Development of a Compact Dipole Loudspeaker

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ABSTRACT

A relatively small size dipole loudspeaker system has been developed using conventional cone-type drivers to obtain sufficiently large volume displacements. The 3-way system has dipole directional characteristics over the 20 Hz to 1000 Hz frequency range for reduced interaction with the listening room. Effects of the baffle shape upon the radiation pattern have been investigated. Active crossovers and dipole specific equalization have been used to obtain a flat frequency response.

1 INTRODUCTION

The idea of designing a dipole loudspeakers started with a sound reinforcement loudspeaker that the author built six years ago for an audio-video presentation in a large gymnasium. It was a vertical line-source dipole, 2.4 m long with twelve 170 mm electro-dynamic drivers, electrically tapered so that at high frequencies only the two center drivers would be active. The loudspeaker had high directivity and provided excellent intelligibilty in the highly reverberant gymnasium with parquet wood floors and hard walls. The existing sound reinforcement system, on the other hand, would play at high volume but the direct sound was masked by the large amount of reverberation in the gymnasium.

The line-source could be separated into two 1.2 m columns for use as a stereo system in a home listening environment. Under these conditions the loudspeaker exhibited surprising qualities despite its uneven frequency response. The sound from the free standing columns was quite open, lower frequencies did not have a boxy character and the vertical extension of the sound image seemed to match the height of the loudspeakers. In some respects the author was reminded of planar electrostatic or magnetic loudspeakers.

At the time the author used two small satellite loudspeakers with a center channel subwoofer. They represented his latest thinking after he had designed a variety of closed box systems [1]. The satellites were free hanging, 0.75 m from the rear wall and with the tweeter 1 m above the floor. A major audible difference between this system and the dipole columns was the restricted vertical extension of the sound stage image. It was, as if listening through a window with a vertical opening of 0.4 m, the height of the satellites, and with a width corresponding to the separation between the satellites. The most often used listening position was a rather distant 5 m, for a loudspeaker separation of 2.2 m, so that a more directional loudspeaker seemed desirable to improve the ratio of direct to reverberant sound.

The above observations about reduced boxiness of the sound, vertical image height and the desire for lower room contributions started the investigation into directional loudspeakers. It meant a complete change from previous designs which tried to realize small, point-source-like monopole loudspeakers. The compact dipole loudspeaker, (Fig. 1), which is the result of the new endeavour, has evolved through four iterations over the last seven years [2].

2 DIPOLE CONCEPTS

An idealized dipole can be modeled as a positive and a negative acoustic point source, spaced at a distance D from each other (Fig. 2). The impulse response, p(t), of the dipole is a positive pulse at time 0 and a delayed, negative pulse at time T.

$$p(t) = 1 - e^{-sT} \qquad (1)$$

with $s = \sigma + j\omega$ as complex frequency. The frequency response $F(\omega)$ of the dipole is determined from (1) by replacing s with $j\omega$, where $\omega = 2\pi f$.

$$F(\omega) = | 1 - e^{-j\omega T} | \qquad (2)$$

$$F(f) = | 1 - \cos(2\pi fT) + j \sin(2\pi fT) |$$

$$F(f) = \sqrt{2(1 - \cos(2\pi fT))} \qquad (3)$$

The polar pattern follows from replacing D with $D(\cos\alpha)$ for off-axis angles α in the expression for $T = D/v$, where $v = 340$ m/s is the velocity of sound.

$$F(f) = \sqrt{2(1 - \cos(2\pi fD(\cos\alpha)/v))} \qquad (4)$$

The frequency response is plotted for D = 0.25 m and for different angles α (Fig. 3).

The response is sloping at 6 dB per octave (20 dB/dec) below the frequency of the first peak. The on-axis peak occurs where $D = \lambda/2$, or at a frequency

$$f_{peak} = 0.5\ v/D \qquad (5)$$

The rear radiation is in phase at this frequency with the front radiation and the output is doubled, i.e. increased by 6 dB. The peak at 680 Hz is followed by nulls at even multiples of f_{peak} and further peaks at odd multiples of f_{peak}.

The off-axis response decreases with $\cos\alpha$ and is 3 dB down for $\alpha = 45^0$ and -6 dB for $\alpha = 60^0$. The low frequency cosine or figure-of-eight polar response changes to patterns with multiple lobes at higher frequency. It can be seen from Fig.3 that the maximum occurs at +/- 60^0 when the on-axis response has its first null.

Of particular interest is the frequency, f_{equal}, at which the on-axis response is unity, or 0 dB. Knowing f_{equal} allows to determine the sound pressure level (SPL) from a dipole in comparison to a monopole with equal source strength. Expressing f_{equal} relative to the peak frequency yields $f_{equal} = 0.34\ f_{peak}$ and in terms of path length difference D between the positive and negative point source:

$$f_{equal} = 0.17\ v/D \qquad (6)$$

The excursion requirements or the sound pressure level of a dipole can be estimated from (6) relative to those of a monopole. For example, assume a driver is mounted at the center of a 0.5 m diameter circular baffle and radiates front and back in dipole fashion with a certain cone excursion. The rear radiation has to travel a distance D = 0.25 m before coming to the front and therefore f_{equal} = 230 Hz. At this frequency the SPL from the dipole is the same as if the same driver were mounted in an acoustically small box. At 70 Hz, though, the dipole SPL would have dropped by a factor of (230 Hz)/(70 Hz) = 3.3 or 10.3 dB. To achieve again the same output as the closed box loudspeaker requires 3.3 times larger excursions. If a 100 mm diameter driver was sufficient at 100 Hz in the closed box, then a 182 mm driver would be necessary for the dipole because it moves 3.3 times the air volume for the same excursions as the 100 mm driver.

The above relationships, (1) to (6), are for an idealized dipole model. They give only an approximation of the sound pressure level when the driver is mounted on a baffle of more complex shape than a circle. The polar pattern changes when the baffle is folded back in order to reduce the frontal area. A complete theory of diffraction for the dipole is still outstanding. Present investigations [3] are limited to the case of thin baffles.

A dipole radiates 1/3 the acoustic power of a monopole with the same on-axis sound pressure level [4, chapter 4]. A dipole, therefore, feeds 4.8 dB less power into the reverberant sound field than a comparable monopole. The dipole has a correspondingly larger ratio of direct to reverberant sound and the "critical distance" where the direct sound equals the reverberant sound is 3 times larger than for the monopole.

3 LOUDSPEAKER DESIGN

The compact dipole loudspeaker design is the result of several dipole implementations. Early versions tried to achieve a similar frequency response for the rear radiation as for the front. The loudspeakers were 4-way designs with a closed box, monopole subwoofer and dipole arrangements for lower midrange and upper midrange. In the first version, two dome tweeters, back to back, covered the frequencies above 4 kHz. Extending the rear radiation through the tweeter range was found to be unnecessary and even detrimental. In all cases active crossovers and equalization were used to simplify the design task and for the advantages from separate power amplifiers for each frequency range [5].

3.1 Driver selection

The present, compact dipole loudspeaker is a 3-way design (Fig. 1). Frequencies up to 100 Hz are reproduced by dipole woofers using two 300 mm drivers for each channel. The 100 Hz to 1.7 kHz range is covered by two 200 mm drivers mounted symmetrically above and below a 25 mm dome tweeter.

The choice of two 200 mm drivers was based on the experience with 100 mm drivers in a closed box satellite configuration where two drivers per channel gave adequate output levels in conjunction with a 70 Hz crossover to a subwoofer. The 200 mm drivers in the compact dipole loudspeaker are mounted on a baffle with an effective rear to front path length D_{r-f} = 0.25 m. From equation (6) f_{equal} = 230 Hz. The dipole would, therefore, require 3.3 times the volume displacement. A 200 mm driver with about 4 times the cone area and similar excursions as the 100 mm unit should achieve a comparable sound pressure level in dipole configuration. The excursion requirement is even less for the 100 Hz crossover frequency chosen. By going to the higher crossover frequency the excursions requirements for a constant sound pressure level decrease by a factor of $(100/70)^3 = 2.9$ and the 200 mm units are, therefore, more than adequate for the task.

Earlier versions of the dipole loudspeaker used a center channel woofer consisting of four 300 mm drivers in two separate closed boxes. It was always a strong design goal to keep the physical size of the system small and unobtrusive. Replacing the woofer with dipoles of similar overall dimensions meant that the rear to front distance would be about 0.4 m with f_{equal} = 145 Hz from (6). Therefore, a dipole woofer would require 3 times the excursions at 50 Hz as the closed box design, or twelve instead of four 300 mm drivers to reach the same sound pressure level. The excursion limited SPL from an acoustically small closed box can be calculated [6] using

$$SPL_{rms} = 94.3 + 40\log(f) + 40\log(d) + 20\log(x_{pp}) - 20\log(r) \quad (7)$$

With f = 50 Hz, piston diameter d = 0.3 m, piston excursion x_{pp} = 0.01 m and a distance from the piston r = 1 m the SPL becomes 101 dB for one 300 mm driver radiating into free space. Assuming half space conditions for the listening room adds 6 dB, and using four drivers increases the SPL by another 12 db to a total of 119 dB SPL at 50 Hz. When the same four drivers are used in a dipole with D_{r-f} = 0.4 m the SPL at 50 Hz decreases by 20log(50Hz/145Hz) = -9 dB to 110 dB SPL. This level still seems adequate for much of home listening but it is on a steep slope and falls to 92 dB SPL at 25 Hz (Fig. 4).

A thorough study of subwoofer performance [7] points out the large volume displacement requirements for accurate reproduction of music. The author hesitated for a long time to build a dipole woofer. He had heard a system that uses dipoles at a friend's house [8] and had been extremely impressed with the quality and naturalness of the bass reproduction aside from the sheer volume. This system was and still is, in his opinion, better than anything he had ever heard. The system uses six 300 mm drivers in each channel but the size of 2 m x 0.4 m x 0.4 m for each enclosure was not compatible with his living room. Only after another friend had tried a two driver per channel arrangement and reported very adequate performance [9], did he design the relatively small dipole woofers described in this article.

3.2 Power response

A uniform power response, represented by smooth frequency response at off-axis angles, was an important design goal. The off-axis radiated sound reaches the listener's ears via reflections and via the reverberant sound field and should have minimal spectral irregularities. Any driver shows increased directivity as its piston diameter becomes a larger percentage of the wavelength [4, Fig. 4.20]. At low frequencies, a driver in an acoustically small, closed box acts as a monopole and radiates uniformly in all directions (Fig. 5). A dipole has a cosine or figure-eight pattern in vertical and horizontal planes. The total acoustic power radiated by the dipole when integrated over all directions is one third the power of a monopole with the same on-axis SPL. The power response of dipole and monopole fall off at high frequencies but the dipole will have 3 dB higher output because of the rear radiation. Early designs tried to take advantage of the more constant power response of the dipole. Indicated in Fig. 5 are the relative frequency ranges for the 200 mm dipole driver and the 25 mm monopole tweeter. The 200 mm driver benefits in power response uniformity by being operated as a dipole vs. a monopole.

An additional increase in directivity in the vertical plane is caused by the vertical array of the two 200 mm drivers with 0.36 m separation (Fig. 6). The total power response, as a consequence, is reduced by 3 dB in the frequency range where the vertical polar response has multiple lobes [10].

3.3 Driver measurements

Drivers were mounted in their enclosures and measured outdoors. Each enclosure was placed on a flat surface to simulate a normal listening setup. The first set of measurement data shows the frequency response of the unequalized drivers (Fig. 7 to Fig. 15).

The woofer data are for the final enclosure which measures 680 mm x 280 mm x 510 mm (H x W x D). It is open at both ends. The 300 mm drivers are mounted at an angle of approximately 45^0, zig-zag about the center line of the cabinet to reduce its width. The response is flat from 80 Hz to 20 Hz when measured close up at 0.5 m from the enclosure center (Fig. 7). This is to be expected because the measurement is so close to the front of the dipole that the rear radiation has no cancelling effect. The roll-off below 20 Hz is due to the 18 Hz mechanical resonance of the driver. The rise above 80 Hz is caused by the $\lambda/4$ length of the cavity in front of the drivers. The $\lambda/4$ length improves the impedance match between the cone of the driver and the air at the opening of the enclosure. The maximum SPL occurs at about 250 Hz and is lower than expected from a simple calculation for a (510 mm)/2 cavity depth which would give 333 Hz. Placing the microphone at 1 m and 2 m distance shows increasingly the effect of the rear wave cancelling the front radiation. The slope of the frequency response tends towards 6 dB/oct except in the 20 Hz to 40 Hz region where it is flattened by reflection from an adjacent wall on the outdoor test site. Measurement of the woofer's off-axis response is difficult in the given location because it is perturbed by reflections from nearby objects. An indication of the directional behavior, though, can be obtained (Fig. 8), particularly when comparing the off-axis frequency response to a closed box woofer of similar dimensions (Fig. 9).

Midrange and tweeter were measured in a prototype enclosure of 660 mm x 275 mm x 110 mm (H x W x D). It is a folded back baffle to give a visually smaller frontal area than an acoustically equivalent flat baffle. The internal depth is 90 mm and kept shallow to minimize cavity resonances in the frequency range of the 200 mm drivers. The off-axis response exhibits the $\cos\alpha$ output reduction of a dipole. The response is down approximately 1 dB, 3 dB and 6 dB for 30^0, 45^0 and 60^0 angles respectively (Fig. 10). Between 550 Hz and 700 Hz the polar response becomes constant over the measured 0^0 to 60^0 angular range. A somewhat similar behavior can be seen in the theoretical dipole response which becomes less directional around the frequency where the first peak occurs (Fig. 3). The path length difference D_{r-f} for the enclosure is estimated as 250 mm which gives f_{peak} = 680 Hz from (5). The sloping response, though has peaked at a lower frequency around 400 Hz. The enclosure affects the polar response obviously in a more complex manner than the simple model of Fig. 2 would predict. The tightening of the response curves around 600 Hz is reduced by a shallower enclosure (Fig. 11), which is desirable for a more uniform off-axis and power response.

The influence of the rear radiation was removed for test purposes by closing off the rear of the enclosure. The loudspeaker then becomes somewhat more directional above 600 Hz, (Fig. 12), than the dipole configuration (Fig. 11).

The rear radiation is almost identical to the front radiation, as expected, when the enclosure is open in the back (Fig. 13). Radiation is reduced at the 90^0 angle, although the minimum of the SPL occurs at slightly larger angles because of the folded back baffle. The closed rear prototype, by contrast, exhibits decreasing rear radiation with increasing frequency (Fig. 14).

The high frequencies are reproduced by a dome tweeter with a closed back. The particular tweeter chosen has a small amount of directivity at lower frequencies (Fig. 15). This helps to match the off-axis response of the midrange drivers through the crossover region around 1.7 kHz.

3.4 Frequency response equalization

The inherent 6 dB/oct low frequency roll-off of a dipole must be equalized to obtain constant on-axis SPL. The woofer operates completely in the roll-off frequency range below the 100 Hz crossover to the midrange (Fig. 7). The equalization then consists merely of an increase in amplifier output at a rate of 6 dB/oct. The 10 Hz low frequency extension of the drive signal boost was chosen with regards to the driver resonance. The 20 Hz free air resonance of the 300 mm drivers is actually lowered by about 10% by mounting in the dipole enclosure. The resonance controls the low frequency roll-off and no attempt has been made to equalize the woofer response for an even lower cutoff. The acoustic response will, therefore, fall off at 18 dB/oct below 10 Hz.

The low power requirements for the woofer may be surprising. A voltage of 10 V peak-to-peak at 20 Hz drives the cone to full excursions. This is equivalent to 1.5 W into 8 Ohm. To achieve the same excursions at 80 Hz requires $(1.5W)(80Hz/20Hz)^2 = 24$ W. Each of the four 300 mm drivers in the system is driven from its own 50 W amplifier which is more than adequate.

