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Instantaneous Angular Speed (IAS) processing and related angular applications

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1 Introduction

Nowadays, condition monitoring and diagnosis of rotating machines, especially in energy production, are among the major societal and scientific problems for improving machine availability. Under these industrial requirements, analysis and comprehensive expertise involve many research fields ranging from the understanding of phenomena at different scales, the precise modeling of component and machine behaviors to the development of accurate signal processing tools and complex data analyses.

For many years, *angular approaches* have been emerging in various published research works on rotating machines incorporating technological elements with discrete geometry such as bearings, gears, synchronous belts, etc.

Under *angular approaches*, there are two main features evidently linked and concerned with different research domains which can be classified into two main categories:

- Angular sampling and its consequences on signal processing. The key feature lies in directly sampling signals in the angular domain to provide insensitivity to non-stationary speed conditions and direct order analysis through the classical Fourier Transform. Angular resampling of time signals is also concerned with this topic and presents a renewed scientific interest. Angular sampling happens to open some new theoretical issues such as aliasing and non-uniform sampling, and new relationships with other recent works, such as cyclostationarity for example.
- Measurement of the Instantaneous Angular Speed as a new source of information of the machine condition. The IAS signal, which can be naturally sampled in the angular domain, also reveals a great sensitivity to different types of defects such as bearing or gear faults over a large bandwidth of orders, offering the possibility to monitor a complete machine with a reduced number of sensors.

Moreover, some modeling methods are also being proposed to deal with the classical equations of motion in the angular domain in order to take benefit of the true angular periodicity of defects in geared transmissions and in bearing diagnostics. This new point of view seems very promising for describing the behavior of rotating machines such as in wind turbine or helicopter applications under non-constant speed operating conditions.

2 Some scientific key points

This section is devoted to the guest editors' perception about scientific challenges, developments and issues opened by works presented in this special issue. Concepts in rupture with the traditional approaches are gathered in the following sections concerning terminology, measurements, precision, signal processing, transfer path and convolution, and mechanical models. All these concepts are deeply related to machine behavior and monitoring

2.1 Terminology precision

The two main concepts of this special issue are concerned with terminology and require the definition of new terms recognized and used by the scientific community.

When sampling signals in the angular domain, periodicity in this domain must be clearly defined and dissociated from time periodicity as these periods are equivalent only when machines are rotating at exactly constant speed. What's more, this angular periodicity is generally directly linked to the angular geometry of rotating parts like gears or bearings. "Angular frequency" would be a natural extension of frequency when angular sampled signals are Fourier transformed, but in English engineering terminology this word is currently in use! "Cyclic frequency" could also be a good choice as this term is used in the field of cyclostationarity but application to rotating machines is a particular case for this scientific community. Therefore we propose to retain the term *angle frequency* to define the abscissa axis in the Fourier transform of angular sampled signals. Associated to this definition, we also suggest choosing a dedicated unit for this new frequency variable. Rather than (rad^{-1}) to be chosen if angular variable is graduated in rad or (order) which is deeply associated with turbomachines and generally considered as integer or half integer, we prefer to propose a new unit defined by the number of events over one angular revolution, that is to say *event per rev (epr)*. Note that this is dimensionless. With this convention, gears with z_1 teeth will have a gearmesh component located at z_1 (epr) in the angle frequency and characteristic frequencies for bearing will be defined directly in relation with the shaft revolution as events per revolution.

The *Instantaneous Angular Speed (IAS)* must also be correctly defined and surely dissociated from the *instantaneous frequency* concept traditionally used in signal processing. IAS must be considered as one of the dynamic responses of the machine to different kinds of excitation and as a signal or a particular source of information. On the other hand, the instantaneous frequency must be rather used to denote (the inverse of) a local periodicity which can be encountered in any signal. These two quantities are obviously related since the instantaneous frequency is generally an indirect estimation of the IAS, extracted from other dynamic responses of the machine.

