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TRAFFIC CALMING AND ASSOCIATED GROUND VIBRATIONS

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1. INTRODUCTION

Installation of road humps and speed cushions (Fig. 1) is a simple method of reducing the severity and number of road accidents as a result of decrease in speeds at which drivers choose to travel. However, the experimental investigations carried out by the Transport Research Laboratory (TRL) have demonstrated that such a gain is achieved partly in expense of the increased traffic noise and ground-borne vibration (Watts 1997). It has been shown during these investigations that speed control cushions and road humps can produce perceptible levels of ground vibration which depend on vehicle type and hump and cushion design.

Theoretical investigations of ground vibrations generated by road traffic have been carried out by several authors. A number of works has been done for vehicles travelling on statistically rough surfaces of rather good quality (Taniguchi et al. 1979, Le Houedec et al. 1982, Hunt 1991, Hanazato et al. 1991) and for accelerating and braking vehicles (Krylov 1995a-c, 1996a,b). However, vibrations caused by vehicles travelling over single obstacles were analysed only very briefly (Krylov 1995a,c) and no calculations directly relevant to traffic calming road humps and speed cushions were carried out.

In the present paper, ground vibrations generated by vehicles travelling on roads with installed humps of different shapes and sizes are investigated in more detail on the basis of the earlier developed general approach (Krylov 1995a,c). According to this approach, a road vehicle is modelled as a mechanical system interacting with the ground surface and having four degrees of freedom, associated with its main low-frequency resonances. Solving the system of the corresponding dynamic equations, the elastic Lame equation describing ground motion, and taking into account the boundary conditions on the ground surface, which incorporate dynamic forces caused by the interaction of a moving vehicle with a hump, results in the analytical expressions for generated ground vibration spectra. It is shown that amplitudes and spectra of generated ground vibrations depend on shapes and sizes of the road humps, on vehicle speeds and loads, and on ground elastic properties. The results are compared with the recent experiments carried out by the TRL.
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2. VEHICLE INTERACTION WITH HUMPS AND CUSHIONS

In what follows we give a very brief description of the mechanism of vehicle interaction with road humps and speed cushions necessary for understanding the process of generating ground vibrations.

Typical mechanical model of a road vehicle travelling on uneven roads possesses four degrees of freedom corresponding to four main resonance frequencies of low-frequency vibrations related to body bounce and pitch, or to front- and rear-axle hops (Hunt 1991, Wong 1993). Frequencies of body bounce and pitch resonances are normally very low (in the range of 1-3 Hz). Axle-hop resonance frequencies are essentially larger (from 8 Hz to 12 Hz) and are therefore more important from the point of view of generating ground vibrations (we remind the reader that ground wave generation efficiency is higher at higher frequencies).

Keeping this in mind, we use the simplified model of a vehicle, considering its carriage as immobile in vertical direction and taking into account only axle vibrations. This model consists of two identical vibrating systems, each having one degree of freedom and comprising an axle mass $m$ and two springs with constants $K_1$ and $K_2$ modelling respectively the elasticity of tyre and suspension (Fig. 2). Axles are separated from each other by the distance $L$ (wheel base). We also assume that a hump or cushion cross-section in the plane $y = 0$ is described by the function $z_f = f(x)$ (see Fig. 1).

According to the model considered, the equation describing vertical displacements of each axle versus its static position $z_2$ has the form

$$m\ddot{z}_y + Q\dot{z}_y + Kz_2 = K_1z_1(\tau t), \quad (1)$$

where $K = K_1 + K_2$ is a combined elasticity of tyre and suspension, and $Q$ is a total damping coefficient.

Assuming that hump area is small as compared with wavelengths of generated vibrations and its centre is located at $x = 0$ and $y = 0$, the related normal stress $T_{zz}$ applied to the ground can be written in the form

$$T_{zz}(\rho, t) = K_1[(z_2(t) - Z_2(\tau t - L/\nu) - Z_1(\tau t - L/\nu)]\delta(x)\delta(y), \quad (2)$$

where $Z_1(t) = z_1(\nu t)$ and $Z_1(\nu t - L)$ are the input functions for the front and rear axles respectively, $\rho = \{x, y\}$ is the surface radius-vector, and $\delta(z)$ is Dirac's delta-function.
Solving eqn (1) by Fourier method, one can derive the following expression for the Fourier transform $z_2(\omega)$ of a front wheel axle vertical displacement $z_2(t)$:

$$z_2(\omega) = \frac{\omega_1^2 Z_1(\omega)}{\sqrt{(\omega_0^2 - \omega^2)^2 + (2\omega \alpha)^2}} \exp \left[ -i \tan^{-1} \left( \frac{2\omega \alpha}{\omega_0^2 - \omega^2} \right) \right], \quad (3)$$

