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The computation of the squared envelope spectrum (SES) on vibration data collected from a rotating machine is a common tool used to diagnose a defective bearing. To enhance the diagnosis, pre-processing methods have to be implemented, before the evaluation of the SES, to suppress vibrations from sources other than the bearings. Conventionally suppression of the spurious components is achieved by exploiting either their separation in the frequency domain or the contrast between deterministic signals and the random vibration components from a defective bearing. Recently the phase editing method (PE) was used to exploit another characteristic of the vibration signal to improve diagnosis in stationary speed conditions. PE caters to, and exploits the scenario where vibrations from a defective bearing have small amplitude compared to vibrations from other components, effectively thresholding the amplitudes of the spectral components of a signal. In this paper the PE method is applied analytically and experimentally to a broader class of machinery, encompassing machines with varying speed conditions. It is demonstrated that the separation of the bearing component and masking components is equally effective in the non-stationary case.

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Phase editing to enhance bearing fault detection in variable speed condition

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Abstract

The computation of the squared envelope spectrum (SES) on vibration data collected from a rotating machine is a common tool used to diagnose a defective bearing. To enhance the diagnosis, pre-processing methods have to be implemented, before the evaluation of the SES, to suppress vibrations from sources other than the bearings. Conventionally suppression of the spurious components is achieved by exploiting either their separation in the frequency domain or the contrast between deterministic signals and the random vibration components from a defective bearing. Recently the phase editing method (PE) was used to exploit another characteristic of the vibration signal to improve diagnosis in stationary speed conditions. PE caters to, and exploits the scenario where vibrations from a defective bearing have small amplitude compared to vibrations from other components, effectively thresholding the amplitudes of the spectral components of a signal. In this paper the PE method is applied analytically and experimentally to a broader class of machinery, encompassing machines with varying speed conditions. It is demonstrated that the separation of the bearing component and masking components is equally effective in the non-stationary case.

1 Introduction

The diagnosis of a defective bearing on a rotating machinery can be carried out by analysing vibration data. A defective bearing produces a series of impacts throughout its rotation and each impact generates a burst of energy which propagates in the machine, from the bearing to the vibration transducer. The detection of such impacts is the signature of a defective bearing and is commonly realised in the spectral domain. However the occurrence time of the impacts is not periodic, even for a machine operating at constant speed, but is characterised by a random jitter. For this reason it is recognised that the squared envelope spectrum (SES) has to be preferred to spectral

analysis for bearing diagnosis.[1] A problem with the SES is that vibration transducers gather vibrations from all the components of the machinery, including for example the gears, and therefore the SES presents several peaks and the results are difficult to analyse. Several envelope pre-processing techniques have been introduced to suppress unwanted components. One approach exploits the separation between the high resonant frequency of the impacts versus the lower gear meshing frequencies. Common methods include a high pass filter, a kurtosis maximising band-pass filter[2] or the calculation of the residual after time synchronous averaging (TSA), corresponding to a comb filter.[3] A different approach exploits the statistical difference between the deterministic components from gears versus the random component from the bearing, as in the discrete random separation (DRS)[4] and the cepstrum pre-whitening.[5]

Recently Barbini et al.[6] proposed phase editing (PE) as a novel method to enhance the vibration component from a defective bearing, as a modification of a speech denoising algorithm.[7] PE uses the fact that the component from the bearing has a small amplitude compared to the masking components. It consists of a threshold in the amplitude of the spectral components, independent of their frequency or statistical properties: components with a spectral amplitude above a threshold are suppressed. Therefore the remaining signal contains the weak vibration from the defective bearing.

In this paper, PE is applied to vibration signals from machinery operating at varying speed, in contrast to the stationary signals analysed in previous work.[6] It is shown that PE is effective regardless of the non-stationary speed, as long as the signal exhibits separation in spectral amplitude between the unwanted components and the bearing component. The paper is organised as follows: section 1 presents the proposed methodology, section 2 shows a numerical example while section 3 presents results from the analysis of real operational data. Finally conclusions are presented in section 4.