Equalization of the 200 mm drivers is considerably more complex because they exhibit dipole or monopole behavior depending upon the frequency range as a result of the folded baffle shape. The equalizer compensates for the 6 dB/oct slope at low frequencies but then corrects at a greater rate up to the first peak of the dipole (Fig.16). The driver frequency response is essentially flat beyond the peak and behaves as if it were in a closed box. The transition from the peak to the flat portion of the response requires careful adjustment of the parameters in the bridged-T derived active equalization network (Fig. 17).

Some equalization is required for the tweeter to remove a shallow 2 dB trough in the response around 6 kHz.

3.5 Crossover networks

The active crossover networks are designed for a 24 dB/oct acoustic filter response [5]. The 100 Hz lowpass filter that attenuates the high frequency output from the woofer and the 1.7 kHz lowpass for the midrange to tweeter crossover are realized as electrical filters without any further correction for the acoustical behavior of the drivers. The 100 Hz highpass filter circuit [1] in the midrange channel compensates for the mechanical resonance of the 200 mm driver at 40 Hz (Fig. 18). Similarly, the 1.7 kHz highpass filter circuit in the tweeter channel is designed with the 870 Hz resonance of the 25 mm driver in mind. The frequency responses of the lowpass and highpass circuits are therefore not symmetrical about the 1.7 kHz crossover frequency (Fig. 19). The signal to the tweeter is also delayed electrically [5] to compensate for a 42 mm mechanical offset between the acoustic centers of tweeter and midrange. The delay is necessary to bring the phase of the acoustical response closer to the theoretically required value, so that the driver outputs add in-phase.

The overall frequency response of the drive signals for woofer, midrange and tweeter (Fig. 20) includes equalization and crossover filters to obtain a flat on-axis acoustic response and 24 dB/oct slopes for the transitions between drivers at 100 Hz and 1.7 kHz.

3.6 Loudspeaker frequency response measurements

The frequency response when measured outdoors shows indeed the desired behavior (Fig. 21). The measurement includes imperfections of the test site. They can be accounted for after a large number of data has been taken from different positions, but they cannot be eliminated from the single positon measurement shown here. The off-axis response in the horizontal plane matches the on-axis response over a wide range of angles and frequencies. Even the transition region between midrange and tweeter around 1.7 kHz is a smooth extension of the lower frequency dipole behavior. Only the 2 kHz to 6 kHz range shows a widening of the polar pattern as indicated by the close spacing of the off-axis response curves. At higher frequencies the tweeter properties cause an increasing response fall off for angles over 30^0 from its axis.

The frequency response information was obtained by Fourier transform of a 40 ms long impulse response segment. The frequency response was 1/5 octave smoothed to remove the fast amplitude fluctuations in the upper kHz range caused by reflections from the floor. The time record length yields a 1/(40ms) = 25 Hz frequency resolution which is not sufficient for assessing the low frequency performance. A 250 ms long portion of the impulse response gives a 4 Hz resolution so that the woofer frequency response can be examined (Fig. 22). The transition between woofer and midrange can be tested by reversing the polarity of the woofer and noting the notch around the crossover frequency that is to be expected when the phase between the two frequency ranges is not correct.

The frequency response for vertical off-axis angles shows the increasing directivity of the two midrange drivers due to their separation from each other (Fig. 23). The radiation becomes less directional above the crossover frequency where the response is determined by the tweeter. Fortunately, most of the listening takes place at a fixed vertical height. With a tweeter height of 1 m and a listening distance of 3 m, the $+/-10^0$ angle change gives a 0.5 m to 1.5 m vertical window. This is much wider than the variation in ear height for most listening positions.

The rear of the compact dipole loudspeaker is open, allowing the midrange drivers to radiate towards the back. The midrange frequency response shape is different from the front radiation because of the effects of the folded back baffle and the crossover filter cutoff (Fig. 24). The tweeter radiates towards the back only to the extend that its output is diffracted around the edge of the baffle.

The outdoor measurements shown present a less ambiguous picture of the loudspeaker's radiation characteristics than measurements taken in a closed room unless it is absorber lined. There are far fewer reflecting boundaries that introduce their signature into the measurerment data. Never-the-less, measurements in the listening room are instructive and can point towards deficiencies in speaker placement and listening position. The author's living room has two prefered listening positions. Position A, more close up for concentrated listening, and position B, for casual occasions (Fig. 25). Position A has better spatial imaging than B, but overall tonal balance is subjectively the same in both locations, even in positions C and D which are off the line of symmetry.

The frequency response of left and right loudspeakers in position A is generally flat when the data are smoothed over 1/3 octaves (Fig. 26). The 200 Hz drop in the response of the right loudspeaker looks quite objectionable but could not be confirmed when listening to program material. The drop is due to the corner position of the loudspeaker and caused by reflection of the rear radiation from adjacent walls. The path length difference between the direct signal to the listener and the reflected signal has to be a wavelength for a response reduction, or 1.7 m at 200 Hz. The loudspeaker is about half this distance away from rear and side walls, so that a cancellation could be expected. Moving the loudspeaker or drastically toeing it in, reduces the response aberration. Treating the corner with acoustic absorbing materials has not been tried and would seem difficult because of the low frequencies involved. Absorbers are likely to be bulky and may not match the rest of the decor. The left loudspeaker has a flatter response. It is located near the open door way to an adjacent room.

The frequency response is calculated from the first 50 ms of the impulse response and does not necessarily represent what we hear. The ears receive signals from the left and right loudspeaker which are spectrally and temporally shaped by the interaction of the loudspeaker with the room. The two traces of Fig. 26 are a gross simplification of a real listening event.

More information about the frequency domain behavior is obtained by analyzing an even longer time slice of 250 ms (Fig. 27). It extends the response to lower frequencies with 4 Hz resolution. Some of the detail of the combined room and loudspeaker response can be seen when the reponse is not smoothed over 1/3 octave (Fig. 28 and Fig. 29).

The frequency response in listening position B at 4.5 m distance from the loudspeaker should be even more strongly affected by the room than the response in position A at 2.8 m (Fig. 30 and Fig. 31). The off-axis radiation, particularly below 2 kHz contributes, to the tonal balance. The 200 Hz drop in the response from the right loudspeaker is not observed at position B. It is not at all obvious from a comparison of the last two figures with the previous response data for position A, that A is clearly the preferred place for better imaging and full enjoymment of sound reproduction.

3.7 Mechanical construction

The increased excursions of a dipole relative to a monopole cause higher levels of mechanical energy that have to be dealt with. The excitation of structural resonances in the enclosure and with it the storage and slow release of energy have to be minimized. Three precautions have been taken in the design. The cabinet size and surface area have been minimized, layers of damping material have been applied to the surfaces, and the midrange drivers have been quasi-elastically mounted. The drivers are held by the magnet to a spine like vertical post. The rim of the drivers' basket rests elastically in an oversize cut out hole in the front baffle. Sound absorbing material fills the shallow rear cavity of the enclosure.

The law of the preservation of momentum, $(m_1 \times v_1) = (m_2 \times v_2)$, applies to these as any other loudspeaker to the extend that mechanical energy is not dissipated as heat. The enclosure will move in reaction to the movement of the cone and in proportion to the ratio of cone to enclosure mass. The ratio is approximately (120 g)/(20 kg) or -44 dB in case of the dipole woofers. The movement of the enclosure is easily felt by hand. It has little acoustic effect as long as the movement is non-resonant. The surfaces are too small and light to resonate below 100 Hz. The woofer enclosure is constructed from 13 mm plywood, sufficient to serve as a sound duct. The high internal sound pressure levels of a closed box woofer which dictate stiff enclosures are not generated in a dipole configuration.

4 FUTURE WORK

The interaction between the dipole loudspeaker and the room requires further investigation. The room excitation should be different for dipole and monopole because of different off-axis responses. Some work has already been done on this subject [11]. In particular, the woofer and lower mid frequency range where room resonances are sparsely distributed [12] needs further study. The author is of the opinion that sound from a dipole is less masked by room modes than a monopole.

The subjective difference between a dipole and a monopole woofer needs a substantiated explanation. Is it the lower non-linear distortion level of the dipole or a different room excitation that cause it to be prefered over a monopole?

5 CONCLUSION

The compact dipole loudspeaker that has been described strikes a satisfying balance between acoustic and aesthetic values, in the author's situation. It is a compromise, like most engineering solutions, but in this case one that sacrifices little to acoustic performance and enjoyment. The positive, subjective assessment of the loudspeaker can be supported to a large extent with conventionally measured results, even though knowing what to measure and to look for in the data is still an evolving science. It is safe to state that our auditory perceptive system, two ears and a brain, extract more comprehensive information from a sound field than the single microphone and digital signal processor that generate the visual presentation of impulse and frequency response. Critical listening after the design is done and executed is crucial to assess the validity of the assumptions that went into the development of the loudspeaker. Conclusions drawn from listening to reproduced versus live sound were at the start of several development cycles and have led, over time, to the described compact dipole loudspeaker.

6 REFERENCES

[1] S. Linkwitz, "Loudspeaker System Design", Wireless World, Vol.84, May, June, December 1978. Reprinted in Speaker Builder Magazine, 1980 Issues 2,3,4. (Speaker Builder Magazine, P.O. Box 494, Peterborough, NH 03458-0494, Tel. 603-924-9464)

[2] S. Linkwitz, "A Loudspeaker Design for Reduced Reverberant Sound Power Output", 83rd AES Convention, New York, Oct. 1987, no preprint.

[3] J. Vanderkooy, "A Simple Theory of Cabinet Edge Diffraction", J. Audio Eng. Soc., Vol. 39, No.12, pp. 923-933, Dec. 1991

[4] L. L. Beranek, "Acoustics", McGraw-Hill, New York, 1954

[5] S. Linkwitz, "Active Crossover Networks for Non-coincident Drivers", J. Audio Eng. Soc., Vol. 24, No.1, pp. 2-8, Jan./Feb. 1976.

[6] S. Linkwitz, "Excursion-limited SPL Nomographs", Speaker Builder Magazine, 1984, Issue 4.

[7] L. D. Fielder, "Subwoofer Performance for Accurate Reproduction of Music", 83rd AES Convention, New York, Oct. 1987, preprint 2537.

[8] B. J. Elliott, Consultant in Electro-Acoustics, Palo Alto, CA, 415-856-7822. Discussion and demonstration of dipole woofer consisting of six 300 mm drivers per channel. December 1988.

[9] D. Barringer, Audio Engineer, US Marine Band, Washington, DC, 703-528-2227. Phone conversation November 1991.

[10] J. Vanderkooy, S. P. Lipshitz, "Power Response of Loudspeakers with Non-coincident Drivers", J. Audio Eng. Soc., Vol. 34, No.4, p. 236, 1986.

[11] S. P. Lipshitz, J. Vanderkooy, "Experiments in Direct/Reverberant Ratio Modification", 79th AES Convention, New York, Oct. 1985, preprint 2301.

[12] O. J. Bonello, "A New Criterion for the Distribution of Normal Room Modes", J. Audio Eng. Soc., Vol. 29, No.9, pp. 597-606, Sept. 1981

[13] R. F. Allison, "The Influence of Room Boundaries on Loudspeaker Power Output", J. Audio Eng. Soc., Vol. 22, No.5, pp. 314-319, June 1974.

[14] K. O. Ballagh, "Optimum Loudspeaker Placement Near Reflecting Planes", J. Audio Eng. Soc., Vol. 31, No.12, pp. 931-935, Dec. 1983.

[15] S. E. Olive, F. Toole, "The Detection of Reflections in Typical Rooms", J. Audio Eng. Soc., Vol. 37, No.7/8, pp. 539-553, July/August 1989.

[16] G. Plenge, "On the Behavior of Listeners to Stereophonic Sound Reproduction and the Consequences for the Theory of Sound Perception in a Stereophonic Sound Field", 83rd AES Convention, New York, Oct. 1987, preprint 2532.

[17] P. J. Walker, "New developments in Electrostatic Loudspeakers", J. Audio Eng. Soc., Vol. 28, No.11, p. 795, 1980.

[18] J. H. Streng, "Sound Radiation from a Vibrating Membrane", Philips Tech. Rev., Vol. 44,, No. 6, pp. 180-192, December 1988.

7 ADDITIONAL READING

[19] A. Gabrielsson, "Loudspeaker Frequency Response and Perceived Sound Quality", J. Acoust. Soc. Am., Vol. 90, No. 2, pp.707-719, August 1991.

[20] W. M. Hartmann, "Localization of a Source of Sound in a Room", Proc. of the AES 8th International Conference, THE SOUND OF AUDIO, Washington, May 1990, pp.27-32.

[21] F. E. Toole, "Loudspeakers and Rooms for Stereophonic Sound Reproduction", Proc. of the AES 8th International Conference, THE SOUND OF AUDIO, Washington, May 1990, pp.71-91.

[22] H. L. Han, "Frequency Responses in Acoustical Enclosures", 82nd AES Convention, London, March 1987, preprint 2448.

[23] A. Weckstrom, "Directive Loudspeaker Design", 82nd AES Convention, London, March 1987, preprint 2448.

[24] J. Salmi, A. Weckstrom, "Listening Room Influence on Loudspeaker Sound Quality and Ways of Minimizing it", 71st AES Convention, Montreux, March 1982, preprint 1871.

[25] R. J. Newman, "Dipole Radiator Systems", J. Audio Eng. Soc., Vol. 28, No.1/2, pp. 35-39, Jan./Febr. 1980.

APPENDIX

Some thoughts that might stimulate further investigation into the interaction between a dipole loudspeaker and a reverberant room are presented as appendix A-1. Potential problems with the design of a dipole loudspeaker are summarized in A-2.

A-1 LOUDSPEAKER AND ROOM INTERACTION

It is well known that the perceived sound at the listening position in a room is influenced by the directionality of the loudspeaker and by the acoustic properties of the room. All loudspeakers become more directional as frequency increases, because the size of the radiating element becomes equal to or larger than the wavelength of the radiated sound. At low frequencies, where box and radiator size are small compared to the wavelength, closed box loudspeakers are omni-directional and behave like monopoles. A dipole type loudspeaker, though, maintains directivity to the lowest frequency and will therefore interact differently with the room.

The contribution of the room depends upon the ratio of room dimensions to sound wavelength. For illustration, consider a room of 7.5 m length, 4.6 m width and an angled ceiling that changes linearly in height between 2.7 m and 3.8 m across the width of the room (Fig. 25).

A-1.1 Very low frequencies

At very low frequencies for which length, width and height of the room are less than half a wavelength, i.e. below (340 m/s)/(2 x 6.5 m) = 23 Hz for a maximum dimension of 6.5 m, the sound pressure at the listening position is a function of the rigidity and air tightness of the room. Sound pressure is lost because the walls are not perfectly rigid and absorb energy as they flex. Sound is also lost to openings like doorways and windows.

Inside any room, sound pressure will increase until an equilibrium is reached between the acoustic energy delivered by the loudspeaker and the sound energy absorbed by the room. The total power output of a dipole loudspeaker is one third (-4.8dB) of that for a monopole, when both produce the same on-axis sound pressure level under free-field conditions. The average sound pressure level in the room will therefore be 4.8 dB lower for the dipole than for the monopole.

A-1.2 Low frequencies

With increasing frequency of the sound, the wavelength decreases and one or several of the room dimensions become equal to a half-wavelength or an integer multiple thereof. Under these conditions transverse standing waves may be excited by the loudspeaker and a sinusoidal sound pressure distribution develops up in the room. The walls act as boundaries, where the sound particle velocity is zero, and the sound pressure reaches a maximum. The sound pressure will have maxima and nulls at discrete locations in the room (Fig. 32). The room modes are resonance phenomena. Energy is stored and released at a rate that depends upon the absorbing properties of the room. The sound pressure at these frequencies typically builds up to higher levels and decays more slowly than the signal that excited the resonance.

