Mechanical Systems and Signal Processing 84 (2017) 200–226

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Envelope analysis of rotating machine vibrations in variable speed conditions: A comprehensive treatment

D. Abboud [a,b,*], J. Antoni [a], S. Sieg-Zieba [b], M. Eltabach [b]

[a] *Laboratoire Vibrations Acoustique, Univ Lyon, INSA-Lyon, LVA EA677, F-69621 Villeurbanne, France*
[b] *Technical Center of Mechanical industries (CETIM), CS 80067, 60304 Senlis Cedex, France*

ARTICLE INFO

Article history:
Received 26 August 2015
Received in revised form
4 May 2016
Accepted 20 June 2016

Keywords:
Squared envelope spectrum
Envelope enhancement techniques
Variable speed conditions
Vibration analysis
Bearing diagnostic

ABSTRACT

Nowadays, the vibration analysis of rotating machine signals is a well-established methodology, rooted on powerful tools offered, in particular, by the theory of cyclostationary (CS) processes. Among them, the squared envelope spectrum (SES) is probably the most popular to detect random CS components which are typical symptoms, for instance, of rolling element bearing faults. Recent researches are shifted towards the extension of existing CS tools – originally devised in constant speed conditions – to the case of variable speed conditions. Many of these works combine the SES with computed order tracking after some preprocessing steps. The principal object of this paper is to organize these dispersed researches into a structured comprehensive framework. Three original features are furnished. First, a model of rotating machine signals is introduced which sheds light on the various components to be expected in the SES. Second, a critical comparison is made of three sophisticated methods, namely, the improved synchronous average, the cepstrum prewhitening, and the generalized synchronous average, used for suppressing the deterministic part. Also, a general envelope enhancement methodology which combines the latter two techniques with a time-domain filtering operation is revisited. All theoretical findings are experimentally validated on simulated and real-world vibration signals.

1. Introduction

Envelope analysis has been recognized for long as a powerful technique for rolling element bearing (REB) diagnosis operating at constant speed. Typically, it consists of a bandpass filtering step around a frequency band wherein the impulsive excitation is amplified followed by a demodulation that extracts the signal envelope. The spectrum of the envelope – known as the *envelope spectrum* – is expected to contain the desired diagnostic information, including the repetition rate of the fault and potential modulations [19]. At the time, the filtering and the demodulation operations were performed using analog techniques (e.g. [1]) with inherent limitations regarding the filter characteristics and the analog rectifier [11]. Thanks

Abbreviations: ; REB, rolling element bearings; SE, squared envelope; SES, squared envelope spectrum; CS, cyclostationary; SC, spectral correlation; VSC, variable speed conditions; ISA, improved synchronous average; CPW, cepstrum prewhitening; GSA, generalized synchronous average; SOI, source of interest; AT-CS, angle/time cyclostationary; BPOO, ball-pass-order on the outer-race

* Corresponding author at: Laboratoire Vibrations Acoustique, Univ Lyon, INSA-Lyon, LVA EA677, F-69621 Villeurbanne, France.
E-mail addresses: d-abboud@live.com, dany.abboud@insa-lyon.fr (D. Abboud), Jerome.antoni@insa-lyon.fr (J. Antoni), sophie.sieg-zieba@cetim.fr (S. Sieg-Zieba), mario.eltabach@cetim.fr (M. Eltabach).

http://dx.doi.org/10.1016/j.ymssp.2016.06.033

Nomenclature

t	time variable
θ	angle variable
α	cyclic order variable
ω	angular speed of the reference
$\mathcal{F}\{*\}$	Fourier transform
$\mathbb{E}\{*\}$	ensemble average
$SES_y(\alpha)$	squared envelope spectrum of signal y
$SE_y(t)$	squared envelope of signal y
$cov_{x,y}(t_1, t_2 \mid \omega)$	covariance of x and y conditioned to ω
$\bar{\theta}$	angular location in the cycle: $\bar{\theta} \epsilon [0, 2\pi]$
$m_Y(\bar{\theta}, \omega)$	GSA of Y
$m_Y(\theta)$	GSA trajectory tracked for a given speed profile $\omega = \omega(\theta)$
$\delta\omega$	speed resolution
Φ	the angular sector spanned during the time record
$\mathbb{R}$	the set of real numbers
$\mathbb{Z}$	the set of all integer numbers

to the advances of digital signal processing, considerable improvement has been made taking advantages of the Hilbert transform [3]. This latter returns the (complex) analytic signal whose modulus uniquely defines the envelope. In this context, it has been shown in Ref. [2] that it is preferable to use the *squared envelope* (*SE*) instead of the envelope inasmuch as the latter introduces extraneous components that appear as misleading peaks in the envelope spectrum. Since that time, the *squared envelope spectrum* (*SES*) has probably become the benchmark technique for bearing diagnostics, in particular due to its low computational cost [20].

