SOME REMARKS ON THE PREDICTION OF ROAD TRAFFIC INDUCED GROUND-BORNE VIBRATIONS

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ABSTRACT

In urban areas road traffic induced vibrations are rising some problems since they are often considered to be responsible for minor damages and for nuisance in building close to major road sections. The approach of the problem appears extremely complex since different expertises are involved. On a methodological point of view the study of the problem can be tackled by separately analysing the three main phases in which the phenomenon can be split: the generation phase due to the dynamic interaction between the heavy vehicle and the road profile, the propagation phase through the pavements and the underlying soils, the reception phase in the buildings nearby.

In this paper, following an extensive research that has been carried out on this subject, vibration generation and propagation models derived from literature are reviewed and major advantages and drawbacks of the different modelling approaches are highlighted.

Furthermore, a new 3-D model for the prediction of traffic induced ground borne vibration is proposed. The model is based on a hybrid numerical-FEM procedure and allows the evaluation of the vibration level in the time and frequency domain at an arbitrary distance from the road axis caused by a moving heavy vehicle. Input parameters are kinematical, mechanical and inertial properties of the vehicle, road profile and layout, mechanical properties of the pavement and soil materials.

The model has been experimentally validated through a comparison with field data reported in literature. In addition, an application of the model to the traffic calming design is presented. Results from numerical simulations showed that a optimized sinusoidal road hump profile may induce lower vibration level if compared with that provided by a conventional trapezoidal shaped one currently adopted in Italy.

Keywords: traffic induced vibrations, traffic calming, mitigation.

1. INTRODUCTION

An increasing number of complaints from residents living close to trafficked city streets has recently induced technicians to focus their attention on road traffic induced vibrations. Road traffic vibration are claimed to be responsible for minor (cosmetic) structural damage and for causing nuisance, especially if it is coupled with traffic noise. As a matter of fact, different factors may have played a relevant role in emphasising the problem:

- road maintenance standards of urban pavement are usually worse than those adopted on rural road or on highways;
- stone block pavements are still extensively used in urban areas but construction techniques and design methods have not evolved as much as necessary to sustain the dramatic increase of vehicle traffic;
- hydraulic pipeline network is often “embedded” with road superstructure and manholes are very numerous;
- in historical urban areas, masonry buildings with wooden floors are the most frequent structure layouts and their resonance frequencies are close to those pertaining traffic vibrations;
- axle loads of public transport vehicles are sometimes as high as the most heavy commercial vehicles and traffic flows are also relevant with respect to that of light vehicles on main urban links.

The approach to the problem is usually tackled by detecting three main phases: the generation of vibrations due to the dynamic interaction between the heavy vehicle and the road surface roughness, the vibration propagation through the pavement layers and the underlying soils, the reception phase when vibrations reach the building close to the road.

Countermeasures to eliminate or alleviate this issue are not always available or feasible and their effectiveness is not simple to be evaluated since different expertises are involved: the mechanical engineer as regards vehicle dynamics, the highway engineer with reference to the characterization of road surface roughness and pavement dynamics, the geotechnical engineer as far as vibration propagation is concerned and structural engineer with respect to the building response. For these reasons, there are few studies in the literature where the problem has been addressed as a whole. Up to now, the approach followed has often been mainly experimental or theoretical.

An extensive experimental study (WHIFFIN et al., 1971) (WATTS, 1989) on ground-borne traffic induced vibrations has been carried out at Transport Research Laboratory (TRL) within the past thirty year, where relationships between heavy vehicle traffic, vehicle speed and height of localized surface irregularities (humps) have been observed. In Italy, few experiments have been recently conducted on traffic induced vibrations and most of them were aimed at evaluating possible damaging effects for heritage buildings (CLEMENTE et al., 1998) (CRISPINO et al., 1999) (CRISPINO et al., 2001).

Prediction models for traffic vibration level, can be broadly divided into two groups: analytical and numerical ones, on one hand, and empirical and semi-empirical ones, on the other.

Among the latter ones, the most noticeable appears to be that developed by TRL, where an estimate of the vertical Peak Particle Velocity (PPV) vibration induced at the foundation level when an heavy vehicle is moving over a localized unevenness is proposed. The formula takes into account the maximum height or depth of a singular surface irregularity (hump) over which the heavy vehicle transits, the speed of the vehicle, the type of road surface, soil properties and the distance between the unevenness and the building foundation (WATTS, 1990) (WATTS, 1992). An extension of this model has been recently proposed in order to take into account longitudinal distributed surface roughness (CRISPINO et al., 2001).

