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TIRE/ROAD NOISE: COMPARISON OF 2D AND 3D MODELS FOR HORN EFFECT

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ABSTRACT
This paper deals with the modelling of amplification effect of tyre/road contact noise (horn effect), due to the multiple reflections between the curved and hard surface of the tyre and the road pavement. First an analytical model based on the modal decomposition of the sound pressure, was used for the 2D case of an infinite rigid cylinder and the 3D case of a rigid sphere, both on a flat reflecting plane. This model provided the reference results. Next, a 2D-BEM model was used in which sound absorption properties of the road surface were introduced. Comparisons with 2D analytical method for purely reflecting case were very favourable, and the effect of a porous asphalt on amplification was evaluated. Finally a 3D-BEM model was developed and validated on the rigid sphere case by comparison with analytical results. A very good agreement was found.

1 - INTRODUCTION

Tyre/road noise is known to be generated by different phenomena, such as vibration of the tyre or "air pumping". The resulting noise source is located near the contact patch and is amplified by horn effect. This amplification is due to the multiple reflections between the tyre circumference and the road surface, generally both purely reflecting surfaces, and the amplification can reach 10 to 20 dB at certain frequencies. In this paper, different models were used for horn effect. The first one was an analytical model based on the modal decomposition of the sound pressure. The 2D case where the tyre is taken as a rigid cylinder of infinite length, and the 3D case where the tyre is taken as a rigid sphere, were studied. In order to introduce more realistic conditions, the boundary element method (BEM) was used: absorption effects on a porous road surface were introduced in 2D, and a 3D BEM was developed in order to predict real 3D effect. The analytical model provided the reference results for validating and adjusting the parameters in BEM models. Comparisons of 2D and 3D BEM results with the analytical results are presented in the following, as well as the effects of sound absorption on the road surface. A more detailed presentation of 3D BEM results for a tyre of real geometry can be found in a separate paper by Fadavi & al. [1].

2 - THE 2D AND 3D ANALYTICAL MODEL: REFERENCE CASES

The 2-D model implementation is based on an already existing model described in [2]. The tyre is considered as a rigid cylinder of infinite length laying on a perfectly reflecting plane surface. The noise source is defined as a vibration distribution on the contour of the cylinder. It can be extended or localised (point source). Indeed it can represent either the radiation of the vibrating tyre (f<1 kHz) or the "air-pumping" source due to successive compressions and dilatations of air trapped in road and tyre cavities (f>1 kHz). The horn effect considered in all this paper is the sound pressure level amplification of the

radiating tyre, due to the presence of the road surface (i.e. the difference in sound pressure level between with and without the road surface) for the case of a point source.
The principle of the model is to consider the image of the cylinder with respect to the plane surface in order to fulfil the perfectly reflecting surface condition. The sound pressure is thus the sum of the cylinder and its image contributions. Both contributions are expanded in their respective coordinates system in cylindrical modal outgoing wave functions. Modal coefficients are determined by fitting the velocity boundary conditions on the plane surface and on the cylinder contour.
A similar approach has been applied to the 3D geometric case of a sphere [3].

