MULTI-SCALE ENVELOPING SPECTROGRAM FOR BEARING DEFECT DETECTION

Ruqiang Yan and Robert X. Gao*
Department of Mechanical and Industrial Engineering
University of Massachusetts
Amherst, MA 01003, USA
* Phone: (413) 545-0868; Email: gao@ecs.umass.edu

ABSTRACT
This paper presents a new signal processing technique for bearing defect detection, called Multi-Scale Enveloping Spectrogram (MUSENS). The technique decomposes vibration signals measured on rolling bearings into different scales by means of a continuous wavelet transform (CWT). The envelope signal in each scale is then calculated from the modulus of the wavelet coefficients. Subsequently, Fourier transform is performed repetitively on the envelope of the signal at each scale, resulting in an “envelop spectrum” of the original signal at the various scales. The final output is a three-dimensional scale-frequency map that indicates the intensity and location of the defect-related frequency lines.

INTRODUCTION
Bearing defect detection, severity assessment, and remaining service life prediction have been major research topics for the past decades. Of the various types of parameters considered indicative of defective bearing operations, vibration has been widely investigated, as it directly reflects upon the dynamics of the bearing structure, and hence serves as an effective indicator of potential bearing failures.

Every time when rolling elements (balls or rollers) in a bearing roll over a structural defect (e.g. crack or spalling) on the surface of bearing raceways (inner or outer), a series of impacts will be generated due to the interactions between the two objects. Traditionally spectral analysis based on Fourier Transform, while able to identify the Defect Characteristic Frequency (DCF) caused by the repetitive impacts, faces difficulty when noise contamination and interference from mechanically coupled structures compromise the signal-to-noise ratio. Frequencies related to such resonance modes are often located in higher frequency regions than those caused by vibrations from other structural components, and are characterized by energy concentration within a relatively narrow band centered at one of the harmonics of the resonance frequency, as illustrated in Fig. 1(a) and (a’). By utilizing such mechanical amplification provided by structural resonances, defect-induced vibrations can be separated from background noise and interference (Fig. 1(b) and (b’)). A subsequent demodulation operation will extract the corresponding envelope of the defect-induced vibrations (Fig. 1(c)). Finally, Fourier transform can be performed on the envelope signal to identify the repetitive occurrence of the DCF component, which is characteristic of the existence of localized structural defect (Fig. 1(d)).

While envelope extraction has been traditionally implemented by rectifying and low-pass filtering the band-pass filtered, defect-induced vibration signals, Hilbert transform has shown to present a good alternative to forming a signal’s

these techniques require a priori knowledge about the possible location of defect-related frequency lines in order to determine the size of the analysis windows. In practice, such determination is satisfied only through a trial-and-error process.

Comparing to STFT or RFT where predetermined, fixed time interval is used for signal analysis (which leads to fixed time-frequency resolution), the wavelet transform enables flexible time-frequency resolution through its scaling operations. This paper introduces a new, wavelet-based signal decomposition technique called Multi-Scale Enveloping Spectrogram (MUSENS), which combines the advantages of wavelet transform, spectral analysis, and color mapping techniques for more effective bearing defect detection.

METHODOLOGY
For localized bearing defects detection, spectral analysis of the signal’s envelope has been widely employed [2]. This is based on the consideration that structural impacts induced by the localized defect often excite one or more resonance modes of the structure, which are amplitude-modulated by the DCF. Frequencies related to such resonance modes are often located in higher frequency regions than those caused by vibrations from other structural components, and are characterized by energy concentration within a relatively narrow band centered at one of the harmonics of the resonance frequency, as illustrated in Fig. 1(a) and (a’). By utilizing such mechanical amplification provided by structural resonances, defect-induced vibrations can be separated from background noise and interference (Fig. 1(b) and (b’)). A subsequent demodulation operation will extract the corresponding envelope of the defect-induced vibrations (Fig. 1(c)). Finally, Fourier transform can be performed on the envelope signal to identify the repetitive occurrence of the DCF component, which is characteristic of the existence of localized structural defect (Fig. 1(d)).
envelope [3]. Performing Hilbert transform on a signal leads to the formulation of a corresponding analytic signal, with its real and imaginary parts being the original signal itself and the Hilbert transform of the signal, respectively. The modulus of the analytic signal represents the signal’s envelope. Such a technique, however, requires that appropriate filtering bands be chosen upfront to obtain consistent results under varying machine operating conditions, because changes of machine operation conditions will cause different resonance modes to be excited.

Wavelet transform essentially measures the “similarity” between the signal being analyzed and the scaled mother wavelet, thus can be viewed as a band-pass filter that can extract specific information from a time series, e.g. defect-induced vibrations. Since the imaginary part of a complex wavelet [4] is inherently the Hilbert transform of its real part, the wavelet coefficients of a transformed signal, in which the complex wavelet is used as the mother wavelet, are analytic in nature, and their corresponding modulus forms the signal’s envelope. Therefore, a complex wavelet-based signal transformation combines the ability of band-pass filtering with envelope. Since the imaginary part of a complex wavelet signal represents the signal’s envelope, with its real and imaginary parts being the original signal itself and the Hilbert transform of the signal, respectively. The modulus of the enveloped signal then can be obtained by performing the Fourier transformation on the wavelet coefficient modulus of the signal at the various scales (as illustrated in Fig. 3), resulting in a three-dimensional scale-frequency map that indicates the intensity and location of the defect-induced frequency lines, and improves the consistency of localized bearing defect detection.

Wavelet transform essentially measures the “similarity” between the signal being analyzed and the scaled mother wavelet, thus can be viewed as a band-pass filter that can extract specific information from a time series, e.g. defect-induced vibrations. Since the imaginary part of a complex wavelet [4] is inherently the Hilbert transform of its real part, the wavelet coefficients of a transformed signal, in which the complex wavelet is used as the mother wavelet, are analytic in nature, and their corresponding modulus forms the signal’s envelope. Therefore, a complex wavelet-based signal transformation combines the ability of band-pass filtering with envelope. Since the imaginary part of a complex wavelet signal represents the signal’s envelope, with its real and imaginary parts being the original signal itself and the Hilbert transform of the signal, respectively. The modulus of the enveloped signal then can be obtained by performing the Fourier transformation on the wavelet coefficient modulus of the signal at the various scales (as illustrated in Fig. 3), resulting in a three-dimensional scale-frequency map that indicates the intensity and location of the defect-induced frequency lines, and improves the consistency of localized bearing defect detection.

EXPERIMENTAL EVALUATION

Vibration signals were measured from an SKF6207 deep groove ball bearing with a seeded defect of 0.2 mm on the outer raceway. The signals were sampled at 16 kHz, under a bearing rotational speed of 500 rpm. Based on the geometrical dimension of the bearing, the repetitive DCF component was calculated to be at 29.7 Hz. As illustrated in Figure 3, such a DCF component could not be identified by the conventional Fourier transform. Applying the developed enveloping spectrum analysis technique where the complex Morlet wavelet was chosen as the mother wavelet, a three-dimensional scale-frequency map was obtained (Figure 4), which clearly indicate the existence of the 29.7 Hz DCF component and its harmonics at various scales.

CONCLUSIONS

A wavelet-based Multi-Scale Enveloping Spectrogram technique, which enables a multi-domain, multi-scale signal decomposition and representation, has been investigated. Experimental study has shown that the presented technique could effectively detect bearing structural defect. In addition to bearing diagnosis, the presented technique is generally applicable to rotating machine diagnosis, such as spindles and gearboxes, where vibrations are caused by periodic structural interactions between the defects and rotating machines.

REFERENCES