The transverse and higher order standing wave modes can be determined from the room dimensions [4]. There are, for example,

Fig. 25, seven calculated transverse modes below 105 Hz. They occur at 26, 52, 78 and 105 Hz due to the 6.5 m length, at 37 and 74 Hz due to the 4.6 m width and at 53 Hz for an average ceiling height of 3.23 m. There will be floor-to-ceiling standing wave modes even with a slanted ceiling. Not all modes will necessarily be excited by the loudspeaker. Its placement and directionality determine which modes contribute to the soundfield in the room.

It is difficult to state specifics for a given loudspeaker position, but some general statements can be made about mode excitation. Most loudspeakers are placed near the room boundaries. These are high pressure regions for standing wave modes and for the loudspeaker acoustic output. A monopole loudspeaker will therefore feed energy effectively into the modes in these locations.

Assume either a monopole or a dipole loudspeaker along the sidewall and 1.1 m out from the corner of the room (Fig. 25, right woofer). The modes at 26, 52, 78 and 105 Hz will have nulls at 3.25, 1.63, 1.08 and 0.81 m distance from the end wall respectively. The monopole could be expected to couple poorly to the 78 Hz mode with a pressure null at 1.08 m. A dipole loudspeaker as a velocity source, on the other hand, should feed energy effectively into the same mode because the pressure null is also the location of the maximum sound velocity. Listening position A is at a pressure maximum for the 78 Hz mode. The measured response at position A, though, gives no clear indication of a maximum (Fig. 28). More work is needed to understand which of the potential modes are actually excited by either a monopole or a dipole and to obtain correlation to measured results.

The dipole, unlike the monopole, will not radiate at 90 degrees to the opposite sidewall and not at 90 degrees towards the ceiling. The dipole should therefore have much less of a tendency to excite the 37 Hz and 74 Hz side-to-side and the 53 Hz floor-to-ceiling modes or the higher frequency multiples of these modes than the monopole. The dipole should, therefore, have reduced mode related variations in the frequency response at the listening position.

A-1.3 Medium frequencies

With further increase in frequency to above a few hundred Hertz, the the room dimensions become large compared to the wavelength of the radiated sound. The number of room resonances per octave of frequency coverage increases drastically (Fig. 28 and Fig. 29). The room behavior is now best described statistically by the time at which sound decays to -60 dB, i.e. its reverberation time. The reverberation time includes the effect of sound reflected from one room surface to any other room surface until it has decayed. Reverberation is a description of the room's time domain behavior, useful at higher frequencies. Resonances or room modes are a description in the frequency domain, applicable only at low frequencies.

Again, a dipole interacts differently with the room than a monopole. Overall, the dipole radiates only one third of the acoustic power into the room for the same on-axis sound pressure level as the monopole. It also has only one third of the power available for the reverberant field. The room will therefore contribute 4.8 dB less to the timbre of the reproduced sound. Recorded ambience will be presented more accurately at the listening position since the reverberant field in the room is reduced. Stated differently, the "critical distance", the distance at which the direct sound level from the loudspeaker has decreased to equal the reverberant sound level in the room, is three times larger for the dipole than the monopole. This means, in practice, that for a fixed ratio of direct to reverberant sound, the listening position can be three times further away from the dipole than for the monopole loudspeaker.

A-1.4 High frequencies

At frequencies above a few kHz most loudspeakers become directional because of the size of the radiating elements (Fig. 5). The power output decreases, even when the loudspeaker maintains a constant on-axis sound pressure level. Less power is therefore available for the reverberant field. Also, most rooms absorb sound more effectively at high frequencies. The shorter reverberation time leads to a lower reverberant sound field level. Both effects, reduced available sound power and increased room absorption, make this frequency range less critical. There is no advantage in using a dipole loudspeaker at high frequencies with regards to room reverberation.

A-1.5 Reflections

Sound from the loudspeaker is reflected from all six surfaces of the room. Reflections occur at all frequencies. The first reflection of the sound from a nearby surface is usually of concern to the loudspeaker designer [13, 14]. It degrades the smoothness of the frequency response and may affect the stereo image. Reflection of the sound, as it bounces between multiple surfaces, until it has decayed through absorption by air and walls, is the cause for the reverberant sound field. The first reflection is merely the beginning of a reverberation process and should not be viewed in isolation only. The effect of the first reflection upon the loudspeaker frequency response is easily measured and difficult to avoid in response measurements below a few hundred Hertz. It does not necessarily follow, that these clearly visible effects upon the frequency response are also audible. The ear and brain combination processes acoustic information quite differently from the test eqipment and much work still needs to be done on the perception of sound, especially under reverberant conditions [15, 16].

A-1.5.1 Rear wall reflection

Dipoles are often thought to be particularly sensitive to the reflection from the rear wall. Dipoles radiate the same sound to the rear as to the front, 180^0 out-of-phase. It is standard practice to place a dipole at some distance from the rear wall.

The author had observed that all his previous closed box designs would benefit subjectively from being moved out into the room and away from the walls, even when provisions had been made to flush-mount the loudspeakers. Flush-mounting removes the rear wall reflection, yet the sound from the loudspeaker, when at least 0.6 m from the rear wall, was preferred for greater image depth.

A dipole could be expected to behave similarly to a closed box, even though its rear radiation is phase reversed from the front radiation. One difference between the two loudspeakers types is the extend of the frequency spectrum that is radiated towards the rear. The other is in the frequency response since reflections from the rear wall will produce valleys where the closed box had peaks, and peaks where it had valleys. The rear radiation from the closed box decreases naturally with increasing frequency, reducing this effect. The rear radiation of the compact dipole was intentionally reduced, after earlier experiments with full range rear radiation showed some problems in the kHz range.

A-1.5.2 Floor reflection

The floor reflection is difficult to avoid in the 100 Hz to 3 kHz frequency range unless the loudspeaker is highly directional or flush with the floor. A loudspeaker would have to be much taller than a wavelength, 3.4 m at 100 Hz, to obtain directivity at low frequencies. The acoustic length would have to decrease 30 to 1, proportionally to the change in wavelength from 100 Hz to 3 kHz, to maintain directivity and the same sidelobe structure over the whole frequency range.

Alternatively, the loudspeaker could be placed flush with the floor. This works only for very low frequencies. One can easily tell that the sound is coming from the floor, if the loudspeaker is allowed to reproduce the spectrum above 100 Hz, even though there is no floor reflection.

An earlier version of the dipole consisted of a vertical array of drivers, symmetrical around a center tweeter. The tweeter was 0.6 m above the floor and the whole loudspeaker was tilted backwards, so that the tweeter axis aimed towards a 1 m ear height at the listening position. This arrangement gave the distinct impression of listening downwards, towards the floor. The loudspeaker was raised to a 1 m tweeter elevation for a more natural sound stage presentation.

It should be noted, that all our listening experiences, and not just with loudspeakers, include floor reflections. We may have adapted our hearing process to this fact [16]. Regardless of the psycho-acoustics involved, a dipole loudspeaker causes similar floor reflections as a comparably constructed monopole. The reduction in reflected sound level due to the dipole's vertical directivity is small.

A-1.5.3 Side wall and ceiling reflections

The reflection from the sidewall can be reduced significantly with a dipole by angling the loudspeaker towards the listening position. This orientation takes advantage of the cosine or figure-of-eight polar pattern of the dipole, where the null in output points towards the side walls. Likewise, the same behavior of the polar pattern in the vertical direction reduces the ceiling reflection. Usually, the ceiling is at a greater distance and the signal that is reflected from the ceiling had to exit the dipole at a large off-axis angle where its amplitude is already reduced. A closed box loudspeaker, in contrast, is usually omni-directional up to several hundred Hertz and sends its output equally to all the reflecting surfaces in the room.

A dipole loudspeaker, in summary, excites fewer room resonances, provides less power for the reverberant field and has lower reflected signal levels from side walls and ceiling than a closed box, monopole loudspeaker. Reflections from the floor are similar for the two types of loudspeakers and so are rear wall reflections, if the rear radiation from the dipole is restricted to low frequencies.

A-2 POTENTIAL PROBLEMS

A dipole loudspeaker has its own unique set of problems. It radiates sound bi-directionally, with the sound towards the front phase- reversed from the sound towards the back. The two tend to cancel each other very effectively at low frequencies where the path length between front and back is short compared to a wavelength. The cancellation becomes less with increasing frequency. At the frequency where the path length equals half a wavelength, the rear radiation has undergone a phase reversal and adds to the front radiation.

The frequency response rolloff can be equalized electronically at the expense of increased power required to drive the dipole. The more serious drawback is the associated increase in excursions for the radiating element. The volume of air that has to be moved to maintain a constant sound pressure level increases at a rate of 18 dB per octave (60 dB/dec). A dipole radiator requires, therefore, 1000 times the excursions at 50 Hz compared to 500 Hz for the same output. A monopole would require only 100 times the excursions to maintain constant output between 50 Hz and 500 Hz.

Dipole loudspeakers are usually designed with large planar radiating elements to move sufficient volumes of air while keeping excursions small. The large elements become directional radiators at higher frequencies where their size is no longer small compared to the wavelength. The polar pattern tends to have many lobes because of the acousticaly large radiator size. Different design approaches [17, 18] have been used to reduce the resulting beaming effect which would make the optimum listening position very critical.

Conventional cone type drivers were chosen as the radiating elements for the compact dipole loudspeaker to overcome the mentioned potential problems. The excursion requirements can be satisfied by using multiple drivers. Undesired increases in directivity can be avoided by selecting appropriate driver and panel sizes. Furthermore, multiple lobes and beaming can be eliminated by using dipole operation only for the frequency range for which room interaction is significant and by using a conventional tweeter for high frequencies. The availability of electro-dynamic drivers from a variety of manufacturers gives a wide selection of units suitable for a dipole loudspeaker and keeps costs reasonable.

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8 FIGURES

Fig. 1. Front and side view of the compact dipole loudspeaker.

Fig. 2. Dipole modeled as two point sources of opposite polarity.

Fig. 3 Frequency response of dipole model at 0, 30, 45 and 60 degrees off-axis.

Fig. 4. Theoretical sound pressure level at 1 m distance in half-space when excursion limited to 10 mm peak to peak.
a) Monopole with four 300 mm drivers.
b) Dipole with four 300 mm drivers.
c) Dipole with twelve 300 mm drivers.

Fig. 5. Power response of monopole and dipole relative to piston diameter.

Fig. 6. Power response and beam width of an array of two dipoles.

Fig. 7. Frequency response of dipole woofer vs. distance from its center. Woofer measured outdoors on a flat surface.

Fig. 8. Off-axis response of dipole woofer at 0, 30, 45 and 60 degrees.

Fig. 9. Off-axis response of closed box woofer at 0, 30, 45 and 60 degrees. No equalization.

Fig. 10. Off-axis response of midrange at 0, 30, 45 and 60 degrees. 110 mm deep folded baffle.

Fig. 11. Off-axis response of midrange at 0, 30, 45 and 60 degrees. 90 mm deep folded baffle.

Fig. 12. Off-axis response of midrange at 0, 30, 45 and 60 degrees. Folded baffle with closed rear opening.

Fig. 13. Off-axis response of midrange at 0, 90 and 180 degrees. 90 mm deep folded baffle.

Fig. 14. Off-axis response of midrange at 0, 90 and 180 degrees. Folded baffle with closed rear opening.

Fig. 15. Off-axis response of tweeter at 0, 30, 45 and 60 degrees.

Fig. 16. Frequency response of midrange dipole equalizer.

Fig. 17. Circuit topology of midrange dipole equalizer.

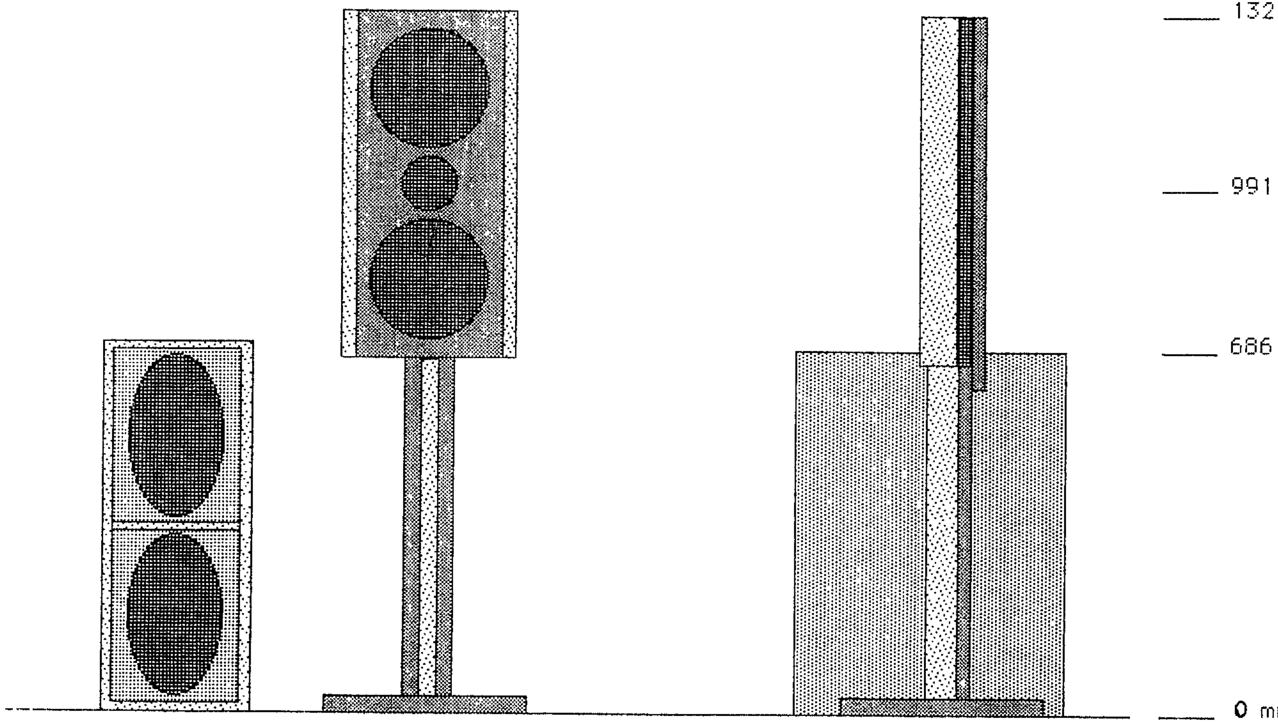


Fig. 1. Front and side view of the compact dipole loudspeaker.

5/18/92 SL

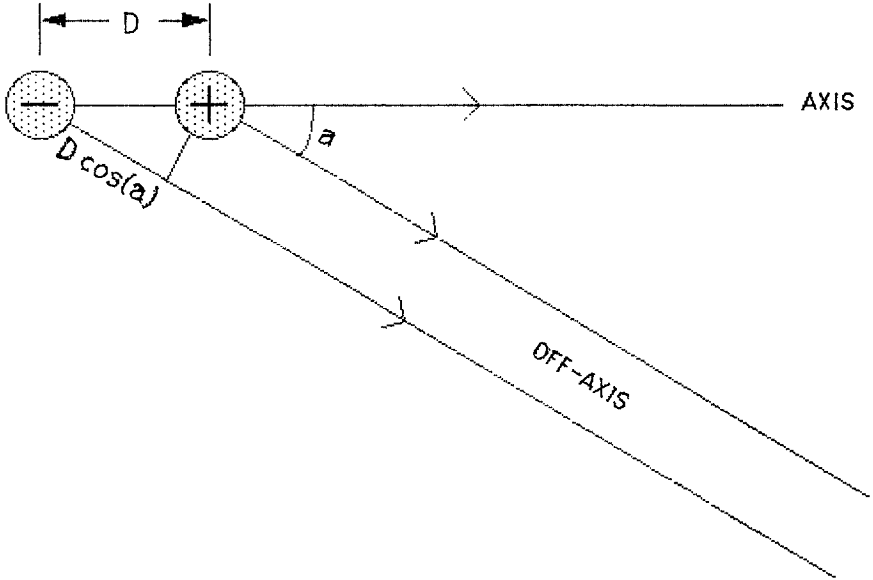


Fig. 2. Dipole modeled as two point sources of opposite polarity.

