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AUTHORS' REPLY

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1. INTRODUCTION

The authors thank Jonsson [1] for his interest in their paper [2]. Measurements of ground vibration from trains are usually obtained in the course of the investigation of complaints concerning vibration in particular buildings. Investigations undertaken for railway engineering purposes usually focus on the track as the primary interest with the vibration of the ground, away from the track, warranting only one or two measurement channels. The measurement campaign presented in reference [1] therefore represents a useful addition to the data available to study.

The difficulty in analysing measured ground vibration from trains in order to identify the mechanism of the generation of particular features in the time history, or spectrum, is well known. This is one reason why a theoretical study, examining the mechanisms, was chosen in reference [2].

2. COMPARISON BETWEEN MODEL AND MEASUREMENT SITUATIONS

A number of differences exist between the data presented in reference [1] and that presented, from the model calculations, in reference [2]. The most important one is that the model results are the response to a single-axle load only. The purpose of this was to simplify the situation so that the mechanisms of generation of propagating waves could more easily be discussed. In reference [2], the load at the track was analysed in three separate parts as: a moving non-harmonic load, a dynamic load moving with the vehicle and a dynamic load at a fixed point with respect to the track. It was shown by reference to the dispersion diagram, that whilst either of the dynamic loads will produce propagating waves, the moving non-harmonic load only does so if the train speed exceeds the ground wave speed.

The effect of multiple axle loads for a real train can be predicted using this model by superposition of the response to each axle with suitable time/distance delays imposed. However, an issue that remains to be resolved in this process is whether the loads at different axles/wheels are phase correlated and, if so, their relative phases (i.e., other than that imposed by their distance along the train).

Another difference between the data presented is that in reference [2], the results of the model are in the frame of reference moving with the load, whereas the measured data given in reference [1], is for fixed points on the ground. Moreover, the model results show the displacement response at a single frequency whereas the measurements are presented as acceleration time-series data, albeit frequency filtered.

3. EXCITATION MECHANISMS

The angle of the wave produced by a single dominant frequency component is, as Jonsson correctly identifies, related to the finite speed of propagation in the ground. Either of the two moving-load types of excitation could produce waves near to the track with this character.

In Figure 2 of reference [1], a small number of strong frequency components appear to be present. In the case of measurements of the vibration from a full series of axle loads, a number of factors cause such frequencies to arise. Most important of these is the periodicity of the axles of the train. During the passage of a long train of similar wagons, the pattern of axles of the wagons will give rise to strong harmonic components. The relative strengths of these correspond approximately to the Fourier series coefficients of the function representing the loading pattern [3]. In reference [4], measurement and calculation data are shown for the velocity response of both the sleeper and the ground surface 10 m from the track, from a train of two-axle wagons. There, the strongest components are at approximately 4 and 6 Hz. These are shown to be due to the moving static load excitation for those particular wagons travelling at 14 m/s, i.e., rather slower than the train presented in reference [1], which had a speed of 25·6 m/s. The identification of a strong component in Jonsson's measurement at 7 Hz (Figure 4 of reference [1]) is therefore not unexpected.

In addition to this, a dynamic excitation may exist. The wagons of the train may be excited into "bouncing" and "pitching" resonances which apply a sinusoidal moving load at the track. The frequency of such a resonance, for a single-stage suspension two-axle freight wagon, is, typically, around 4 Hz. Such a resonance would appear as a load with a periodicity of 6·4 m along the track and of 0·25 s in the time-series data for the speed of 25·6 m/s. The exact frequencies of this kind of dynamic loading are, of course, dependent on the vehicle type and the load it is carrying. Although the magnitude of this dynamic excitation would be small compared to the effect of the quasi-static loads and therefore the corresponding response at the track would be small, both references [2, 4] show that it is expected to play a more significant role in the response only a few metres away from the track.

4. EFFECT OF GROUND STRUCTURE

It is shown in reference [2] that whether the wave in the ground is propagating or evanescent depends on the parameters of the layered structure of the ground and on the frequency of excitation. For the example soil in reference [2], waves propagating in the soft top layer of soil are only generated above about 20 Hz. For a soft clay of considerable depth, as studied in reference [1], it would be expected that a propagating wave type would exist in the layer at a lower cut-on frequency than for the example in reference [2]. Therefore, strong surface propagation may be excited at 7 Hz by a dynamic excitation. However, even for the quasi-static excitation mechanism, reference [2] shows that, at low frequency, vibration due to the evanescent wave is significant up to some distance from the track. The amplitude of evanescent waves at 7 Hz would be significant for distances of the order of 10 m, this being a wavelength of the Rayleigh wave at this frequency.

