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Fault detection method for railway wheel flat using an adaptive multiscale morphological filter

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ABSTRACT

This study explores the capacity of the morphology analysis for railway wheel flat fault detection. A dynamic model of vehicle systems with 56 degrees of freedom was set up along with a wheel flat model to calculate the dynamic responses of axle box. The vehicle axle box vibration signal is complicated because it not only contains the information of wheel defect, but also includes track condition information. Thus, how to extract the influential features of wheels from strong background noise effectively is a typical key issue for railway wheel fault detection. In this paper, an algorithm for adaptive multiscale morphological filtering (AMMF) was proposed, and its effect was evaluated by a simulated signal. And then this algorithm was employed to study the axle box vibration caused by wheel flats, as well as the influence of track irregularity and vehicle running speed on diagnosis results. Finally, the effectiveness of the proposed method was verified by bench testing. Research results demonstrate that the AMMF extracts the influential characteristic of axle box vibration signals effectively and can diagnose wheel flat faults in real time.

1. Introduction

Wheel flats are the most common local surface defects in railway wheels [1]. They can result in cyclic wheel-rail impact during the running process, thus inducing the coupled vibration of the entire vehicle-track system. This vibration in turn endangers running safety and damages the wheel and the rails further. Consequently, the establishment of methods for the early detection and identification of wheel flats is an interesting research topic.

Various methods have been developed over the years for this purpose. These methods presented thus far can be classified into two categories according to their measurement principles:

(a) Wayside methods. The measurement of the wheel-rail impact forces on an instrumented rail is the most common wheel flat detection technique [2,3]. Similarly, acceleration sensors are fixed on the rail instead of strain gauges to measure rail vibration in order to estimate the wheel status [4]. Moreover, some mechanical [5] and ultrasound systems [6] are also used for the purpose of wheel fault identification. Overall, wayside monitoring systems are utilized at a single point over

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which all vehicles pass. They are inexpensive; however, these methods cannot detect the running state of the vehicle throughout the entire process in real time.

(b) On-board methods. The widely used technology includes instrumented wheelset and axle box acceleration measurement. Specially adapted wheels are employed to measure wheel-rail forces during train motion, and wheel condition is assessed according to the magnitude of wheel-rail impact force [7]. The drawback of the instrumented wheelset is the volume of work required for its preparation, including the tedious calibration process and the specific design of the instrumented wheels according to different vehicles. The second type of on-board identification methods is not to use instrumented wheelset. Accelerometers are simply fixed on the axle box. The axle box acceleration signals are a measure of the wheel in the vehicle-track system and are excited during wheel-rail interaction. Therefore, they can indicate irregularities at the wheel-rail interface. What's more, they are more sensitive than the signals from other parts of the car body without the attenuation of secondary suspension system of railway vehicles. In this paper, we will focus on this type of identification method.

In the previous study, axle box acceleration has been successfully applied in the detection of rail corrugation and squats [8–10]. Similarly, the concept can be used to automatically detect wheel defects [11,12]. Compared to other monitoring systems, the main advantage of axle box acceleration measurement system is its ease of implementation and maintenance in trains with lower-cost. However, the vibration status of axle box is not exactly the same as for the wheel and always is influenced by various interferences, such as track irregularity, speed alteration and natural vehicle vibration. Moreover, many of the vibrations are also excited by normal wheel-rail rolling contact. The accuracy of extraction of fault-relevant signal characteristics is the main problem of wheel fault diagnosis using axle box acceleration.

The use of intelligent methods to enhance the quality of the signals has been crucial for wheel fault diagnosis. Short-time Fourier transform and wavelet transform are the most frequently employed methods [11,13]. However, both methods possess common theoretical flaws. Regardless of how data change, the same basic functions are used for approximation; thus, adaptive analysis cannot be conducted. When the preselected window or basic function do not match the waveform and frequency characteristic of the data, incorrect analysis results may occur. Hilbert-Huang transform is an adaptive signal analysis method, which does not require predetermined basic function. Therefore, it can be applied to the nonlinear and non-stationary characteristic of axle box vibration response. However, on account of its inherent mode mixing problem, the detection ability decreases sharply when the track condition deteriorates [12].

Unlike these time-frequency domain analysis methods, mathematical morphology is capable of extracting the geometric structure of the impulsive feature purely in the time domain. Increasing attention has been focused on applying mathematical morphology for detecting machinery faults in recent years [14–22].

Classical morphological filters perform single-scale analysis in which a fixed structure element (SE) is utilized [14–16]. However, the single-scale analysis may suffer from a lack of completeness in the extracted impulsive features. Later, multiscale morphological filtering (MMF) emerges. It performs the single-scale analysis morphological transforms multiple times (every time, the scale is different). The results from [18–21] show that the multiscale morphology analysis of vibration signals is more effective than single-scale analysis. Although this multiscale morphology analysis is an interesting attempt to examine the signal in different resolutions, the scales far away from the theoretical central scale are too contaminated to reflect the factual features. Therefore, the averaging of the results from all scales as the final output of morphology filter used in [18–21] may likely be non-optimal. Therefore, Li et al. [22] proposed a weighted multiscale morphological gradient (WMMG) algorithm. In WMMG, the larger scales take larger weights. The main advantage of this method is that it can depress the noise more effectively at large scales. However, at the same time, the impulse details, which are more important to indicate fault features preserved by small scales, are not weighted much. Based on this consideration, an adaptive multiscale morphological filtering (AMMF) method is put forward in the present paper. We believe that there is a subset of scales near the theoretical central scale, which can reflect the characteristics of fault better out of the total scales. We will find this subset and then calculate the weighted average of the scales based on frequency domain kurtosis in this subset only.

The current paper presents an online detection method of wheel flats based on the measurements of axle box vibration by installed accelerometers. The organization of the rest of this paper is as follows. Section 2 introduces the fundamentals of traditional multiscale morphology analysis. Section 3 proposes the improved multiscale morphology filter, which has the adaptive property, and demonstrates the advantages of AMMF over the traditional MMF approach and WMMG. Sections 4 and 5 apply the AMMF to wheel flat detection in simulated vehicle operation situations and the test rig experimental situation, respectively. Conclusions are given in Section 6.

2. Reported multiscale morphology analysis methods

Mathematical morphology was initially introduced as an image processing methodology based on the set theory [23]. Subsequently, it was used in signal processing [24]. The basic concept of morphological signal processing is investigating the relationship between signal parts and extracting the main features of the original signal by employing a “probe” SE in continuous movement. In this procedure, the pre-defined SE is utilized to match the original signal, maintaining the details and reducing noise.