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HORN EFFECT CHARACTERISATION FOR TIRE-ROAD NOISE RADIATION

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ABSTRACT

The horn effect is a major factor in the radiation of tire-road noise. Its characterisation is to be based on two quantities: the sound pressure level amplification and the total radiated power amplification. Two kinds of sound sources are considered here: quasi-monopole sources and vibration modes of the surface. These considerations are applied to two geometries: an infinitely long cylinder (bi-dimensionnal case) and a sphere (three-dimensionnal case) both baffled with a perfectly reflecting plane surface. The 2D approach uses an existing analytical model. The 3D approach is similar: it considers an expansion of the acoustic field in spherical outgoing wave functions. Some considerations are developed about the radiation efficiency of these acoustical radiators.

1 - INTRODUCTION

It is generally admitted that tire-road noise sources are amplified by the geometry made by the tyre and the road surface. This so-called horn effect has been experimentally studied and some analytical and empirical models have been proposed [1], [2]. Its characterisation often consists in comparing the sound pressure, created by a monopole source within the horn to a reference pressure created by the source without the tyre. Only one study [3] compares the total power radiated in both configurations and finds a 6 dB radiated power amplification. This paper deals with horn effect characterisation based on analytical sound pressure models for two geometries: an infinite cylinder and a sphere baffled with a perfectly reflecting plane surface.

2 - 2D AND 3D ANALYTICAL MODELS

The 2D model implementation is based on an already existing model described in [2]. The tyre is considered to be an infinite cylinder baffled with 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). The sound pressure is the sum of contributions from the cylinder and its image introduced to fulfil the perfect reflection condition at the road surface. Both contributions are expressed in terms of cylindrical modal outgoing wave functions whose coefficients are determined by fitting the boundary conditions on the plane surface and on the cylinder contour.

A similar approach is applied to the 3D geometrical case of a sphere of radius a=0.3 m [4]. The sound pressure is expressed as the sum of contributions from the sphere and its image (figure 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 ($e^{j\omega t}$ convention):

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

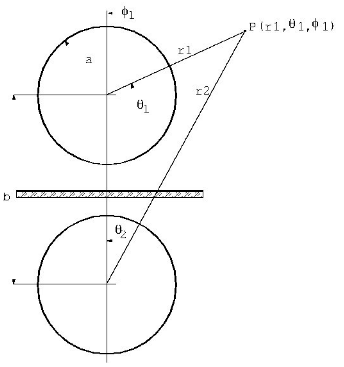

Figure 1: Description of the 3-D case of a sphere (for all results b=2a=0.6 m).

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).

Taking into account the boundary conditions on the road and on the sphere leads to $A_{mn} = B_{mn}$ and to the equation for A_{mn} where $V\left(\theta_1, \varphi_1\right)$ is the velocity defined on the sphere:

$$-\frac{1}{j\omega\rho}\sum_{m=0}^{+\infty}\sum_{n=-m}^{m} A_{mn}\left\{kh_m^{(2)'}\left(ka\right)P_{m|n|}\left(\cos\theta_1\right)+r\left[\begin{array}{c} k\dfrac{a-b\cos\theta_1}{r_2}h_m^{(2)'}\left(kr_2\right)P_{m|n|}\left(\cos\theta_2\right) \\ -\dfrac{b\sin\theta_1\sin\theta_2}{r_2^2}h_m^{(2)}\left(kr_2\right)P_{m|n|}^{'}\left(\cos\theta_2\right)\end{array}\right]\right\}e^{jn\varphi_1} = \mathrm{V}\left(\theta_1,\varphi_1\right)$$

3 - HORN EFFECT CHARACTERISATION

The models described above permit the sound source to be defined as a vibrating surface. One can consider vibrating modes (extended source). By defining a portion of the belt of smaller size than the sound wavelength, the source can also be assimilated to a point source of volumic flow Q. Horn effect is characterised by sound pressure or sound power amplification due to a point source and by the radiation efficiency of the vibrating modes.

3.1 - Sound pressure amplification (SPA)

The first approach consists in comparing local sound pressure created by a monopole within the horn to a reference pressure. This reference pressure is chosen to enable comparison with commonly performed experiments. It is the sound pressure due to a point source of volumic flow Q, baffled with the plane surface.

Sound pressure amplifications are shown in figures 2 and 3. At low frequency the amplification is about 6 dB for the cylinder (due to its infinite length) while it is 0 dB for the sphere as it is the case for a real tyre. On the other hand in high frequency ranges the highest amplification levels obtained with the cylinder are closer to experimental results.

