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STUDY OF DETERMINING FACTORS FOR TRAFFIC INDUCED VIBRATIONS IN BUILDINGS

DWTC Research Programme Sustainable Mobility
Research Project MD/01/040

SUMMARY

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1 Introduction

Ground-borne traffic induced vibrations in buildings are a matter of growing environmental concern. The growing traffic volume, the higher vehicle speeds and the larger axle loads are generally considered to be responsible for the increasing hindrance due to road traffic indcuced vibrations. Considering rail traffic, vibration nuisance is related to increasing train speeds and larger freight loads. Belgium is an important link in the European high speed train network.

Figure 1: Passage of a bus on the transition between an asphalt surface and a paved surface.

Traffic vibration nuisance in buildings is mainly due to heavy vehicles that pass at relatively high speed on a road with an uneven surface profile (figure 1). Interaction between the wheels and the road surface causes a dynamic excitation which generates waves that propagate in the soil and impinge on the foundations of nearby structures. After attenuation at the foundation level, vertical vibration components can be amplified at the resonance frequencies of flexible floors, while the horizontal components are amplified over the height of the building. Dominant frequencies are typically situated in a low frequency band between 8 and 20 Hz.

Foreign norms and guidelines recognize discomfort to people, malfunctioning of sensitive equipment and damage to buildings as possible consequences of vibrations. An extensive survey by Morton-Williams et al. of Social and Community Planning Research in the UK has shown that 37 % of the population is bothered by ground-borne vibrations, while 8 % is seriously bothered. Whereas 90 % of the respondents reports nuisance due to noise, the number of people seriously bothered by vibrations (8 %) has the same order of magnitude as the number of people seriously bothered by noise (9 %). In the MIRA-2 report, 7 % of the people is estimated to be seriously bothered by vibrations. Road traffic is the most important source (65 %), whereas other sources are railway traffic (16 %), industrial activities (15 %) and building construction (4 %). Between 1995 and 2000, the Department of Environment and Infrastructure of the Ministry of the Flemish Community, that is responsible for the maintenance of the regional road network in Flanders, has performed 51 measurement campaigns to evaluate nuisance and the possibility for damage due to traffic induced vibrations.

The existing gap in knowledge regarding the physical interpretation of in situ measurements, the formulation of norms and guidelines defining allowable vibration levels and the estimation of the efficiency of vibration isolating measures justify continuing scientific research.

2 The aim of the present research project

The objective of the DWTC research project MD/01/040 'Study of determining factors for traffic induced vibrations in buildings' is to obtain more insight in the relevant physical phenomena and the relative importance of determining factors related to traffic induced vibrations. Within the frame of the 'Sustainable Mobility' programme of the Prime Minister's Services of the Belgian Federal Office for Scientific, Technical and Cultural Affairs, only the present research project deals with the problem of traffic induced vibrations.

As a part of this research project, a numerical model is developed for the prediction of traffic induced vibrations. The model accounts for dynamic soil-structure interaction (SSI) and includes a wide range of parameters that characterize the vehicle, the road unevenness, the road and the soil. In situ measurements are used to perform an experimental validation and demonstrate the predictive qualities of the numerical model. Furthermore, the model is used for an extensive parametric study that allows to identify the determining factors ("pressures") for traffic induced vibrations in buildings and the measures ("responses") that can be taken to diminish or avoid problems related to ground-borne vibrations. The development of the numerical model and the results support the development of other numerical models for the prediction of railway induced vibrations or the vibrations induced by underground metro or tram traffic.

Compared to the project proposal, considerably more effort has been spent to the development and the experimental validation of the source module. As a result, less attention has been paid to the study of the interaction of the incident wave field and nearby structures. Preliminary results, however, have been obtained during a 6 months post-doctoral stay of Dr. Anita Uscilowska of the Institute of Mathematics of the Poznan University of Mathematics in Poznan (Polen) within the frame of the DWTC programme 'Scientific and Technology Cooperation with Central and Eastern Europe'. The results of this study are summarized in a research report [23].

