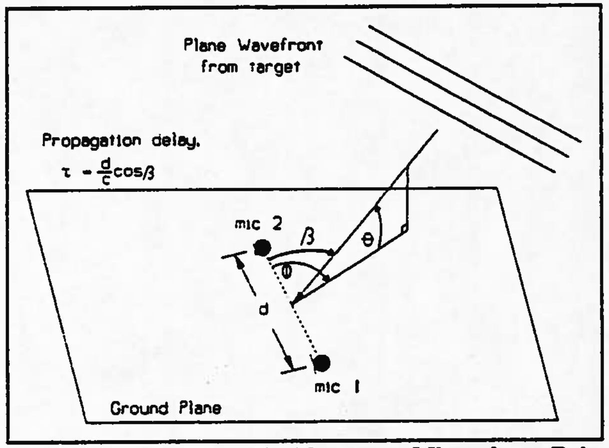

Figure 3 Acoustic Ray Incident on a Microphone Pair

PERSONAL SOUND

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1. INTRODUCTION

Introducing more and more audio/video equipment (CD, DCC, TV, CD-i etc.) into a room creates a new audio problem, one of multiple sound sources with multiple listeners. A solution to this problem would be the realisation of `Personal Sound'. When different persons, denoted as A, B, C, etc., listen to different programmes, denoted as `a', `b', `c', person A experiences programme `a' as sound and programmes `b' and `c', as noise. Each person would prefer a high Sound/Noise (hereinafter S/N) ratio at his or her listening position. This can be realised in a number of ways, using a loudspeaker array to control directivity, active noise control, or a combination of the two. Various situations, as depicted in Figures 1, 2 and 3, may occur.

Figure 1 shows two people, denoted as A and B, who both want to listen to their own programmes. This case may refer to two (multimedia) PCs in an office, or to two people watching two exhibits with accompanying sound. The latter application is considered in [1], which refers to an exhibition hall. Here, the sound source is positioned above the head of the listener, whereas in Figure 1, the sound is projected from in front of the listener. In both cases, the distance between the listener's ears and the sound source is approximately 0.5 - 1 m. while the `noise source' (ie. sound programme `b' in the case of person A) is at a distance of approximately 2m.

A different situation is shown in Figure 2, where one group of people are listening to a (HD)TV, whilst another person, sitting outside the listening area, does not wish to be disturbed by the TV sound. In this case, a constant sound pressure level (SPL) is required over the entire listening area, whilst a low SPL level is required at the position of the single listener. This problem may be solved with the aid of active noise control [2] , using microphones and loudspeakers built into the chair of person A.

A third situation is shown in Figure 3. In this case, a certain sound pressure level is required at one listener position, whereas a low SPL is required in the rest of the room. If a loudspeaker array is used for this situation, the directivity of the array reproducing programme `a' should have one sharp maximum in the direction of person A.

For these three situations, the requirements are as follows :

Figure 1: High S/N ratio, with a pleasant sound level for both users.

Figure 2: Low noise at one position, and a pleasant sound level at other positions.

Figure 3: A pleasant sound level at one position, and a low noise level at other positions.

In this paper, the situation depicted in Figure 1 will be considered, the relevant dimensions being as follows:

distance between sound source and listener : 0.5 m.
distance between sound and noise sources : 2 m.

In section 2 a target specification is derived from the results of two listening tests.

In section 3 a number of design specifications for the loudspeaker array are described, firstly for the case of no reflections (anechoic environment, section 3.2). In sections 3.3 and 3.4 the case of a real (living) room, with reflections from the walls, is considered.

If it is considered acceptable for the listener to use a microphone for detecting the sound level at his listening position, a kind of active sound (noise) control can be used. A special feature of this type of active noise control is that the noise signal is known at the source.

2. SPECIFICATION

In the situation depicted in Figure 1 person A would of course prefer the lowest possible SPL of programme `b' at his listening position. However, this is not a practical specification. In order to obtain a practical specification, two listening tests were performed. The specification is expressed in a S/N ratio, which, at listening Position A, is the ratio of the B-weighted [3] levels of programmes `a' and `b' .

In the first listening test, two TVs were placed next to each other (without separation) in front of the listener. The pictures from the two TV's were different. A loudspeaker was placed on each TV to reproduce the accompanying sound programmes. The sound of the right TV at the listener's position was set to a fixed level of 61 dB(B) . Each subject was asked to adjust the left sound signal, whilst watching the right TV picture, until the left sound signal just started to cause interference with the perception of the right sound signal. Next the subject was asked to watch the left TV picture and to adjust the volume of the left signal until the right signal started to cause interference.The difference between the two adjustments of the left signal was taken as twice the required S/N ratio whilst watching a TV programme. Different types of programmes were used: news, music and sport.

Eleven subjects performed the tests. On average, a value of 11 dB(B) was found for the S/N ratio, in this case of sound and picture. The standard deviation from this value was found to be 3.5 dB(B) for all subjects over all programmes. It is of interest to note that the standard deviation of a single subject's responses was less than the standard deviation of the group, ie. although each subject may have a preferred S/N ratio that remains roughly constant during different programmes, this ratio varies between different subjects.

The second listening test was performed differently, without pictures on the TV screens. The sound level of programme `b' was set to the level preferred by person B. The subject, person A, was asked to adjust the sound level for programme `a' so that sound programme `b' just started to cause interference . The material for the listening tests was taken from the SQAM-CD [4] . On average 20 dB(B) was found for the S/N ratio in this case of sound only. The standard deviation of the mean S/N ratios for each programme (ie. averaged over the subjects) was 2.4 dB(B).

The results of these two listening tests conclude that the S/N ratio of a reproduction system for Personal Sound in a living room or office needs to be above 11dB(B) but ideally needs to be around 20dB(B).

3. OUTLINE OF THE DESIGN OF THE LOUDSPEAKER ARRAY

3.1 INTRODUCTION

In order to realise a high S/N ratio over the full audio frequency range, the directivity pattern of the loudspeaker array at A must be adjusted in such a way that, for all frequencies, the main lobe, and therefore the maximum SPL, is in the direction of listener A. At the same time, the minimum SPL has to be in the direction of listener B. To obtain the desired directivity pattern, the mutual distances between the loudspeakers, and the amplitude and phase of each loudspeaker can be varied.

In this paper, simple one-dimensional loudspeaker arrays are considered, where the phase between the loudspeakers is the same. (An exception is treated in section 3.4, where the phase is also variable.)

The full frequency band was split up into different bands. In each band, the distance between the loudspeakers, and the weighting of the amplitude of each loudspeaker is kept constant.

3.2 DIRECT SOUND : ANECHOIC ENVIRONMENT

In the situation shown in the right hand side of Figure 6, if the loudspeakers are considered as point sources the pressure from programme `a', using the array is :

$$|p_d(A)| = 2b_1\cos\frac{kd\sin\theta}{2} + 2b_2\cos\frac{3kd\sin\theta}{2} \qquad (1)$$

where b_1 and b_2 are the excitations of the inner and outer loudspeakers and $k = 2\pi/\lambda$. In Figures $4^{a\text{-}d}$ the directivity patterns are shown for $b2/b1 = 0.4$ and for various values of d/λ (4^a $d/\lambda = 0.2$, 4^b $d/\lambda = 0.4$, 4^c $d/\lambda = 0.6$, 4^d $d/\lambda = 0.8$). Figure 4 shows that with a relatively simple array it should be possible to realise, in the situation shown in Figure 1, an S/N ratio much larger than 30dB in a limited frequency range.

Table I shows some results deduced from calculations for a specific case of four loudspeakers. For these calculations, the loudspeakers were taken as point sources. Since the distance to the array was not much larger than d, the distance between the loudspeakers, Equation (1) was not valid, and therefore the calculations were performed numerically. The ratio of the SPL from programme `a' at A and B (ref. Figure 1) is the S/N ratio. The excitation of the outer two loudspeakers is 0.4 times the excitation of the inner two loudspeakers.

Table I Calculated S/N Ratios

Frequency (Hz)	d/λ	S/N in dB	d/λ	S/N in dB
	d = 0.26m		d = 0.53m	
300	0.23	19	0.46	34
400	0.31	27	0.62	36
500	0.39	42	0.78	16
600	0.47	42	0.93	8
700	0.54	45	1.09	8
800	0.62	45		
900	0.7	29		
1000	0.78	17		

In this example a simple array of 4 loudspeakers was considered. Since the value of d/λ is the essential parameter in determining the directivity pattern, more than four loudspeakers are acceptable at higher frequencies. However, at low frequencies, the width of the total array would be too large for a normal TV set, for example, in the situation discussed in Table I, where $d/\lambda \approx 0.5$, the total width of the array is already 0.8 m.

