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A comparison of cepstral editing methods as signal pre-processing techniques for vibration-based bearing fault detection

Cédric Peeters *, Patrick Guillaume, Jan Helsen

Vrije Universiteit Brussel, Department of Mechanical Engineering, Pleinlaan 2, Elsene, Belgium

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ABSTRACT

The detection and diagnosis of incipient rolling element bearing faults is not an undemanding task and signal analysis of vibration measurements therefore often incorporates the use of various complex processing techniques. One of the key steps in the processing procedure is the proper separation of the bearing signal from other influencing sources like shafts or gears. The latter sources produce deterministic signal components showing up as discrete frequencies in the amplitude spectrum, while bearing signals are assumed to be (quasi-) cyclostationary resulting in a smearing of the bearing frequencies in the spectrum. This property gave rise to the idea of using the cepstrum for the purpose of separating the deterministic signal content from the second-order cyclostationary bearing signal. The cepstrum essentially groups the deterministic multi-harmonic signal content in a cepstral peak at the corresponding quefrency, making it more suitable for easy removal of the discrete frequency peaks. Even though initially there was a tendency to only remove or 'lifter' the selected cepstral peaks, nowadays the full real cepstrum is set to zero instead of only certain quefrency bands. This technique, called *cepstrum pre-whitening*, is easy to implement, can be performed quickly without the need for additional input parameters or fine-tuning and would be well-suited for practical applications. However, these advantages do come at the cost of some control and insight over the editing procedure of the signal. In order to assess the performance of this cepstrum pre-whitening technique, it is compared to an *automated cepstrum editing procedure*. It automatically selects certain peaks in the real cepstrum and only sets them to zero instead of the full real cepstrum. Both methods perform quite well in separating deterministic signal content from more random content, but there are some differences to observe when using them for diagnosis purposes. An analysis of the methods is made for both simulated and experimental signals.

1. Introduction

Rolling element bearings are one of the most vital components of rotating machinery. Regrettably, they are also prone to premature failure due to a copious amount of possible influence factors [1,2]. Luckily, these faults produce characteristic vibrations conveying information about the type, severity and location of the fault. Retrieving this information for a general case is not that simple though, and the processing procedure necessary to go from raw vibration signal to diagnosis is not as

* Corresponding author.
E-mail addresses: cedric.peeters@vub.ac.be (C. Peeters), patrick.guillaume@vub.ac.be (P. Guillaume), jahelsen@vub.ac.be (J. Helsen).

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straightforward. Lately, there has been an ever-increasing amount of attention towards vibration-based condition monitoring of machines, and correspondingly there has been an increase in contributions towards tackling the problem of designing such a processing procedure. While some researchers focus on just a single step in this usually multi-step procedure, others focus on an entire procedure in itself.

A first example of such a processing step is the denoising of the measured vibration signals as to increase the signal-to-noise ratio of the bearing fault. Dron et al. used the spectral subtraction method [3] to improve the sensitivity of health indicators like kurtosis or crest factor for incipient bearing faults. The amount of studied wavelet-based denoising approaches is also quite significant and is too vast to discuss completely here, but some denoising examples are the use of the standard wavelet transform [4], the wavelet packet transform [5], the dual-tree complex wavelet transform [6], and multi-wavelet transforms [7]. Denoising is not the only required step though, possible additional steps could be enhancing the impulsive bearing signal content (e.g. through minimum entropy deconvolution [8] or band-pass filtering [9]), compensating for possible speed variations in the measured signals (e.g. through estimating the instantaneous angular speed using interpolation [10], Vold-Kalman filters [11], or a probablistic approach [12]), estimating the fault size/properties (e.g. through wavelet transforms [13], cepstrum analysis [14], or matching pursuit [15]), or reducing the interfering signal content originating from other vibration sources like gears or shafts (e.g. through autoregressive filtering(AR) [16], self-adaptive noise cancellation (SANC) [17] or discrete/random separation (DRS) [18]). This last step will be assessed further in the paper.

