) and discrete random separation (DRS)

Order tracking [23], as the name suggests, is to track the orders/multiples of the shaft/rotor speed. The ultimate aim of order tracking is to remove the speed fluctuations from the signal by mapping the signal into the angular domain and maintaining a strictly constant number of samples per revolution. Order tracking provides the analyst with a time synchronous averaged signal (TSA), which when subtracted from the resampled signal gives a residual signal. The residual for rolling element bearing fault detection is targeted as it contains the information about the defect frequencies. In the case of a gearbox with multiple shafts, this process has to be repeated for each shaft to enable removal of the synchronous components for each shaft. Recently a more selective and targeted approach for removing the discrete components without the need for a tachometer signal, using cepstrum editing, has been proposed [24].

Discrete/random separation (DRS) [25] is an efficient way of separating discrete frequency signals from others. This is made possible by producing a linear transfer function (using FFT methods) between the signal and a delayed version of it. This results in principle in a value of 1 where there are discrete frequencies and zero otherwise. The amplitude of this transfer function is employed to filter out the discrete frequency components (efficient FFT methods) and produces the random part by subtraction. In order to generate the linear transfer function and implement the DRS, the analyst has to select a suitable time delay and decide on the filter length. The minimal filter length should be inversely proportional to the minimal frequency spacing between two discrete components in the power spectrum, which are to be enhanced independently. The minimal time delay must be longer than the autocorrelation length (memory) of the random signal to be filtered out. In [20] it was shown that when the frequency range of the signal is limited DRS can give an undesirable effect by removing the low harmonics of bearing related frequencies from the spectrum. This is because when the frequency range is limited, only one or two harmonics of the impulse train are included and are not sufficiently smeared by the random spacing variation. They appear as discrete components in the low frequency region and the defect signature will be close to sinusoidal, thus non-impulsive and no longer detectable using envelope analysis. A review of a number of separation techniques is given in ref [18].

SK analysis (AR-MED-SK)

Spectral kurtosis analysis (SK) for rolling element bearings was introduced by Antoni [2]. The *kurtogram* [4], which is a more advanced SK analysis for optimum selection of the best bandwidth analysis has been widely accepted and used for diagnosing faults in rolling element bearings.

Sawalhi and Randall [21] showed that pre-whitening using the residual of an autoregressive model (AR) enhances the performance of the spectral kurtosis by providing a uniform presentation of frequencies and thus enhancing the impulsive components in the signal. Sawalhi et al [10] further showed that if this is followed by a deconvolution filtration, to further enhance the impulsiveness of the signal and remove the effect of the transfer path (Minimum entropy deconvolution (MED)), the result will be further and more clearly enhanced. This was initially applied to enhance the fault detection for an inner race fault from a high speed test rig, but was later used on wind turbine and bladed fan signals to reduce the effects of the transfer path [26]. Finally the *wavelet kurtogram* [27], which is based on the complex Morlet wavelet, was proposed as an alternative to the *kurtogram*. A number of cases [28] were presented to show the effectiveness and efficiency of the AR-MED-SK algorithm in detecting localized faults in rolling element bearings.

Experimental Results

DSTO Helicopter Gearbox

The Bell 206-transmission system (helicopter gearbox) is shown in Figure 1. This is a two stage reduction gearbox, which has a defective planetary bearing (inner race and roller defects). The "Bell 206" data contains a tachometer signal (taken from the high speed shaft) and a front accelerometer signal on the ring. The sampling frequency is 51200 Hz. All the necessary information about this case is discussed in [5].

The ball pass frequency of the inner race was calculated as (BPFI =117.2 Hz) and the fundamental train frequency (FTF=9.8 Hz). Other frequencies of interest are the carrier speed (5.73 Hz), the planet pass frequency (3×5.73) and the epicyclic mesh frequency (99×5.73 Hz).