At mid-term, the results of the research project support the development of a sustainable mobility policy. The effectiveness of measures such as the limitation of the gross vehicle weight, speed limits, an alternative design of speed reducing infrastructure and the influence of the thickness of the pavement have been investigated in an extensive parametric study. The resulting insight can be used to formulate national or international guidelines for nuisance due to traffic induced vibrations.

These results are not only of great importance to the administrations that are responsible for the maintenance of the road network, but also to contractors or consulting engineers that are confronted with problems related to traffic induced vibrations.

3 The numerical prediction model

The dynamic vehicle-road interaction is theoretically a coupled problem that requires a simultaneous solution of the equations of motion of the vehicle and the road. Due to the large stiffness of the road compared to the vehicle's tyre or suspension stiffness, the problem can be uncoupled. This enables a prediction of the free field vibrations in two stages. First, the equations of motion of the vehicle are solved and the dynamic axle loads are computed. Next, these axle loads are applied to the road and the road-soil interaction problem is solved.

The dynamic component of the axle loads is induced by the road unevenness and depends on the road profile, the vehicle characteristics and the vehicle speed. A forward Fourier transformation of the longitudinal road unevenness $u_{w/r}(y)$ to the wavenumber domain reveals the wavenumber content $\tilde{u}_{w/r}(k_y)$ of the profile in terms of the wavenumber k_y or the wavelength $\lambda_y = 2\pi/k_y$.

The basic mathematical models for the simulation of the vehicle ride behaviour are also used to predict the dynamic axle loads. These vehicle models are composed of discrete masses, springs, friction elements and dampers (figure 2). A linear 2D vehicle model with a limited number of degrees of freedom is used to calculate the dynamic axle loads from the longitudinal road unevenness.

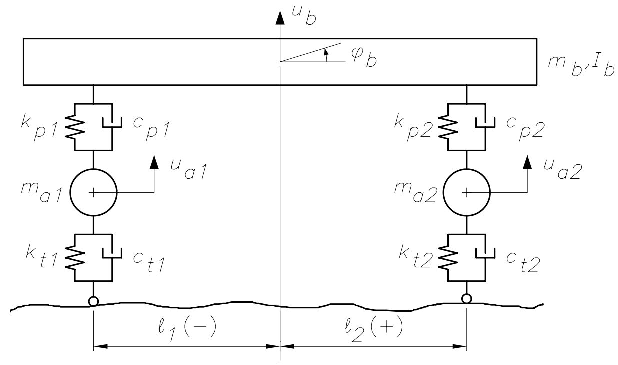

Figure 2: 2D 4DOF model for a passenger car or a truck with two axles.

For linear vehicle models, frequency response functions (FRF) can be used for the calculation of the dynamic axle loads. The FRF $\hat{h}_{f_k u_l}(\omega)$ relates a harmonic input at an axle l of the vehicle to the k-th axle load. Two groups of eigenmodes dominate the frequency content of the axle loads: the pitch and bounce modes at relatively low eigenfrequencies between 0.8 Hz and 3 Hz and the axle hop modes at frequencies between 8 Hz and 15 Hz.

The axle hop modes play a crucial role in the generation of traffic induced vibrations. For regular vehicle speeds between 8 m/s and 20 m/s, the range of wavelengths λ_y of the road unevenness that leads to an excitation of the vehicle at the axle hop frequencies is situated between 0.5 m and 2.5 m. In this range of wavelengths, a traffic plateau with a relatively large height has the same wavenumber content as a joint in a road surface with a much smaller height. The slope of speed reducing infrastructure has a determining influence on the relevant wavenumber content.

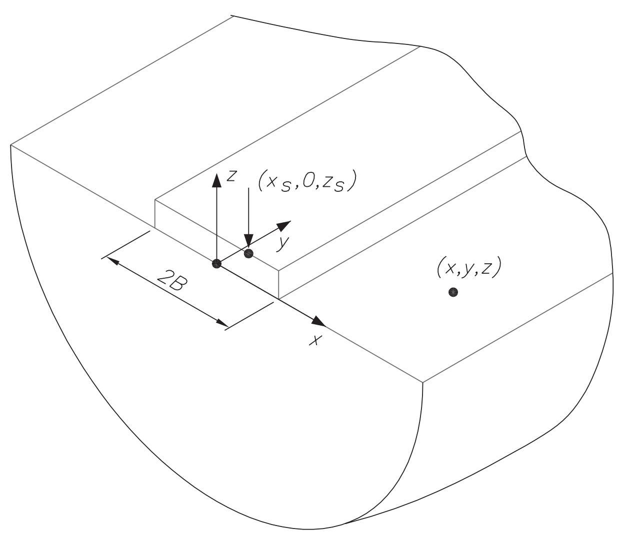

Figure 3: The road-soil interaction problem.