It can thus be concluded that for the situation depicted in Figure 1, a S/N ratio substantially larger than 20 dB(B) can be reached in an anechoic environment with a four loudspeaker array in a limited frequency range. At low frequencies in order to obtain a good focusing, the dimensions of the array become unpractically large, also it can be seen from Table I that the S/N ratio decreases for values of d comparable to the distance between the listener and the loudspeakers.

3.3 REVERBERANT ENVIRONMENT

Obviously, the reflections of the sound in a room will lower the S/N ratio obtained in an anechoic environment. The main parameter in determining this is the ratio r/r_r, that is, the quotient of the distance between the listener and the source, where the reverberation radius r_r is the distance from the source to the point where the levels of the direct and reverberant sound are equal.

Another parameter is the amount, by which, the reverberant sound field is diffuse. As far as this effect is concerned, the focusing of the direct sound of the array A toward listener A will, in most cases, also lead to a focusing of the reverberant sound field. This will hold especially for some early reflections.For a living room with dimensions 7x4x3 m^3 and a reverberation time of 0.3 secs , a rough estimate of the reverberation radius is $r_r \approx 1m$ [1].

In practical situations the reverberation radius will be longer for higher frequencies (as absorption is stronger at higher frequencies) , which will result in a higher direct to reverberant ratio for higher frequencies. The experiments described in section 4 were performed a room with dimensions of approximately 9.3 x 6.3 x 8 m^3 with r_r = 1.2 m for 100Hz and r_r = 1.5 m for 1000Hz .

The S/N at position A can be calculated as follows:

$$\frac{S}{N} = \sqrt{\frac{p_d^2(A) + p_r^2(A)}{p_d^2(B) + p_r^2(B)}} , \qquad (2)$$

where p_d and p_r denote the direct and reverberant pressure respectively. Equation (2) can then be approximated by:

$$\frac{S}{N} \approx \sqrt{\frac{p_d^2(A)}{p_r^2(B)}} , \qquad (3)$$

if $$p_d^2(A) \gg p_r^2(A) \qquad (4)$$

and $$p_r^2(B) \gg p_d^2(B) . \qquad (5)$$

Equation (4) is easily satisfied if A is close to the loudspeaker array, that is, far inside the reverberation distance r_r of the room, or if the array is strongly directive.

[1] Equation V.38, p. 118, H. Kuttruff, Room Acoustics, Applied Science Publishers Ltd (1973).

In the case where Equation (5) is satisfied, the reverberant term in the denominator of Equation 2 is the dominant noise source and increasing the directivity of the array will give only a modest improvement of the S/N ratio. Equation (2) implies that in order to obtain a maximum S/N ratio between A and B, it is not sufficient just to maximise the directivity of the array; this is true for anechoic conditions only. It may be advantageous to have a dip in the polar pattern in the direction of a strong reflective surface.

3.4 MICROPHONE AT LISTENER POSITION

From what has been said in the preceding sections, it is clear that the main problems in realising a high S/N ratio are in the low frequency region. These main problems are the previously mentioned problems of a large array and lower absorption in a real room at lower frequencies. One solution for these low frequency problems may be active noise control. The theory behind active noise control clearly shows [2] that it works much better at low frequencies than at higher frequencies. However, a prerequisite for successful active noise control is the use of a microphone. In the situation depicted in Figure 1, where listener B considers programme `a' to be noise, the noise level can be reduced by applying the signal `a' to loudspeaker B, such that at position B it is equal in magnitude but with reversed phase. Since the distance from loudspeaker B to listener A is four times larger than to listener B and the signal `a' at B is much smaller than at A, the distortion of the sound field of signal `a' at A by the active noise control will be small.

As an example, let us assume that in a small frequency band, the S/N ratio for programme `a' is 14dB, then, by applying a signal `a' via an omnidirectional loudspeaker B, such that at listener position B its magnitude is equal to the signal `a' from loudspeaker A, an increase of 0.4 dB occurs at listener position A.

