APPLICATION OF ENTROPY-BASED ANALYSIS OF SIGNALS TO IDENTIFICATION OF ROLLING ELEMENT BEARINGS FAULTS

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Summary

The paper deals with an application of entropy of signal in frequency domain to vibroacoustical diagnostics of ball bearings. Crossing of rolling elements over a crack located at one of the raceways is a reason of appearance of a sequence of shocks. Presented method of diagnosing is based on an assumption that impulses, which are results of bearing faults cause instantaneous changes of signal in frequency domain. This changes of signal are estimated with use of entropy of signal in frequency domain. During the research the Shannon entropy and the relative entropy were applied. Distribution of signal in frequency domain was estimated with use Fourier Transform (normalized Power Spectrum Density) or Discrete Wavelet Transform. In the paper the influence of rotational speed of shaft on efficiency of proposed method were presented.

Keywords: vibrations, diagnostics, signal processing, entropy, rolling element bearings.

ZASTOSOWANIE WYKORZYSTUJĄCYCH ENTROPIĘ ANALIZ SYGNAŁÓW DO IDENTYFIKACJI NIESPRAWNOŚCI ŁOŻYSK TOCZNYCH

Streszczenie

Artykuł poświęcony jest zastosowaniu entropii widma sygnału do wibroakustycznej diagnostyki łożysk tocznych. Przetaczanie się elementów tocznych przez lokalne uszkodzenie jednej z bieżni łożyska powoduje wystąpienie szeregu uderzeń. Prezentowana metoda diagnozowania bazuje na założeniu, że impulsy które są wynikiem uszkodzeniem łożyska wywołują chwilowe zmiany sygnału w dziedzinie częstotliwości. Te zmiany są oceniane z wykorzystaniem entropii widma sygnału. W badaniach zastosowano entropię Sharona i entropię względną. Rozkład sygnału w dziedzinie częstotliwości wyznaczano z zastosowaniem transformacji Fouriera (znormalizowane widmo mocy sygnału) albo dyskretnej transformacji falkowej. W artykule przedstawiono wyniki opisujące wpływ prędkości obrotowej wału na wyniki zaproponowanej metody.

Słowa kluczowe: drgania, diagnostyka, analiza sygnałów, entropia, łożyska toczne.

1. INTRODUCTION

Typical failures of rolling bearings can be caused by material fatigue, insufficient lubrication, corrosion or plastic deformation. The most common defects, such as pitting and spalling, are caused by the material fatigue of the bearing raceways. The first symptoms of the bearing defects, related to the material fatigue, are fatigue cracks appearing at contact surfaces of the bearing elements.

Crossing of rolling elements over a crack located at one of the raceways is a reason of appearance of a sequence of shocks. The majority of methods concerning the rolling bearing diagnostics is based on observation and analysis of vibrations caused by these shocks [1, 8].

The impact caused by crossing of rolling elements over a fatigue crack (as a unit delta function) produces a broad spectrum of energy in the frequency domain. Natural frequencies of the bearing elements and housing are excited up to a few dozens kilohertz.

General assumption of the research is that impulses, which are results of bearing faults cause instantaneous changes of signal in frequency domain. This changes of signal will be estimated with use of entropy of signal in frequency domain.

2. ENTROPY OF SIGNAL IN FREQUENCY DOMAIN

The Shannon entropy is a measure of the uncertainty or disorder in a given distribution. Let us now suppose that we have the distribution $\{p_j\}$ of power of signal in frequency domain, for example power spectral density [3].

We define the entropy of signal in the frequency domain as

$$H\ (p) = -\sum_{j=1}^{J} p_j \cdot \log_2[p_j] \tag{1}$$

$$\sum_{j=1}^{J} p_j = 1$$

where:

p_j $(j = 1, 2, \ldots n)$ – distribution $\{p_j\}$ of signal segment in frequency domain, for example power spectral density,

J – the number of the levels of distribution (spectral lines).

Spectral entropy of signal appears as a measure of the degree of order/disorder of the signal, so that it can provide useful information about the underlying dynamical process associated with the signal.