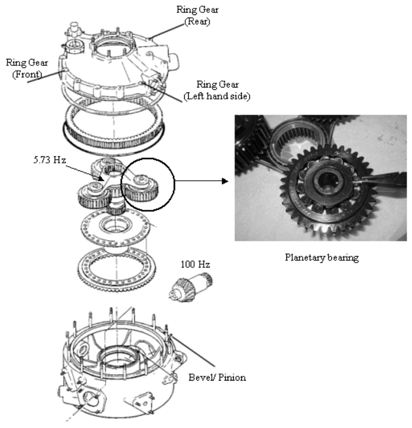

Figure 1 DSTO Bell 206 planetary gearbox

Figure 2 shows the raw time domain signal and its frequency content using the Welch estimate with a Hanning window of 8192 and 50% overlap (6.35 Hz/line). The surveillance using the pre-whitening approach (full bandwidth envelope analysis of the pre-whitened signal) is shown in figure 3 and further zoomed in and expanded in figure 4. Figures 3 and 4 show the clear presence of the BPFI (117.2 Hz) and the FTF (9.8 Hz) in the squared envelope and can on their own give a clear diagnosis of the fault. This is also clearly reflected in the filtered signal. Note also the presence of the carrier speed and the strong presence of the planet pass frequency.

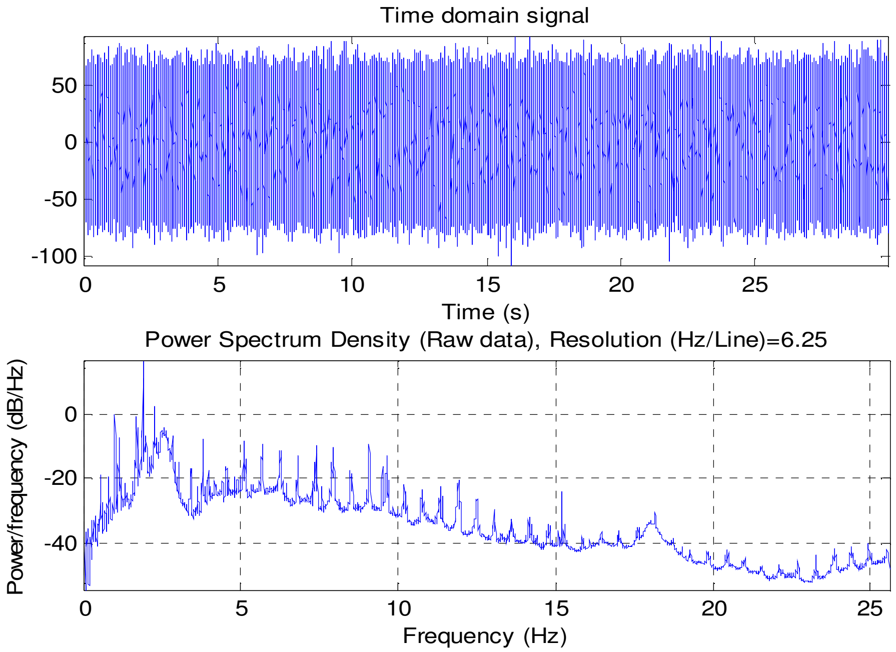

Figure 2 Bell 206-3p front accelerometer data. Top: Raw data . Bottom: Power spectral density

