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The local maxima method for enhancement of time–frequency map and its application to local damage detection in rotating machines

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ABSTRACT

In this paper a new method of fault detection in rotating machinery is presented. It is based on a vibration time series analysis in time–frequency domain. A raw vibration signal is decomposed via the short-time Fourier transform (STFT). The time–frequency map is considered as matrix $(M \times N)$ with N sub-signals with length M. Each sub-signal is considered as a time series and might be interpreted as energy variation for narrow frequency bins. Each sub-signal is processed using a novel approach called the local maxima method. Basically, we search for local maxima because they should appear in the signal if local damage in bearings or gearbox exists. Finally, information for all sub-signals is combined in order to validate impulsive behavior of energy. Due to random character of the obtained time series, each maximum occurrence has to be checked for its significance. If there are time points for which the average number of local maxima for all sub-signals is significantly higher than for the other time instances, then location of these maxima is "weighted" as more important (at this time instance local maxima create for a set of Δf a pattern on the time–frequency map). This information, called vector of weights, is used for enhancement of spectrogram. When vector of weights is applied for spectrogram, non-informative energy is suppressed while informative features on spectrogram are enhanced. If the distribution of local maxima on spectrogram creates a pattern of wide-band cyclic energy growth, the machine is suspected of being damaged. For healthy condition, the vector of the average number of maxima for each time point should not have outliers, aggregation of information from all sub-signals is rather random and does not create any pattern. The method is illustrated by analysis of very noisy both real and simulated signals.

1. Introduction

In this paper a new method of localized damage detection in rotating machinery is presented. The most frequent medium for such damage detection is still vibration signal (acceleration) [1,2]. The basis for localized damage detection is the assumption that two surfaces being in touch (rolling element and inner/outer race, two teeth from gear-pair, etc.) during

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sliding/rolling generate shocks due to damage of one of the surfaces. Such a local change of stiffness results in singularity in the signal. From theoretical point of view, one should expect impulse in time domain for time instance when damaged part is in contact. For rotating machines (gears, bearings) the signature of local damage is a series of impulses with period (or more general cycle) related to the so-called fault frequency [3].

One might consider a diagnostic scheme: (i) detect impulsive nature of the signal, (ii) check if there is periodic nature of disturbance and try to match it to expected fault frequencies in the machine. Unfortunately, in practice, such a cyclic impulse train can be hardly seen. There are two main possible reasons. First, one might not see impulses due to weakness of such disturbance and the level of noise present during the experiment – this case is called ”detection of damage at early stage”. Second, damage is in developed form, however, due to high level of noise coming from the other part of machine or other machines, diagnostic information is completely masked/hidden.

From methodological point of view, the problem is the same for both cases. One needs to “extract” informative signal from mixture of signals coming from different sources [2,4–18]. By “noise” in such a context one might consider narrowband contribution (discrete frequencies) coming from shaft, mesh, resonance, ghost, etc. components, wide-band Gaussian noise, or others. The most reasonable approach is to design a filter that would be able to extract the signal of interest [12–16,19,20]. However, the task could also be defined as “information” extraction (not exactly “signal” that contains information). In such a context one might model the signal, or try to analyze properties of the signal using another signal representation.

In this paper a raw vibration signal is decomposed via the short-time Fourier transform. Time–frequency representation is very reasonable method of non-stationary signal analysis [9–11,21–27]. The STFT method is the simplest, the most intuitive for engineers and it will be used in the paper to present the algorithm [21]. However, it should be said that there is no objection to apply the proposed approach to another time–frequency representation as Wigner–Ville or time-scale [28] one.

When the signal is represented by the STFT time–frequency plane, it can be interpreted as energy flow in time for a set of frequency bins Δf. One might expect that due to damage related shocks impulses invisible in time domain will be present in the time–frequency plane, as wide-band (for family of frequency bins Δf) disturbances occurred in a cyclic way. Unfortunately, when the signal-to-noise ratio is really poor (amplitudes of impulses are small in comparison to energy of non-informative sources) changes of energy are too small to be seen on the map clearly.

In practice, even time–frequency representation of complex signal may require some extra activities, i.e. enhancement of time–frequency plane readability before feature extraction and decision making. This is the case for the analyzed signals. It has given “an impulse” for searching a way to “enhance” time–frequency map and ”extract” information about cyclic, impulsive behavior at some frequency range.

In this paper a novel method of spectrogram enhancement and extraction information required for local damage detection in rotating machinery is proposed. The basic idea comes from the interpretation of STFT map as a set of sub-signals (one signal for frequency bin Δf) with much smaller complexity and application of simple tools as local maxima finder for each sub-signal separately. Local maxima are searched because a local increase of energy is expected when damage occurs. So basically it can be said that the signal is “decomposed” into a set of sub-signals, each sub-signal is processed/analyzed in order to check if for investigated frequency bin Δf an impulsive energy exists and finally information for all sub-signals is fused in order to validate impulsive behavior of energy. Local maxima finder is looking for the local maximum value of sub-signal in short moving window. It might happen that as a result one might obtain a set of random maxima. So, due to random character of the obtained time series, each maximum occurrence must be checked for its significance.

Validation of local maxima detection is done by comparison of results obtained for different sub-signals. If there are time points for which the average number of local maxima for all sub-signals is significantly higher than for the other time instances, then location of these maxima is “weighted” as more important (this time instance creates a pattern on the time–frequency map).

This information, called vector of weights, is used for enhancement of spectrogram. When vector of weights is applied for spectrogram, non-informative energy is suppressed while informative features on spectrogram are enhanced. If the distribution of local maxima on spectrogram creates a pattern on wideband cyclic energy growth the machine is suspected of being damaged. For healthy condition, the vector of the average number of maxima for each time point should not have outliers, aggregation of information from all subsignals is rather random and does not create any pattern. The method is illustrated by analysis of very noisy both real and simulated signals.

The paper is organized as follows: in Section 2 a proposal of new time–frequency map enhancement procedure is presented. Section 3 contains analysis of simulated data according to the presented procedure. In Section 4 we describe the experiment while in Section 5 we present the results for the described real data. In Section 6 we present the discussion and the last section contains conclusions.

2. Methodology

In this section we present in detail the local maxima method which was previously based on non-overlapping windows in short time Fourier transform [4]. Here we describe how to adapt it to highly overlapping windows. The local maxima method starts with a transformation which converts a signal in time domain into a two-dimensional map (time–frequency), where spikes in time domain become wide-band excitations. In this paper we use the short-time Fourier transform that is