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Ground vibrations generated by superfast trains

The continuous increase in passenger train speeds on European railways makes it important to consider the environmental impact of such trains. Professor Victor V Krylov of the Centre for Research into the Built Environment at Nottingham Trent University presents the results of research into the expected ground vibrations of the new generation of trains.

Ground vibration fields from superfast trains—those travelling at speeds close to or greater than 300 km/h—have been studied, taking into account the contribution of each sleeper of the track subjected to the action of the carriage-wheel axles. The final results were calculated numerically. They are illustrated by graphs of spatial distributions and frequency spectra of ground vibrations generated by trains moving at different speeds (figure 2).

The study predicts that a very large increase in vibration level in comparison with conventional trains (more than 70 dB) may occur if train speeds exceed the velocity of Rayleigh elastic surface waves in the ground. These trains, which might be called “trans-Rayleigh” trains, would typically travel at speeds of over 500 km/h (i.e. over 138.8 m/s). Such speeds, which are achieved by French TGVs, pose a similar problem to that presented by supersonic jets. Calculations show that the absolute level of ground vibration velocities generated by trans-Rayleigh trains might be as high as 10 mm/s (140 dB re 10⁻⁹ m/s). Vibrations of such a high level may cause damage to nearby properties.

The large increase in ground vibration level results from the effect of a moving source approaching the “sound barrier”, with regard to the velocity of Rayleigh surface waves propagating through the ground. The velocities of such waves in soft sandy soils may be very low (90–130 m/s). The field superposition effects for radiated vibration waves might therefore be expected in these areas, similar to those of Mach radiation of shock waves by supersonic jets or Cherenkov radiation of light by electrons moving at speeds exceeding the velocities of light in the media.

Modelling the vibration patterns

The mathematical model under investigation considers a train moving at speed v on a welded track with sleeper periodicity d (figure 1a). The quasi-static pressure mechanism of excitation results from load forces applied to the track from each wheel axle, causing downward deflection of the track (figure 1b). This produces a wave-like motion along the track at a speed of v, resulting in a distribution of each axle load over all of the sleepers involved in the deflection distance, xo.

Each sleeper in turn acts as a vertical force applied to the ground during the time necessary for a deflection curve to pass through it. Seven or eight sleepers are usually involved in the deflection distance. Actions of all of these forces contribute to the railway-induced ground vibrations, which propagate from the track to the surface.

Figure 1: (a) Geometrical parameters of a track and a train. (b) Quasi-static mechanism of ground vibration generation: the track experiences mainly downwards deflections due to an axle load, T. (c) Superposition of ground vibrations generated by different sleepers at the point of observation (x, y).

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buildings as bulk longitudinal, shear elastic and Rayleigh surface waves. Calculating the vibration field radiated by a moving train requires the superposition of fields generated by each sleeper activated by all axles of all carriages, with the time and space differences between sources (sleepers) being taken into account (figure 1c).

It follows from the analytical expressions derived that the maximum radiation of ground vibrations takes place if the train speed, \(v\), and the Rayleigh wave velocity, \(c_R\), satisfy the relation \(\cos \Theta = \frac{c_R}{v}\), where \(\Theta\) is the angle of wave radiation. The above relation is similar to the conditions of Mach or Cherenkov radiation. It means that elastic fields radiated by all sleepers are combined in phase at the point of observation. Since \(\Theta\) should be real (\(\cos \Theta \geq 1\)), the train speed, \(v\), should be larger than the Rayleigh wave velocity, \(c_R\). In this case the ground vibrations are generated as quasi-plane Rayleigh surface waves symmetrically propagating at angles of \(\Theta\) with respect to the track, and with amplitudes much larger than for “sub-Rayleigh” trains.

