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TIRE/ROAD NOISE: 3D MODEL FOR HORN EFFECT

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ABSTRACT
Within the problem of tire/road noise, this work deals with the horn effect. Between the curved tire tread fore and aft of the tire/road interface and the road surface there is a space which forms an acoustical horn which increases the radiation efficiency backwards and forwards up to 10 dB(A). This effect has to be considered in a general model for tire/road noise. A 3D tire model is used for this purpose. The tire is modeled by a cylinder. An excitation source is placed on the tread and sidewalls near the contact patch. The sound pressure and sound amplification are calculated in the space around the 3D tire model using the Boundary Element Method (BEM). The influence of different parameters such as the position and size of the source are studied in terms of amplification and sound pressure spectrums. It is shown that the position of the source has a very important influence when its size has negligible influence. To validate the 3D model, a comparison between numerical and analytical solutions is proposed for the case of a sphere on a flat surface. The 3D analytical model for the sphere is based on an existing model using modal decomposition of the sound pressure. Finally, the 3D solution is compared to the 2D solution. An important difference between theses solutions is observed.

1 - INTRODUCTION
Within the problem of tire/road noise, this work deals with the horn effect. Between the curved tire tread fore and aft of the tire/road interface and the road surface there is a space which forms an acoustical horn. This horn increases the radiation efficiency backwards and forwards up to 10 dB(A). This effect had to be considered in a general model for tire/road noise. A 3D tire model is used for this purpose. The tire is modeled by a cylinder. An excitation source is placed on the tread and side walls near the contact patch. The sound pressure and sound amplification are calculated in the space around the 3D tire model using the boundary element method (BEM). The influence of different parameters such as position and size of the source are studied in terms of amplification and sound pressure spectrums.

2 - THEORY AND MODEL DEFINITION
An estimation of sound amplification needs the definition of a reference pressure. The two methods used in general are the standard method and the Kropp method. Each method use a different reference sound pressure. For the standard model the reference sound pressure is generated by the vibration source on the ground without the tire. In this paper, we use the Kropp model which suggests a reference sound pressure generated by the vibration of the source without the road. The sound amplification is then given by

$$A = 20\log_{10}\left(\frac{p}{p_{ref}}\right) \tag{1}$$

where p is the sound pressure generated by the vibration of the source on the tire when the tire is on the road and p_{ref} is the reference sound pressure described above (see also references 2 and 3). The two dimensional tire model is a circle with a radius of 30 cm. The excitation source is given by a uniform speed distribution which has only normal components. It has $2\delta\varphi$=10 degrees length and it is placed near the contact patch, φ_0=10 degrees from the vertical axe and on the right as shown in Figure 1.

