Quantile-based risk measures as a tool for local damage detection in rotating mining machinery

Kwantylowe miary ryzyka jako narzędzie diagnostyki uszkodzeń lokalnych w górniczych maszynach wirnikowych

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Keywords: quantile, risk measures, rotating machinery, local damage

Abstract

In this paper a new method for local damage detection in rotating mining machinery is presented. Complex machines used in mining industry make the use of advanced signal processing necessary. Our approach is an extension of previously used methods based on the time-frequency analysis. Vibration signal of rotating machinery is acquired and then signal processing tools are used to obtain the time-frequency map. It is known that local damage in rotating machinery results in cyclic wide-band excitation that can be noticed in the frequency spectrum. Quantile-based risk measures are proposed to indicate this behavior. The presented procedure is illustrated by real vibration signals acquired from housing of both damaged and undamaged belt conveyor pulley bearings.

Abstrakt

Zaprezentowano nową metodę detekcji lokalnych uszkodzeń w górniczych maszynach wirnikowych. Złożone systemy maszynowe używane w górnictwie wymagają zaawansowanych narzędzi przetwarzania sygnałów. Nasze podejście do tego problemu jest rozwinięciem spotykanych w literaturze metod opartych na analizach czasowo-częstotliwościowych. Wibracje maszyn wirnikowych są
mierzone, a następnie, przy użyciu metod przetwarzania sygnałów, tworzona jest mapa czasowo-częstotliwościowa. Uszkodzenie lokalne maszyny wirnikowej skutkuje cyklicznym szerokopasmowym wzbudzeniem zauważalnym w widmie amplitudowym. Kwantylowe miary ryzyka zostały zaproponowane jako wskaźniki tego zjawiska. Zaprezentowana metoda została zilustrowana na przykładzie wibracji sprawnego oraz uszkodzonego łożyska bębna napędowego przenośnika taśmowego.

1. Introduction

Vibro-acoustics is one of the most leading methods in rotating machinery diagnostics. It provides a lot of local damage detection methods based on non-destructive testing. Usually, they are founded on the idea of signal filtering, i.e. applying an operator for the noisy signal obtaining only the informative part. The basis for many filters is the kurtosis - used as a measure of dispersion in a signal. The prominent examples that incorporate this idea are the spectral kurtosis [1-3] and the fast kurtogram [4]. We propose to use quantile based risk measures as indicators of uncommon behavior of the signal. They are widely-used in finance where a lot of attention is paid to the outlying events finding. It is known that the kurtosis is sensitive to single accidents which may occur during the measurement under industrial, e.g. mining, conditions. The analysis performed in this paper will show sensitivity of quantiles versus fourth central moment to single undesirable excitations. Also the ability of distinguishing damaged machinery from healthy will be checked.

The paper is organized as follows. Description of the methodology is contained in Section 2. In the next section we present analysis of the belt conveyor pulley bearing’s signal. Also theoretical properties of methodology are confirmed. The last section contains conclusions.

2. Methodology

One of the most known methods used to indicate wide-band cyclic excitation is kurtosis. Many studies have shown that the spectral kurtosis (SK) calculated as a normalized fourth central moment of time series of each frequency bin can be useful in local damage diagnostics [2-3]. In the case of signal from locally damaged rotating machinery some time series of time-frequency map should reveal leptokurtic feature. Otherwise, no time series should be distinguished as informative in the sense of local damage detection. In fact, kurtosis is very sensitive to non-cyclic excitations that can be observed when the measurements are performed under industrial conditions, e.g. during normal
operation of the machine in an open pit mine. In this case certain frequencies will be selected as very informative, although there are no wide-band excitations.

In this paper we present an alternative way to distinguish frequency bands that are informative in the case of local damage detection. Our method is based on quantile-based risk measures, which are widely-used in quantitative finance. In this approach we apply these measures as indicators of outliers in time series from the time-frequency map. We focus on the Expected Shortfall – a fundamental risk measure which is the base of distortion risk measures [5]. It can be interpreted as an arithmetic mean of given percentage of the highest values. Analytical formula for $ES_\alpha$ is:

$$ES_\alpha(X) = E[Y],$$

(1)

where $Y$ is a random variable which cumulative distribution function is $F_Y = f \circ F_X$, where $F_X$ denotes CDF of $X$ and $f(x) = \max\left(\frac{x-1}{\alpha}, 0\right)$. If distribution of $X$ is continuous, then $ES_\alpha(X)$ is just the expected value of $100\alpha\%$ percent values from the right tail of distribution of $X$. In the mixed or discrete case a little correction must be used to preserve properties of Expected Shortfall. For a sorted in descending order random sample $X_1, X_2, \ldots, X_n$ formula for $ES_\alpha$ is as follows [6]:

$$ES_\alpha(X) = \frac{1}{\alpha} \left( \left[ \frac{n\alpha}{n} \right]^{-1} \sum_{i=1}^{\left[ \frac{n\alpha}{n} \right]} X_i + (n\alpha - \left[ \frac{n\alpha}{n} \right] + 1)X_{\left[ \frac{n\alpha}{n} \right]} \right).$$

