Opracowanie modelu matematycznego badanych sygnałów
Autorzy: Urbanek J., Jabłoński A., Barszcz T

Sprawozdanie z wykonania zadania nr 6 projektu badawczego IP2012 061572 pt. „Opracowanie nowatorskich narzędzi analizy sygnałów wibroakustycznych generowanych przez maszyny wirnikowe pracujące w ekstremalnie zmiennych warunkach operacyjnych”

Dokument zawiera opis sygnałów drgań generowanych przez maszyny pracujące w zmiennych warunkach eksploatacyjnych i motywacje podjęcia tematu oraz opis propozycji modelu matematycznego nowej klasy sygnałów nazwanej roboczo GATD. Sprawozdanie zawiera dodatkowo propozycje metody doboru współczynników modelu i ilustruje przykładowe wyniki. Rezultaty pracy badawczej, która pozwoliła opracować unikatową, nową klasę sygnałów, przedstawione zostały w formie publikacji naukowej zgłoszonej na konferencję The 4th International Conference on Condition Monitoring of Machinery in Non-Stationary Operations (CMMN0'2014), która odbędzie się w Lyon (Francja), 15-17.12.2014. Dokument sporządzono w języku angielskim.

2014-8-20

Outline

1 Introduction

Vibro-acoustical behavior of mechanical parts like shafts or gearboxes are often modeled as a sum of sine/cosine waves with frequencies related to rotational speed of the machine. On the other hand, signals originated from elements like rolling element bearings or pistons are described by either cyclostationary or more precisely, angular-temporal deterministic processes. However, it is still unclear how to include the influence of varying rotational speed and load while staying close to the well established principles of aforementioned modeling techniques.
The following paper gives overall view on modeling of machine vibration signals generated under highly varying operational conditions based on the generalized principles of cyclostationarity and angular-temporal determinism. Signals are modeled as random processes driven by two independent external functions. Namely, time-dependent rotational speed together with time-dependent load of the modeled object. The mathematical model that includes signals originated from both shafts and rolling element bearings is presented.

Modeling of signals generated by rotating machinery is intrinsically connected with the concept of signal classification. Over the years, a number of schemes of tree-structured classification patterns have been presented by the researches. In this paper, the classifications proposed by Randall [1] and Antoni [2] are recalled as a research baseline. Apart from formulation of mathematical recipes for vibration signals, modelling aids in signal analysis by helping in selection of proper tools, transforms, and techniques for data analysis. For instance, if a steady-state signal is to be analyzed, Fourier Transform precisely determines frequency content. If a machine run-up is analyzed for determination of critical speed values, a waterfall plots would be a more suitable tool. The current paper accepts a hypothesis that all vibration signals generated by rotating machinery might be classified as stochastic processes containing some components varying non-periodically and independently with respect to some generic variables. Within this classification, any simpler model of a vibration signal is just a particular case of the general model, including the fundamental harmonic motion as a most fundamental one.

Chapter 2 illustrates the significance of signal processing techniques for non-stationary operational conditions. Chapter 3 shows a proposition of new models of vibration signal components. Chapter 4 aims in development an exemplary method for the estimation of the model coefficients' values. Chapter 5 presents an exemplary implementation of proposed method for modelling of a generated signal.

2 Mechanical vibrations generated under varying regime

Typical, modern condition monitoring systems take advantage of automatic calculation of energy estimators corresponding to characteristic frequencies of interest from vibration signals. In this approach, it is important that other factors which cause changes in vibration signals are considerably reduced or eliminated [1]. However, Some kinds of machinery inherently work in quickly changing operational parameters. This group of machines include wind turbines, mining machinery, excavators, etc. The concept of data analysis of machinery under varying operational conditions has been illustrated in works [3-5]. The literature states that operational parameters have significant influence on the frequency contents of vibration signals. As Combet and Zimroz stated in [5]:

> "(…) *considering the wide variation in operating conditions (…) and the dependence between the operating conditions and the diagnostic features, there is a need to take the operating conditions (…) into account during the reasoning process. If the operating conditions are neglected, one may obtain an unclear basis for diagnostic decision taking due to the crossing effect between the good condition and the bad one on a diagnostic feature distribution.*"

Fig. 1 and fig. 2 illustrate two typical examples of the ostentatious influence of the variable operational conditions on the vibration signal even in a raw time wave form. Fig. 1 shows a simple test rig case, where the speed increases monotonically. Although local critical speeds are not visible, the general rise in signal amplitudes is clear. Fig. 2 illustrates an example of utmost importance, because clearly shows that the generic variables of interest, namely speed and load are only long-term related, which is indisputably unacceptable for the purpose of machine diagnostics. Therefore, the current paper claims a strong need for definition and mathematical formulation of a class of signal describing this particular scenario. In this paper, the relation between speed/load and amplitude is the general motivation to establish the generalized angular-temporal deterministic (GATD) processes and then use it for modeling of vibration signals.

