Improvements in Intelligibility through the Use of Diffuse Acoustic Radiators in Sound Distribution 4634 (K-4)

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Improvements in intelligibility through the use of diffuse acoustic radiators in sound distribution

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Abstract

The unique sound generation and radiation characteristics of distributed mode panel loudspeakers (DML) are shown to produce improved intelligibility under given listening conditions. The improvement mechanisms are investigated and are shown to be related to a number of unique features of this new type of radiator including transient response, synergetic decay, lower inherent distortion, the directivity and the diffuse nature of acoustic radiation.

1 Introduction

In distributed sound systems, the desired goal is to produce as even a coverage as possible both spatially and spectrally. That is a minimum variation in terms of sound pressure level (or more correctly, early sound energy arriving within 35 to 50 mS of the direct sound) and frequency response. Conventional, pistonic devices exhibit the well known limitations of falling power response with increasing frequency and narrowing of acoustic radiation (coverage) angle with increasing frequency. [resulting in increasing directivity (Q)]. They also exhibit essentially spherical (or hemispherical) radiation resulting in an inverse square law sound pressure level fall off with increasing distance from the source.

By contrast, the unconventional acoustic behaviour of a recently developed loudspeaker technology, namely Distributed Mode Loudspeaker (DML) would appear to overcome these problems and offer a new technology for improved sound distribution. DML theory facilitates the design of essentially planar radiating elements with a unique set of properties. They combine a flat power response characteristic with an essentially constant wide directivity, significantly augmented by a theoretical intensity fall off rate that initially follows a linear rather than inverse square law. The inherently lower potential distortion of the radiating mechanism and fast transient response results in a signal broadcast with very high clarity. The diffuse nature of the radiation also suggests a lower degree of boundary interaction and spectral interference.

Based on the above theoretical considerations and the subjective view expressed by a number of observers that distributed mode panel loudspeakers appeared to be able to produce better speech intelligibility than conventional cone devices, a series of investigations was carried out to examine this. Tests were carried out with the devices operating both in isolation and in combination and compared to traditional cone transducers. A number of parameters were investigated and comparisons made between the technologies under different listening environments.

A series of experiments was performed to compare the potential for intelligibility improvement with this new technology as compared to conventional practice. A double blind technique was adopted for the subjective tests. A mock up of a ceiling surface was constructed and comparisons made between different loudspeaker types under controlled conditions.

To complement the subjective intelligibility tests, comparisons were made with recognised objective measures such as STI and modulation transfer functions as well as the more traditional % alcons and C50/C35 early to late ratio scales.

2 Introduction to Distributed Mode Loudspeaker Technology

Bending Wave Radiators and Distributed Mode

Bending behaviour in plates and related panels is extensively documented [1,2,3] Generally the theoretical work has been concentrated on the control of such bending to minimise the transmission and radiation of sound energy.

The solutions to the bending wave equations are complex and depend critically on the boundary conditions. Many conditions have been worked out.

In contrast to theoretical, exact numerical solutions, an empirical approach using statistical methods can be useful at high frequencies, where the short wavelength results in a high bending wave density which can be modelled on the basis of power distribution.

Historically a number of attempts have been made to construct effective loudspeakers using quasi -rigid panels operating partly or largely in bending. Bending wave operation over part of the frequency range is trivial, many diaphragms suffer departures from the intended pistonic operation enter bending and possess areas of operation where bending holds.

Any panel may be set into vibration to radiate sound power. Generally at high frequencies, if the losses are low and if the bending stiffness is sufficiently high, dense vibration will be supported, potentially well distributed over the surface of a free boundary plate. At lower frequencies a panel or plate will have characteristic pronounced modality with discrete dominant resonances accounting for much of the radiated power. (see figure 1).

All designers of panel speakers have faced this lower range behaviour which constitutes a major problem when fabricating a wide range bending wave acoustic radiator. Many empirical solutions have been devised with varying degrees of success but to the authors' knowledge, none have hitherto addressed the problem directly, nor have theoretical solutions been defined which suppress the characteristic resonances sufficiently to define a practical wide band loudspeaker using bending wave panel radiation.

In the case of the DML or distributed mode loudspeaker, solutions have been defined for groups of bending wave equations which in conjunction with calculated points of optimal excitation, determine an essentially uniform power distribution with frequency. Extending into the lower frequency range, useful output is available within an octave of the lowest bending frequency for the panel. The latter may be readily placed well below the required working range. (see figure 2).

From a theoretical standpoint some difficulties remain. Any practical panel exhibits coincidence, a specific frequency where the wave speed in the panel matches that in the air and strong coupling occurs at a near tangential radiating angle. Above coincidence any size of panel whether finite, free edge or clamped, radiates sound freely. Below coincidence first inspection of classical radiation theory inconveniently suggests that an infinite plate is required for significant radiation.

Fortunately further analysis confirms that for a finite plate the boundaries represent significant discontinuities which do radiate useful sound power. Overall an eight octave band pass is possible for a DM panel loudspeaker.

Fundamental to the design is the equation describing wave speed in the panel

speed , $\quad v(\omega) = \sqrt{\omega}\,.(B / \mu)^{1/4}$

By inspection the wave speed varies with frequency, thus describing a dispersive medium, i.e. the wave shape is not held during propagation. [B = Bending Stiffness, μ = Surface Density]

When designing for wide range distributed mode operation the following have to be taken into consideration:

Surface density
Bending stiffness
Geometry - aspect ratio
Surface area
Location of drive point[s]
Transducer parameters [typically 4 components]
Shear modulus of core
Internal damping and its function with frequency
Edge termination and suspension method

If these parameters are inappropriately chosen, the resulting panel will radiate sound, but the modal distribution will be so irregular as to produce an uneven acoustic output with frequency. In addition the low frequency range will be unnecessarily curtailed.

Some intriguing properties are exhibited by the Distributed Mode acoustic panel or diaphragm. Consider a pistonic derivative speaker. This has a reactive mechanical impedance seen at the driving point. The moving assembly has properties of moving mass, overall suspension compliance and mechanical resistance. These affect the resulting frequency response and ultimately limit bandwidth and performance.

In particular above resonance there is only a narrow portion of the range where a flat acoustic output with frequency is obtained for the usual constant input voltage. This is called the mass controlled region. Constant voltage and thus constant current i in the motor coil results, constant force F giving constant diaphragm acceleration with frequency. It is under mass control, M. The air load impedance is reactive in the low frequency range where kr is below 2.

$F = Ma = Bli$

where r is the piston radius, B the flux density, l the coil wire length immersed in the magnetic flux. Thus the acceleration,

$a = Bli$

and is independent of frequency.

Under this condition the velocity of the 'piston' falls with frequency complementing the reciprocal rising component of the air load.

For kr greater than 2, typically 300Hz, equivalence fails and the usual narrowing directivity due to finite source size results in the familiar rising axial frequency response (see figure 3). By contrast the bending wave panel exhibits a directivity at higher frequencies which is typically wide [160 degrees] and varies little with frequency. (see figures 4a & 4b).

Bending waves couple resistively to the air load while the panel, if well designed, has a dense modal structure. The mechanical impedance closely approaches a non reactive transfer function i.e. the mechanical impedance of a DM panel is itself purely resistive.

Where R is the mechanical resistance of the panel we can use

$F = Rm.U,$

also $F = Bli$

Thus the velocity $U = Bli / Rm$

A constant voltage into this device provides constant current and constant velocity. This is the drive required for a resistively coupled air load to generate a flat power response with frequency.

For a low loss panel, most of the mechanical input power is delivered to the air load, typically 95 to 98% of that of a pure piston of the same driven area.

Consequently the DM panel has the potential of a naturally flat frequency amplitude frequency response, where there is no upper bound.

In practice residual inductance in the transducer coil and limitations in panel build, for example skin stiffness , mass and core shear, limit the upper range to between 25 to 30kHz. Again, available panel materials naturally define a low frequency limit where design for an impracticably low first bending frequency results in a panel which does not show good energy coverage all over its surface to the highest frequencies. Practical material science results in panels with good uniformity and radiation properties over an eight octave frequency range, this is unprecedented for a single radiating element.

One analytical approach considers the panel as randomly vibrating.

The solution for mechanical impedance of a simple elastic plate is :

$$Zm = Eh^3 / [12(1-\delta^2)]$$

where δ is Poissons ratio, E is Young's Modulus, and h is the plate thickness.

The power in the plate is a function of velocity squared. Assuming near lossless coupling to the air load impedance, the criterion of a flat power response with frequency is attained by constant velocity excitation.

For a resistive mechanical impedance such as a randomly vibrating plate an electromagnetic transducer supplies the required drive without adaptation.

While the term randomly vibrating is an approximation of the real behaviour of wide range panel such as DML, it is a good starting point. Sound radiation from a DML is largely non directional, and emanates from the equivalent of numerous multiple sources sited all over the panel. Such radiation may be termed diffuse and this has significant implication for sound distribution.