(2)

In fact, some time series exhibit sinusoidal pattern, thus they do not represent vector of independent and identically distributed random variables. In this case one cannot use formula (2), which is defined for i.i.d. series. Because of lack of information about wide-band excitations in those time series we decided to treat them as completely uninformative, i.e. value of selector is set to 0. We propose sample autocorrelation function as an indicator of determinism. A slice is said to be deterministic if its autocorrelation function exceeds confidence intervals in a significant way.

It is known that different frequency bins contain different levels of energy. Most of energy is related to low frequencies, which are considered to represent deterministic behavior of rotating machinery. High-frequency bins contain low-energy noise. Therefore, the pure Expected Shortfall will result in the highest value of selector for frequencies that carry the highest energy. To avoid this
undesirable behavior we propose to normalize each time series by its sample mean and standard deviation. It is noteworthy that if the variance is caused by several outliers (leptokurtic case), mean of high-order quantiles of normalized time series might be lower than in the non-leptokurtic case.

3. Real data analysis

In this section we will present results of our methodology on a real data set. Signals that we will analyze represent vibrations of conveyor belt pulley bearings. One of them is known to be locally damaged and the second one is healthy. In fact, vibrations of a bearing can be hardly isolated when the mechanical system is complex, e.g. other machinery is mechanically connected with the bearing. In our case a gearbox is located nearby bearings, which results in strong contamination in the acquired signal. What is more, load of the conveyor belt is changing in time, so it is very difficult to make a model of the signal of gearbox and obtain signal of the bearing as residual. Analysis of these signals is the subject of several previous papers [7-10]. One can find broader description of the machinery there as well as different approaches tested on the same dataset.

Recall, that sampling frequency is 19.2 [kHz] and duration of both signals is 2.5 [s]. Number of FFT points used to calculate time-frequency map is $N_{FFT} = 1024$. We decided to use non-overlapping Kaiser windows of length 125 to avoid additional dependency in time series. Expected fault frequency is
12.69 [Hz] which results in about 31 wide-band excitations on the time-frequency map. During the healthy bearing signal acquisition no undesirable signals of wide-band character were observed. Time-frequency maps corresponding to healthy and unhealthy bearing are presented on Fig. 1. One can see wide-band character of impulsive local damage signal as well as high-energy low-frequency contamination from gearbox visible in both spectrograms.

Theoretical fact that un-normalized value of the quantile-based risk measure is useless in frequency band selection is illustrated on Fig. 2.

Fig. 2 $ES_\alpha$: pure (left panel) and normalized by mean and standard deviation (right panel).

Fig. 3 Kurtosis (left panel) and final selector based on $ES_\alpha$ (right panel).
Value of pure $ES_\alpha$ strongly depends on energy contained in a given frequency band. $ES_\alpha$ normalized by mean and standard deviation exhibit easily seen difference between analyzed signals.

To set up a filter, the relationship between “healthy” and “unhealthy” signal has to be expressed by values between 0 and 1. Values of selector should be close to 1 for informative frequency bands and close to 0 elsewhere. Fig. 3 shows values of analyzed selectors ready to prepare a filter. It is obtained as Fig. 2 with vertical axis inverted and scaled appropriately. One can see that our selector has reduced false-positive error presents in kurtosis. Thus, setting the threshold of selector value that distinguishes “healthy” from “unhealthy” signal is easier.

4. Conclusion

In this paper a procedure of local damage detection in rotating mining machinery is presented. It is based on informative frequency band selection. The methodology presented here is an extension of selecting frequency bins based on kurtosis. Instead of kurtosis, we proposed to use Expected Shortfall – a widely-used quantile based risk measure. Some post-processing was necessary to obtain frequency response of a linear filter that distinguishes the damaged machinery from healthy. Our novel selector results in a greater difference between signals representing damaged and healthy bearing. Also a false-positive error of kurtosis is reduced which is a serious advantage in establishing a threshold between “healthy” and “unhealthy” signal.

References:


