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Loudspeaker Reproduction: Study on the Subwoofer Concept

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Abstract

A pair of full range stereo loudspeakers and a pair of stereo loudspeakers reproducing not the low frequencies plus one common low frequency sound loudspeaker ("subwoofer") are compared. AB-AB listening tests were used to determine the absolute threshold of audible differences in dependence on the parameters "cross-over frequency" and "subwoofer location" in the room. It is concluded that the cross-over frequency should be no higher than 100 Hz or 140 Hz, dependent on the placement of the subwoofer. Looking at the attractive advantages with respect to low frequency response in the room and loudspeaker design, and bearing in mind future multi-channel sound systems, the subwoofer concept should be considered as an alternative even in the studio.

1. Introduction

The well-known subwoofer concept is based on the phenomenon that the lower frequency components do not contain relevant stereophonic information, and that there is some freedom in the placement of low-frequency loudspeakers (subwoofers) radiating the lower end of the frequency range of stereophonic signals. Borenus /1/ concluded from his studies that in practical applications the cross-over frequency should "probably be somewhere between " 100Hz and 200Hz. Fielder /2/ recommends that this frequency should not be higher than 100Hz.

The present study investigates the correlation between highest possible cross-over frequency and subwoofer location. It was the aim to specify the optimum cross-over frequency which should be as high as possible, however, on the other hand, which should ensure accurate stereophonic reproduction and sufficient flexibility in the placement of the subwoofer.

2. Listening tests

2.1. Test design

Method

Using an AB-AB test, the absolute threshold of perceptibility concerning the difference between two different acoustical presentations was examined.

A: Fullrange loudspeakers in stereo standard position.

B: Subwoofer system, consisting of a pair of stereo speakers in standard position radiating the frequency spectra down to the cut-off frequency and one common subwoofer, located at three different positions in the room.

Loudspeaker location

The position of the loudspeakers and the reference listening position are given in **fig. 1**. To avoid differences in sound colour between the presentation via the conventional system and via the subwoofer system, only one type of monitor loudspeakers were used.

In case "A", the two loudspeakers were 2.8 m apart from each other, located about 1.5m away from the walls.

In case "B", the two stereo speakers were positioned at the same place as the fullrange speakers. The common subwoofer was positioned at three different locations which are of practical interest.

L1: Subwoofer at the front wall

L2: Subwoofer in the front right corner

L3: Subwoofer at the right wall

In position L1, the subwoofer is located symmetrically to the acoustical axis of the stereophonic triangle. In positions L2 and L3, the subwoofer is located asymmetrically to the stereophonic triangle (**fig. 1**).

The positions of the subwoofer were chosen for the following reasons:

Subwoofer placed in front of the listener

We can conclude from the results of Borenus /1/ and our own that delay errors due to separate subwoofer locations become perceptible if the subwoofer is located more than about 1...2 m closer or 3...6 m farther from the listener than the stereo speakers. Placements behind and/or close to the listener may be unfavourable because of the resulting delay errors which had to be compensated electronically.

Subwoofer placed beside the listener

In a living room, the subwoofer should be placed as inconspicuously as possible. Therefore, a location in an edge or a corner may be preferred in most cases. Further more, it was the intention of the listening test to include a wide range of room stimulations.

Crossover network

Subwoofer crossover frequencies of 70, 100, 140, 200 and 300 Hz were used. The filter characteristic of the network was third order Butterworth.

Test items

In preliminary tests, six test sequences were found to behave very critically.

- Item 1: male voice
- Item 2: double-bass
- Item 3: big drum
- Item 4: synthesiser
- Item 5: electro-bass
- Item 6: pink noise

Room

The size ($A = 44 \text{ m}^2$, $V = 120 \text{ m}^3$) and the acoustics of the listening room were chosen to be comparable to the characteristics of a living room. The 1/3 octave averaged reverberation time of the room is about 0.5 s for frequencies above 100 Hz (**fig. 2**). At lower frequencies the reverberation time increases to values of more than 1 s. The mean room mode density at low frequencies is shown in **fig 3**. The behavior is typical for a living room, where the low frequencies absorption is usually poor. Low-frequency response measurements are presented in section 3.

Test procedure

The subwoofer was hidden by a curtain in each case. Twelve listeners individually took part in the tests. About three quarter of them already had listening test experiences, about one third of them were female.