Advantages of Diffuse Sources

i. Boundary interaction

While approximating point source, coherent radiators suffer specular reflection from low loss local boundaries with comb type interference patterns, the diffuse source benefits from diffuse reflections whose sound power can add constructively with direct output and where comb filter effects are largely suppressed.

ii. Multiple sources

For a given observer position the arriving signals from multiple sources will have differential delays resulting in comb type interference patterns in sound intensity with frequency. These will be a function of source placing and observer position.

For a diffuse source there is effectively a complex random array of multiple sub sources for which no significant comb filter effect can be generated between sound panel units for any moderate spacing or observer position.

iii. Off axis radiation

Simple cone type speaker systems are pistonic or semi pistonic and possess a radiation angle which narrows strongly with increasing frequency above a few kHz, depending on the effective size of source. (see figure 3)

For a typical ceiling mounted system, an observer located 2m away will be located well off axis and generally endures a significantly modified frequency response, generally a substantial curtailment of the upper frequencies. In consequence several aspects of sound quality are degraded, apparent coloration is increased, while clarity, articulation and intelligibility are impaired. These effects are particularly apparent for standing observers auditioning speakers in an average ceiling height of 2,7 to 3.3m.

In the case of the bending wave panel, its largely diffuse higher frequency radiation characteristic produces a well maintained high frequency level and distribution at relatively extreme off axis angles. In theory at least such a speaker, if of sufficient primary quality, should result in superior sound quality over a wider area of distribution.

3 Subjective Listening Tests

In order to establish whether the apparent improvements in intelligibility, informally reported from observers listening to DM panel loudspeakers in isolation, were in fact correct and statistically meaningful, a series of formal listening tests using a panel of listeners was carried out. The initial tests reported here were based on a double blind format. A listening panel of six listeners was employed. Three conventional cone loudspeakers and a Distributed Mode panel loudspeaker were mounted in a typical office ceiling but totally disguised with a black, acoustically transparent loudspeaker cloth. The office had a conventional acoustic tile grid ceiling and carpeted floor making it fairly dead and resulting in an average reverberation time of 0.2 to 0.25 seconds.

The three conventional loudspeakers employed were all industry standard units and selected for their reportedly wide sound coverage and large price range. (price ratio was 4 to 1 from the least to most expensive). Loudspeaker A) was 6 inch single cone unit mounted directly to a 600 mm (2 ft square tile size) baffle board. Loudspeaker B) was a co-axial 8 inch unit, again mounted directly to the baffle board. Unit C) was a Distributed Mode Loudspeaker, fabricated to directly fit into the ceiling grid. Loudspeaker D) was a 4 inch driver mounted in a matching enclosure which was then mounted to the baffle board.

The ceiling height was 2.4 m. The listening tests were carried out with the panellists standing both directly under each loudspeaker (ie on axis) and also to the side 1200 mm (4 ft) away - equivalent to an angle of approximately 50 degrees off axis. Due to the low reverberation time and general acoustic conditions, all the loudspeakers were expected to produce a high intelligibility score. Therefore for the initial experiment, the loudspeakers were rated for their performance on 5 counts in the manner of Hi-fi panel listening test rather than a traditional word score [4,5]. This also enabled a wider view of the sound quality to be taken. The parameters scored were :- Articulation / Intelligibility, Coloration, Tonal Balance, Clarity and Loudness. The SPL for each loudspeaker was set using a calibrated potentiometer, this having been previously set using a pink noise test signal and calibrated precision grade (Type 0) sound level meter. (This resulted in a slight discrepancy for one of the loudspeakers which was subjectively noted as being apparently louder on test material. Speech from the Syn Aud Con test disc was used as the test material. All the loudspeakers were fed at low impedance, thereby eliminating any potential bias due to 100 V line matching transformer quality. The following is an excerpt from the data analysis and commentary.

Subjective test on four ceiling speakers A, B, C, D.

Number of sessions	12
Number of repeats	50%
Number of subjects	6
Number of scored subjective parameters	432

11 point scoring range, 0 -10. 5 = average.
Reliability +/-4% for group averaged scores

Results

Marking range 4.3 to 6 points; the data is significant.

<u>*Speaker A on axis*</u>

Gave the lowest on axis aggregate score of 5.2 with below average clarity, some loss of articulation and poorer than average result for coloration.

<u>*Speaker A off axis*</u>

A low aggregate score of 5.0 though the performance differential between the on and off axis position is a little better than average. Loss of loudness off axis rated average; coloration, clarity and articulation remained fairly constant.

<u>*Speaker B on axis*</u>

On aggregate score, the result averages at 5.4. No particular parameter stood out except clarity which rated a little above average.

Speaker B off axis

Comparing with the on axis data, off axis, the performance differential was average, e.g. for loudness, tonal balance and coloration. Clarity was judged to be poorer than average off axis, but was still superior to speaker A either on or off axis.

Speaker C on axis

On aggregate score it was above average at 5.6. Clarity was above average, similar to speaker B on axis, while tonal balance was just average [slightly treble dull.] Articulation rated above average, coloration about average.

Speaker C off axis

The promising scores seen on axis showed further improvement for the off axis positions, to 5.8 marks, the only speaker in the test to do so. The differential for on and off axis locations was greater, significant at a typical 0.5 points. Articulation, coloration, tonal balance [more accurate treble] and clarity all improved. The loss in perceived loudness was fairly typical for the group.

Speaker D on axis

The averaged score for D was at the group average, 5.4 points. It scored high for perceived loudness [6.5 points] yet this was not associated with a significant gain in articulation [just below average] or clarity [average]. Tonal balance was poorer than average [4.7] associated with poorer coloration 4.7, significantly below average. If the high 'loudness' is discounted the average score rates at 5.1, lowest of the group.

Loudspeaker D off axis

Generally the results are poorer off axis with a global average of 4.9 the lowest for the group. Coloration was poorer than the rest as was articulation, while the loudness differential was greatest between on and off axis for this loudspeaker test.

Observations:

1) In this group the overall rank order for decreasing merit was C, B, A, D.

2) For the off axis performance it was C, B, A, D, with speaker C showing a significant lead over the group.

3) On axis, the variation was less with the merit sequence remaining at C, B, A, D; [D was corrected for a mild subjectively noted excess loudness].

4) For articulation and clarity the rank order was C first, followed by B, A ,D, these being approximately equivalent. [C scored 5.7 averaged, a figure of 5.2 was computed for the rest.]

As can be seen from the above results, the rank order for the loudspeakers remained consistent throughout. The rank order in terms of loudspeaker type was 1) Distributed Mode Panel, 2) 8 inch co-ax unit, 3) 6 inch cone and 4) 4 inch cone unit.

The albeit limited blind listening test would appear to confirm the observed informal subjective comment regarding the performance and clarity of the Distributed Mode Loudspeaker. A series of further tests were therefore undertaken to investigate the general behaviour and superior performance of the DML.

Figures 5 to 8 present the on and off axis frequency responses for the above test loudspeakers and listener positions. Figure 5 shows the on and off axis response for loudspeaker (A). The on axis response ie well extended and better than many in its price range. The off axis response shows a substantial high frequency loss being approximately -10 dB down by 4 kHz. [Inverse square law losses should account for only -3.8 dB]. Loudspeaker (B) exhibits generally similar behaviour as shown in figure 6 though has a slight high frequency lift above 1 kHz. The off axis performance shows a greater relative high frequency loss than speaker (A) but in absolute terms the off axis performances of loudspeakers (A) & (B) are in fact very similar.

Figure 7 presents the on and off axis responses for the Distributed Mode loudspeaker (C). A very different response plot emerges, with the off axis frequency response completely tracking the on axis curve. In the mid band from around 300 Hz to 1 kHz, the off axis level is only 3 dB down. Above this the off axis response is a consistent at 8 dB down being virtually independent of frequency ! This is quite a remarkable result and has a number of implications for sound system design. For example the result implies that not only will the sound quality will be constant for off axis positions but will be of similar character to the on axis response. Two further inferences can then also be made. Firstly that the degree of equalisation required will be less (and the resultant sound quality will be far more consistent) which implies greater available dynamic range. Secondly the feedback margin will be more consistent and more amenable to selective notch filtering to achieve greater installed gain.

Finally figure 8 shows the on and off axis responses for loudspeaker (D). The large high frequency peak at around 2 - 4 kHz and substantial off axis differential loss well explain the listening panel's subjective comments with regard to coloration and overall impression.