2   Methods

For the vibration signal $x[k]$ with Fourier transform (FT) $\hat{x}[l]$ where $k, l \in \{0, \cdots, N-1\}$ are the indexes of time and frequency, the phase editing (PE) method consists of the calculation of the residual with its denoised version $p[k]$. The denoised signal is given by

$$p[k] = Real \left\{ IFT \left\{ |\hat{x}[l]| \, e^{\angle \hat{x}_L[l]} \right\} \right\} \tag{1}$$

where $\hat{x}_L[l] = \hat{x}[l] + L[l]$ and

$$L[l] = \begin{cases} +\lambda[l] & 0 \le l < N/2 \\ -\lambda[N-1-l] & N/2 \le l \le N-1. \end{cases} \tag{2}$$

For each frequency index n PE returns a sinusoidal component:[6]

$$x_{pe,n}[k] = x_n[k] - Re\{p_n[k]\} = K[n]\frac{2|\hat{x}[n]|}{N}cos\left(\frac{2\pi}{N}nk + \angle\hat{x}[n] + \theta[n]\right) \qquad (3)$$

The differences between the original sinusoid $x_n[k]$ and $x_{pe,n}[k]$ are the terms $K[n]$ and $\theta[n]$. In particular the term $K[n]$ vanishes[6] for $|\hat{x}[n]| \gg |L[n]|$ while is unitary for $|\hat{x}[n]| \ll |L[n]|$. Therefore PE suppresses all the spectral components with amplitude greater than a threshold, independently from the frequency index. The value of the threshold is defined by $\lambda[l]$ which is a function selected by the user and in the simplest case is a constant. However the threshold can also be chosen to suppress entire frequency bands of the signal as in a common filter.

Equation 3 is valid also in the case considered in this paper of a machine operating at varying speed and PE can be applied directly on the time non-stationary signal provided that $\lambda[l]$ is chosen as

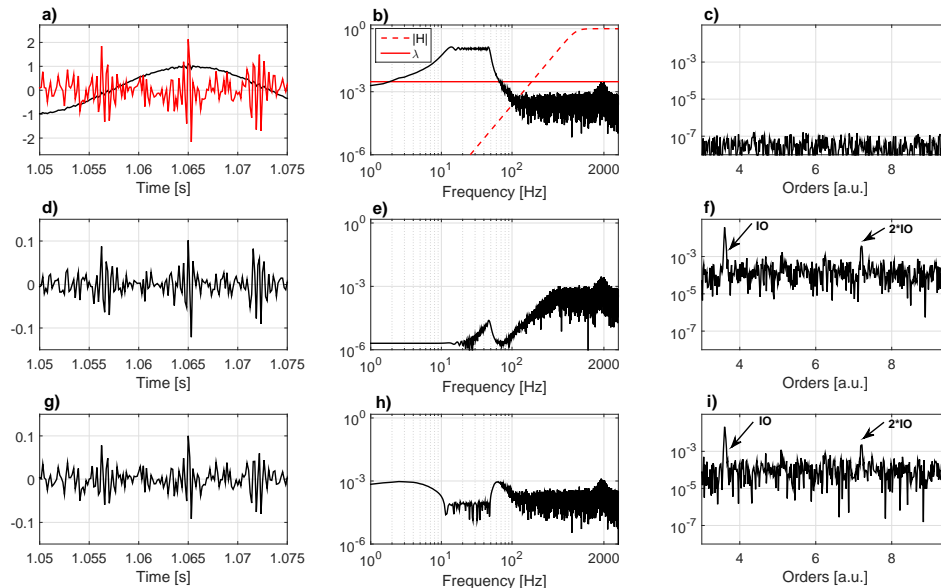$$\hat{x}_b[l] \ll \lambda[l] \ll \hat{x}_g[l] \qquad (4)$$

Figure 1: Numerical simulation. First row the original signal, second row the signal after high pass filtering, third row the signal after PE. First column time domain, second column amplitude spectra, third column SES after OT.