where $\omega_0 = (K/m)^{1/2}$ is the hop resonance frequency, $\omega_1 = (K/\ell)^{1/2}$ is the tyre “jumping” resonant frequency, $\alpha = Q/2m$ is a normalised damping coefficient, and $Z_1(\omega)$ is the Fourier spectrum corresponding to the hump profile. The Fourier transform for a rear wheel axle vertical displacement $z_2(t-L/v)$ differs from (3) only in phase shift $\omega L/v$ and is omitted here for shortness. The Fourier transform of the force applied from vehicle to the ground, $T_{zc}(\rho, \omega)$, is easily obtained from (2) via replacing $z_2(t)$, $Z_1(t)$, $z_2(t-L/v)$, and $Z_1(t-L/v)$ by their Fourier spectra:

$$T_{zc}(\rho, \omega) = K_1[(z_2(\omega) - Z_1(\omega))e^{i\omega L/v} - Z_1(\omega)e^{i\omega L/v}j(x)\delta(y)]. \quad (4)$$

3. VEHICLE-GENERATED GROUND VIBRATIONS

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

$$(\lambda + 2\mu) \nabla \cdot \mathbf{u} - \mu \nabla \times \nabla \times \mathbf{u} - \rho_0 \frac{\partial^2 \mathbf{u}}{\partial t^2} = 0, \quad (5)$$

and the boundary conditions on the ground surface taking into account the vertical force (2) resulting from the interaction of the vehicle with an uneven surface. Here $\mathbf{u}$ is the particle displacement vector with the components $u_i$; $\lambda$ and $\mu$ are the elastic Lame' constants; and $\rho_0$ is the ground mass density.

The ground surface geometry is rather complex due to the presence of road humps and cushions. Therefore, strictly speaking, the problem under consideration is difficult for rigorous solution. However, since the characteristic height $h$ of road humps and cushions is very small in comparison with characteristic wavelengths $\lambda_w$ of generated vibrations, it can be simplified by using the method of projection of the actual boundary conditions onto the flat surface $z = 0$. One can show that the projected boundary conditions differ from the real ones only by the additional small terms proportional to $h/\lambda_w << 1$. In further consideration we will neglect these terms and write the boundary conditions at $z = 0$ in the form:
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\[
\sigma_{xx} = 2\mu u_{xx} = 0,
\sigma_{yy} = 2\mu u_{yy} = 0,
\sigma_{zz} = \nu u_{nn} + 2\mu u_{zz} = -T_{zz}({\rho},t).
\]  

(6)

Here \( u_{ij} = (1/2)(\partial u/\partial x_j + \partial u/\partial x_i) \), where \( i,j = 1,2,3 \), are the components of the linearised deformation tensor; and \( \sigma_{ij} \) are the components of the elastic stress tensor. Without loss of generality, we limit our calculation of frequency spectra to the vertical component of ground vibration velocity \( v_z = du/dt \) which is usually measured during experimental observations.

Solving the boundary value problem (2)-(6) by the Green's function method and taking into account only generated Rayleigh waves, one can derive the following expression for the vertical component of the surface vibration velocity spectrum:

\[
v_z(\rho,\omega) = \left( \frac{2\pi}{k_R\rho} \right)^{1/2} \frac{(-i\omega)k_Rk_R'v_i}{2\pi\mu F'(k_R)} T_z(\omega) e^{-k_{R}'\rho} e^{ik_{R}'\rho - 4\pi k_{R}'^{1/2}r / \rho}. \tag{7}
\]

Here \( T_z(\omega) = T_{zz}(0,\omega) \) (see eqn (4)); \( \rho = \rho(x,y) \) is the distance to the observation point; \( k_R = \omega/c_R \) is the Rayleigh wave number, where \( c_R \) is Rayleigh wave velocity; \( v_{i,t} = (k_R^2 - k_{i,t}^2)^{1/2} \) are nonspecified expressions, where \( k_{i,t} = \omega/c_{i,t} \) are the wavenumbers of bulk longitudinal and shear acoustic waves, \( c_i \) and \( c_t \) are their phase velocities; \( F'(k_R) \) is the derivative \( dF(k)/dk \) of the Rayleigh determinant \( F(k) = (2k_R^2 - 3k_{R}'^2)^2 - 4k_R^2v_i^2v_t \) taken at \( k = k_R \).

In writing (7) 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 \( k_R' = k_R(1 + ri) = (\omega/c_R)(1 + ri) \). 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 \( \gamma \) are in the range from 0.01 to 0.2 (Gutovski et al. 1976). In what follows we will be interested only in amplitudes of ground vibrations \( V_z(\rho,\omega) = |v_z(\rho,\omega)| \), ignoring the phase information.