A series of other detailed acoustic measurements for each of the loudspeakers was also made including STI, C50 and EDT all parameters known to correlate highly with potential intelligibility [6]. Interestingly, although subjectively rated ahead of the other loudspeakers, the Distributed Mode panel scored marginally lower on these parameters. For example, the other three loudspeakers all scored

0.94 for 'on axis' STI whereas the DML scored slightly lower at 0.91. Off axis the other speakers scored either 0.87 or 0.88 STI whereas the DML scored 0.86 This latter result is only just statistically significant but shows an interesting trend. The 500 to 4 kHz averaged EDT results also showed the DML to excite the room a little more than the other speakers. All the STI matrix results exhibited a monotonic decay and suggest that the noted reduction is due to a higher density of later arriving reflections. Figure 9 shows the impulse response for the DML panel. It is interesting to note that in a highly sound absorbing room with a reverberation time of only 0.25 seconds (max) and with all boundaries within 50 mS return path, that the STI should be so affected. The explanation would seem to lie in the lower directivity (ie greater coverage) of the DML panel as compared to the conventional loudspeakers - particularly at higher frequencies. Yet it is just this factor which enables essential voice fricatives and plosives to be better broadcast by the DML than conventional speakers ! Some further investigations were therefore carried out to gain a better understanding of the radiation from Distributed Mode loudspeakers.

4 Loudspeaker Radiation

In order to study the radiation characteristics of typical ceiling loudspeakers, a mock up ceiling was built and in situ time windowed (gated) measurements were made of the four loudspeakers employed in the listening tests.

Figure 10 shows the in situ polar responses for the 6 inch loudspeaker from 500 Hz through to 5000 Hz. The characteristic reduction in radiation angle at high frequencies can be clearly seen - particularly in figure 11 which shows an overlay of the 500 and 5000 Hz polars.

Figure 12 shows the polars for the 8 inch co-ax unit. The effect of the tweeter can be clearly seen to maintain the dispersion at the higher frequencies of 4000 and 6300 thereby offering a wider off axis frequency response than the 6 inch single cone unit. At 8000 Hz however, the dispersion has again narrowed considerably as shown in figure 13.

Figure 14 shows the polars for the 4 inch driver, which becomes surprisingly narrow at the upper frequencies. (for example compare the 5000 Hz narrow beam with the hemispherical radiation result at 500 Hz as shown in figure 15).

Figure 16 shows the in situ polars made for the Distributed Mode loudspeaker. The inherently wider dispersion is clearly seen. The polars are slightly skewed at 500 Hz and 1000Hz - though in opposite directions. Normalising the polars enables the radiation pattern to be more clearly seen as shown in figure 17 which is for a panel taken under free field conditions. The results show the DM loudspeakers to radiate over a very wide angle to high frequencies. Rather than narrowing in dispersion, the radiation actually increases off axis. (See figure 18 which presents the in situ polar response at 500 Hz & 5 kHz and compare this to the conventional loudspeaker radiation). This is almost an ideal response, the radiation characteristic helping to overcome inverse square law losses. How this effect worked in practice was then examined by means of a series of tracking experiments which measured the direct sound radiation component in the listening plane.

In other words, this enabled the spl from a loudspeaker to be measured in a form that corresponds to the level that would be heard by a normal listener either a seated or standing.

5 Listener Plane Measurements

Single Loudspeakers

Measurements were made using a vertical mock up ceiling so that an adequate time window (approx 9 mS) could be achieved for the direct sound radiation without interference from other room boundary reflections. Measurements were made on the DM panel loudspeaker and the 4 inch driver for comparison purposes.

Figure 19 shows the resultant Direct Sound component spl for the two test loudspeakers as a function of the linear distance away from the loudspeaker axis. (i.e. as a listener stands or sits further away from the loudspeaker). The dotted line indicates the theoretical inverse square loss corrected for tracking geometry. At 500 Hz the plots are effectively as expected, although both loudspeakers exhibit an interesting characteristic in that they both show a slightly lower loss than expected at distances more than 3m away from the loudspeaker. (Particularly the 4 inch unit which effectively shows no loss at 4 to 5 metres). This effect was unexpected and is to be further investigated.

At 2 kHz, the 4 inch driver clearly shows the effect of reducing radiation angle (increasing directivity) [see figure 20]. The fall off in spl with distance is well below the theoretical curve. Conversely, the DM loudspeaker effectively exhibits "gain", its radiation apparently compensating for the inverse square law losses.(eg no apparent loss at 4 metres and only -3 dB down at 5 metres as compared to the 4 inch driver losses of - 15 dB).

At 4 kHz, the 4 inch cone falls off in level very much as expected with a loss of 5 dB more than inverse square law would predict. However the DML panel shows quite remarkable result exhibiting no loss at all right out to 5 metres and thereby exhibiting a 15 dB advantage over the 4 inch loudspeaker and 10 dB advantage over inverse square (see figure 21). indeed from the graph it is clear that the Diffuse Mode Panel loudspeaker does not follow the inverse square law at all at the higher frequencies.

Two loudspeaker tracking tests

In order to see how units combine as would be the case in a distributed sound system, the linear tracking tests were repeated but using two sources, 3m apart and in phase. Again the tracking distance was 2m away from the plane of the ceiling.

Figure 22 shows the result for the 500 Hz test. The dotted line indicates the theoretical power sum resultant curve for two sources. The DML again shows a remarkable result, exhibiting a virtually constant level (with 4-5 dB of gain) out to 3.5m beyond which it falls off and tends to the theoretical case. The 4 inch cone loudspeaker on the other hand exhibits substantial deviations due to mutual interference between the sources with a clear dip between the drivers and an accelerated fall off after passing by the second source. Deviations of up to 9 dB are shown to occur.

At 2 kHz, both loudspeakers track the theoretical curve quite well, as shown in figure 23 though with the DML showing a slightly greater loss beyond the second driver than the 4 inch unit.

At 4 kHz, the positions of the drive units are evident on the spl curves. A significant dip occurs for the 4 inch cone 1/2 way between the source positions due to the narrowing dispersion failing to provide overlap coverage. The DML on the other hand exhibits remarkably constant coverage between the two sources, again decreasing as expected after the second source has been traversed.

<u>Comments on the tracking experiment results</u>

At 500 Hz the way the two Distributed Mode loudspeakers couple, suggests that the DM loudspeakers are partially incoherent. From other auditioning tests however, it would appear that individual loudspeakers exhibit sufficient coherence to produce satisfactory localisation and stereo effects. However in the case of two loudspeakers, they may be considered to be mutually de-correlated. Therefore one could reasonably expect good power summation.

At 4 kHz, the 4 inch loudspeaker exhibits a peak to peak variation of 10 dB and an expected loss in coverage between the loudspeakers due to increasing directivity. The DM panel Loudspeaker however, suffers only a 4 dB variation over the same area, exhibiting virtually no loss between the two sources and completely overcoming this potential problem. Off axis (ie beyond 3.5 m track, the DML still retains its coverage advantage over the 4 inch driver by approximately 3 dB.

The tests, were based on a sound source spacing of 3m which would be considered good practice for 4 inch loudspeakers at a 2 metre listening plane separation. (Total nominal coverage angle is approximately only 80 degrees.) The DML summation advantage however advantage however suggests that the spacing could be significantly increased. This implies that in a distributed loudspeaker system, fewer loudspeakers would be required than by using traditional cone drivers, be they 6 inch, 8 inch coaxials or 4 inch single drivers.

The smooth summation offers support to the contention that the acoustic output of the Distributed Mode loudspeaker is largely diffuse.

6 Conclusions

The measurements and subjective tests reported in this paper support the anecdotal evidence that Distributed Mode loudspeakers can offer significant objective and subjective advantages over conventional loudspeaker technology. The measurements show that that DM loudspeakers offer wider maintained high frequency dispersion and of a form that that tends to counteract normal inverse square law losses. Indeed the single source experiments showed that considerable gain over and above inverse square law occurs.

The Distributed Mode loudspeakers would also appear to mutually couple and interact in a unique way, the measurements suggesting a degree of incoherency between loudspeakers. This could be used to considerable advantage in distributed sound systems. The data also suggests that fewer Distributed Mode loudspeakers would be required to provide coverage to a given area as compared to conventional cone units.

The diffuse radiation properties of the DML although apparently offering a subjective advantage may require a different measurement precept to be adopted. Examination of the experimental and raw measurement data suggests that conventional loudspeaker measurement and evaluation techniques, formulated for sources with a coherent output and whose behaviour approximates to inverse square law behaviour, may not be wholly appropriate to DM loudspeakers. The diffuse radiation from a typically larger radiating area presents a problem in defining a suitable reference point / measurement microphone position that adequately encompasses the true radiation characteristics of a panel. Spatial averaging of the forward response would seem to offer the most practical approach - yet this still needs referencing to standard loudspeaker measurement practice. It is hoped to report further on this work in the future and to further discuss investigations relating subject based intelligibility scores to conventional electro-acoustically based intelligibility measures.

