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Numerical evaluation and experimental measurements of traffic-induced vibrations

S. Chiostrini, F. Lancieri, A. Marradi, M. Nocentini, A. Vignoli
Department of Civil Engineering, University of Florence, Via di S. Marta, 3, I-50139, Florence, Italy

Abstract

A numerical approach is presented for the evaluation of the power spectrum of ground vibrations in the vicinity of a roadway. The method accounts for actual road surface roughness, vehicle mechanic characteristics, vehicle speed and soil parameters. Dynamic models for generation and propagation of vibrations are developed, from the source (the vehicle) through the ground, until the building foundations. An application is presented, in which the road roughness power spectrum has been obtained directly from road displacement field measurements in Florence. The reliability of the computational method has then been verified comparing numerical results with experimental measurements in the same conditions.

1 Introduction

Despite the constant rise in urban traffic, in the evaluation of the structural safety of constructions problems related to vibrations induced by vehicle circulation are often neglected. Moreover, as introduced by [1], only few analytical methods for predicting levels of traffic-induced ground vibration are available, largely because of the mathematical complexity of a realistic dynamic modeling of the ground. Gutowsky and Dym [2] recognized that simple predictive models reveal generally not adequate for any serious purpose, and so a certain degree of mathematical complexity must be tolerated.

For practical purposes, in the light of the difficulties encountered with theoretical investigations, it was often found preferable and more expedient to carry out experimental investigations at a particular site, as performed in [3, 4]. In none of these studies, anyway, was any attempt made to relate experimental observations to an analytical model.

The present study has been performed in order to address this lack and to develop a model simple enough for practical applications and, on the other hand, with the appropriate theoretical effectiveness to guarantee the validity of results.

Vehicles are described by a double-degree-of-freedom single-axle dynamic model; the ground, through which vibrational energy is transmitted, is treated as a visco-elastic continuum because of the mathematical complexity of a more realistic dynamic modeling. The predictive model of wave generation and propagation here developed can also be employed for design purposes, in estimating the correct dimensions, stiffness and damping characteristics of an isolating structure and to evaluate the reduction of the peak particle velocity at foundation level due to the adoption of such device.

2 Numerical model

For the correct setup of the model, the following basic elements have to be considered, as explained in the following paragraphs:

- **road-surface roughness**, assumed as the origin of the running vehicle oscillations, thereby as the main cause of the vibrational phenomenon;
- **vehicle mechanical characteristics**, that have to be carefully considered in order to define the "vehicle type";
- **soil characteristics;** the soil is treated as an elastic damping halfspace, transmitting the vibration waves, from the road infrastructure to nearby building foundations.

2.1 Pavement surface undulations

Pavement surface undulations are classified according to their wavelength regimes (λ) as specified in [5]:

1. $\lambda > 50$ m — topographical undulations;
2. 10 cm $< \lambda <$ 50 m — road roughness;
3. 0.5 mm $< \lambda <$ 10 cm — road macrotexture;
4. $\lambda <$ 0.5 mm — road microtexture.

The above wavelength regimes apply for measurements along a longitudinal profile of the highway lane. The temporal frequency of vibrations experienced by a tire traversing the pavement is then related to the wavelength by the relationship:

$$f = \frac{v}{\lambda} \tag{1}$$

being f the temporal frequency of excitation, v the axle speed and λ the wavelength of the undulation. Thus, f.i., a tire moving at an axle speed of 100 km/h (27.8 m/s), traversing a sinusoidal undulation with a wavelength of 27.8 m, would experience vertical displacement excitations at a frequency of 1 Hz

The undulations in regimes of "road roughness" and "road macrotexture" are the ones that significantly affect the aspect of traffic-induced vibration, while the "microtexture" regime is important for skid resistance and in adhesion processes governing tangential tread vibration excitation at tread release. This last contribution is non influential to the analysis of the examined phenomenon.

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2.2 Power spectrum of the road surface profile

In the present study, the actual profile of the road surface has been obtained directly by field measurements. In the application presented, the road pavement was composed of the stone slabs of "Lungarno Archibusieri" in Florence, furnishing the profile in Figure 1, where x represents the road longitudinal axis and y the ordinate of the profile, i.e. the vertical movement impressed by the road surface to the point of contact of the tire.