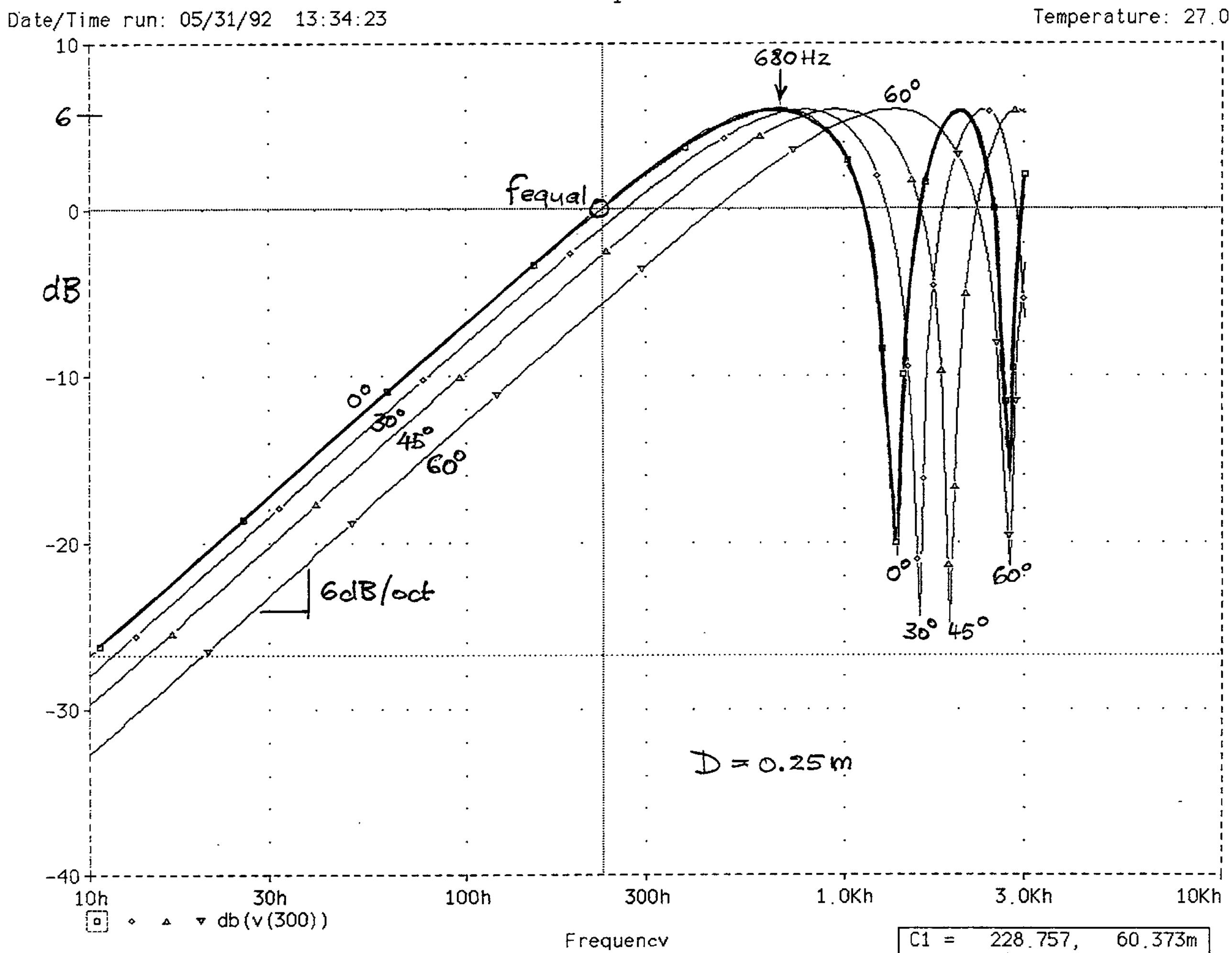


Fig. 3 Frequency response of dipole model at 0, 30, 45 and 60 degrees off-axis.

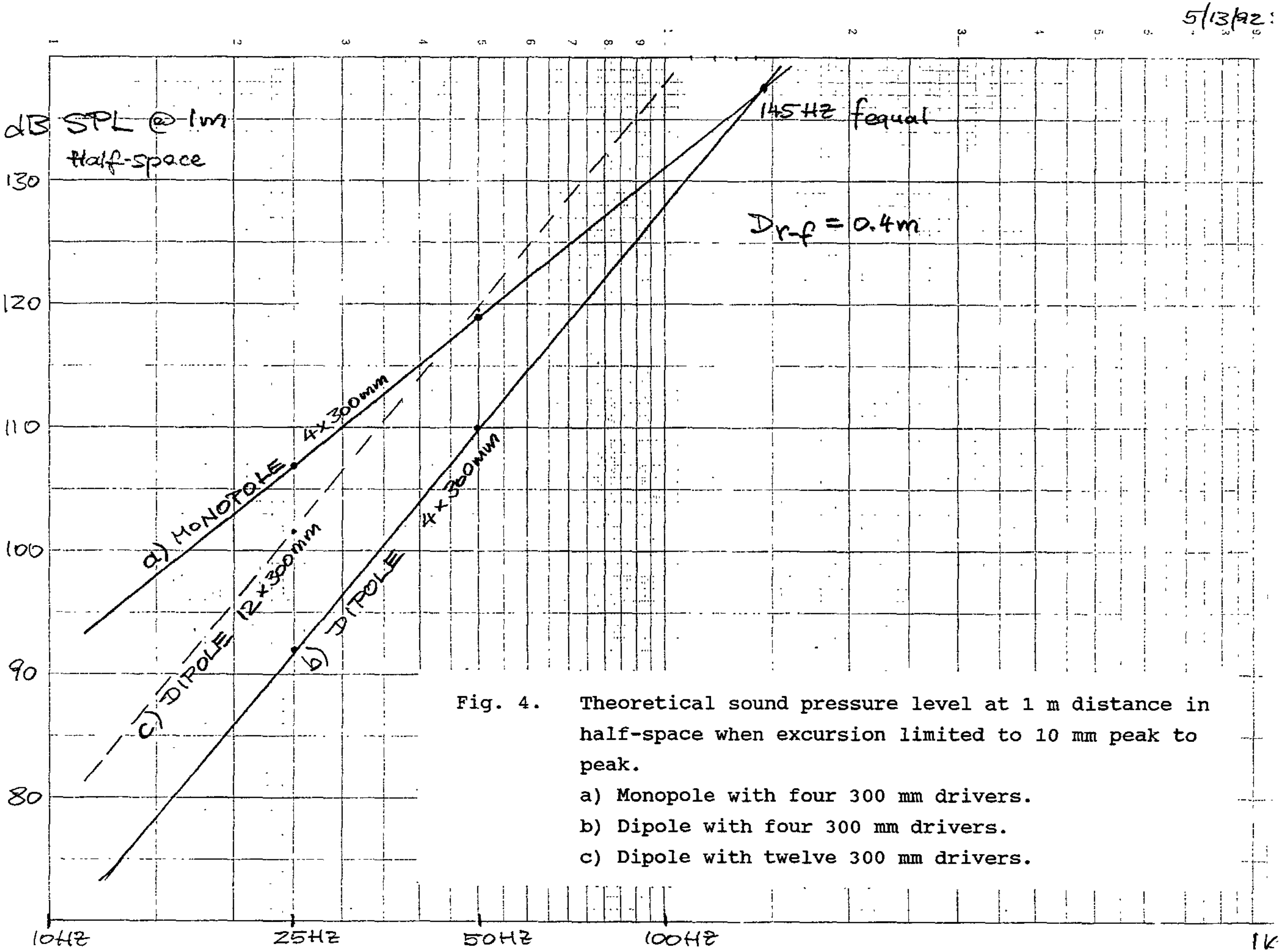


Fig. 4. Theoretical sound pressure level at 1 m distance in half-space when excursion limited to 10 mm peak to peak.

a) Monopole with four 300 mm drivers.

b) Dipole with four 300 mm drivers.

c) Dipole with twelve 300 mm drivers.

POWER RESPONSE vs. PISTON DIAMETER

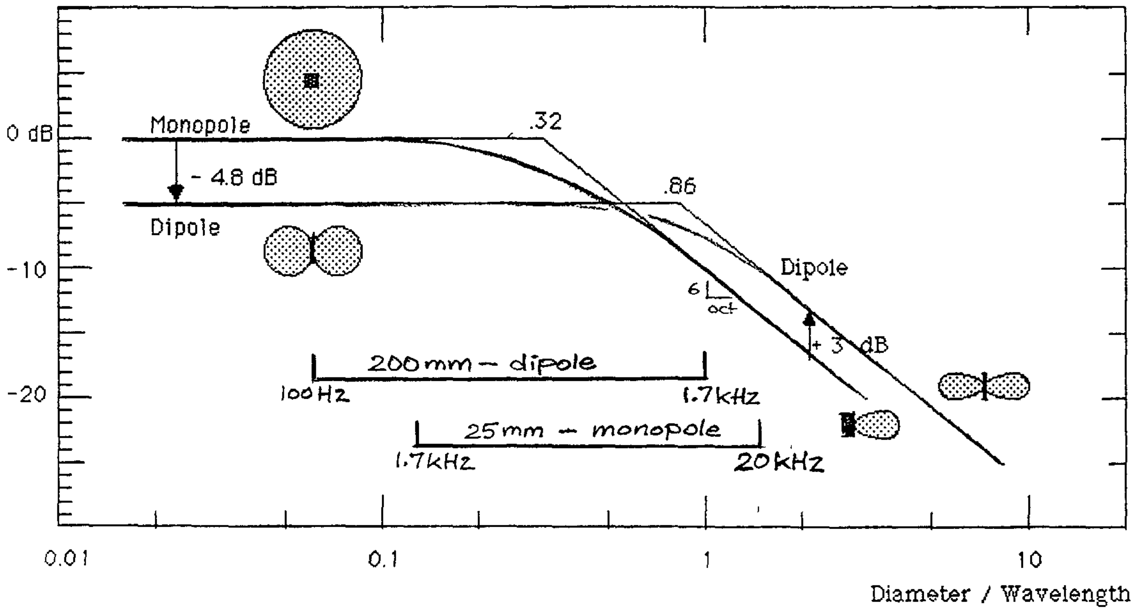


Fig. 5. Power response of monopole and dipole relative to piston diameter.

4-9/87 SL

Beamwidth & Power Response of 2-Dipole Array

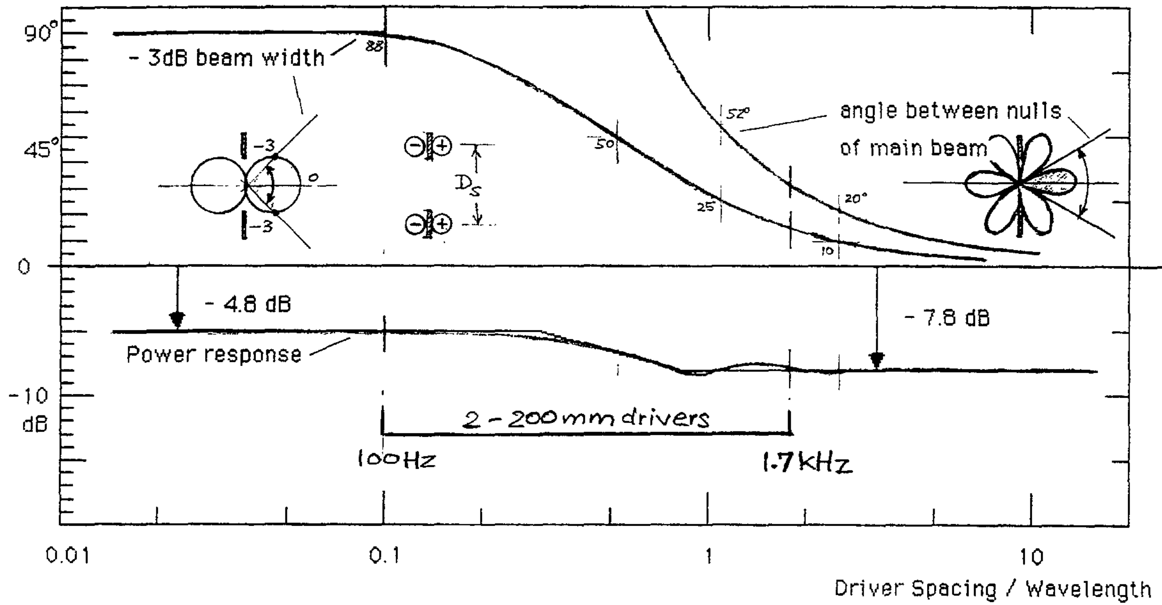


Fig. 6. Power response and beam width of an array of two dipoles.

5-9/87 SL

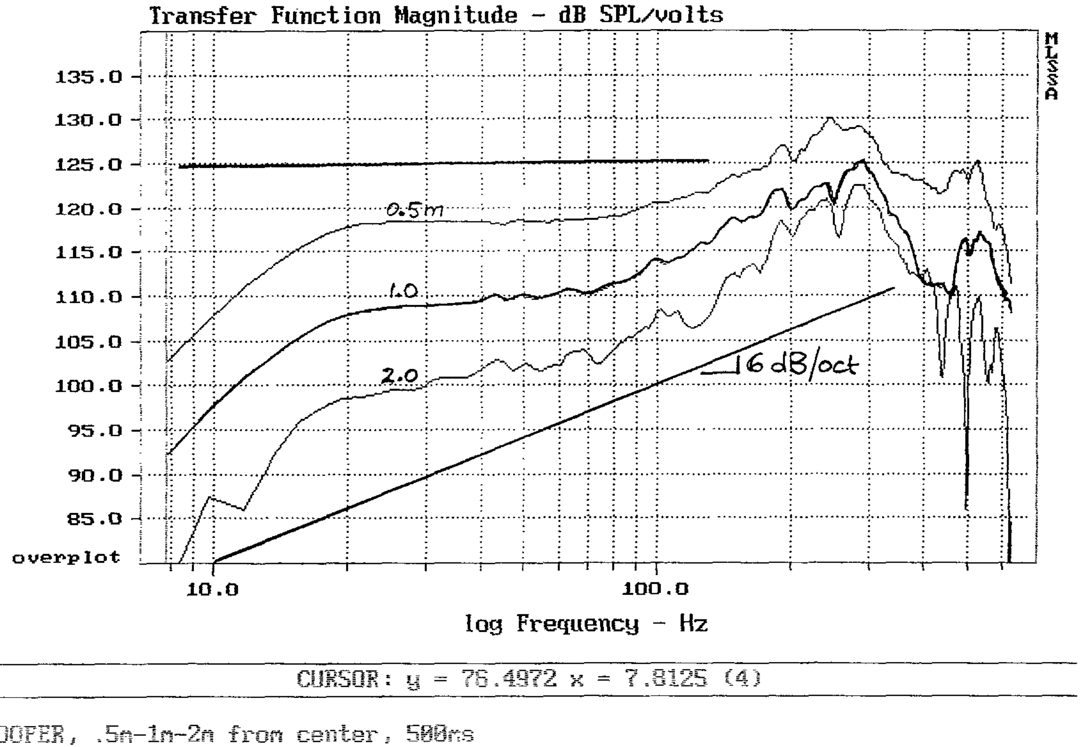


Fig. 7. Frequency response of dipole woofer vs. distance from its center. Woofer measured outdoors on a flat surface.