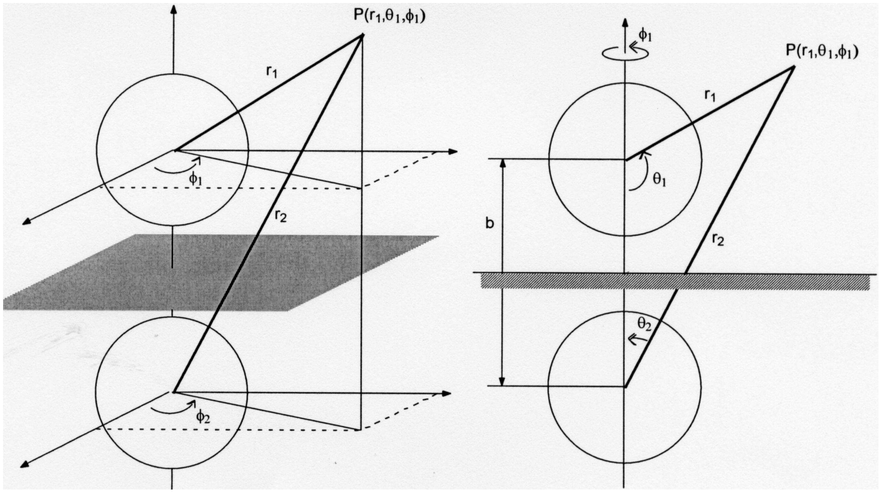

Figure 1: Description of the 3D case of a sphere.

The sound pressure is expressed as the sum of contributions of the sphere and its image with respect to the plane surface (see Fig. 1):

$$\mathrm{P}\left(\mathrm{r}_1, \theta_1, \varphi_1\right) = \mathrm{P}_1\left(\ \mathrm{r}_1, \theta_1, \varphi_1\right) + \mathrm{P}_2\left(\mathrm{r}_2, \theta_2, \varphi_2\right)$$

Each contribution is expanded in spherical outgoing wave functions as:

$$P_1 = \sum_{m=0}^{+\infty} \sum_{n=-m}^{m} A_{mn} h_m^{(2)}\left(kr_1\right) P_{m|n|}\left(\cos\theta_1\right) e^{jn\varphi_1} \quad , \quad P_2 = \sum_{m=0}^{+\infty} \sum_{n=-m}^{m} B_{mn} h_m^{(2)}\left(kr_2\right) P_{m|n|}\left(\cos\theta_2\right) e^{jn\varphi_2}$$

where ${h_m}^{(2)}$ represents the m^{th} order spherical Hankel function of second kind and P_{mn} the Legendre function of order $(m{,}n)$.
The perfectly reflecting surface condition leads to:

$$A_{mn} = B_{mn} \quad , \quad \forall m, n$$

The velocity condition on the sphere surface is expressed as

$$\nu_{\mathrm{r}}\left(\mathrm{a}, \theta_1, \varphi_1\right) = -\frac{1}{\mathrm{j}\omega\rho}\left(\frac{\partial \mathrm{P}}{\partial \mathrm{r}_1}\right)_{(\mathrm{r}_1=\mathrm{a})} = \mathrm{V}\left(\theta_1, \varphi_1\right) \quad \forall\theta_1 \in [0;\pi] \quad \forall\varphi_1 \in [0;2\pi]$$

where $\mathrm{V}\left(\theta_1, \varphi_1\right)$ is the sphere velocity distribution, and leads to a linear system, the solution of which gives the modal coefficients A_{mn} and B_{mn}.

3 - THE 2D BEM: EFFECT OF ABSORPTION ON ROAD SURFACES

In order to introduce sound absorption conditions on the road surface and predict the resulting reduction in horn amplification, a BEM model was used for the two-dimensional case. The acoustic impedance of the porous road layer − such as drainage asphalt − is described by a phenomenological model using 3 parameters: porosity (Ω), specific flow resistance (R_s) and tortuosity (K). Furthermore, specific numerical procedure has been developed to take into account the non local type of absorption condition at the interface air / porous road surface [4]. This is of particular importance for grazing incidence of sound, and tyre/road contact noise typically generates grazing incidences.

First, a validation of this numerical approach was performed by comparison with analytical results for case of the rigid cylinder of infinite length laying on a flat reflecting surface. A very good agreement was found as shown in Fig. 2 where the sound source is localised at θ=5 degrees with vertical. In this figure, the effect of absorption on a typical 4 cm thick porous layer (Ω=15%, R_s=20000 MKS Rayls/m, K=3.5) is also represented: as expected, one can see that road surface absorption significantly reduces the sound amplification, especially in the frequency range where the absorption coefficient of the porous layer is high, i.e. from 500 Hz to 2 kHz. This can have important consequences on the overall tyre/road noise emission, the main contribution of which is precisely in this frequency range.

