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FREQUENCY RESPONSE EFFECTS OF SPECULAR VERSUS DIFFUSE REFLECTIONS

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1 INTRODUCTION

One of the main advances in the acoustical design of Control and listening rooms has been the realisation that, as well as reverberation time, the time evolution of the sound energy in the room is important. Because of this control and listening rooms are often designed to achieve a large initial time delay gap between the direct sound from the loudspeakers and the first early reflection. This allows the sound engineers and producers to listen through the system to the acoustic space being recorded. A variety of ways [1-4] have been used to achieve this based on either absorption specially shaped rooms or walls or diffusion.

The main purpose of these structures is to suppress the amplitude of early reflections in order to avoid both the psychoacoustic cues from the control room, which affect the perception of "space", and the comb filtering effects, which can degrade the frequency response and stereo image [5, 11].

The purpose of this paper is to show how the frequency response of the sound from a monitoring loudspeaker in a control room is affected by the presence of specular or diffuse early reflections. The paper will first discuss the effect of specular and diffuse early reflections on the frequency response using a simple theoretical model. It will then present simulated results and discuss the results.

2 THEORY

In order to calculate the effect of reflections one must consider the pressure and not the intensity of the sound wave. Unlike the intensity the pressure contains a phase shift, which is dependent on both the frequency (or wavenumber) and the distance the sound has propagated, in addition to the reduction of amplitude. By adding the pressure components of the different reflections that arrive at a given point the pressure at that point can be calculated as a function of frequency.

2.1 The level of the direct sound.

The pressure of the direct sound, assuming an omnidirectional source, is given by:

$$P_{direct\,sound} = \frac{Ae^{jkr}}{4\pi r}$$

where $P_{direct\,sound}$ = the sound pressure

$$k = \left(\frac{2\pi}{\lambda}\right) = \text{the wavenumber} \tag{1}$$

A = the amplitude of the source

and r = the distance from the source

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2.2 The level of specular early reflections.

The pressure levels of the early reflections are affected by both the distance and the surface from which they are reflected. The pressure of the early reflections, in the absence of absorption, can be calculated from the extra path length due to the reflection and using that distance in place of r in equation (1).

$$P_{specular\ reflection} = \frac{Ae^{jk(r_s+r_d)}}{4\pi(r_s+r_d)}$$

$$\text{where } r_s = \text{the distance from the source to the surface} \qquad (2)$$

$$\text{and } r_d = \text{the distance from the surface to the listener}$$

In general most surfaces absorb some of the sound energy and so the reflection is weakened by the interaction. Therefore the level of specular reflections will be less than that which would be predicted by the inverse square law due to surface absorption. The amount of energy, or power, removed by a given area of absorbing material will depend on the energy, or power, per unit area striking it. As the sound pressure is related to the power per unit area this means that the pressure of the sound reflected is reduced in proportion to the absorption coefficient. That is:

$$P_{specular\ reflection} = K(f)\frac{Ae^{jk(r_s+r_d)}}{4\pi(r_s+r_d)} \qquad (3)$$

$$\text{where } K(f) = \text{the reflection coefficient of the surface}$$

In general $K(f)$ will be a complex function of frequency.

2.3 The level of diffuse early reflections.

Diffuse surfaces on the other hand scatter sound in other directions than the specular [6-10]. In the case of an ideal diffuser the scattered energy polar pattern would be in the form of hemisphere. In the case of a typical diffuser which only scatters in one dimension then the polar pattern would be in the form of a cylinder. The effect of diffusers can be calculated by modelling the scattered energy as a source whose initial pressure is given by the incident pressure. Thus, for an ideal scatterer, the pressure of the reflection is give by the product of the equation describing the pressure from the source and the one describing the sound pressure radiated by the diffuser. For the geometry shown in figure 1 this is given by:

$$P_{diffuse\ reflection} = \left(\frac{Ae^{jkr_s}}{4\pi r_s}\right)\times\left(\frac{2e^{jkr_d}}{4\pi r_d}\right) \qquad (4)$$

The factor 2 in the second term represents the fact that diffuser only radiates into half a hemisphere. Equation (4) shows that diffusion offers a twofold advantage over a specular reflection. Firstly there is an initial drop in pressure due to the fact that the pressure incident on the surface is being re-radiated into directions other than the specular. Secondly there is a faster reduction in pressure as a function of distance due to the re-radiation pattern.

However the simple equation for calculating the pressure of early reflections, shown in equation (4), breaks down as one approaches the wall as it predicts an infinite level of early reflection from a diffuser at zero distance! This is due to the use of the incident sound pressure directly. In fact it should be scaled to the radiating area in the near field and this approaches zero as one gets close to the wall. Thus one must be careful to use this equation away from the wall, a distance on the order of 0.5m seems to be sufficient in practice.

3 SIMULATION AND RESULTS

The effect of diffuse and specular reflections from the walls of a 6mX4mX2.5m room were simulated using MATLAB. A two dimensional simulation was used due to the need to save computer time. The two side walls and the rear wall were either diffusing or reflecting and the speakers were assumed to be flush mounted on the front wall so that there were no reflections from it. The reflections from the ceiling and floor were not considered. The loudspeakers were mounted symmetrically 1m about the centre of the front wall and the diffuser was assumed to have a maximum depth of 20cm. Two aspects were considered and simulated:

- The intensity versus time curve at the normal listening condition for both the diffuse and specular case.
- The frequency response at the listening position for both the diffuse and specular case.

In the first case both the amplitude and time of the reflections from a single speaker were calculated. The amplitudes were calculated using intensity versions of equations (1), (3) and (4) and the times were calculated using the time of flight based on the distance plus an extra delay due to the diffuser wells. This was given by:

$$extra\ delay = \frac{2 \times depth}{c} \tag{5}$$

The diffuser wells were considered to be 10cm wide and the pressure and time for a reflection was calculated for each well as shown in figure 3. The arrival times and intensities of the three specular reflections that would arise if the walls were not diffuse were also calculated. The results are shown in figures 4 and 5 which show the intensity time curves for the case of the shorter wall as the front wall and the longer wall as the front wall respectively. Figure 4 clearly shows that the effect of the diffusing side walls is to reduce the amplitude of the reflections considerably and spread them in time as predicted. The highest reflection level for the diffuse wall is -10.25dB relative to the direct sound at that point whereas for the non diffuse wall the highest reflection is only -4.75dB lower. Figure 5 which represents the longer front wall is even better. In this case the highest reflection level for the diffuse wall is -18.5dB relative to the direct sound at the listening point whereas for the non diffuse wall the highest reflection is -8.5dB lower. This represents an improvement of 10dB for the diffuse wall over the specular wall.

In the second case the amplitude and phase of the reflections from a single speaker were calculated using equations (1), (3) and (4) for the same room configurations as the energy time curves. The results as a function of frequency are shown in figures 6 to 9 for the two different room orientations.

The results are surprising. One would expect from an examination of the energy time curves that the diffuse reflections would result in a lower level of frequency response variation due to their lower amplitude. However this is not necessarily the case as figures 6 and 7, which compare the specular and diffuse case for the first room orientation. In this case the specular case has a lower spectral variation at lower frequencies compared to the diffuse case. At higher frequencies the diffuse case is slightly better than the specular. However there are still frequencies for which the diffuse case has notches which rival that of the specular case. Note that these frequency responses represent only one point in the room and would vary with position. Figures 8 and 9 show the frequency response at the listening position for the second room orientation. For this condition the diffuse reflections show a clear advantage compared with the specular one at frequencies above 1kHz. However the low frequency variation is still greater for the diffuse compared to the specular case.

4 DISCUSSION

So diffusion can result in a reduction of the amplitude of the early reflection from a given point. However there will also be more reflections, due to the diffusion, arriving at the listening position from other points on the wall, as shown in figure 2. Surely this negates any advantage of the technique? A closer inspection of figure 2 reveals that although there are many reflection paths to the listening point they are all of different lengths, and hence time delay. Furthermore the phase reflection diffusion structure will add an additional temporal spread to the reflections. As a consequence the initial time delay gap will be filled with a dense set of low-level early reflections instead of a sparse set of higher level ones, as shown in figures 4 and 5. However this does not cause a reduction of the comb filtering effects that high level early reflections cause. Examination of figures 10 and 11 which show the comb filtering due to purely the first specular and diffuse reflection clearly show that the reduced amplitude of the diffuse reflection considerably reduces the variation in the frequency response. So what is the reason for this apparently paradoxical result?

A possible explanation is as follows. Closer examination of the arrival times of the different reflections show that the diffuse reflections are separated by very small time periods , in some cases less than a millisecond. Also bursts of dense reflections are concentrated around the arrival times that one would expect for specular reflections from the three walls. This is clear if one examines the energy time curves shown in figures 3 and 4. Reflections which have similar times of arrival with respect to the direct sound will cause a similar rate of amplitude response with respect to frequency. In other words the cluster of dense reflections will cause frequency response ripples which add constructively, resulting in a greater frequency response variation which can rival that of the equivalent specular reflections. The effect of the slight time spread will result in a "beating' of the frequency response ripples in the diffuse case compared to the specular case and this can be observed in the frequency responses shown in figures 6 to 9.

The poorer low frequency response is probably due to the fact that all parts of the surfaces are contributing to the sound received at the listening position and at low frequencies the will be highly correlated and so cause extreme response variations. However one caveat on these results is that they represent only the first reflection from the surfaces and at low frequencies the modal behaviour due to multiple reflections is likely to be more dominant.

These results do not mean that the use of diffusion should be abandoned because although the peak to peak frequency response variation may be as high as the specular case the average behaviour is likely to be better simply because more components are being added to form the effective pressure at a given point. Because of the central limit theorem this means that the likelihood of extreme frequency response variations will be less for the diffuse compared to the specular case. This means that the frequency response variation as a function of position are likely to be less extreme if the reflections are diffuse.

5 CONCLUSION

A comparison of the frequency response variation due to specular and diffuse reflections has been presented. Although diffusion results in a lower level of early reflection amplitude it, paradoxically does not necessarily result in a lower level of frequency response variation. This

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is due to the correlation of frequency response ripples due to the close time spacing of the low level diffuse reflections. However diffuse wall may result in a frequency response performance which is less critical of the listener's position in the room.

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THE REFLECTION FULL ZONE

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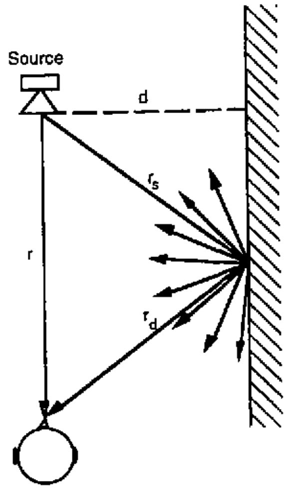

Figure 1 The geometry for calculating the pressure of an early reflection from a specular or diffuse surface

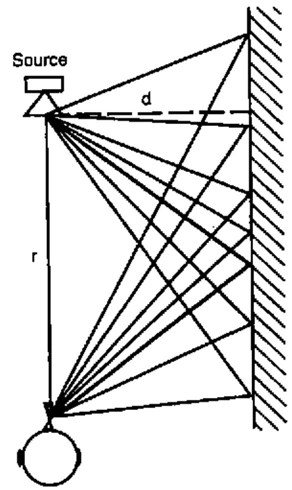

Figure 2 Additional early reflection paths due to a diffuse surface.

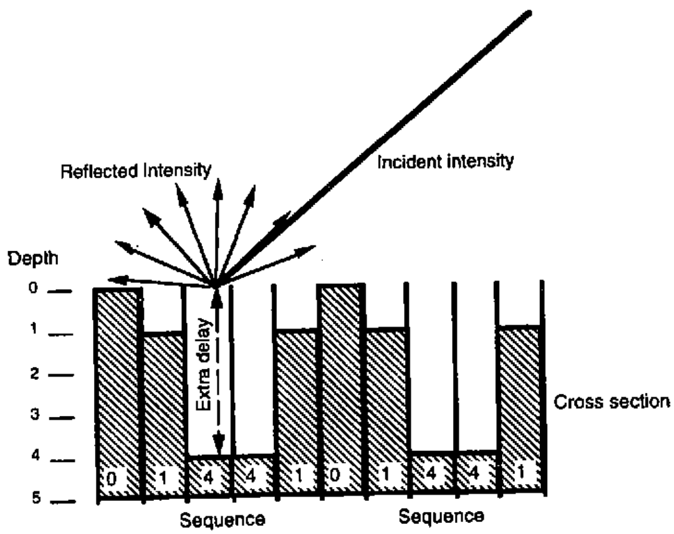

Figure 3 Geometry for calculating pressure and time from a diffuse surface.