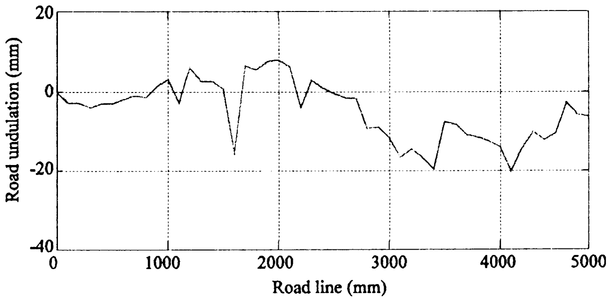

Figure 1: Site measurement of the road surface profile

The trend of the road surface profile is assumed to be a random, stationary and ergodic process. According to Fourier transformer of sampled data in Figure 1, the spectral density of the movements is obtained, related to the spatial wavenumber γ of the road surface roughness ($\gamma = 2\pi/\lambda$).

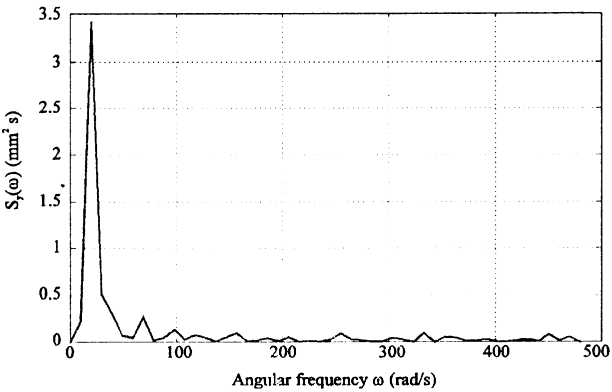

Figure 2: Power spectrum of road surface profile

The spectral density related to circular frequency ω, see also Figure 2, is then expressed as:

$$S_y(\omega) = \frac{1}{\nu} S_y(\gamma) \tag{2}$$

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2.3 Vehicle model

The vehicle is represented by a two-degrees-of-freedom system (see Figure 3) composed by the vehicle axle mass m_2 and the residual vehicle mass m_1. Tires and suspensions are respectively interposed between mass m_1 and the ground, and between the two masses; they are schematized through an elastic spring and a viscous linear damping organ.

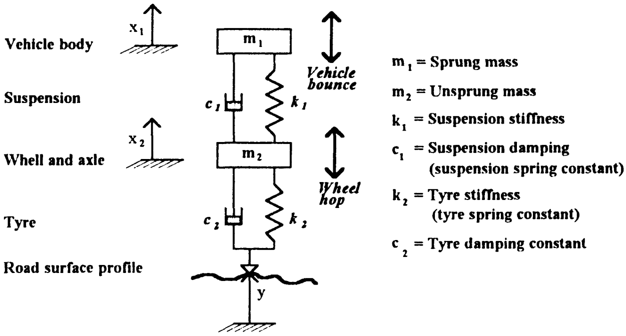

Figure 3: Vehicle model

Considering the differential equations of motion of the system:

$$\begin{cases} k_1(x_1-x_2)+c_1(\dot{x}_1-\dot{x}_2)=-m_1\ddot{x}_1 \\ -k_1(x_1-x_2)-c_1(\dot{x}_1-\dot{x}_2)+k_2(x_2-y)+c_2(\dot{x}_2-\dot{y})=-m_2\ddot{x}_2 \end{cases} \tag{3}$$

and expressing $y(t)=Y(\omega)e^{i\omega t}$ results in an harmonic output $x_i(t)=X_i(\omega)e^{i\omega t}$.

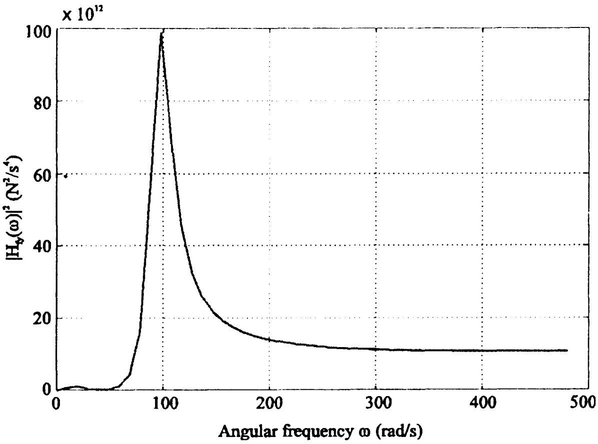

Figure 4: Vehicle frequency response function

The expression of transfer function H_{fy} from movements y(x) to forces applied to ground foundation, showed in Figure 4, is thereby derived, where the acceleration term $\ddot{Z}(\omega)$ in Eq. (4) is assumed as the weighted-mean acceleration, also according to [6].