4. EXPERIMENTS

4.1 EXPERIMENTAL SET-UP

The audio frequency band was split into a number of smaller bands, and in each band a fixed array configuration was used. Each array consisted of four small loudspeakers, type Philips PSS297, mounted in small closed boxes. The amplitude of the signals to the two outer boxes was 0.4 times the amplitude of the inner boxes. The distance between the two loudspeakers was such that at the centre frequency of the band under consideration, $d/\lambda \approx 0.5$. Table I shows that in order to obtain a large S/N ratio (over 30 dB) under anechoic conditions. the value of d should be such that $0.39 < d/\lambda < 0.62$.

The configuration of the measurements is shown in Figure 6. When noise was applied to the array at A the S/N ratio was obtained from the difference between the SPL values at A and B.

4.2 EXPERIMENTAL RESULTS

4.2.1 Anechoic Room. The frequency band 360-5000 Hz was split into six bands. Table II shows the relationship between the centre frequency and the distance between the loudspeakers.

Table II. Loudspeaker array in an anechoic room.

Frequency Band	Distance d, cm
400 (⅓ octave)	42.9
500 (⅓ octave)	34.3
630 (⅓ octave)	27.7
800 (⅓ octave)	21.5
1250 (octave)	13.7
2500 (octave)	9

For each band the measured S/N ratio was larger than 30 dB. Over the full band of 360 - 5000 Hz the S/N ratio was 34dB(B). A recording was made using multitrack techniques. Music was reproduced via an array at position A, which interfered with a speech signal reproduced by a single loudspeaker at B. The volume of the speech signal from loudspeaker B was such that, using noise, the SPL value from loudspeaker B at listener position B is equal to the SPL value of the array at A at listener position A. The recording will be reproduced at the conference.

4.2.2 Real Room. Since the experiments in the anechoic room had yielded a S/N ratio greater than 30dB(B), the next experiments were done in a reverberant environment. The first experiments were done in a studio with dimensions of 9.3x6x3.8 m^3 with reverberation times T_{60}(500 Hz) = 0.3 sec, r_r(100 Hz) = 1.2m and r_r (1000 Hz) = 1.5m. The frequency band 200-5000 Hz was split into five bands, corresponding to five fixed arrays.

Table III. Loudspeaker array in a real room

Frequency Range, Hz	Distance d, cm
205 - 579	36.7
579 - 729	30.5
729 - 1150	18.5
1150 - 2900	9
2900 - 5000	6

The results for the S/N ratio are plotted in Figure 7 as a function of frequency, averaging the levels in 1/24 octave bands.

A recording was made using a microphone at listener position B with music reproduced via the array at A and speech via the loudspeaker B. This recording will be reproduced at the conference.

Figure 7 shows that for frequencies ≥ 1500 Hz the target of S/N ≥ 20dB is reached. However, this is not the case for frequencies ≤ 1000Hz . Summation of the contributions from each of the individual bands gives a S/N ratio of just over 20 dB(B) .

In order to obtain a S/N ratio larger than 20 dB at low frequencies, a very simple active sound control experiment was performed. With the aid of a microphone at listener position B a noise signal from the array, positioned at A, was simulated in 1/24 octaves, using 5 sine tones. This same simulated noise signal was then applied to loudspeaker B, so that the SPL value at the listener position B was the same as the level from the array. The phase of the signal applied to loudspeaker B was determined by minimising the total SPL value at B. The obtained increase in S/N ratio (in a 1/24 octave band) is plotted in Figure 8 as a function of frequency.

5. CONCLUSIONS

With respect to the situation depicted in Figure 1, in the case of two persons in a living room listening to two different sound programmes, it appears to be possible to reduce the levels of the programmes to a point where they no longer cause interference with each other.

The results of the listening experiments described in section 2, show that the difference of the sound levels of the two programmes should be about 20 dB.

Using a simple loudspeaker array consisting of four loudspeakers in each frequency band, and using 5-6 frequency bands, a difference of over 30 dB can be realised in an anechoic environment. In a `real-room' a difference of 20 dB(B) can be obtained under certain conditions.