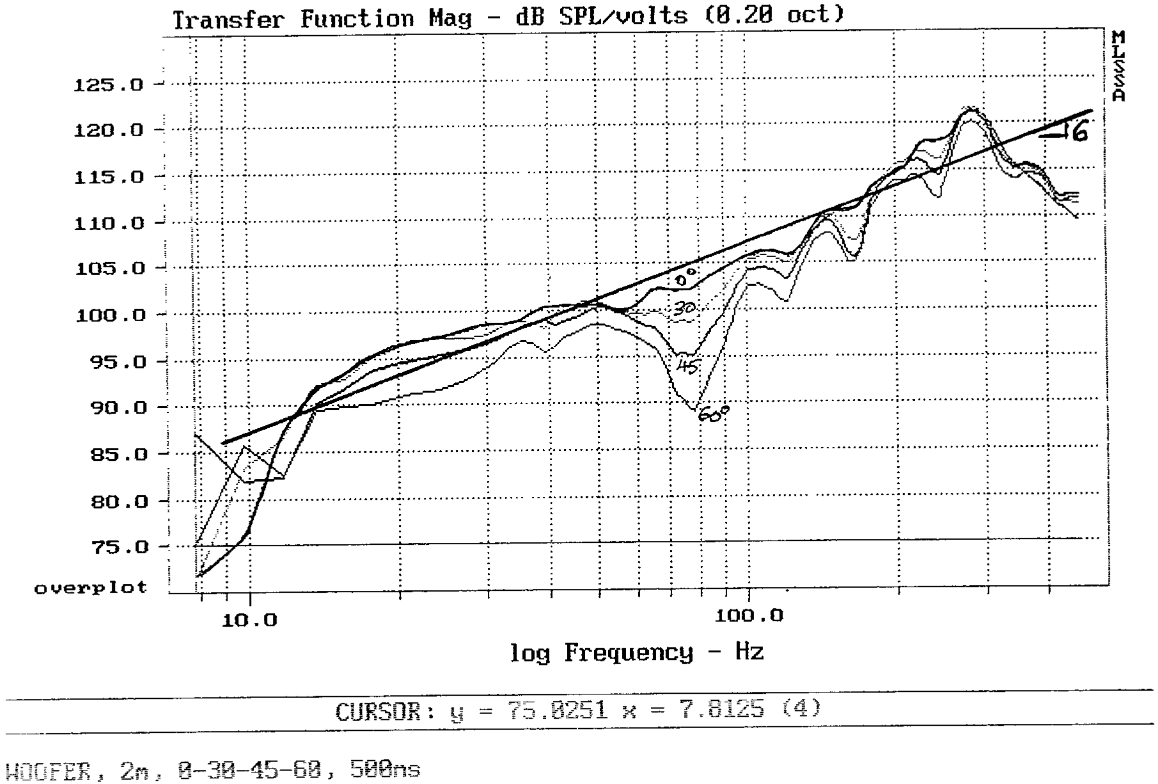


Fig. 8. Off-axis response of dipole woofer at 0, 30, 45 and 60 degrees.

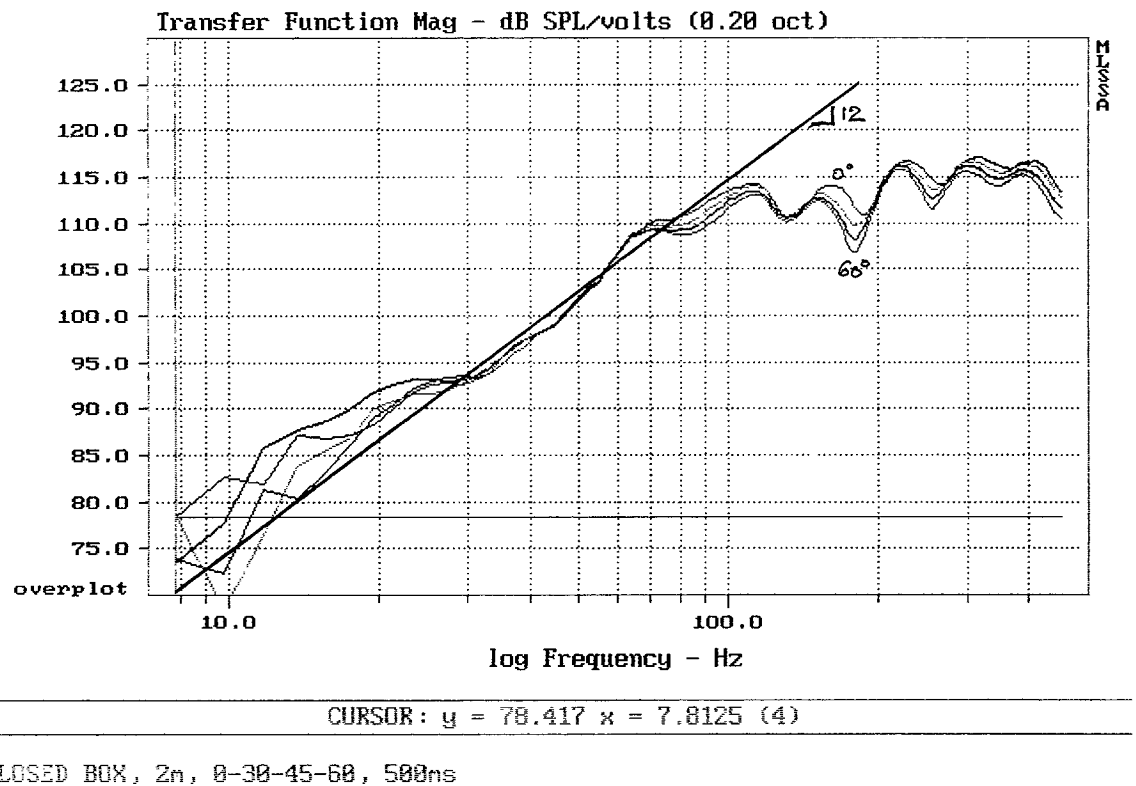


Fig. 9. Off-axis response of closed box woofer at 0, 30, 45 and 60 degrees. No equalization.

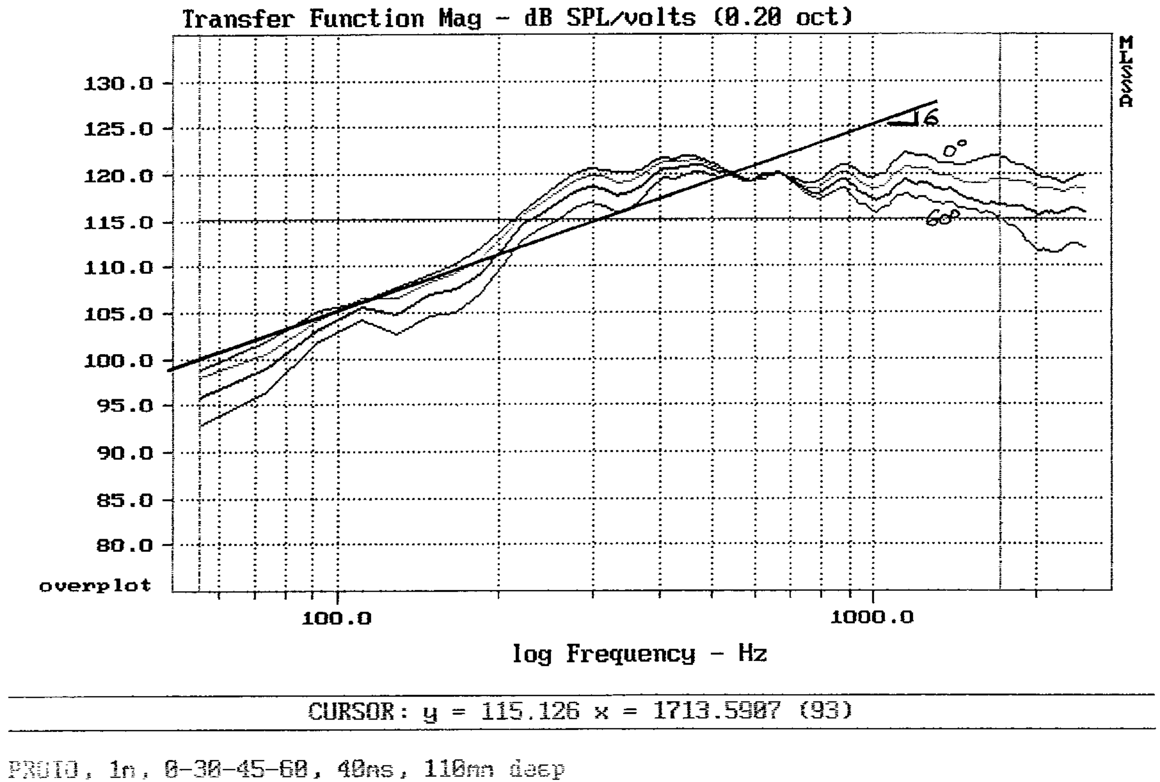


Fig. 10. Off-axis response of midrange at 0, 30, 45 and 60 degrees. 110 mm deep folded baffle.

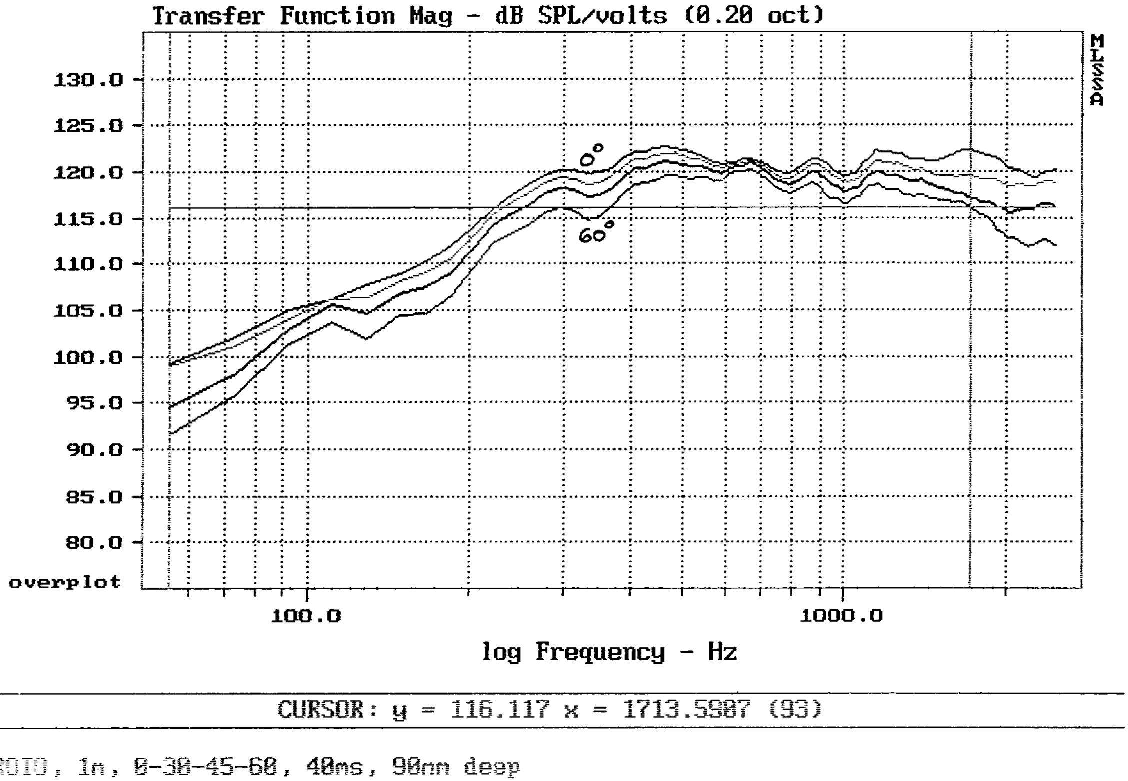


Fig. 11. Off-axis response of midrange at 0, 30, 45 and 60 degrees. 90 mm deep folded baffle.

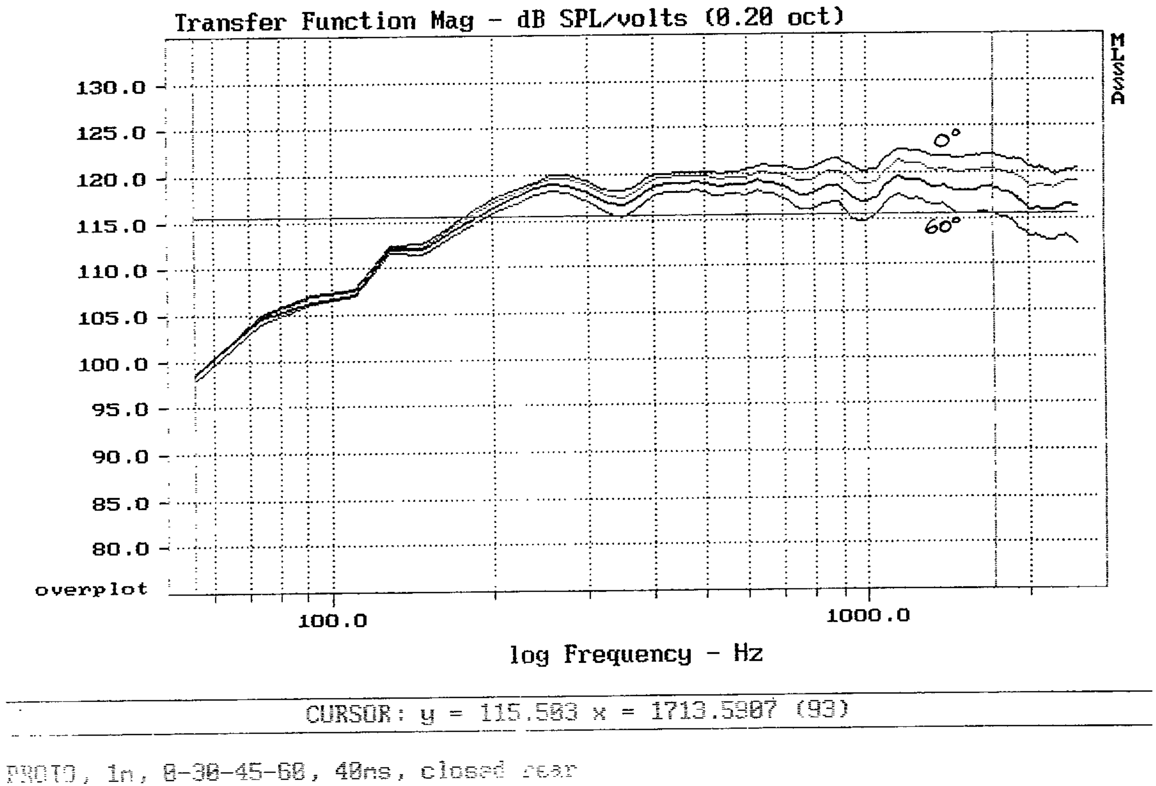


Fig. 12. Off-axis response of midrange at 0, 30, 45 and 60 degrees. Folded baffle with closed rear opening.