3.2 - Radiation efficiency (RE)

The second approach consists in comparing the total power radiated by the vibrating surface with and without the plane reflector. This permits characterisation of the radiation efficiency.

The radiation efficiency is calculated for vibration mode shapes (cylindrical for 2D case, spherical harmonics of (m,0) orders for 3D case). Results are shown in figures 4, 5, 6, 7, 8 and 9. The main result to be pointed out is that the cylinder or the sphere radiate more power with the plane surface than without). This effect is very significant for frequency ranges below the coincidence frequency for which there is no radiation in free space due to short circuit phenomenon (fig. 7). Even for frequency ranges above the coincidence frequency, there is a noticeable power amplification. This effect is due to the fact that, for a given vibrating mode, in order to fit the boundary conditions, lower order modes A_{mn} are required in the expansion. This is called ”order lowering” in [5].

In addition, as for sound pressure amplification, sound power amplification is calculated for a point source. The reference power is the total power radiated by the cylinder or the sphere without the road. Amplification levels are shown in figures 10 and 11 for different source positions. One can observe similarities between sound pressure and sound power amplification curves. Relatively high levels of power amplification are reached while for certain frequencies there is less radiation than in the reference

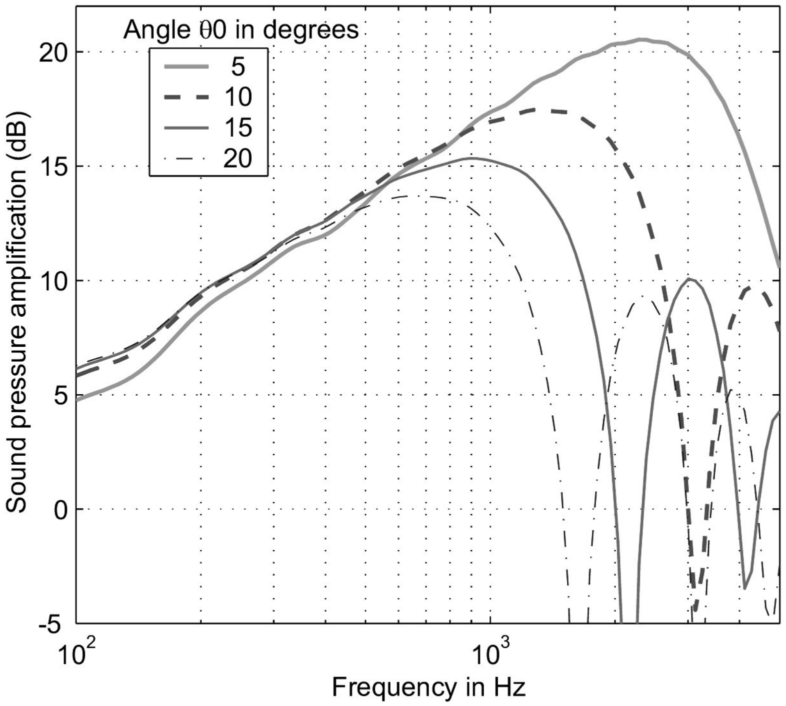

Figure 2: SPA: cylinder.

case. Because vibrating modes with the reflector are not orthogonal, there is no simple relation between vibrating modes radiation efficiencies described above and these power amplification results.

4 - CONCLUSION

Horn effect has been characterised using 2D and 3D analytical models for sound pressure prediction due to a cylinder or a sphere vibrating near a perfectly reflecting plane surface. Local sound pressure and total radiated power have been used to compare the results with the adapted reference case. It has been shown that the total radiated power is increased by the presence of the reflector. The sound power amplification levels obtained in the case of a point source require further investigations to better understand the physics of the phenomenon. The principle of analytical model described in this paper could be adapted to 3D vibrating bodies closer to tyre geometry than the sphere, oblate spheroid for example.

