SELECTED METHODS OF FINDING OPTIMAL CENTER FREQUENCY FOR AMPLITUDE DEMODULATION OF VIBRATION SIGNALS

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Summary

The paper concerns the subject of the optimal center frequency selection for the amplitude demodulation, which is a principal tool for detection of bearing faults. In the first part, existing methods along with their advantages and drawbacks are discussed. A special attention is paid to methods implementing kurtosis-based estimators. In following sections, the authors demonstrate a novel method based on the so called "max-med" estimator. The method is validated on a real signal containing a bearing fault signatures.

Keywords: machine diagnostics, amplitude demodulation, kurtosis, median, Protrugram.

WYBRANE METODY ZNAJDOWANIA OPTYMALNEJ CZĘSTOTLIWOŚCI NOŚNEJ
W PROCESIE DEMODULACJI AMPLITUDOWEJ SYGNAŁU DRGAŃ

Streszczenie

Tematyka artykułu dotyczy optymalnego wyboru częstotliwości nośnej w procesie demodulacji amplitudowej, która jest podstawowym narzędziem detekcji uszkodzeń łożysk. Pierwsza część pracy przedstawia obecnie używane metody wskazując ich zalety oraz wady, ze szczególnym uwzględnieniem metod bazujących na kurtozie. W kolejnych częściach pracy autorzy ilustrują nową metodę z wykorzystaniem operatora „*max-med*" (od ang. *maximum-median*). Działanie zaprezentowanej metody jest weryfikowane na sygnale rzeczywistym zawierającym komponenty generowane przez uszkodzone łożysko.

Słowa kluczowe: diagnostyka maszyn, demodulacja amplitudowa, kurtoza, mediana, Protrugram.

1. INTRODUCTION

The amplitude demodulation has been a successful technique in diagnostics of rotating machinery over the years. The development of fast processors has enabled the engagement of highly-memory-consumption signal processing methods with a minor time consumption cost. One of such method is based on narrowband envelope spectra calculated via Hilbert Transform in the frequency domain [1]. The authors have successfully used the method to develop a number of diagnostic algorithms employed in commercial monitoring and vibration system [2].

One of the major advantage of this method is the ability to create a basis for determination of an optimal band for signal demodulation. Frequently, resonance frequencies tend to overlap one another, which complicates the selection of a single frequency band. The authors have proposed the estimator based on kurtosis of the envelope spectrum (in contrary to typical approach, where the kurtosis is used for time signals [3]). In contrast to other techniques engaging kurtosis-based estimators, the method presented in the paper takes advantage of the "max-med" estimator, which emphasizes the presence of characteristic frequencies and its harmonics, and as a result, it provides an aid to the selection of the optimal band for demodulation.

2. EXISTING METHODS

2.1. Db direct spectrum comparison

A comparison of frequency spectra is a relatively old, yet valuable technique for determination of significant spectrum changes. The comparison may be carried out by plotting a difference between a younger and older data. In this matter, spectral regions where amplitude has risen are emphasized. However, the method has got two major drawbacks. Firstly, it is relatively poorly accurate. Secondly, the selection of the optimal spectrum calculation technique from commonly available (*fft*, *psd*, *cpb*, etc.) is not obvious, and may lead to different results depending on a selected spectrum calculation technique.

2.2. Fast Kurtogram

Fast Kurtogram is a relatively new tool, presented by Antoni in 2008 [4]. The tools illustrates the kurtosis-based estimator values representing the peakiness of the filtered envelope time signals for a defined combination of center frequencies and bandwidths. The result of the tool for a single vibro sample is a 2D colormap, where colors represent the kurtosis levels. The main drawback of the method is a high sensitivity to random extraneous components, which can give ambiguous results.

Another version of a kurtogram-based methods was presented by Zimroz in [5,6], where the optimal center frequency (indirect) detection algorithm is divided into "starting" and "ending" frequency. Even though the presented results are satisfactory, once again the kurtosis-based estimator shows the tendency to point out misleading frequency intervals, as stated by Zimroz. One of the solutions is the synchronous averaging, but it may cause the loss of information as well [5].

2.3. Spectrogram

Spectrogram is one of the most common time-frequency analysis map, which illustrates how the spectral density of the signal varies with time. The technique may enable to select the frequency range, where the damped impulses from local faults occur [5]. A spectrogram may be calculated from a sequence of band-pass filters (obsolete) or via STFT (short-time Fourier transform). The latter one is accomplished by breaking up the time signal into intervals (usually overlapping), and calculating the power spectrum for each part. Main drawbacks of the method include: i) the knowledge of the number of intervals into which the signal is to be divided, ii) complicated and time-consuming calculation, iii) frequently challenging interpretation of the resultant color map.

2.4. Protrugram

The Protrugram is a tool developed by the authors in 2009 for optimal center frequency selection [3]. The tool illustrates the kurtosis values of spectral amplitudes of narrowband envelope signals calculated in the frequency domain via Hilbert transform. In the algorithm, the selected bandwidth (as a function of the sought characteristic frequency) is shifted by a defined step (100Hz default), and the narrowband envelope spectrum is recalculated. At each step (i.e. for each center frequency), the kurtosis from all spectral amplitudes is calculated, and is stored in a vector as a single scalar value.