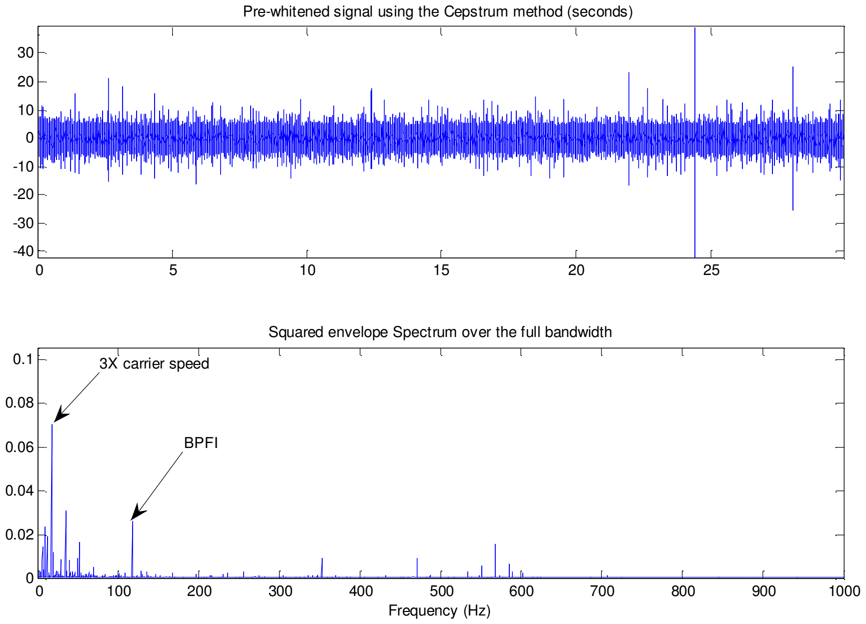

Figure 3 Bell 206 Cepstrum Pre-whitened signal. Bottom: Squared envelope analysis of the top signal

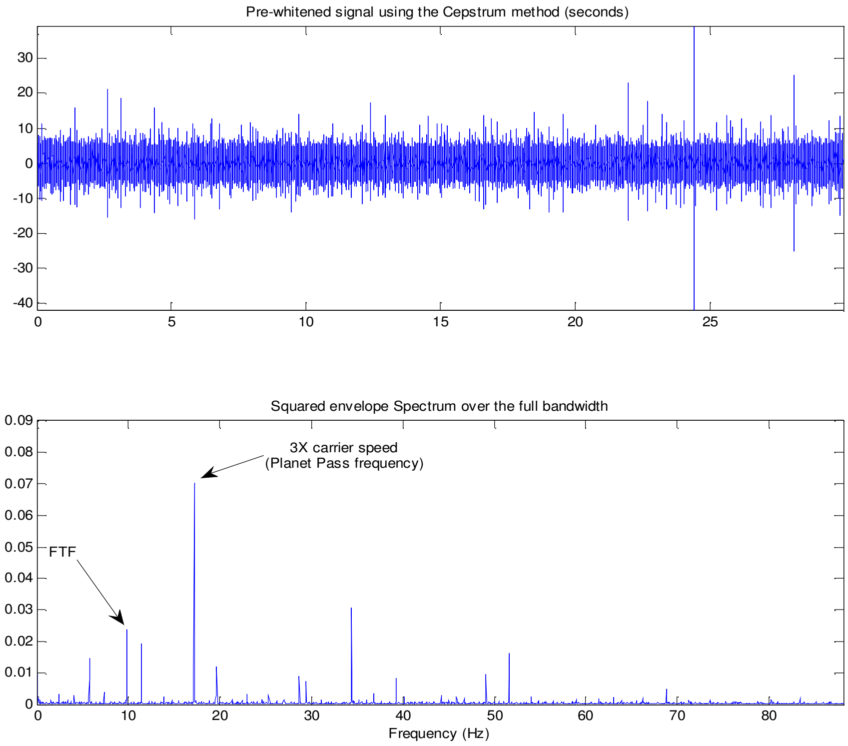

Figure 4 Bell 206-3p Cepstrum Pre-whitened signal. Bottom: Squared envelope analysis of the top signal. Zoomed in [0-80 Hz) to show the presence of the FTF.

The result from the simple differencing (4th derivative) and smoothing (10 samples) approach presented in [22] is presented in figure 5. The BPFI and the FTF are obvious in the figure.

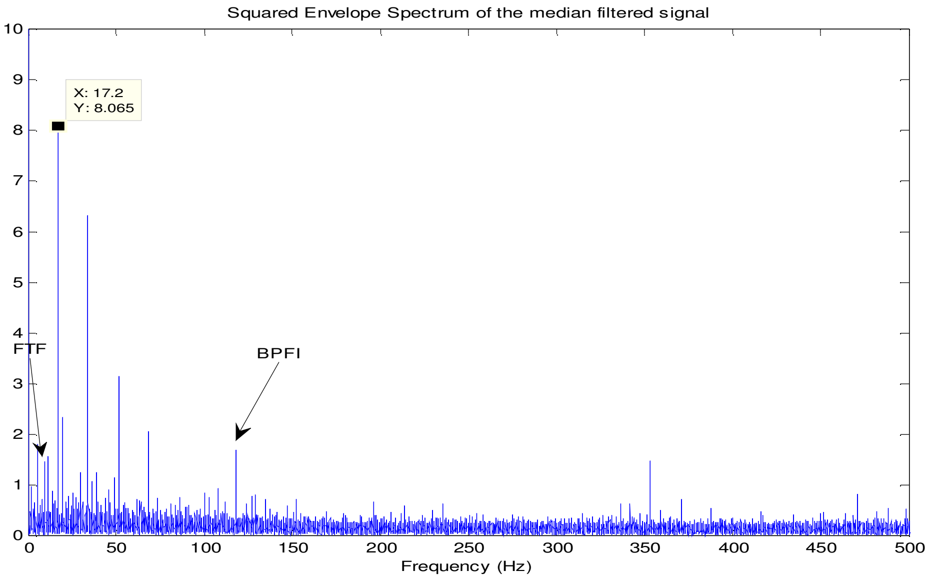

Figure 5 The squared envelope spectrum obtained by signal differencing and smoothing

The AR-MED-SK analysis after order tracking and the removal of harmonics of the shafts using DR is shown in figures 6 and 7. Figure 6 shows the wavelet kurtogram and indicates that the best filter to maximize the kurtosis has a centre 197 orders (19.7 kHz) and a bandwidth of 12.3 orders (1.23 kHz). The filtration using this filter gives figure 7 with clear indications as to the source of the faults. This is further illustrated in figure 8.

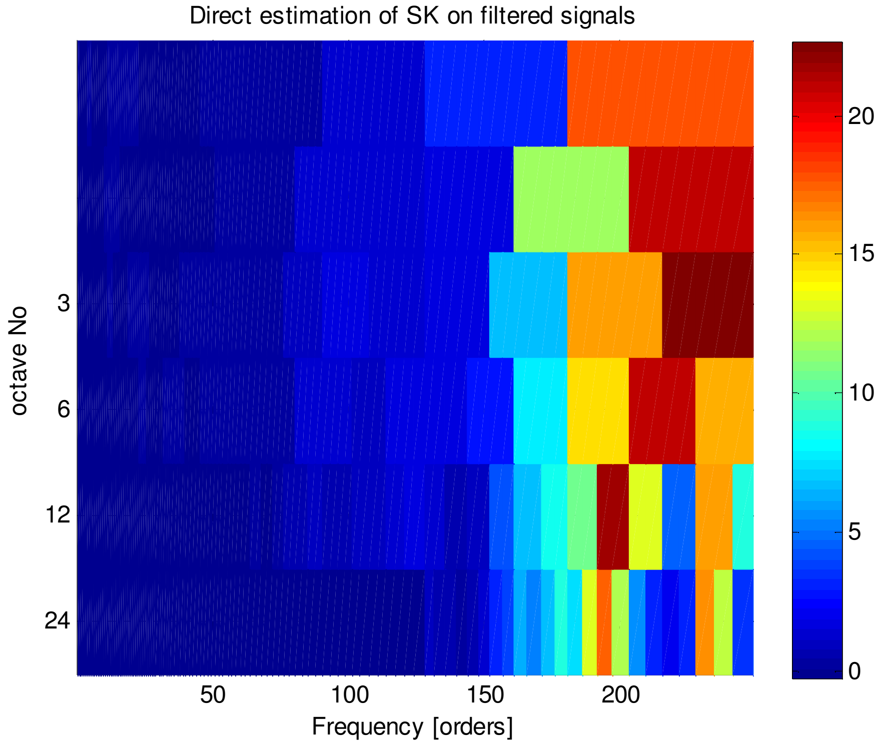

Figure 6 Bell 206 Wavelet Kurtogram (order tracking- DRS- MED -AR whitening)