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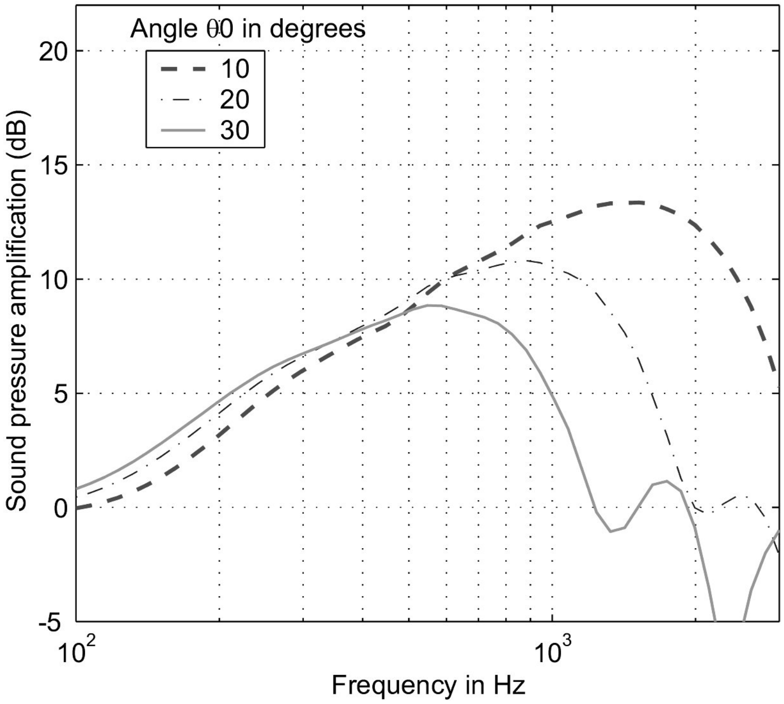

Figure 3: SPA: sphere.

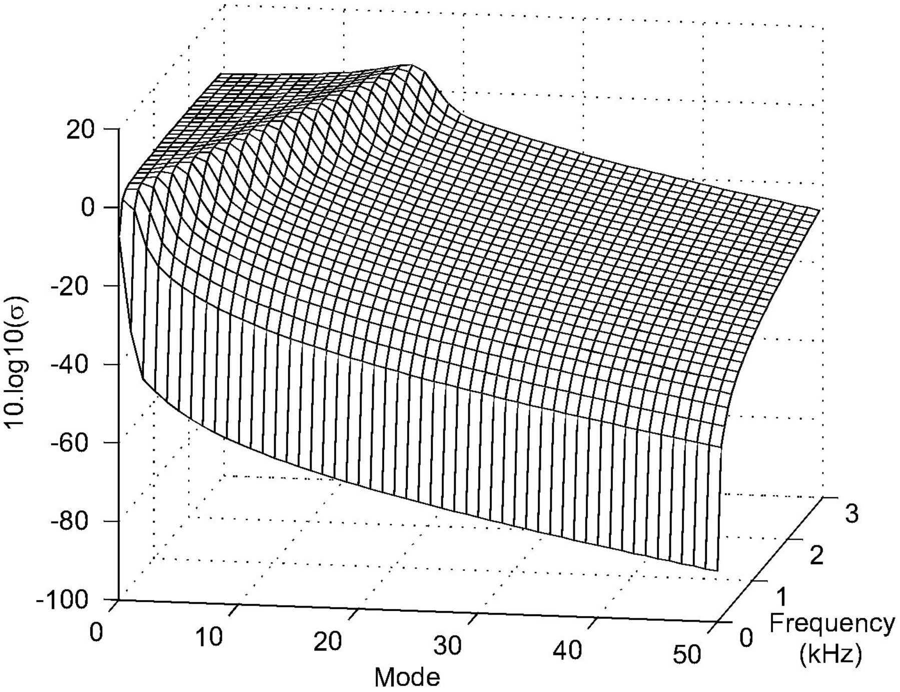

Figure 4: RE: cylinder with plane surface.