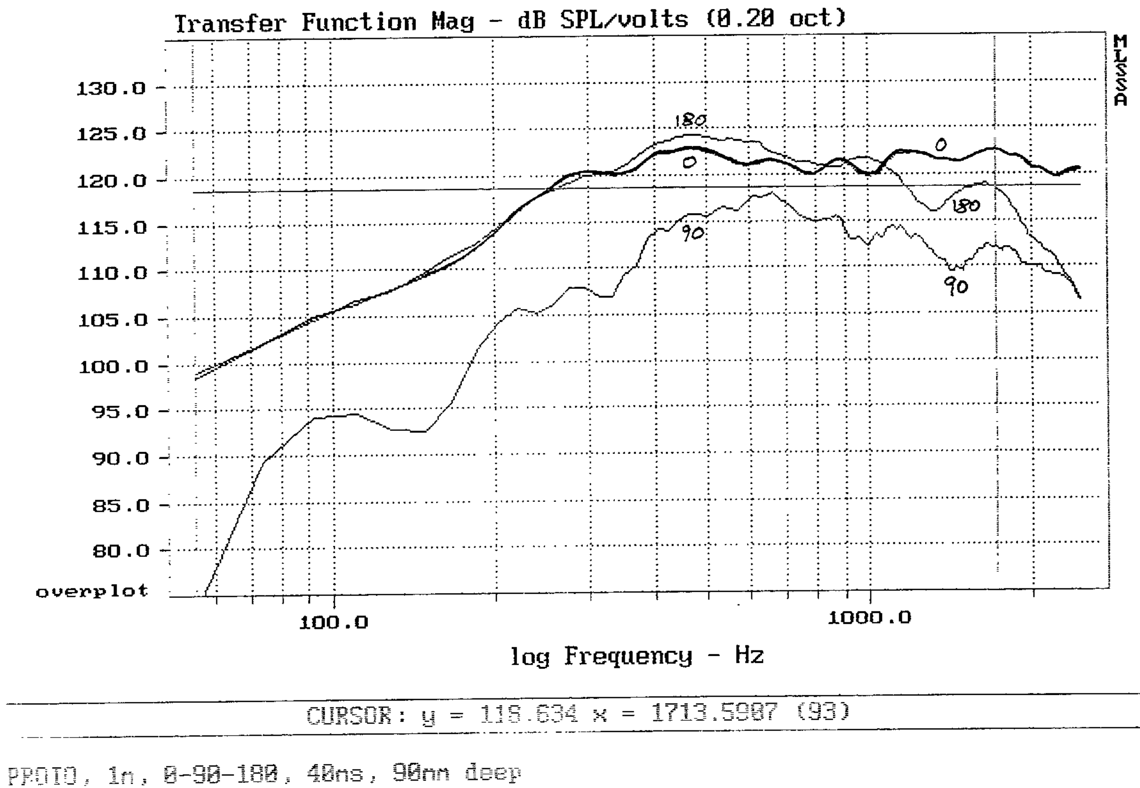


Fig. 13. Off-axis response of midrange at 0, 90 and 180 degrees. 90 mm deep folded baffle.

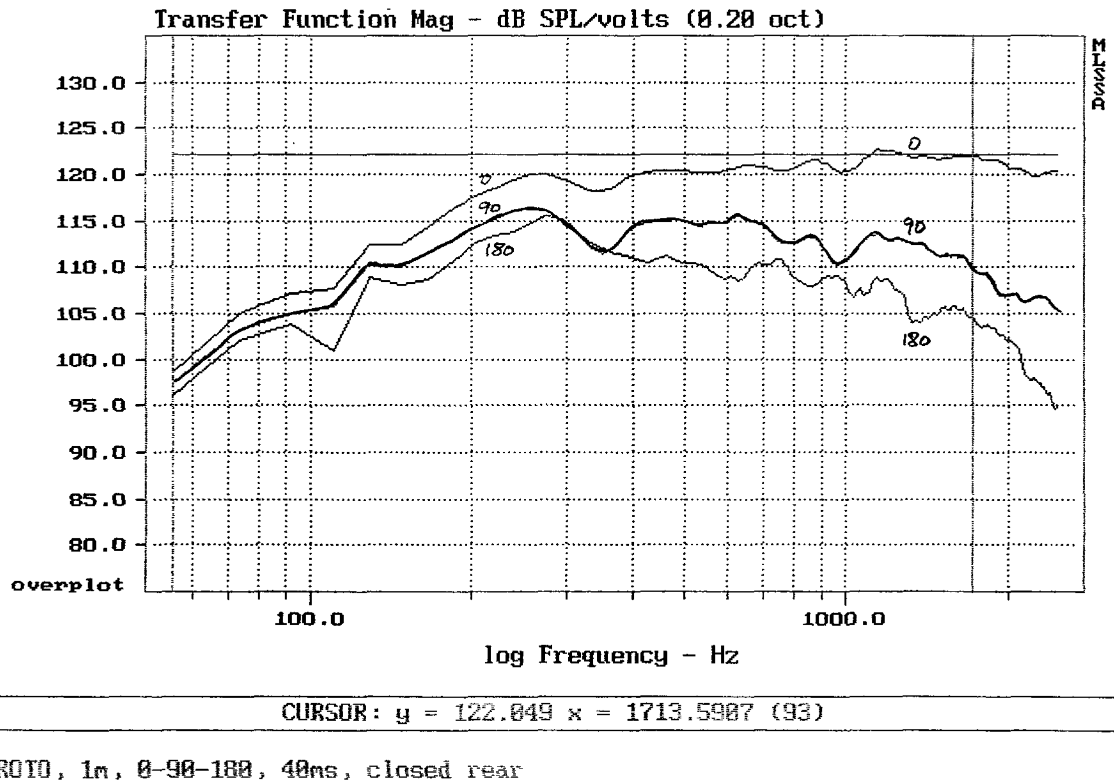
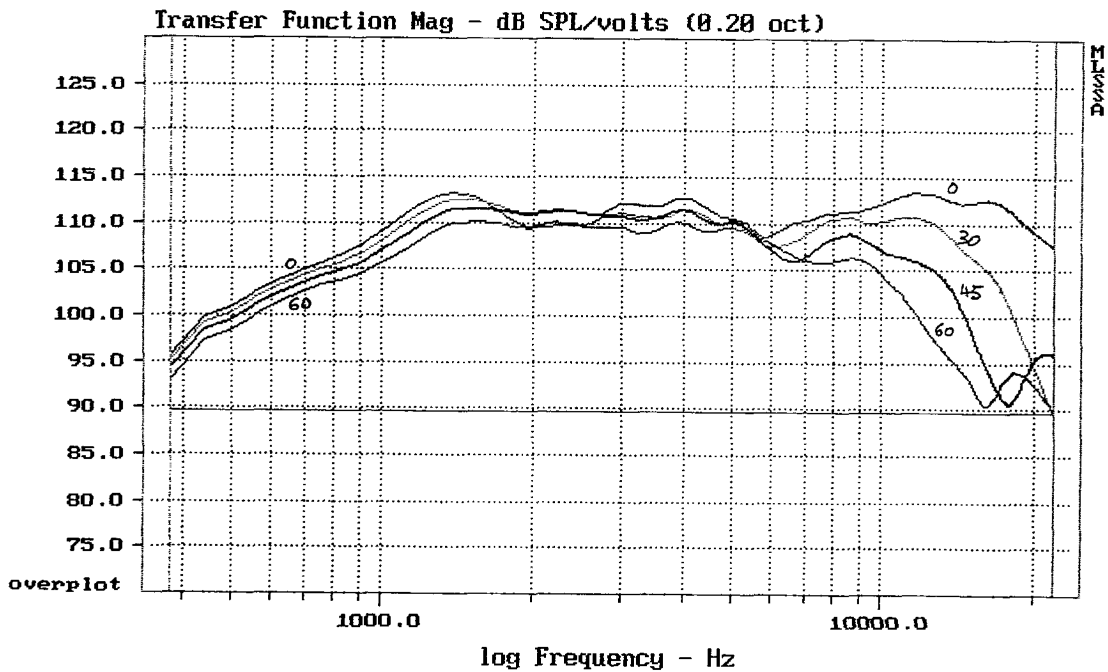


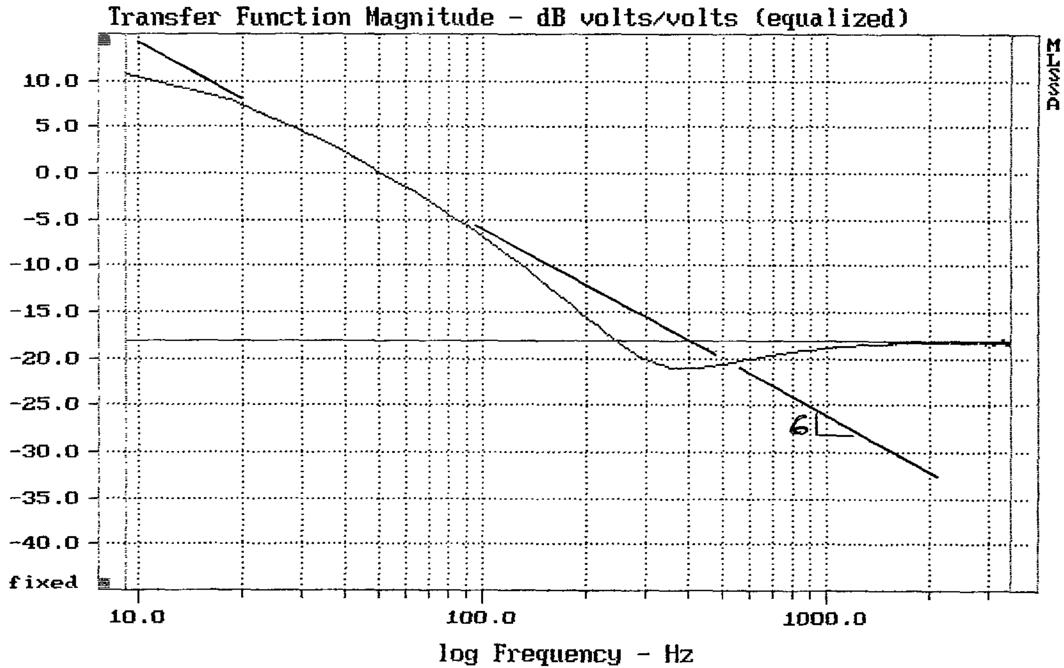
Fig. 14. Off-axis response of midrange at 0, 90 and 180 degrees. Folded baffle with closed rear opening.



CURSOR: y = 89.5314 x = 21925.4031 (348)

PROTO, 1m, 0-30-45-60, tweeter, 4ms

Fig. 15. Off-axis response of tweeter at 0, 30, 45 and 60 degrees.



MIDRANGE DIPOLE EQ

Fig. 16. Frequency response of midrange dipole equalizer.

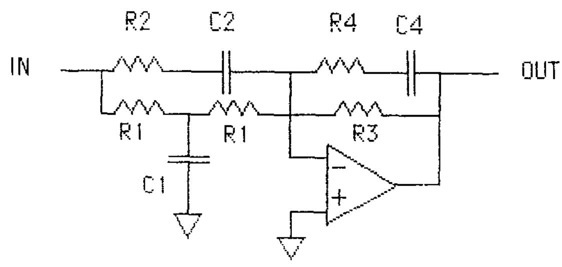


Fig. 17. Circuit topology of midrange dipole equalizer.

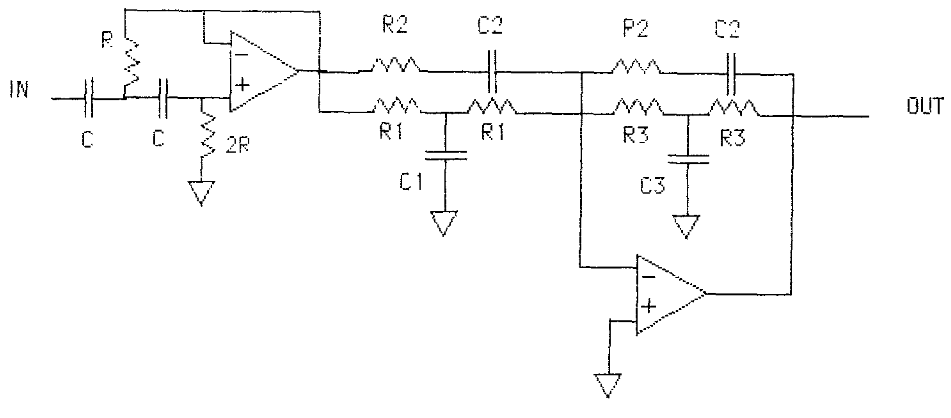


Fig. 18. Circuit topology of tweeter highpass filter.

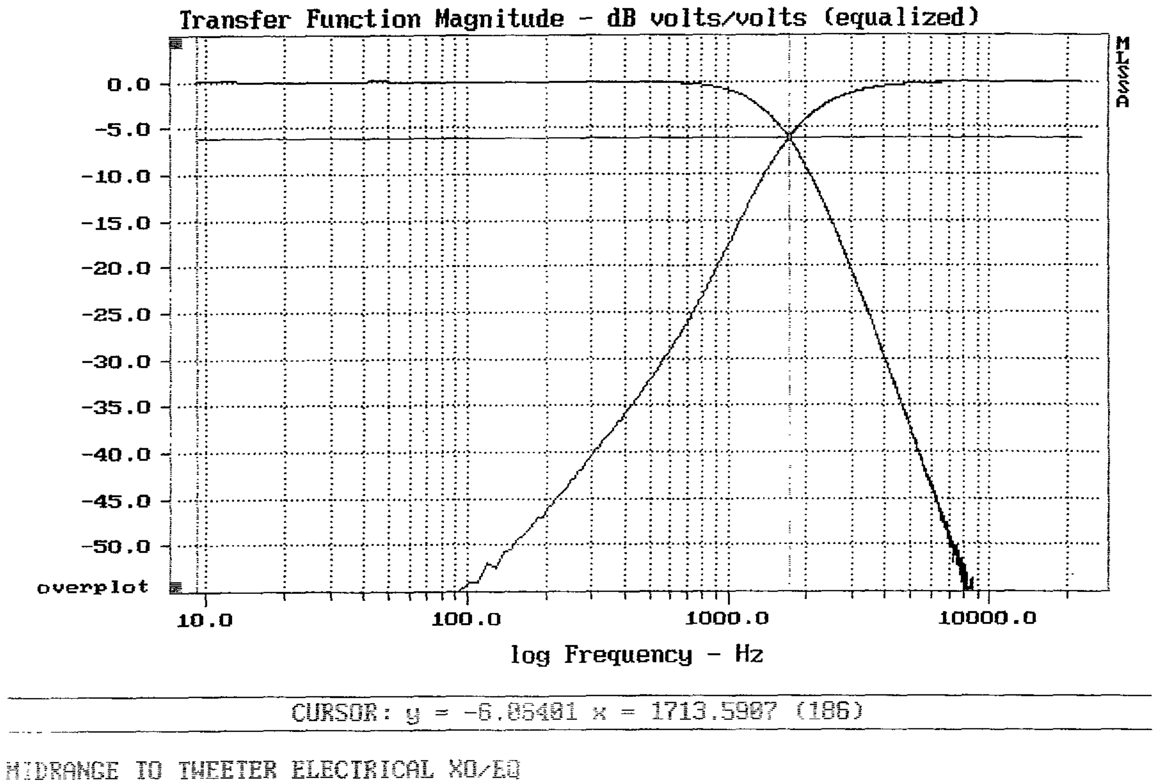
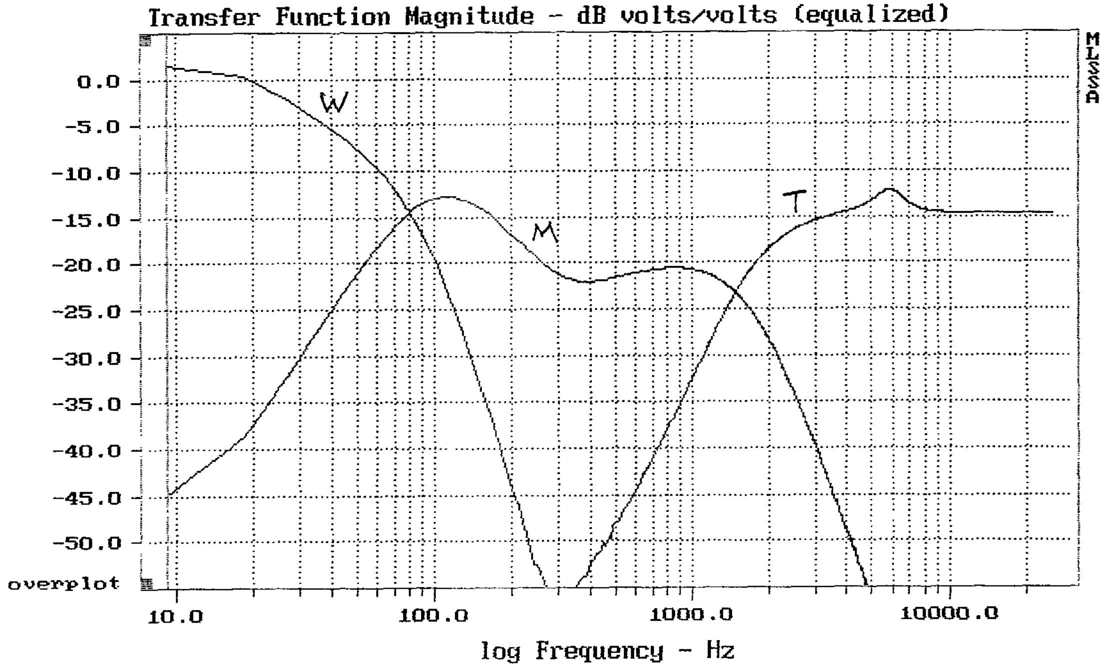
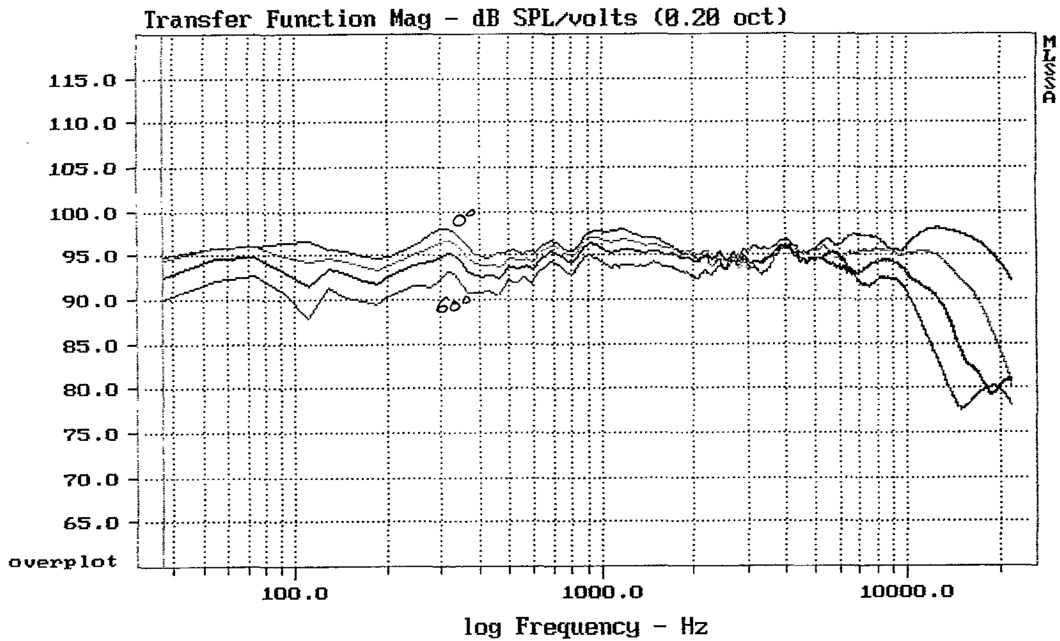


