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# Application of cepstrum prewhitening on non-stationary signals

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**Abstract** In the field of vibration based condition monitoring a trusted symptom of a defective bearing is the observation of peaks, at characteristic frequencies, in the squared envelope spectrum (SES). If a machine is operating in a varying speed regime the SES is computed on the order tracked signal, i.e. the signal resampled at constant angular increments, and the SES can still be used for diagnostic. Despite its versatility a common problem with the SES is that peaks from other sources of vibrations, as for instance gears, can prevent the diagnosis of a defective bearing. Therefore pre-processing techniques are applied to the vibrational signal before the computation of the SES to enhance the signal from the bearings. Among these techniques cepstral prewhitening (CPW) has gained much attention offering a remarkable capability of eliminating, in a blind way, both harmonics and modulation side-bands of the unwanted components. In the case of a varying speed regime the usual procedure consists of three steps: order track the signal, calculate the CPW, evaluate the SES. In this paper on the contrary the CPW is applied before the step of order tracking; therefore the proposed approach is: CPW the raw time signal, order tracking, evaluation of the SES. The remarkable observation is that for this approach the cepstrum does not present peaks at characteristic quefrencies, being the raw signal acquired in a varying speed regime. However this paper shows by means of numerical simulations and analysis of experimental data, that with the proposed methodology the masking components coming from the gears are suppressed and the signal from the defective bearing is enhanced.

**Keywords** bearing diagnosis · non stationary conditions · cepstrum prewhitening · order tracking

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## 1 Introduction

In a faulty bearing an impact occurs every time a rolling element hits a defect in the raceway or a defective rolling element hits the raceway. The detection of the shock generating from each impact is often a challenge due to the presence of other sources of vibrations, in particular gears, masking the presence of the defect. Therefore signal pre-processing methods have to be implemented before the evaluation of the widely established diagnostic technique of the squared envelope spectrum (SES). Cepstrum editing (CE) has been proposed as an efficient method for the suppression of gear components from a vibrational signal [1] and it performs well when compared with other techniques [2]. The working principle uses the fact that vibrations from gears result in a series of peaks at constant distances in the frequency spectrum. Therefore all these peaks can be eliminated suppressing, by means of a lifter, the corresponding peak in the cepstrum. Sawalhi et al. [3] introduce the cepstral pre-whitening (CPW) as a further application of the cepstrum for the removal of all the discrete components from the spectrum, both vibrations from the gears and resonance effects.
When machines are operating at varying speed peaks corresponding to the vibrations from gears are smeared in the frequency domain and the cepstrum does not present significant peaks. In such cases the CPW is implemented in the order domain, after the operation of order tracking (OT)[4,5]. However changing to a rotation angle basis smears the resonance frequencies excited by the impacts from the faulty bearing . Recently [6,7] has been suggested to enhance the signal from the bearing directly in the time domain and to implement the OT only after this operation. Borghesani et al. [6] propose to band-pass filter the non stationary signal and Randall et al. [7] compare the performances of the application of three common techniques:spectral kurtosis for band selection, minimum entropy deconvolution and an exponential lifter. The paper follows these methodologies and shows that CPW can be applied directly on time vibrational signals from machinery operating at varying speed conditions, before the operation of OT. The paper is organised as follows: section 3 presents the proposed method, section 2 evaluates its performance on a numerical simulation and section 3 on experimental data sets. Conclusions are presented in the final section.