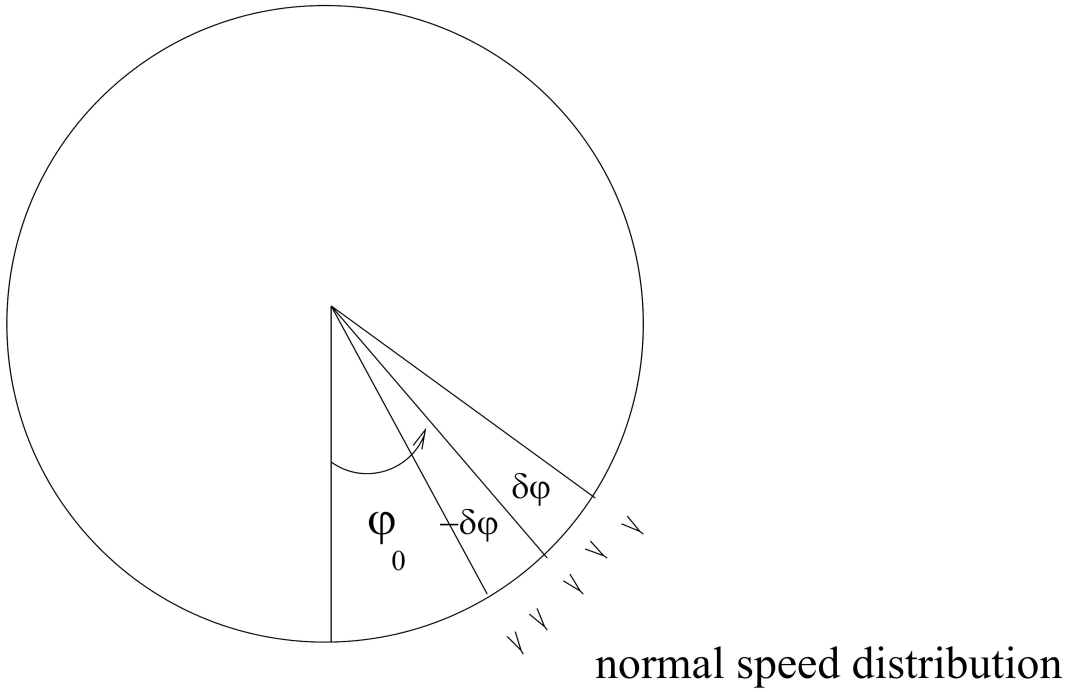

Figure 1: 2D model.

The 3D tire is modeled by a cylinder of the same radius. The tire width is 14 cm. As in the 2D model, the excitation source is placed also at φ=10 degrees from the vertical axe and its height is 10 degrees from the vertical axe. The excitation source has the same length as in the 2D model and its width is 14 cm. As can be seen in Figure 2, a circle with radius of 20 cm marks the boundaries of a zone on the side walls which vibrates with the same amplitude as the source.
To calculate the sound pressure, we use the boundary element method (BEM). In both 2D and 3D models, the equation that calculates the sound pressure is an integral equation on the boundary of the tire.

$$\frac{1}{2}p\left(\underline{y}\right) = \int_{\partial\Omega}\left(\frac{\partial G\left(\underline{y},\underline{x}\right)}{\partial n_x}p\left(\underline{x}\right) - \frac{\partial p\left(\underline{x}\right)}{\partial n_x}G\left(\underline{y},\underline{x}\right)\right)d\Gamma + p_i\left(\underline{y}\right) \tag{2}$$

In equation (2), $\underline{x}$ and $\underline{y}$ are two points on the boundary, p_i is the incident pressure (pressure without the tire), n_x denotes the outward normal unit vector at the corresponding position, $G\left(\underline{y},\underline{x}\right)$ represents the fundamental solution of Helmholtz equation and is of the form

$$G\left(\underline{y},\underline{x}\right) = \frac{i}{4}H_1^0\left(kr\right) \text{ in two dimensions, with } r = \left|\underline{y}-\underline{x}\right|$$

$$G\left(\underline{y},\underline{x}\right) = \frac{\exp\left(ikr\right)}{4\pi r} \text{ in three dimensions}$$

where H_0^1 is the Hankel function of the first kind of zero order and $i = \sqrt{-1}$. This reduces the original problem to a simple one in which only the solution on the boundary Γ needs to be considered. Unfortunately, because of some so-called forbidden frequencies, the integral operator in equation (2) is not uniquely solvable. In this work, the real equation that has been solved is given by a method proposed by Burton and Miller in 1971 (see reference [3]).