Although prediction models developed through an empirical or semi-empirical approach appear to be more feasible, their field of application is limited by on-site conditions operating when the experimental study has been carried out. As a matter of fact, most of them may provide poor information on vibration level and can not be used in order to evaluate the effectiveness of mitigation countermeasures.

As far as theoretical models are concerned, the most noticeable appears to be that developed by H. M. Hunt (HUNT, 1991) that allows to evaluate the vertical vibration level (vertical displacement, velocity or acceleration) in terms of Power Spectral Density (PSD) function, at an arbitrary distance from the road. It is also worth to mention a recent analytical model developed by Lombaert at alii (LOMBAERT et al, 2001) (LOMBAERT et al, 2004a) (LOMBAERT et al, 2004b) that allows to evaluate the vibration level, expressed in terms of PSD or frequency spectrum, produced by an half-car model that is interacting with a stochastic (PSD) or a deterministic road profile, and is moving on a visco-elastic layered medium. On the other hand, different authors have also developed prediction models employing a Finite Element Method (FEM) approach in order to study the propagation through the road pavement and through underlying soils (HANAZATO et al, 1991) (D’APUZZO, 2000) (CONI et al. 2000) (D’APUZZO, 2001) (D’APUZZO et al. 2003) (DONDI et al., 2006).

Analytical and numerical models may represent a powerful tool for the prediction of the vibration level, provided that they are conveniently validated through experimental measures. In this paper, following an theoretical prediction model previously developed, a further refinement allowing the prediction of vibration level in time and frequency domain at an arbitrary distance from road induced by an heavy vehicle passing on a singular surface irregularity has been proposed. A preliminary experimental calibration and an application to traffic calming design is also presented.

2. DESCRIPTION OF THE MODEL

The theoretical prediction model proposed in this study is composed of two sub-models according to the several phases in which the phenomenon can be divided: the vibration generation where the dynamic interaction between vehicle and road surface unevenness is simulated and the vibration transmission where dynamic overloads evaluated in the previous stage are applied to the road surface. The model is able to predict, with reasonable approximation, the vibration level induced by heavy vehicles at a defined distance from the road. On a computational point of view, the model can be regarded as hybrid since the generation sub-model is mainly analytical whereas the propagation one is numerical. Detail on two sub-models are reported in the followings.

2.1 Vibration generation modelling

Vehicles moving onto the road surface are dynamically excited by the variations of the elevations of road profile and, as a result of this, dynamic overloads are transmitted by vehicle axles to the pavement. These forces are universally regarded as the main responsible for the development of road traffic induced vibrations (WHIFFIN et al., 1971) (DOMENICHINI et al., 1998).

As regards the assessment of vertical overloads, a dynamic analysis of the vehicle-road profile system has to be performed. In this connection, since mass and stiffness of pavement involved in the vibration phenomenon are much more larger than those pertaining the heavy vehicles, the dynamic coupling between vehicle and road superstructures can be neglected. It is also important to define the vehicle model and the road profile model to be used. As far as the road profile is concerned, the variation of the surface elevation can be mainly described into two ways: deterministic and stochastic by means of power spectral density (PSD) of vertical elevation of road profiles. This latter approach has been employed by International Standard Organization in order to codify the degree of irregularity of a road surface.

As far as the vehicle model is concerned, in this study, discrete models are used. The vehicle is considered as a system made of point masses or rigid bodies interconnected between each other through springs and dashpots. Basing on the degree of approximation that is required to “capture” the vehicle behaviour, these models can be very simple (such as a one-degree-of-freedom system), but may become quite complex (up to several degrees-of-freedom). In highway engineering the most used rigid body model is the “Quarter Car Model” (Figure 1a). This is a two-degree-of-freedom system in which the sprung mass represents one fourth of the vehicle chassis and it is connected to the unsprung mass through the suspension system that is usually modeled by a spring and an dashpot in parallel. The unsprung mass, representing half axle, is connected to the road surface profile through another spring coupled with a dashpot in order to take into account the tyre vertical stiffness and damping coefficient.