The dynamic road-soil interaction problem is first solved for an implusive load that is applied at a fixed position (figure 3). The road is modelled as an elastic beam with a rigid cross section, located at the surface of a horizontally layered halfspace. Both the road's bending and torsional deformations are accounted for. The soil's impedance is calculated by means of a boundary element method.

The solution of the road-soil interaction problem allows to determine the tractions at the road-soil interface for a fixed implusive load. From these tractions, the response in the free field can be determined. The solution serves as a transfer function and is mainly determined by the soil characteristics.

The dynamic Betti-Rayleigh reciprocal theorem is used to compute the free field response for the moving axle loads. The motion of the load position is replaced by an equivalent motion of the receiver position. The previously derived transfer functions for a fixed impulsive load on the road are now employed for the calculation of the free field response.

Although traffic induced vibrations are mostly generated by discrete irregularities, the overall road roughness is often considered in theoretical studies. The road unevenness is described by a power spectral density function as a function of the wavenumber k_y along the road. In this case, the axle loads are a set of random moving loads. Within the frame of the present work, the Wigner-Ville method is applied to develop a non-stationary stochastic method that allows to calculate the time-dependent statistical properties of the response due to a random moving load. The development of this solution procedure is an important extension of the existing numerical tools for the analysis of the response due to random moving loads.

4 The experimental validation

Figure 4: The passage of a DAF FT85 truck and trailer on the artificial unevenness at the DAF test circuit in Sint-Oedenrode (The Netherlands).

The numerical model has been experimentally validated with the results of two measurement campaigns. A first measurement campaign has been performed in December 1999 at the test circuit of the truck manufacturer DAF in Sint-Oedenrode (the Netherlands) [5, 22]. With the cooperation of DAF, the truck and the free field response have been measured simultaneously during the passage of a DAF FT85 truck with trailer on an artificial unevenness (figure 4). The design of the unevenness is based on an analysis of the signal that is applied to the vehicle's axles at various vehicle speeds [11]. A limited number of channels has been used for the measurement of the free field response.

The measurement of the vehicle's response facilitates the interpretation of the field data, can be used to determine the dynamic vehicle characteristics and allows to check the accuracy of the vehicle's response predictions. The experimental validation has demonstrated that the vehicle's speed and the dynamic soil characteristics have an important influence on the prediction of the free field vibrations and the experimental validation [14].

A more elaborate measurement campaign has been performed in June 2000 at the 'de Hemptinne' site of the Belgian Army in Heverlee (Belgium) within the frame of the 'OROS European University Millennium Award' project: "Vehicle response measurements as a validation tool for a prediction model for free field traffic induced vibrations" [13, 17]. The truck's response and the free field response have been measured during the passage of a Volvo FL6 truck on the artificial unevenness (figure 5). The parameters of the numerical model are determined carefully. The results of a spectral analysis of surface waves (SASW) test and a seismic cone penetration test (SCPT) provide complementary information on the dynamic soil characteristics.

Figure 5: The Volvo FL6 truck and the artificial profile at the 'de Hemptinne' site of the Belgian Army in Heverlee.

The measurements allow to validate both the prediction of the vehicle's axles and the free field response. The peak values of the response of the vehicle and the response in the free field are well predicted. The main difference between the predicted and the measured time history of the response is the duration of the transient signal that corresponds to the passage of the rear axle on the artificial profile. When the rear axle mounts the profile, a loss of contact occurs that is not predicted with the present linear vehicle model. The results further show how an increase of the vehicle speed shifts the frequency content of the vehicle's and the free field response to higher frequencies.

The results of the validation are very satisfactory and show that the prediction model describes the essential physical phenomena with a very reasonable accuracy. The model is therefore well suited to perform a parametric study and to predict free field traffic induced vibrations.

