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ON THE SOUND RADIATION FROM TYRES

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ABSTRACT
A two-dimensional model for the sound radiation from tyres is presented here. Based on the multipole synthesis, it is shown to be robust and converge rapidly even with a low number of modes taken into account. Despite obvious deviations due to its two dimensional character, its prediction of the horn effect agree well with measurements and BE calculations. Due to its efficiency the model allows for studying the influence of parameters such as geometry or surface impedance on the sound radiation from tyres. Results of such a parameter study are presented in the following. However there is a need for an extension of the model to three dimensions.

1 - INTRODUCTION
Due to noise reduction from the engine or the exhaust system, tyre / road noise is nowadays the main source and limits of a substantial reduction of the overall traffic noise. Tyre / road noise implies several fundamental mechanisms from non-linear contact to outdoor propagation, and the complexity of the problem is probably the reason of the lack of engineering solution in the domain. This paper deals with the sound radiation from tyres focusing especially with modelling of the horn effect. The general ideas of the model are presented (section 2) and the radiation efficiency of the tyre is discussed (section 3). The last section presents a brief study of key parameters such as the road impedance or the geometry of the horn.

2 - THEORETICAL MODELLING OF THE SOUND RADIATION FROM TYRES
The model for the radiation from tyres used here is two-dimensional (i.e. in the plane of the tyre) and it is based on the multipole synthesis where sources (multipoles) are placed inside a radiating closed surface. The work is based on the one published in [1] and [2]. The road is taken into account by means of an image source located symmetrically below the road surface. The amplitudes of these sources are determined in such a way that the sources fulfil a prescribed boundary condition on the surface of the tyre, for instance in the form of a normal velocity distribution. The boundary condition on the ground surface is given as a reflection factor in the normal direction to the surface.
The error made for the field simulation is directly proportional to the boundary error. Whereas theoretically, increasing the order of the multipole would make the error converge towards zeros, implementing the method with a too high order multipole leads to numerical instabilities and makes the equation being ill-conditioned. However, within those bounds any accuracy can be reached by increasing the order of the multipole. Meanwhile the computational time of the calculation increases also.

3 - RADIATION EFFICIENCY OF CIRCUMFERENTIAL MODES ON THE TYRE SURFACE
The model can be applied to calculate the radiation efficiency for individual modes on the tyre surface with and without the influence of the road surface. Figure 2 shows the radiation efficiency of each vibration mode on the circumference of the tyre for a freely vibrating cylinder, i.e. without the influence

of the road. The radiation efficiency has low values at low frequency, and takes maximum values where the wavelength on the cylinder is close to the wavelength in the surrounding medium. One can conclude that the tyre is a weak radiator in the frequency range of interest. Only low order modes can contribute to the radiation. However studies in [3] show that the free vibration pattern is determined by the high order modes in this frequency range.

The picture changes when taking into account the road surface. A radiation pattern is assumed where a node is at the contact between the tyre and the road, which is quite similar to the situation in reality. The radiation efficiencies presented in Figure 3 show bigger values both below and above the coincidence frequency. One should note that the modes in this case are not anymore orthogonal with respect to their radiation. This implies that the sound radiation consists not only of a summation of the sound power from each individual mode. There is also an interaction between the fields from each mode.