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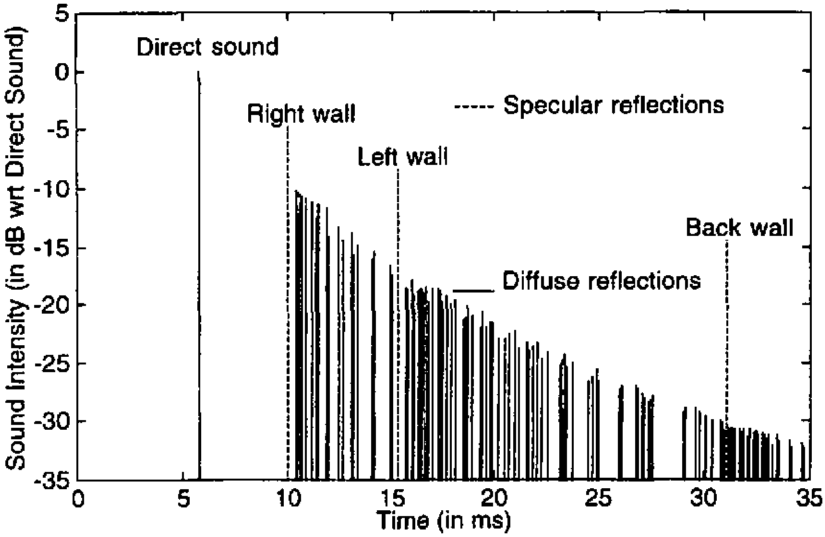

Figure 4 The intensity time curves at the listener position for room orientation 1.

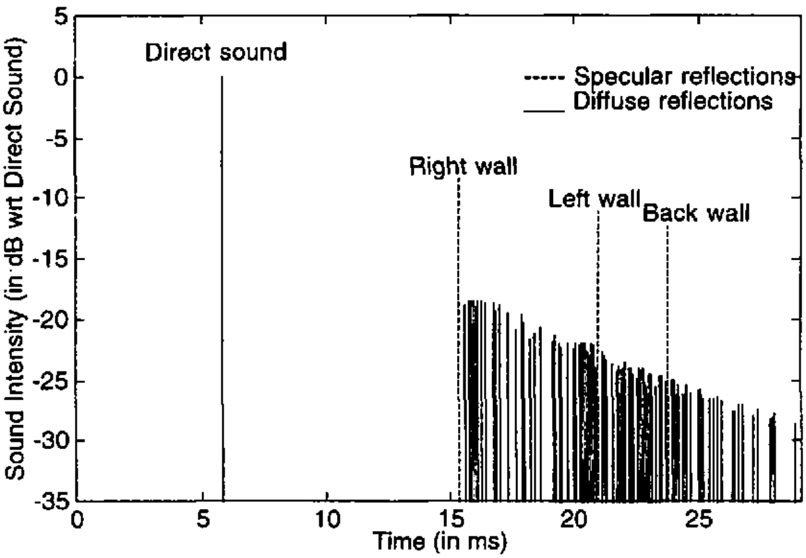

Figure 5 The intensity time curves at the listener position for room orientation 2.

