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ESTIMATION OF GROUND-BORNE VIBRATIONS FROM MOVING TRUCKS

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ABSTRACT

The paper focuses on providing details on the application of a continuum-based finite-layer model to estimate ground-borne vibrations induced by moving trucks. The computational model incorporates important pavement response factors such as the noncircular contact area, complex 3-D contact stress distributions (normal and shear), vehicle speed, and viscoelastic material characterization. The proposed method is much more computationally efficient than the moving-load models based on the finite element method. Predictive capability of the approach relative to vehicle-induced vibrations has been demonstrated using realistic pavement loading. As an important design application, particle velocity responses from conventional dual and its recent substitute, viz. wide-base (super-single) tires have been computed and compared.

INTRODUCTION

An inevitable by product of the moving traffic is the vibrations transmitted through the surrounding medium. The vibration generated by moving trucks is a complex physical phenomena characterized by its amplitude, frequency and duration (or number of cycle). Many case histories (Lacy and Gould 1985; Leathers 1994) have demonstrated that ground-borne vibrations are not only disturbing to humans, but can also be detrimental to structures and equipment. Correlations between traffic induce vibration, expressed in terms of acceleration and peak particle velocity, and its effects on humans and existing structures are available (Drabkin et al. 1996; Dowding 1995). To use these correlations the characteristics of the vibrations (e.g. maximum particle velocity) generated by the moving traffic loads should be known.

The characteristics of the vehicle-pavement interaction has been drastically changing over the years. For example, the tire pressures have increased to more than 760 kPa from 520 kPa used in the sixties; type of tires used in the sixties was bias ply, whereas the commonly used tires now are radials. Another important change being considered in recent years is the use of a single wide-base (super-single) tires instead of the traditional dual tires in trucks. This change offers significant economic advantage to the trucking industry. There are many national and international efforts underway to address any possible detrimental engineering concerns relative to the use of wide-base tires as opposed to the conventional dual tires. The study of de Beer et al. (1996) and Siddharthan et al. (1999) focused on pavement distress. This paper focuses on characterizing ground-borne vibrations caused by moving trucks, with special attention given to comparing the vibrational response produced by wide-base and dual tires. The procedures developed here will enable the study of the transmission of ground-borne vibration in a fundamental way with due considerations given to vehicle-pavement interaction, material and pavement structure (thickness) properties. The approach described is a moving-load model, which is built on the work of Zafir et al. (1994) and Siddharthan et al. (1998). It treats the vehicle-pavement interaction as a complex 3-D loaded area. A limited verification of this approach using existing analytical solutions and laboratory model test results has been presented by Siddharthan et al. (2000a). Recently a field verification study using two ful-scale field tests also has been reported (Sidharthan et al. 2000b).

BRIEF DESCRIPTION OF THE FINITE-LAYER MECHANISTIC MODEL

Siddharthan and his co-workers (1998) reported on the formulation of a continuum-based "finite-layer" model to evaluate the response of a layered medium subjected to a moving surface load. The pavement layer system may be characterized as consisting of a number of viscoelastic or elastic horizontal layers (as many as necessary) with each layer characterized using a set of uniform properties.

Since the surface load moves at a constant speed, V, and the pavement layer properties do not vary in the horizontal direction, any response, for example, the horizontal displacement, u, using the Fourier transform, can be written as,

$$u = u(x-Vt) = \sum_{n=1}^{N} \sum_{m=1}^{M} U_{nm}(z) e^{i\lambda_n(x-Vt)} e^{i\mu_m y} \qquad (1)$$

in which $U_{nm}(z)$ reflects the variation in displacement of u with z only for the nth and mth harmonics; λ_n and μ_m are wave numbers; x is the longitudinal axis, which is also the direction of wheel path; y and z are the transverse and vertical axes, respectively. The major advantage in writing the response in this fashion is that the derivatives with respect to x, y, and t are straightforward; thus any response can be written in terms of z only. Under these circumstances, if the response to a single harmonic surface loading can be found, then the principle of superposition can be used to obtain the pavement response as an algebraic sum of the contributions from all the harmonics present.

Solution for a Single Harmonic Pressure

Dynamic equations of motion for a 3-D elastic continuum can be written using index notation (Timoshenko and Goodier, 1970) as,

$$\sigma_{ij,j} = -\rho \frac{\partial^2 u_i}{\partial t^2} \qquad (2)$$

in which σ_{ij} = the stress tensor, ρ = mass density, and u_i = the displacement in the ith direction. The comma that appears between ij and j represents differentiation with respect to the direction j. According to Timoshenko and Goodier (1970), the elastic stress-displacement relationships in index notation can be written as,

$$\sigma_{ij} = M\delta_{ij} u_{k,k} + G(u_{i,j} + u_{j,i}) \qquad (3)$$

in which δ_{ij} = the Kronecker delta and M and G are Lame's constants. Substituting Eq. 3 into Eq. 2 results in three equations in terms of three unknown displacements. Therefore, the solution of the problem is possible.