Where $\hat{x}_b[l]$ and $\hat{x}_g[l]$ are the spectral amplitudes of the non-stationary vibrations from the bearing and from the gears. The approach of enhancing the bearing component directly from the time non-stationary signal avoids problems with the suppression of masking components after order tracking (OT).[8] Recently this approach has been implemented using classical signal separation techniques such as band-pass filtering,[9] spectral kurtosis and cepstral pre-whitening,[10] while it is proposed using PE for the first time in this paper. Only after the enhancement of the bearing components the signal is subjected to OT and the SES is evaluated in the order domain. The envelope is calculated on the full band analytical representation of the signal and the SES is normalised as $S\tilde{E}S[l] = SES[l]/SES[0]$, the tilde is omitted in the following. The selection of the best threshold is achieved maximising the peaks in the SES at the bearing characteristic fault orders by user inspection.

Therefore the proposed approach comprises in total three steps: PE the time non-stationary signal, re-sample the signal at constant angular increments using a tachometer signal (OT), evaluate the SES in order domain.

3   Numerical investigation

The proposed methodology is applied on a time non-stationary signal comprising a masking component, a sequence of impacts and background noise. The masking component is a chirp with frequency increasing linearly from $10\ Hz$ to $50\ Hz$. The sequence of impacts has occurrence time at 3.57 orders of the chirp instantaneous frequency and a random jitter of 1%, and the resonant frequency is in the band $1700-2200\ Hz$. Total length of the signal is 20 seconds and sampling frequency $6.4\ kHz$. The amplitude of the chirp is ten times that of the sequence of impacts. Figure 1(a) shows the signal in time domain, in black the simulated signal comprising the three components, while in red the sequence of noisy impacts multiplied by a factor 10. Figure 1(b) shows the amplitude spectrum of the signal, with the disturbing chirp and the peak around the resonant frequency representing the random and time non-stationary sequence of impacts. Fig. 1(c) shows the normalised SES of the full band signal in the order domain after OT. As expected no peak at the impacts order (IO) is seen. In the simulated signal the resonant frequency band and the varying frequency of the chirp are separated, therefore a classical high-frequency filter is sufficient for the enhancement of the impacts. As an example this is done with a fourth order Butterworth filter of cut-off frequency $400\ Hz$. The amplitude response $|H[l]|$ of the filter is shown with the red dashed line in Fig. 1(b). Figure 1(d) shows the filtered signal in time domain, and Fig. 1(e-f) the amplitude spectrum and the SES after OT. The masking chirp is suppressed and the SES displays peaks at the IO and harmonic. We address the question

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whether similar results are achievable using the PE method.

