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Study of traffic induced ground vibrations using a combined finite difference model

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Résumé

Les vibrations induites par la circulation sont une source fréquente de problèmes environnementaux. Cette communication présente les résultats d'un modèle numérique proposé pour analyser la nature et l'impact de ces vibrations. Après une validation du modèle sur des mesures expérimentales rapportées dans les littératures, le modèle est utilisé pour analyser l'efficacité de l'utilisation des tranchées comme dispositifs d'isolation. Les résultats montrent qu'une tranchée ouverte dont la profondeur de l'ordre de demi-longueur d'onde peut réduire l'amplitude des vibrations de 50%.

Abstract

Traffic induced vibrations are a frequent source of environmental problems. This paper presents the results of a proposed numerical model to analyze the nature and impact of these vibrations. After validation of the model on experimental measurements reported in the literature, the model is used to analyze the efficiency of isolation devices such as a trench. The results show that an open trench with a depth of about half wavelength can reduce the amplitude of vibration by 50%.

Mots clefs: Traffic, vibrations, prediction, numerical model, road irregularity

1 Introduction

Ground vibrations generated by road vehicle, especially by heavy trucks and buses, are a common source of environmental problem. A series of measurements of road traffic-induced vibrations have been conducted to analyze various problems related to these vibrations. Watts and Krylov [1] showed that the vibration levels increase with the vehicle speed and with the height and depth of pavement irregularity. D'apuzzo *et al* [2, 3] established an equation experimental to represent the vibration amplitude as a function of the road irregularity and vehicle speed using a modified Watts' formula. Hunaidi *et al* [4, 5] studied the effect of the vehicle suspension system and to the seasonal climate variation on the vibration characteristics (level and frequency content). Theoretical studies and numerical models have been proposed by many researchers. Lombaert and Degrande [6, 7] used the boundary element method to compute the amplitude of vibration induced by moving source. Shen-Haw Ju [8] proposed a finite element model to investigate the impact of these vibrations on an adjacent building. Xu and Hong [9] showed that traffic-induced ground vibrations impede the normal operation of high-tech facilities by using a stochastic approach. Moreover, Hajek *et al* [10] reported that the vehicle axle load applied on the pavement due to a surface irregularity may be divided into two basic types: The suspended mass also called (the body bounce) which has a frequency in the range (0.8-4Hz), and the axle hop which has a frequency in the range of (8-15 Hz). The time-domain finite element method is seldom used to simulate the free field vibrations induced by road roughness. In this paper, a numerical model for calculating the free field vibrations in the time domain will be validated. The analysis is presented for a half car model of truck passing on locale road unevenness described by a deterministic function. In addition, this global approach can provide reliable answers

in case of complex geometry with the presence of superstructure, soil stratification and could be used to analyze the efficiency of isolation barriers and preventive strategy.

2 Numerical model and validation

The numerical modeling includes two parts: Firstly, the dynamic load resulting from pavement irregularity is determined using a discrete vehicle model. The resulting axle dynamic response of vehicle is then injected in a 3D finite difference modeling to analyze the induced wave propagation.

2.1 Vehicle axle load

Half car model with four degree-of-freedom is adopted in order to investigate the vehicle dynamic response to discrete irregularity as showed in fig. 1. This model has the main advantage of integrating the vehicle pitch motions, body motions and center of gravity effect. Furthermore, the differences between front and rear dampers and spring characteristics can be modeled properly.

