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Detection of damaged supports under railway track based on frequency shift

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ABSTRACT

In railway transportation systems, the tracks are usually fastened on sleepers which are supported by the ballast. A lot of research has been conducted to guarantee the safety of railway track because of its importance, and more concern is expressed about monitoring of track itself such as railway level and alignment. The ballast and fasteners which provide strong support to the railway track are important as well whereas the detection of loose or missing fasteners and damaged ballast mainly relies on visual inspection. Although it is reliable when the fastener is missing and the damaged ballast is on the surface, it provides less help if the fastener is only loose and the damaged ballast is under the sleepers, which are however frequently observed in practice. This paper proposes an approach based on frequency shift to identify the damaged supports including the loose or missing fasteners and damaged ballast. In this study, the rail-sleeper-ballast system is modeled as an Euler beam evenly supported by a series of springs, the stiffness of which are reduced when the fastener is loose or missing and the ballast under the sleepers is damaged. An auxiliary mass is utilized herein and when it is mounted on the beam, the natural frequencies of the whole system will change with respect to the location of the auxiliary mass. The auxiliary mass induced frequency shift is analyzed and it is found the natural frequencies change periodically when the supports are undamaged, whereas the periodicity will be broken due to damaged supports. In fact, the natural frequencies drop clearly when the auxiliary mass moves over the damaged support. A special damage index only using the information of the damaged states is proposed and both numerical and experimental examples are carried out to validate the proposed method.

1. Introduction

Railway inspection plays an important role in ensuring the safe operation of railway transportation. Rail track is usually fastened on the sleepers, which are supported by a compacted ballast layer. The ballast retains the sleeper in its required position and the fasteners ensure the leveling and alignment of rail track. Once the fasteners are loose and even missing, or the ballast is damaged due to reduced size, the rail track will be unevenly supported and furthermore geometrically deteriorated. In fact, several serious accidents have been reported in the last decade due to this reason; therefore it is necessary to develop an effective approach to detect the damaged supports under railway track.

Currently, the most frequently used railway inspection method is visual inspection, either by manual operation or image

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processing. Although costly and time consuming, it is effective for detection of missing fastener; however, it is difficult to identify the loose fasteners and the damaged ballast under the sleepers. Ultrasonic testing is usually used for inspection of rail track geometry and overhead line, which can be easily conducted through a specific inspection vehicle. Ground Penetrating Radar (GPR) is capable of evaluating the ballasted track bed condition, which is similar to ultrasonic pulse echo technique by using electromagnetic waves instead of ultrasonic waves. However, it may be unsuitable for identifying damaged ballast: the size of damaged ballast changes gradually from small to large, but GPR usually requires layer reflections; on the other hand, GPR focuses on the average thickness and stiffness of the whole layer of ballast, whereas the ballast is always damaged locally.

Because loose or missing fasteners and damaged ballast always result in reduction of local stiffness, which influences the vibration characteristics of the rail-sleeper-ballast system; therefore, it is suitable to identify the damaged supports under the railway track by analyzing the dynamic response. In fact, a lot of research on vibration based damage detection has been carried out for many years [1,2]. Various vibrational characteristics have been investigated and among them, mode shape curvature [3], strain energy [4], flexible matrix [5] and flexibility curvature [6] are very famous, based on which many advanced damage detection methods and indices are developed. Fang and Ricardo [7] proposed a concept of power mode shape which is equivalent to the square of mode shape to detect damages in linear structures. Grande and Imbimbo [8] presented a fusion approach to detect multiple damage locations based on changes of flexibility. Sakaris et al. [9] used a time series generalized functional model for precise damage localization. Yang et al. [10] proposed a novel curvature calculation method based on Fourier spectral to improve the noise resistance for damage detection. Dervilis et al. [11] considered damage detection as an outlier identification problem and used robust regression to detect multiple outliers from structural health monitoring (SHM) data. Dilena et al. [12] recently used frequency response function interpolation method to localize damage in bridges. Because the incomplete identified modal parameters and uncertainty are frequently met in practice, Chatzieleftheriou and Lagaros [13] developed a two-loop trajectory method to solve the ill-conditioned problem. And Chandrashekhar and Ganguli [14] used mode shape curvature and fuzzy logic to assess stracture damages with uncertainty. They [15] further extended this approach to composite plate structures even with material uncertainty. Law et al. [16] also proposed a decentralized damage detection methods for identifying damages with subsets of parameter.