2.2 Revisiting signal sampling and processing

Numerous scientific works have been focused on signal sampling for several decades; moreover, the scientific literature evidences more and more applications of condition monitoring of rotating machines mainly centered on angular sampling. The existence of a theoretical framework for non-uniform or random sampling is a precious background for applications requiring a mapping between time and angular domains, particularly when operating conditions are non-stationary. Under reasonable assumptions about speed operating condition, signal characteristics can be investigated using classical processing tools. For instance, although cyclostationarity is a subclass of non-stationary signals, it would apply only to time signals produced by machines operating at stationary speed. Angular sampling extends its range of applications to operating conditions with slightly fluctuating speeds, but much work is still to be done to generalize the theory to strongly varying regimes, a situation that has recently given rise to the concept of cyclo-non-stationarity. Angular sampling is obviously the best way to process signals over large operating durations even for non-stationary speed conditions.

The knowledge of the history of the machine speed is obviously necessary information for resampling signals. But in association with kinematic description of the machine this speed history becomes also a very attractive tool when aliasing occurs for locating and dissociating resonance frequencies. Taking advantage of these characteristics rather than filtering out useful information by using tracking anti-aliasing filters seems to be also very promising. All these fields of investigation must be screened in order to evaluate and understand how signal information is transformed and therefore which is the best way to extract it in a valuable form. Non-stationary operating conditions are certainly the area where time and angular information must be *commonly* – and not separately – processed in order to characterize the machine behavior.

2.3 Revisiting measurements and precision

As mentioned in the previous section, IAS is a behavioral characteristic of the machine under operation and can be measured by the help of various sensors (magnetic or optical encoders, phonic wheels, etc) with industrial integration. The most popular method, known as the Elapsed Time method, is based on counting of high frequency clock pulses between two successive pulses of the sensor. Implicitly angular sampled, the IAS is directly estimated with the encoder resolution and the clock precision by a numerical process. This numerical process is basically different from traditional ADC (Analog to Digital Converter) and it would be of interest to reconsider the whole acquisition process (from sensor to data) which consists in locating in time some pulses delivered by the sensor. To the authors' knowledge, methods based on parsimony could be an investigation frame for sensor and acquisition system manufacturers.

Precision of measurements is mainly due to different phenomena introducing perturbations related to the sensor, to the signal and to the acquisition process. Engraving quality of encoders is obviously the first way to improve measurement precision but it does not need necessarily to be associated with high resolution. The main goal for the sensor is to deliver pulses at true constant angular step. The quantification phenomenon has been investigated and first results validated through numerical and experimental study can be used to design an IAS monitoring system in regard to the cyclic phenomena expected on peculiar mechanisms. These results have also shown the predominance of quantification noise amongst other kinds of perturbation like electronic noise or engraving errors which are also and obviously areas for further investigation.

2.4 Revisiting transfer function and convolution

Since experimental works have demonstrated the added value of the angular domain, particularly under non-stationary conditions, it is important to consider the signal model introduced by the transfer function. As one can consider that excitation in rotating machines is mainly associated with components having angular periodic geometry and that transfer paths between excitations and responses can be described by time differential equations, the signal convolution must be written as (with abuse of notation from a theoretical point of view):

$$R(\theta, t) = h(t) \otimes E(\theta). \quad (1)$$

This underlines the fact that responses must be considered both in time and angular domains depending on changes in operating conditions. During the inspection duration, if the excitation sprays energy over a frequency bandwidth where the transfer function is constant with respect to non-stationary conditions in speed, angular sampling should be a good choice for acquiring response signals. This can be the explanation why IAS appears as a good monitoring indicator as torsional modes are higher in frequency than flexural modes.

From a theoretical point of view, solving equation (1) implies the knowledge of the relationship between angle position and time in order to be able to pass from the angular domain to the time domain and vice-versa. Here again, the IAS seems to be a key knowledge in order to solve this theoretical

problem. This must be also related to the first attempts to write classical time differential equations of motion in the angular domain as presented in the following section.