The block diagram of the test system is shown in **fig.4**. The high pass signals directly feed the stereo loudspeakers STEREO (left) and STEREO (right), the low pass signals pass the A/B-switch. In case A, the low pass signal is fed stereophonically to the two loudspeakers SUB (left) and SUB (right) which are located at the same positions as the stereo loudspeakers (reference loudspeaker configuration). In case B, the low pass signals are summed and the resulting mono signal is aligned to the common subwoofer (SUB (common)), located at the positions L1, L2 or L3.

2.2. Results

For each position of the subwoofer, 432 data (12 listeners x 6 signals x {5 crossover frequencies + 1 AA test}) were available. In the diagrams **fig. 5** to **fig. 10**, the percentages of judgements 'difference audible' are presented graphically. The diagrams 6, 8 and 10 show the results for the individual items, the diagrams 5, 7 and 9 show average values. AA tests were included in order to investigate the assessment ability of the listeners (see **figs. 5, 7, 9**).

The results demonstrate the expected general behavior of increasing detectability due to an increase of the crossover frequency. Furthermore, comparing the results plotted in **figs. 5, 7, 9**, the detectability is clearly effected by the location of the common subwoofer, and, looking at the diagrams **figs. 6, 8, 10**, it depends on the test item. The results are discussed in section 4 under consideration of frequency response measurements.

3. Frequency response measurements

The listening tests were accompanied by corresponding low-frequency response measurements in the range 20 to 200 Hz in order to find correlations to the results of the listening tests. For all measurements, the 1/3 octave bandwidth setting of the FFT-Analysator was used.

In a first series, the low frequency response of the subwoofer in the room was measured at the reference listening position (H0) for four different subwoofer positions (L0, L1, L2, L3), see **fig. 11**.

The frequency responses (**fig. 12**) show distinct deviations from a continuously course (about +/- 5 dB) for all positions of the subwoofer which is a typical behavior for a weakly damped room. The differences between the frequency responses at the different positions of the subwoofer are in the same order of magnitude. The amplitude transfer function at the reference loudspeaker position (L0) has a constantly decreasing tendency between 160 Hz and 31.5 Hz. On the other hand, the transfer functions of the subwoofer near the walls stay quite constant from 160 Hz down to 50 Hz, decreasing abruptly to lower frequencies. This distinct difference of the transfer functions may cause an audible difference.

The presentation of the difference sound pressure levels in **fig. 13** shows that the 1/3 octave averaged amplitude transfer function of the subwoofer in the corner position (L2) differs most, that one of the subwoofer in the position at the right wall (L3) differs least from the amplitude transfer function of the subwoofer at the reference point (L0). This result correlates with the listening tests, which show that the biggest audible difference occurs between the presentation using the subwoofer in the corner of the room and the presentation using the reference system (**fig. 7**). More detailed informations concerning the room responses can be found in /8/.

4. Discussion of results

The effect of standing waves at low frequencies in terms of pressure distribution and frequency response as measured in the room obviously has a significant influence on the sound colour. In the comparison test the listeners perceived differences which were mainly characterized by a change of the sound colour rather than a change of the stereophonic image. However, here we touch a general problem of loudspeaker reproduction: in practice even in carefully designed control rooms and listening rooms the sound colour depends on the loudspeaker placement, particularly in small rooms providing insufficient density of room modes.

Considering this, the determination of the absolute thresholds of differences in dependance of the subwoofer location in the room will not distinctly identify the maximum permissible subwoofer cross-over frequency with respect of the stereophonic image (in the freefield !). The dominant factor is related to sound colouration caused by room modes. We assume that the results of the listening tests as plotted in **figs. 5 to 10** reflect mainly the frequency response curves. Each of them is a possible condition in practical situations and non of them is "correct". It seems to be very difficult to investigate the effect of the subwoofer placement (in dependance on the crossover frequency) on the stereophonic presentation without the influence of the room modes. Therefore, the determination of the absolute thresholds of differences in the room is assumed to be a particular critical test method, and we come to the

Conclusion:

The permissible crossover frequency of a subwoofer system must be no higher than 100 Hz. If the subwoofer is located symmetrically to the stereo loudspeaker arrangement, the crossover frequency may be increased to a maximum of 140 Hz.