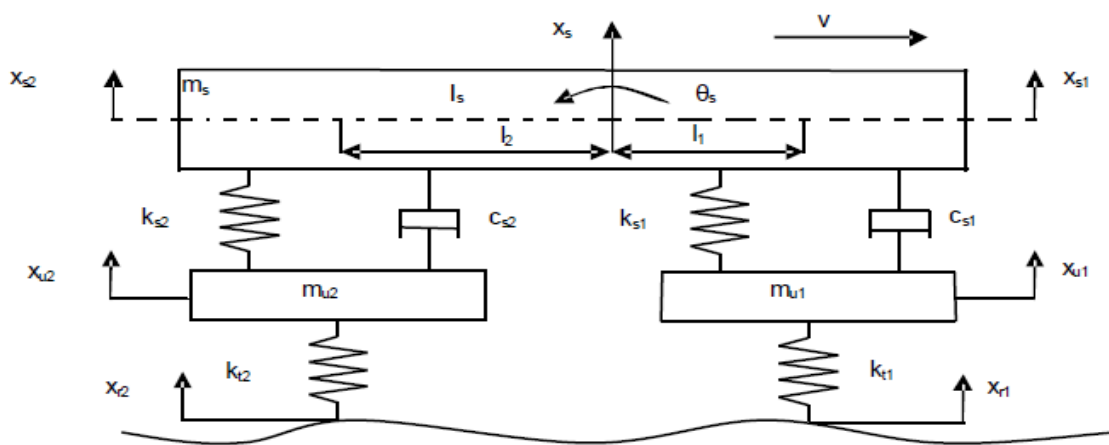


FIG. 1 - 4DOF half car model of the vehicle

The equations of motion for the vehicle body, front and rear wheels can be written as follow:

$$[M] \ddot{X} + [C] \dot{X} + [K] X = (P) \quad (1)$$

$[M]$, $[C]$, $[K]$ are the matrix of mass, damping and rigidity respectively. (P) is the interaction forces between the front and rear axle and the pavement, where:

$$P_1(t) = K_{t1} (x_{u1}(t) - x_{r1}(t)) \quad P_2(t) = K_{t2} (x_{u2}(t) - x_{r2}(t)) \quad (2)$$

k_{t1} and k_{t2} are the front/rear stiffness, x_{u1} and x_{u2} are the vertical displacement of the vehicle body at the front/rear suspension location. x_{r1} and x_{r2} are the irregularity excitation from the pavement surface at the location of front/rear tire. Law *et al* [11] provide detailed information about the matrix in eqn. (1).

2.2 Validation of the proposed model

The proposed model is validated using a field experimental study conducted by Lombaert and Degrande [6] who measured free field vibrations due to passage of the Volvo FL6 truck on artificial road unevenness at vehicle speed between 23 and 58 km/h. The artificial unevenness is taken as traffic plateau with two ramps of length 0.3m and a flat top part with a length $L=1.3$ m and has a total height $H = 0.054$ m. The characteristics of road pavement, subgrade soil layers and the vehicle are taken following the validation reference Lombaert and Degrande [6].

2.3 Axle load forces

The equation of motion (1) is resolved using an explicit Runge-Kutta scheme in a Matlab program that calculates the vehicle axle load. The car parameters are summarized in Table [3]. Eigen analysis gives the two eigen modes of the truck: 10.8 and 12.4 Hz which correspond to the front and rear axle hop; 1.9 and 1.4 Hz which correspond to the body bounce and pitch of the front and rear axle respectively. Fig. 4 displays the front axle load of the truck for two vehicle speeds $V=30$ and 58 km/h.

