Measurement 107 (2017) 120–127

Contents lists available at ScienceDirect

Measurement

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

Application of Lock-In Amplifier on gear diagnosis

Mario Luis Ruiz Barrios [a], Fidel Ernesto Hernández Montero [b,*], Julio César Gómez Mancilla [c], Evelio Palomino Marín [d]

[a] University of Pinar del Rio, Department of Telecommunications and Electronics, Pinar del Río, Cuba
[b] Department of Telecommunications and Telematics, Technical University of Havana José Antonio Echeverría, Havana, Cuba
[c] Laboratorio Vibraciones & Rotodinámica ESIME, Instituto Politécnico Nacional, IPN, Mexico
[d] Innovation and Maintenance Center, Technical University of Havana José Antonio Echeverría, Havana, Cuba

ARTICLE INFO

Article history:
Received 22 November 2016
Received in revised form 25 January 2017
Accepted 7 May 2017
Available online 11 May 2017

Keywords:
Gear fault detection
Lock-In Amplifier
Time analysis

ABSTRACT

Detection of faults in gears under variable rotational speed by vibration analysis becomes in a difficult task because events characterizing faults are not periodic. In this work, the use of Lock-In Amplifier (LIA), which leads to a time analysis approach, is proposed to be applied on gear fault detection. In this work, LIA is synchronized to the rotational frequency of any of the gear shafts and is used in order to determine spectral components related to a gear fault. In order to compare effectiveness and efficiency of the proposed technique with previously developed techniques, two gear-failure indicators are presented. These two indicators are determined in such a way that distributed teeth wear and faults producing a vibration with amplitude modulation can be detected. Several study cases, including numerical simulations and real vibration analysis, were carried out in order to validate the effectiveness of the proposed technique.

1. Introduction

Vibration analysis is widely applied on gear fault detection for preventing from catastrophic failures. To achieve that, a continuous monitoring of the gear condition must be conducted, which leads to the need of lower computational cost of the involved signal processing techniques (spectral analysis is the most used technique [1]). However, when the rotational frequencies of the shafts are not constant, the mechanical system becomes non-stationary and the spectral analysis must be combined with other techniques. This problem can be solved by gathering the rotation speed signal of the system (reference signal), which can be attained by means of encoders or the implementation of techniques for reference signal estimation [1,2].

In general, techniques for reference signal estimation have been applied in case of low variability of rotation speed, although in [2], a method dealing with high speed variability was proposed with the inconvenience of requiring a high computational cost.

Obviously, techniques that can directly use the reference signal from encoders are more accurate, exhibit lower computational cost and perform vibration analysis under a wide range of rotational speed variability. One of these techniques is order tracking, which can be implemented by applying resampling methods or transform based methods [3]. On one hand, resampling methods, or Computed Order Tracking (COT), means higher computational cost due to the use of sophisticated interpolation algorithms. On the other hand, although Fourier transform-based techniques, such as the velocity synchronous discrete Fourier transform (VSDFT), switch directly to order domain from time domain and, in consequence, the use of interpolation algorithms is avoided, the implementation of such techniques takes too much time (this is due to the use of a non-constant kernel). Although both approaches achieve the identification of the spectral components related to faults, they intrinsically incorporate the discrete Fourier transform limitation referred to the compromise between spectral resolution and computational cost. That is, it is not possible to keep the same spectral resolution along the full spectral domain at a constant sampling frequency: increasing spectral resolution is achieved by increasing the number of samples, which requires increasing the number of calculus operations [4].

Time-frequency analysis is other group of techniques that use the reference signal from encoders. Wavelet transform [5,6] and Hilbert-Huang transform [7] are the most used techniques. They require a relative high computational cost which does not make them suitable to be applied on continuous monitoring [8].

* Corresponding author.
E-mail addresses: mruiz@upr.edu.cu (M.L.R. Barrios), fhernandez@tele.cujae.edu.cu (F.E.H. Montero), gomezmancilla@gmail.com (J.C. Gómez Mancilla), e.palomino@ceim.cujae.edu.cu (E.P. Marín).

http://dx.doi.org/10.1016/j.measurement.2017.05.015
0263-2241/

In this work, a new technique, implemented at a low computational cost, is proposed for detection of fault in gears at variable rotational speed. The goal is to obtain a technique that not only requires lower computational cost, but also is more effective than other techniques. For this purpose, the application of Lock-In Amplifiers, joined to a frequency synthesizer with the ability to produce the frequencies needed for fault characteristic frequency identification, is proposed.

2. About Lock-In Amplifier

Lock-In Amplifier (LIA) has been widely used for measurement of sinusoid signals corrupted by noise [9]. This system uses a technique known as phase-sensitive detection, which allows for detection of the input signal spectral component at the frequency of the so-called reference signal. To do that, input signal is multiplied by both the reference signal and a signal in quadrature with respect to such reference signal. This operation yields two signals, called as in-phase signal (signal I) and in-quadrature signal (signal Q), which can be processed in order to obtain amplitude and phase of the spectral component to analyze. Fig. 1 shows the procedure implemented for the estimation of the amplitude of the spectral component at frequency f_o.