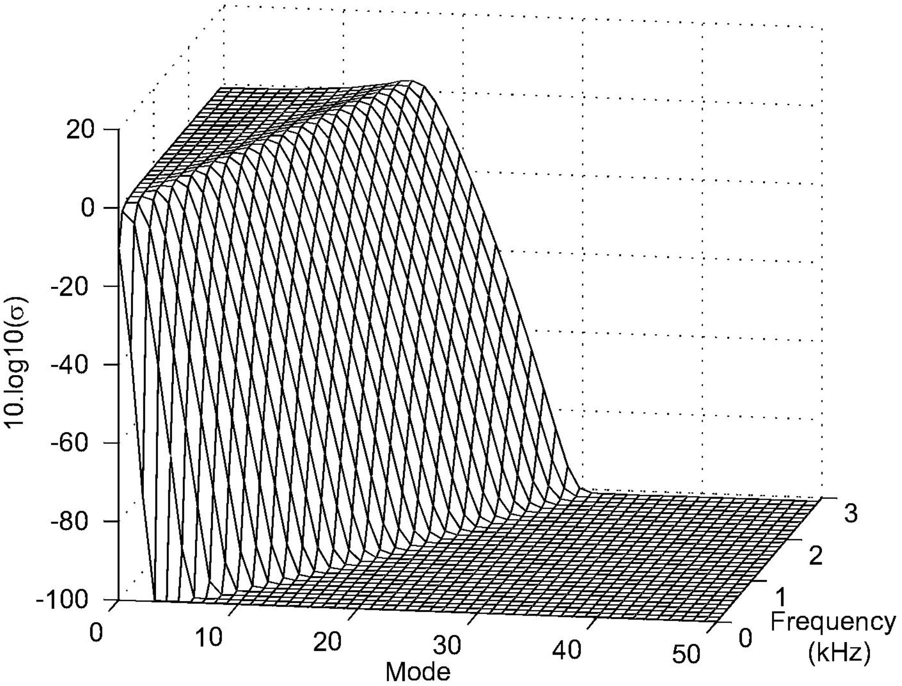

Figure 5: RE: cylinder in free space.

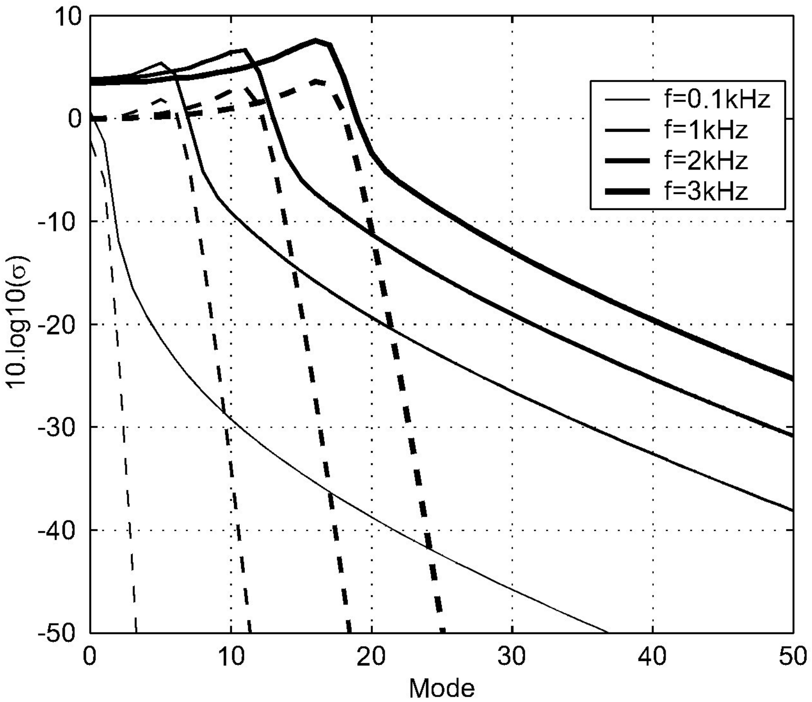

Figure 6: Details of fig. 4 – with (continuous line) and without (dotted line) the road.