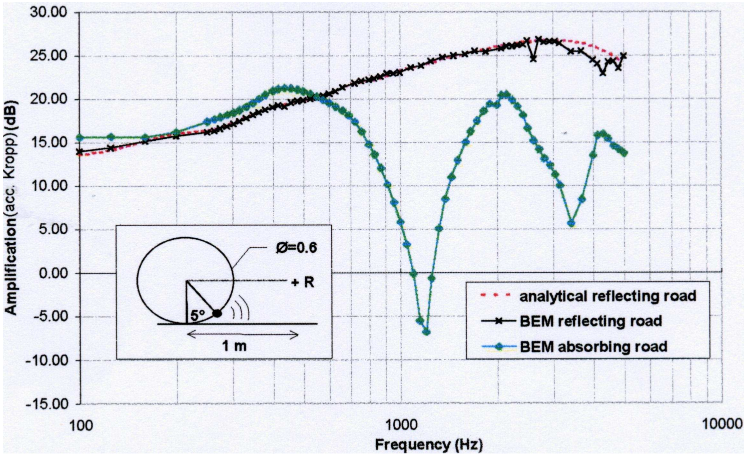

Figure 2: Comparison 2D analytical / 2D BEM and effect of absorption on the road.

4 - THE 3D MODEL: VALIDATION FOR A SPHERE

In order to validate the 3D calculation of the tyre/road noise, one can study the case of a sphere on the ground. The sound amplification is calculated both analytically and numerically at 1 meter in front of the sphere ($r_1 = 1$ m, θ_1=$\pi/2, \varphi_1 = 0$). The radius of the sphere is a=30 cm. The excitation source is given by a uniform speed distribution which has only normal components and it is placed near the contact patch at θ_1=10 degrees (see Fig. 3). Its length is $\delta\varphi$=15 degrees and its width is $\delta\theta$=15 degrees. If there is no absorption, the sound pressure generated by the sphere on the ground is then given by P=P_1+P_2, where P_1 is the reference pressure generated by the sphere without the ground (Kropp method) and P_2 is the pressure generated by the image sphere.

The analytical case is presented in §2. The numerical resolution uses the boundary element method. Figure 4 shows the numerical solution and the analytical solution for the sound amplification in function of the frequency. Same agreements have been found for the amplification in terms of the sound power instead of the sound level. This last study shows that amplification is not simply a change in the directivity of the sound but a real amplification in terms of power of the sound generated. These studies validate the 3D numerical calculation.

5 - CONCLUSION

For horn effect modelling, a very good agreement has been found between an analytical method (the reference case) and BEM models. In 2D, predictions show that horn effect can be considerably reduced by absorption on the road surface in the 500 Hz- 2 kHz range. Experimental assessments are currently. The 3D-BEM model developed was validated on the sphere case. The modelling of a real tyre geometry with 3D BEM is presented elsewhere in this congress [1].