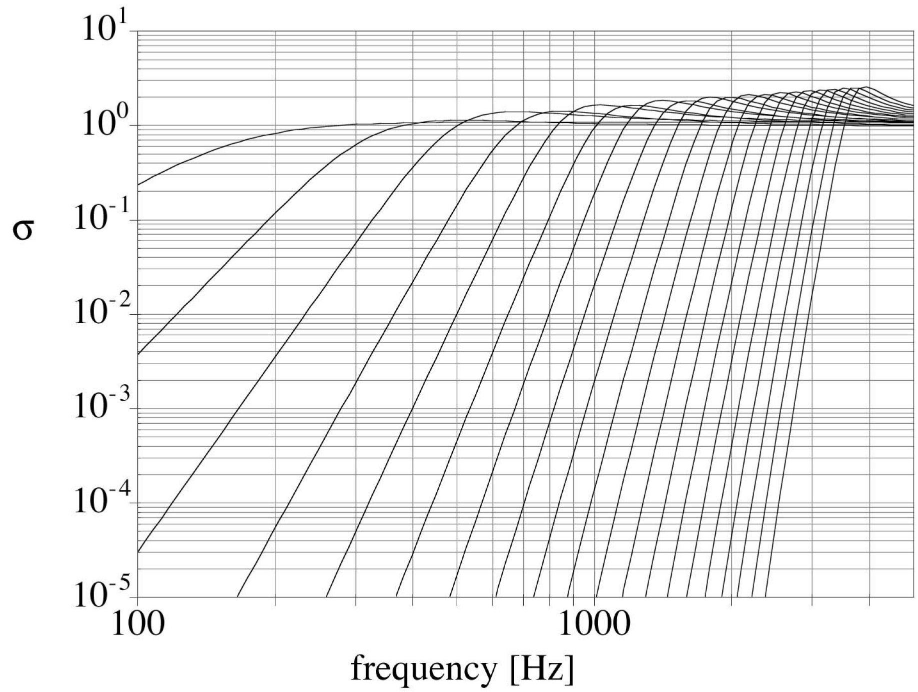

Figure 1: Radiation efficiency: free tyre.

The radiation efficiency presented in both figures shows that the radiation is more likely due to low order modes than due to high order modes. This explains why, even taken into account a low number of modes, the calculations from the model converge quite fast.

4 - APPLICATION OF THE MODEL TO CALCULATE THE HORN EFFECT

The model presented above can be applied to simulate the horn effect. The results of the model are compared with measurements. The amplification is evaluated when calculating the pressure on the ground at a distance l equals 1 m from the horn centre (see Fig 3). The source is located at distances d equals 10, 20, 40, 80 mm.

For practical reasons measurements were carried out using the acoustic reciprocity principle and taking as reference pressure the pressure without the tyre. To distinguish deviations due to the two-dimensional character of the multipole model from possible other deficiencies, calculations are also compared with results from a standard BE code. The model is valid up to 6 kHz and it is interesting to note that calculations with the BE model, for equal mesh size, take about five times longer than with the multipole model although both were run on the same computer and the Matlab code was not compiled.

The four curves represent the amplification for the four positions of the microphone inside the horn. A maximum level of 22 dB is measured (see Fig 4) at 2 kHz when the source is the closest to the contact patch. Moving the source away from the horn centre reduces the amplification, and the maximum frequency at which the amplification occurs is shifted downwards, as already shown in [3]. As expected the multipole model fails in the low frequency range below 1 kHz due its two-dimensional character (see Fig 5). However the maximum amplitudes of the amplifications as well as the frequencies at which these