During the last two decades, a wave of signal processing techniques rooted on the theory of *cyclostationary* (*CS*) processes [39] has appeared in multiple applications such as gears [13,40,42–44], REBs [11,45] and internal combustion engines [46–48]. In particular, a new model of REB vibrations has been introduced in Refs. [2,11], providing an insightful understanding of the REB fault signature within the CS framework [9]. Accordingly, it has been shown that the *mechanical signature* generated by a faulty REB is random in nature and has symptomatic properties that can be detected by means of second-order CS tools such as the SES, the *spectral correlation*, the *spectral coherence,* the *cyclic modulation spectrum* and others [11,17,18,8,30]. In this context, Ref. [11] has established the relationship between the spectral correlation and the SES. Since then, the SES has been considered as a (second-order) CS tool.

All the above techniques rely on the assumption of constant – or possibly fluctuating but in a *stationary* way – operating speed. Unfortunately, in some applications, the permanent acquisition of (quasi-) constant speed records is not available. A typical example is a wind turbine whose speed is mostly dependent on the random behavior of the wind. Evidently, the CS tools – including the SES – fail in describing such signals. Specifically, it has been shown in Refs. [27,29] that the vibrations emitted by rotating machines are likely to witness an interaction between time- and angle-dependent components. For instance, the REB fault signal can be viewed as a series of cyclic impacts locked to the shaft angle and exciting structural resonances [4,27,33]. Clearly, the positions of the impact excitations are dictated by the shaft angle while the resonance responses are governed by differential equations that impose time-invariant properties (e.g. natural frequencies and relaxation times). Therefore, efforts have been directed toward the extension of existing diagnostic tools in variable speed conditions (VSC). The recent advances in this framework can be classified into two directions.

1)In the first one, works have been oriented toward the coupling between the SES and computed order tracking to obtain an order domain representation. In order to deal with the non-consistency of the dynamical response and to eliminate potential interfering deterministic components, two general strategies have been adopted. The first strategy filters the time signal around a high-frequency resonance band (or simply high-pass filtering the signal) [23,37,38], while the second one eliminates the contribution of deterministic sources like gears with sophisticated "deterministic/random separation" tools and directly applies the SES on the residual signal [20,28,26].

2)In the second direction, efforts have been oriented toward the generalization of existing CS tools. In particular, Urbanek et al. [35] proposed an angle-frequency distribution – namely the averaged instantaneous power spectrum – based on a time filtering step followed by an angle averaging operation of the squared output. A similar solution was proposed by Jabłoński et al. [5] who introduced the *angular-temporal spectrum* to jointly represent the angular and time properties of the signal. More interestingly, a prominent solution was proposed by D'Elia et al. [33] who explore the order-frequency approach. Their idea was to replace the frequency–frequency distribution by a frequency-order distribution that jointly describes the time-dynamics and the angle-periodicities of the signal. They proposed intuitive estimators for the spectral correlation and cyclic modulation spectrum which were coined as the *α-synchronized spectral correlation density* and *α-synchronized cyclic modulation spectrum*, respectively. Later on, a fast version of the former estimator, called "speed correlation", was proposed in Ref. [34] wherein the *speed transform* was used in the algorithm. Recently, Refs. [16,29] set up the foundations of angle/time cyclostationarity which extend the CS framework to enfold speed-varying signals. These references equally provide (i) a rigorous definition of the *order-frequency spectral correlation* together with its normalized form (namely the *order-frequency spectral coherence*), as well as a consistent Welch-based estimator.

This paper is particularly concerned with the first direction and tries to organize existing works into a structured comprehensive framework. It is intended to serve as a guideline on how to exploit the SES in rotating machine diagnosis and to optimize it under given operating conditions. Overall, this paper also brings a number of original results that provide a more comprehensive view of some previously published materials.