Figure 1(b) displays the characteristic which is the key point for the application of PE: the separation in spectral amplitude between the disturbing components and the impacts for the time non-stationary signal. Therefore the enhancement of the impacts can be achieved by a threshold in the spectral amplitudes and PE results are effective also for machinery operating at varying speed. In particular for the simulated signal it is sufficient to use a constant value for λ, as shown in Fig. 1(b) with the red line. The resulting phase edited signal is presented in Fig. 1(g-h-i) with impacts revealed in the SES at the IO and its harmonics. The amplitude spectrum of the PE signal, Fig. 1(h), displays the suppression of the spectral components above the selected threshold. Comparison with the high frequency filtered signal shows a good agreement as well
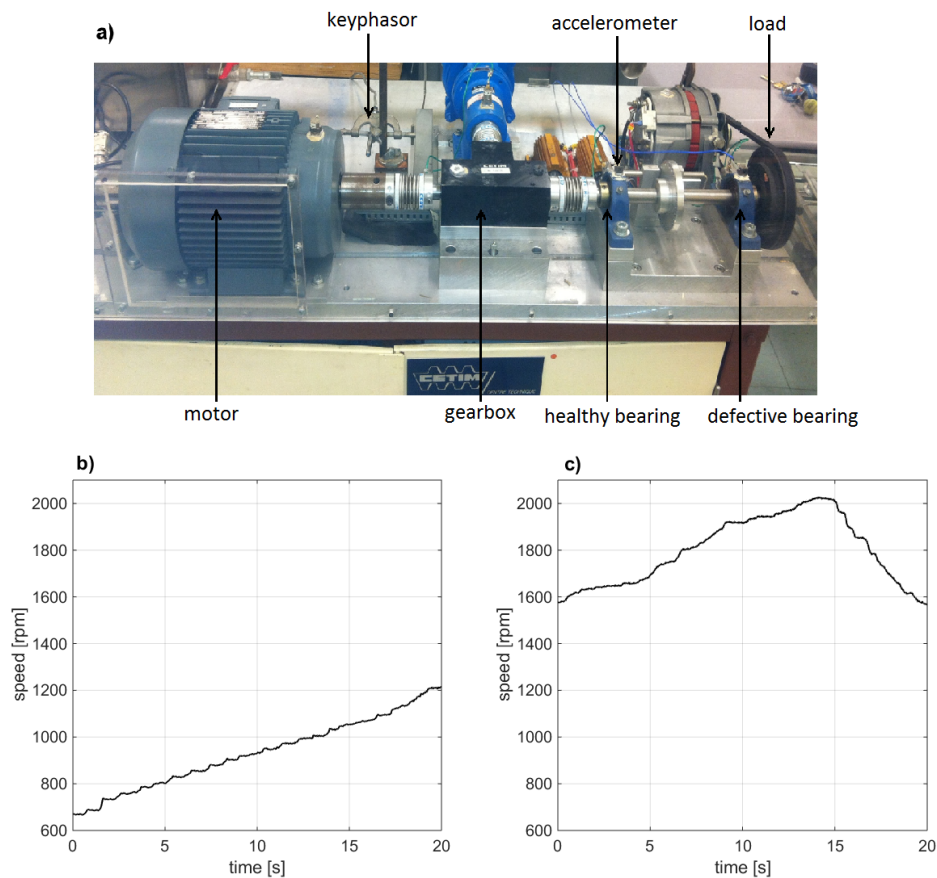

Figure 2: Photograph of the test rig (a). Run-up speed profile (b). Run-up and rundown speed profile (c).

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as comparison with the noisy impacts in time domain, Fig. 1(a) in red.

4 Experimental investigation

4.1 Test rig & data sets

A photograph of the test rig is presented in Fig. 2(a). It consists of a variable speed asynchronous electric motor, a parallel spur-gear of ratio one, and an alternator applying a constant load. The shaft rotational speed is measured by a keyphasor mounted close to the motor. Two rolling elements bearings support the output shaft and the one far from the gearbox has an outer race defect with expected repetition of 3.04 orders (BPOO). An accelerometer mounted on the casing of the bearing close the gearbox is used as a vibration transducer.