5. Practical considerations

Subwoofer

The location of the subwoofer(s) only has to meet the room acoustical requirements: One or several subwoofers can be placed in order to stimulate the room modes which combine to the flattest possible amplitude response at the reference listening position or even within a certain listening area. It seems to be worthwhile to investigate the performance of a subwoofer system providing several individual subwoofers. Preliminary experiments of our own using four separate subwoofers have shown that an arrangement along the front wall can produce a more uniform pressure distribution than possible with only one subwoofer.

The location of a subwoofer near to walls has the well-known effect /8/ of increased power output. Corresponding measurements at the reference point have shown that the subwoofers at the room edges (L1, L3) produced about 3 dB more sound pressure level, the subwoofer in the room corner (L2) about 6 dB more spl than the subwoofer at the reference loudspeaker position (L0). This results in a corresponding advantage in terms of required acoustic power. Therefore the area of the diaphragm and the net volume of the loudspeaker can be reduced according the following table, remaining the spl at the listeners position.

Table 1: Estimated relative change of speaker size in dependance on radiated spl

radiated spl	0 dB	- 3 dB	- 6 dB
acoustic power	100 %	50 %	25 %
required area of diaphragm (*)	100 %	70 %	50%
required net volume (*)	100 %	70 %	50%

(*) retaining the excursion of the diaphragm

Stereo loudspeakers

The stereo loudspeakers have to be located according the requirements of stereophonic imaging, so they cannot be "hidden in room edges". Fortunately the size of the stereo loudspeakers can be reduced dramatically, compared to conventional fullrange loudspeakers, because their low frequency cutoff (= cross-over frequency) can be limited to 100...140 Hz. This is about one to two octaves higher than the required low frequency cutoff of the fullrange speaker (30...50 Hz).

Table 2: Estimated relative change of speaker size versus low -frequency cutoff (according fig. 14 and fig. 15)

low frequency cutoff	30 Hz	60 Hz	120 Hz
required area of diaphragm (*)	100 %	30 %	10 %
required net volume (*)	100 %	30 %	10 %

(*) considering the reduced excursion of the diaphragm for smaller chassis diameters

6. Proposal

We conclude that there is an attractive goal to improve the loudspeaker response within the listening area by using a separate low-frequency loudspeaker, which is located due to optimum low-frequency response rather than optimum stereophonic presentation. Previous papers (e.g. /3, 4, 5/) on the effects of standing waves in a room demonstrate that it is most advantageous to optimize the loudspeaker placement with respect to low-frequency performance, in particular sound pressure distribution and low-frequency cutoff point ("placement equalization"). Thus, the correct installation of one (or more) subwoofers and resonance absorbers in the control room could be done once, widely irrespective of the arrangement of the stereo loudspeakers.

Another aspect is related to the design of the stereo loudspeakers. An increase of the low-frequency cutoff from, for example, 30 Hz to 120 Hz reduces the constraints in terms of required net-volume and weight, choice of transducer principle etc. dramatically. The volume could decrease approximately 90%, and important electro-acoustical parameters such as impulse response and directivity-index could be optimized with less compromises.

Low-frequency mono reproduction of stereophonic signals by means of a common subwoofer system is obviously particularly advantageous for multi-channel sound applications. The universal "stereophonic multi-channel sound system with and without accompanying picture" according Draft Recommendation of CCIR TG 10-1 comprises three front loudspeakers (left/center/right), supplemented by at least one pair of surround loudspeakers ("3/2-format") /6/, /7/. Five fullrange loudspeakers having identical low-frequency sound pressure level performance would require an overall net-volume significantly higher (factor 2.5) compared with a corresponding subwoofer system. Small stereo loudspeakers in the 3/2-arrangement and flexible placement of the common subwoofer(s) allow aesthetically acceptable solutions in the living room.

Considering all these aspects it seems to be very useful to study the performance of the subwoofer concept and to develop corresponding design criteria. Important results with this respect have already been published, for instance by Fielder /2/ and Borenus /1/. There is some evidence that the subwoofer system in fact could improve not only the acceptance of multi-channel loudspeaker arrangements but also the performance of loudspeaker reproduction in the home and even in the studio.