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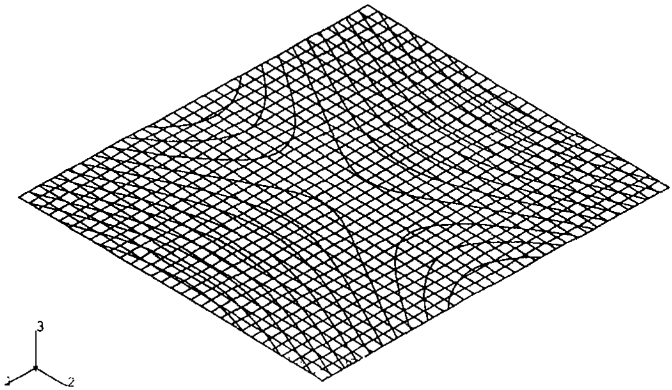


FIGURE 1 NON DIFFUSE PANEL ACOUSTIC MODES

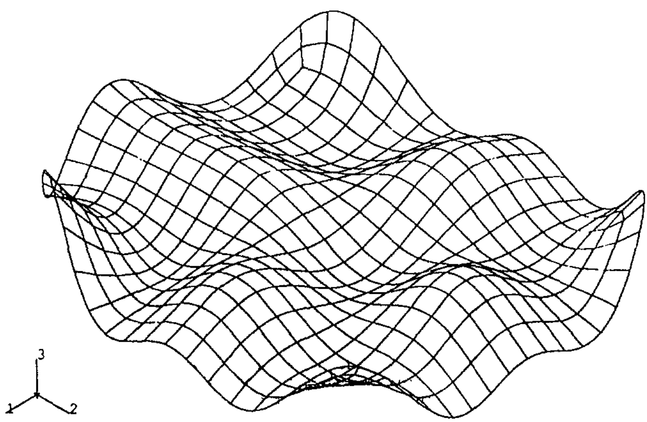


FIGURE 2 DIFFUSE PANEL MODES (DM LOUDSPEAKER)

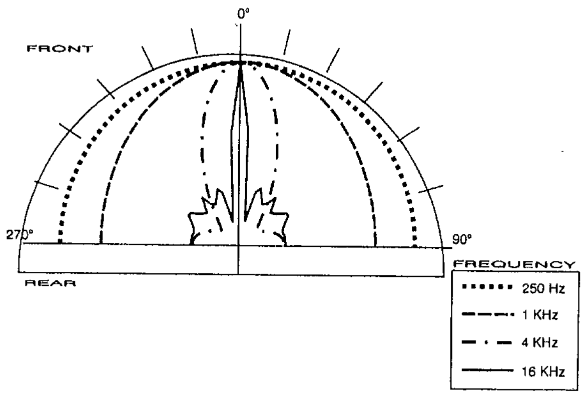


FIGURE 3 NARROWING OF LOUDSPEAKER ACOUSTIC RADIATION ANGLE WITH INCREASING FREQUENCY

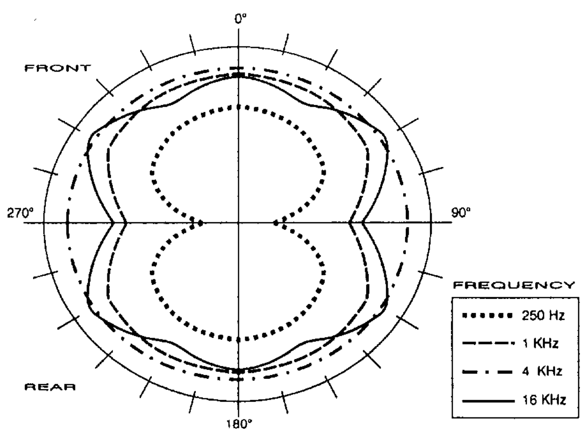


FIGURE 4 DIFFUSE MODE LOUDSPEAKER - ACOUSTIC RADIATION (IDEALISED)

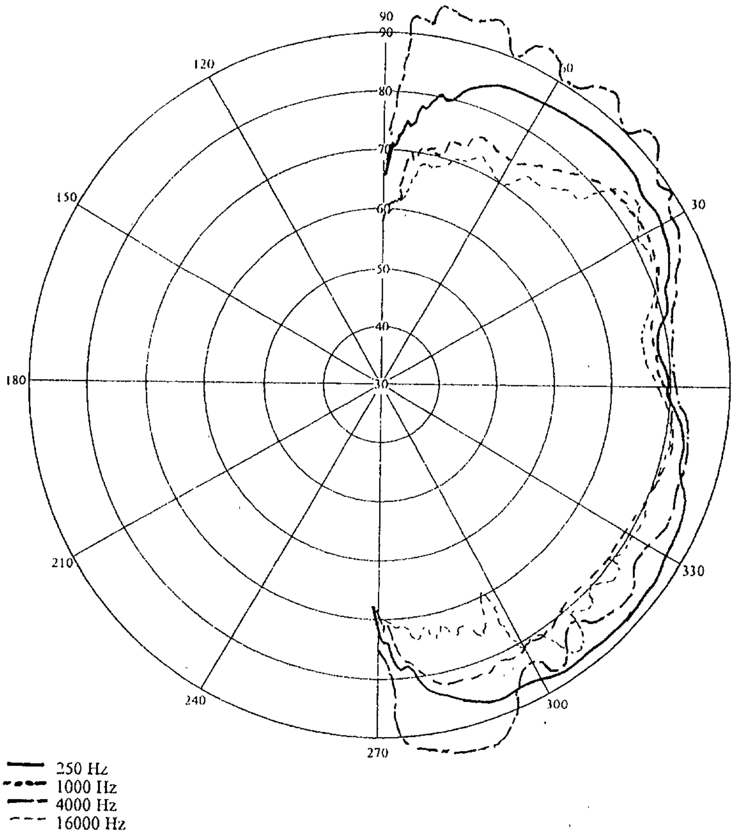
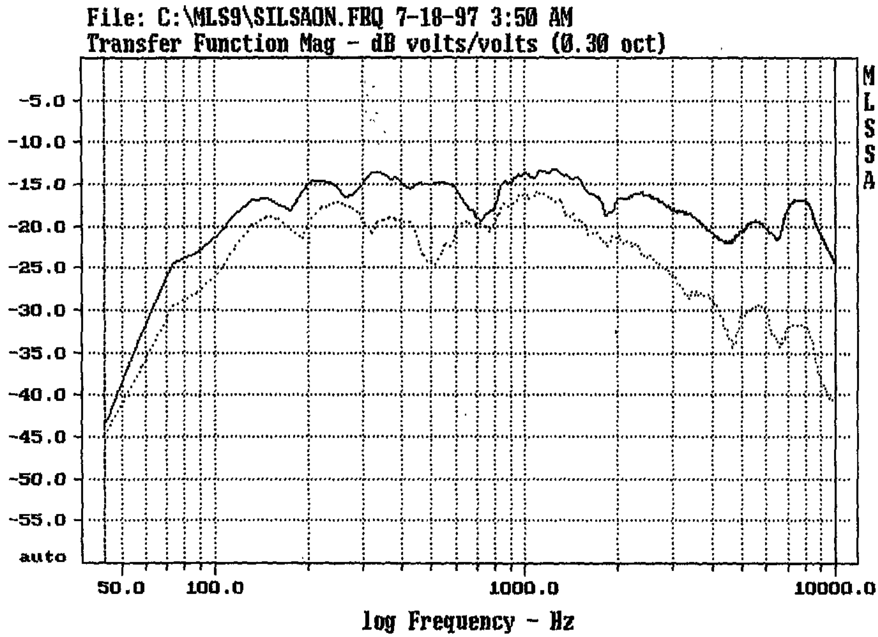
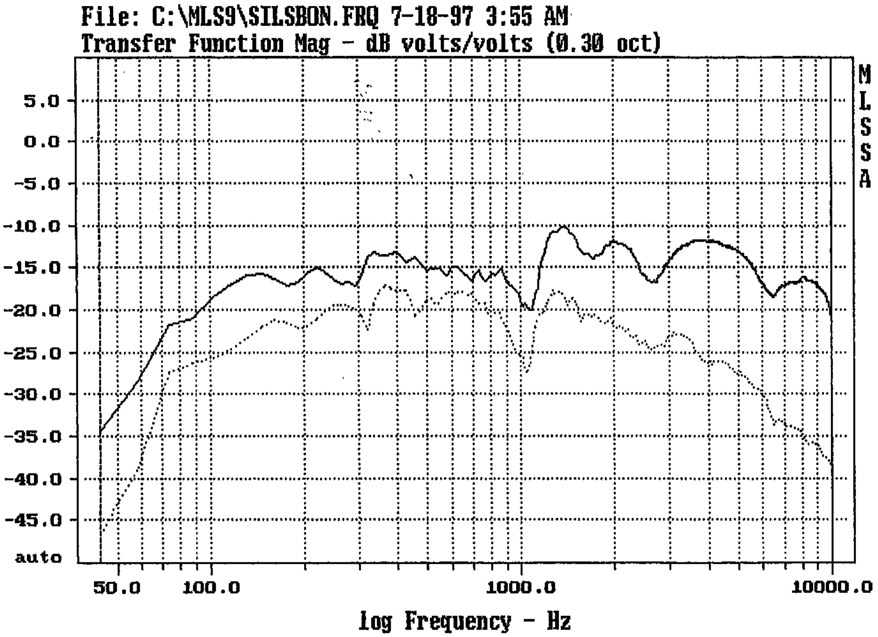