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$$H_{fy}(\omega) = \frac{F(\omega)}{Y(\omega)} = \frac{m\ddot{Z}(\omega)}{Y(\omega)} = (m_1 + m_2)\left[\frac{(m_1\ddot{X}_1 + m_2\ddot{X}_2)}{(m_1 + m_2)}\right] \tag{4}$$

In the present study, the mechanical parameters k_i and c_i that characterize the generation model have been assumed in compliance with data furnished by producers of Florentine urban bus. Experimental tests performed by producers showed a good agreement between the actual behavior and the linear behavior assumed for the model, in particular about the static-balance configuration.

The spectral density of ground forces, $S_f(\omega)$, is finally obtained by:

$$S_f(\omega) = \left|H_{fy}(\omega)\right|^2 S_y(\omega) \tag{5}$$

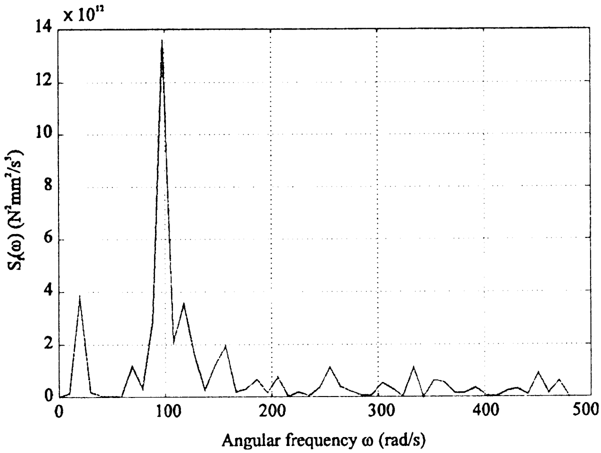

Figure 5: Power spectrum of forces applied to the roadway

Two peculiar ways of vibration are observed in the spectral density's trend showed Figure 5. The former is located at low frequencies and it is due to the sprung mass of thè vehicle; the latter, called wheel-hop, is at considerably higher frequencies and it is due to swinging masses of wheels and axle, between the road and suspension (see also Figure 3).

2.4 Vibration propagation through the ground

As known, Rayleigh surface waves propagating in an elastic, homogeneous, isotropic, not damped halfspace, decay with velocity proportional to the inverse of the square root of the distance from the source, whereas body waves decay proportionally to the square of the distance.

Miller and Pursey [7] showed that Rayleigh waves account for 67% of the total energy radiated from the source, independently from the elastic properties of the halfspace, while shear and compressive waves account for the remaining 26% and 7% respectively. It is thereby possible to conclude that the disturbance felt on the surface of the halfspace at a certain distance from the impulse source is due mostly to the propagation of Rayleigh waves.

For this reason, the frequency response function of an elastic, isotropic, homogeneous, not damped halfspace can be found taking into account only the Rayleigh waves contribution, whose velocity is here indicated with c_R.

When viscous damping is introduced in the ground model, the frequency response function related to the damped system can be obtained from the one of the elastic system by means of the *Correspondence Principle* otherwise known as *Elastic-Viscoelastic Analogy* [8]. According to this theory, the elastic moduli are written as complex quantities and the ratio between imaginary and real parts of the quantity represents the damping factor D(ω), which is assumed to be constant in the range of frequency of interests. Introducing such assumptions, as also made in [1], the frequency response function $H_{wf}(r,\omega)$ of the vertical component of vibration through the ground results:

$$H_{wf}(r,\omega) \approx \frac{\omega}{2\rho}\frac{K}{c_R^3} e^{\frac{-D\omega^2 r}{2c_R}} H_0^{(2)}\left(\frac{\omega r}{c_R}\right) \tag{6}$$

where ω is the angular frequency of the impulse, ρ is the density of the halfspace, K is a material constant introduced in [1] and finally $H_0^{(2)}$ is the Hankel function, as introduced in [9]. Parameters utilized for the representation of the ground were derived from a series of experimental tests managed on purpose, furnishing the result depicted in Figure 6.