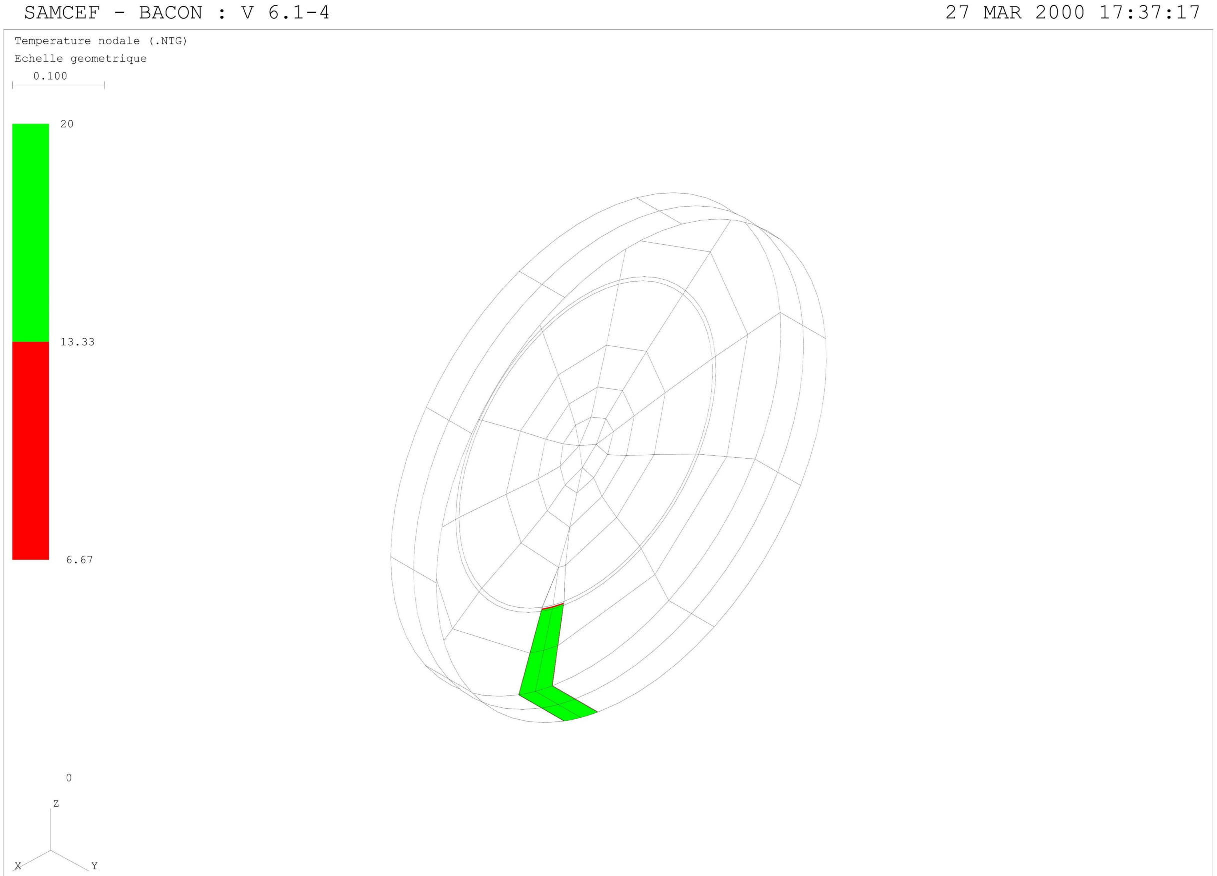

Figure 2: 3D model, mesh of the tire.

3 - NUMERICAL SIMULATION RESULTS

For all the results, the sound pressure and the sound amplification are calculated at 1 m from the tire axe ($\underline{y}$) and in front of it on the right (see Figure 1). One can see in Figure 3 the sound amplification for the three dimensional tire model calculated with the Kropp method. The sound amplification is given for two different positions of the source φ=5 degrees and φ=15 degrees in term of sound amplification spectrum. It can be observed from Figure 3 that the position of the source has a very important influence on the sound amplification, specially for the high frequencies.

In figure 4, one can see the sound amplification of the same tire for which the position of the excitation source is now kept constant (φ=10 degrees) but its size is varying from 5 to 15 degrees. It is shown that the size of the source has a negligible influence on the sound amplification.

In Figure 5, one can see the radiation patterns in a horizontal plane which passes through the center of the tire (the equation of this plane is z=30 cm). Because of the $\underline{y}$ -symmetry, we show only half of the space around the tire ($y > 0$). Figure 5 shows the sound amplification in this square plane of 2 m side for 4 different frequencies (100, 500, 1000, 2000 Hz) in function of the angle. The frequency has a large influence on the radiation patterns. For low frequencies, the radiation patterns stay regular. For high frequencies, interference appears. The sound amplification increases at the sides of the tire and in front of it as the frequency increases.

For the purpose of comparisons between the 2D and the 3D models, the sound amplification calculated with both models are shown in the same Figure (Figure 6). One can conclude that the results are very different. The fact that the sound can turn around the tire in the 3D model and can then interfere differently from the 2 dimensional case may explain this difference.

4 - CONCLUSION

From these studies, we give the following conclusions for the sound pressure level and the sound amplification. Interferences increase as the frequency increases. The position of the source has an important influence when its size has no significant influence. The sound pressure level and the sound amplification have also been calculated at 100 m from the axe of the tire and in front of it. It is shown that the