FIGURE 4(b) DIFFUSE MODE LOUDSPEAKER - ACOUSTIC RADIATION (MEASURED)



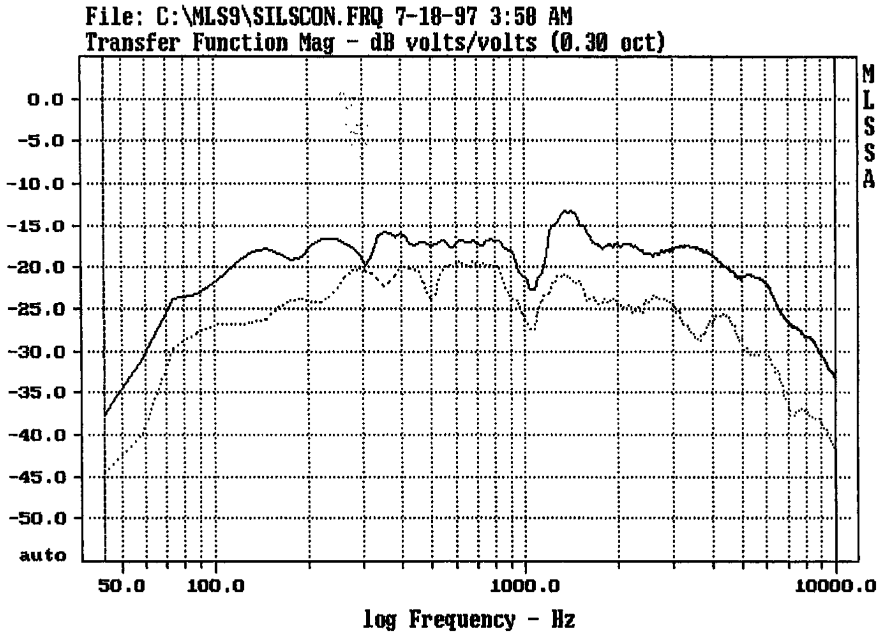
LS A ON & OFF AXIS

FIGURE 5 CEILING LOUDSPEAKER (A) ON & OFF AXIS RESPONSE



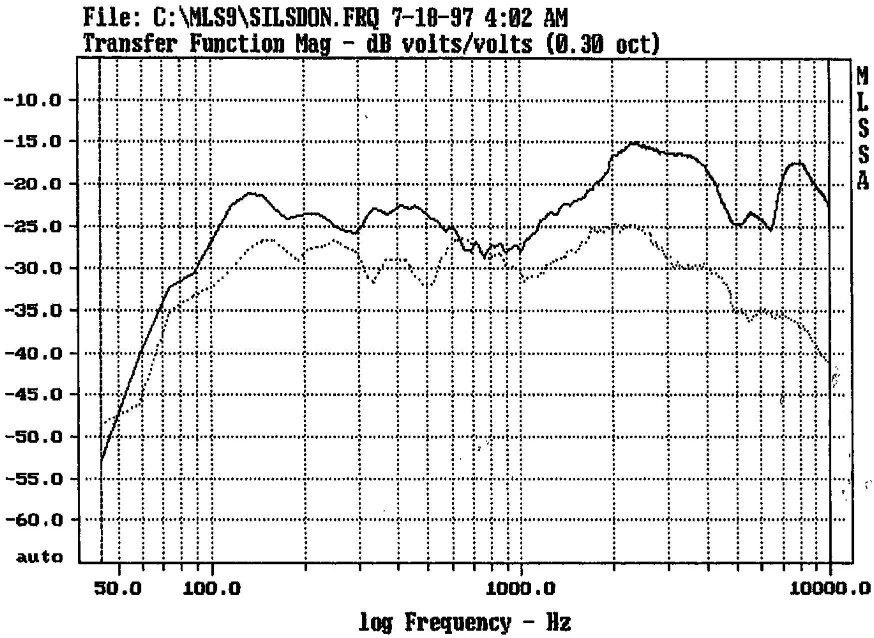
LS B ON & OFF AXIS

FIGURE 6 CEILING LOUDSPEAKER (B) ON & OFF AXIS RESPONSE



LOUDSPEAKER C ON & OFF AXIS RESPONSES AT LISTENER POSN

FIGURE 7 CEILING LOUDSPEAKER (C) ON & OFF AXIS RESPONSE



LOUDSPEAKER D ON & OFF AXIS

FIGURE 8 CEILING LOUDSPEAKER (D) ON & OFF AXIS RESPONSE

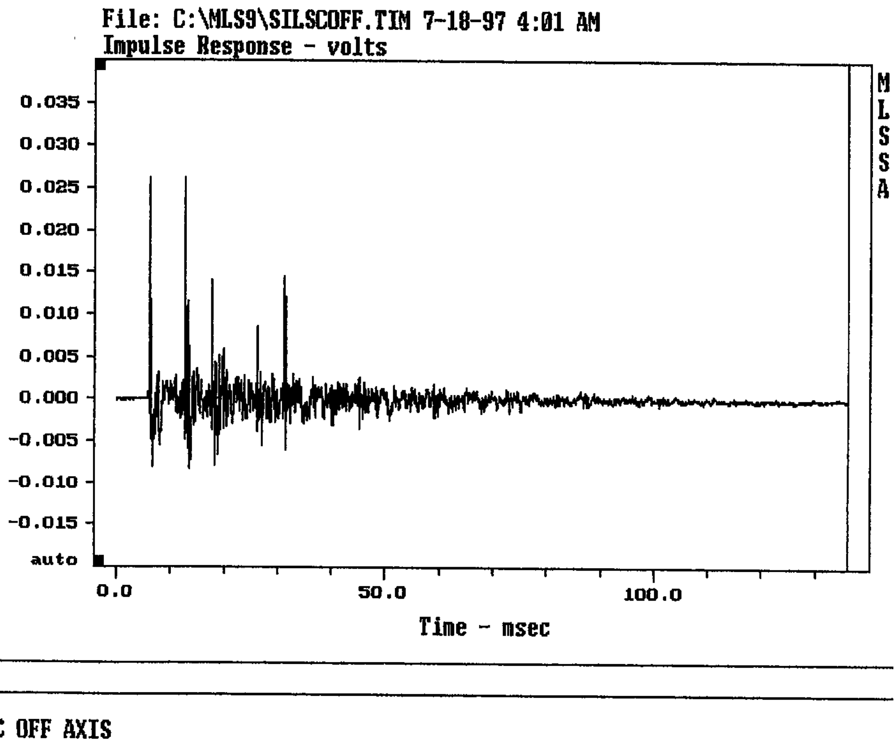


FIGURE 9 DIFFUSE MODE LOUDSPEAKER - ROOM IMPULSE RESPONSE