Knowing that the response will be in the form given in Eq. 1 for each harmonic, steps similar to those followed by Siddharthan et al. (1998) and Zafir et al. (1994) will lead to solutions for horizontal displacement component (Eq. 1) U_{nm} as,

$$U_{nm}(z) = U_1 e^{-n_1 z} + U_2 e^{n_1 z} + U_3 e^{-n_2 z} + U_4 e^{n_2 z} \qquad (4)$$

in which, n_1 and n_2 depend wave numbers and material properties, and U_1 - U_4 are integration constants.

In the case of horizontally layered deposits with different properties, an equation similar to Eq. 4 exists for each layer. These constants can be evaluated by satisfying the top and bottom boundary conditions, interface continuity conditions in displacement, and normal and shear stresses.

A computer code 3D- Moving Load Analysis (3D-MOVE) has been developed incorporating the above solution technique . It may be noted that, since the entire domain has been treated as layers extending to infinity in the lateral direction (i.e., without any artificial lateral boundaries), the radiation damping has been implicitly incorporated into the proposed analysis. For more details on the formulation of this analytical approach see Siddharthan et al. (1998).

MATERIAL CHARACTERIZATION

The proposed finite-layer response model can handle viscoelastic (rate-dependent) characterization of pavement layers. Since only AC layer exhibits strong rate-dependent behavior, the viscoelastic layer characterization is used for the AC layer while the unbound material (the base and the subgrade) layers are assumed to be elastic.

Sousa and Monismith (1987) studied the effects of many different parameters on the resilient modulus of AC. They tested AC samples under three different temperatures, 11°C, 25°C, and 40° C using sinusoidal cyclic axial and torsional loading with varying frequencies. They found that, for AC, the amplitude of the dynamic complex shear modulus, |G*|, is a function of the temperature and frequency of the loading (Fig. 1). The figure shows that the dynamic shear modulus for AC increases with an increase in frequency and decreases with an increase in temperature. Other material properties, such as the dynamic Poisson's ratio and the internal damping, ζ have also been reported by Sousa and Monismith (1987). This database has been used to assign properties to the AC pavement layer.

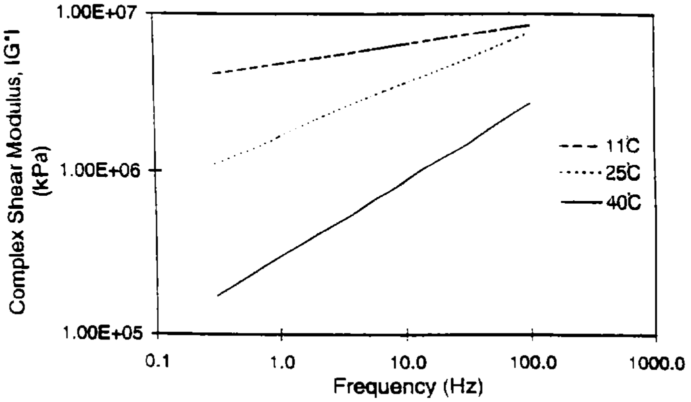

Fig. 1. Variation of complex shear modulus with frequency and temperature (after Sousa and Monismith, 1987).

APPLICATION TO FIELD PROBLEMS

Description of Example Problem

To illustrate the application of the proposed approach, two different pavements, representing a thin and a thick pavement, were subjected to loading from a moving tandem axle. Figures 2(a) and 2(b) show the pavement layer thicknesses and a sketch of the moving tandem axle loading. The physical material properties of base and subgrade, which were assumed elastic are given in the figure. The dynamic material properties of the AC layer were assigned from the database of viscoelastic material properties shown in Fig. 1. The measured values of complex shear modulus, which are appropriate for the temperature of 40°C were chosen for the AC layer in this study.