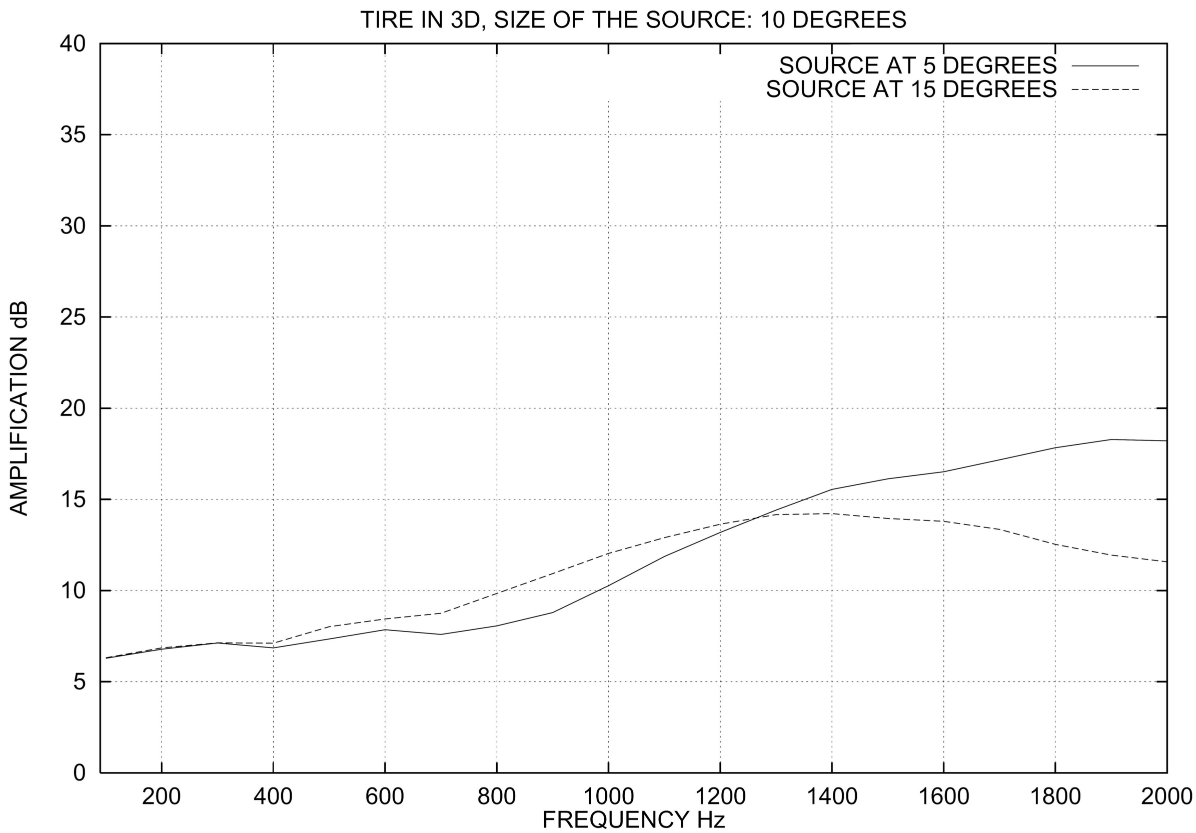

Figure 3: Sound amplification, influence of the position of the source.

pressure level and the amplification are very similar to the previous case.