As a result, these kurtosis values are plotted as a function of the center frequency. The major drawback of the method, which is to be overcame in this paper, is the negative influence of harmonic components on the final estimator's value, which in practice is expected to behave in an opposite manner.

3. ENHANCED ALGORITHMS

3.1. Algorithm description

The aforementioned Protrugram algorithm is based on kurtosis values calculated form amplitudes of positive frequencies of a number of narrowband envelope spectra. This solution has the disadvantage of gathering all signal signatures "into a single pot". If the envelope spectrum is not masked by superfluous components, e.g. fundamental harmonics, the method works fine. However, in many cases, the envelope spectrum (even narrowband) will include superfluous components, which may ruin the Protrugram algorithm. One of solutions to the problem is to add an extra step, i.e. an "extraction criterion" to the algorithm.

The authors propose such enhancement to be oriented towards extraction of sought characteristic frequencies from a defined set, which implies a knowledge of the machine kinematic configuration data. Once a particular characteristic frequency is on the spotlight, for a current narrowband envelope spectra, a set of neighborhoods of possible harmonic lines is selected. Next, for each harmonic line, a ratio of the maximum amplitude value of the selected region to the median value of all current narrowband spectrum amplitudes is calculated, and may be multiplied by a weighing function, for instance proportional to the harmonic index, in order to highlight the presence of higher harmonics. It is worth stating that a kurtosis-based estimator may not be used as a selection criterion, since it is a function of number of samples. Therefore in practice, kurtosis estimators require relatively large number of samples, which is contradictory to the idea of single-peak spectral detection.

As endorsed by a many publications [5, 7], it is of additional benefit to emphasize the presence of higher harmonic components, as opposite to the Protrugram criterion, where the presence of additional harmonics lowered the estimator's ultimate value. Finally, it needs to be stated firmly that following algorithm requires a knowledge of the machine kinematics, namely the set of characteristic frequencies.

3.2. Algorithm steps

The algorithm is as follows:

1. Calculate FFT from a given time signal x(t)
2. For a starting center frequency f_i, select amplitudes from a defined bandwidth *BW*, and calculate a narrowband envelope spectrum NES_i via Hilbert transform
3. For each frequency f_i from the set *F*, select the intervals on NES_i of neighboring samples up to the kth harmonic of f_i
4. Calculate the sum of the weighted (weighing function equal to m) ratios of the maximum values of amplitudes from selected interval to the median value of all amplitudes of the current NES_i:

$$Q(NES_i, f_i) = \sum_{m=1}^{k} \left\{ \frac{\max[amp(m \cdot f_i - \delta, m \cdot f_i + \delta)]}{median[amp(NES_i)]} \cdot m \right\} \quad (1)$$

where:

δ - half of the *bw* (i.e. local NES_i bandwidth as opposed to the global *BW*)

NES_i - consecutive narrowband envelope spectrum. The parameter rewers actually to the center current frequency *CF*

amp - spectral amplitudes of $x(t)$

5. Repeat point 3 for all $f_i \in F$
6. Shift the *BW* by a defined step towards the sampling frequency and repeat points 2-5
7. Plot the resultant *max-med* vector as a function of center frequencies, creating an array:

$$PQ \sim f\,(Q(NES_i\,, f_i)) \qquad (2)$$

The center frequencies on the horizontal axis for the largest values on the vertical axis represent frequencies, for which the modulating components are most clearly visible when demodulated. Note that it is most probable to anticipate high *Q* values for relatively high frequencies, i.e. over 2 kHz.

3.3. Algorithm block diagram

Fig. 1 presents the block-diagram representation of the algorithm:

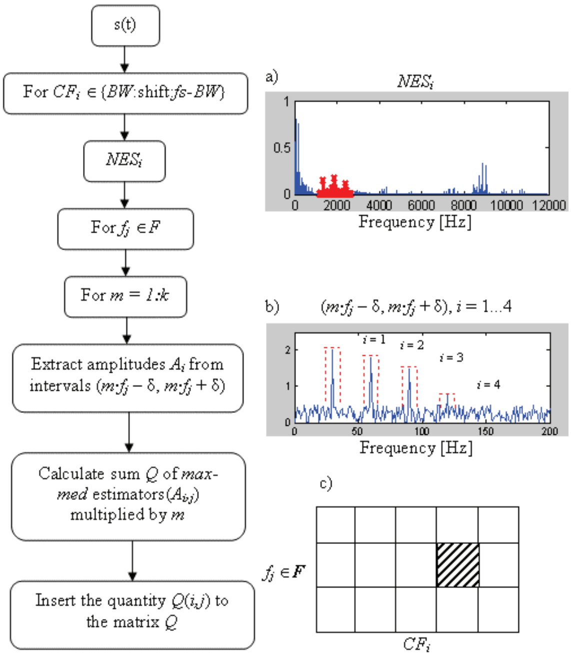

Fig. 1. Block diagram of the proposed algorithm a) Scaled amplitude spectrum (positive frequencies only) with a marked *i*-th demodulated band. b) *I*-th narrowband envelope spectrum with marked harmonic lines of the *j*-th characteristic frequency. c) An illustration of the representation of a single *Q(i,j)* scalar value.