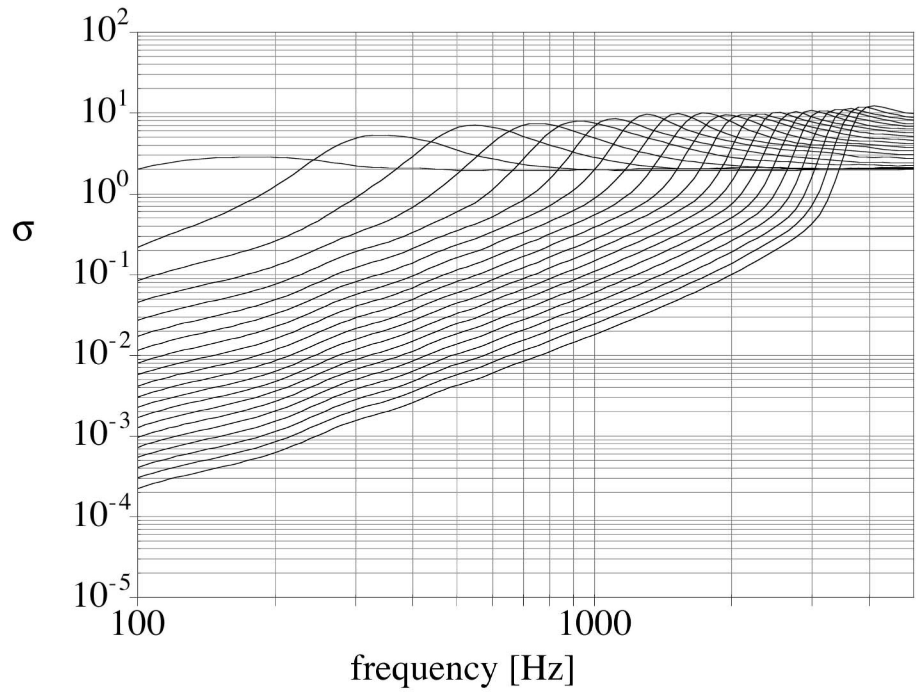

Figure 2: Radiation efficiency: tyre with road.

maxima occur are correctly predicted in the model. The model also correctly predicts the dips in the amplification due to interference.
The results from the multipole model agree very well with the results from the BE model (Fig 6) which also underlines that the deficiency between theoretical models and measurements is due to the two-dimensional character of the models. To achieve a better agreement at low frequencies the model has to be extended to three dimensions taking into account the finite width of the tyre.

5 - A BRIEF PARAMETER STUDY

Although the model is restricted to two dimensions, it provides some insight into the influence of the road surface on the sound radiation from tyres. First an absorbing road surface is taken into account. Secondly, the influence of the geometry on the horn effect is discussed.
In the previous text the road surface was assumed to be acoustically rigid. A finite impedance for the road surface is introduced in the multipole model using two different formulations of the reflection factor. First a reflection factor independent of the angle of incidence for plane waves is applied. Secondly the multipole model is modified and a plane wave reflection coefficient depending on the angle of incidence is implemented. However regarding the geometry and the surface properties, a reflection coefficient for cylindrical waves would be correct. The impedance of an absorbing material is measured in a Kundt's tube and then used to estimate the reflection coefficients for the two formulations. Calculations from the model are shown in Figure 7 and compared with measurements made for a tyre placed above the absorbing material. It is clear that the modified model gives better results than when using a constant reflection factor, although both of them overestimate the amplification levels in the high frequency range. This might be due to erroneous values of the impedance of the absorbing material. The model, as expected, fails in the low frequency range due to its two-dimensional character. Finally the modified model works reasonably well in the middle frequency range around 1 kHz.
The geometry of the horn effect is studied by varying the minimum distance between the tyre and the road. The amplification levels are shown on Figure 8 for different heights of the tyre over the road surface. Both calculations and measurements show that lifting up the tyre leads to a reduction of the sound amplification due to the horn effect. It is also shown that the frequency from which the amplification decreases is shifted downwards when increasing the height. This explains the often measured and surprising result that very rough road surfaces lead to a lower radiated sound at high frequencies. For such roads, the tyre is rolling only on the roughness peaks while the acoustical reflecting plane is situated somewhat lower.

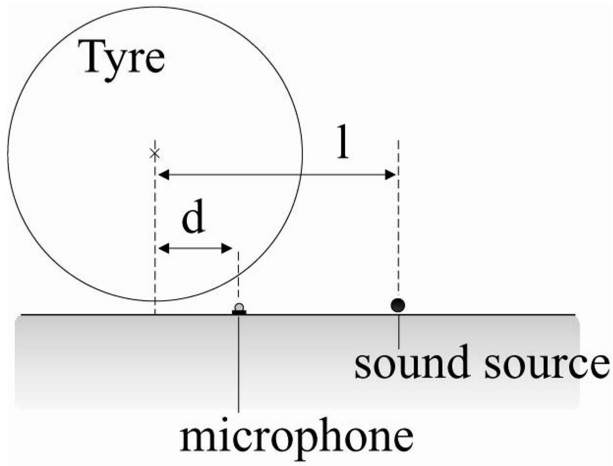

Figure 3: Parameters for the evaluation of the horn effect.