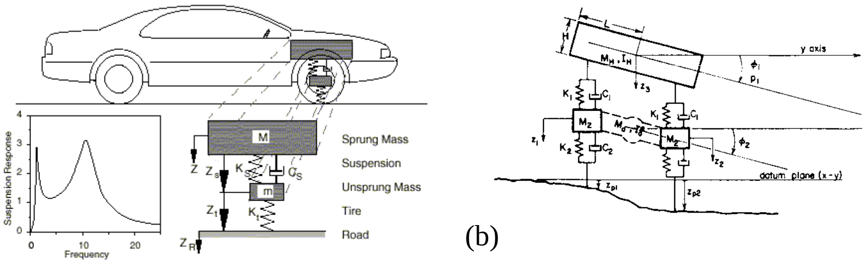
This model, coupled with a deterministic or a stochastic representation of the road profile, has been used (HUNT, 1991) in order to evaluate the PSD or the frequency spectrum of vertical dynamic loadings. However, it has been observed that when near-field conditions are reached, this model is not able to adequately capture the whole phenomenon and therefore it is necessary to use, at least, a four-degree-of freedom model (namely an Half Car Model) where both front and rear axles are taken into account. The main reason for this is related to the “wheel base filtering” problem. According to this problem, when a two-axle vehicle is moving at a specific speed on an irregular surface, the road profile that is “sensed” by the front axle, is also “sensed” by the rear axle with a time lag that depends on the vehicle speed and wheel base. For certain speed and wheel base values, this may dramatically modify the shape of the Transfer Function between the road excitation and the vertical load transmitted by the vehicle and therefore unexpected resonant frequencies may occur.

Following these remarks, an Half Car Model (Figure 1b) has been used in order to evaluate the spectral content of dynamic loads. In this model, the vehicle chassis is represented by a rigid frame with a specific mass and rotational inertia that are computed by considering half vehicle. The rigid vehicle body is connected to the front and rear axles through the suspension systems that are modeled by linear springs and dashpots in parallel. Similarly to Quarter Car Model, the axles are represented by point masses, computed on half vehicle, and they are connected to road surface profile through spring-dashpot systems accounting for tire vertical stiffness and damping.

By means of a Fourier Transform, the set of linear differential equations describing the vehicle moving on irregular road profile is transformed into an algebraic set of equation and it is solved, by means of a symbolic math software. Therefore, complex transfer functions between road profile vertical excitation and dynamic overloads are algebraically derived.

The discrete function describing the road profile (either deterministic or stochastic) is scaled, according to the vehicle speed, and it is transformed, according Fourier, to derive the complex spectral function in the frequency domain.

Finally, the road profile spectral function is multiplied by the vehicle transfer function and an Inverse Fast Fourier Transform is performed in order to evaluate the time histories of the vertical loads applied to the pavement surface that will represent the input forces for the subsequent propagation sub-model.



(b)

(a)

Figure 1 Analytical models for vehicle dynamics: Quarter Car model (a) and Half Car Model (b)

2.2 Propagation modelling and experimental validation

In order to mathematically simulate the vibration propagation phenomenon, the dynamic response (in terms of displacement, velocity or acceleration) for a point located at a defined distance from a vertical pulsating force acting on the surface of a medium (within which the phenomenon can still be considered relevant) has to be evaluated.

When the geometrical layout of this medium is not complex, such as for simple or multi-layered half-space, approximated analytical solutions are available (HUNT, 1991) (AUERSH, 1994). When finite pavement cross-sections, trenches or anisotropic soil properties are present, the geometrical layout is more complex, and a Finite Element Method (FEM) approach may be preferable. The effectiveness of a FEM model in simulating vibration propagation, is greatly affected by boundary conditions. As a matter of fact, since the medium modelled is inherently finite, vibration waves impacting to boundary surfaces are reflected and may propagate back to the source. As a results of this, the dynamic response at a defined point provided by a FEM model is biased since in the real conditions, vibration waves are not reflected but propagate to the infinite and, moreover, they undergo to an attenuation due to the well-known "radiation damping" effect. In order to correctly simulate this aspect, very complex boundary conditions have been developed by several authors (WOLF et al., 2002) (HANAZATO et al, 1991) or Finite Element Method combined with Boundary Element Method (AA. VV., 1993) approaches have been used.

In this study, the propagation phenomenon has been simulated by a transmission sub-model, that employs a FEM technique where nor particular boundary conditions neither BEM elements have been used. All the vibration waves directed to the external surfaces of the finite medium are progressively attenuated within a damping zone (D'APUZZO, 2000) that envelopes the whole finite medium. Material properties of the damping zone are equal to those of the adjoining medium, except the damping coefficient that increases according to a quadratic law when going far away from the vibrating source whereas mesh discretization density diminishes.

