Mechanical Systems and Signal Processing 62-63 (2015) 100–112

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Time domain cyclostationarity signal-processing tools

François Léonard

Institut de recherche d'Hydro-Québec (IREQ), 1800 boul. Lionel-Boulet, Varennes, QC, Canada J3X 1S1

ARTICLE INFO

Article history:
Received 7 February 2014
Received in revised form
21 October 2014
Accepted 29 October 2014
Available online 18 March 2015

Keywords:
Cyclostationarity
Gear mesh graph
Time-domain
Resampling
Coherency
Keyphasor

ABSTRACT

This paper proposes four different time-domain tools to estimate first-order time cyclostationary signals without the need of a keyphasor signal. Applied to gearbox signals, these tacho-less methods appear intuitively simple, offer user-friendly graphic interfaces to visualize a pattern and allow the retrieval and removal of the selected cyclostationarity components in order to process higher-order spectra. Two of these tools can deal with time-varying operating conditions since they use an adaptive resampled signal driven by the vibration signal itself for order tracking. Three coherency indicators are proposed, one for every sample of the time pattern, one for each impact (tooth shock) observed in the gear mesh pattern, and one for the whole pattern. These indicators are used to detect a cyclostationarity and analyze the pattern repeatability. A gear mesh graph is also proposed to illustrate the cyclostationarity in 3D.

1. Introduction

A cyclic mechanical displacement generates a vibration signal having statistical properties that vary cyclically with time. Called cyclostationary signal, this signal includes one or more cyclostationarities, each associated with a mechanical subset of the cyclic process. Identification of cyclostationarities allows the separation of the different mechanical sources. Moreover, the descriptive parameters of a cyclostationarity carry useful information for diagnosing a specific mechanical subset of the equipment. The reader can consult the broad surveys by Gardner et al. [1,2] on cyclostationarity in different fields of application. In a tutorial constructed from many examples, Antoni [3] applies the tools provided by Gardner in the context of rotating machine vibration. The common practice for rotating machinery in the mechanical domain is to use spectrum and high-order spectra applied to an angular order sampled signal with the help of a keyphasor. A good introduction to the use of a tachometer in order to process cyclostationarity in rotating machinery a is found in Antoni et al. [4]. In the last decade, a number of authors have introduced tacho-less methods [5,6] which generate a time order sampled signal rather than an angle order sampled signal. In stable operating conditions, angle and time cyclostationarities are equivalent [4] and indicators of cyclostationarity yield accurate results [7]. The next chapter explains why, in time-varying operating conditions, when the signal is measured away from the keyphasor location, a tacho method introduces a phase blur: the time cyclostationarities observed by the vibration sensor are not accurately phase-locked with the corresponding angle cyclostationarities at the keyphasor location.

The tools proposed here have been implemented considering gearbox cyclostationarity as the targeted signal. Gearbox cyclostationarity can generally be explained as a mix of the vibration shock patterns of gears. In the presence of more than

E-mail address: leonard.francois@ireq.ca

http://dx.doi.org/10.1016/j.ymssp.2014.10.013

one gear stage, considering misalignment and bearing contribution, there are many cyclostationarities, all contributing to a vibration signal which appears as a jumble of superimposed shock patterns. In the time domain, a first-order cyclostationarity appears as a repetitive pattern. A second-order cyclostationarity exhibits a statistical repetitive time pattern, usually phase-locked with a first-order cyclostationarity, e.g. a pump generating a cavitation noise as the propeller blade passes. Although the proposed tools address first-order time cyclostationarities, their signal input can be processed in order to search for higher-order cyclostationarities after removing first-order cyclostationarities, e.g. an envelope detector or a high-order spectrum can be applied to the residual signal. By finding the first-order cyclostationarity at the sensor location, the proposed method simultaneously estimates the resampling needed to minimize the phase blur in the higher-order spectrum.

Since it is unrealistic to explain a coded algorithm in detail, mathematical expressions are presented only for principal algorithms. The author hopes that the following description allows a person skilled in signal processing to reproduce the proposed tools. The LabView™ source code is available upon request.