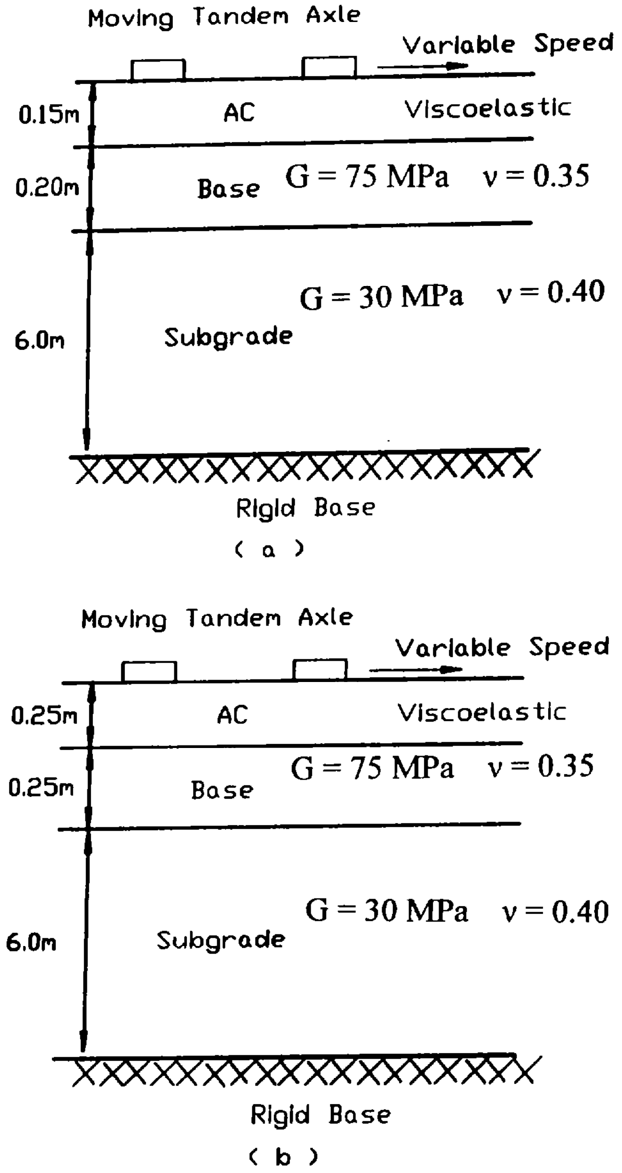

Fig. 2. Pavement structure properties: (a) thin pavement (b) thick pavement.

The responses caused by both wide-base and dual tires (conventional) are needed to compare the effects of vehicle-induced vibrations. A typical tandem axle carries a total axle load of 180 kN and when wide-base tires are used the load carried by each tire is 45 kN/tire. On the other hand, when typical dual tire configuration is used, the tire load is 22.5 kN/tire. Both types of tire configurations are shown in Fig. 3.

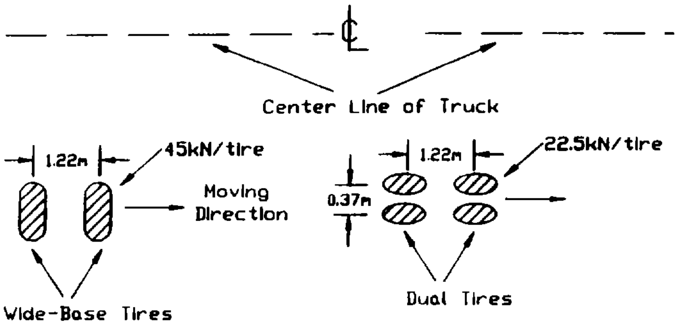

Fig. 3. Moving tandem axle with wide-base and dyal tire configurations.

Traditionally, the pavement interaction pressure distribution is often assumed to only comprised of uniform normal stress, even though many studies have indicated the importance of the non-uniform normal stress distribution and the interface shear stresses (Perdomo and Nokes 1993; Tielking and Roberts 1987). The tire-pavement interaction stress distributions used in this study is based on the recent most comprehensive work on wide-base tires carried out by the South African Institute of Road (CSIR) (de Beer et al. 1996). These researchers outlined a procedure to measure all three components of tire-pavement interaction stresses under a moving load. They developed an advanced measuring system referred to as Vehicle-Road Surface Pressure Transducer Array (VRSPTA) which is capable of measuring vertical and transverse and longitudinal shear stresses simultaneously under a moving tire.

Vertical (σ_{zz}), longitudinal (τ_{xz}) and transverse (τ_{yz}) contact stresses reported by de Beer et al. (1996) for Bridgestone wide-base 425/65R22.5 tire were used to represent the pavement surface loading. As a typical plot, the variation of σ_{zz} within the loaded area is shown in Fig. 4.

