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# Phase editing as a signal pre-processing step for automated bearing fault detection

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ABSTRACT

Scheduled maintenance and inspection of bearing elements in industrial machinery contributes significantly to the operating costs. Savings can be made through automatic vibration-based damage detection and prognostics, to permit condition-based maintenance. However automation of the detection process is difficult due to the complexity of vibration signals in realistic operating environments. The sensitivity of existing methods to the choice of parameters imposes a requirement for oversight from a skilled operator. This paper presents a novel approach to the removal of unwanted vibrational components from the signal: phase editing. The approach uses a computationally-efficient full-band demodulation and requires very little oversight. Its effectiveness is tested on experimental data sets from three different test-rigs, and comparisons are made with two state-of-the-art processing techniques: spectral kurtosis and cepstral pre- whitening. The results from the phase editing technique show a 10% improvement in damage detection rates compared to the state-of-the-art while simultaneously improving on the degree of automation. This outcome represents a significant contribution in the pursuit of fully automatic fault detection.



## 1. Introduction

Research into fully automated algorithms for the application of condition based maintenance on an industrial scale has gained much attention in recent years. There is a practical need for reliable diagnostic methods to help avoid human errors and to allow affordable implementations of multi-sensor architectures without employing expert users. In this field, vibration based condition monitoring is a well established approach, present in the literature since the 1980s, and a variety of vibration transducers are currently used: for example, accelerometers, acoustic emission and ultrasound [1,2]. It is well known that bearings play a vital role in the health of many industrial machines and that they are particularly prone to failure [3]. This paper is concerned with automated algorithms for the assessment of bearing health using vibrational data.

The mathematical formulation of the second order cyclostationary nature of defective bearings signal and the clarification of its relationship with the high-frequency resonance technique [4] has allowed the introduction of a widely accepted model of bearing faults [5,6]. According to this model, features from defective bearings can be extracted by the squared envelope spectrum (SES) of the vibrational signal, as an estimation of the integrated cyclic coherence. The main difficulty in such feature estimation is that studying the SES of the full band raw signal usually does not provide a reliable assessment of

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the bearing condition and can result in defective bearings being classified as healthy. In complex machines, such as those used in industrial applications, this is due to the presence of vibration signals from other sources which are superimposed on those from the bearing itself. For instance, gears can contribute non-trivial vibration signals masking the presence of bearing defects. In such cases the SES of the raw vibrational signal shows various peaks, and the results are difficult to classify without the analysis of an expert user. From the point of view of an automated feature estimation there is then the need to find reliable methods to process the raw vibration signals, before the computation of the features from the SES, in order to simplify the diagnostic of a defective bearing.

Attempts have been made to automate common methods for the enhancement of bearing signals, however the results are not sufficiently reliable for industrial applications. For example the well established spectral kurtosis (SK) [7] is often used to select the frequency band containing bearing impact signals, but when automated there is a high risk of selecting the wrong demodulation band [8]. One solution to this problem is to edit the vibration signal such that the full frequency band is considered. This approach can be found in a method introduced by Borghesani [8], known as the zero cepstrum (ZC), where all the cepstral coefficients are set to zero and the SES is calculated for the full band edited signal. However this methods results highly sensitive to noise levels, as will be investigated in the following section. In the paper the focus is on an automated algorithms and cepstral approaches were preferred to other methods for removal of gear signals, as time synchronous averaging or discrete random separation, because somewhere else [9,10] they performed comparably well but require a faster implementation and result easier to automate.

This paper presents a novel automated signal processing method for feature detection in bearing vibration signals, based on phase editing (PE). As with ZC, the PE method has the advantage of using the entire band for demodulation, so avoids the risk of selecting the wrong frequency band. The novelty lies in the procedure for the removal of vibrational signals not originating from bearings. In many enhancement techniques only the amplitude spectrum of a noisy signal is modified while the phase spectrum is unchanged. The PE approach on the other hand keeps the amplitude unchanged and recombines the signal with an edited phase spectrum. The result is a modified spectrum where small amplitude components are attenuated more than large amplitude components. It is well established that in a vibrational signal the energy from bearings is low compared to that from the other components [11], hence in order to discard the misleading information and enhance the weak signal from the bearings, the final step is to calculate the residual between the original signal and the PE signal. To the best of authors' knowledge the present paper is the first to propose the use of phase editing in the field of condition monitoring. The effectiveness of this novel technique has been tested by comparing its performance on experimental data sets with that of two state-of-the-art methods. The first consists of two steps: removal of discrete components, implemented by means of an automated cepstral editing procedure (ACEP) [12] and SK for selection of the band for demodulation; the second method tested in the comparison is the ZC.

The paper is structured as follows. Section 2 presents details and discussion of the three methods. Section 3 describes the experimental rigs. Results are presented in Section 4 and conclusions are drawn in Section 5.

## 2. Methods

In the signal acquired by an accelerometer positioned on a gearbox casing at least three components superimpose: vibration induced by gears, vibration from bearings and noise. Usually a suggested operation is that of order tracking for removal of speed fluctuations [11], however in this paper machines are operating at a constant speed and this step will be omitted. All the three methods described below are be intended as enhancement procedures implemented before bearings fault feature estimation by means of the SES. They are automated such that the user needs to provide only the bearing defect frequencies and the rotation speed of the shaft where the bearing is mounted. Diagrams of the three methods ACEP + SK, ZC, PE are shown respectively in Figs. 1, 2, and 4.

### 2.1. Existing method (I): ACEP + SK

Method I consists of two blocks, ACEP and SK. The first one minimises the components from the gears, which are likely to mask the weak signal from bearings. This is achieved using an edited version of the cepstrum. Advantages on editing the cepstrum are that it can be automated [12], without the need of adjustment from the user, and that it has performed well when compared with other methods for gears signal removal as time synchronous averaging, auto regressive modelling, self-adaptive noise cancellation, discrete/random separation [9,10]. In more details three steps are involved in the ACEP block: spectral subtraction is applied to the high-pass liftered real cepstrum of the raw signal and afterwards a comb lifter is automatically generated for removal of impulses in the quefrency domain related to gear vibrations. This procedure provides an edited real cepstrum which is recombined with the original phase spectrum of the raw signal to obtain an edited vibration signal with enhanced bearing components $x_{ce}$.

The second step of Method I is the selection of the band of the spectrum where are present mainly vibrations from bearings, this is achieved using the SK. Its fast implementation was introduced by Antoni in [13], the algorithm gives as results: the bandwidth $B_w$ and central frequency $f_c$ of the demodulation band where the signal has the highest kurtosis and also the demodulated signal $x_{ce+sk}[k]$. From the perspective of automation two problems can be identified. Firstly the possible presence of vibration sources characterised by a kurtosis level higher then that of the defective bearings; secondly, the presence