A numerical validation has been carried out in order to verify the effectiveness of this approach. In detail, dynamic response provided by the FEM model has been compared with that derived by an equivalent closed-form analytical solution. According to several authors (HUNT, 1991) (DOMENICHINI et al, 1999), within the frequency domain, the dynamic vertical displacement in far field conditions, at a defined distance from a vertical pulsating force acting on the surface of a viscoelastic half-space, can be synthetically expressed through the following expression:

$$H_z(r, \omega) = (\omega\, K/2\rho c_R{}^3) \bullet \exp(-D\, \omega^2 r/2c_R) \bullet H_0{}^{(2)}(\omega\, r/c_R) \qquad \text{(Eq. 1)}$$

Where r is the distance from the pulsating point force, ω is the circular frequency, K is a function that depends on Poisson's Ratio of the material, ν, ρ is the material density, c_R is the velocity of Rayleigh surface waves, D is the damping coefficient, $H_0{}^{(2)}$ is the second type Hankel function of zero order.

As far as the FEM model is concerned, an axisymmetric model has been developed. Minimum element size is derived when material properties (density and Young modulus) and maximum frequency of interest are defined, basing on the relationship $c = \lambda \bullet f$ that ties wave velocity, c, with wavelength, λ, and frequency, f, where, by fixing the wave speed and the maximum frequency of interest, the minimum wavelength and thus the minimum element dimension (at least, equal to $\lambda/4$) is determined, although recent studies seems to suggest to halve this value (D'APUZZO, 2007) (GARDIEN et a., 2003).

Dynamic response in terms of time history of vertical velocity at defined distance from excitation pulse force has been evaluated by a direct integration in time domain, since this procedure has proved to yield more reliable results if compared with a eigen-value dynamic analysis, as far as wave propagation phenomena are concerned.

Results from numerical simulations carried out are detailed elsewhere (D'APUZZO, 2001) (D'APUZZO et al. 2003) (D'APUZZO, 2007) however, it is worth to mention that a fairly good agreement between numerical and analytical predictions has been observed.

On the other hand, a preliminary experimental validation has been carried out through a comparison with field data derived from literature. In (WATTS, 1992) Non

Destructive Tests (NDT) have been carried out by means of a Falling Weight Deflectometer (FWD) on various flexible and rigid pavement resting on different soils and vertical vibration measurement have been performed at increasing distance from the source. Experimental frequency response functions (FRF) have been derived at various distance from the vertical pulse force. FRF Modulus of surface vertical vibration velocity measured at 12 Hz for increasing distance has been compared with that provided by FEM model. A sensitivity analysis has been performed by varying FEM input parameter values, according to characteristic ranges reported in literature, in order to account for uncertainty in evaluating on-site soil parameters. Main input data are detailed in Table 1.

Table 1 Input parameter values employed in numerical FEM simulations.

	Lower Limit				**Upper limit**			
Soil type	**E (Mpa)**	**ρ (kg/m^3)**	**ν**	**c_R (m/s)**	**E (Mpa)**	**ρ (kg/m^3)**	**ν**	**c_R (m/s)**
Peat	10	1800	0.4	47	15	1200	0.4	63
Alluvium	56	1920	0.4	94	84	1300	0.4	127
London clay	152	2040	0.4	170	228	1360	0.4	231
Gravel/sand	234	2160	0.35	209	350	1440	0.35	283
Boulder clay	1478	2280	0.35	512	2216	1520	0.35	693
Chalk rock	3370	2400	0.3	768	5054	1600	0.3	1039

Result of comparison are conveniently reported in Figure 2. As it can be seen, agreement between experimental and numerical dynamic response seems acceptable for most of soil examined thus demonstrating the soundness of the FEM modelling developed. Optimal model parameters derived for the axisymmetric scheme have been implemented in a full three-dimensional FEM model developed in order to simulate vibration propagation induced by a moving vehicle.

2.3 The moving force problem

Vibration level, expressed in terms of time history and frequency content, induced by vehicle passing on a irregular surface can be predicted by combining generation and propagation sub-models previously described. As regards the representation of moving vertical dynamic forces acting on the road surface, it is necessary to correctly identify road roughness properties.

As a matter of fact, road roughness may be viewed as uniformly distributed or singular. In the former case, as previously stated, the unevenness is represented by means of a stationary and ergodic random process, therefore vehicle oscillations and, in turn, dynamic forces are random stationary too if the dynamic system is linear. Therefore, assuming that the geometry of the problem is constant along the path of the moving force, the dynamic response at a specific point of the surface induced by a moving vibration source can be evaluated by invoking the dynamic Betti-Rayleigh reciprocal theorem. According to this theorem, the response at a specific surface point, P, induced by a dynamic force moving along a defined path, is equal to the response induced by a fixed dynamic force along the path of an observer moving in parallel with the path of the force and passing through the point P (LOMBAERT et al. 2001) (D’APUZZO et al. 2003) (D’APUZZO, 2007).

