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GROUND VIBRATIONS FROM ACCELERATING AND BRAKING ROAD VEHICLES

Victor V. Krylov

Centre for Research into the Built Environment,
The Nottingham Trent University,
Burton Street, Nottingham NG1 4BU, UK

SUMMARY

The problem of generation of ground vibrations by accelerating and braking road vehicles is considered theoretically for vehicles accelerating (decelerating) with a constant acceleration \( a \) from rest to a constant speed, or braking to a stop from a constant speed. According to the low-frequency approximation considered, an accelerating or braking vehicle of mass \( M \) is modelled as a point horizontal traction force \( F_x = aM \) applied to the ground and moving along with the vehicle. Frequency spectra of the vertical component of the ground vibration velocity are investigated using the Green’s function method for different values of acceleration, final (initial) speed and other parameters.

According to the survey of vibration nuisance from road traffic undertaken by the UK Transport Research Laboratory [1], among the most annoying mechanisms of traffic-induced ground vibrations are: 1) vehicles accelerating and braking - respectively 49.7% and 30.2% of the respondents, and 2) damaged or bumpy road surfaces - 39.4% of the respondents. However, despite the reported significance of ground vibration radiation caused by accelerating or braking, there is no adequate theoretical analysis of vibrations from accelerating or braking vehicles. The existing literature on elastic wave radiation by forces moving at nonconstant trans-Rayleigh speeds along a free surface of an elastic half space [2] is not directly applicable to the case of road-traffic-induced ground vibrations where vehicle speeds are invariably much lower than Rayleigh wave velocities. Note in this connection, that trans-Rayleigh train speeds are a reality and have important implications for generation of ground vibrations [3].

In this paper we consider generation of ground vibrations by vehicles accelerating at constant acceleration \( a \) from rest to a constant speed \( v \), or braking with constant acceleration \(-a\) from \( v \) to a complete stop. It should be emphasised that the main mechanism of ground vibration generation by accelerating or decelerating vehicles is the action of horizontal traction forces which are applied from tyres to the ground only during the time of accelerating or braking (the contribution of normal load forces is relatively small for speeds and accelerations typical for road traffic).

Being interested only in the low-frequency ground vibrations typical of traffic-induced mechanisms of generation, we model a vehicle as a point load moving along the surface either with acceleration or deceleration (Fig.1). The low-frequency approximation assumes that the shortest wave-lengths of the generated ground vibration spectra are larger than the dimensions of the vehicle. This is usually satisfied for all frequencies of traffic-induced ground vibration spectra, which have an upper limit around 30 Hz.
If a vehicle is accelerated or decelerated at constant absolute value $a$, then the point load force applied from a vehicle to the ground surface is a horizontal traction force that moves along the $x$-axis with a vehicle and has the amplitude

$$F_x = aM.$$  

The related mechanical shear stresses applied to the ground surface during acceleration or deceleration, i.e. during the period of time from $t = 0$ to $t = v/a$, where $v$ is the final or initial speed, are described respectively as follows:

$$T_{xz}(\rho, t) = -F_x \delta(x - at^2/2)\delta(y),$$  

and

$$T_{xz}(\rho, t) = F_x \delta(x - vt + at^2/2)\delta(y).$$

Here $T_{ij}$, where $i,j = 1,2,3$, are the components of a load stress tensor applied to the surface, $\rho = \{x, y\}$ is the surface radius-vector, and $\delta(z)$ is Dirac’s delta-function.

The ground vibration field generated by accelerating or braking vehicles in an elastic half space, which we assume to be homogeneous and isotropic, should satisfy the elastic Lame’ equation

$$(\lambda+2\mu) \text{grad} \text{ div } u - \mu \text{ rot rot } u - \rho_0 \partial^2 u / \partial t^2 = 0,$$  

and the boundary conditions on the ground surface taking into account only horizontal traction forces (2) and (3):

$$\sigma_{xz} = 2\mu u_{xz} = -T_{xz}(\rho, t),$$

$$\sigma_{yz} = 2\mu u_{yz} = 0,$$

$$\sigma_{zz} = \lambda u_{nn} + 2\mu u_{zz} = 0.$$  

Here $u$ is the particle displacement vector with the components $u_i$; $\lambda$ and $\mu$ are the elastic Lame’ constants; and $u_{ij} = (1/2)(\partial u_i/\partial x_j + \partial u_j/\partial x_i)$ are the components of the linearised deformation tensor. Without loss of generality, we will limit our calculation of frequency spectra to the vertical component of ground vibration velocity $v_z = du_z/dt$ which is usually determined in experimental observations.