The wave speed of 71 m/s for the dominant surface wave observed in reference [1] is not unusual in the authors' experience. However, one should be wary of assuming that the clay is homogeneous to a depth of 40 m. Clay "weathers" by the absorption of moisture at the surface leading to a soft material with the Poisson ratio close to 0·5, i.e., representing a constant volume material. At greater depths, the retention of moisture in the clay reduces because of the overpressure. This leads to a varying of the stiffness of clay with the first few metres of depth. This can be represented as a layered structure, which is significant in the frequency range of ground vibration from trains. The effect of layered structure has been shown both in calculation and measurements to produce a strong rise in the response level in the frequency range from about 10 to 20 Hz depending on the ground [2, 4, 5]. In reference [6], calculations of the response at a site with a similar deep drift of soft clay to the ground of reference [1] are presented.

5. EXAMPLE RESULTS

The model cannot be made to correspond exactly to the measurements presented in reference [1], for reasons that are apparent from points already discussed and because not all the parameters of the case are available. However, example displacement responses over the ground surface are shown in Figures 1 and 2. The parameters of the track in both cases are those used in reference [2], but the ground is modelled here as a half-space with a Rayleigh wave speed of 71 m/s. The model has been extended to account for multiple axle loads using superposition. Six axles, of three two-axle wagons, have been modelled with an axle spacing of 9·34 m within a vehicle and 4·48 m between axles of adjacent vehicles.

Figure 1 shows the response of the ground surface to the six moving non-harmonic loads. In this plot, as in those of reference [2], the instantaneous displacement of the ground is shown in the frame of reference moving with the train. Downward displacement is shown as positive (upward) in this figure. On the track, and very close to it, the individual passing axles can be distinguished clearly in the displacement pattern. Although the effect of the quasi-static deformation of the ground extends to some 10–20 m from the track, at the speed of 25·6 m/s no propagating waves are excited.

Figure 2 is for a dynamic load at each axle having a wagon bouncing or pitching frequency of 4·5 Hz. Again the train is moving along the track at 25·6 m/s. In the real case, the precise phase relationship between loads applied by the axles of different vehicles is

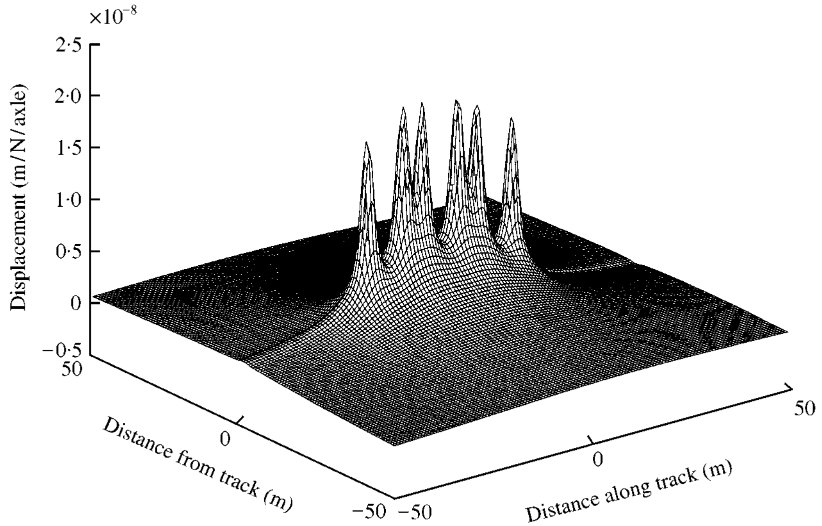

Figure 1. Response to unit non-harmonic axle loads of three two-axle wagons travelling at 25·6 m/s on a ground with a Rayleigh wave speed of 71 m/s.