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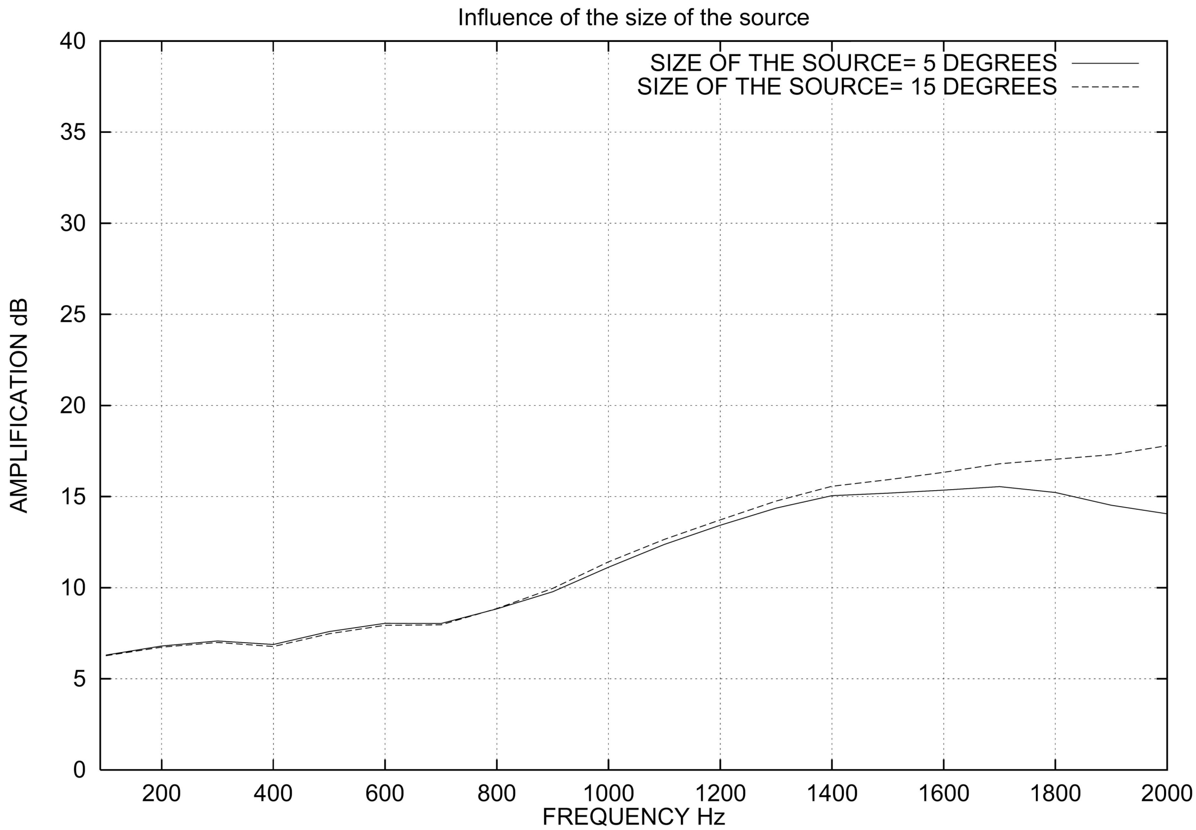

Figure 4: Sound amplification, influence of the size of the source.