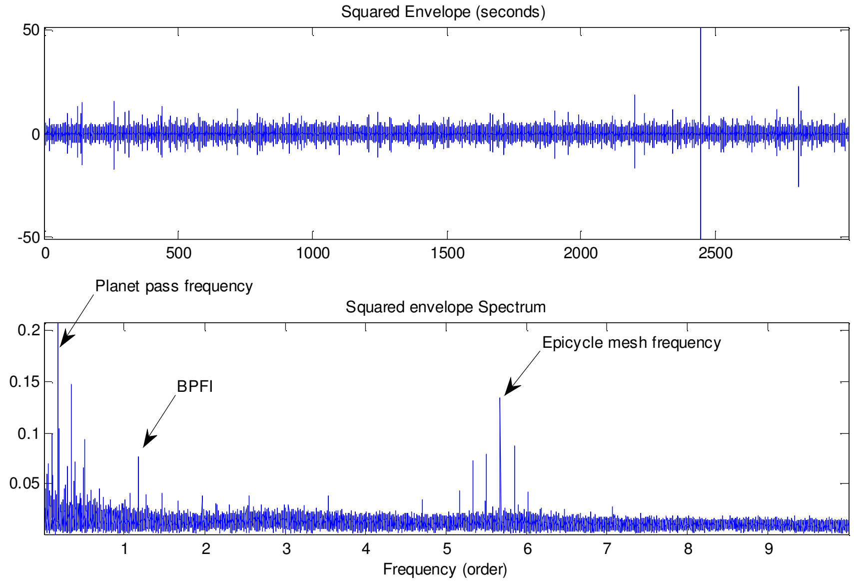

Figure 7 Bell 206 3-p Squared envelope spectrum (order tracking- DRS- AR whitening)

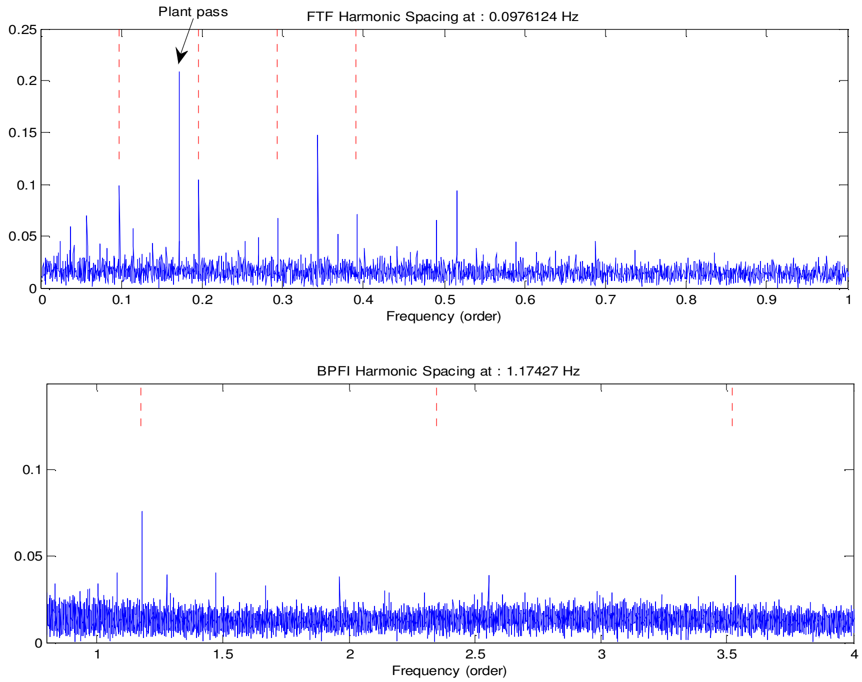

Figure 8 Further illustration (zoom in analysis). Top (0-1) showing the FTF harmonics. Bottom: (1-4) showing the BPFI harmonics

Discussions and Conclusions

This paper presents a summary of a number of innovative processing approaches for detecting localized faults in rolling element bearings. The algorithms have been placed into two phases. A simple phase (phase 1), which provides the envelope spectrum of the signal over the full frequency bandwidth and a detailed phase, which has a number of processing stages and provides the envelope spectrum over a selected bandwidth. A comparison between figures 3, 5 (phase 1) and figure 7 (phase 2) shows that the simple processing of the signal and the envelope spectrum over the full frequency bandwidth (figures 3 and 5: phase 1) has the main frequency content compared to the envelope spectrum over the selective bandwidth after a number of processing stages (figure 7: phase 2). Phase 1 is very simple and requires less parameters to use compared to phase 2 and thus it is very advantageous to use it for surveillance and diagnosis before attempting the more detailed approach (phase 2).

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