Two varying speed profiles are analysed in this paper as shown in Fig. 2(b-c). The first one is a run-up profile with a doubling of the rpm, the second one a run-up and run-
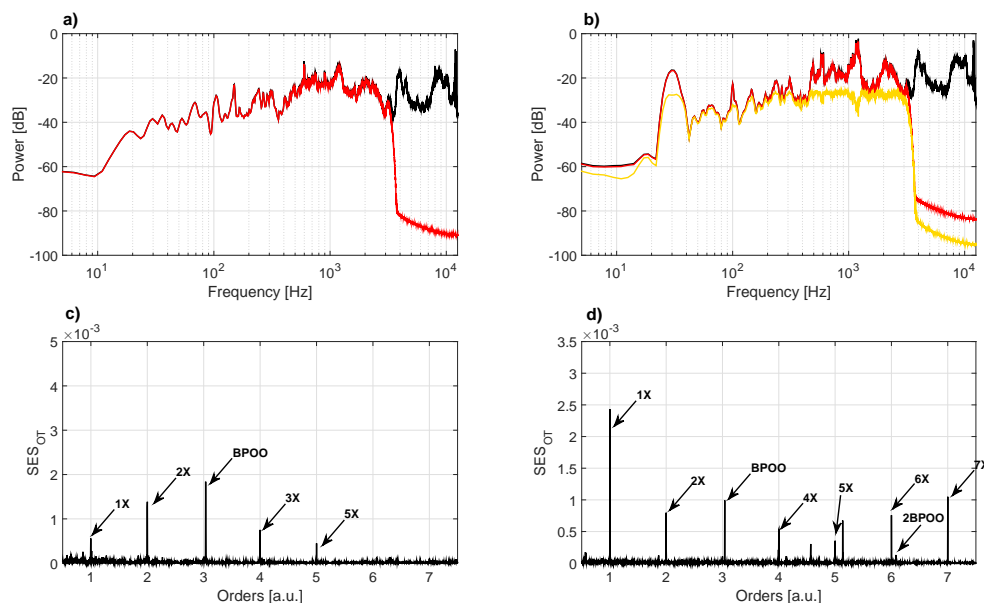

Figure 3: Welch power spectra for the run-up speed profile (a) and run-up run-down speed profile (b). In black raw signal and in red PE signal with α_1, in yellow PE signal with α_2. Squared envelope spectrum after OT the raw signals, run-up (c) run-up run-down (d)

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down of the motor. The recorded data sets are $20\ s$ long and are sampled at $25.6\ kHz$. The Welch power spectra of the data sets are shown respectively in Fig. 3(a-b), black line, with Hamming window of 10000 samples and 50% overlapping.

4.2 Results

The speed variations for both cases are strong enough to smear out spectral peaks and the SES computed directly on the time non-stationary signals does not allow diagnosis. On the contrary after OT peaks appear in the SES as shown in Figure 3(c-d). Peaks at order 1 and harmonics correspond to vibrations from the gearbox while at orders 3.04 and harmonics correspond to impacts from the defective bearing. In both cases despite the peak at the characteristic defective bearing frequency, the diagnosis could be misleading due to the presence of the vibrations from the gearbox, particularly for the closeness of the BPOO and 3X. Therefore PE is applied for the suppression of the unwanted peaks.

For the analysed data the resonant frequency of the bearing appears in a band around $2000\ kHz$ while vibrations from the gears occur at higher frequencies.[11] For this reason a logistic function was chosen as the threshold for PE, akin to low pass filtering:

$$\lambda[l] = \alpha \left(1 - \frac{1}{1 + e^{-\beta(v[l]-1)}} \right) \tag{5}$$

where α is the value above which the spectral amplitudes are suppressed and β controls the steepness of the curve. The vector $v[l]$ linearly increases from 0 to r, where r selects the cutoff frequency. Substitution of Eq. 5 in Eq. 2 gives the anti-symmetric threshold function $L[l]$ as shown in Fig. 4, with $r = 4$ and $\beta = 20$.

Firstly the high frequency components are suppressed to check whether the detection is enhanced. In Eq. 5 parameters are chosen as $\alpha_1 = max\left\{|\hat{x}[l]|\right\}$ and $r = 4$ so that
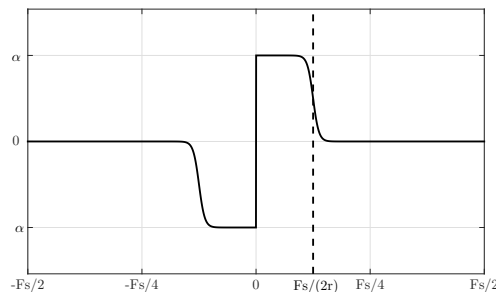

Figure 4: Threshold function $L[l]$ for $\lambda[l]$ with $\beta = 20$ and $r = 4$.

