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Properties of train load frequencies and their applications

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ABSTRACT

A train in motion applies moving steady loads to the railway track as well as dynamic excitation; this causes track deflections, vibration and noise. At low frequency, the spectrum of measured track vibration has been found to have a distinct pattern; with spectral peaks occurring at multiples of the vehicle passing frequency. This pattern can be analysed to quantify aspects of train and track performance as well as to design sensors and systems for trackside condition monitoring. To this end, analytical methods are developed to determine frequency spectra based on known vehicle geometry and track properties. It is shown that the quasi-static wheel loads from a moving train, which are the most significant cause of the track deflections at low frequency, can be understood by considering a loading function representing the train geometry in combination with the response of the track to a single unit load. The Fourier transform of the loading function describes how the passage of repeating vehicles within a train leads to spectral peaks at various multiples of the vehicle passing frequency. When a train consists of a single type of repeating vehicle, these peaks depend on the geometry of that vehicle type as the separation of axles on a bogie and spacing of those bogies on a vehicle cause certain frequencies to be suppressed. Introduction of different vehicle types within a train or coupling of trainsets with a different inter-car length changes the spectrum, although local peaks still occur at multiples of the passing frequency of the primary vehicle. Using data from track-mounted geophones, it is shown that the properties of the train load spectrum, together with a model for track behaviour, allows calculation of the track system support modulus without knowledge of the axle loads, and enables rapid determination of the train speed. For continuous remote condition monitoring, track-mounted transducers are ideally powered using energy harvesting devices. These need to be tuned to optimise energy abstraction; the appropriate energy harvesting frequencies for given vehicle types and line speeds can also be predicted using the models developed.

1. Introduction

When a train runs along the track it will apply moving steady loads to the track and dynamic excitation due to track unevenness or wheel out-of-roundness. These loads cause vibration, noise and deflections of the track. Understanding the frequency spectrum of track vibration and its relation to train geometry, loading and sources of excitation and as well as properties of the track, is important for interpreting measurements, explaining vibration and track movement and evaluating track performance. This paper addresses the understanding and interpretation of the spectrum of low frequency track vibration.

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At low frequency, spectra of track vibration have a distinct shape in which peaks at certain frequencies are prominent. Several authors have identified that these peaks occur at multiples of the vehicle passing frequency and they have previously been termed 'train load dominant frequencies' [1–6]. Auersch [7] showed that high and low amplitude regions of the spectra are characterised by the axle spacing of a vehicle bogie. Ju et al. [6] showed that the dominant peaks are caused by the repeated loading from vehicles within a train. Ni et al. [8] and Kouroussis at al. [9] demonstrated that this property can be exploited for determining the train speed using the peaks in spectra for track deflection and ground vibration. Jurdic et al. [10] matched the vibration spectrum for the complete train geometry to avoid errors that may arise from the difference between the actual and assumed frequency of the peaks. By considering a model of track deflection in the frequency domain, Le Pen et al. [5] showed that the relative amplitudes of these peaks are influenced by the track stiffness and used this property to obtain the track system support modulus.

Quasi-static loading and dynamic excitation are responsible for track vibration. The quasi-static contribution is from the weight of the train transferred through the suspension system to the track through each wheel, at a steady speed. Dynamic excitation arises from track and wheel unevenness and impact at discontinuities at the wheel/rail interface. The significance of these different mechanisms varies with frequency [11]. Models and measurements by Sheng et al. [12,13] showed that track deflection from the steady quasi-static loading are the most significant mechanism for low frequency track vibration, whereas dynamic excitation from other mechanisms is usually more significant at higher frequencies. Studies by Lombaert et al. [14], Auersch [7], Triepaischajonsak et al. [15] and Alves-Costa et al. [16] confirm the differing importance of these mechanisms with varying frequency. Furthermore, neglecting wheel unevenness, every wheel will be excited by the same rail roughness leading to the same dynamic load at a point on the track. The time lag between each load, for both the quasi-static and dynamic contributions, is governed by the axle spacing within the train. This leads to a modulation of the low frequency spectrum that is the same for both dynamic and quasi-static loading [17,18]. This means that quasi-static models for track deflection and the sequence of wheel loads are adequate for interpreting track vibration at low frequency.

In this paper, the Fourier transforms of the response of a beam on an elastic foundation to a point force, a simple analytical model for track deflection, and sequences of applied wheel loads representing different trains are used to explain the frequency and magnitude of the peaks found in measured track vibration spectra. This is done initially for trains consisting of a single repeating vehicle type. It is shown how the relative amplitudes and reliability of the spectral peaks from the wheel load sequence depend on the vehicle geometry. The effects of more complex train geometry, consisting of multiple vehicle types or coupled trainsets, are also investigated, as is the influence of variation between wheel loads. The significance of these frequencies, their relative amplitudes and their dependence on the properties of the track, is demonstrated with reference to three applications: obtaining the track system support modulus from track deflection measurements, determining the train speed [8–10] and tuning a track-mounted energy harvester for powering transducers for condition monitoring [6]. The insights gained in this paper provide a more rigorous justification for methods used in these three applications by considering the role of the vehicle geometry and the influence of bogie and axle spacing on the shape of track vibration spectra, and the sensitivity of the spectral peaks to the number of vehicles and variation in wheel loads.

2. Low frequency track vibration

2.1. Track vibration measurements

Track-mounted vibration transducers such as geophones or accelerometers may be used to record track deflections caused by passing trains [19–24]. In this study, measurements of vertical velocity made on the sleeper have been obtained from different locations with well-performing track using geophones. The train types and vehicle geometries associated with the measurements are given in Table 1. These trains have been categorised according to whether they comprise single or multiple vehicle geometries. Vehicle geometry is described using the vehicle length L_v, bogie spacing L_b and axle spacing L_w. These are shown for twin bogie and articulated vehicle types in Fig. 1.

Fig. 2 shows frequency spectra obtained from sleeper velocity measurements for trains having a single vehicle type. The sleeper velocity was measured using geophones in each case and sampled at 500 Hz. The spectra shown are the magnitudes of the Fourier transforms of these signals over a 20 s duration, giving a frequency resolution of 0.05 Hz. The measurements are for the passage of a 6 car Javelin, a 5 car Voyager, an 11 car Pendolino and a 16 car Valero. The corresponding train speeds were 56.4, 56.1, 54.4 and 80.8 m/s. The frequency axis has been non-dimensionalised by the vehicle passing frequency $f_1=v/L_v$ giving $N=f/f_1$ where f is frequency in Hz and v is the speed of the train. The vehicle passing frequencies in these examples are 2.82, 2.44, 2.27 and 3.26 Hz respectively.

Peaks in the sleeper velocity spectrum correspond to integer multiples of the vehicle passing frequency. However certain multiples are suppressed, such as $N=4$ and 5 for the Javelin in Fig. 2(a). The peaks for the shorter trains with 5 and 6 vehicles (Fig. 2(a, b)) are broader and the spectra show clear subsidiary maxima between the main peaks. The spectral peaks for longer trains with 11 and 16 vehicles (Fig. 2(c, d)) are narrower and more prominent.

Some trains, such as the HST and TGV/Eurostar, comprise different vehicle types (see Table 1); others comprise two or more trainsets joined together with a coupling length different from that within each trainset. Sleeper velocity spectra are given for examples of such trains in Fig. 3. The non-dimensional frequency is based on the length of the most common (primary) vehicle in the train.