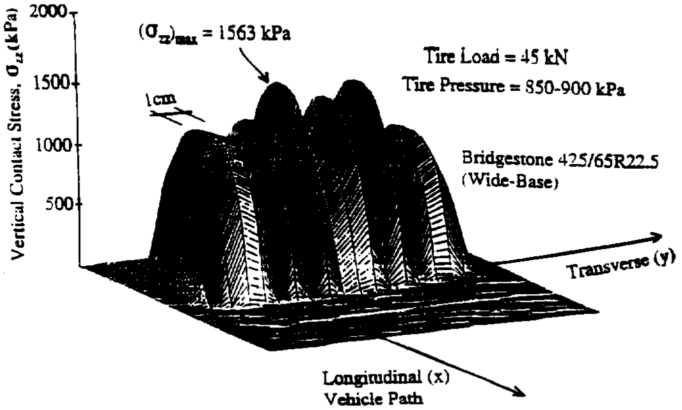

Fig. 4. Nonuniform contact vertical stress distribution under a wide-base tire (after de Beer et al. 1996).

This stress distribution was obtained for a vertical load of 45 kN with tire inflation pressure range varying between 850 and 900 kPa. It is clear that the contact pressure variation is nonuniform and the loaded area is noncircular with maximum dimensions of about 32.0 and 16.0 cm in the transverse and longitudinal directions respectively. The maximum σ_{zz} is much higher than the tire inflation pressure and is as much as 1563 kPa. The longitudinal and transverse shear stresses also indicated nonuniform stress distributions, but of much lower values. The maximum longitudinal and transverse shear stresses are 180 kPa and 254 kPa respectively. This means that the contact shear stresses are only about 12 and 16% of the maximum vertical stress. The tire-pavement interaction stresses for conventional tires (295/75R22.5) reported by Sebaaly et al. (1992) were used in the case of the vehicle with the dual tire configuration.

Results and Interpretation

Though the program 3D-MOVE can compute any response such as displacement, velocity or acceleration, at any point, only the response in terms of velocity (particle) is presented in the paper. This is because by far the particle velocity is considered the critical input parameter in assessing the impact of vibration on human tolerance and sensitive equipment. At any point, there are three components representing magnitude of velocities in all three directions. The pavement vibration response in terms of absolute particle velocity is presented below.

The program 3D-MOVE was used to obtain this parameter for both the thin and thick pavements identified earlier. Computed time history response of absolute velocity at a point on the surface along the center line of the wide-base tires is shown in Fig. 5. The vehicle is assumed move at 72 km/hr.

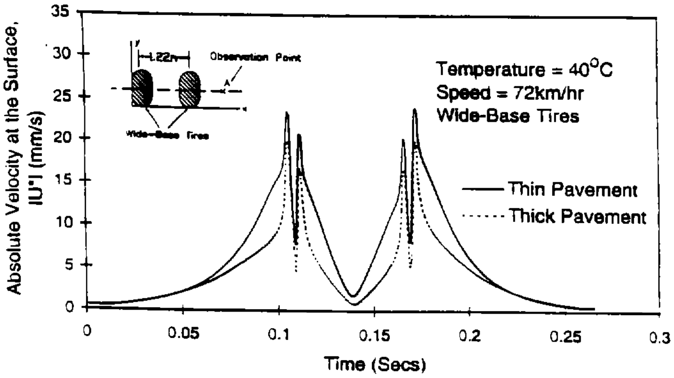

Fig. 5. Absolute particle velocity time history at the surface under the loading from wide-base tires.

Many observations can be made from the figure. First of all, as expected the velocity in the case of thick pavement is smaller and the peak value is about 15% lower than the velocity that corresponds to the thin pavement. There are altogether four sharp peaks, consisting of two peaks per tire. There is a drop in velocity between the two peaks associated with each tire, indicating the influence of complex interaction of tire-pavement interface stresses. It should be noted that though the σ_{zz} component of the tire-pavement interface stresses is symmetric about he transverse axis (Fig. 4), the other stress components τ_{xz} and τ_{yz} are not. Secondly, a closer look at the lag between similar velocity responses indicates that the separation in time is about 0.061 secs, which corresponds to a distance of 1.22 m for a vehicle traveling at 72 km/hr. As shown in Fig. 3, this distance is the spacing between the tires. Thirdly, it appears that the coupling in velocity response between the tires is minimal. This means that the vibrational characteristics of tandem (or multiple) axles may be studied using superposition of responses from single axles.

Extensive correlations between human tolerance and vibration level caused from transient loads have revealed that particle velocities less than 2.5 mm/s can be barely sensed by humans, however, particle velocities in excess of 50 mm/s can be dangerous to structures and equipment (Drabin et al. 1996; Dowding 1995). This means that from Fig. 5 it may be concluded that vibration levels induced near the wheel path by trucks moving at 72 km/hr with wide base tires though can be sensed by humans, are not detrimental to structures.