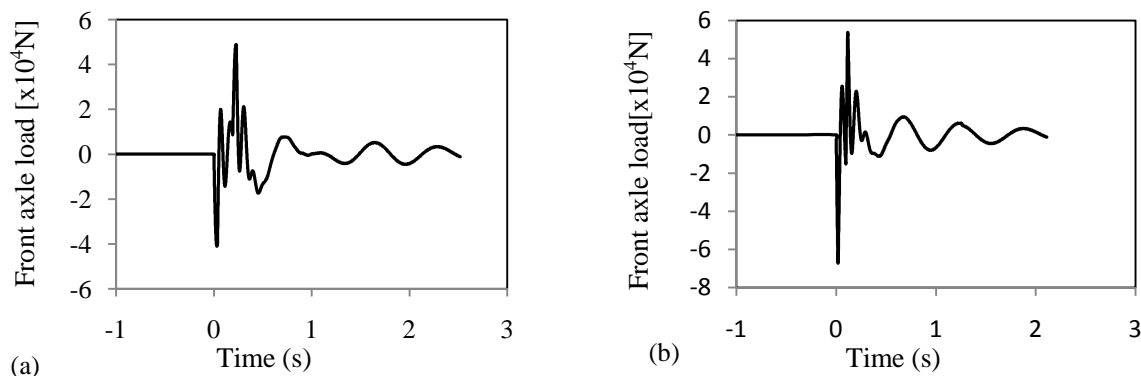


FIG. 2 - The time history of the front axle load for the passage of the vehicle on the road unevenness with the vehicle speed (a) $V=30$ km/h, (b) $V=58$ km/h

2.4 Finite Difference modeling

Numerical analyses are conducted using a finite difference scheme. Wave propagation induced by road traffic could be correctly described using viscoelastic model. In order to prevent wave reflection, viscous dashpots are used in the normal and shear directions at model boundaries. A general damping effect provided by Rayleigh damping has been introduced. The finite difference model used for the road structure and the soil surrounding is shown in fig. 5. The size of the model is $30 \times 21 \times 15$ m³ (length/width/depth). The mesh sizes are refined near the applied forces ($0.3 \times 0.3 \times 0.15$) and increase gradually with the distance from the source of vibration along the axe X and Z. The model is symmetrical about the road centre. By the application of the axle load showed in the fig. 4 as a pressure on the pavement, we have found the free field calculated as peak particle velocity in vertical direction (PPV_z) at a distance 8, 16 m from the load. Fig. 6 shows the comparison between the predicted vibrations velocities and the measured vibrations velocities published in the reference [6].

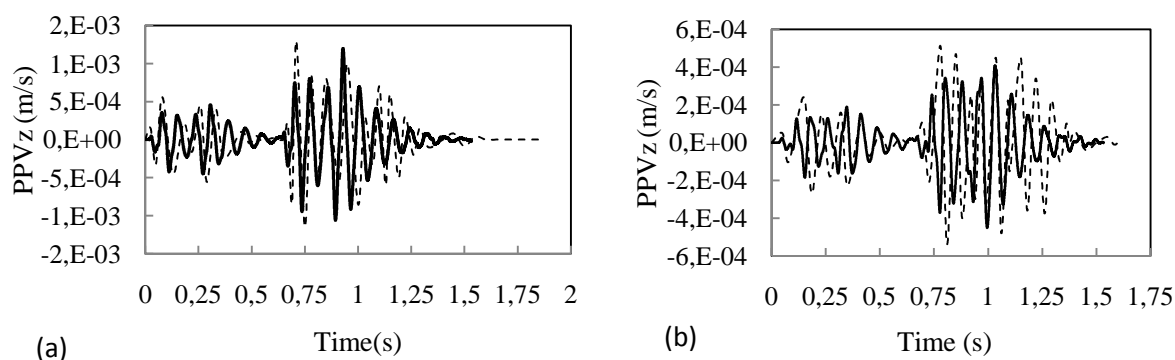


FIG. 3 - Time history of measured (dashed line) and predicted (solid line) free field velocity (PPV_z) at 8m (a), and 16 m (b) from the vehicle moving at $V=30$ km/h.

A good agreement is observed between the measured and predicted results. Predicted and measured PPV_z are of the same order of magnitude for both distances $X=8$ m and $X=16$ m.

3 The influence of road surface unevenness

Three kinds of local road unevenness are taken in this study as shown in fig. 7. These speed reducers are selected according to the recommendation of French regulations CERTU [12]. The speed cushion has the total length of 2m including two ramps of 0.5m, the traffic hump has a sinusoidal shape of 420 mm long, 50 mm high, while the wide trapezoidal traffic calming has a flat top part of 3m and two ramps of length 1m.



