Mechanical Systems and Signal Processing 36 (2013) 370–384

Contents lists available at SciVerse ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Application of cepstrum pre-whitening for the diagnosis of bearing faults under variable speed conditions

P. Borghesani [a,*], P. Pennacchi [a], R.B. Randall [b], N. Sawalhi [b,1], R. Ricci [a]

[a] *Politecnico di Milano, Dipartimento di Meccanica, via la Masa 1, 20156 Milano, Italy*
[b] *University of New South Wales, School of Mechanical & Manufacturing Engineering, Sydney, NSW2052, Australia*

ARTICLE INFO

Article history:
Received 18 January 2012
Received in revised form
4 September 2012
Accepted 8 November 2012
Available online 4 December 2012

Keywords:
Cepstrum
Whitening
Bearing diagnostics
Deterministic/random separation

ABSTRACT

Diagnostics of rolling element bearings involves a combination of different techniques of signal enhancing and analysis. The most common procedure presents a first step of order tracking and synchronous averaging, able to remove the undesired components, synchronous with the shaft harmonics, from the signal, and a final step of envelope analysis to obtain the squared envelope spectrum. This indicator has been studied thoroughly, and statistically based criteria have been obtained, in order to identify damaged bearings. The statistical thresholds are valid only if all the deterministic components in the signal have been removed. Unfortunately, in various industrial applications, characterized by heterogeneous vibration sources, the first step of synchronous averaging is not sufficient to eliminate completely the deterministic components and an additional step of pre-whitening is needed before the envelope analysis. Different techniques have been proposed in the past with this aim: The most widely spread are linear prediction filters and spectral kurtosis. Recently, a new technique for pre-whitening has been proposed, based on cepstral analysis: the so-called *cepstrum pre-whitening*. Owing to its low computational requirements and its simplicity, it seems a good candidate to perform the intermediate pre-whitening step in an automatic damage recognition algorithm. In this paper, the effectiveness of the new technique will be tested on the data measured on a full-scale industrial bearing test-rig, able to reproduce the harsh conditions of operation. A benchmark comparison with the traditional pre-whitening techniques will be made, as a final step for the verification of the potentiality of the cepstrum pre-whitening.

© 2012 Elsevier Ltd. All rights reserved.

1. Introduction

The application of condition-based maintenance on the industrial scale, as for instance in complex process plants or rail fleets, is generating a need for highly automated algorithms for the assessment of the health state of the machine components, in particular bearings. This is usually performed on the basis of vibration signals collected by accelerometers installed on the surface of the machine casings. Among the numerous techniques developed since the 1980s for the analysis of those signals, cyclostationary tools have proved to be very effective. McCormick and Nandi [1] were the first to address bearing diagnostics with a cyclostationary approach, understanding the second-order cyclostationary nature of

* Corresponding author. Tel.: +39 2 2399 8486.
E-mail address: pietro.borghesani@mail.polimi.it (P. Borghesani).
[1] Now at: Mechanical Engineering Department, Prince Mohammad Bin Fahd University (PMU), P.O. Box 1664, AlKhobar 31952, Saudi Arabia.

0888-3270/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ymssp.2012.11.001

damaged bearing signals, but the work of Antoni [2] is the first, to the best of the authors' knowledge, to analyze in detail the effectiveness of the different tools for the specific application of bearing diagnostics. In his work, he discusses in detail the above-mentioned tools: i.e. the *averaged cyclic periodogram*, the *cyclic coherence*, the *integrated cyclic coherence* and the squared envelope spectrum. In particular the last has been identified as the most suitable tool for industrial application, thanks to the low computational effort required and to the availability of *statistical thresholds* for the evaluation of the damage probability. If the signal under investigation has cyclostationary components, the squared envelope spectrum will show peaks at the specific cyclic frequency of the phenomena, identifiable also by an automatic algorithm by means of the statistical thresholds, calculated in[2]. These thresholds have been obtained analytically on the assumption that the only cyclostationary components in the signal are related to the damaged bearing (i.e., a healthy bearing would produce a white noise signal). Unfortunately the complexity of most machines makes this assumption unrealistic: Gears, shafts and electric motors will produce strong deterministic vibrations that will affect the measured signal. In this case, the squared envelope spectrum will show numerous peaks which on one hand can lead to false-alarms, and on the other hand can significantly affect the calculation of the thresholds, based on the mean power of the signal.

