BEARING CONDITION DIAGNOSTICS USING ENTROPY OF SIGNAL IN FREQUENCY DOMAIN

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Summary

This paper focuses on the application of entropy of the vibration signal in frequency domain for rolling element bearing defect detection and diagnosis. Impacts, which are results of bearing faults, cause instantaneous changes of vibration signal in frequency domain. Presented method of diagnosing is based on an assumption that mentioned above changes of signal can be estimated with use of entropy of signal in frequency domain. During the research the Shannon entropy and the relative entropy (Kullback – Leibler 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, radial load of bearing and additional noise of signal on efficiency of proposed method was presented.

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

DIAGNOZOWANIE ŁOŻYSK Z ZASTOSOWANIEM ENTROPII SYGNAŁU W DZIEDZINIE CZĘSTOTLIWOŚCI

Streszczenie

Artykuł przedstawia przykłady zastosowania entropii widma sygnału do wibroakustycznej diagnostyki łożysk tocznych. Impulsy drgań, które są wynikiem uszkodzeniem łożyska wywołują chwilowe zmiany sygnału w dziedzinie częstotliwości. Prezentowana metoda diagnozowania bazuje na założeniu, że te zmiany sygnału mogą być oceniane z wykorzystaniem entropii widma sygnału. W badaniach zastosowano entropię Shanona i entropię względną (Kullback – Leibler entropy). Rozkłady sygnałów 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, obciążenia promieniowego łożyska i zakłóceń sygnału na wyniki zaproponowanej metody.

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

1. ROLLING ELEMENTS BEARING VIBRATION

Most modes of failure for rolling-elements bearing involve the growth of discontinuities (fatigue cracks) on the bearing raceway or on a rotating element. Rollers or balls rolling over a local fault in the bearing produce a series of force impacts (a sequence of shocks). The majority of methods concerning the rolling bearing diagnostics are based on observation and analysis of vibrations caused by these shocks [7].

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. These changes of signal can be estimated with use of entropy of signal in frequency domain.

During the research the Shannon entropy and the relative entropy (Kullback – Leibler entropy) were applied. Spectral entropy of signal is 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.

2. THE METHODS OF BEARING DIAGNOSIS

2.1. The method using Shannon entropy

In the following, the signal is assumed to be given by the sampled values $x = \{x_n, n = 1, 2 \dots, N\}$, 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 [1, 4].

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

$$p_j = \frac{E_j}{E_{tot}} \tag{1}$$

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

Then the Shannon entropy values H^i of each spectral distribution $\{p^i_j\}$ is estimated. Entropy is a measure of the uncertainty or disorder in a given distribution. We define the entropy of signal in the frequency domain as [2]

$$H\,(p) = -\sum_{j=1}^{J} p_j \cdot \log_2[p_j] \tag{2}$$

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

where:
p_j (j = 1, 2, ... n) – distribution $\{p_j\}$ of signal segment in frequency domain, J – the number of the levels of distribution.

The obtained value of the entropy is assigned to the central point of the time window. 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) [6].

Fig. 1 presents obtained results in case of fault of outer ring, while distributions in frequency domain were estimated with use of Fourier 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.

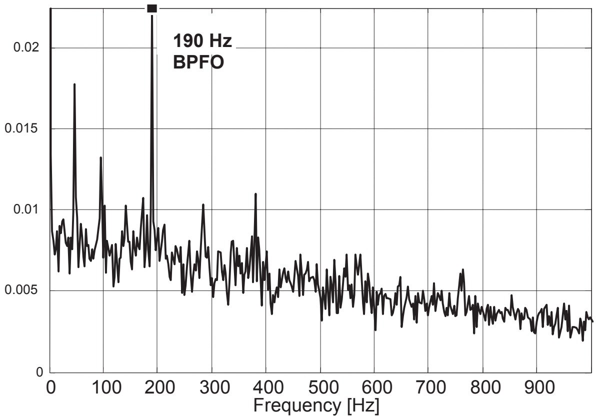

Fig. 1. Spectrum of vector of entropy values while the outer ring had medium fault while distribution of signal was estimated with use Fourier Transform

2.2. The method using relative entropy

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 [3, 5].

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

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

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

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 transformations 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.

3. RESULTS OF BEARINGS DIAGNOSTICS

3.1. Analysed signals

Analysed signals were recorded on a laboratory stand. 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.

3.2. Efficiency of the proposed method of bearings diagnosis

In the chapter the influence of: rotational speed of shaft, radial load of bearing and additional noise of signal on efficiency of proposed method was presented.

As mentioned above confirmation of the bearing fault is a distinct magnitude of this spectral line, whose frequency is equals to the bearing characteristic frequency. 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}

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

The influence of rotational speed of shaft on efficiency of proposed method was presented in Fig. 2. In more 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 powers of impulses produced by a fault in different speed conditions.

Fig. 3 presents obtained results in case of fault of different bearing elements while bearing load in radial direction was changed. The results of the analysis of signals recorded for different loads were similar.

The signals were recorded on a laboratory stand that allows simulating vibration interferences. While the vibrations of bearing were measured vibration interferences (noise) was caused by additional bearing (mounts on the shaft) with large corrosion of the raceways. Shaft rotation velocity was 2900 rpm.

