Mechanical Systems and Signal Processing 44 (2014) 14–30

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Precision of the IAS monitoring system based on the elapsed time method in the spectral domain ☆

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ARTICLE INFO

Article history:
Received 3 September 2012
Received in revised form
27 March 2013
Accepted 18 June 2013
Available online 25 July 2013

Keywords:
Instantaneous angular speed
Angular sampling
Aliasing
Quantization precision

ABSTRACT

Instantaneous Angular Speed (IAS) has recently appeared as an original and promising tool for monitoring mechanical parts of rotating machines. Mechanisms running under non-stationary conditions, such as wind turbine, are especially suited to this method since the issued signal is intrinsically sampled in the angular domain. Although processing tools are developed to enhance its use in the industry, this method is lacking a proper identification of its limitations and this paper aims at precisely understanding two of its main shortcomings: the aliasing and the quantization phenomena. After having presented the measurement method, both the aliasing and the quantization error are theoretically dissected. Formula is proposed to estimate their influence in the spectral observation of the IAS, and a good signal-to-noise ratio appraisal for this measurement technique is finally obtained. It can eventually be used as a first guide to conveniently design an IAS based control/monitoring system.

1. Introduction

In the last twenty years, Instantaneous Angular Speed (IAS) has been prospected for different purposes and by different means. The spectral observation of the IAS signal has been revealed as an effective tool for engine combustion related diagnosis [1] and recently appeared as a promising tool for bearing health monitoring, the running conditions being stationary or not [2]. Yuhua et al. reviewed angular speed measurement methods by categorizing them into two broad groups: timer/counter-based methods and ADC-based methods. It will be shown in this paper that this categorization could rather be made between the system counting the number of pulses in a given time duration and those measuring the elapsed time for a single cycle of encoder signal [3]. This simplification therefore distinguishes the speed measurement systems sampling data in the time domain from those sampling data in the angular domain. The latter is the only concerned with the results obtained in the present paper. Angular signals are especially suited to deal with non-stationary rotating mechanism and IAS based monitoring is even more attracting since it is remarkably easy to obtain through these techniques [4].

☆ IAS: Instantaneous Angular Speed.

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http://dx.doi.org/10.1016/j.ymssp.2013.06.020

Nomenclature

IAS	instantaneous angular speed
F_c	zero crossing detection clock speed
$T_c = 1/F_c$	time separating two counter pulses
R	resolution of the encoder, number of encoder segments
N	length of the measurement (number of points)
f_θ	cyclic frequency (rad^{-1})
θ_i	encoder segments angular position (starting from θ_0 at the beginning of the measurement)
$\Delta\theta = 2\pi/R$	angular increment between two segments of the encoder
$t_i = t(\theta_i)$	actual time for the ith segment
$\tau_i = \tau(\theta_i)$	actual time difference between the segments respectively labeled i and $i-1$
$\omega_i = \omega(\theta_i)$	actual IAS at the exact position θ_i
$\overline{\varpi}(\theta)$	actual IAS issued from moving average along $\Delta\theta$: virtual signal to be sampled by ET measurement
$\hat{t}_i, \hat{\tau}_i, \hat{\omega}_i$	measured time, measured time difference and measured angular speed
$X(\theta, \xi)$	corresponds to a set of sequence of the discrete variable θ, the set being indexed by the variable ξ. A random signal is a bivariate quantity, depending both on the angular position θ and the trial ξ
$X(\theta, \xi_i) = X_i(\theta)$	random process realization obtained once the trial is fixed (i.e. $\xi = \xi_i$)
$X(\theta_i, \xi) = X_i$	random process reduced to a simple random variable once the variable θ is fixed
$\tilde{X}(f_\theta)$	discrete Fourier transform of realization $X_\xi(\theta)$ normalized by the length of the realization
$\mathcal{D}_{XX}(f_\theta)$	power spectral density of random signal X at cyclic frequency f_θ
$\lceil\rceil$	rounding to the highest integer value
x^*	complex conjugate

As far as the authors know, there is no way to analogically filter an angular domain IAS signal; this makes it prone to aliasing, a phenomenon that has not been detailed yet regarding this technique, the only proposed answer being to increase the angular sensor resolution to the highest possible value [5]. This solution may yield a counter productive effect over the signal spectral observation since other sources of perturbation could depend on the sensor resolution in a negative way. In this regard, Youssef et al. brought a visual description of the spectral noise of the IAS obtained through an angular domain observation, distinguishing the discrete error coming from the angular sensor irregularities and the large band perturbation induced by the derivation phenomenon [6]. Nevertheless, the relation between the system parameters and the signal-to-noise ratio has not been studied and this ignorance appears as a major drawback for this attractive technique, especially since the observed IAS amplitude of variation has appeared alarmingly weak.

This paper proposes an other step towards the determination of the overall precision of the IAS obtained through the elapsed time technique. Once the measurement methods have been described, the existence of aliasing and its influence is theoretically presented. This first step aims at understanding the relation between the actual IAS variations and those, possibly aliased, observed on its spectral observation. Subsequently, the quantization phenomenon is tackled: the case of stationary speed is shown to lead to inevitable perturbations which take the shape of spectral ghost components. The theory of non-stationary speed condition is eventually addressed with a statistical approach. The results are finally validated numerically and experimentally on an automotive gear-box test rig. Amongst the practical and beneficial results, the speed variations experienced by the mechanical system along with the quantization process will now be understood as valuable for the monitoring process.

2. Instantaneous angular speed monitoring system

2.1. Angular speed sensor

IAS can be obtained from several methods. All of them are based on the observation of a rotating system through a sensor able to convert the angular position into an electrical signal. Most of these sensors are optical encoders, magnetic pick-ups and hall effect tooth wheels [7]. If optical sensors are known to reach higher resolution and precision, the other two can often be set in more extreme conditions. Typically, optical encoders are of common use to precisely synchronize asynchronous generator converter with the rotor speed while phonic wheels are used to warn the operator in the extreme case of a mechanical coupling breakdown. Other measurements are done with costly laser vibrometers [8], low resolution resistive potentiometric sensor [9] or resolver whose precision and magnetic sensibility decrease as soon as the resolution increases [10].

The terminology *angular sensor* is of use in this paper to associate every element able to convert an angular position into an electrical signal with the results presented hereafter. The signal conditioning applied on these angular sensor includes several common steps, resumed in Fig. 1, possibly improved by an interpolation process to yield a square signal whose resolution is higher than the physical one, as mentioned in [11].

Although the result quality may depend on the selected sensor type, it is important to notice that this technological choice is almost independent of the method chosen to compute the instantaneous angular speed.