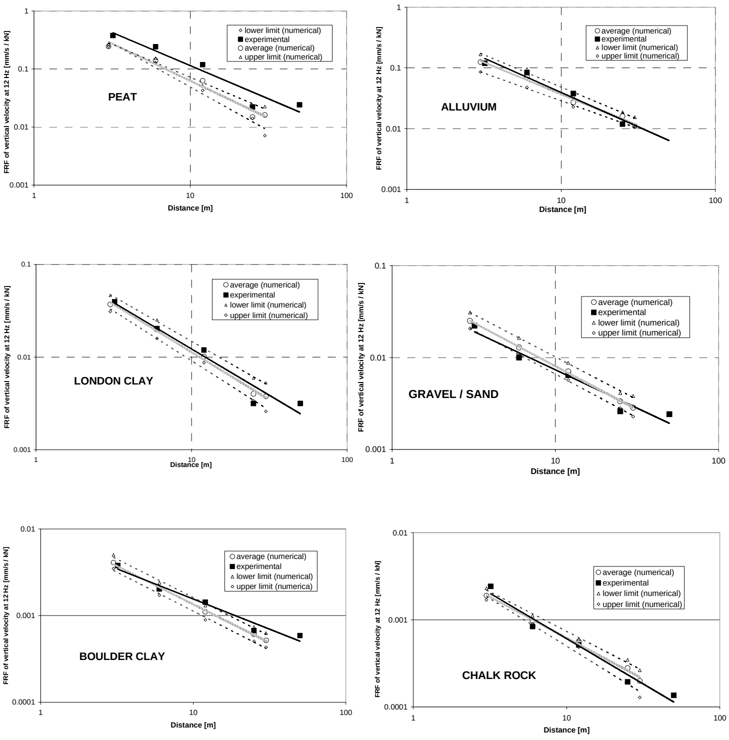


Figure 2 Comparison between experimental and theoretical 12 Hz FRF.

On the other hand, if road roughness is described through a singular surface unevenness, the stationarity of excitation is not fulfilled and transient feature of the vertical dynamic forces have to be correctly represented. In this case, time varying vertical excitation forces have to be actually moved on the FEM propagation model and dynamic response can be recorded at a fixed point.

The application of moving dynamic forces on a FEM model is not a trivial task because of intrinsic finite nature of the numerical model itself, as already explained. Ideally, moving forces should begin their approaching path at an infinite distance from the observer and therefore dynamic response should be expected to gradually increase as the dynamic forces come close to the receiver. It is obvious that these ideal conditions may not apply to a FEM model.

As a matter of fact, if a simple constant moving force is applied at the beginning of the numerical simulation (and therefore at the boundary of the FEM model) a “pulse” effect is immediately detected by the fixed observer whose dynamic response will therefore dramatically differ from the real one (see Figure 3). In order to mitigate this unrealistic phenomenon is necessary to filter the time history of the moving force imposing a more smooth increase of the force amplitude. A time filter based on a Hanning window may be effective in reducing the pulse noise of the signal, as it can be easily observed from the time history comparison reported in Figure 3.

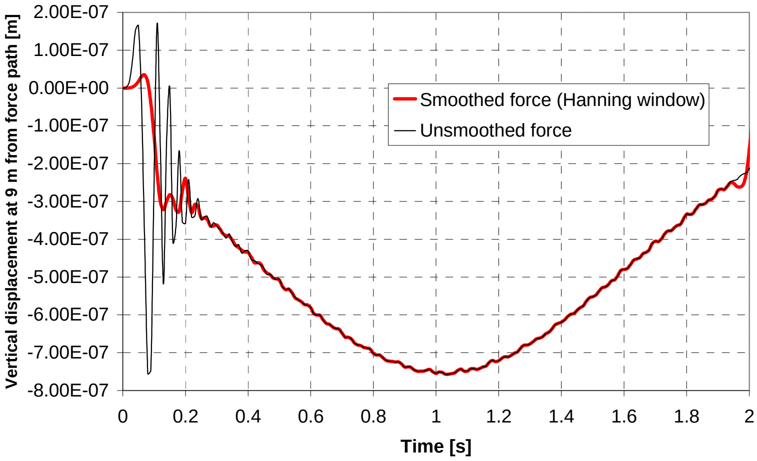


Figure 3 Time history of vertical displacement induced at 9 m by a constant moving load: comparison between unfiltered and filtered force.