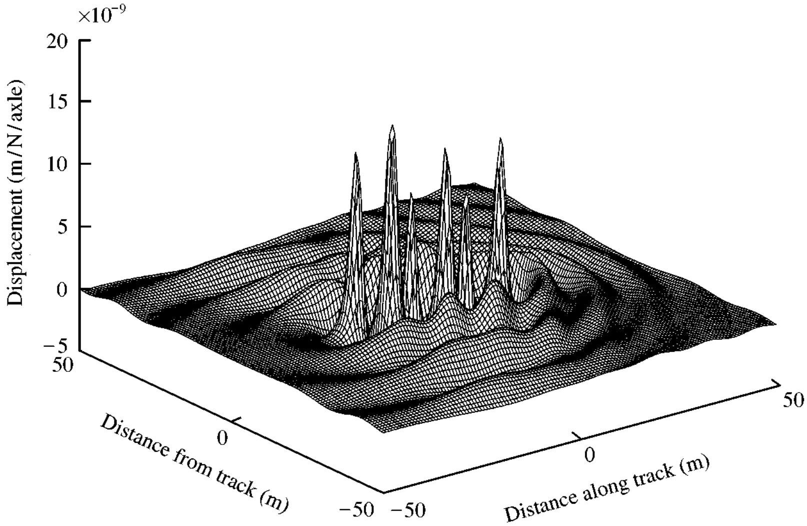

Figure 2. Response to unit dynamic axle loads at a frequency of 4·5 Hz for three two-axle wagons travelling at 25·6 m/s on a ground with a Rayleigh wave speed of 71 m/s.

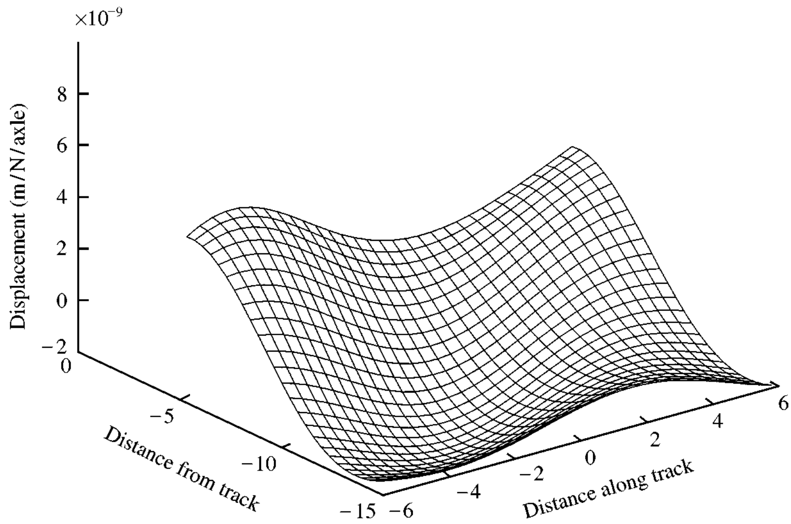

Figure 3. Dynamic response to the multiple axle loads of Figure 2 shown over the distance range of the measurement grid used in reference [1].

complex to model. For the present case, it has been assumed that the loads are coherent and have a phase shift corresponding to the distance between them and the speed of travel, i.e., that the loads are in phase in the moving frame of reference. With the Doppler shift corresponding to the train speed and wave speed in the ground, the load frequency of 4·5 Hz gives response frequencies having strong components at 3·3 and 7 Hz at points fixed relative to the ground.

The figure indicates that, close to the track, a peak corresponding to the passing of individual axles can be seen. However, individual axles cannot be picked out in the vibration response a little further from the track. By a distance of 50 m, Figure 2 shows that it is reasonable to approximate a train as a finite line source producing linear wavefronts normal to the track. Such an approximation has been used in empirical predictions of vibration from trains.

Figure 3 presents the same results as Figure 2 but only for the range of the ground surface covered by the measurements in reference [1]. It should be remembered that Figure 3 shows displacement rather than acceleration, does not represent a single frequency component and therefore that the displacement response is not strictly proportional to the acceleration at 7 Hz. Nevertheless, the results can be seen to be qualitatively similar to Figure 4 of reference [1]. However, without more detailed examination of the measurement data and correlation with vehicle characteristics, the interpretation of the measurement implied by Figures 3 and 4 of reference [1] must be regarded as a suggestion only, rather than a conclusion.

6. SUMMARY

Predictions from multiple axles show that, distinct axle loads can be identified in the vibration response at the track. In the farfield waves appear resembling those of a finite length line source without distinct features corresponding to the individual axle loads. Even for vibration from trains travelling below the Rayleigh wave speed of the ground, in the near field there is a transition between the two characteristics, which requires very detailed analysis to decipher. The measurements presented in reference [1] fall within this range and this is of interest because line side dwellings are often also at these distances from the track. For the bow waves produced by a train travelling at speeds exceeding the lowest ground wave speed [2], the distinctness of each axle would be expected to persist in the farfield.

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