## 2 Methods

In this paper two techniques will be used to pre-process, before the computation of the squared envelope spectrum (SES), vibrational signals from machines operating at varying speed. The two techniques are cepstral pre-whitening (CPW) and order tracking (OT). CPW can be implemented without the computation of the cepstrum [4], using only the Fourier transform:

$$x_{cpw} = IFT\left[\frac{FT\left(x\right)}{\left|FT\left(x\right)\right|}\right] \tag{1}$$

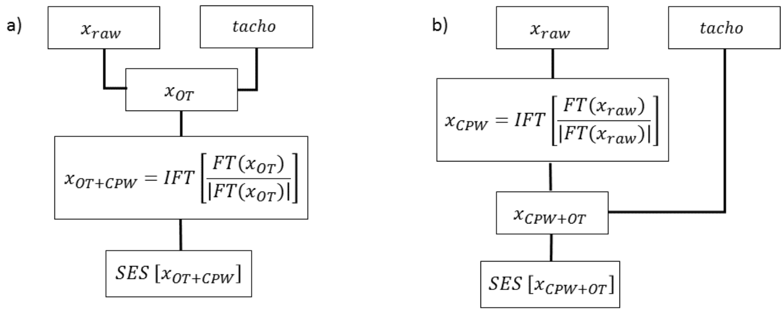


Fig. 1: Schemes of the two processing methods

This operation is equivalent to setting to zero the real cepstrum and recombine it, in the frequency domain, with the phase of the original signal. The result is a white signal with a flat spectrum of amplitude one. OT is applied in the time domain implementing a digital re-sampling of the signal synchronously with the shaft rotation speed. In this paper the shaft rotation speed is considered to be provided by a tachometer. The envelope for the computation of the SES is calculated as the absolute value of the analytical representation of the full band signal. The SES is normalised by means of the ratio: $\tilde{SES}[l] = SES[l]/SES[0]$. In the following the ˜ will be omitted. The common procedure using such techniques consists of a first step of OT and afterwards CPW the $x_{OT}$ signal [4, 5], as it is shown in Fig. 1(a). However the resonant frequencies excited by the impacts from a faulty bearing are constant or vary more slowly than the operational speed of the machine. OT effectively produces a sequence of impacts equally spaced in the time domain, but the resonant frequencies excited by the impacts will be smeared [6] by the re-sampling. Therefore after OT the dynamic information is lost and the application of CPW may result in unwanted amplification of low signal to noise ratio bands [5].
To address this issue in this paper the CPW is applied directly on the non stationary signal and afterwards the OT is performed. The proposed approach is shown in Fig. 1(b). The central assumption is that the restriction of applying CPW only to signals showing periodic components in a spectrum can be relaxed. Eq. 1 is more generally effective and able for instance to enhance impacts masked by a strong non stationary signal, as shown by a numerical simulation in the next section. This follows from the observation that Eq. 1 is equivalent to what has been called the phase only signal [8] and used in [9] for detection of defects on surfaces.

## 3 Numerical investigation

The numerical simulation consists on the application of CPW to a signal constructed as the superposition of a deterministic non stationary component and a sequence of random impacts. Such signal does not show peaks in the cep-

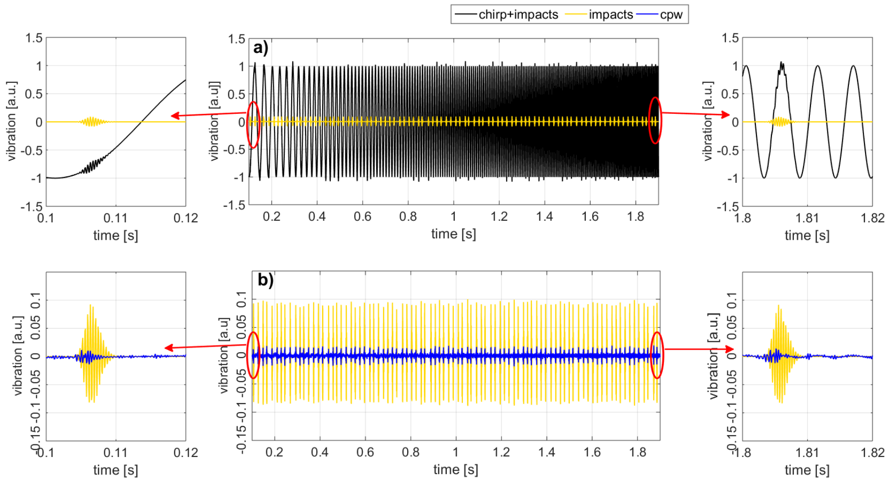


Fig. 2: (a) Simulated non stationary signal. (b) Simulated non stationary signal after CPW. See legend for description of signals.