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7. ACKNOWLEDGEMENTS

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8. FIGURES

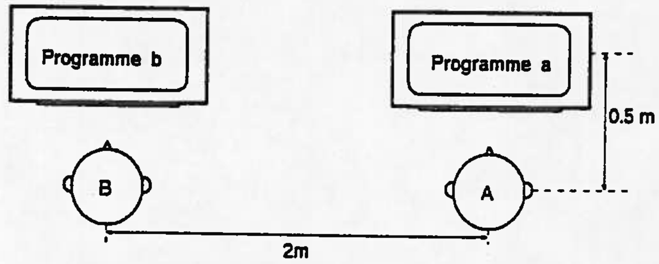

Figure 1 Two people, both wanting to hear their own programmes.

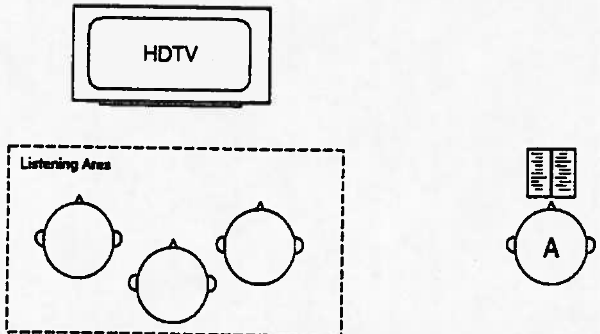

Figure 2 One person not wishing to be disturbed by a group of listeners.

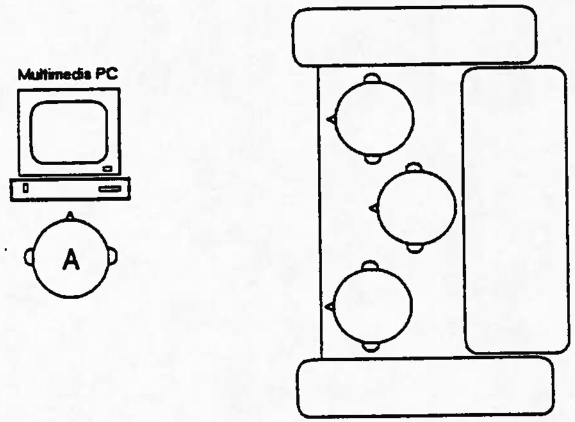

Figure 3 One listener required not to disturb the rest of the room.

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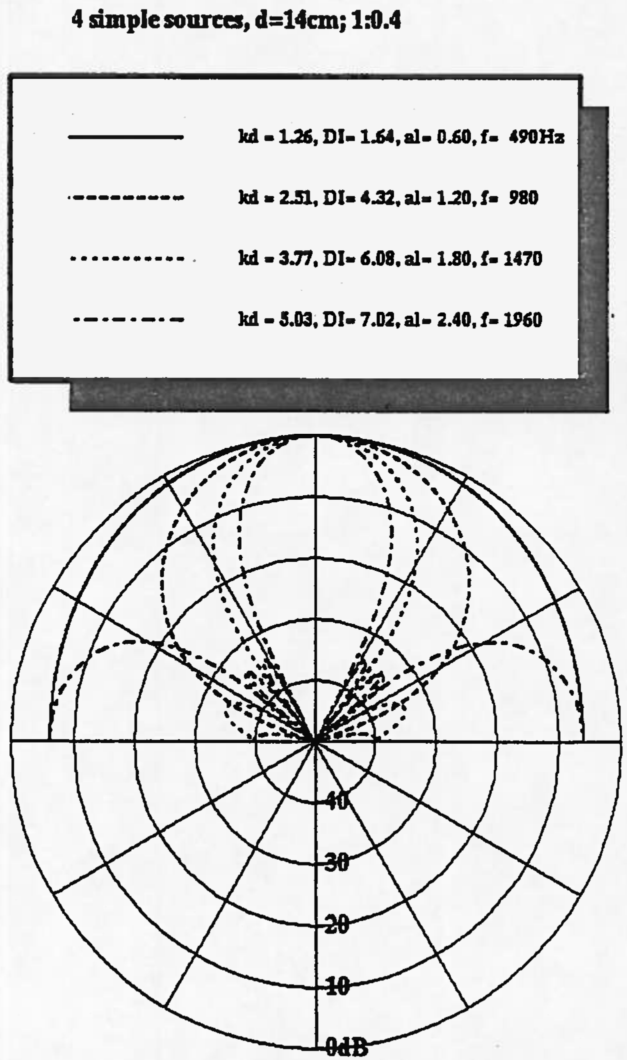