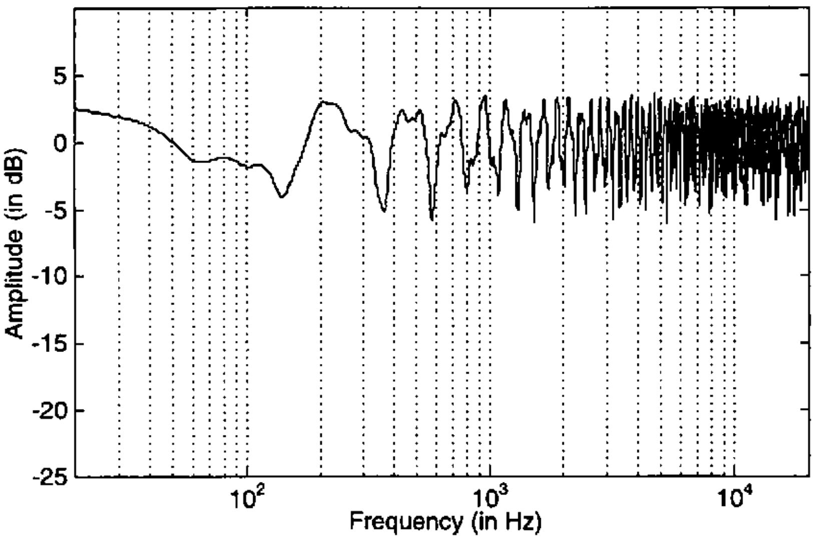

Figure 6 The specular reflection response at the listener position for room orientation 1.

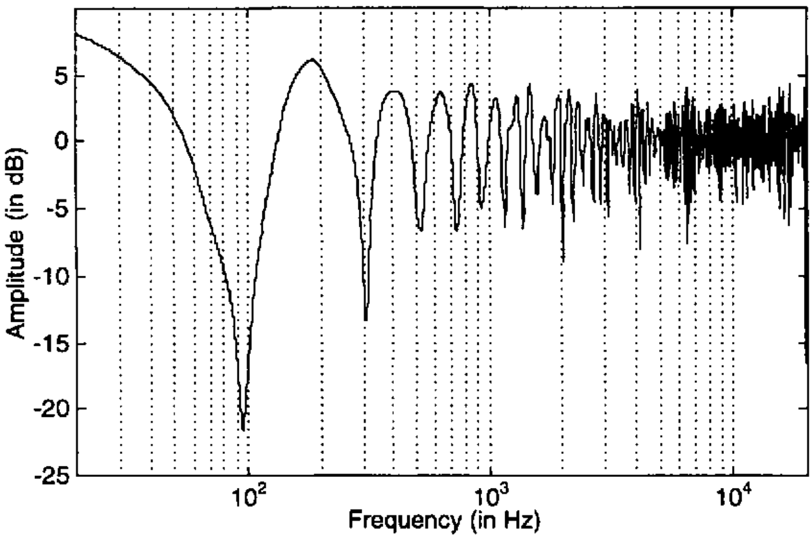

Figure 7 The diffuse reflection response at the listener position for room orientation 1.

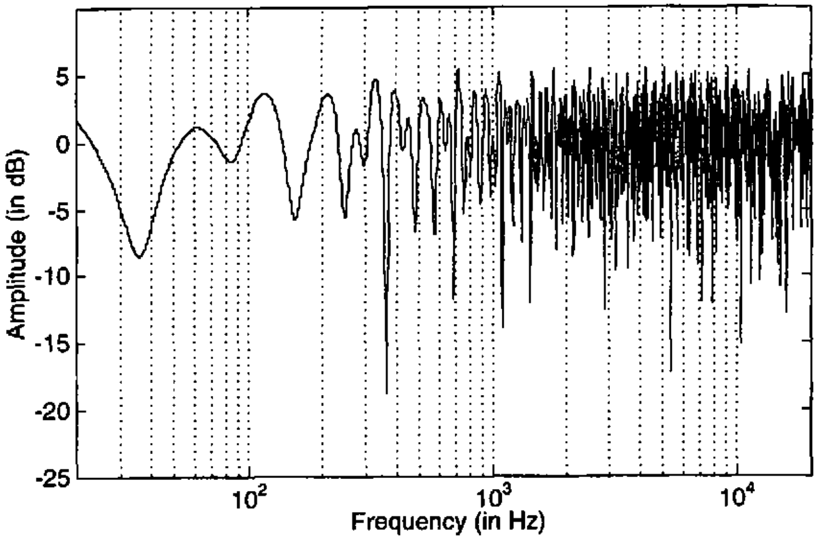

Figure 8 The specular reflection response at the listener position for room orientation 2.

