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GENERATION OF GROUND VIBRATIONS BY ROAD VEHICLES CROSSING TRAFFIC CALMING HUMPS AND CUSHIONS

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1. INTRODUCTION

Road humps and speed cushions 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). The results are compared with the recent experiments carried out by the TRL.

2. OUTLINE OF THE THEORY

In what follows we give a very brief description of the mechanism of vehicle interaction with road humps and speed cushions (Fig. 1) 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 $z_1 = f(x)$.

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

$$m\partial^2 z_2 / \partial t^2 + Q\partial z_2 / \partial t + Kz_2 = K_1 z_1(vt), \quad (1)$$

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

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

where $Z_1(t) = z_1(vt)$ and $Z_1(t-L/v) = z_1(vt-L)$ are the input functions for the front and rear axles respectively, $\rho = \{x, y\}$ is the surface radius-vector, and $\delta(x)$ 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 $z_2(t)$:

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

where $\omega_0 = (K/m)^{1/2}$ is the hop resonance frequency, $\omega_1 = (K_1/m)^{1/2}$ 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 ground vibration field generated by vehicles in an elastic half space, which we assume to be homogeneous and isotropic, should satisfy the elastic Lamé' equation 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.

Solving the above mentioned boundary value problem by the Green's function method and taking into account only generated Rayleigh waves, one can derive the following expression for the vertical component $v_z = du_z/dt$ of the surface vibration velocity spectrum:

$$v_z(\rho, \omega) = \left(\frac{2\pi}{k_R \rho} \right)^{1/2} \frac{(-i\omega) k_R k_i^2 v_1}{2\pi \mu F'(k_R)} T_{zz}(\omega) e^{-k_R \rho} e^{ik_R \rho - i3\pi/4}. \quad (4)$$

Here u is the particle displacement vector with the components u_i ; μ is shear modulus of the ground; ρ_0 is the ground mass density; $T_{zz}(\omega) = T_{zz}(0, \omega)$ (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; $v_{Li} = (k_R^2 - k_{Li}^2)^{1/2}$ are nonspecified expressions, where $k_{Li} = \omega/c_{Li}$ 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 $F(k) = (2k^2 - k_t^2)^2 - 4k^2 v_L v_t$ taken at $k = k_R$.

3. NUMERICAL CALCULATIONS AND DISCUSSION

Numerical calculations of generated ground vibrations have been carried out according to eqn (4) 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 ω_0 , 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: $h = 0.074 \text{ m}$, $l = 0.9 \text{ m}$; and $h = 0.064 \text{ m}$, $l = 3.7 \text{ m}$, 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 show 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 (Fig. 3,a). 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 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 ω_0 .

The directions of these modifications are different for steel and air suspensions: for the first case the frequency ω_0 decreases, whereas for the latter case it increases. According to the above theory, the resulting ground vibrations depend on the balance between the load force spectrum and frequency response of the Green's function for modified hop resonance frequencies. For typical parameters of the problem 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.

e) Effect of ground parameters. The presence of the ground shear modulus μ in the denominator of eqn (4) implies that for the softer ground (smaller values of μ) the generated ground vibrations are more intensive.

4. 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.

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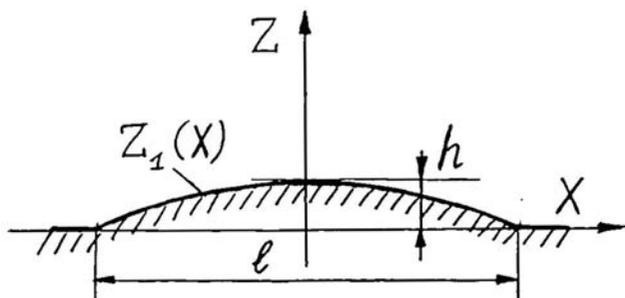


Fig. 1. Typical geometry of a road hump

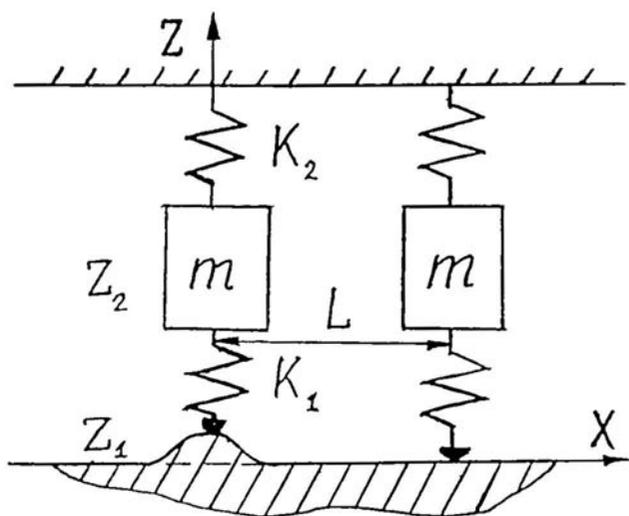


Fig. 2. Simplified mechanical model of a vehicle taking into account only axle-hop resonance

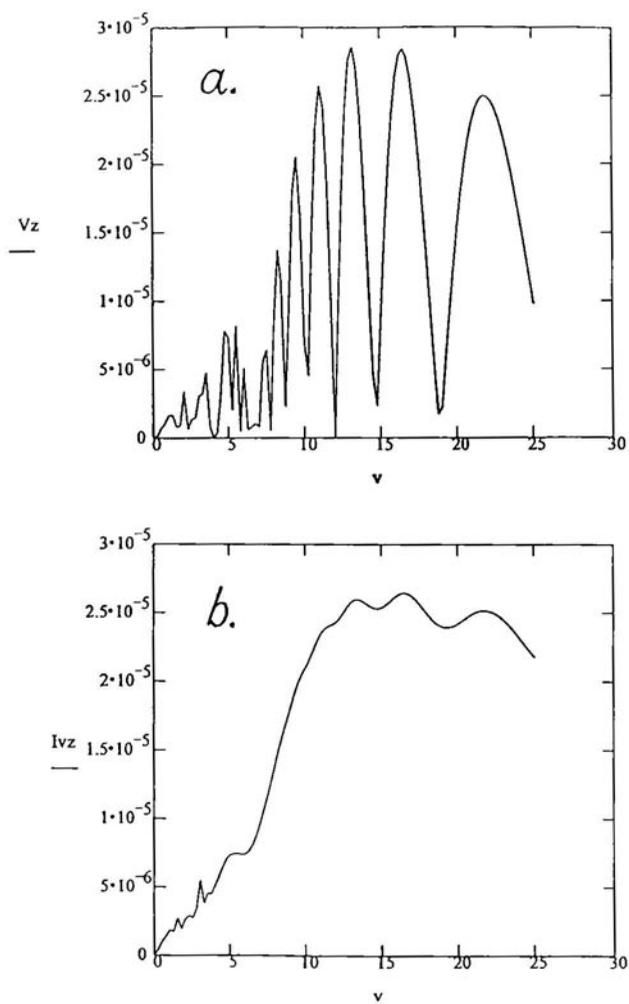


Fig. 3. Dependence of generated ground vibrations on vehicle speed v [m/s]