Figure 4 Polar plots for various values of d/λ

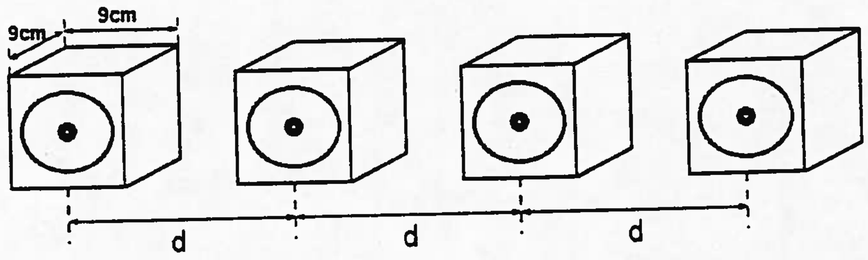

Figure 5 Typical four-loudspeaker array used in experiments.

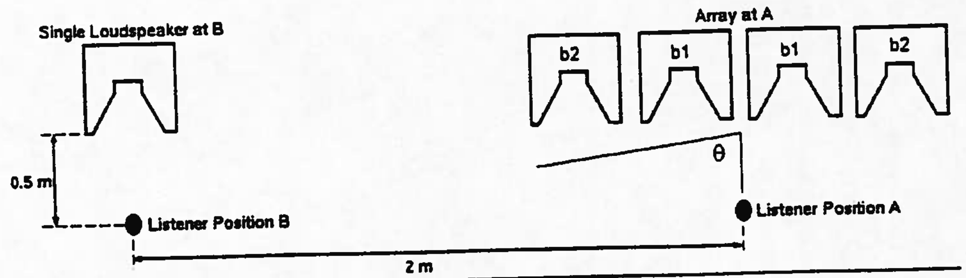

Figure 6 Method used for deducing S/N ratio.

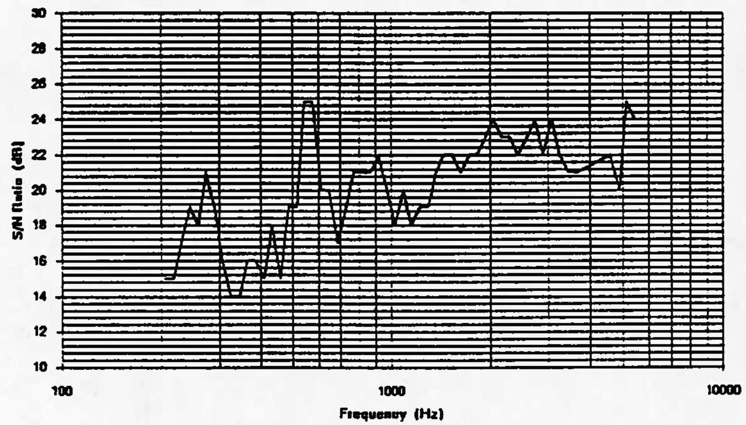

Figure 7 S/N Ratio for real room.

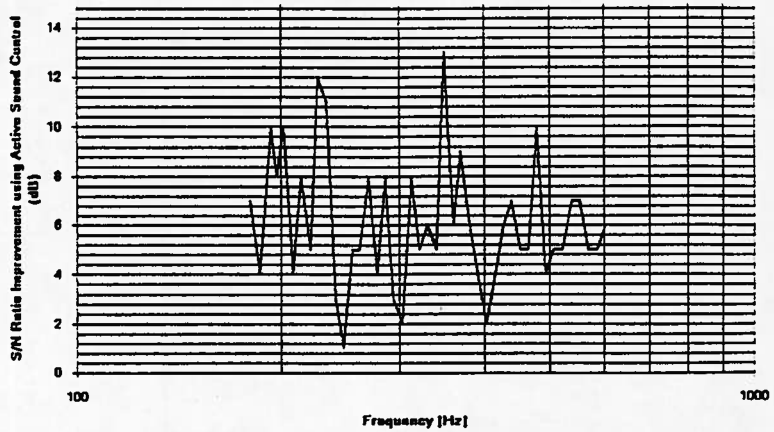

Figure 8 Improvement gained by using Active Sound Control.