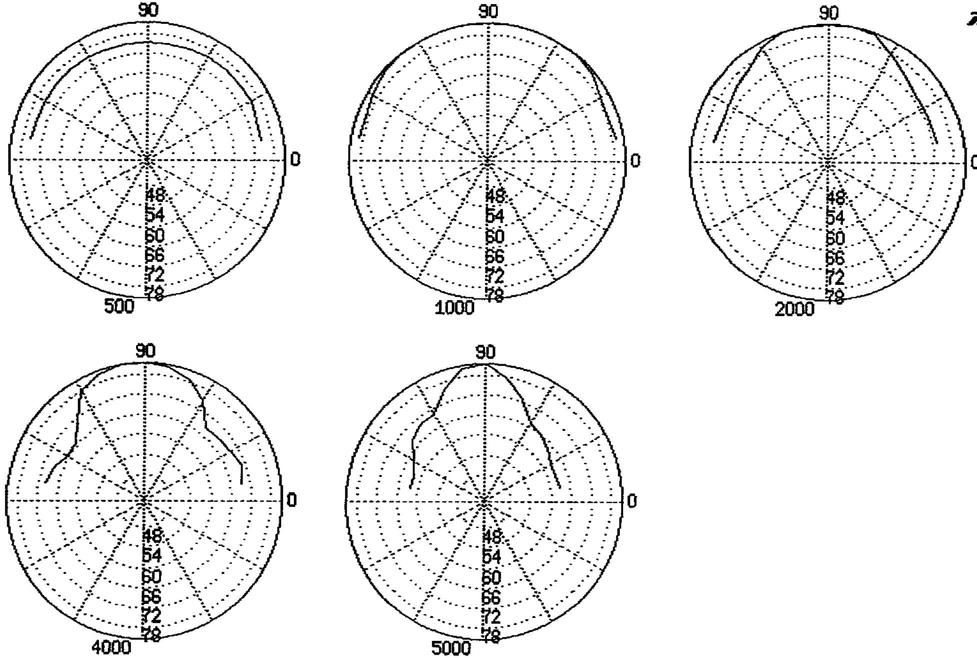


FIGURE 10 CEILING LOUDSPEAKER (A) [6"] IN SITU POLAR RESPONSES

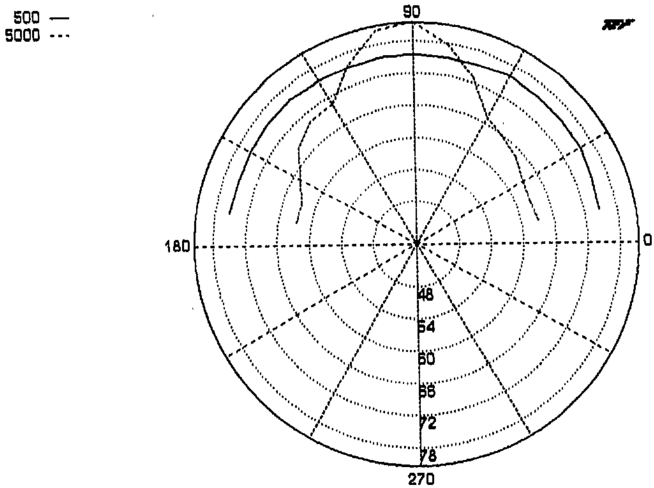


FIGURE 11 CEILING LOUDSPEAKER (A) 500Hz & 5kHz POLAR RESPONSE

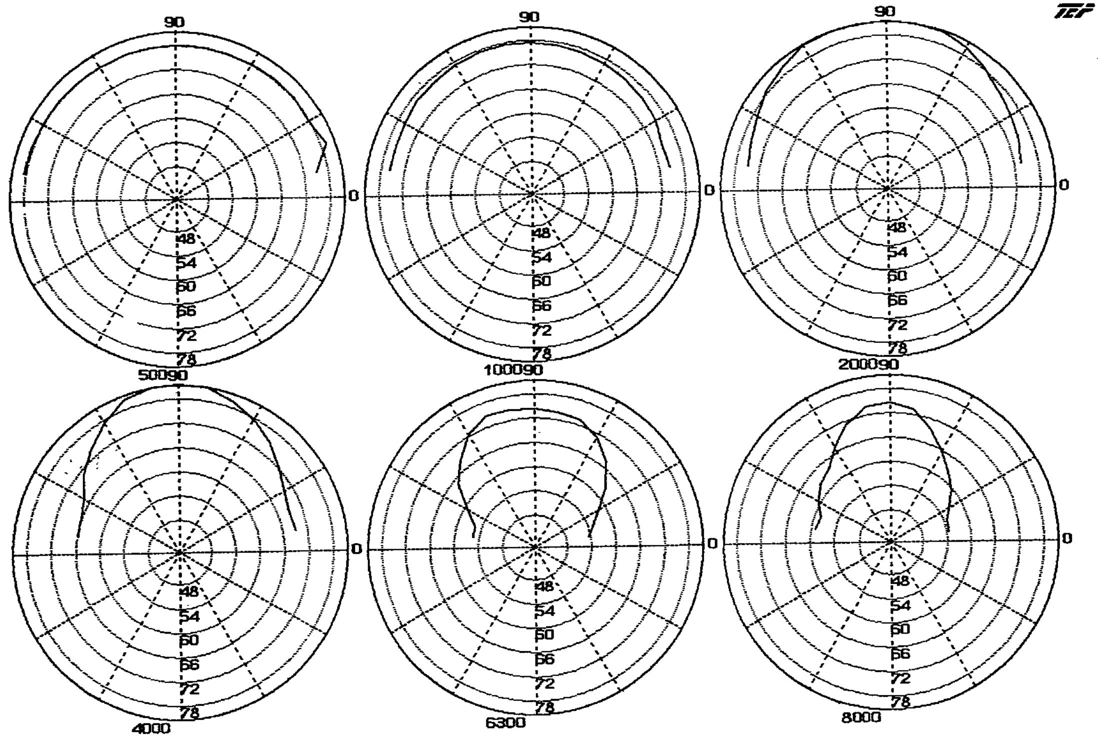


FIGURE 12 CEILING LOUDSPEAKER (B) [8" CO-AX] IN SITU POLAR RESPONSES

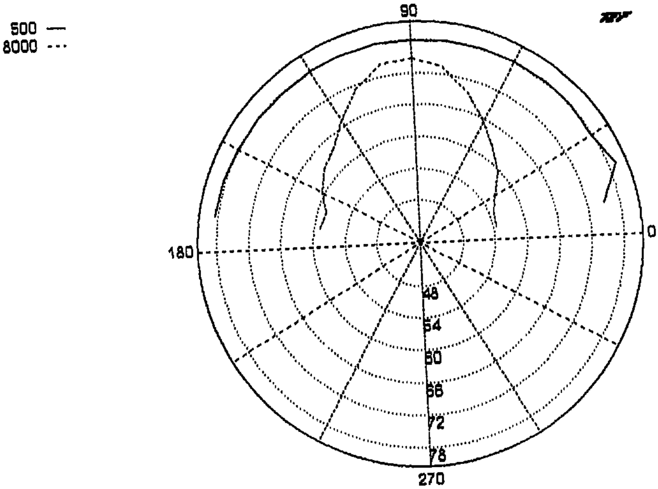


FIGURE 13 CEILING LOUDSPEAKER (B) 500Hz & 8kHz POLAR RESPONS

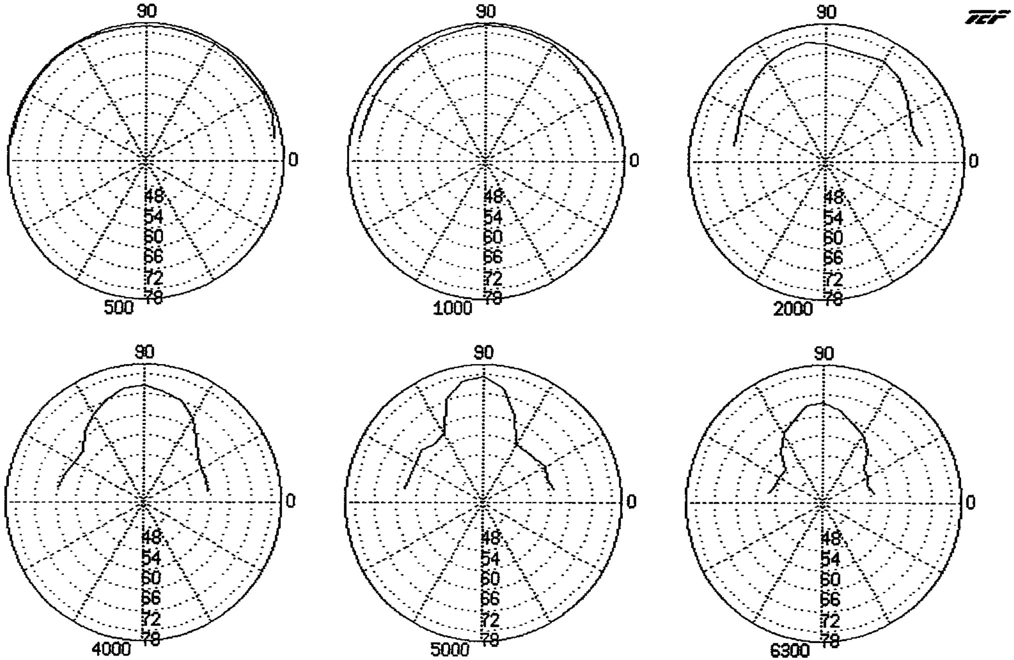


FIGURE 14 CEILING LOUDSPEAKER (D) [4"] IN SITU POLAR RESPONSES

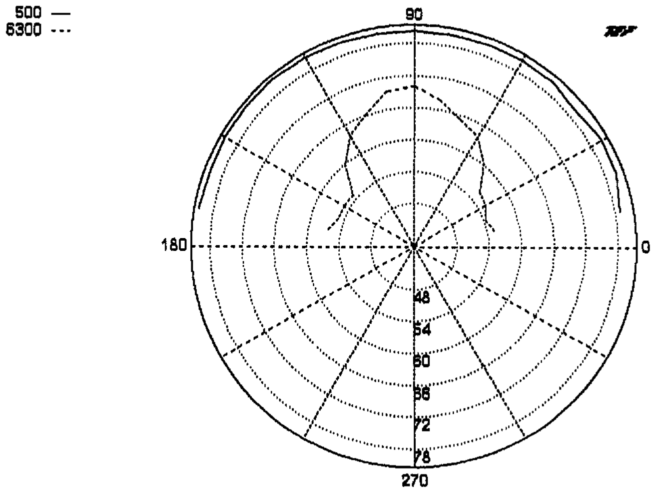


FIGURE 15 CEILING LOUDSPEAKER (B) 500Hz & 5kHz POLAR RESPONSE

