Opracowanie metod identyfikacji oraz separacji komponentów charakterystycznych badanych sygnałów

Autorzy: Urbanek J., Jabłoński A., Barszcz T

Sprawozdanie z wykonania zadania nr 8 projektu badawczego IP2012 061572 pt. „Opracowanie nowatorskich narzędzi analizy sygnałów wibroakustycznych generowanych przez maszyny wirnikowe pracujące w ekstremalnie zmiennych warunkach operacyjnych”

Z dumą informujemy, iż wynik przedstawionej pracy badawczej, który został przedstawiony na konferencji The 4th International Conference on Condition Monitoring of Machinery in Non-Stationary Operations (CMMN0'2014), Lyon (Francja), 15-17.12.2014 został wyróżniony prestiżową nagrodą „Best Paper Award”. Nagroda została przyznana za serię artykułów, które powstały w ramach realizacji projektu. Oficjalną informację ze strony internetowej Akademii Górniczo-Hutniczej w Krakowie o przyznaniu nagrody umieszczono w raporcie (Appendix A). Dokument zawiera opis wyników pracy badawczej w zakresie nienadzorowanej dekompozycji sygnałów drgań generowanych przez maszyny pracujące w silnie zmiennych warunkach prędkości i obciążenia. Przedstawiona metoda dekomponuje sygnał w na dwie klasy. Pierwsza klasa sygnałów to komponenty bezpośrednio związane z obrotami wałów. Druga klasa to komponenty, które posiadają charakterystykę periodycznych wzbudzeń strukturalnych, których okres zależy od chwilowej wartości prędkości maszyny. Opracowana metoda bazuje na transformacie STFT, która jest wykorzystywana do estymacji funkcji przejścia użytej w procesie dekompozycji. Jednakże, z uwagi na wysoki stopień niestacjonarności, zespół badawczy musiał opracować nową transformatę, tak, aby sygnał można było przedstawić jako sumę komponentów periodycznych i stochastycznych. Nowatorska transformata została opracowana z wykorzystaniem technik przepróbkowania kątowego oraz estymacji chwilowej, znormalizowanej amplitudy komponentów sygnału. Po dekompozycji, indywidualne komponenty są przetransformowane z powrotem do oryginalnej dziedziny czasu w celu zachowania cech niestacjonarności. Raport przedstawia implementację opracowanych metod na sygnale ze stanowiska badawczego w celu prostej ilustracji działania. Dokument sporządzono w języku angielskim.

2014-12-31

Outline

1 Introduction

According to signal processing theory, signals may be divided into deterministic signals and random signals [1]. In the field of vibrodiagnostics, where signals are collected from real machines, signal components must always be a mixture of the two [2]. Actually, a real machine signal may not be strictly deterministic, since by definition, the amplitude prediction for deterministic signals must be exact, and in real world it is never the case. However, for practical purposes of vibrodiagnostics, the term “deterministic” is understood as being “sufficiently predictable”, i.e. to acceptable extent of error, reproduction of measurement produces signals of the same contents [1]. Within the random group of signals, new classification terms have been accepted over the years, namely stationary, nonstationary, cyclostationary, ergodic, pseudo-stationary, etc. signals have been defined in order to classify components according to certain distinguishable characteristics. The evolution of signal classifications has led to development of signal separation techniques, history of which is given by Antoni in [3]. Some recent major developments in this topic are described in references [4-7], which include time-domain, frequency-domain, time-frequency domain, and neural network algorithms [8]. As presented in references [9-11], recent researches on signal separation frequently take advantage of the application of empirical mode decomposition (EMD). The method illustrated in this work might be classified as novel because it extends a known STFT-based DRS separation

technique to the case of non-stationary signals taking advantage of a novel transform of amplitudes and frequencies. Chapter 2 recalls the principles of recently developed model of non-stationary signals generated by machinery operating under varying regime, and presents the novel concept of signal separation. Chapter 3 illustrates the performance of the method on a test rig signal.

2 Proposed method

2.1 Basic Principles

In this paper, a method for blind separation of vibration signals into component related directly to shaft rotation and component containing excitation of structural resonances and noise is proposed. When considering vibration signals generated by machinery operating under varying load and speed, it is inherently prohibited to consider separation into deterministic and random components, as all of signal components are random in nature as both: frequency and amplitude of the signal depend on operational parameters. However, following well established philosophy of discrete-random separation (DRS) separation [7], the concept of extracting components generated during the rotation of unbalanced parts of kinematic chain (e.g. shafts) from the rest of the signal, that is mainly excitation of local resonances (e.g. by faulty rolling element bearings) and random noise unrelated to machine operation is illustrated.

