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Multicomponent decomposition of a time-varying acoustic Doppler signal generated by a passing railway vehicle using Complex Shifted Morlet Wavelets

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ABSTRACT

Complex Shifted Morlet Wavelets (CSMW) present a number of advantages, since the concept of shifting the Morlet wavelet in the frequency domain allow the simultaneous optimal selection of both the wavelet center frequency and the wavelet bandwidth. According to the proposed method, a cluster of CSMW wavelets is used, covering appropriate ranges in the frequency domain. Then, instead of directly processing the instantaneous frequency of each CSMW, an invariance approach is used to indirectly recover the individual harmonic components of the signal. This invariance approach is based actually on the same rotational approach, using the same matrix properties, which consists the core of the well known ESPRIT algorithm. Moreover, the DESFRI (***DE***tection of ***S***ource ***F***requencies via ***R***otational ***I***nvariance) approach is introduced to support the proposed CSMW method to semi-automated selection of the center frequency of the applied Morlet window. This approach is based on the singular values that are extracted as an intermediate product of the proposed decomposition process. By the application of the method in a multi-component synthetic signal a way to select the critical parameters of the Morlet wavelet, is investigated. The method is further tested on a time-varying acoustic Doppler signal generated by a passing railway vehicle, indicating promising results for the estimation of the variable instantaneous frequency and the multi-component decomposition of it.

1. Introduction

Traffic by rail is facing a growing pressure from the competition with all other forms of traffic (road, air or ship). One of the biggest problems it has to face is the safety and cost pressure caused by unexpected damages in the wheel sets, such as hollow wear or bearing defects.

Even if they do not result to major accidents, they cause a significant increase in scheduled and especially in unscheduled maintenance, which always means a not moving freight wagon and hence increasing costs. It is known from several interviews (Herrmann and Markus, 2013) with freight wagon owners that there are up to three unscheduled stays in the workshops per year and wagon. This and the high costs for maintenance reduce the profit in this sector. As a matter of fact this makes this sector seem unattractive and causes competitive disadvantages compared to road traffic.

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For this reason, operators have developed a series of preventive maintenance procedures and diagnostic systems for condition-based maintenance employing vehicle-based and track-based sensors. Today, most of the commercially products emphasize on railway infrastructure (point machine, level crossing, rail line, etc), and bogie system and body frame of wagon (wheels, axle bearings, etc). The following functional categories of automated condition monitoring inspection systems are employed: acoustic bearing detectors, bearing temperature detectors (Kypouros et al., 2011; Wilson et al., 2012), hot bearing detectors (Choe et al., 1997), wheel impact load detectors, hunting truck detectors, wheel temperature trending, wheel profile monitoring, warm bearing trending, bogie performance detectors and machine vision inspection. Thus, a modern railway system relies on sophisticated monitoring systems for maintenance and renewal activities (Ngigi et al., 2012) covering a wide field of affordable and high quality services for railway traffic.

Currently, a novel approach (Asada et al., 2013) for fault detection of point machine using Wavelet Transform and Support Vector Machines was introduced. According to the results, the proposed methodology can diagnose misalignment faults of electrical railway point machine to a high degree of accuracy.

A hybrid diagnosis system combining eddy current sensor data and structural knowledge (Oukhellou et al., 2008) has been developed for the detection of broken rail for railway infrastructure. A local tree classifier based on the analysis of these data achieves to detect real rail defects and singular points on the track. Then a Bayesian network helps the local classifier to classify broken rail and fishplate joints based on global knowledge about the structure.

Wheel-flats are amongst the most common local surface defects on railway wheels. For this reason, an innovative technique (Brizuela et al., 2011) has been introduced to detect and quantify the wheel-flats analyzing the variations in the round-trip time of flight of measured ultrasonic pulses to the rail wheel contact point.

Acoustic condition monitoring technology is certainly a very successful commercial solution that is based on the assumption that diagnostically relevant information is stored in the acoustic signal generated by the passing vehicle. Consequently, stationary wayside condition monitoring systems positioned near the track of the moving vehicle are considered. Although these systems are far more advantageous from the overall operation and maintenance purposes, a critical technical problem they have to face is the Doppler Effect that causes change of the values of the frequencies in the measured signal and introduces a lot of difficulties in the fault detection procedures. Thus, in order to improve the effectiveness of the conventional signal processing methods, the disturbances caused by the Doppler Effect has to be minimized. The signal distortion due to Doppler Effect depends on the speed of the moving source shifting the interesting frequencies to different bands. For this reason, methods, which are based on the extraction of the instantaneous frequency (IF) are used allowing the acquired information to be connected to the proper running of the moving vehicle, indicating the useful carrier frequencies of the source signals. The estimation of the IF has been an issue of intensive research (Boashash, 1992a) due to its importance in a significant number of applications other that machine condition monitoring, such as communications, speech processing and biomedical applications. The IF estimation algorithms can be grouped as phase differencing methods, signal modeling methods, phase modeling methods and time-frequency-representation methods (Boashash, 1992b).

One approach to instantaneous frequency estimation is based on RLS adaptive filter (Cioffi and Kailath, 1984). Sharman and Friedlander (1984) proposed an IF estimator based on time-varying AR modeling of the signal data. The IF was obtained from the roots of the time varying AR polynomial in much the same way as frequency is derived from the stationary transfer function.

Dybala and Radkowski (2013) introduce a method of reducing the non-stationarity of a signal which relies on task-oriented dynamic signal resampling. This method removes the Doppler Effect using the curve obtained by bandpass filtration of the signal around the carrier frequency and the differentiation of the phase of the analytic signal produced by Hilbert transform.

He et al. (2013) investigated a wayside acoustic analysis solution for bearing defect diagnosis. Firstly, the Doppler Effect of the acoustic signal is reduced by a resampling method based on a local cost function. Then, an adaptive stochastic resonance method based on a genetic algorithm is used to enchase the weak information as much as possible. Experiments simulating real train passing by a wayside microphone are implemented to verify the effectiveness of the proposed methodology.

In (Hu et al., 2013a) a new de-noising approach has been proposed based on the Doppler shift. The crazy climber detection algorithm based on Short Time Fourier Transform (STFT) is used to extract all the instantaneous frequencies. Then, according to the Morse acoustic theory, the information of the position of the acoustic sources is revealed. The instantaneous frequencies that match the Morse theory with Doppler shift are attained to design the FIR variable digital filter. Thus, the noise from the other parts of the train is removed due to the filtering process.

A Doppler shift elimination method for wayside acoustic signals is proposed in (Hu et al., 2013b). Firstly, the instantaneous frequency is estimated applying the STFT. Then, a non-linear curve-fitting based on the Morse theory is employed to improve the accuracy of the resampling vector. The results after the resampling process demonstrate that the Doppler Effect is restrained in the measured signals.

Zhang et al. (2013) demonstrated an approach to intelligent fault diagnosis of train bearings acoustic signals without eliminating the Doppler Effect. The measured signal is decomposed into intrinsic mode functions (IMFs) through Empirical Mode Decomposition (EMD). Then, the variance of the first 8 IMFs that include the most dominant fault information is calculated. Simultaneously, 10 time-domain features are extracted by the original signal. After feature extraction, a Back Propagation Network (BPN) is trained using as inputs the above feature vector. As it is mentioned, the results of test samples demonstrate that the removal of the Doppler Effect is not necessary and the proposed methodology can discriminate different fault conditions of train bearings.