FIG. 4 - The road surface unevenness used in the numerical model

Fig. 8, 9 show the front axle loads and frequency content during the passage of the vehicle on these speed reducers at a speed of 36 km/h. It can be noticed that the frequency content has mainly two peaks: the first corresponds to the bitch and bounce mode and the second corresponds to the axle hop mode. Table 4 summarizes the influence of the speed reducer on the free field particle velocity induced by the vehicle passage. It can be observed that the short hump (case 2) produces the highest response despite its lower height. Furthermore, the induced vibration in this case exceeds the threshold of vibrations allowed in urban areas. This result meets the recommendation of the UK department of transport which limits the height of humps used as traffic calming measure in proximity to building to 40 mm, Watts *et al* [13]. The comparison between the speed cushion (case 1) and the trapezoidal traffic calming (case 3) shows that the ramp slope is of significant importance. Despite a greater height in the latter case, the vibration level is greater in the former. It is mainly attributed to a steeper slope of 12% in the case of speed cushion in comparison of 10 % in case 3.

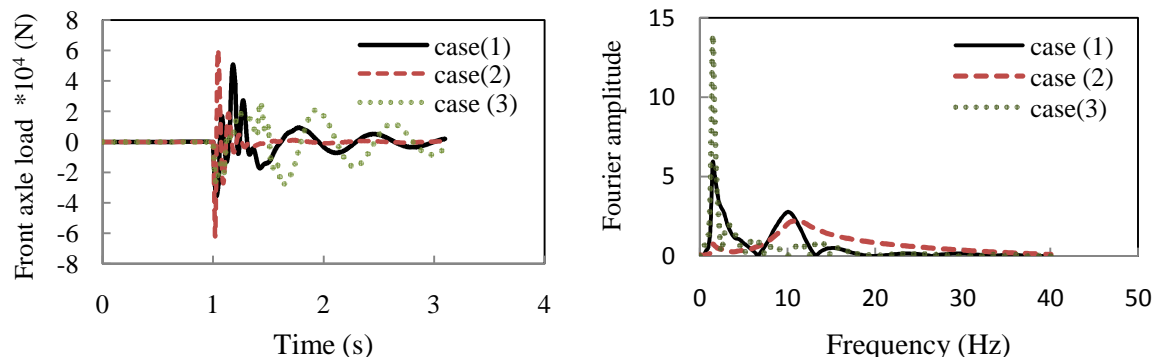


FIG. 5 - Time history and frequency content of the front axle load induced by different speed reducers: $V=36$ km.

Table 4: PPVz (mm/s) in the free field for different speed reducers $V=36$ km/h

case	Distance from the road centre (m)					
	4	8	12	16	20	24
(1)	1.45	0.57	0.42	0.36	0.29	0.19
(2)	6.48	2.46	2.08	1.97	1.52	0.93
(3)	1.02	0.43	0.28	0.18	0.15	0.13

4 Vibration reduction using trench barrier

The proposed numerical model is used to evaluate the efficiency of the trench barrier in screening the vibrations generated by a heavy vehicle. A trench barrier is installed at a distance of 1m from the source to reduce the ground vibrations, the trench is assumed to have a depth $d = \lambda/2$ where ($\lambda \approx 10\text{m}$) is the wavelength. The width of trench is chosen as $w = 0.3\text{ m}$. The reduction in the vibration levels measured in terms of soil particles velocity is usually evaluated using the amplitude reduction ratio (Ar), this method was proposed by Wood (1968). It consists in calculating (Ar) by normalizing the vertical amplitude of grounds surface with the wave barrier, (PPV_z) after, to the vertical amplitude of ground surface without the wave barrier, (PPV_z) before.

