Opracowanie metod detekcji komponentów charakterystycznych badanych sygnałów

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Dokument zawiera opis metody umożliwiającą detekcję komponentów charakterystycznych w sygnałach drgań z maszyn pracujących w silnie zmiennych warunkach eksploatacyjnych. Jako zmienne warunki, w trakcie badań przyjęto zmienną prędkość obrotową i zmienne obciążenie, które wg. literatury są parametrami o największym znaczeniu w procesie generowania drgań jako wynik chwilowych zmian w siłach i naprężeniach elementów maszyny. W raporcie opisano nowatorską metodę dwuwymiarowego widma (zaproponowana nazwa w jęz. angielskim „angular-temporal spectrum", czyli „widmo czasowo-kątowe") opracowaną przez zespół badawczy. Dodatkowo, zaproponowana została metoda normalizacji amplitudowej, dzięki której narzędzie może być wykorzystywane w praktyce inżynierskiej. Rezultaty pracy badawczej, która pozwoliła opracować nową metodę przetwarzania 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.

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1 Introduction

Digital signal processing of vibration signals for detection of rolling-element bearings (REB) faults has been addressed in scientific literature for decades. The reason for the popularity of the subject comes from a few major sources. Firstly, the physical characteristics of the difference in signals generated by healthy and faulty REB is very challenging in terms of mathematical modeling. Secondly, bearings experience different kinds of faults, each of which manifests itself by individual symptoms. Tertiary, any existing methodology for REB fault detection has been proven to be opened for enhancement along with the growth of the computational power as well as the lowering of the equipment cost. Last but not least, the problem of early REB fault detection has a very quantitative impact on industrial process, because REB faults are one of major causes of total machine failure [1]. Nevertheless, few aspects of REB have not been bench-marked yet, namely:

- detection of distributed REB faults,
- separation of REB faults in presence of other cyclostationary components,
- modeling of REB faults-induces signals in case of varying operational conditions, which is the topic tackled in the current paper.

The major technique used in REB diagnostics is the envelope spectrum, which enables illustration of the frequency of impulses generated upon contact of the damaged bearing surface with subsequent rolling elements. As stated in [2], the envelope spectra show the repetition frequency even with the small amount of slip, despite the fact that the higher harmonics in the latter case are slightly smeared.

The envelope technique, which realizes the process of amplitude demodulation, requires a quasi-stationary signal, i.e. the random REB components must be induced at a relatively constant rate. In case of a highly fluctuating speed, or generally a large speed change, the ratio of impulse responses loses its periodic characteristics, and the final envelope spectrum becomes smeared. On the other hand, if the signal is resampled in order to minimize spectral smearing of the first-order components, the impulse responses become easily disturbed and lose their quasi-stationary characteristics. The fundamental hypothesis is that the non-stationary behavior of the object reflected in non-stationary data comes from inevitable time-varying conditions, like changing wind or fossil and ore contents [3]. The current paper shows how a novel concept of angular-temporal spectrum might serve as a tool in detection of REB faults.

The paper is organized as follows. Chapter 2 recalls signals generated by faulty REBs. Chapter 3 illustrates the concept of angular-temporal spectrum. Chapters 4 and 5 show the results of the implementation of the presented method in simulated and real signals, respectively.

2 Signals generated by faulty REBs

Faulty REBs might generate two general types of signals, depending whether the fault is local or distributed. As described thoroughly in [2]: for localized faults (as illustrated in fig. 1), the question arises as to the correct way to model the random spacing of the impacts. For extended spalls, there will often be an impact as each rolling element excites the spall, and in that case envelope analysis will often reveal and diagnose the fault and its type. However, there is a tendency for the spalled area to become worn, in which case the impacts might be much smaller than in the early stages. Cases have been encountered where extended spalls no longer give sharp impacts, but they can still be detected and diagnosed if the bearing is supporting a machine element.