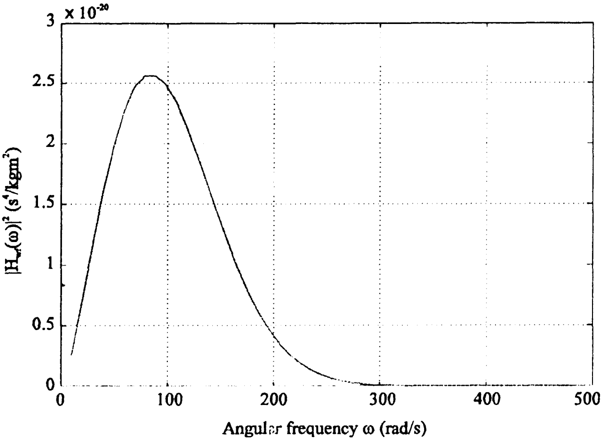

Figure 6: Halfspace frequency response function

The frequency response function related to the particular site under examination has then been calculated, referring to a distance r = 2.75 m and a bus running speed of 40 km/h (the maximum speed compatible with vehicle characteristics and the size of the road way). r represents the minor distance between the assumed point of impact of the tire with the road profile irregularities, and the basement of the building for which the disturbance was to be examined (in this case the “Galleria Vasariana” colonnade [10]).

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3 Experimental measurements and validation of the model

A series of experimental measurements of traffic induced vibrations was performed in order to validate results from the method introduced. Tests consisted in measuring the effects induced by Florentine urban line buses, fully loaded, passing by several times to simulate regular service. The surveys have been made measuring accelerations and velocity in some points of the Corridoio Vasariano, on the "Lungarno Archibusieri" and "Ponte Vecchio". A more detailed account of the experimental procedure and of the instrumentation used may be found in [10]. The comparison between the spectral density functions obtained from the model setup and directly from the experimental measurements is showed in Figure 7.

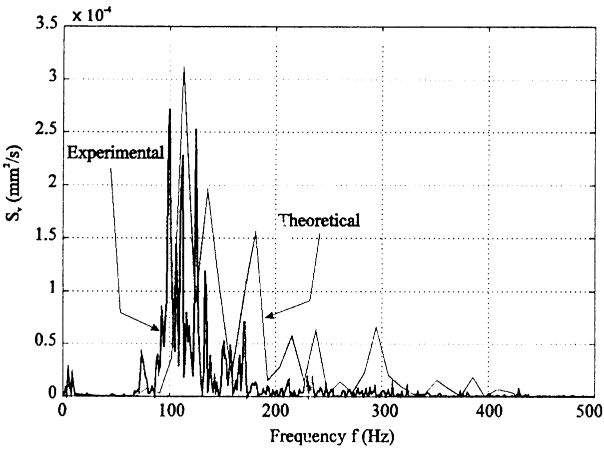

Figure 7: Comparison between theoretical and experimental results

Some differences between the two trends in Figure 7 are noted in the high band of frequency, due to the fact that the model examines the punctual contact with road surface irregularities and consequently accounts for an increase of contribution in frequency related to little wavelength undulations, whereas in the real event little wavelength loose importance because of actual imprinted area and tire stiffness.

Moreover, according to Hunt [1], in almost all spectra measured in this study, it is found that the spectral peak corresponding to axle hop occurs at a frequency somewhat lower than is predicted theoretically. A likely explanation for this is that absorption of energy at higher frequencies is grater than that predicted by damped half-space theory alone.

4 Conclusions

The power spectra of vertical ground vibration in the vicinity of a roadway is calculated by a numerical model whose effectiveness has been verified through experimental measurements.

The model is based on the dynamic excitation of a single axle vehicle model

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induced by the road roughness and on a model of damped half-space used for the ground.

Some comments are to be introduced regarding the different influence of the model parameters:

- the sampling of the road roughness must be performed with regard to the typical vehicle speed and its tire imprinted area in order to obtain effective results in the frequency range of interest.
- vehicle parameters values c_1 and k_2 (see Figure 3) were found to be very important for the correct setup of the model, as their variations largely affect the results in term of the peak velocity v_{max} of soil particles. In particular, f.i., a 50% variation of the k_2 value was found to correspond to a 60% variation of v_{max}.
- the accurate characterization of the soil mechanical characteristics was found to be less important for the effectiveness of the results, also considering that Rayleigh waves mainly propagates in the halfspace surface whose characteristics can be determined without particular difficulties in practice.

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