Ideally, a future end-user would use a black box procedure with the raw vibration signals as input and diagnostic information about the machine as output. The current state-of-the-art however is not yet mature enough to provide such a system, and researchers still have a lot of work ahead in understanding all the difficulties concerning this complex issue. Attempts have been made however to incorporate several techniques into one method chain in order to offer a more elaborate and/or automated analysis of vibration measurements. Randall & Antoni proposed a semi-automated procedure for bearing diagnostics using a combination of order tracking, discrete component removal, minimum entropy deconvolution, spectral kurtosis and envelope analysis [2]. A great deal of researchers also try combining several machine learning methods (e.g. artificial neural networks, support vector machines, genetic algorithms, etc.) in order to improve the robustness of automated bearing fault detection [19]. In theory, a lot of method combinations are conceivable and deciding the optimal one is still an open question.

This paper assesses only one step in such a potential procedure, namely the separation of stochastic signal content (e.g. bearing signals) from deterministic content (e.g. gear harmonics). However, this step is considered to play a significant role in the proper detection of bearing faults. Bearing faults are typically detected by analysis of the measured signal's envelope spectrum [20–22], unfortunately its presence in the envelope spectrum is often masked by high energy deterministic components [23]. Separating the bearing faults from these masking signal content assumes that a bearing fault signal is stochastic due to random jitter on the fundamental period of the fault frequency [24]. This corresponds to the random slip of the rolling elements and a bearing signal can be considered to be second-order (quasi-) cyclostationary. These effects cause a smearing of the bearing frequencies in the amplitude spectrum, while the deterministic signals manifest themselves as discrete peaks [25]. This property forms the basis for the cepstrum editing methods investigated in this paper for signal separation. Other methods have been proposed in the past trying to achieve a similar goal, such as discrete/random separation [18], self-adaptive noise cancellation [17], linear prediction filtering [26], and recently (generalized) synchronous average [27,28]. However, a comparison of cepstrum editing to the other mentioned methods is not made in this paper.

Cepstrum analysis is a signal processing tool with already quite a lengthy history. Bogert et al. [29] introduced the cepstrum first in 1963 as "the power spectrum of the logarithmic power spectrum" with the purpose of detecting echoes in seismic signals. Since then the description of the cepstrum has evolved and other definitions for the cepstrum have been identified afterward, like the "complex cepstrum" by Oppenheim and Schafer [30,31]. Various discussions were held about the proper definitions and properties of the cepstrum [32,33] and different forms were described like the differential cepstrum [34] and the mean differential cepstrum [35], which have their use mainly in operational modal analysis (OMA). Recently however the cepstrum has come into the limelight for its use in the field of vibration-based condition monitoring. It is now understood that the real cepstrum can be used to edit the log amplitude spectrum of stationary signals and combined with the original phase to achieve edited time signals. This particular finding has given rise to the development of cepstrum editing methods for the separation of deterministic signal content from stochastic content. Initially, most of the research focused on developing a cepstrum editing procedure to selectively set certain cepstral peaks belonging to masking discrete frequencies to zero [33,36,37]. The idea here is mainly to filter out the deterministic frequencies while preserving the rest of the signal's content. Lately however, there has been an increasing usage of a so-called cepstrum pre-whitening method [38–40]. Instead of setting only a selection of peaks to zero, this method sets the whole real cepstrum to zero, except for the zero quefrency. This technique is very easy to implement and has a very low computational cost, but alters the signal content substantially in a rather uncontrolled fashion.

In this paper a comparison is made between these two developments in cepstral processing of vibration measurements, namely between an automated cepstrum editing procedure (ACEP) and cepstrum pre-whitening (CPW). While this comparison investigates some important influences on the performance of both methods, it is not an exhaustive review of all possible influencing factors. It assesses the potential benefits and/or disadvantages of each method in order to make future end-users aware of this when choosing between the two methods. This paper presents an initial report about the performance of both methods on virtual and experimental signals.