5 The parametric study

The results of an elaborate parametric study [16] allow to identify the key factors for the generation of free field traffic induced vibrations. Two groups of parameters have been studied. The first group is related to the source mechanism and contains parameters that determine the road unevenness and the vehicle dynamics. The second group of parameters is related to the transmission of the vibrations and characterizes the road and the soil. The influence of the vehicle speed is discussed extensively in the experimental validation of the numerical model [14, 17].

The following conclusions can be drawn from the parametric study:

- A study of the longitudinal unevenness profile in the wavenumber domain reveals that the relevant content of wavenumbers k_y is situated between 2.5 rad/m and 12 rad/m, corresponding to wavelengths $\lambda_y = 2\pi/k_y$ between 0.5 m and 2.5 m. In this range, the wavenumber content of a joint in the road surface with a limited height has the same order of magnitude as the profile of a traffic bump with a much larger height. As a result, the free field vibrations generated by the passage of a vehicle on a traffic plateau and a joint in the road surface have the same order of magnitude.
- The parametric study further shows that the height and the slope of the ramps are the predominant factors. The wavenumber content increases linearly with the height H, while steep ramps result in a disadvantageous high wavenumber content. The shape of the ramps is only of secondary importance.
- Simulations show that, for the passage of a vehicle on a traffic plateau with sine shaped slopes, the free field vibration levels can increase with a factor of 3 when the vehicle speed increases from 8 m/s to 20 m/s [6]. The vehicle speed has no large influence, however, on the vibrations that are generated during the passage on a joint in the road surface.
- An excitation of the axle hop modes is responsible for the generation of the free field vibrations in the frequency range between 8 Hz and 15 Hz. A study of the vehicle FRF shows that, more than the gross vehicle weight, the masses of the individual axles are important. Vehicles with high axle masses will therefore generate the largest vibrations, both in laden and unladen state. The stiffness of the tyres and the damping of the suspension system are parameters that affect the FRF's in an equally important way.
- The parameters related to the road section do not play an important role.
- For the receivers that are at a large dimensionless distance from the source, the soil's material damping is very important. For a homogeneous halfspace, the vibration levels are inversely proportional to the soil's stiffness. In the case where the soil is stratified, however, the nature of the stratification determines at which frequencies the response is attenuated or amplified [21]. The dynamic soil properties have to be determined upto a sufficiently large depth in order to accurately predict the low frequency content of the response.
- Compared to the use of simple empirical models, an elaborate numerical model, that is based on the physical nature of the problem, has the advantage that it provides physical insight and that it is well suited for a parametric study.

6 Conclusion

The main emphasis in the DWTC research project MD/01/040 'Study of determining factors for traffic induced vibrations in buildings' (1 July 1998 - 30 June 2001) goes to the development and the use of a prediction model for free field road traffic induced vibrations.

The numerical model is based on a mathematical description of the phenomena that occur when a vehicle encounters a road unevenness. The dynamic axle loads are calculated from the longitudinal road unevenness and the vehicle dynamics. The road-soil interaction problem is solved with a substructure method where a beam model is used for the road and a boundary element method is used for the supporting soil. The free field vibrations are calculated by means of the Betti-Rayleigh reciprocal theorem. The results of an extensive parametric study have been translated into practical guidelines [16].

Two measurement campaigns have been performed for the validation of the numerical model. The results of the validation are very satisfactory and indicate that factors as the experimental determination of the dynamic soil characteristics are very important for a succesful prediction of traffic induced vibrations.

The results have been presented at one national conference [10] and seven international conferences [1, 3, 7, 8, 9, 12, 15, 18, 20]. The description of the numerical model [19] and the experimental validation of the model [14] have already been published in the journal 'Soil Dynamics and Earthquake Engineering'. Three more journal papers [2, 4, 21] have been accepted for publication. Furthermore, a mobile data acquisition system with four measurement channels and a value of 25000 Euro has been obtained within the frame of the 'Oros European University Millennium Award', [13, 17]. The extensive list of publications shows that the present research project has brought the Belgian research related to traffic induced vibrations to an international scientific level.

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