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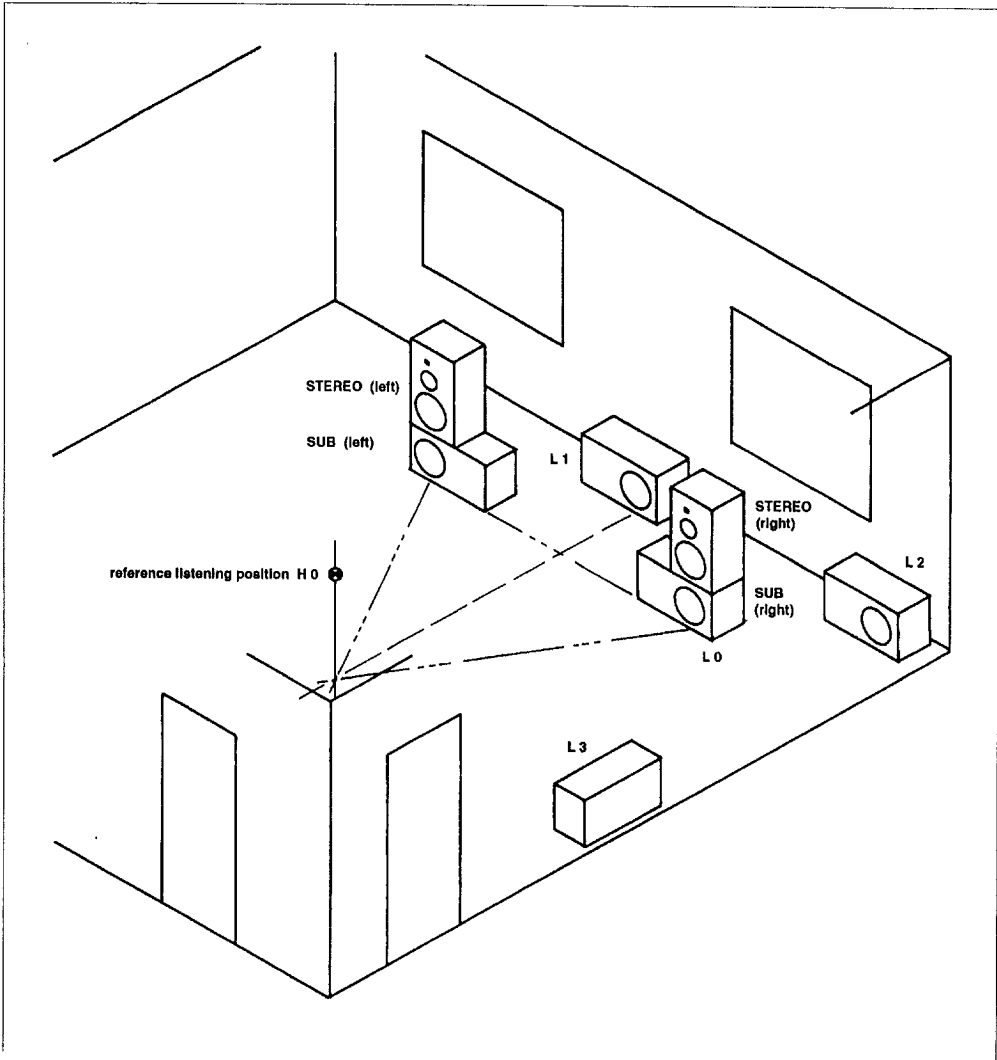


