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A novel method for speed recovery from vibration signal under highly non-stationary conditions

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ABSTRACT

Many engineering structures operate under non-stationary conditions resulting in signals containing time-varying frequency components. Analysis of such signals in time or frequency domain naturally yields smeared results. Typically implemented solution to this problem is the angle and order domain analysis. However, in some scenarios, acquisition of speed signal may be not available, due to practical limitations. If the speed fluctuations are limited, or recorded vibrational signal is free from environmental and measurement disturbances, it is possible to extract the speed signal from raw time waveforms. State-of-the-art methods include e.g. semi-automatic tracking of the ridges of the Short-Time Fourier Transform for speed signal reconstruction. However, these methods can fail if the time-varying frequency components cross with each other. Moreover, it is very common that complicated structures operating in non-stationary conditions are controlled by sophisticated electronic systems, which can introduce constant frequency noise to the measuring equipment. This can lead to some interference of these time-invariant and time-variant frequency components. The paper presents a simple and easy way to use a tool for hand selection and tracking of desired components, thus making complex time-frequency filtration easy. Finally, instantaneous frequency is calculated with use of Centre Moments of Frequency to extract the speed signal. The presented method shows how a particular tool developed within 3-dimensional image processing branch could be implemented in analysis of 2-dimensional signals characterized by time-frequency varying components.

1. Introduction

Vibration signals are nowadays broadly employed for the purpose of rotary machinery diagnostics [1–3]. Most of the state-of-the-art methods (e.g. time-synchronous averaging, order analysis) require, however, either a constant speed during measurements [4] or precise speed reference [5]. Satisfying the former condition is challenging in many practical cases, as many machines operate under variable loads, which causes fluctuations of the instantaneous speed. Latter case requires usage of tachometers, which in some cases are impossible to mount.

It is possible to overcome these issues by recovery of speed information from a vibrational signal itself. There are multiple approaches to perform this task. Early contributions to the area were summarized e.g. in a general review by Boshash [6,7]. Recently, numerous other approaches of speed tracking were proposed. Milloz et al. used for this purpose time-frequency distributions segmentation [8,9]. Time-frequency approach was employed also by Zimroz et al. [10].

Yang et al. proposed method for feature extraction of varying speed of rotating machinery that can be used for fault detection based on parametrized time-frequency analysis [11]. Another interesting fault diagnosis method based on sparse signal decomposition utilising multi-scale chirplets was proposed by Peng et al. [12].

Very interesting approach for steady-state or small speed fluctuation conditions utilizing spectrum correlation was proposed by Lin [13]. Another approach was proposed by Bonnardot et al. [14] and extended by Combet and Gelman [15]. Its principle of operation require a signal to be bandpass filtered around one selected harmonic of the mesh frequency. Such demodulation allow for precise speed reference provided that variations of shaft speed are relatively small (less than 1%). Moreover, since the method takes into account only one selected narrow frequency band, it is vulnerable to modulations caused by load variations or vibration signal transmission path. A more robust method that operates on the whole spectrum at once and is based on speed-gap estimation via scale transform [16] was proposed by Combet and Zimroz [17,18]. Still, it is not recommended to use the method in case of large speed fluctuations [17].

Several of speed-tracking algorithms were compared in papers by

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Coats et al. [19] and Urbanek et al. [20].

Recently, another approach was proposed by Urbanek et al. [21]. It is a two-step procedure that involves angular spectrogram-based re-sampling of a vibration signal and then frequency demodulation in one selected narrow band that contain selected component of the signal.

The aim of this paper is to present a new method of speed estimation based on vibration signal taking advantage of a concept of Region of Interest (ROI) selection around any of the signal components visible in time-frequency representation. It can be used in cases of high speed variations. With respect to Urbanek's method, less signal processing steps are required to calculate speed estimate. Moreover, the method handles cases when time-varying frequency components cross with invariant ones (e.g. caused by environmental factors) or when broadband impulse excitations appear during signal acquisition. Detailed description of the method and two other selected, different, most recent state-of-the art methods is be provided within the article. The methods are compared with one another on the basis of three different industrial examples.

The organization of the paper is as follows: Section 2 introduces the method; Section 3 provides comparison of the scope of the proposed method with scope of selected state-of-the-art literature-based solutions; Section 4 provides experimental validation of the methods; conclusions are given in Section 5. Codes and data required for reproduction of the research are provided in an Appendix A.