3. THE PROPOSED METHOD OF BEARING DIAGNOSTICS

The successive transformation of signals during the analysis were:

- Division of vibration signal into short segments corresponding to time period of short changes of a signal in frequency domain caused by impacts.
- Estimation of distribution for each short segments in frequency domain.
- Estimation of entropy values of each signal segments.
- Creation vector of entropy values (signal of entropy).
- Spectral analysis of the vector of entropy values.
- Analysis of the values of the spectral lines, whose frequencies are equal to the bearing fault characteristic frequencies.

In the following, the signal is assumed to be given by the sampled values $x = \{x_n, n = 1, 2 \ldots, N\}$, corresponding to an uniform time grid with sampling time Δt.

In order to study temporal evaluation, the analyzed signal is divided in i overlapping temporal windows of length K and for interval L (were K and L are natural numbers). On the basis of laboratory test of bearing with diffrent faults, the best results were obtained when time period of signal windows (short segment) was equal 1 ÷ 4 [ms].

Temporal window number i of signal x one can write $x^i = \{x^i_k\} = \{x_n, n = i \cdot L, i \cdot L+1, \ldots, i \cdot L+K\}$. The number of temporal windows is equal to $I = (N-K)/L$. The time period between two windows is equal to $\Delta t_L = L \cdot \Delta t$.

For each short signal windows $\{x^i_k\}$ distribution of power in frequency domain $\{p^i_j\}$ is estimated. Distributions in frequency domain were estimated with use of Fourier Transform or Wavelet Transform.

In the case of Fourier Transform a normalized Power Spectrum Density represented spectral distribution of signal. In the case of Wavelet Transform in order to obtained an orthogonal results of decomposition a Discrete Wavelet Transform was applied [2, 5].

The number of distribution levels was equal to the number of wavelet decomposition levels. Decomposition was taken up to the level j = 24 or 32. During the research as mother wavelet function was applied the Daubechies 7.

Relative wavelet energy for the resolution level j of spectral distribution p_j is define as

$$p_j = \frac{E_j}{E_{tot}} \qquad (2)$$

where E_j - energy for the resolution level j, E_{tot} – total energy of signal window.

Then entropy values H^i of each spectral distribution $\{p^i_j\}$ is estimated in accordance with the formula (1). The obtained value is assigned to the central point of the time window.

a)

b)

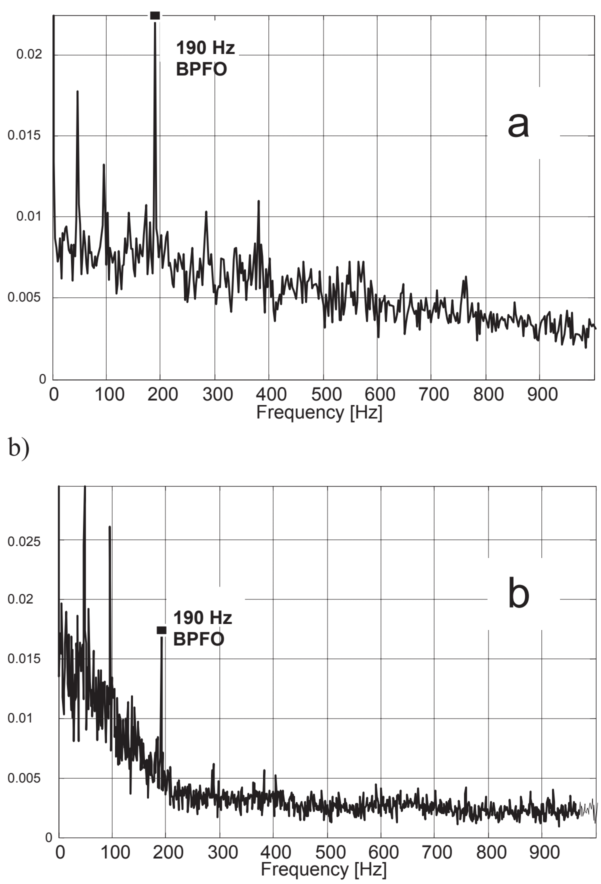


Fig. 1. Spectrum of vector of entropy values while the outer ring had medium fault. Distribution of signal in frequency domain: a - Fourier Transform, b - Wavelet Transform

A vector of entropy values (signal of entropy) is created. The vector included I values with sampling time Δt_L.