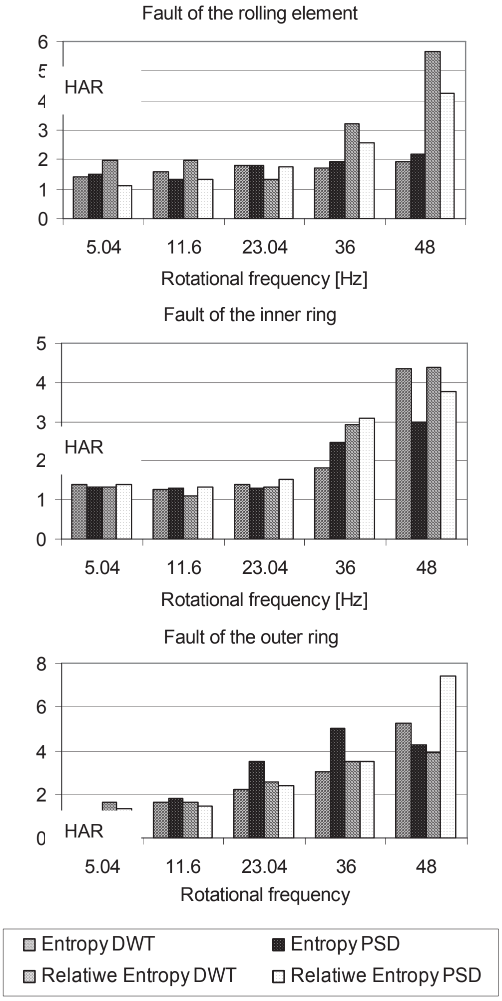

Fig. 2. The influence of rotational speed of shaft on the harmonic amplitude ratio HAR

Fig. 4 presents obtained results while vibration interferences were changed. The influence of additional noise on efficiency of proposed method was small. We can suppose that practical application of proposed method will be detecting failures while additional sources of vibrations (noise) are present.

4. CONCLUSIONS

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.

In more cases of analysis the best results were obtained while the relative entropy (Kullback – Leibler entropy) was applied and distribution of signal in frequency domain was estimated with use Fourier Transform (normalized Power Spectrum Density).

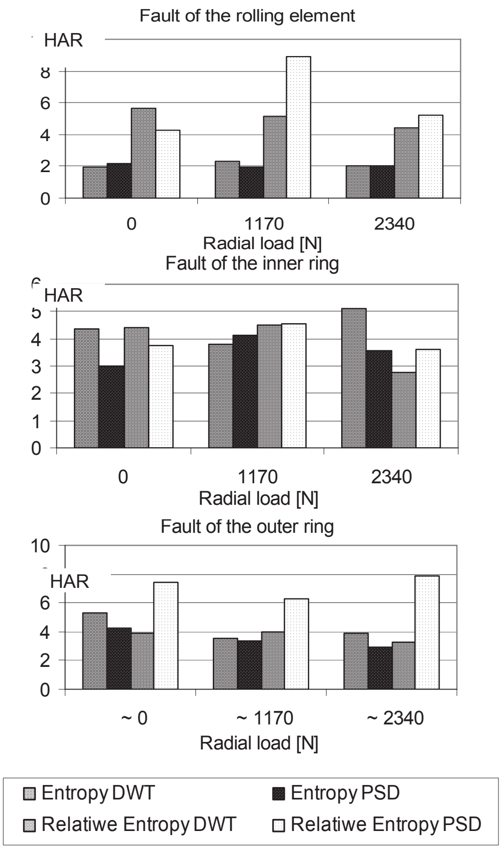

Fig. 3. The influence of bearing load in radial direction on the harmonic amplitude ratio HAR

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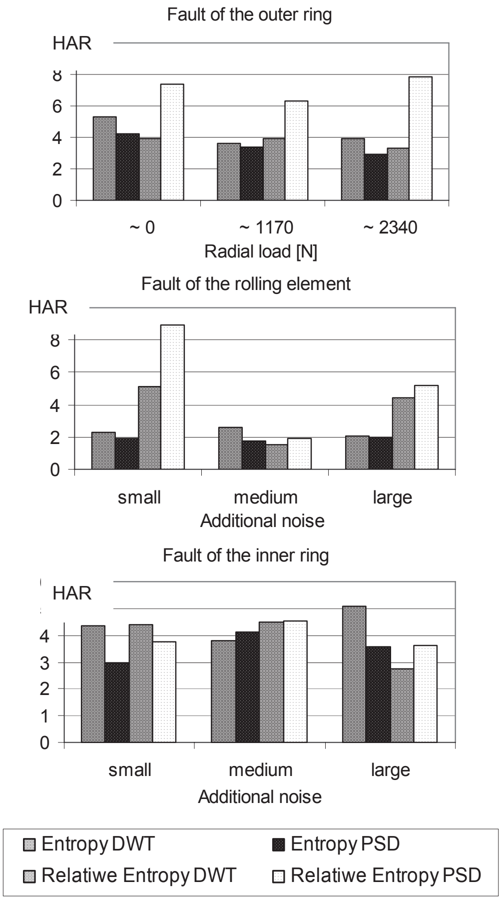

Fig. 4. The influence additional noise on the harmonic amplitude ratio HAR

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