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PE acts similarly to a low pass filter with cut off frequency of $3200Hz$. Figure 3(a-b) in red shows the Welch power spectra of the time non-stationary PE edited signals. As expected the low frequency amplitudes coincide with the original, in black. The edited signals are subjected to OT and the SES are computed. The corresponding SES are shown in figure 3(a-b) respectively for the run-up case and the run-up run-down case. The suppression of the high frequency components removes all the unwanted peaks from the SES for the first speed profile, compared to Figure 3(c). On the other hand for the second speed profile, peaks are still present other than the BPOO and its harmonics. These peaks can be suppressed by exploiting the separation in amplitude between gears and bearing components. The value of the parameter α in Eq. 5 is decreased so that PE implements simultaneously a threshold in the spectral amplitudes and a low pass filter. Figure 3(c) in yellow shows the Welch power spectrum of the resulting PE signal with $\alpha_2 = 0.07 \ max \{|\hat{x}[l]|\}$. The SES computed after performing OT on the PE signal is shown in Fig. 5(c). The unwanted peaks are removed, compared to Figure 3(d), leaving only the BPOO and its harmonic.
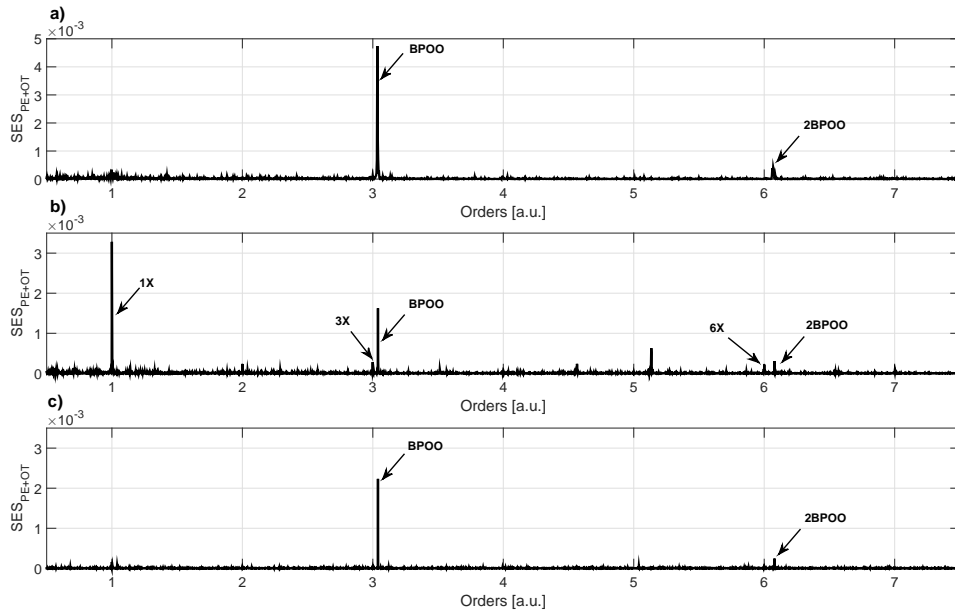

Figure 5: Squared envelope spectrum after PE with α_1 followed by OT, for run-up (a) and run-up run-down speed profile (b). PE with α_2 for run-up run-down (c).

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5   Conclusion

This paper tested the effectiveness of phase editing (PE) as an envelope pre-processing method to enhance the diagnosis of defective bearings from a machine operating in non-stationary speed conditions. The procedure consists of applying PE to the time non-stationary signal, order tracking the edited signal, and finally computing the SES. The performance was tested both on a simulated signal and on experimental data.
PE implements a threshold on the amplitude of spectral components. It was shown that if there is separation between spectral amplitudes, PE works irrespective of the stationary/non-stationary properties of the signal. It was also shown that the threshold function used for the PE can be selected to obtain a combination of frequency filtering and suppression of components with higher spectral amplitudes.

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