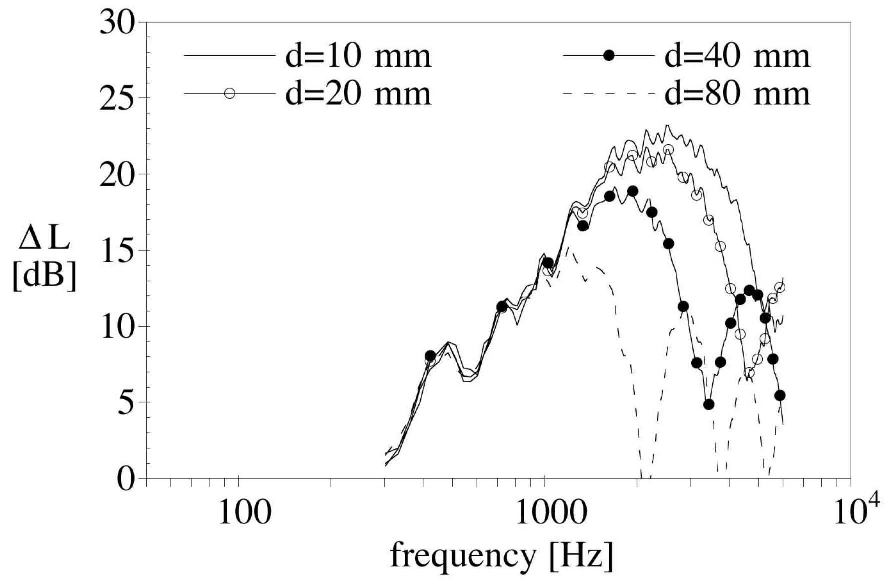

Figure 4: Estimations of the horn effect by measurements.

6 - CONCLUSIONS

The model presented here is shown to overestimate the horn effect at low frequency while in the middle and high frequency range the agreement with measurements is good. The model shows that the tyre is a weak radiator regarding its free vibration pattern. Moreover regarding the fast convergence of the calculations, it has been shown to be an efficient tool for calculating the sound radiation from tyres. Furthermore it has been shown to be adapted for parametrical studies, although there is a clear need for an extension of the model to three dimensions. The results show that the amplification is very sensitive to changes in the surface impedance and the roughness of the road. This would lead not only to a lower horn effect but to a clear reduction of tyre / road noise.

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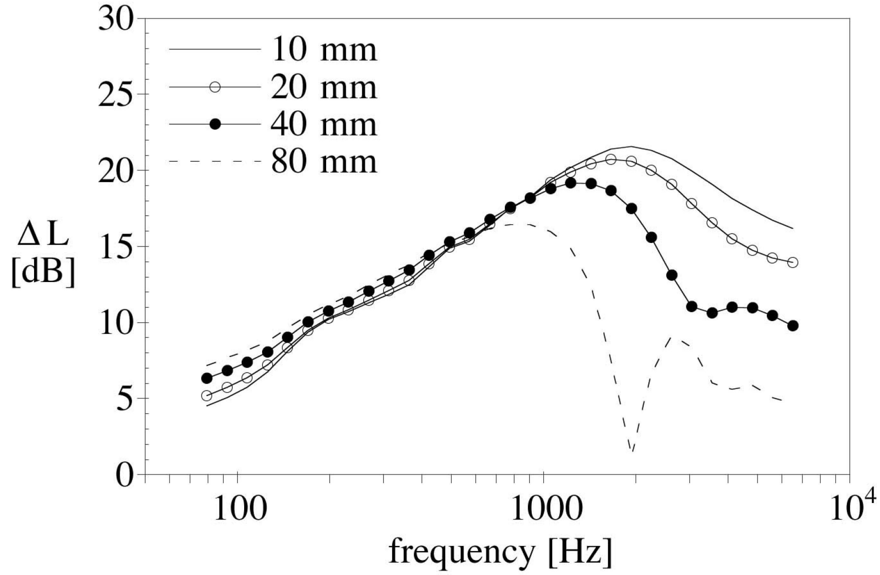

Figure 5: Estimations of the horn effect by multipole model.