Fig. 1. Outer race defect of the rolling element bearing type EKTN9 [4]

In the current paper, a general signal generated by localized REB fault is investigated. Such signal is currently depicted in literature as a process consisting of the series of repeated patterns corresponding to consecutive excitations of machines structural resonances by faulty REB [5]. In this paper we will introduce simplified model of vibrations generated by faulty REB operating under varying rotational speed. In order to do that we include varying amplitude of each pulse expressed by A_n and time-varying yet angle-fixed period between consecutive pulses expressed by $t(n\Phi - \varphi_0)$. Therefore, for given angular increments φ and time increments t simulated signal is expressed by:

$$b(t) = \sum_{n=-\infty}^{\infty} A_n \omega(\mathrm{t} - t(n\Phi - \varphi_0) - \tau_n) \tag{1}$$

for $\mathrm{n} \in \mathbb{Z}$.

Where $\omega(\mathrm{t})$ is a single acoustic wave generated when rolling element strikes damaged surface, Φ is the characteristic angular period for REB fault, φ_0 denotes initial phase, A_n denotes an amplitude of n'th pulse and τ is a set of independent identically distributed random variables responsible for simulating rolling elements jitter effect.

3 Angular-temporal spectrum

In the current paper, the investigated scenario assumes a localized REB fault on a machine operating under highly variable conditions, which are detrimental factor in terms of available processing techniques. Therefore, within this work, a novel concept of the angular-temporal spectrum (ATS) is presented. Introduced tool returns the distribution of signals components in bi-frequency domain of Ω and f. Where Ω is the frequency related to angle-fixed events (expressed in Orders) and f denotes events occurring with time-fixed instances (expressed in Hz). Proposed ATS is expressed as follows:

$$ATS_T(\Omega, f; \varphi_0) = \lim_{\Theta \to \infty} \frac{1}{\Theta} \int_0^{\Theta} |Z_T(\varphi, f; \varphi_0)|^2 e^{-j2\pi\Omega\varphi} \, d\varphi \tag{2}$$

Where $Z_T(\varphi, f)$ denotes angle-synchronized short-time Fourier transform of signal $z_T(t, \varphi; \varphi_0)$ given by:

$$Z_T(\varphi, f; \varphi_0) = \lim_{T \to \infty} \frac{1}{T} \int_0^{T} z_T(\varphi, t; \varphi_0) \, e^{-j2\pi f t} \, dt \tag{3}$$

Where $z_T(t,\varphi;\varphi_0)$ is an angular-temporal normalized signal x(t) and is expressed by:

$$z_T(\varphi,t;\varphi_0)=\frac{x\big(t-\tau(\varphi+\varphi_0)\big)w_T(t)-\mu_T(\varphi)}{\sigma_T(\varphi)} \tag{4}$$

For $w_T(t)$ being a windowing function with non-zero values between ${}^{-T}/_{2}$ and ${}^{T}/_{2}$ and $\tau(\varphi)$ denoting angle-fixed time increments used for positioning of the window. Additionally, we define $\mu_T(\varphi)$ as a local angular-temporal mean value of signal x(t) as:

$$\mu_T(\varphi;\varphi_0)=\frac{1}{T}\int\limits_{u=t-\tau(\varphi+\varphi_0)-{}^{T}/_{2}}^{t-\tau(\varphi+\varphi_0)+{}^{T}/_{2}} x(u)\ du \tag{5}$$

and $\sigma_T(\varphi)$ beinglocalized angular-temporal standard deviation of x(t) defined as:

$$\sigma_T(\varphi;\varphi_0)\ =\sqrt{\frac{1}{T}\int_{u=t-\tau(\varphi+\varphi_0)-{}^{T}/_{2}}^{t-\tau(\varphi+\varphi_0)+{}^{T}/_{2}}\big(x(u)-\mu_T(\tau(\varphi)\big)^2\,du} \tag{6}$$

The purpose for transformation of signal x(t) into its angular-temporal normalized version $z_T(t,\varphi;\varphi_0)$ is to remove amplitude fluctuations between different time periods T and as a result obtain standardized distributions for each instances of angle-synchronized short-time Fourier transform. Amplitudes of $z_T(t,\varphi;\varphi_0)$ and magnitudes of $|Z_T(\varphi,f;\varphi_0)|$ are now expressed by the units of local standard deviation $\sigma_T(\varphi;\varphi_0)$. It can be seen that transformed signal $z_T(t,\varphi;\varphi_0)$ preserves