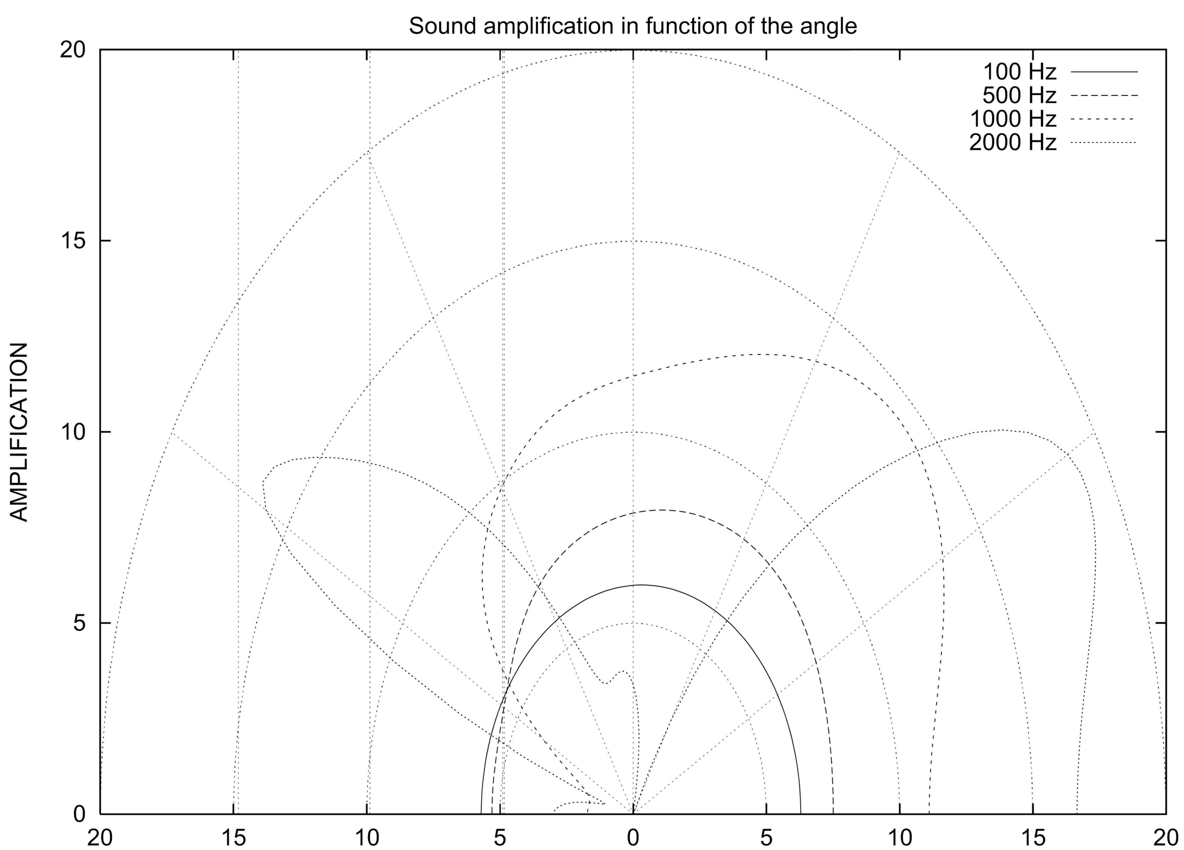

Figure 5: Sound amplification and sound pressure level in a horizontal plane in function of the angle.

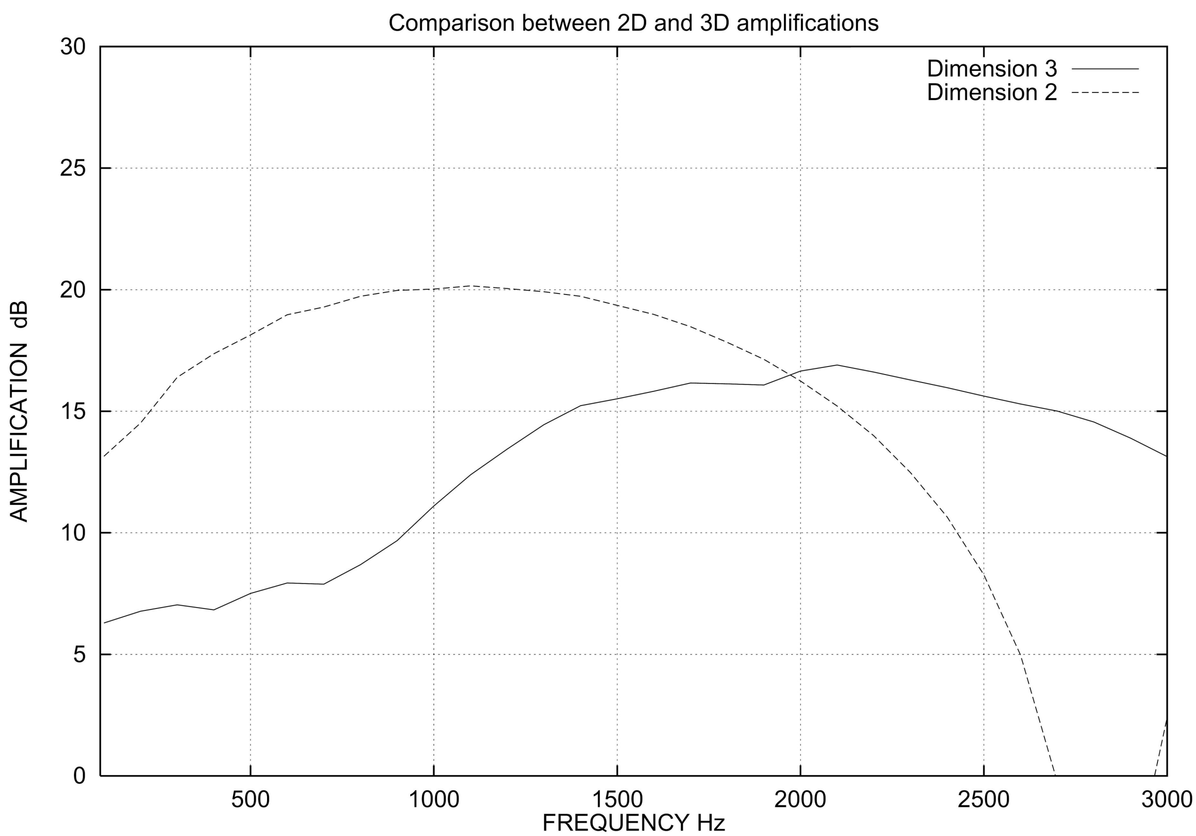

Figure 6: Sound amplification, comparison between the 2D and 3D models.