It is interesting that for trans-Rayleigh trains the amplitudes of the generated vibration field do not depend on the sleeper periodicity, \(d\). This means that the radiation of ground vibrations by trans-Rayleigh trains may take place also on tracks without sleepers. However, for conventional low-speed trains \((v < c_R)\) the ground vibrations in the form of waves are not generated without sleepers in the framework of the mechanism considered. This agrees with the results of the elasticity theory. These indicate that, for loads moving along the free surface of an elastic semispace at a speed of \(v < c_R\), radiated wave-fields do not exist (only localized quasi-static fields can accompany the moving load).

**Results**

The predicted large increase in amplitudes of railway-generated ground vibrations for \(v > c_R\) can be explained by two features. The first is that surface waves radiated by different sleepers are combined in phase. Therefore an increase in the number, \(N\), of effectively radiating sleepers of the track can be expected, compared with the average vibration level for conventional trains (numerical calculations show that \(N \approx 200\)).

The second feature is the dependence of the radiation function for one sleeper on train speed, \(v\). According to the calculations this function provides an average increase of about 10 times for the speed \(v = 138.8\) m/s \((500\) km/h) compared with \(v = 13.88\) m/s \((50\) km/h). Thus a total increase of ground vibration amplitudes by 1000–2000 times \((60–66\) dB) is expected in the case of trans-Rayleigh trains.
Figure 3: (a) Spectra of ground vibration velocity (in arbitrary linear units) generated by a single axle load moving on the track at sub-Rayleigh speeds of 2.5–100 m/s. The results are shown for the frequency band 0–50 Hz. Mesh: Δv = 2.5 m/s, ΔF = 1 Hz. The Poisson’s ratio of soil was set at 0.25 and the mass density of soil at 2000 kg/m³. The Rayleigh wave velocity, c_R, was 125 m/s. With increases in train speed the ground vibration level grows in general, especially in the low-frequency area. For relatively low train speeds the peaks corresponding to the train passage frequencies are clear, indicating linear dependence of the corresponding frequencies on v. For train speeds above 12.5 m/s the broadening and splitting of peaks for the main passage frequencies take place. This can be explained by the influence of phase shifts between waves radiated from different sleepers. (b) The ground vibration spectra generated by a single axle load moving with speeds of 10–250 m/s (including trans-Rayleigh speeds). Mesh: Δv = 10 m/s, ΔF = 1 Hz. Ground vibration spectra grow rapidly for v ≥ c_R = 125 m/s. Details of the spectra for relatively low train speeds shown on (a) are almost invisible on (b) because of the huge increase in vibration level in the trans-Rayleigh range.

Figure 4: The ground vibration spectra (in dB, with regard to the reference level 10⁻⁹ m/s) generated by a full train consisting of N = 5 equal typical carriages for both sub-Rayleigh and trans-Rayleigh train speeds. L = 8.3 m, D = 4.88 m, a = 2.2 m, T = 100 kN, β = 1.25 m⁻¹, Y₀ = 30 m. The Rayleigh wave velocity in the ground is c_R = 125 m/s and the soil attenuation coefficient, γ, is 0.00478. The averaged ground vibration level from a train moving at a trans-Rayleigh speed of 500 km/h is approximately 70 dB higher than from a train travelling at a speed of 50 km/h.

The numerical results for spatial distributions of generated elastic waves (figure 2a–c) and their frequency spectra for one axle load moving at different speeds (figure 3a, b) for typical British Rail track parameters confirm the above qualitative conclusions. The numerical calculation of ground vibrations generated by a train of five equal carriages (figure 4) indicates that the average ground vibration level at trans-Rayleigh speed (500 km/h) is ~70 dB higher than from a conventional train at 50 km/h.

Superfast trains moving at speeds around the Rayleigh wave velocity in the ground can thus cause large increases in ground vibration level relative to conventional trains. Fortunately, soils with low Rayleigh wave velocity (~100 m/s) are uncommon, the most typical range of c_R values being 250–500 m/s. Nevertheless the designers and builders of tracks for superfast trains should be aware of the potential risk of excessive ground vibrations. Either areas such as soft sandy soils with low Rayleigh wave velocity must be avoided or special mitigation measures to protect the built environment from the expected severe ground vibrations must be undertaken.

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