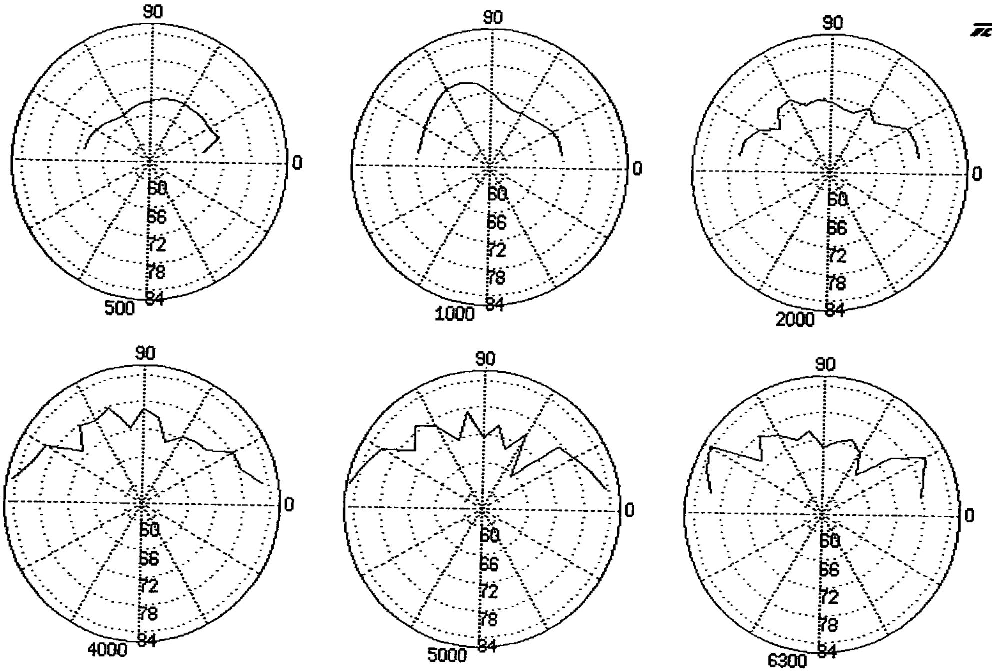


FIGURE 16 CEILING LOUDSPEAKER (C) [DML] IN SITU POLAR RESPONSES

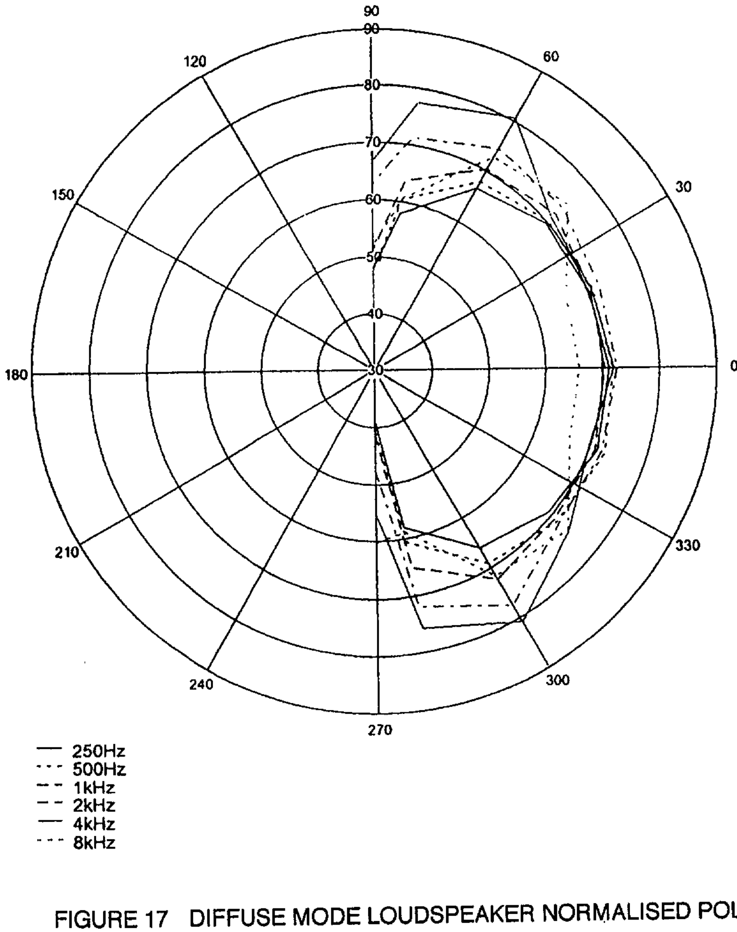


FIGURE 17 DIFFUSE MODE LOUDSPEAKER NORMALISED POLAR RESPONSE

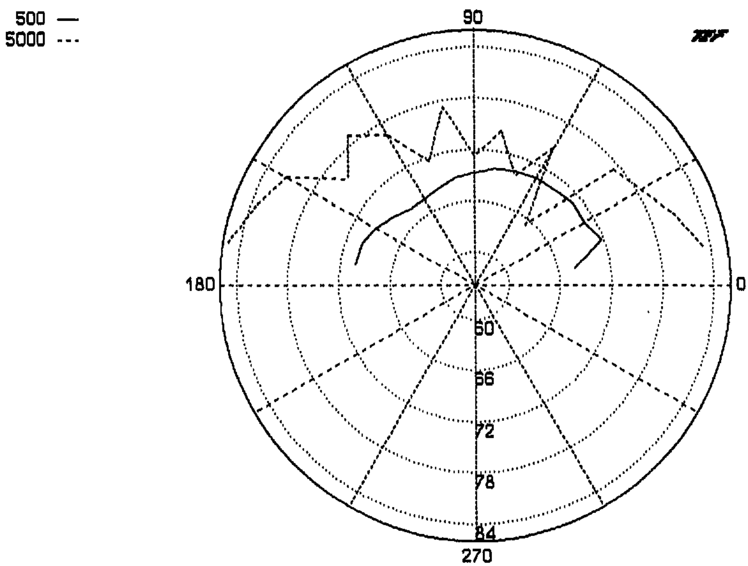


FIGURE 18 CEILING LOUDSPEAKER [DML] 500Hz & 5kHz POLAR RESPONSE

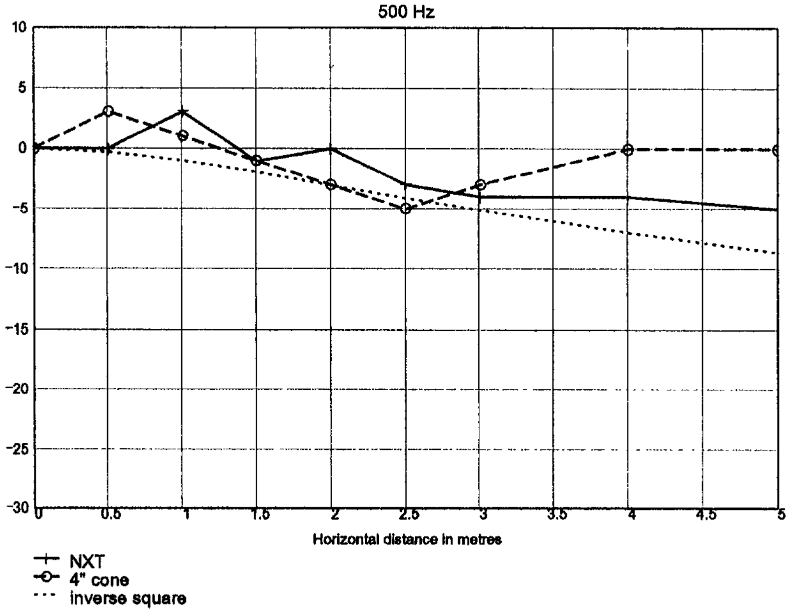


FIGURE 19 SINGLE LOUDSPEAKER LINEAR TRACKING AT 2M FROM SOURCE : COMPARISON OF 4" DRIVER AND DM LOUDSPEAKERS AT 500 Hz

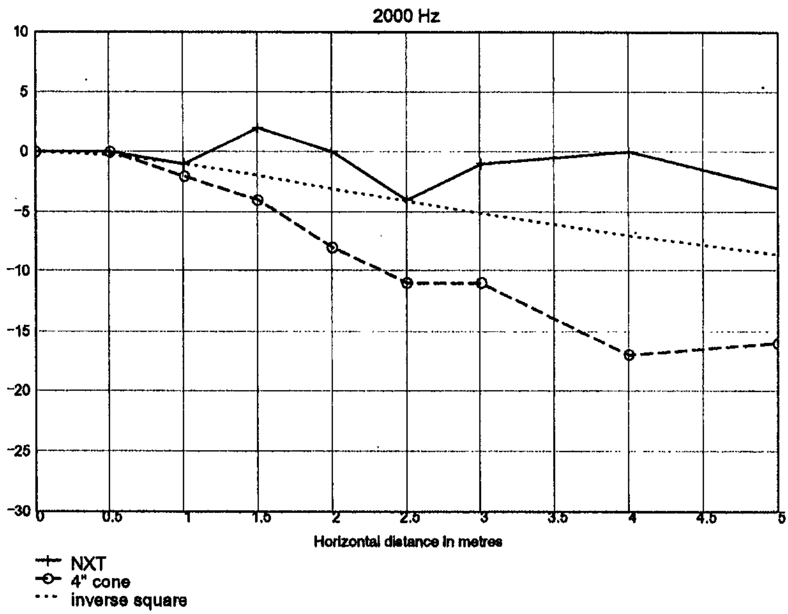


FIGURE 20 SINGLE LOUDSPEAKER LINEAR TRACKING AT 2M FROM SOURCE : COMPARISON OF 4" DRIVER AND DM LOUDSPEAKERS AT 2K Hz

