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Identification of rail-sleeper-ballast system through time-domain Markov chain Monte Carlo-based Bayesian approach

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ABSTRACT

This paper reports the step-by-step procedures for identification of the rail-sleeper-ballast system with the use of the measured vibration data of an in situ sleeper on an existing ballasted track. The rail-sleeper-ballast modeling method, which has been used for modal-based model updating, was used to fit the measured time-domain vibration from the field test. However, the match between the measured and model-predicted responses was not good at some measured locations. Based on the observed discrepancy, the rail-sleeper-ballast modeling method was modified in this paper for suitable use in time-domain model updating. Based on the field test data and the modified modeling method, this study puts forward the time-domain Markov chain Monte Carlo (MCMC)-based Bayesian model updating and model class selection method for identification of the rail-sleeper-ballast system. MCMC was used to ensure that the proposed method can be applied even when the problem is unidentifiable. The proposed method identified the distribution of railway ballast stiffness under low-amplitude vibration and the "equivalent" rail stiffness and mass using impact hammer test data. The model updating results confirmed that the ballast stiffness under the sleeper was uniform, which implies that there was no ballast damage under the tested sleeper. Based on the proposed method, a comprehensive study was carried out to quantify the posterior uncertainties of the identified ballast stiffness when different amounts of measured information were used for model updating. The results showed that the uncertainty of the identified ballast stiffness was at an acceptable level even when using the measured data from only one sensor.

1. Introduction

An effective public transportation system is an essential component of a region's economic growth, and railway ballasted track systems are the most popular type of mass transit system worldwide. With developments in high-speed trains [1], the rate of railway ballast degradation has increased [2,3]. If remedial work is not carried out, this degradation will result in uneven support of railway tracks and increase the chances of rail buckling and train derailment, which would obviously endanger the safety and comfort of railway users [4].

The rail-sleeper-ballast system is usually modeled as a Timoshenko beam on an elastic foundation, with the two rails modeled as equivalent masses [5–8]. This modeling method was found to be adequate in model updating with modal parameters, such as natural frequencies and mode shapes [9,10]. However, its applicability in time-domain response prediction and model updating has not been verified. One of the objectives of this paper was to investigate the efficacy of this modeling method in the prediction of the time-domain responses of a ballasted track system. An accurate time-domain rail-sleeper-ballast model is essential for the study of train-track vibration. In this study, large discrepancies were found between the model-predicted and field test responses at some measured locations. Based on the observed discrepancies, the existing modeling method was modified in this paper for suitable use in time-domain model updating.

Many studies have been done on the model updating of a railway system using modal parameters. Ribeiro et al. [11] presented the calibration of the numerical model of a railway track on a bridge based on measured modal parameters. They carried out model updating with a generic algorithm that allowed the optimal values of 15 parameters of the numerical model to be determined. The updated numerical model was validated based on a laboratory test for the characterization of the modulus of deformability of the concrete sleeper and a dynamic test under railway traffic. Lam et al. [8] reported a feasibility study on the use of a deterministic model updating method in which the measured modal parameters were used to identify the model parameters of a segment of ballasted track constructed indoors. Feng and Feng [12] presented a