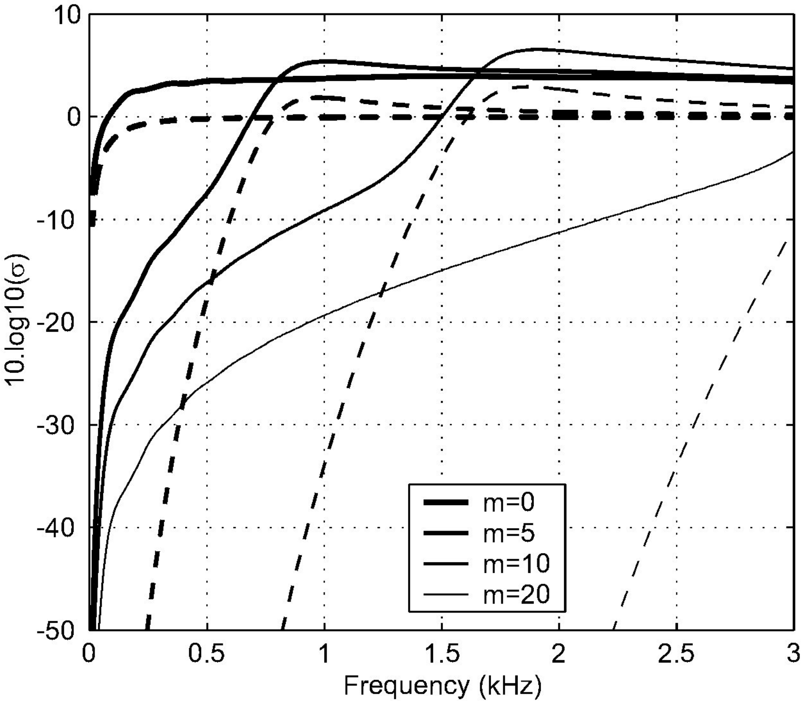

Figure 7: Details of fig. 5 – with (continuous line) and without (dotted line) the road.

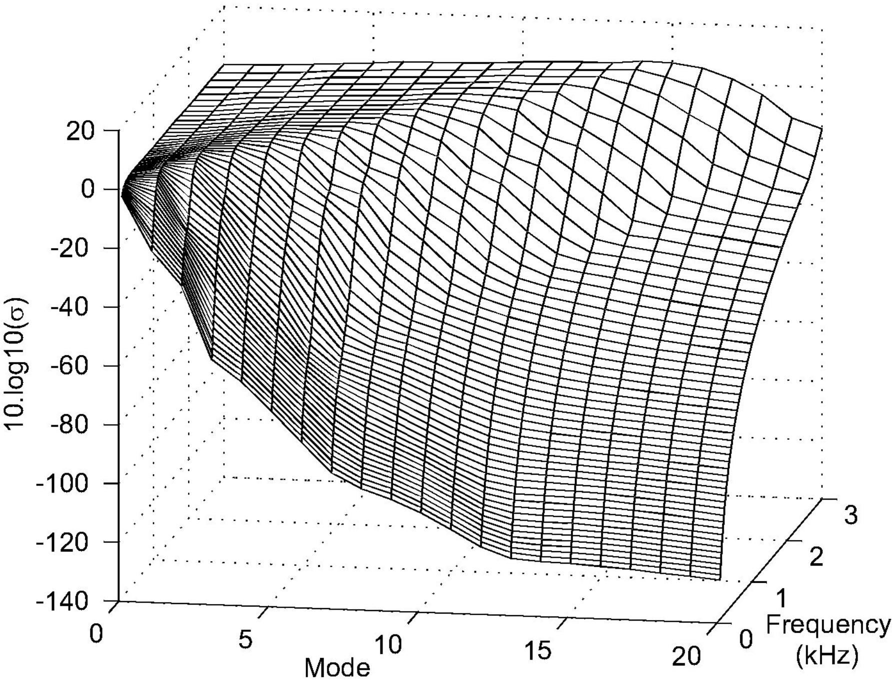

Figure 8: RE: sphere with plane surface.

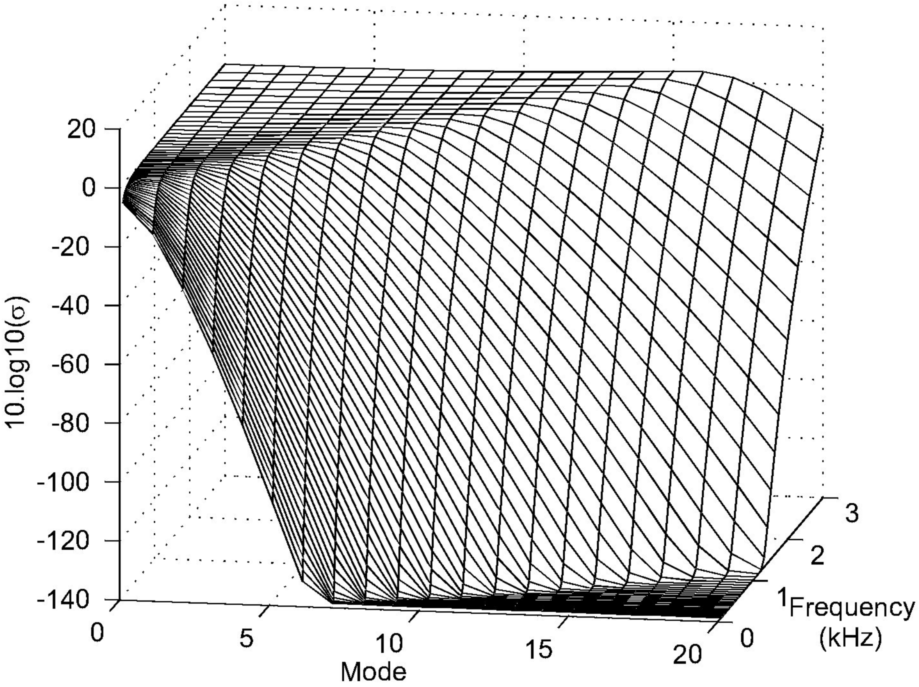

Figure 9: RE: sphere in free space.