Unfortunately, many industrial applications are characterized by harsh and variable operating conditions, with multiple heterogeneous vibration sources. Therefore, the signals measured by the accelerometers, installed on the system under investigation, often present different components, among which the damage related ones are not always dominant. These heterogeneous components are not compatible with the hypothesis of white noise as in the case of a healthy bearing, and alter the standard deviation of the signal, compromising the correctness of the threshold. Various *signal enhancement* techniques have been developed and refined in the past to clean the signal from these externally generated vibrations: from the simplest one, *synchronous averaging* (SA) [3], to the more elaborated ones such as *linear prediction filtering* (LPF) [4] and *spectral kurtosis* (SK) [5]. SA is easily applicable as a byproduct of the *order tracking* (OT) of the signal, always performed in order to manage the speed fluctuation. However, as demonstrated in [6], the application of SA is not able to delete completely the effect of deterministic components, such as gear coupling and misalignments, when speed is not constant, even if the frequency of the vibration source is known. Recent research about the cepstral domain has led to the development of a new tool, the *cepstrum pre-whitening* (CPW), exhaustively described in [7] and [8].

The aim of this paper is to demonstrate the effectiveness of this new signal enhancing technique, applied to vibration signals acquired from a bearing test-rig rotating in two different conditions: constant and variable speed. A first evaluation will be performed applying the CPW after the SA and comparing the results obtained before and after the CPW with the statistical thresholds. The paper will also present a benchmark comparison with other traditional signal enhancement techniques, namely LPF and SK, based as well on the compliance with the statistical thresholds and on the clarity of the damage symptoms. The benchmark will also point out drawbacks and criticalities of each technique in relation to the operating conditions of the machine. Experimental data has been obtained by means of a full-scale experimental test-rig, equipped with a train traction system and able to reproduce the harsh, noisy conditions of the real application.

2. Cepstrum pre-whitening

Considering mechanical systems such as gears and motors, the idea of *cepstrum pre-whitening* (CPW) is based on the fact that deterministic excitations related to shaft harmonics and gear meshing are periodic, but not sinusoidal, and therefore produce a spectrum with multiple harmonics of the first excitation frequency. This results in a periodicity of the spectrum of the signal, with peaks equally spaced in the frequency domain. In the cepstral domain [9], the periodicity of the spectrum results in a peak at a quefrency equal to the period of the base frequency of the multi-harmonic vibration. In particular, given a signal $x(t)$, the cepstrum pre-whitening is based on the *real cepstrum* ([7] and [8]), calculated as follows:

$$C = IFT\{\log[|FT(x)|]\} \tag{1}$$

where *FT* and *IFT* indicate the Fourier transform and its inverse operation.

Peaks in the absolute value of the real cepstrum indicate the presence of a deterministic multi-harmonic component in the signal. The pre-whitening operation consists in setting a zero value for the whole real cepstrum (except possibly at zero quefrency), then, once transformed back to the frequency domain, the obtained signal is recombined with the phase of the original signal and inverse transformed to time domain. This is equivalent to a series of liftering operations ([7] and [8]) around the quefrencies of the deterministic excitations, resulting in the almost complete deletion of their effect on the signal, as well as a removal of resonance effects. On the other hand, the bearing damage related components, which are cyclostationary of the second order and not strictly periodic, will not present any strong peak in the absolute value of the cepstrum and will not be affected by the liftering. This procedure can also be implemented in a very simple way, avoiding the transformation to the cepstral domain, just by dividing the Fourier transformed signal by its absolute value and transforming back to the time domain.

$$x_{cpw} = IFT\left\{\frac{FT(x)}{|FT(x)|}\right\} \tag{2}$$

Download English Version:

https://daneshyari.com/en/article/565562

Download Persian Version:

https://daneshyari.com/article/565562

Daneshyari.com