Bearings condition is not determined on the basis of maximum value of entropy as effects of bearing faults. Fundamental to its state identification is the frequency of instantaneous changes of entropy value. At the end power spectrum density of the vector of entropy values is estimated.

Confirmation of the bearing fault is a distinct magnitude of this spectral line, whose frequency is equals to the frequency of crossing of a roller over the cracks (bearing characteristic frequency) [7].

Fig. 1 presents obtained results in case of fault of outer ring, while distributions in frequency domain were estimated with use of Fourier Transform and Wavelet Transform. The distinct magnitude of the spectral line whose frequency is very close to the bearing characteristic frequency (BPFO = 192 Hz) confirmed existence of the fault of the outer ring.

Results of preliminary research presented in the Fig. 1 proved that the use of the entropy of signals makes it possible to obtain distinct symptoms of the bearing faults.

4. RELATIVE ENTROPY OF SIGNAL IN THE FREQUENCY DOMAIN

The purpose of analysis is to recognize instantaneous changes of signal in frequency domain. Relative entropy (Kullback – Leibler entropy) gives a measure of the degree of similarity between two distributions [4, 6].

We define the relative entropy between two (basic and reference) distributions in frequency domain of short segments of signal as

$$H_R(p/q) = \sum_{j=1}^{J} p_j \cdot \log_2 \left[\frac{p_j}{q_j} \right] \qquad (3)$$

$$\sum_{j=1}^{J} p_j = 1 \qquad \sum_{j=1}^{J} q_j = 1$$

where:

p_j *(j = 1, 2, … n)* – distribution in frequency domain $\{p_j\}$ of basic signal window,

q_j *(j = 1, 2, … n)* – distribution in frequency domain $\{q_j\}$ of reference signal window,

J – the number of the levels of distribution (spectral lines).

The successive transformation of signals during the analysis with use of relative entropy were:

- Division of vibration signal into basic and reference short windows. In order to study temporal evaluation, the analyzed signal was divided in *i* overlapping basic windows of length *K* and for interval *L* (were *K* and *L* were natural numbers). For each basic window nonoverlapping reference window of length *K* and for interval *L=K* was determined.
- Estimation of distribution in frequency domain of each window.
- Estimation of relative entropy value for each corresponding basic and reference signal window.
- Creation vector of relative entropy values (signal of relative entropy).
- Spectral analysis of the vector of relative entropy values.

Examples of results of the proposed method with use of relative entropy are presented in the Fig. 2. Distinct magnitudes of the spectral lines whose frequencies are equal to the bearing characteristic frequency (BSF = 222 Hz) for the rolling element defect were obtained.