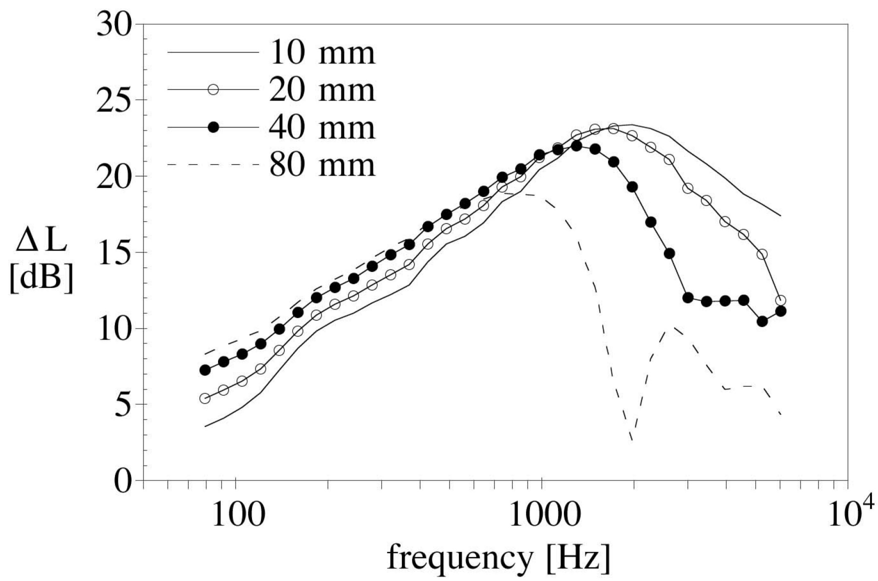

Figure 6: Estimations of the horn effect by BE model.

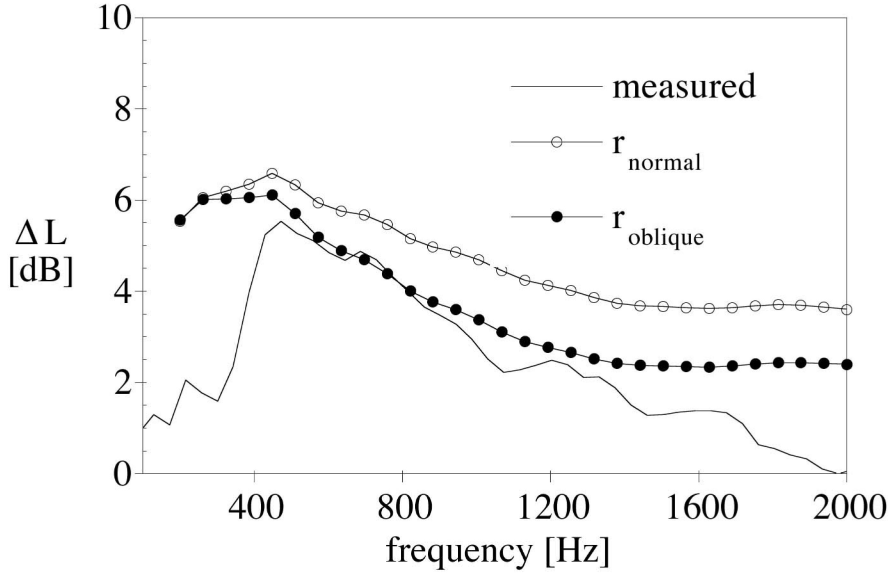

Figure 7: Horn effect for a finite impedance road surface.

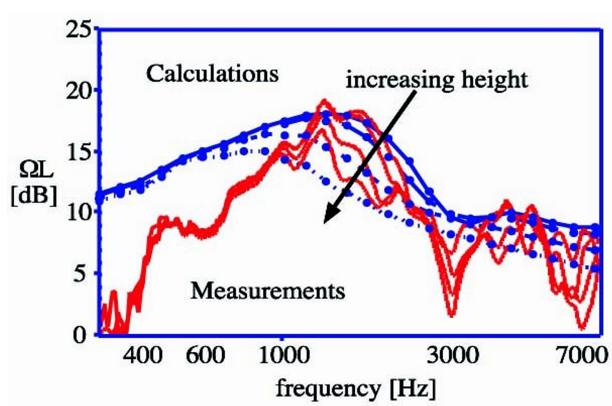

Figure 8: Influence of the minimum distance between tyre and road.