3. A CASE STUDY: DESIGN OF VIBRATION-FRIENDLY TRAFFIC CALMING DEVICE

Following these remarks, a 3D generation and propagation coupled model has been developed in order to evaluate the vibration level induced by a vehicle passing on a road humps (better known as a "sleeping policeman") employed as a traffic calming device. Despite their widespread diffusion all around the world, road humps have been mainly designed with reference to their profile length and height rather than their shape. Furthermore, traffic induced vibration implications have been examined only recently (GERRITSEN et al., 1999) (KRYLOV et al., 2000).

Therefore the prediction model developed has been used in order to compare the traffic vibration level induced by a common 3.6 m long and 7 cm high trapezoidal shaped road hump with that produced by a sinusoidal shaped one, when all the other variables involved are kept constant.

A 4 d.o.f. discrete heavy vehicle model travelling at 8 m/s on the road humps has been implemented whose relevant parameter are reported in table 2. A conventional flexible pavement resting on a alluvium soil has been assumed. Vertical velocity time history has been evaluated at defined distance from vehicle. FRF of vertical velocity at 3 m and 6 m far away from the road humps are depicted in figure 4.

As it can be easily observed, vibration level induced sinusoidal profile is greatly lower than that pertaining the trapezoidal one. Amplitude reductions appear more pronounced within the 5-30 Hz band, where characteristic frequencies exciting building members are usually located.

Table 2 Heavy vehicle mechanical characteristics.

Parameter	**Value**
Wheelbase, L [m]	6
Sprung mass, M [Kg]	12000
Pitch Inertia , J [Kgm^2]	50000
Front axle sprung mass, $m1$ [Kg]	600
Rear axle sprung mass, $m2$ [Kg]	1150
Front axle suspension stiffness, $k1$ [N/m]	930000
Front axle suspension damping coefficient, $c1$ [Ns/m]	32000
Rear axle suspension stiffness, $k2$ [N/m]	1048000
Rear axle suspension damping coefficient, $c2$ [Ns/m]	36000
Front axle tyre stiffness, $k1p$ [N/m]	1789500
Rear axle tyre stiffness, $k2p$ [N/m]	3579000
Tyre hysteretic factor, n	0.04

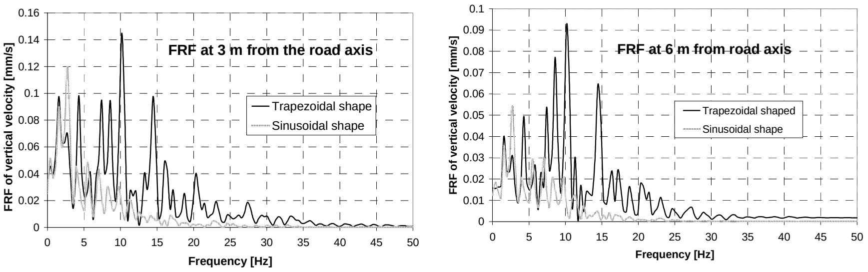


Figure 4 Comparison between the FRF of vertical velocity for trapezoidal and sinusoidal shaped road humps.

4. CONCLUSION

A full three-dimensional hybrid analytical/numerical model that is able to predict vibration level in time and frequency domain induced by heavy vehicles travelling on rough road surfaces has been developed. The model is composed of two sub-models dealing respectively with the generation and the propagation phase of the problem. The generation sub-model is described by a 4 d. o. f. discrete vehicle model able to account for the "wheelbase filtering" problem. The propagation sub-model has been numerically validated against a closed form analytical solution and experimentally corroborated by means of a comparison with vibration field data derived by literature.

The model represents an substantial improvement with respect to those developed in the past since it allows to evaluate vibration level induced by heavy vehicle travelling on singular irregularity. In order to accomplish this task, it has been demonstrated that moving dynamic forces acting to the FEM propagation model have to be filtered by a smoothing procedure. An Hanning window filtering scheme may represent an effective solution to the problem.

Finally, an application of the model to the traffic calming design is presented. Numerical simulations showed a marked reduction of vibration level in the 5-30 Hz band for an optimized sinusoidal road hump profile with respect to a conventional trapezoidal shaped one currently adopted in Italy.

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