When vibration signal is generated by machinery under constant speed and load we assume components related to unbalanced elements to be time deterministic as they can be characterized by certain frequency related to rotational speed and amplitude that is also constant in time. For varying operational condition assumption of time determinism is no longer valid; however, we can assume that frequency of observed machine-related components is constant when observed in angle-fixed time intervals (presented in angular domain). Additionally, we can assume that instantaneous amplitude of the signal is characterized by smooth variations related to varying speed and load. Therefore, we can assume that signals generated by unbalanced element of rotating machinery operating under varying operational conditions fall into class of generalized angular deterministic signals.

Signal x(t) is called a “generally angular deterministic” for given phase increments φ with given angular period Φ when its’ transformation to $z_\Phi(\varphi)$ meets the following criterion:

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

Where $n \in \mathbb{Z}$ and $z_\Phi(\varphi)$ is normalized (z-scored) version of signal x(φ (t))=$x'(\varphi)$ for the angular period Φ:

$$z_\Phi(\varphi) = \frac{x'(\varphi) - \mu_\Phi(\varphi)}{\sigma_\Phi(\varphi)} \tag{2}$$

where $\sigma_\Phi(\varphi)$ is localized angular standard deviation of $x'(\varphi)$ for the period Φ:

$$\sigma_\Phi(\varphi) = \sqrt{\frac{1}{\Phi}\int_{u=\varphi}^{\varphi+\Phi}(x'(u) - \mu_\Phi(\varphi(u)))^2\, du} \tag{3}$$

and $\mu_\Phi(\phi)$ being a localized angular mean of x(t) for the angular period Φ:

$$\mu_\Phi(\varphi) = \frac{1}{\Phi}\int_{u=\varphi}^{\varphi+\Phi} x'(u)\, du \tag{4}$$

Therefore, signal x(t) can be transformed into $z_\Phi(\phi)$ by changing the domain from temporal to angular and normalizing the instantaneous amplitude as presented in eq.2. Such transformation will produce the signal that is angularly deterministic, so DRS techniques can now be applied in the same way as for signals generated under constant operational conditions.

2.2 Method description

Proposed method assumes that if signal x(t) is “generally angular deterministic” then its transformed version $z_\Phi(\varphi)$ will have the same short-time spectral characteristic throughout the whole length of the signal. In other words short-time Fourier transform defined as:

$$Z_\Phi(\Theta,\psi)=\int_{-\infty}^{\infty}\mathrm{z}_\Phi(\varphi)w(\varphi-\psi)e^{-j2\tau\Theta\varphi}\,d\varphi$$

(5)

meets the following identity:

$$Z_\Phi(\Theta,\psi)=Z_\Phi(\Theta,\psi+\Phi)$$

(6)

for each value of ψ, where $w(\varphi)$ is a windowing function of non-zero values from ${}^{-\Phi}/_{2}$ to ${}^{\Phi}/_{2}$ and ψ denotes the angular shift. Therefore, we can use this assumption to create a transfer function:

$$\mathrm{G}(\Theta)=\frac{\langle Z_\Phi(\Theta,\psi)Z_\Phi^*(\Theta,\psi+\Phi)\rangle_\psi}{\langle|Z_\Phi(\Theta,\psi)|^2\rangle_\psi}$$

(7)

where $\langle\cdot\rangle_\psi$ denotes averaging operation along dimension ψ and * is the complex conjugate. It can be seen that $\mathrm{G}(\Theta)$ minimizes itself for those angle-fixed frequencies (orders) where identity given by eq.6 is false and goes to unity otherwise.

Let us now consider the exemplary signal $\mathrm{x(t)}=\mathrm{A(t)}\sin\left(2\pi\int_0^t\dot{\varphi}(\mathrm{t})dt\right)+n(t)$. Where A(t) is a time varying instantaneous amplitude (envelope) of frequency modulated sine wave expressed by $\sin\left(2\pi\int_0^t\dot{\varphi}(\mathrm{t})dt\right)$ where $\dot{\varphi}(\mathrm{t})$ denotes instantaneous frequency of the signal. For simplicity A(t) is proportional to the square of $\dot{\varphi}(\mathrm{t})$. Additionally we add random normally distributed, zero mean noise component $n(t)$. Such time series can be viewed as a simplified model of vibration signal generated by unbalance shaft operating under varying rotational speed. Resulting signals as well as separate components are shown in fig. 1.