Fig. 19. Frequency response of midrange lowpass and tweeter highpass.



CROSSOVER/EQ

Fig. 20. Combined frequency response of electrical crossover and equalization for woofer, midrange and tweeter.



CDL, 1n, 0-30-45-60, 40ms, outdoors

Fig. 21. Compact dipole loudspeaker frequency response at 0, 30, 45 and 60 degrees off-axis horizontally.

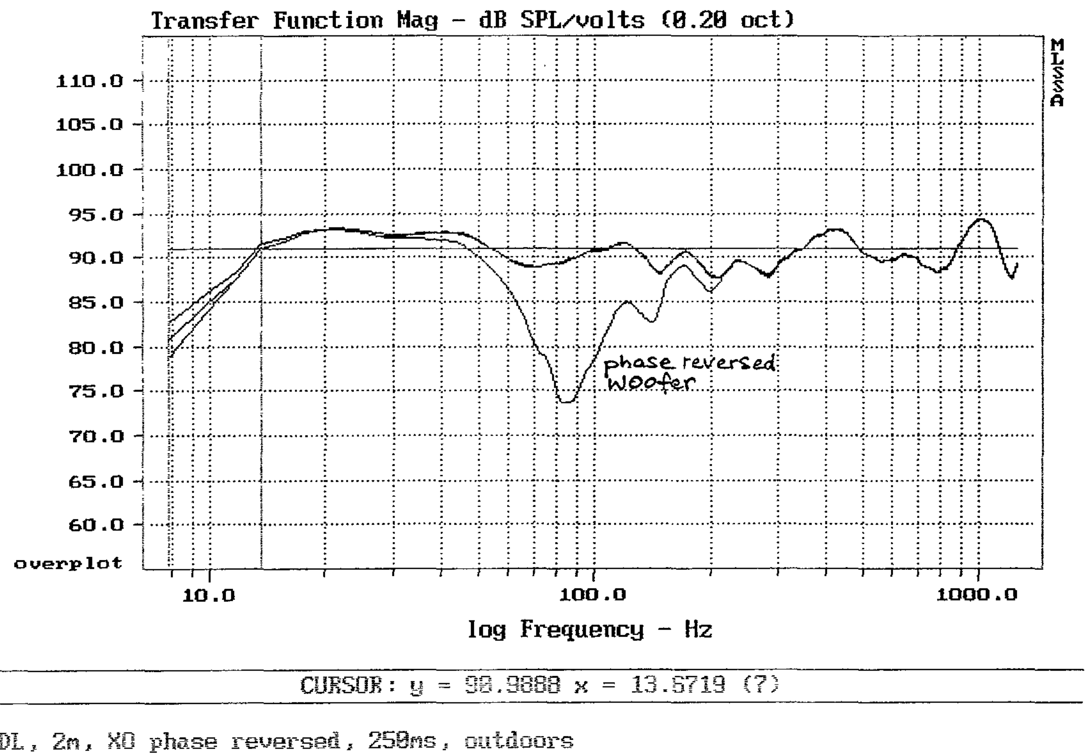
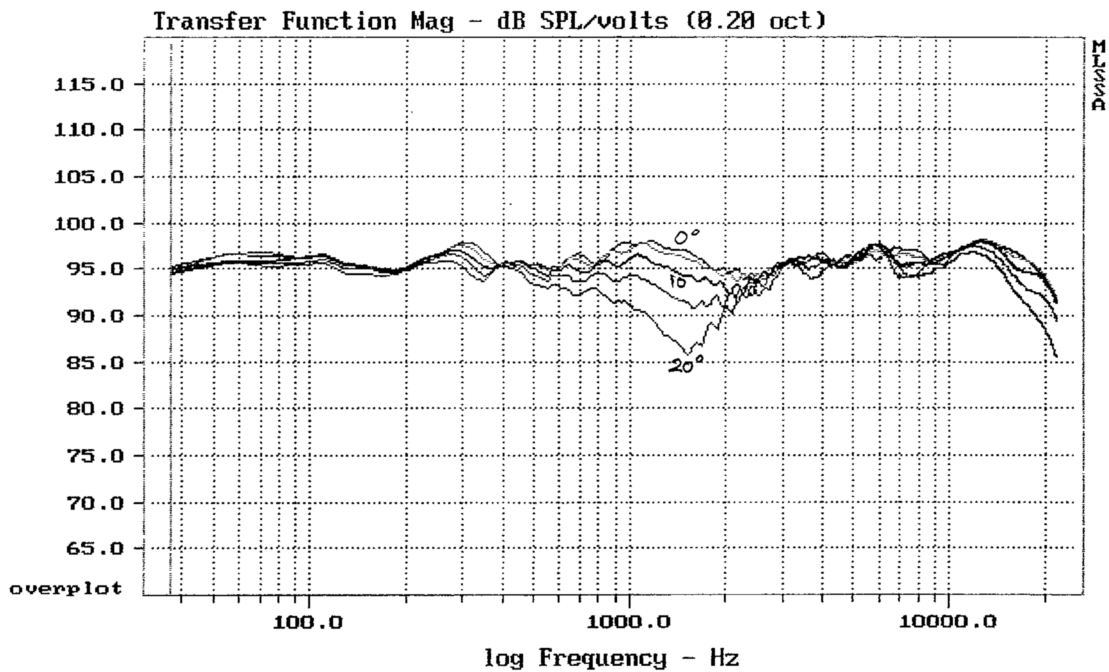


Fig. 22. Low frequency response of compact dipole loudspeaker for in-phase and out-of-phase connection of woofer and midrange.



CDL, 1m, 0-5-10-15-20 vertical, 40ms, outdoors

Fig. 23. Compact dipole loudspeaker frequency response at 0, 5, 10, 15 and 20 degrees off-axis vertically.

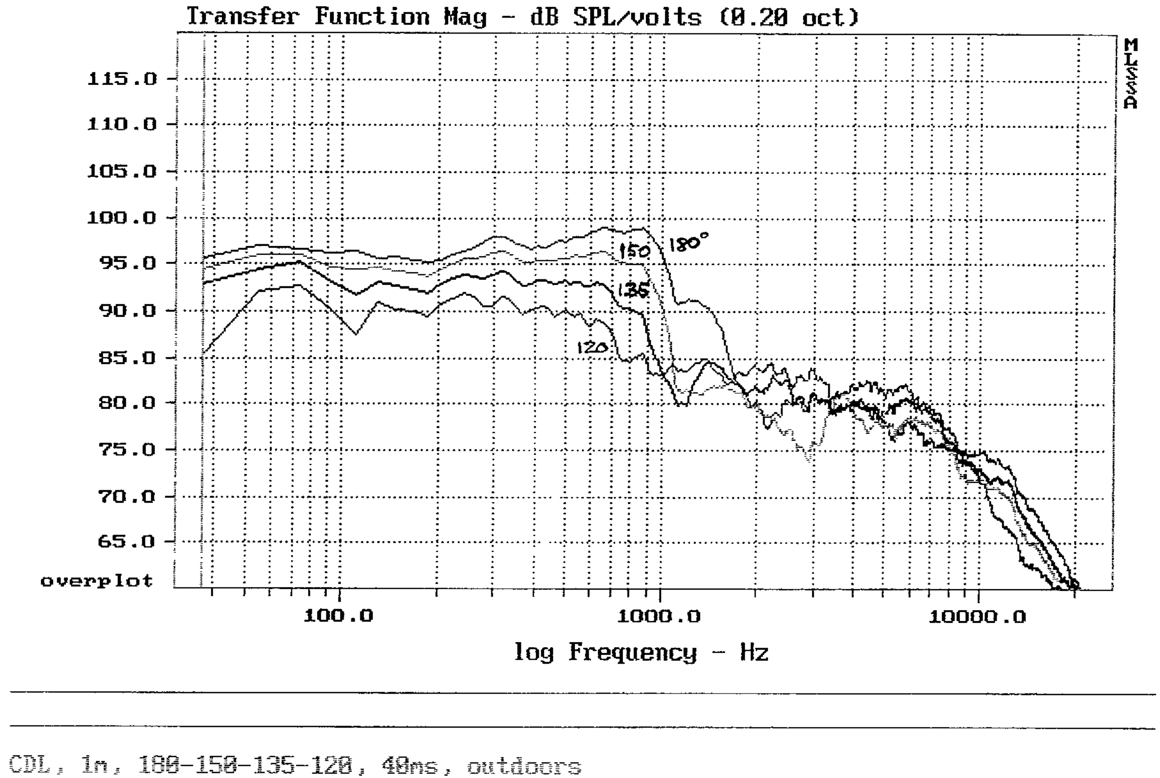


Fig. 24. Compact dipole loudspeaker frequency response at 120, 135, 150 and 180 degrees off-axis horizontally.

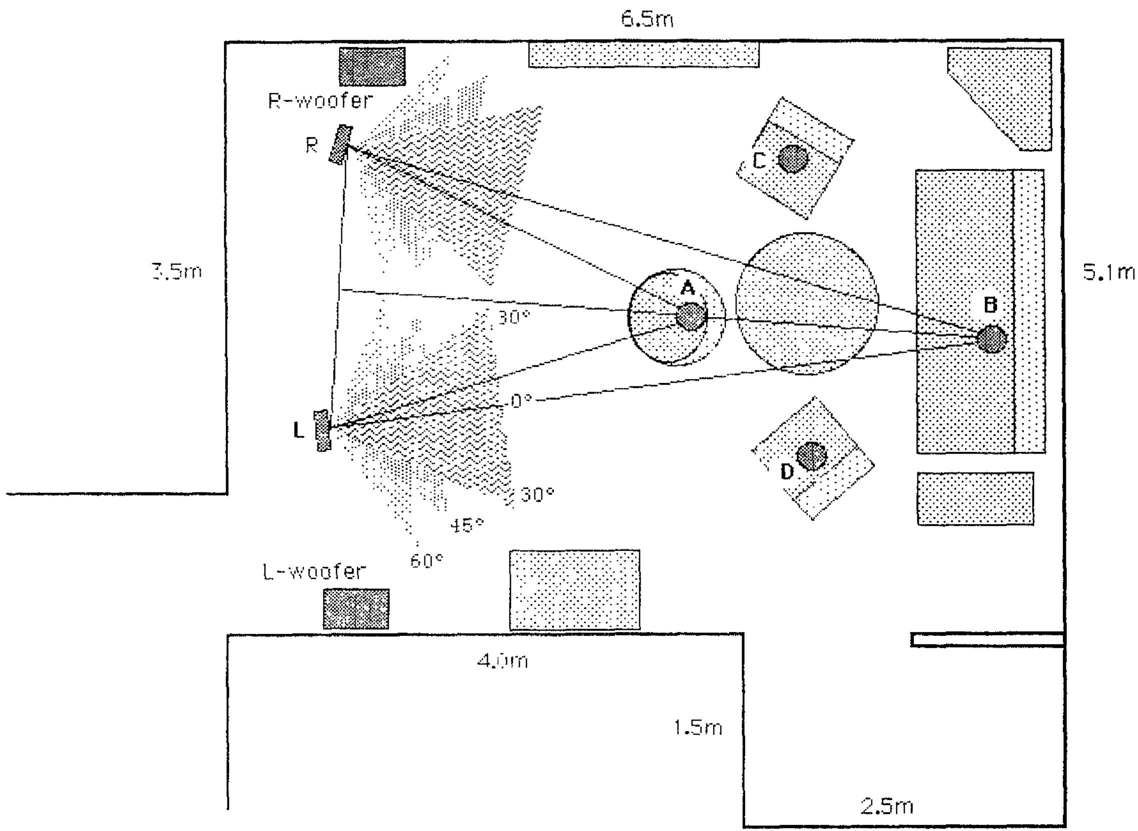


Fig. 25. Floor plan of author's living room. Optimum listening position at A, then B, C, D.

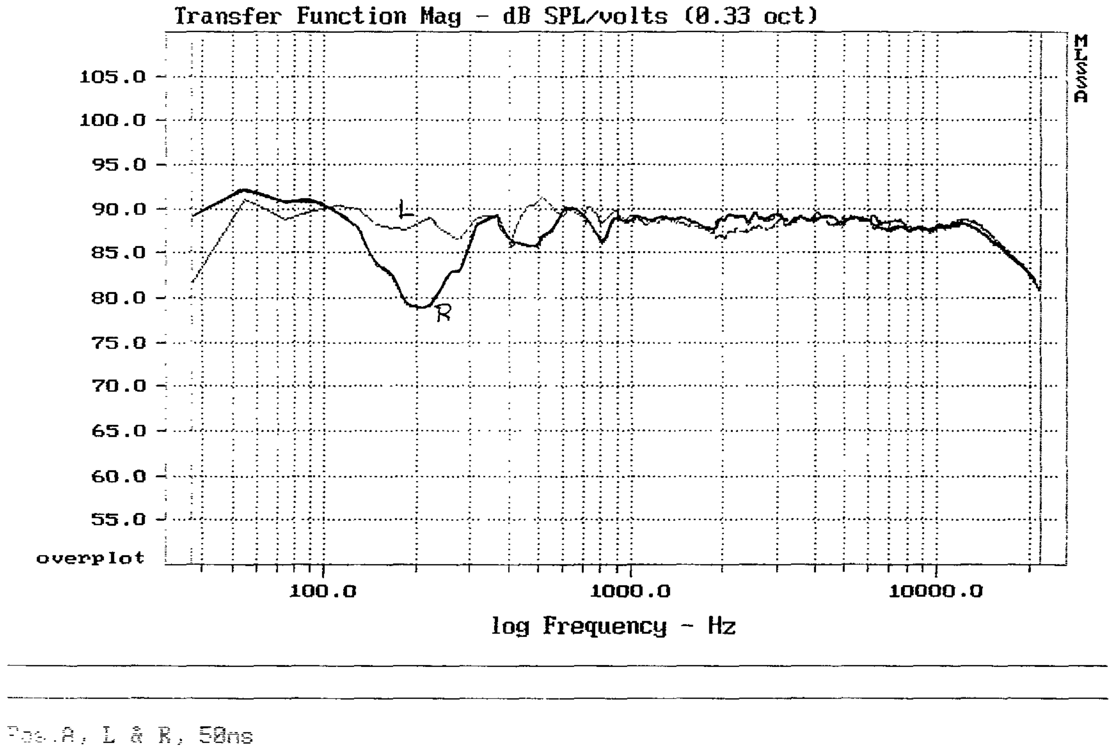


Fig. 26. Third octave smoothed frequency response for left and right loudspeaker at listening position A. Impulse response of 50 ms.