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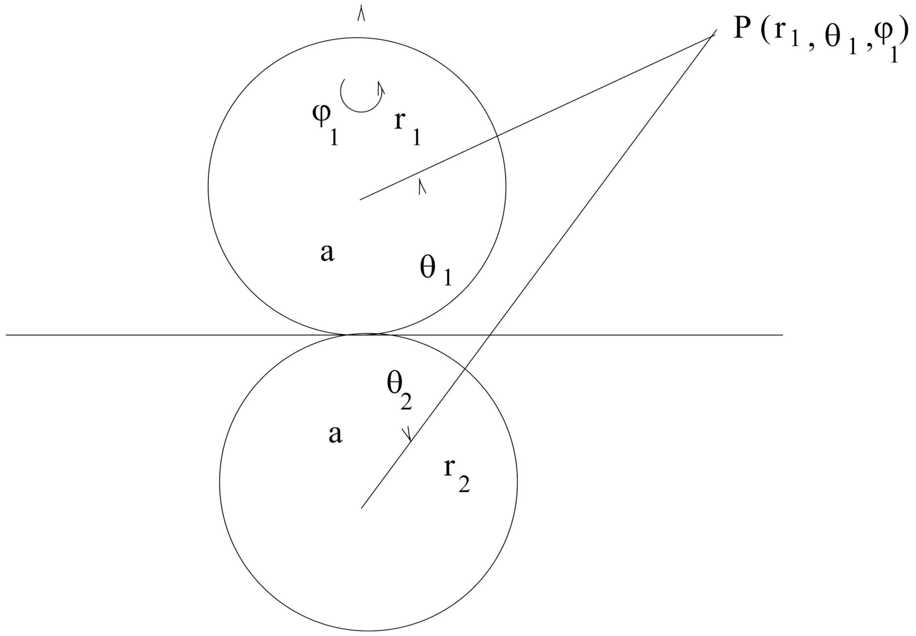

Figure 3: Geometry of the problem.

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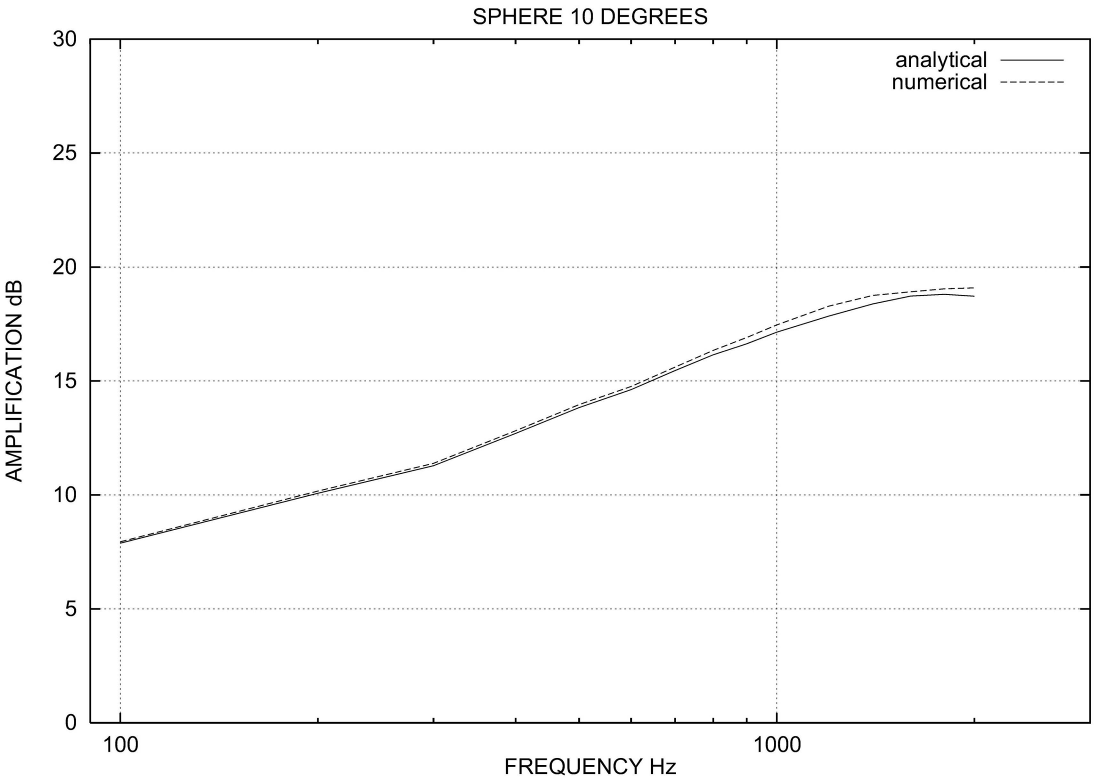

Figure 4: Sound amplification, $100 \leq f \leq 2000$ Hz.