These above mentioned methods highly depend on the quality of identified modal parameters which are extracted from Frequency Response Functions (FRFs) traditionally, and therefore a lot of effect has been carried out on time frequency analysis to improve the identification of dynamics characteristics. Except for conventionally used Short Time Fourier Transform (STFT), wavelet transform is also frequently used because it can overcome the fixed resolution problem occurred in STFT by using adaptive window function. Ruzzene et al. [17] firstly used wavelet transform to extract frequencies and damping. Piombo et al. [18] also proposed a shifted version of wavelet transform to identify modal parameters by using output response. Some researchers have also investigated identification of dynamic characteristics by using measured data from a passing vehicle. Yang et al. [19,20] firstly proposed an idea to extract bridge frequencies by using dynamic response from a passing vehicle. Marchesiello et al. [21] and Bellino et al. [22] identified the dynamic parameters of beam like structures subjected to moving load which are considered nonlinear and time varying.

Several dynamic characteristics can be extracted and used for damage identification; however, it is observed that identification of natural frequencies is more accurate and convenient than other modal parameters. Therefore Zhong et al. [23] proposed a new damage detection method based on the derivative of natural frequencies instead of mode shape curvature. Zhang and Xiang [24] further analytically investigated the auxiliary mass induced frequency shift for beam like structures. Zhang et al. [25,26] later extended this work to plate and cylinder structures and successfully identified damages like corrosion and crack in CNG tank; however, it requires highly accurate measurement of frequency to guarantee the accuracy of the damage index which uses the curvature of frequency shift curve. Because the auxiliary mass induced frequency shift is proven equivalent to mode shape square and the frequencies can usually be measured more accurately, so it is promising to use it for damage identification instead of other modal parameters. On the other hand, earlier vibration based damage identification methods usually require information from either undamaged structures or finite element models, which is quite difficult in practice. Ratcliffe [3] proposed gapped smoothing method (GSM) for beam like structures by using operating curvature shapes from damaged structure only. Yoon et al. [27,28] extended GSM to 2-D plate like structures and further proposed global fitting method. Limongelli [29] also developed the FRF interpolation method in which the baseline is modeled by the spline shape interpolation.

The dynamic response of rail-sleeper-ballast system has been investigated for a long time [30,31],and it is modeled as an Euler Bernoulli beam supported by a series springs in this study. The stiffness of spring is assumed to decrease if the fastener is loose or the ballast is damaged; moreover, it is considered to be zero if the fastener is missing and there is a gap between the railway track and the sleeper, or the ballast is in poor condition making the sleeper unsupported. An auxiliary mass is used herein to generate the frequency shift. Generally, the natural frequencies will be lower if the auxiliary mass is mounted in the middle of two neighbored supports, whereas they will be higher when the auxiliary mass is put above the supports. When the supports are undamaged, the auxiliary mass induced frequency shift is believed to change periodically with respect to the location of the auxiliary mass because of the periodicity of the supports; and the periodicity will be broken if the supports are damaged. The discontinuity in spatial domain can be identified through spatial Fourier analysis. Reddy and Ganguli [32] and Saipraneeth and Ganguli [33] successfully applied spatial Fourier analysis to mode shapes to detect damages in beam like structures. In this study, the situation is easier and the natural frequencies are clearly observed lower when the auxiliary mass moves over the damaged supports. Therefore, the auxiliary mass induced frequency shift can be

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