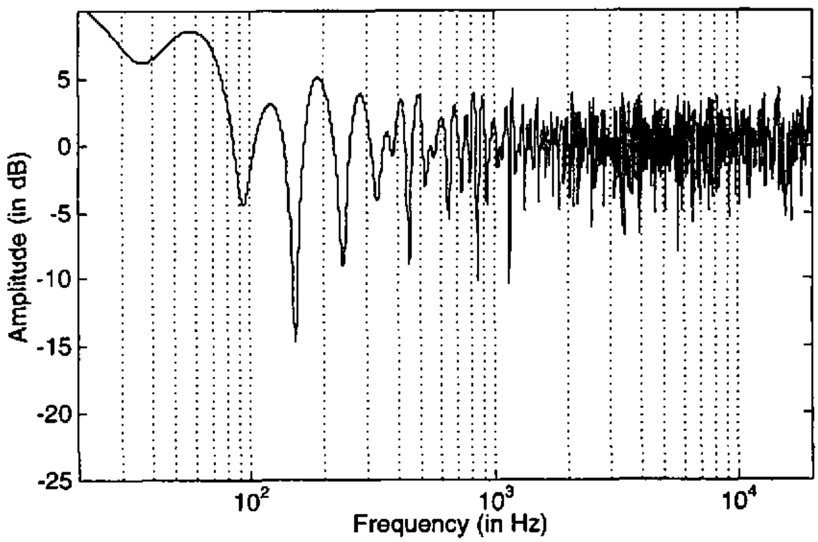

Figure 9 The diffuse reflection response at the listener position for room orientation 2.

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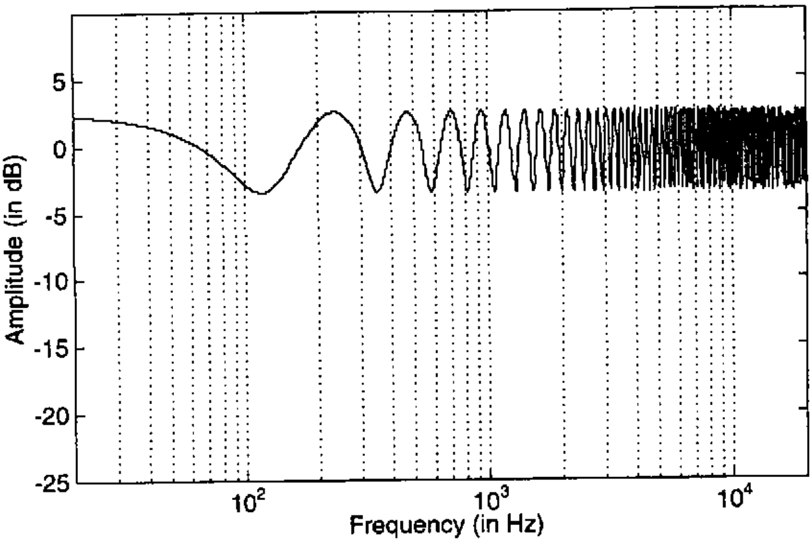

Figure 10 The first specular reflection response at the listener position for room orientation 1.

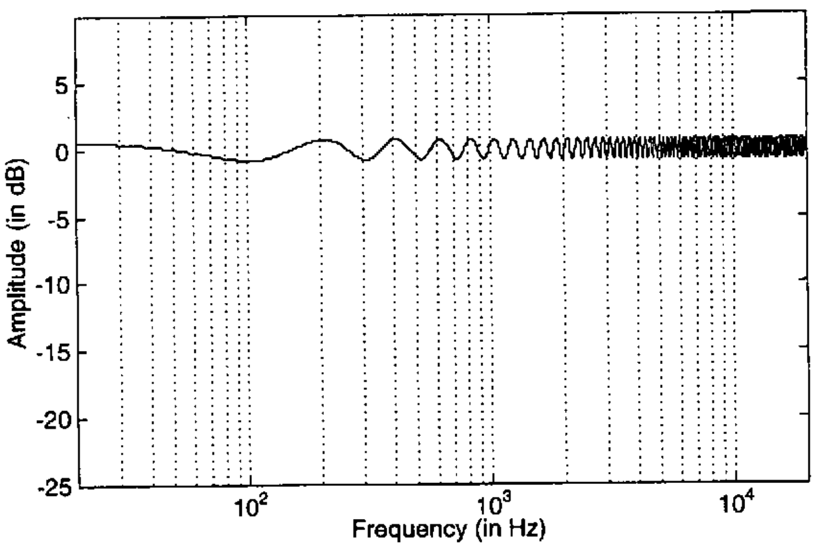

Figure 10 The first diffuse reflection response at the listener position for room orientation 1.