4. DISCUSSION

Numerical calculations of generated ground vibrations have been carried out according to eqn (7) for vehicles travelling at different speeds over road humps and cushions of different profiles and dimensions. Vehicle parameters were: \( \omega_1 = 65 \text{ rad/s}, \omega_0 = 70 \text{ rad/s}, \alpha = 15, L = 6 \text{ m}, \) and \( m = 50 \text{ kg} \). Ground parameters were: Rayleigh wave velocity \( c_R = 125 \text{ m/s} \), Poisson ratio \( \sigma = 0.25 \), ground mass density \( \rho_0 = 2000 \text{ kg/m}^3 \), ground attenuation constant \( \gamma = 0.05 \). Observation distance was \( \rho = 30 \text{ m} \).
Obviously, if the spectrum \( Z_l(\omega) \) has components around the axle hop resonance frequency \( \omega_o \), then the axle vibrations are effectively excited and noticeable generation of ground vibrations takes place. Analysis and numerical calculations show that amplitudes and spectra of generated ground vibrations depend on hump and cushion profile, their characteristic gradient (ratio \( h/l \)), vehicle speed \( v \) and load, and elastic parameters of the ground.

a) Dependence on hump and cushion profile. Calculations show that the smoother the hump the lower is the level of generated ground vibrations. In particular, for typical vehicle speeds \( v \), a bell-shaped hump, \( z_l(x) = h \exp(-x^2/l^2) \), causes approximately 20 dB reduction in the integral level of generated ground vibrations in comparison with a cosine-shaped hump, \( z_l(x) = h \cos(\pi x/l) \), having the same height \( h \) and length \( l \).

b) Dependence on the ratio \( h/l \). Calculations for cosine-shaped road humps, including the ones with typical parameters: \( h = 0.074 \, m \), \( l = 0.9 \, m \); and \( h = 0.064 \, m \), \( l = 3.7 \, m \), have demonstrated that the integral level of generated ground vibrations grows roughly in direct proportion to \( h/l \). This agrees well with the experimental results of TRL for two round-shaped profiles of the above mentioned dimensions (Watts 1997).

c) Dependence on vehicle speed \( v \). Dependence of generated ground vibrations on vehicle speed \( v \) is quite complex for each particular spectral component. Calculated results for a cosine-shaped hump are shown in Fig. 3.a. One can see that for small and medium speeds \( v \) ground vibration amplitudes grow with oscillations (depending on hump length \( l \) and wheel base \( L \) ) and reach a maximum at certain \( v \). Then, for larger values of \( v \), the level of generated vibrations decays inversely proportionally to \( v \). Calculation of the integral level of generated ground vibrations carried out for the same cosine-shaped hump shows that it depends on \( v \) in a more simple way (Fig. 3,b). The dependence is roughly linear for typical values of \( v \) at which drivers chose to travel in traffic calming areas (from 0 to 7 m/s). Note that the initial average growth of generated ground vibrations with the increase of vehicle speed agrees with the TRL experimental results (Watts 1997), although no detailed comparison was possible because of insufficient number of vehicle speeds (four) used in the experimental observations.

d) Effect of vehicle loading. Heavy loads result in the increase of static stresses applied to the vehicle suspension which, due to nonlinearity of material stress-strain relations, will change the stiffness of an equivalent spring and, hence, modify the axle hop resonance frequency \( \omega_o \). The directions of these modifications are different for steel and air suspensions: for the first case the frequency \( \omega_o \) decreases, whereas for the latter case it increases. According to the above theory and in agreement with the experiments (Watts 1997), these result in a small decrease in generated vibrations for vehicles with steel suspension and in their small increase for vehicles with air suspension.
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e) Effect of ground parameters. The presence of the ground shear modulus $\mu$ in the denominator of eqn (7) implies that for the softer ground (smaller values of $\mu$) the generated ground vibrations are more intensive.

5. CONCLUSIONS

Theoretical analysis of ground vibrations generated by vehicles travelling over traffic calming road humps and cushions shows that amplitudes and spectra of vibrations depend strongly on the shape of hump or cushion profile, relation between its height and length, vehicle speed and load, and ground elastic parameters. The developed theoretical model of generating ground vibrations agrees with the existing experiments and can be successfully used in practice.

6. REFERENCES


KRYLOV, V.V. (1996b) Generation of ground vibrations by accelerating and braking road vehicles. Acustica-acta acustica, 82, No 4, 642-649.


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Fig. 1. Typical geometry of a road hump.

Fig. 2. Simplified mechanical model of a vehicle taking into account only axle-hop resonance.
Fig. 3. Dependence of generated ground vibrations on vehicle speed $v$ [m/s]