As an example, consider a signal $x(t) = A\sin(2\pi f_o t + \varphi_1)$ at the LIA's input. If the goal is to estimate the amplitude of the spectral component in $x(t)$ at frequency f_o then the reference signal must be equal to $2\cos(2\pi f_o t + \varphi_2)$. If so, the following signals are obtained at the LIA's multipliers output:

$$\begin{aligned} i(t) &= [A\sin(2\pi f_o t + \varphi_1)]2\cos(2\pi f_o t + \varphi_2) \\ &= A\sin(\varphi_1 - \varphi_2) + A\sin(2\pi 2 f_o t + \varphi_1 + \varphi_2) \end{aligned}$$

$$\begin{aligned} q(t) &= [A\sin(2\pi f_o t + \varphi_1)]2\sin(2\pi f_o t + \varphi_2) \\ &= A\cos(\varphi_1 - \varphi_2) - A\cos(2\pi 2 f_o t + \varphi_1 + \varphi_2) \end{aligned}$$

LIA's low pass filters remove the high frequency terms in $i(t)$ and $q(t)$ and, consequently, the following signals are obtained:

$$i(t)_f = A\sin(\varphi_1 - \varphi_2) \quad (1)$$

$$q(t)_f = A\cos(\varphi_1 - \varphi_2) \quad (2)$$

The proper work with signals represented by expressions (1) and (2) yields the estimation of the amplitude of the particular spectral component, as follows:

$$\begin{aligned} SCA &= \sqrt{[i(t)_f]^2 + [q(t)_f]^2} \\ &= \sqrt{A^2\sin^2(\varphi_1 - \varphi_2) + A^2\cos^2(\varphi_1 - \varphi_2)} = A \end{aligned} \quad (3)$$

LIA's spectral resolution is dependent on the low pass filter bandwidth [9]. In consequence, a spectral resolution higher than those achieved by any of the discrete Fourier transform implementations applied for spectral component estimation can be achieved requiring a lower computational cost.

3. Application of LIA on gear fault detection

Some gear faults are detected by identifying well defined spectral components of the vibration. LIA could be used to estimate the amplitude of any of these spectral components once the reference signal is tuned to the frequency of such spectral component. Since that frequency is given at certain and known integer multiples of the gear rotational speed (e.g., the number of teethes of a gear, the number of teethes of a gear plus one, two times the number of teethes of a gear, etc.), a synthesizer, the input of which is the gathered encoder signal, can be used to generate the sinusoid at such frequency. Fig. 2 shows the proposed procedure. The ability of the tachometer-synthesizer system of being tracked to the rotational frequency will allow for the accurate estimation of a corresponding spectral component amplitude. The synthesizer response must be as instant as possible and able to operate in a wide range of frequencies. That is why, in this paper the frequency synthesizer was implemented through the CORDIC algorithm [10].

3.1. Fault indicators

The identification of a spectral component by itself is not enough for detecting a gear fault. Some gear faults are scuffing, cracking tooth, broken tooth, pitting and fretting corrosive tooth, which produce a vibration characterized by amplitude and frequency modulation, so that, sidebands around the gear frequency and its harmonics arise [4,11]. It is well stated that when the magnitudes of such sidebands increase with respect to the amplitude of the spectral component at the gear frequency, then a gear fault is probable to be running [11]. It has been proven that if a local or a distributed fault is present in a gear, then the two first sideband spectral components around the meshing frequency have the highest amplitude [3,11]. In order to determine the proportion between sidebands amplitudes and gear frequency amplitude, a version of the fault indicator that computes the sidebands energy ratio (SER) [8] is calculated in this work. This SER variant consists of the ratio of the sum of the two spectral components closer to the meshing frequency (spectral components related to the rotational frequency of one of the two involved gears: $f_m \pm f_g$, where f_m is the meshing frequency and f_g is the gear rotational frequency) and the amplitude of the spectral component at the meshing frequency. This procedure is shown in Fig. 3. The fault indicator is represented by parameter m. If m increases, under invariant load conditions, one can estimate that a gear fault producing amplitude

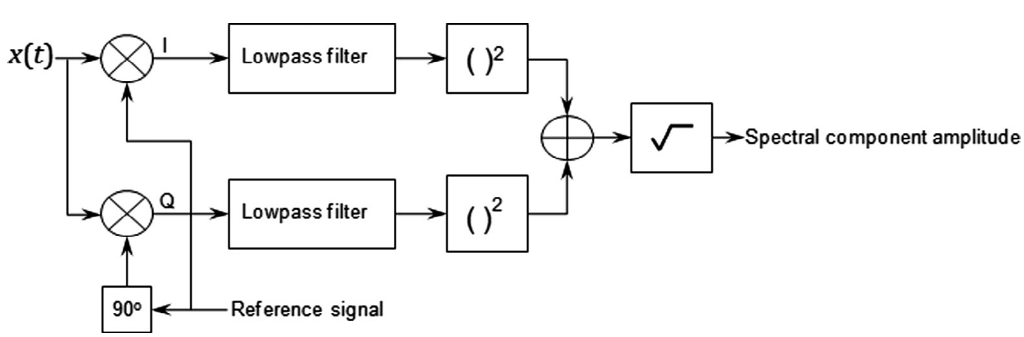

Fig. 1. Application of LIA on estimation of spectral component amplitude.