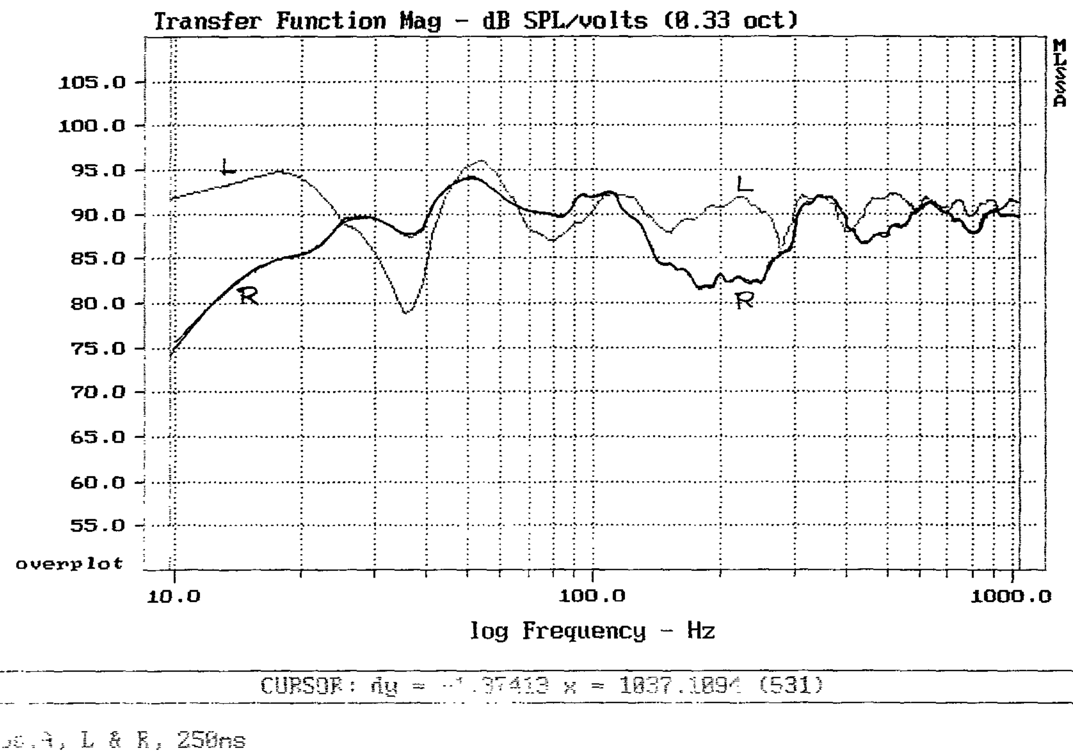


Fig. 27. Third octave smoothed frequency response for left and right loudspeaker at listening position A.
250 ms impulse response for 4 Hz frequency resolution.

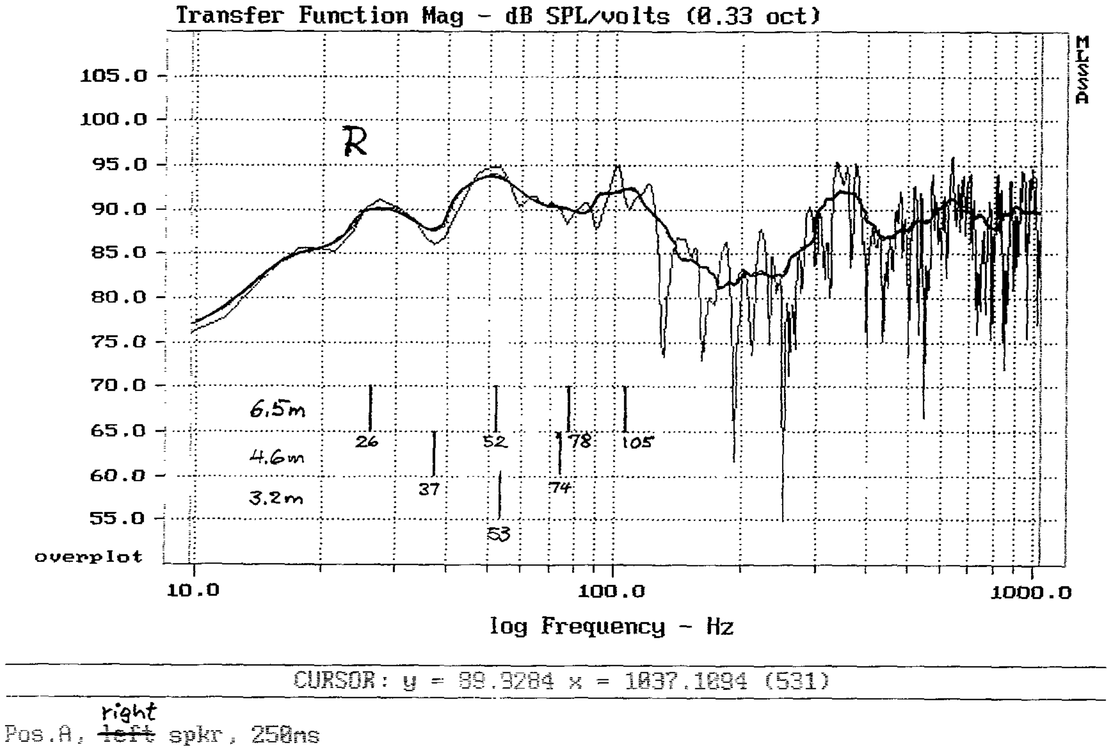
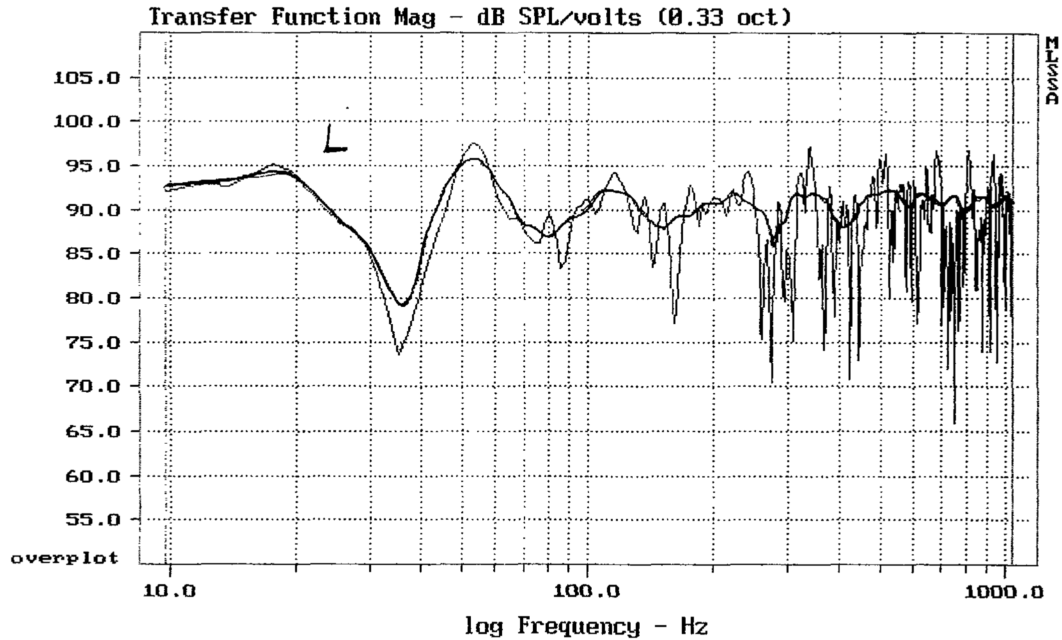


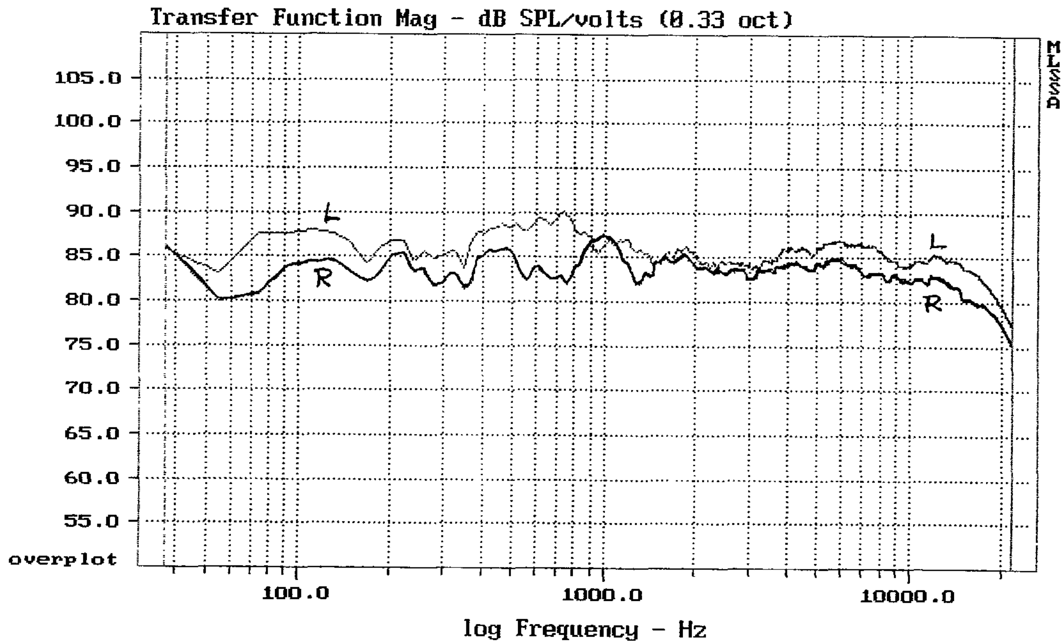
Fig. 28. Frequency response for right loudspeaker at listening position A with superimposed third octave smoothed response.
250 ms impulse response for 4 Hz frequency resolution.



CURSOR: y = 91.1921 x = 1037.1094 (531)

Pos.A, left spkr., 250ms

Fig. 29. Frequency response for left loudspeaker at listening position A with superimposed third octave smoothed response.
250 ms impulse response for 4 Hz frequency resolution.



Pos.B, L & R, 50ms

Fig. 30. Third octave smoothed frequency response for left and right loudspeaker at listening position B. Impulse response of 50 ms.

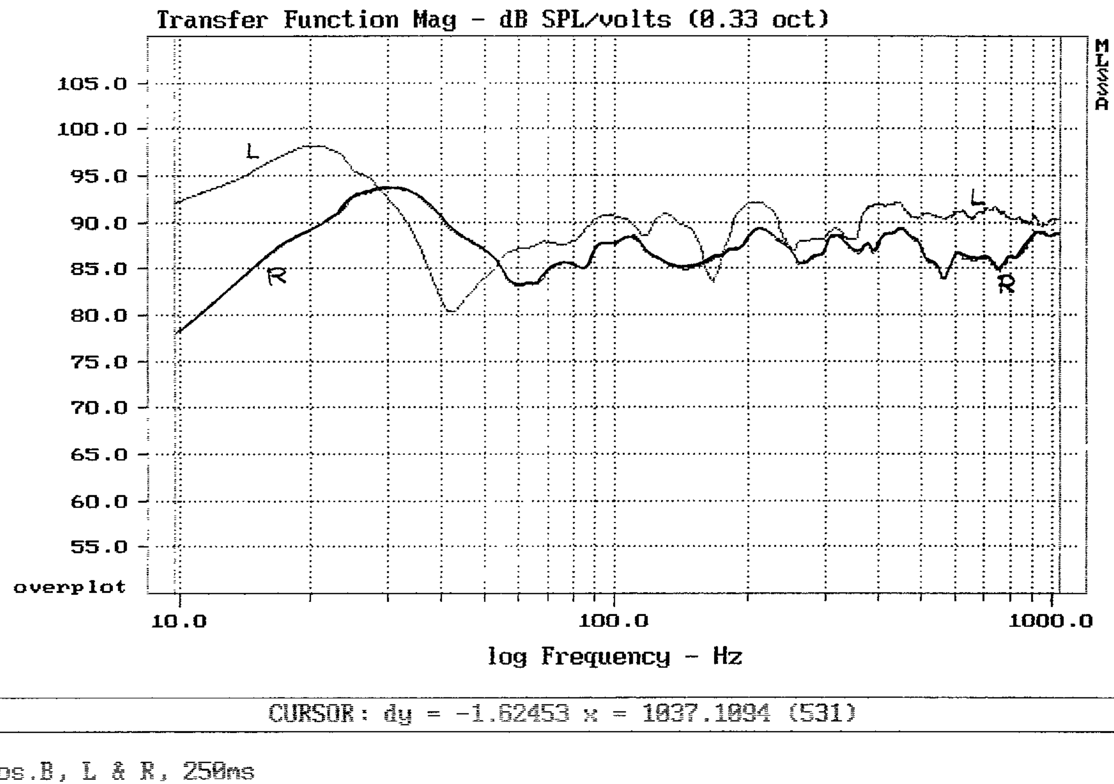


Fig. 31. Third octave smoothed frequency response for left and right loudspeaker at listening position B.
250 ms impulse response for 4 Hz frequency resolution.

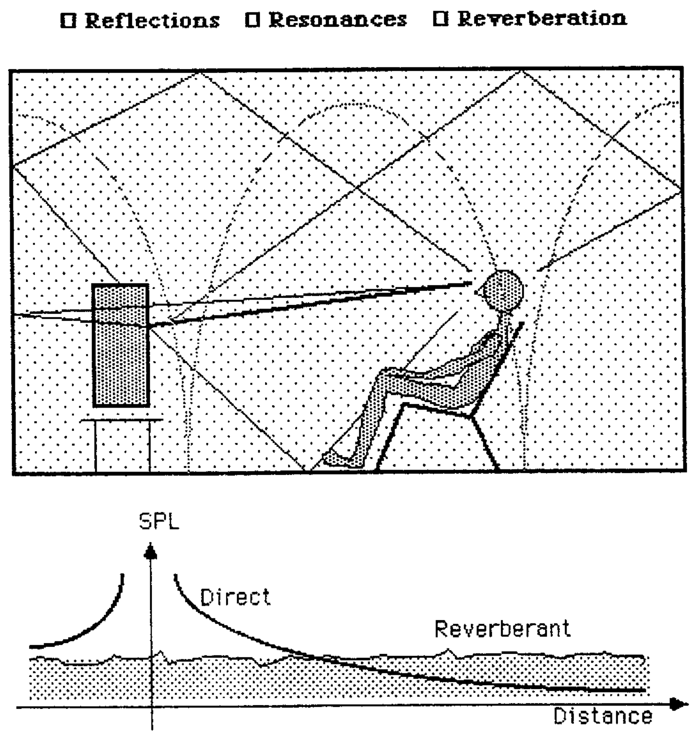


Fig. 32. Listening in a semi-reverberant environment.