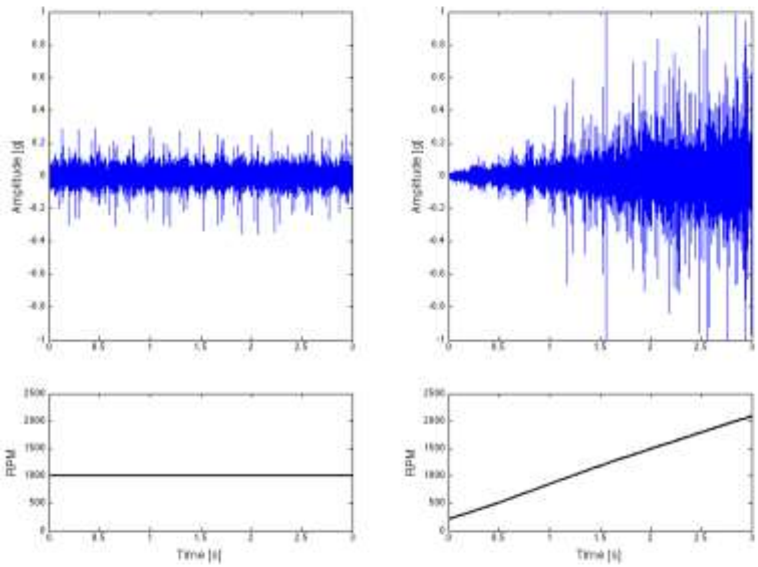

Fig. 1. Time views of vibration signals (top panels) and corresponding shaft rotational speeds (bottom panels).

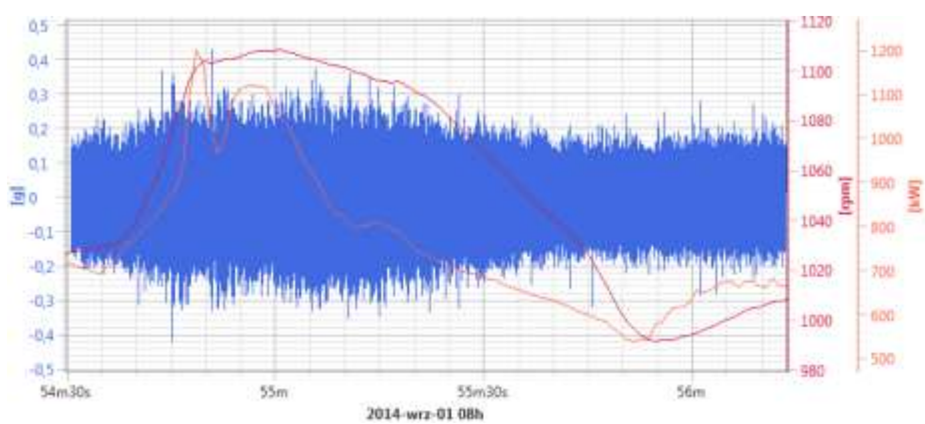

Fig. 2. Time signal from a wind turbine planetary gearbox with corresponding instantaneous speed (generator) and load.

3 Proposed models

In this chapter, two models of generalized deterministic vibration signals generated by machinery operating under varying speed and load are introduced. As it is presented in chapter 2 of this paper, the amplitude of such signals depends strongly on both, rotational speed and machine load. Additionally, characteristic frequencies of components associated with operating mechanical elements are related with rotational speed of these elements explicitly.

3.1 Rotating shaft - generalized angular deterministic signal

Firstly, a shaft rotating with time-varying rotational frequency $\dot{\varphi}(t)$ where $\dot{\varphi}(t) = \frac{d\varphi(t)}{dt}$ is considered, for $\varphi(t)$ being angular position of the shaft at time t. Additionally, it is assumed that the shaft operates under varying load expressed by *l(t)* and both,: $\dot{\varphi}(t)$ and *l(t)* are independent of each other. In this scenario, dynamic forces transmitted to the vibration sensors vary accordingly to these operational conditions. Therefore, the amplitude of measured acceleration varies as a function of both of them simultaneously. For majority of mechanical objects characterized by certain degree of inertia, it is justified to assume that operational conditions are characterized by relatively slow and smooth variations. Aforementioned criteria allow to define a general group of angular deterministic signals characterized by phase-locked cycles and smooth amplitude modulations [6].

In this paper, a signal *x(t)* is defined as "generally angular deterministic" for given phase increments $\varphi(t)$ with given angular period Φ, when the function composition $(\varphi \circ z)(t)$ meets the following criterion:

$$z_{\Phi}(\varphi(t)) = z_{\Phi}(\varphi(t) + n\Phi) \qquad (1)$$

Where $n \in \mathbb{Z}$ and $z_{\Phi}(t)$ is normalized (*z*-scored) version of signal *x(t)* for the angular