2. Speed signal extraction algorithm

In this section, a novel speed signal extraction algorithm is presented step-by-step. At first, Short-Time Fourier Transform (STFT) is used for calculation of time-frequency distribution. Following ROI is hand selected as a polygon, which could be easily achieved with the use of *Matlab* by recently introduced *impoly* function [22]. On the basis of the selected ROI, centre moments of frequencies [6] are used for extraction of the speed along time variable of the time-frequency distribution. Optional step is the simple smoothing of the results, e.g. with moving average filter.

2.1. Time-frequency distribution

The well-known STFT of the vibration signal $x(t)$ is defined as

$$X(\tau,f) = \int_0^t x(t)w(t-\tau)e^{-2j\pi ft}dt \tag{1}$$

where t is time variable, τ is transform operator, f is frequency variable, j is complex variable, and $w(t-\tau)$ is a Hann (also known as "Hanning") window. For this application practical implementation of the STFT utilises concept of filter banks along with zero-phase filters [23]. With use of this implementation STFT will not be limited to predefined frequency bins related to the combination of the sampling frequency and length of time frame for analysis. Additionally, resulting time-frequency distribution will be defined in every time sample assuring phase alignment of all of the samples, which could easily be used for signal reconstruction and phase demodulation for purpose of estimation instantaneous frequency. Authors found that for this application, finally obtained results are of higher quality when utilising centre moments of frequency rather than with use of the signal reconstruction followed by the estimation of instantaneous frequency by means of Hilbert transform. *Matlab* code of this implementation is given in Appendix A.

On the basis of above defined STFT, generally known time-frequency auto-power spectrum (AP) of a vibration signal is defined as

$$AP_{XX}(\tau,f) = X(\tau,f)X^*(\tau,f) \tag{2}$$

where asterisk in superscript $*$ denotes complex conjugate. Time-frequency auto-power spectrum contains informations about time-frequency energy distribution.

2.2. Selection of region of interest

The ROI is a concept commonly known from the 2D/3D image processing techniques, that has found its applicability in processing of signals in time-frequency domain, composed of time-frequency varying components. Properly selected ROI should include the area of time-frequency distribution that contains one continuous trace of interest, which describes the changing speed of the machinery. In many cases it is impossible to select just one continuous trace, due to time-frequency component crossings. To overcome this problem operator have to take into the account peripheral information, e.g. trends of higher or lower orders of the same trace, to make a proper selection of ROI. The ROI selection could be done conveniently with use of the *impoly Matlab* function [22]. To achieve this, a time-frequency auto-power spectrum should be plotted as an image, e.g. with *imagesc Matlab* function [24]. ROI could be extracted via *createMask Matlab* method [25]. ROI has the very same dimension as the auto-power spectrum. On the basis of time-frequency auto-power spectrum and ROI, a new time-frequency plane $AP_{filtered}(\tau,f)$ is obtained as

$$AP_{filtered}(\tau,f) = AP_{XX}(\tau,f)ROI(\tau,f) \tag{3}$$

where $ROI(\tau,f)$ is a mask function from *createMask Matlab* method [25]. Time-varying component, on basis of which speed signal is extracted, could be selected arbitrarily, i.e. it does not have to be a typical $1st$ order of revolutions as discussed in [21]. Selection of TVC (time varying component) is particularly important in diagnostics of gearboxes because higher orders, e.g. Gear Meshing Frequency (GMF), are the most dominant in typical rotary machinery vibration signal and thus can be better suited for speed extraction purpose.

2.3. Centre moments of frequency

Centre moments of frequency defined as [6]

$$f^n(\tau) = \frac{\int_{-\infty}^{+\infty} f^n|AP_{XX}(\tau,f)|^2df}{\int_{-\infty}^{+\infty} f|AP_{XX}(\tau,f)|^2df} \tag{4}$$

where n is the n^{th} harmonic order, which should be normalised as

$$f(\tau) = \frac{f^n(\tau)}{n} \tag{5}$$

Centre moments of frequency could be interpreted as instantaneous frequency for given time instance τ.

2.4. Optional smoothing

Final step considers smoothing of the obtained instantaneous frequency. Simple moving average filter could be used for this

$$f_s(t) = \frac{f\left(t-\frac{l}{2}\right) + f\left(t-\frac{l}{2}+1\right)+...+f\left(t+\frac{l}{2}\right)}{l} \tag{6}$$

where ω_s is smoothed instantaneous frequency, l is length of the moving average filter.

This step is required only for the relatively complex signals containing time-frequency component crossings, in most cases this step could be omitted.

3. Comparison of methods

In this section, the proposed method is compared with the selected state-of-the-art methods. At first algorithms of methods are shortly described and compared, secondly range of application of methods is presented and discussed, lastly limitations will be pointed out.