strum, nevertheless it will be shown that CPW is still capable of enhancing the sequence of impacts. A chirp signal with the frequency increasing linearly from 10 to $200Hz$ and amplitude 1 [a.u.], is used for the deterministic non stationary component. The impacts have mean occurrence frequency of $48.7Hz$ plus a random jitter of 2%, in order to resemble a random component coming from a defective bearing. The resonance frequency is simulated in the band $2200-3000Hz$ and the amplitude of the impacts is 0.1 [a.u.]. The signal is shown in Figure 2(a) in black, the total length is 2 seconds and the sampling frequency is $12.8kHz$, zoomed sections at different times are shown on the left and right sides, in yellow is superimposed only the sequence of impulses. As expected the real cepstrum of the simulated signal has no clear peaks, as shown in Figure 3(a). The real cepstrum is calculated as the inverse Fourier transform of the logarithm of the magnitude of the Fourier transform of the signal. The SES, shown in Figure 3(b), does not present indications of the presence of impulses, being masked by the high energy chirp. The signal after the operation of CPW is shown in blue in Figure 2(b), the chirp is completely removed and the presence of the impacts is highly enhanced, for comparison in yellow it is shown the original sequence of impacts. The SES of the CPW signal is shown in Figure 3(c) where peaks are present at the expected mean occurrence frequency of the impacts and the first harmonic.

## 4 Experimental investigation

This section shows a benchmark comparison between the SES obtained using the proposed approach of Fig. 1(b) and the SES obtained from the usual

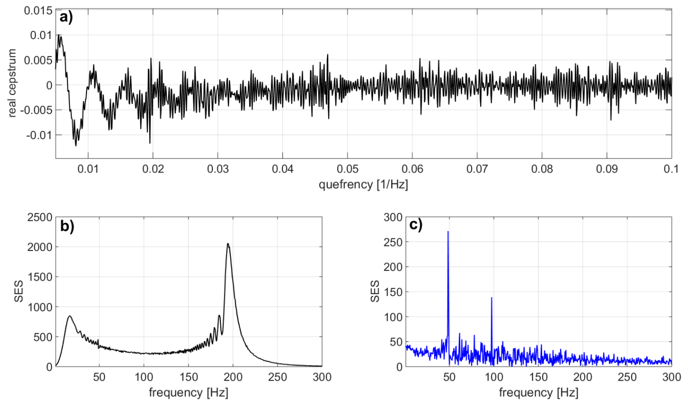


Fig. 3: (a) Real cepstrum of the simulated non stationary signal comprising the two components, (b) corresponding SES. (c) The SES of the CPW signal.

procedure of applying CPW in the order domain Fig. 1(a). The data sets used in this section were provided by the Centre Technique des Industries Mécaniques (CETIM).

## 4.1 Test rig & data sets

Figure 4(a) shows the photograph of the test rig. A variable speed asynchronous electric motor drives the input shaft of a parallel spur-gear of ratio one and 18 teeth, and an alternator applies a constant load. The output shaft is supported by two rolling elements bearings of which the one close to the gearbox is in healthy conditions while the other one has an outer race defect with expected repetition of 3.04 orders (BPOO). An accelerometer mounted on the casing of the healthy bearing is used as a vibration transducer.

Two signals are analysed in this paper: a run-up profile and a randomly varying speed, the lengths of the signals are of 15 seconds and 20 seconds respectively, both are sampled at Fs= 12.8$kHz$. Figures 4(b-c) show the two speed profiles as a function of time: in the run-up the speed is varying approximately of 10 Hz increasing constantly from 25 to 35 Hz, while in the case of random variations the speed changes more drastically for example of approximately 30 Hz in 2.5 seconds. The SES of the run up signal is shown in Fig. 5(a) and for the random speed signal in Fig. 5(b). The speed variations are large in both cases therefore the SES are smeared and no clear peaks are present at the theoretical bearing fault order. The SES after OT the signals are shown in Fig. 5(c-d) and the presence of the defective bearing is revealed, however can be noticed disturbing components among which 1X has the highest energy and 2BPOO is almost masked. The real cepstra of the signals before and after OT are shown in Fig. 5(e) for the run up case and Fig. 5(f) for the random speed

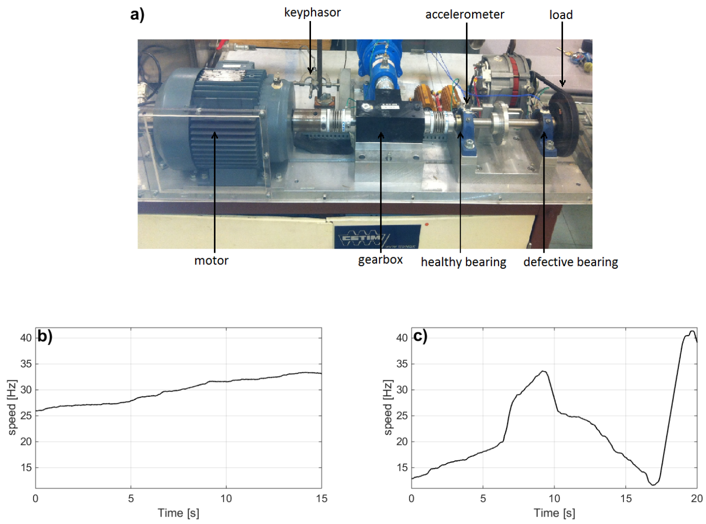


Fig. 4: (a) The photograph of the test rig. (b) The run up speed profile. (c) The randomly varying speed profile

profile. In both cases after the operation of OT, in black, the gear components contribute a periodic spectrum resulting in a cepstrum with peaks separated by 1/X. On the other hand the cepstra for the raw non stationary signals, in blue, do not present peaks.

## 4.2 Results

The aim of the CPW step in the common procedure of Fig. 1(a), is that of removing the disturbing components from the SES of Fig. 5(c-d). After the operation of OT the spectrum shows periodicity contributing the peaks in the cepstra, as shown in Fig. 5(e-f) in black, therefore this is the typical application of cepstral pre-whitening on a non stationary signal [4].
In the method proposed in this paper, as shown in Fig. 1(b), the CPW is applied directly on the time non stationary signals for which the cepstra does not presents peaks at characteristic quefrencies, Fig. 5(e-f) in blue, and the SES Fig. 5(a-b) has smeared peaks. The SES resulting from the two methods are shown in Fig. 6 for the run up case and randomly varying speed respectively, top raw is the OT followed by CPW and bottom raw is CPW followed by OT. The vertical scales are defined, for a comparison, according to the SES of Fig. 5(c-d). The proposed method performs well when compared to the common procedure: the masking components are more suppressed and the peaks at characteristic fault frequencies have higher relative amplitude for both the analysed speed profiles.

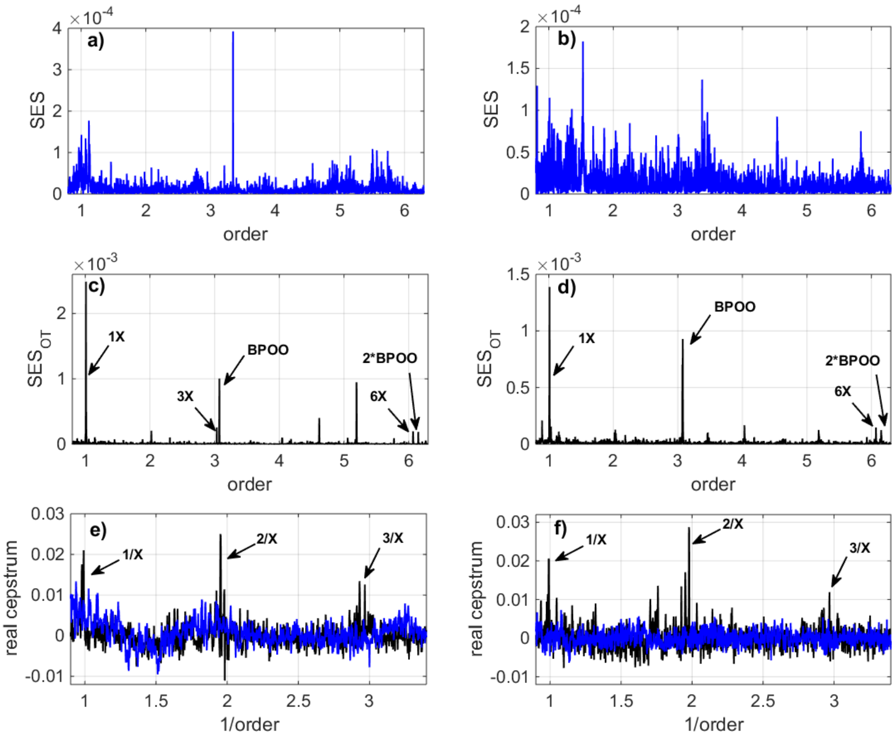


Fig. 5: (a) SES of raw signal for the run-up speed and (b) randomly varying speed. (c-d) Corresponding SES after OT. (e-f) Real cepstra: in blue of the original signals and in black of the OT signals.

## 5 Conclusion

The paper shows the effectiveness of cepstrum pre-whitening to enhance the presence of impacts from a faulty bearing when applied directly on acceleration signals from machinery operating at varying speed. The paper also shows that in variable speed situations it is beneficial to apply cepstrum pre-whitening directly to the time non-stationary signals instead of the order-tracked signals, because the resonant frequencies appear to change with speed in the order domain. The method proposed here consists of order tracking the signal only after the operation of whitening the time non-stationary signal, and finally calculating the squared envelope spectrum for diagnostics.
Both numerical simulations and analysis of experimental data have been carried out. The proposed method has been compared with the common procedure of order tracking the signal as a first step and afterwards use the cepstrum pre-whitening in the order domain. The evaluation of the squared envelope spectra obtained by the two methods shows that, as proposed in this paper,

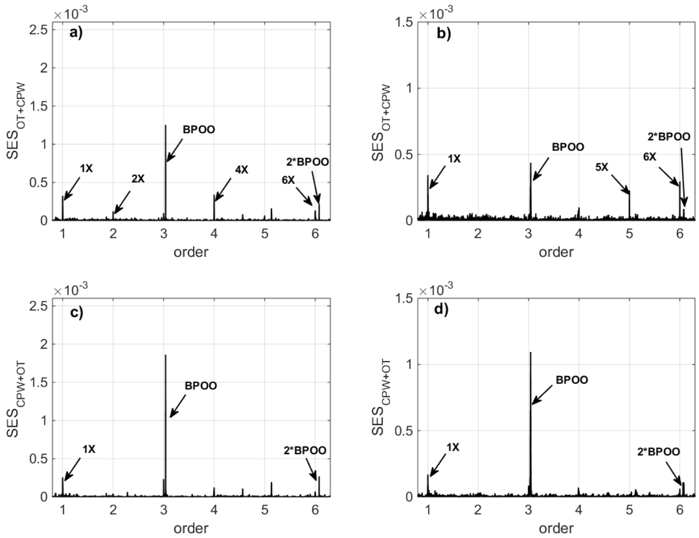


Fig. 6: SES after processing the signals. OT followed by CPW for (a) run up speed, (b) randomly varying speed. CPW followed by OT for (c) run up speed, (d) randomly varying speed.

the cepstrum pre-whitening performs well on the time non-stationary signal and that it is advisable to apply it before order tracking.

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