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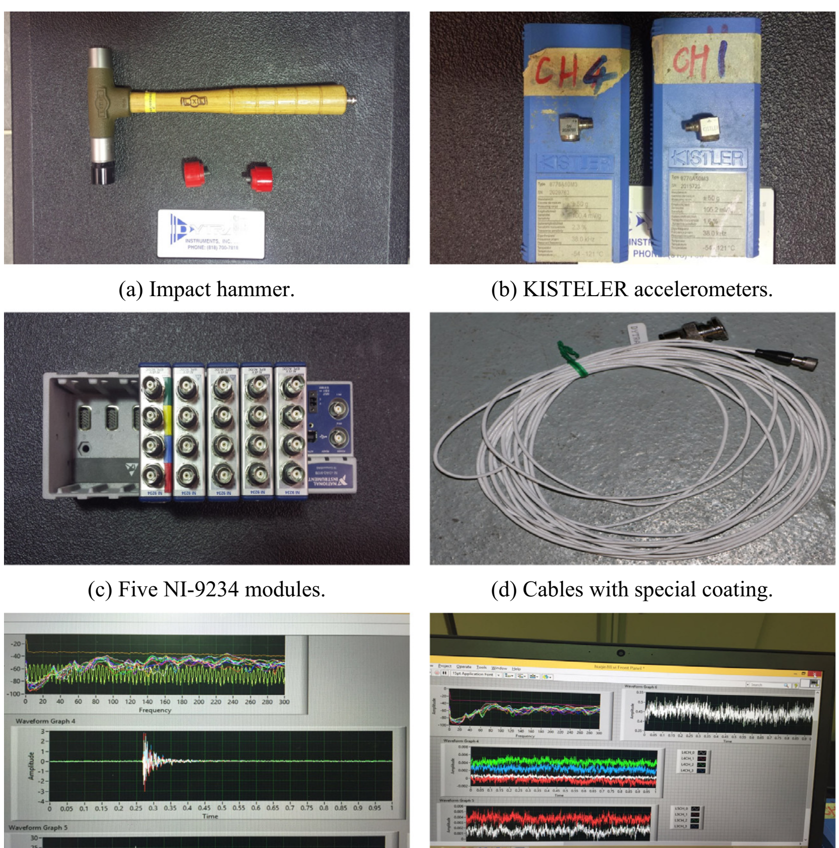
finite-element model updating approach that uses numerical optimization based on in situ measurement of the bridge's dynamic displacement histories under train loads. These studies followed the deterministic model updating approach in which the uncertainties introduced by measurement noise and modeling error cannot be properly handled and quantified. It is well known that the material properties of railway ballast are highly uncertain. In such a situation, the uncertainties associated with the model updating results are high; therefore, deterministic model updating methods may lead to unreliable results.

Lam and colleagues [13,14] sought to explicitly address the uncertainties of the identified track parameters following the Bayesian probabilistic approach. In their studies, the model updating processes were carried out with measured modal parameters, such as natural frequencies and mode shapes, obtained from an indoor test panel in a well-controlled environment. Model updating based on frequency-domain or modal-domain information requires an additional process to convert the time-domain data. To avoid this additional process, this paper presents time-domain model updating of the rail-sleeper-ballast system based on measured field test data. Furthermore, this paper also proposes for the first time the use of MCMC simulation to explicitly handle the uncertainties in model updating of railway ballast stiffness following the Bayesian statistical system identification framework.

The original Bayesian model updating formulation given in reference [15] and the recent interest [16–18] allows an explicit treatment of all the uncertainties and are specially designed for globally or locally identifiable problems. Based on the knowledge from the authors, the model updating problem for identification of ballast stiffness may not follow this assumption because of the highly uncertain nature of railway ballast properties. One possible way to overcome this difficulty is to approximate the posterior probability density function (PDF) of uncertain parameters using samples generated by MCMC simulation [19]. The method proposed by Beck and Au [20,21] was extended to an MCMC-based Bayesian model updating method with the introduction of a novel stopping criterion to ensure the accuracy of the calculated posterior uncertainty. The extended MCMC-based Bayesian model updating method was used for model updating of a coupled-slab system in reference [22]. In this paper, the modal-domain method in [20] was extended to the time-domain MCMC-based Bayesian model class selection and model updating method to identify the rail-sleeper-ballast model based on a set of measured field test data. Unlike most ballast model updating publications, in which measurements were obtained under laboratory conditions, field test data were adopted in this study. The positive results in the case study clearly show the practical value of the proposed method and its potential in damage detection in a ballasted track system.

2. Field test – impact hammer test of in situ sleeper

The measured railway track system was constructed according to the Hong Kong MTR specifications [23]. The basic configuration of the railway track consists of a plain track system with two UIC60 rails sitting on the resilient pad (TRACKLAST FC105A), and Pandrol shoulder and clips are used to hold the rails firmly on the prestressed concrete sleepers (F40) with 700 mm spacing. The concrete sleepers are embedded in a 350 mm thick granite ballast layer, and 250 mm of sub-ballast is placed between the top ballast and the compacted soil subgrade formation. The size of the ballast



(a) Impact hammer.

(b) KISTELER accelerometers.

(c) Five NI-9234 modules.

(d) Cables with special coating.

(e) Computer system with Labview

Fig. 1. Equipment used for the impact hammer test.