The efficiency of a signal-processing tool is a function not only of coded mathematical expressions but also of the coding efficiency and the user interface. Most papers presented these days emphasize the first aspect and neglect the others. In fact, the second aspect, coding efficiency, cannot be illustrated easily in a paper since the details found in a programming code are far too numerous. Only a few points are given here about how to increase the coding efficiency. To address the last aspect, the paper illustrates some graphical results with the corresponding user interface.

After a short explanation about the phase blur that impairs the high-order spectrum, four time-domain cyclostationarity tools are presented followed by the gear mesh graphic interface. Sensitive to the phase blur, the cyclogram is the first time-domain tool introduced. It is a simple tool from which the next two are built. Used in a context of a time-stable cyclostationary signal, the cyclogram yields accurate results. In the context of time-varying periodicities and phase blur actions, e.g. rotational speed variations, a cyclogram can be used only for short time segments where the periodicities appear barely stable. Introduced in the chapter dealing with the parametric resampled time signal, the second tool appears less sensitive to time-varying conditions and phase blur. It extends the available time segment length using a second-order parametric resampling signal in order to apply a time-warping on the sampled signal which compensates the time-varying periodicities. The third tool allows a matching pursuit of a user-selected cyclostationarity by modeling a time-warping function using successive polynomial curves. The last of the four tools presented, namely the fragmented-signal synchronous summation, is similar to a scope with an intelligent trigger which averages a gear mesh pattern by counting a user-defined number of teeth. For these time-domain tools, like any other tools that estimate gear mesh time patterns, the gear mesh graphic interface builds a display of the aligned tooth shocks on the y-axis as a function of time. This graphic interface allows the visualization of sub-patterns contributing to the gear mesh pattern such as the cyclic load, misalignment and ghost patterns from machining artefacts.

2. High-order spectra, order tracking and phase blur

High-order spectra are proposed as indicators of nonlinear mechanical behavior [8]. Used in crack detection [9,10] bispectrum and bicoherence work well with simulated data but fail with measured data on real cracked beams [11]. High-order spectra are also proposed as indicators of mechanical, mainly gearbox, cyclostationarity [7,12,13,15]. The following development argues that high-order spectra show some drawbacks when the time-varying operating conditions impair order tracking. This development is done only for the third-order spectrum but it could be reproduced for any other order.

The third-order correlation

$$M_{3\times}(\tau_1,\tau_2)=E\{x(t)\times x(t+\tau_1)\times x(t+\tau_2)\}, \tag{1}$$

where $x(t)$ is the continuous time signal and τ_n is expressed in seconds, has the corresponding third-order estimated spectrum

$$\widehat{C}^{\alpha}_{3\times}(\tau_1,\tau_2)\overset{N\to\infty}{=}\frac{1}{N}\sum_{n=0}^{N-1}x_c(n)\times x_c(n+\tau_1)\times x_c(n+\tau_2)\times\exp(-j2\pi\times n\alpha),\ 0<\alpha<0.5 \tag{2}$$

with $\{\tau_1,\tau_2\}$ expressed as the number of samples and where

$$x_c(n)=x(n)-M_{1x}(n) \tag{3}$$

is the discrete signal without the synchronous average contribution $M_{1x}(n)=E\{x(n)\}$ corresponding to the first-order cyclostationarity. Deduced from Eq. (3), estimation of high-order cyclostationarity calls for an accurate estimation of the first-order cyclostationarity. Consider the simple analytical case of

$$x_c(n)=\prod_{k=0}^{2}A_k\times\exp\left(j2\pi f_k\times n+\theta_k(n)+B_k(n)\right). \tag{4}$$

where A_k are amplitude constants, $B_k(n)$ is the phase drift related to the frequency carrier k and $\theta_k(n)$ are random variables defined as

$$\theta_1(n)+\theta_2(n)+\theta_3(n)=0 \tag{5a}$$