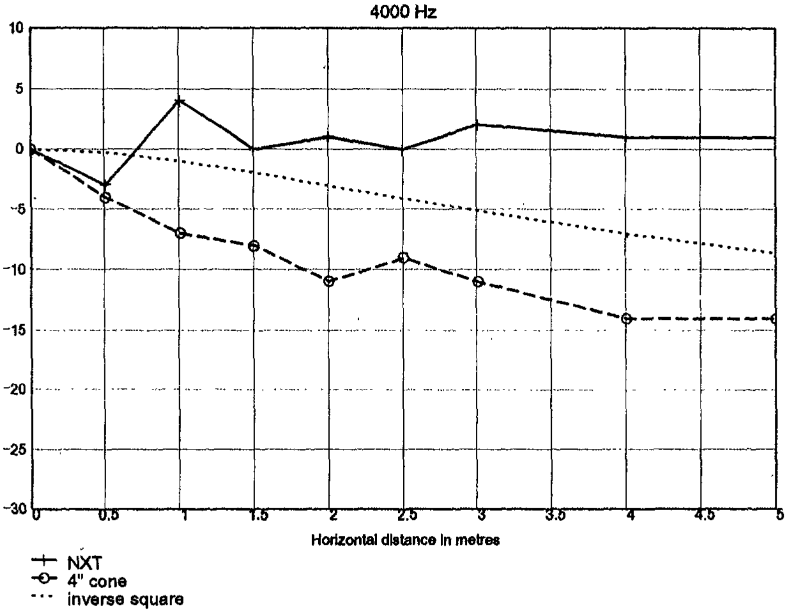


FIGURE 21 SINGLE LOUDSPEAKER LINEAR TRACKING AT 2M FROM SOURCE : COMPARISON OF 4" DRIVER AND DM LOUDSPEAKERS AT 4K Hz

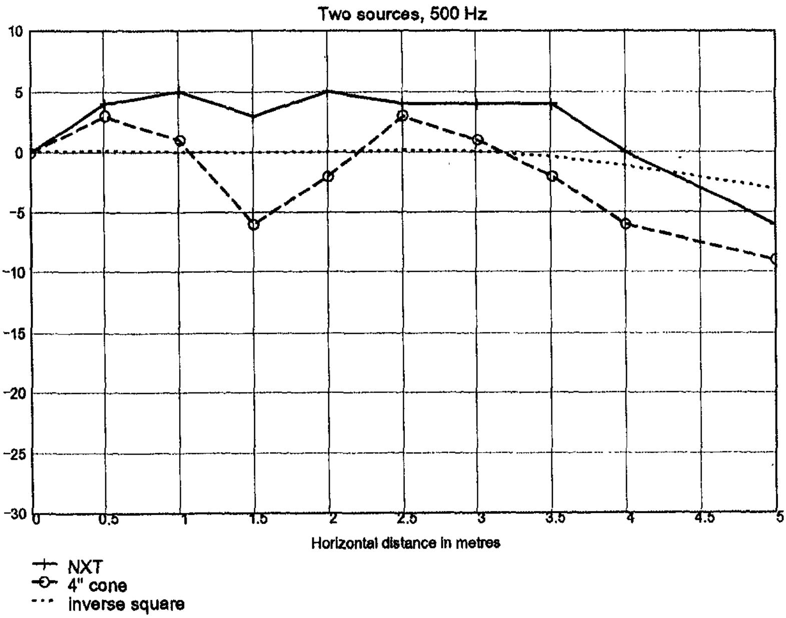


FIGURE 22 TWO LOUDSPEAKER LINEAR TRACKING AT 2M FROM SOURCE : COMPARISON OF 4" DRIVER AND DM LOUDSPEAKERS AT 500 Hz

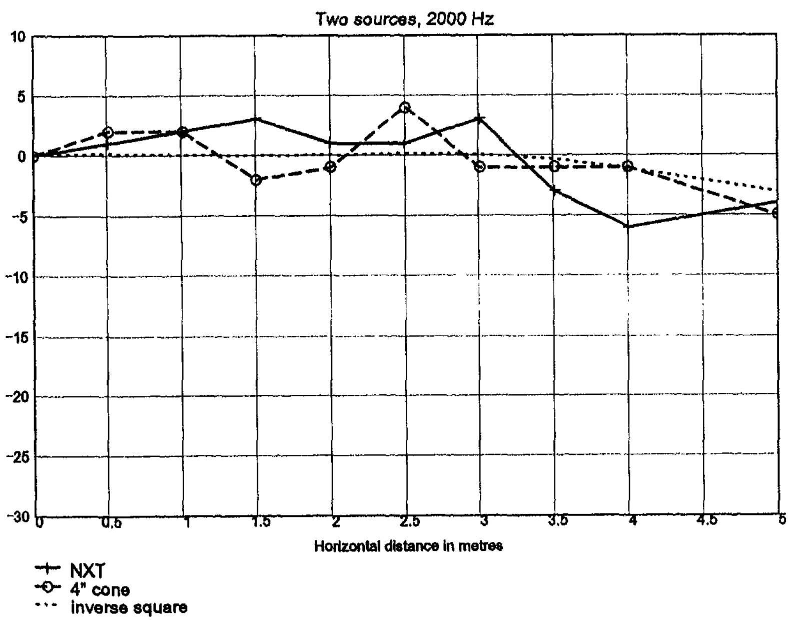


FIGURE 23 TWO LOUDSPEAKER LINEAR TRACKING AT 2M FROM SOURCE : COMPARISON OF 4" DRIVER AND DM LOUDSPEAKERS AT 2K Hz

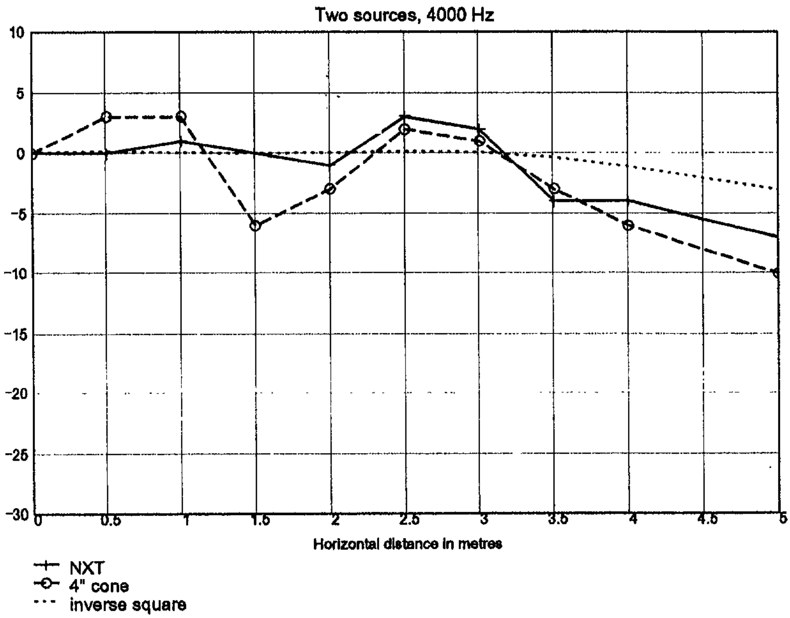


FIGURE 24 TWO LOUDSPEAKER LINEAR TRACKING AT 2M FROM SOURCE : COMPARISON OF 4" DRIVER AND DM LOUDSPEAKERS AT 4K Hz