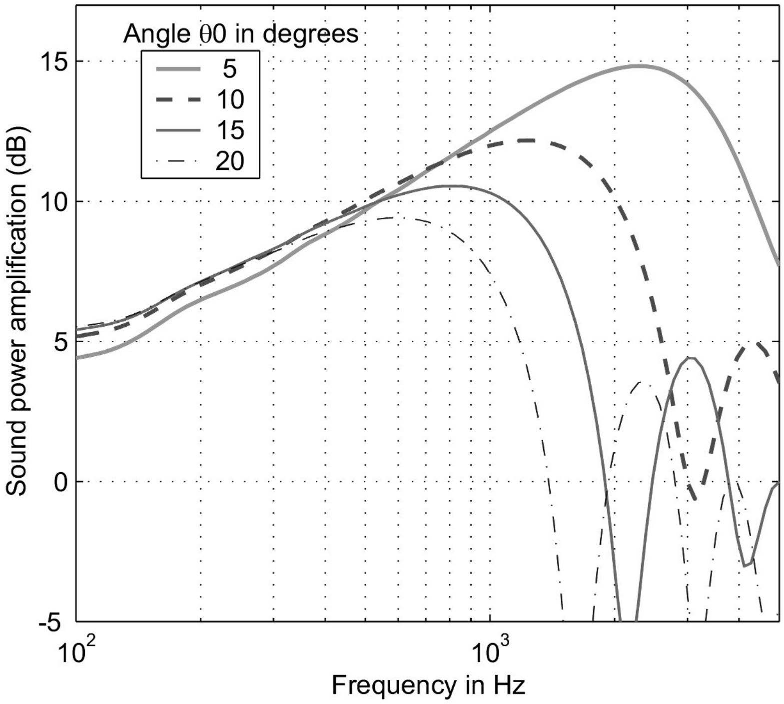

Figure 10: Sound power amplification: cylinder.

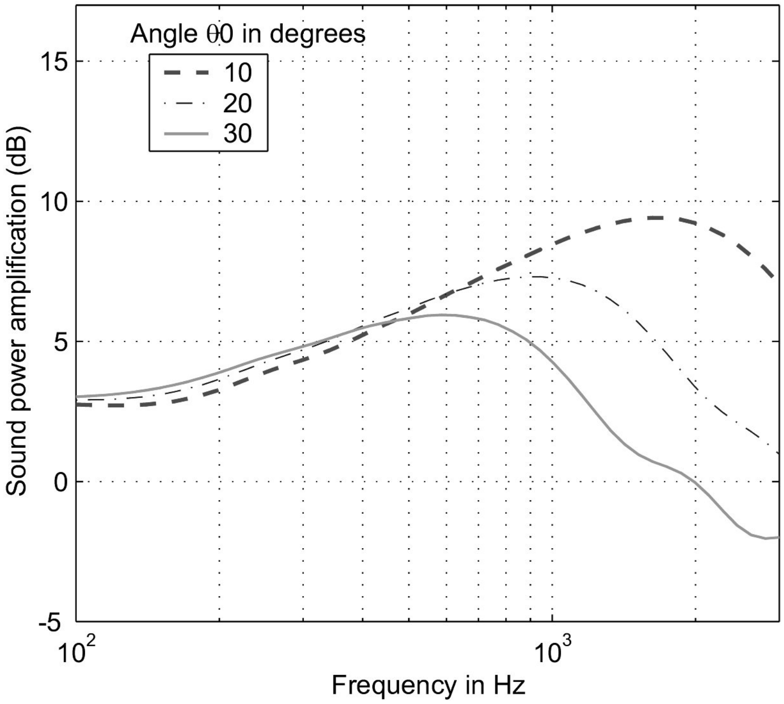

Figure 11: Sound power amplification: sphere.