$$Ar = \frac{PPV_z(\text{After})}{PPV_z(\text{Before})} \quad (3)$$

The effects of material properties of wave barriers are investigated in this study by filling the trench with materials of different stiffness (E_2). The stiffness of filling material is selected to be significantly different from that of the surrounding soil ($E_1 \approx 60\text{MPa}$). Thus, two configurations of trench barrier are investigated: when ($E_2/E_1 > 1$) the trench is considered stiff, otherwise it is considered soft. The amplitude reduction ratio using a soft and rigid trench barrier is plotted in fig.14 and fig. 15 respectively. It can be seen that a part of the wave energy is reflected in front of the soft trench and may increase the vibration levels. Contrary, no vibration amplification occurs in front of the stiff trench because the rigid material can transmit a significant part of the incident waves. When the trench depth is equivalent to a half of wavelength, the isolation effect of open trench is about (50%). However, soft trench barriers are more effective than stiff ones. The performance of trenches filled by a material with very small stiffness such as a soil–bentonite trench ($E_2 = 3.5\text{ MPa}$) is comparable to that of open trenches. On the other hand, the efficiency of isolation by using a stiff trench is limited to the vicinity of the trench (within $0.5d$ behind the trench); its effect deteriorates quickly, with distance behind the trench.

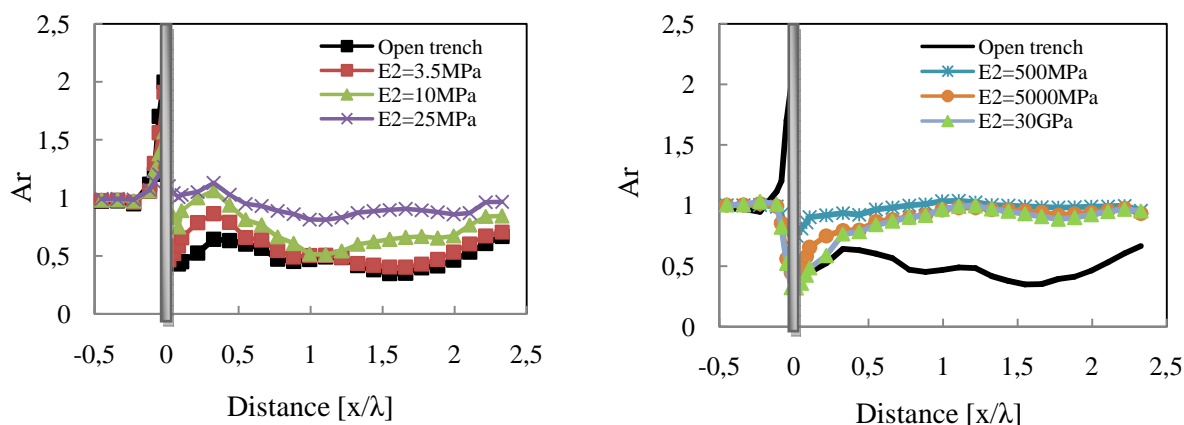


FIG. 6 - Amplitude reduction ratio using soft and rigid barrier ($d = \lambda/2$).

5 Conclusion

In this paper, a half-car model is used to investigate the dynamic forces of truck generated by pavement irregularity. Then a combined numerical model has been used to calculate the free field traffic vibrations and it is validated with experimental measurement. The effect of the irregularity shape was discussed. The current study illustrates that certain combinations of unevenness characteristics (such as the height and length) and vehicle speed can result in very high dynamic effects and consequently a perceptible level of traffic induced vibration may be produced. The efficiency of stiff and soft wave barriers as mitigation measures is also investigated. It is obviously shown that a soft barrier with a length of an order half of the wavelength can reduce the vibration

levels of 50%. Soft barriers were shown to be more effective vibration countermeasure than stiff ones. The proposed valid model can provide reliable answers in case of complex geometry with the presence of superstructure, soil stratification and could be used to analyze the different parameters associated to the isolation.

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