Figure 6 shows the maximum velocity response at the pavement surface along the transverse direction (y-axis) for the case of thin pavement. These values were obtained by selecting the maximum value from the velocity histories computed at many points along the transverse direction. Results from both type of tires (wide-base and dual) for vehicle traveling at 54 and 108 km/hr are presented. The origin of the y-axis is located at the edge of the tire (see insert in Fig. 5). The center of the wide-base tire is located at 16 cm from the edge of the tire (i.e. y = 16 cm). The maximum velocity response is indicated about half-way between the edge and the center of the wide-base tire. As the vehicle speed increases from 54 to 108 km/hr, the maximum velocity response increased from 27 to 44.5 mm/s, an increase of 65%. Lower velocity responses are computed with dual tires. The maximum velocities for these tires are 22 and 36.3 mm/s for vehicle speeds of 54 and 108 km/hr, respectively.

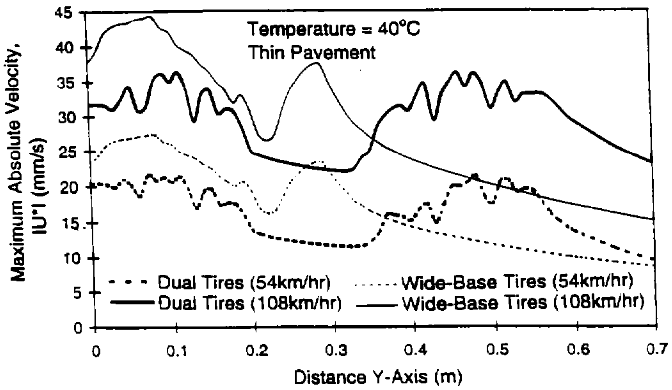

Fig. 6. Maximum particle velocity variation in transverse direction.

As the point of observation moves away from the loaded area the velocity response diminishes. If the 2.5 mm/s triggering criterion associated with human tolerance is used, the study indicates that only beyond a distance of 1.1 m from the center of the wide-base tire the velocity response is lower than the criterion for vehicle traveling at 108 km/hr. For vehicle speed at 54 km/hr, this distance of influence reduces to 0.85 m. Similarly for dual tires, the corresponding distances of influence are lower at 0.4 and 0.47 m from the center of outer tire for vehicle speeds of 54 and 108 km/hr, respectively.

As a summary plot, the maximum particle velocity at the surface (under the tires) for both tire configurations and pavement thickness as a function of vehicle speed are presented in Fig. 7. The velocity response substantially increases as the vehicle speed increases. When the vehicle speed increased from 36 to 108 km/hr, which is a three fold increase, the particle velocity increases by about two fold. All cases reported here show vibration levels more than the triggering limit associated with human tolerance. This include the case of vehicles traveling at a speed as slow as 36 km/hr. It is clear that, irrespective of pavement thickness and vehicle speed, the wide-base tires generate much higher level of vibration, and it is on the average as much as 50% higher than the corresponding values generated by dual tires.

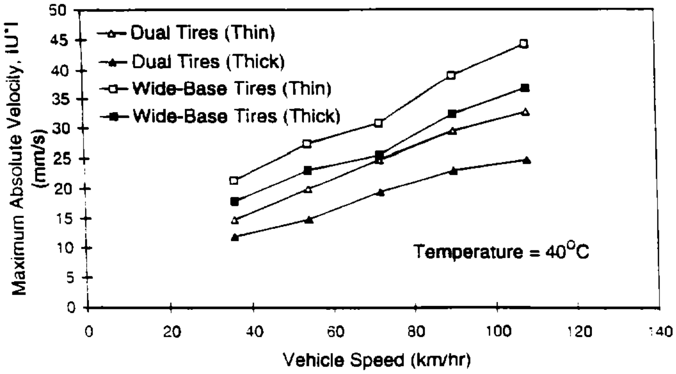

Fig. 7. Maximum particle velocity at the surface under the tires as a function of vehicle speed.

CONCLUSIONS

The applicability of a continuum-based finite-layer approach and the ensuing computer program 3D-MOVE relative to the prediction of vehicle-induced vibrations has been presented. The proposed finite-layer approach is an ideal tool to model the visco-elastic behavior of asphalt concrete layer and to study the effects of vehicle speed and complex 3-D tire-pavement interface stresses on pavement response. As an important design application, particle velocity responses from conventional dual tires and its recent substitute viz. wide-base (super-single) tires have been computed and compared. Two types of pavements, representing a thin and a thick pavement, with realistic material properties have been used in the evaluations.

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