2.5 Revisiting mechanical models

First of all, mechanical models should be considered with a new way of thinking as soon as differential equations are rephrased in the angular domain. This approach introduces the necessity to solve a nonlinear differential equation and shows that time integration solvers must be carefully used if disturbances due to faults have to be correctly introduced. For time integration, one must ensure that angular periodic excitation is correctly introduced at integration steps in time. When using angular description, it is easier to discretize this periodic excitation and to force integration solution at constant steps; thus concern about the integration CPU time is removed since the computation times are shorter. Introducing structure description is not more difficult for the angular approach since the FEM description can be used directly.

Another important modification in mechanical models is derived from the fact that IAS is informative of defect presence. Then, these changes in the rotating behavior of the machine, even very low in magnitude, are the results of torque disturbances introduced by the defects. Therefore engineers, particularly when concerned with bearings, must introduce tangential and not only radial perturbations in the excitation description. The traditional assumption of impulsive excitations in the radial direction must be reconsidered and complemented by a tangential force. This consideration also highlights a lack of mechanical models between the microscopic scale of the contact which is currently well described for small indents and the mesoscopic scale of the component in order to translate correctly tribological phenomena that lead to these excitations. These excitations must be correctly described as the sensitivity of IAS measurement allows detection of responses of very low magnitude.

3 Special issue quick overview

In this special issue, several of the above mentioned research topics are addressed. Thematically, they can be divided into different categories in which proposed papers can be included.

A first group of papers is directly dealing with IAS measurement and topics are related to correction capabilities offered by encoders [1], to precision estimation and aliasing effects [2] and indirect measurement of IAS [3]. IAS is also used as a new information signal for monitoring rotating machines, particularly in papers [4, 5 and 6].

Other papers can be gathered due to their focus on order tracking in stationary or non-stationary speed conditions [7, 8, 9 and 10]. These contributions generally use up to date signal processing techniques when applied on traditional signals.

Some of the other papers are also connected to signal processing because of their proximity with cyclostationarity and the possible extension to cyclo non stationarity [11, 12 and 13]. Other papers open new tracks of investigation on signal processing [8 and 9], on sampling theory [14] or on aliasing [2]. Several of them offer a connection with new ways in modeling [5, 15] and investigating signal and transfer functions [10].

The ensemble of papers in this special issue gives a good overview of current research activities concerning angular approaches and their applications to rotating machine monitoring. The applications covered by the papers are concerned with motor engines, turbines (steam and gas), wind turbines, gear transmissions, bearings and machine tools. Applications of these papers are clearly in the main topic of condition monitoring for rotating machines in non-stationary speed conditions.

- [1] Zebra tape identification for the instantaneous angular speed computation and angular resampling of motorbike valve train measurements (MSSP12-197)*
- [2] Precision of the IAS Monitoring System based on the Elapsed Time method in the spectral domain (MSSP12-509)*
- [3] A Parametric approach for the estimation of the instantaneous speed of rotating machinery (MSSP12-514)*
- [4] Shaft Instantaneous Angular Speed for Blade Vibration in Rotating Machine (MSSP12-373)*
- [5] Introduction of Angularly Periodic Disturbances in Dynamic Models of Rotating Systems under Non-Stationary Conditions (MSSP12-439)*
- [6] Indicators for monitoring chatter in milling based on instantaneous angular speeds (MSSP12-261)*
- [7] Single and Multi-Stage Phase Demodulation based Order-Tracking (MSSP12-587)*
- [8] The velocity synchronous discrete Fourier transform for order tracking in the field of rotating machinery (MSSP12-332)*
- [9] A Tacho-less Order Tracking Technique for Large Speed Variations (MSSP12-435)*
- [10] Nonlinear Model for Condition Monitoring of Non-stationary Vibration Signals in Ship Driveline Application (MSSP12-395)*
- [11] Using the moving synchronous average to analyse fuzzy cyclostationary signals (MSSP12-199)*
- [12] Cyclic impacts as the mechanism of material removal in robotic grinding (MSSP12-367)*
- [13] Cyclostationarity Approach for Monitoring Chatter and Tool Wear in High speed Milling (MSSP12-344)*
- [14] Impact of the Non Uniform Angular Sampling on Mechanical Signals (MSSP12-542)*
- [15] Angular approach combined to mechanical model for tool breakage detection by eddy current sensors (MSSP12-506)*