The solution to the problem (1)-(5) using the Green’s function method and taking into account only the contribution of generated Rayleigh surface waves results in the following final expression for the vertical component of the surface vibration velocity spectrum:

$$v_z(\rho, \Theta, \omega) = \left( \frac{2\pi}{k_R \rho} \right)^{1/2} \frac{\omega k_R^2 \left[ k_t^2 v_t v_t - k_R^2 b(k_R) \right] \cos \Theta}{\pi \mu F'(k_R) k_t^2} \times$$

$$\times T_{xz}(\omega, k_R \cos \Theta) e^{k_y \rho} e^{jk_x \rho - jk_R z/4}.$$  

Here the following notations are used: $\rho(x,y)$ is the distance to the observation point; $k_R = \omega/c_R$ is the Rayleigh wave number, where $c_R$ is the Rayleigh wave velocity; $b(k_R) = 2k_R^2 - k_t^2 / 2$ are nonspecified expressions, where $k_t = \omega/c_t$ are the wavenumbers of bulk longitudinal and shear acoustic waves, $c_l$ and $c_t$ are their phase
velocities; $F'(k_R)$ is the derivative $dF(k)/dk$ of the Rayleigh determinant $F(k) = (2k^2 - k_t^2)^2 - 4k^2 \nu_l \nu_t$ taken at $k = k_R$; $\Theta = \cos^{-1}(x/\rho)$ is the observation angle; and $T_{xz}(\omega, k_R \cos \theta)$ is the Fourier transform of the load force (eqns (2) or (3)) which has the following expressions for accelerating and braking vehicles respectively:

$$T_{xz}(\omega, k_R \cos \theta) = -(1/2\pi) aM \int_{0}^{v/a} e^{i(\omega t - k_R \cos \Theta)(at^2/2)} dt,$$

(7)

$$T_{xz}(\omega, k_R \cos \theta) = (1/2\pi) aM \int_{0}^{v/a} e^{i(\omega t - k_R \cos \Theta)(at^2/2)} dt,$$

(8)

In writing (6) we have taken account of attenuation of generated ground vibrations in the ground by replacing the wavenumber of a Rayleigh wave in an ideal elastic medium $k_R = \omega/c_R$ by the complex wavenumber $k_R' = k_R(1 + i\gamma) = (\omega/c_R)(1+i\gamma)$. Here $\gamma << 1$ is a positive constant which describes the linear dependence of a Rayleigh wave attenuation coefficient on frequency $\omega$. For different types of ground the values of $\gamma$ are in the range from 0.01 to 0.2 [4].

One can prove that (7) and (8) differ from each other only by the phase factor. Therefore, being interested only in amplitudes of ground vibrations $V(\rho, \omega) = |v_z(\rho, \omega)|$, in what follows we describe the results for 1/3-octave ground vibration spectra generated by braking vehicles using both direct numerical calculations of (6)-(8) and calculations based on the simple analytical approximation of (7) and (8) neglecting the exact position of the vehicle during acceleration or deceleration. It is easy to show that this analytical approximation gives the same results for 1/3-octave spectra as ones following from the direct numerical calculations.

Fig. 2 illustrates the behaviour of 1/3-octave spectra of ground vibrations (in dB relative to the reference level of $10^{-9}$ m/s) generated by a braking lorry with $M = 20000$ kg for three different values of deceleration: $a = 1, 5$ and $9$ m/s$^2$ (curves 1, 2, and 3 respectively). The initial speed is $v = 10$ m/s. Other parameters are the following: mass density of the ground $\rho_0$ is 2000 kg/m$^3$, velocity of longitudinal bulk waves - $c_l = 471$ m/s, shear waves - $c_t = 272$ m/s and Rayleigh surface waves - 250 m/s (this corresponds to a Poisson ratio of $\sigma = 0.25$). The constant of ground attenuation of Rayleigh waves was set as $\gamma = 0.05$. It follows from Fig.2 that amplitudes of generated ground vibrations at all frequencies increase with increase of $a$.

The behaviour of generated ground vibration spectra for three different values of the initial speed $v = 5, 10$ and $20$ m/s (curves 1, 2, and 3 respectively) is shown on Fig.3 for $a = 5$ m/s$^2$ and $\Theta = \pi/3$. It is seen that for frequencies higher than 4-5 Hz the spectra are almost independent of $v$.

According to the above calculations, typical levels of 1/3-octave frequency spectra of ground vibrations generated at the angle $\Theta = \pi/3$ by heavy lorries ($M = 20000$ kg) are around 40-50 dB. For the observation angle $\Theta = 0$ the levels of vibration are around 46-56 dB. This is approximately of the same order as the averaged ground vibration velocity spectra generated by stationary traffic on uneven roads of very good quality [5].

In contrast to the case of generating ground vibrations by vehicles travelling on uneven roads, for which the load forces are directed normally to the ground surface, the accelerating and braking vehicles generate ground vibrations dependent on the observation angle $\Theta$ with respect to the vehicle movement. The directivity patterns of ground vibrations from accelerating or braking vehicles averaged over 1/3-octave frequency band are described by the function $\cos \Theta$ showing that there is no radiation at the angles $\Theta = \pi/2$ and $3\pi/2$, i.e., in the directions perpendicular to the vehicle movement.
CONCLUSIONS

The amplitudes of ground vibration spectra generated by accelerating and braking road vehicles for medium and upper bands of the spectra are determined mainly by acceleration and are almost independent of the initial (final) vehicle speed.

For low-frequency spectral bands, oscillations of ground vibration amplitudes versus both acceleration and initial speed may take place. These oscillations may be responsible for large statistical deviations of experimentally observed ground vibration levels.

In contrast to vehicles travelling along uneven roads that generate ground vibrations equally propagating at all directions along the surface, the vibrations from accelerating and braking vehicles are characterised by the directivity function. For vibration amplitudes averaged over the 1/3-octave frequency band this function has the form $\cos \Theta$ which shows that there is no radiation in the directions perpendicular to the direction of vehicle movement.

Ground vibrations from accelerating and braking vehicles are generally less intensive than vibrations from vehicles travelling on uneven roads.

REFERENCES