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Vibration and sound radiation of slab high-speed railway tracks subject to a moving harmonic load

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ABSTRACT

Developments of modern rail transportation require advanced methods for analysing dynamics of a railway track as an infinitely long periodic structure. A Fourier transform-based method has been formulated for calculating the response of a conventional ballasted railway track subject to a moving harmonic load. The method is then extended to account for the track complicated by rail dampers installed between sleepers. Equations derived so far require that all the supports and attachments to the rail are coupled through the rail only. This, however, is not the case for non-ballasted slab tracks such as those used in China for high-speed and underground trains. For those tracks, in addition to the rail, fastener systems within a slab are also coupled by the slab. Therefore, the Fourier transform-based method must be further extended to give revised equations which, in consideration of noise evaluation, should be also appropriate for sound radiation prediction. This is the first task of this paper. The second task of this paper is to propose an appropriate procedure for predicting sound radiations from the track using the 2.5D acoustical boundary element method. The revised equations are then used to investigate the dynamics of a typical high-speed railway track, including dispersion curves of the track, responses of the rail and slab to a moving harmonic load, and vibration decay rate along the rail. And finally, sound radiations from this track are briefly examined using the proposed procedure.

1. Introduction

As an environment friendly and energy efficient transport mode, high-speed railways have been, and are being, built in many countries. In China alone, more than 22,000 km high-speed railways are already in operation at maximum speed 300 km/h. To gain competition advantages over airways and to suit for big countries such as Russia, train speeds are expected to increase even higher.

At the same time, in order to abate city traffic jams and ameliorate air quality, underground railways are also being built in an unprecedented scale. In China, more than 30 cities have opened underground railway operations, giving the total underground railway mileages more than 4000 km.

Safety, environment and energy consumption are main concerns for railway operators. Issues such as growth of rail roughness, formation of rail corrugation and development of wheel out-of-round, are not only threats to safety, but also root causes for rolling noise pollution. It is now universally agreed that those unwanted phenomena are generated mainly from

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dynamical interactions between moving wheels and rails, within a wide frequency range. To effectively and accurately model and predict dynamical wheel/rail interactions, track dynamics must be dealt with and understood adequately.

A railway track can generally be idealised to be an infinitely long periodic structure, exhibiting not only modal behaviours, but also wave propagation characteristics. An important aspect in dealing with track dynamics is to calculate the response of a railway track as an infinitely long periodic structure to a moving harmonic load. Results from such calculations can not only reveal the dynamical characteristics of the track, but can also provide a basis, either in the time-domain or in the frequency-domain, for dealing with wheel/rail interactions [1–6]. Different approaches have been developed to analyse the response of a track to a fast moving harmonic load of high-frequency.

The response of a railway track to a harmonic load moving along the rail can be modelled in the time-domain (e.g. [2,6]) by solving differential equations as an initial-value problem. Traditional time-domain approaches require the track to be truncated into a finite length. To minimise the effect of wave reflections from the truncations and to be able to account for high frequency vibration due to a fast moving load, the track model must be sufficiently long. Computational accuracy and efficiency can be significantly increased using methods based on the theory of dynamics of periodic structures [4,7,8]. This is because in these methods, the track does not have to be truncated and all or part of the calculations are performed in the frequency-domain involving solving integral, rather than differential, equations.

A Fourier transform-based method is developed in Ref. [9] by the first author for a conventional ballasted track as an infinitely long ‘uniform’ periodic structure. The main feature of the method is that the response of the track is expressed as inverse Fourier transform from the wavenumber (in track direction) domain to the space (the longitudinal coordinate relative to the moving load) domain. With this method one can efficiently calculate track vibrations excited by a harmonic load of high frequency and moving at high speed, and explore resonance and propagation characteristics of the track [10]. This method also makes it easy to produce responses for a large range of the track so that the decay behaviour of vibration along the rail can be examined, and to predict sound radiation from the rail using the 2.5D acoustical boundary element method [11].

It is well accepted that the pinned-pinned vibration of the rail has an important impact on noise radiation and roughness growth [12]. Tuned mass dampers (TMDs) [13,14] are thus designed and installed onto the rail between sleepers in order to suppress the pinned-pinned vibration. With the TMDs installed, a ballasted track is still periodic with the period being the sleeper spacing, but becomes ‘non-uniform’ as described in the literature [15]. Various methods have been developed or extended to evaluate the dynamics of the track with TMDs, including the conventional FEM [16], and those based on best fitting of rail receptance using rational fraction polynomials [17–19]. The Fourier transform-based method developed in Ref. [9] has also been extended in Ref. [20] so that it can be applied to the track complicated by TMDs.

However, equations developed in Refs. [9,20] require that all the supports (i.e. rail pad/sleeper/ballast) and attachments (i.e. TMD) to the rail are coupled through the rail only. This, however, is not the case for slab tracks such as those used in China for high-speed and underground railways. In these tracks, the fastener systems within a slab are coupled not only by the rail, but also by the slab. This requires the Fourier transform-based method to be further extended, giving response-calculation equations not only for the rail, but also for the slabs. Equations useful for sound radiation prediction must also be derived. Calculation of slab vibration for frequencies much higher than those concerned by vehicle dynamics is important, since slabs may contribute to wheel/rail noise significantly for low frequency range, as measurements have indicated (a paper analysing the measurement data is under preparation). This may also be explained by the facts that at low frequencies the slab is not sufficiently isolated by the railpads from wheel/rail interactions and the slab has much larger radiation area and efficiency than the two rails.

For sound radiation from a vibrating rail, Thompson et al. [21] compare the sound power radiated into *the full* space by a 2-dimensional model with the one radiated by a 3-dimensional model consisting of a line array of point sources. It is found that the 2-D model to be close to the 3-D model except for high decay rates as well as for short wavelengths in the rail compared with the wavelength in the air. Analysis presented in Ref. [21] is recently extended in Ref. [22], in terms of sound radiation efficiency, to include the effect of the ground as a sound absorbing boundary. In case of short wavelengths in the rail compared with the wavelength in the air, Kitagawa and Thompson highlight an essential property of the acoustic field radiated by the rail [23]: its directivity. Understanding of radiation characteristics of a rail is essential to characterisation of the acoustic field radiated by the rail using a microphone array [24].

Thus, the first task of this paper is to extend the Fourier transform-based method for non-ballasted slab tracks, giving response-calculation equations not only for the rail, but also for the slabs, and deriving equations useful for sound radiation prediction. The second task of the paper is to explore the dynamics of a typical high-speed railway track, including vibration wave dispersion of the track, responses of the rail and slab to a harmonic load moving along the rail, and vibration decay rates along the rail and slabs. The third task of this paper is to develop an appropriate procedure to investigate the sound radiation characteristics of the track based on the vibration result using the 2.5D acoustical boundary element method.

The slab railway track considered in this paper is described in Section 2. Differential equations of motion of the track are also presented in this section. The steady-state response of the track to a moving harmonic load is presented in Section 3. A procedure for predicting sound radiations from the track is proposed in Section 4. Results for a set of typical track parameters are presented in Section 5 and the paper is concluded in Section 6.

It is worthy of noting that, this paper is mainly concerned with vertical track vibrations and associated sound radiations. That ‘a track subject to a harmonic load’ really means that each rail is subject to a harmonic load of the same frequency and same amplitude at the same longitudinal position. Thus, when dealing with track vibration, only half the track needs to be taken into account.

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