A single hatched area represents a degree of a signal-to-noise ratio for a given characteristic frequency fj demodulated at a center frequency CFi in terms of a sum of weighted kurtosis-based estimators.

Note that the weighing function is linear and equal to the harmonic's number. In consequence, the presence of higher harmonics will be emphasized by the algorithm. For instance, if for a given f_j at NES_i, the max-med values equal to $k_{i,j} = \{11, 7, 3, 2\}$, the resultant *Q(i,j)* will be calculated as $\sum (11\cdot 1),(7\cdot 2),(3\cdot 3),(2\cdot 4) = 42$ (dimensionless).

4. VALIDATION

The algorithm's performance is demonstrated on a real vibration signal on a test rig, with the bearing outer race fault. The signal was recorded with sampling frequency equal to 24 kHz. The data acquisition time was 10 seconds. The characteristic frequency was calculated as follows:

$$BPFO = S\,\frac{N_r}{2}\left(1 - \frac{R_d\cos\phi}{P_d}\right) \qquad (3)$$

where:

N_r = 14

ϕ = 0°

R_d = 7.94 mm

P_d = 45.4 mm

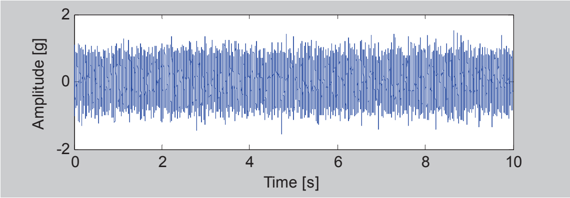

Fig. 2. Time view of the studied signal

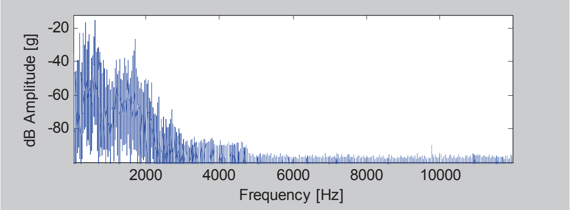

Fig. 3. Amplitude spectrum of the studied signal

Note that both, the time view of the signal as well as the amplitude spectrum do not display a clear information about the fault signature. However, the Fig. 4, presenting the result of the max-med plot, displays unambiguously the presence of harmonic components modulating 4kHz wave.

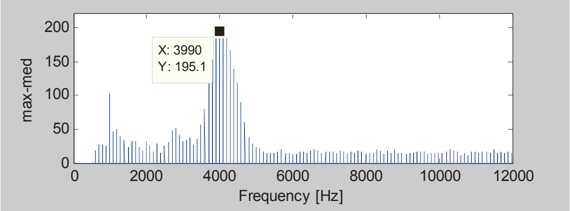

Fig. 4. Max-med plot of the signal under validation. Optimal center frequency equals 3990 Hz

Note: for the clarity of the algorithm, a single characteristic frequency was defined, i.e. $F = \{ f_i \}$. If F contained more than one element, i.e. the algorithm was implemented for a multi-element set of characteristic frequencies, the figures may be plotted "one on the top of another", which is surely readable for up to a dozen figures at one time.

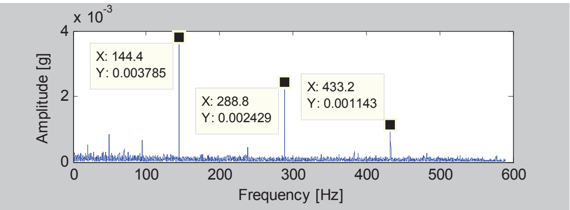

Fig. 5. Narrowband envelope spectrum of the signal for optimal parameters pointed out by the max-med algorithm

The Fig. 5 presents the narrowband envelope spectrum calculated from the band given by the max-med method. The figure clearly shows existence of strong harmonics related to the outer ring fault.

4. SUMMARY

The presented method demonstrates the possible enhancement of the optimal center frequency selection method via a novel "max-med" estimator. The technique enables a more robust selection alternative to existing methods, including Fast Kurtogram and Protrugram, both based on the kurtosis-based estimator.

The authors have shown that kurtosis-based estimators are not feasible for detailed spectral "scanning", since they by definition require large number of samples. The method is yet to be empirically developed in terms of the optimal neighborhood selection δ as a function of the signal length and the sampling frequency, as well as the weighing scale as a function of the number of harmonic lines. Further research concerning the multi-component analysis (e.g. gear meshing frequencies with sidebands) will be conducted by the authors as well.

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