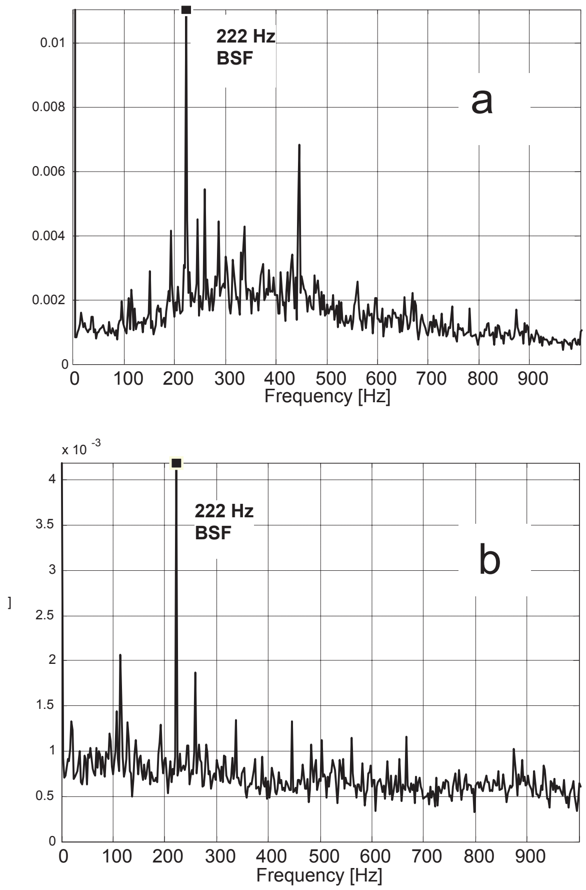


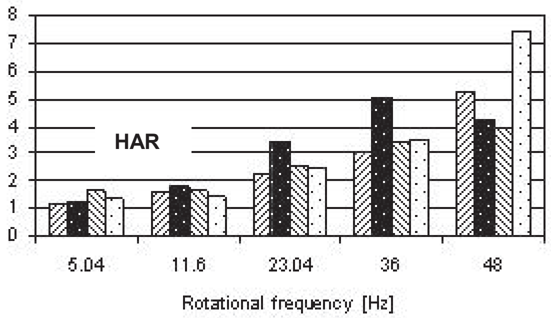
Fig. 2. Spectrum of vector of relative entropy values while the rolling element had medium fault. Distribution of signal in frequency domain: a - Fourier Transform, b - Wavelet Transform

5. IMPLEMENTATION OF THE METHOD

5.1. Analysed signals

Analysed signals were recorded on a laboratory stand. During measurements of vibration signals rotational speed of a shaft was changed. Bearings faults were artificially produced by an electric pen. A radial acceleration signal was picked up from the top of the tested bearing casing by a piezoelectric accelerometer. During measurements of vibration of one bearing 20 records of samples were recorded. Each record included 8192 acceleration values sampled at a frequency equal to 51.2 kHz. MatLab programs were implemented to execute signal analyses.

a)



b)

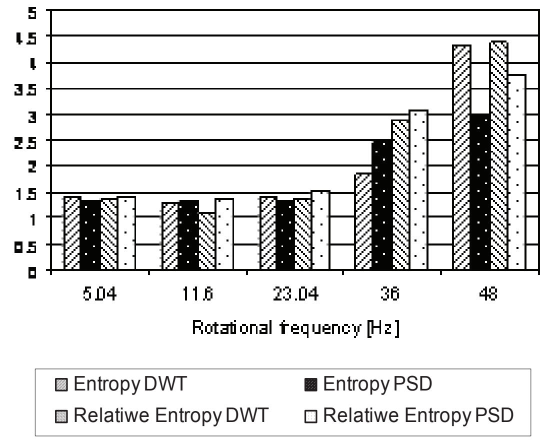


Fig. 3. The influence of rotational speed of shaft on the harmonic amplitude ratio, a – while the outer ring had fault, b – while the inner ring had fault

5.2. Results of bearings diagnostics

The influence of rotational speed of shaft on efficiency of proposed method was presented in Fig. 3. The distinction between the spectral line with the characteristic frequency and adjoining lines was described with application of HAR.

A harmonic amplitude ratio (HAR) is defined as the amplitude value of the spectral line $a(f_k)$, whose frequency is equal to the bearing characteristic frequency, over the average value of amplitude of the spectrum a_{av}

$$HAR = \frac{a(f_k)}{a_{av}} \quad (4)$$

In all cases of application of both entropy and relative entropy the faults of bearings were identified. The best results were obtained while the rotational frequency was high. The reason of that was the difference between the power of impulses produced by a fault.

6. CONCLUSIONS

The paper deals with an application of entropy of signals in frequency domain to identification of ball bearing faults. The main purposes of the research were:

- to prove whether it is possible to diagnose a bearing with the use of measure of changes of vibration signal in frequency domain estimated with application of entropy,
- to determine a set of parameters of signal processing that makes it possible to obtained the best results.

Results of the research presented in the paper proved that the application of the presented method enables us to obtain distinct symptoms of bearing faults.

Practical application of proposed method are:

- detecting failures while additional sources of vibrations (noise) are present,
- detecting faults at the earliest possible stage.

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