Fig. 1: Plan of Listening Room

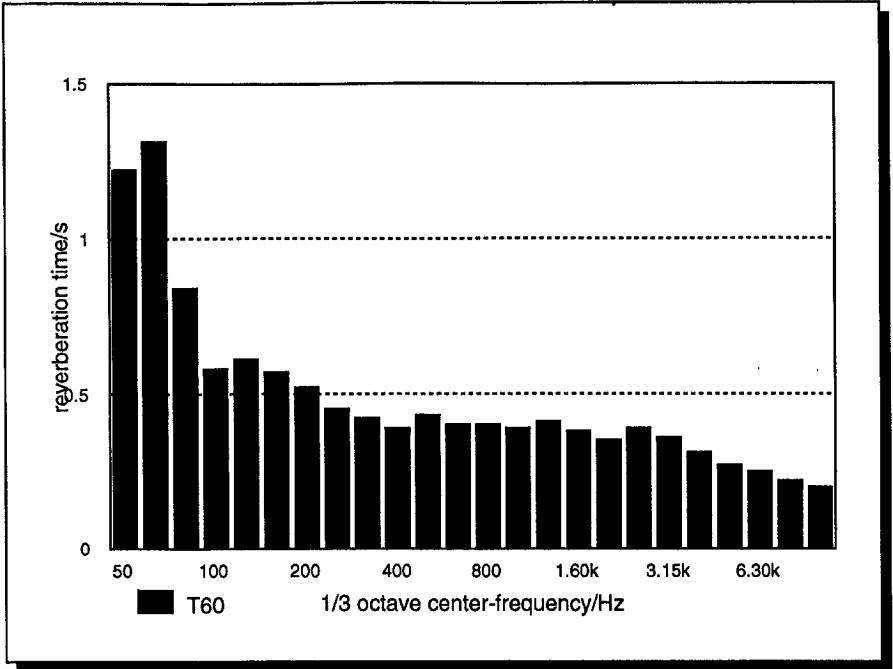


Fig. 2: Third Octave Averaged Reverberation Time of Listening Room

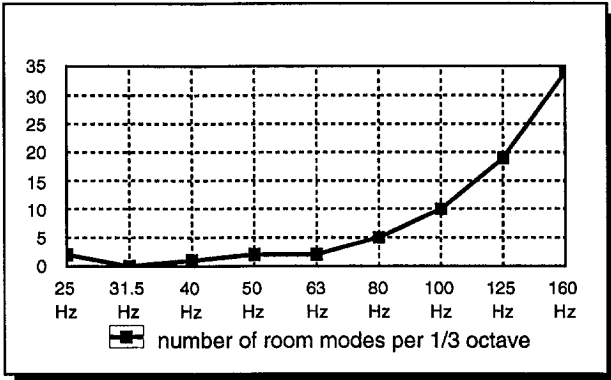


Fig. 3: Room Mode Density of Listening Room

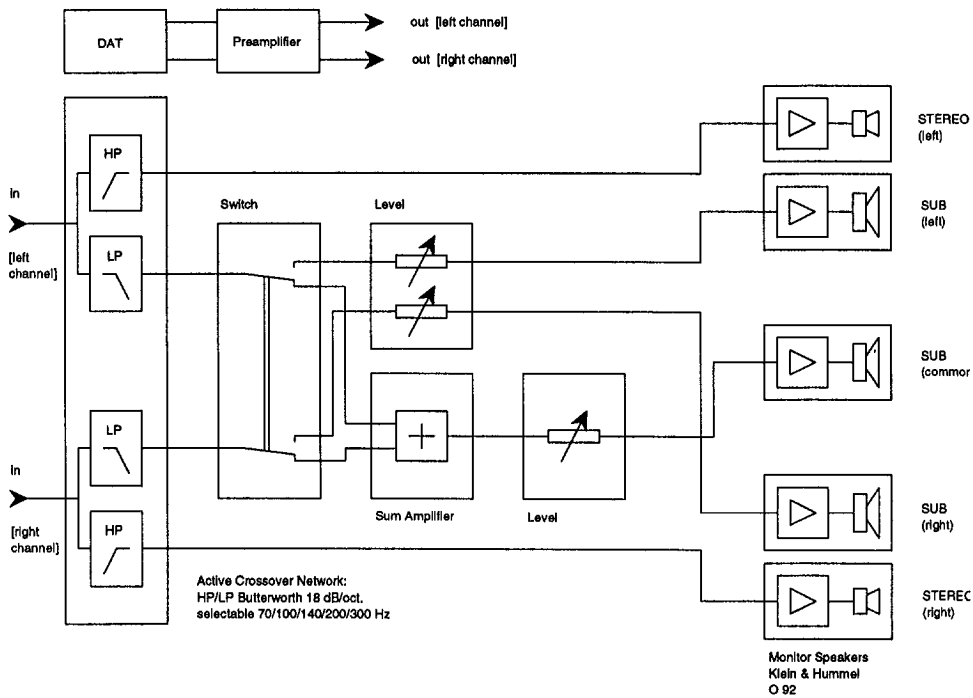


Fig. 4: Block Diagram of the Test System

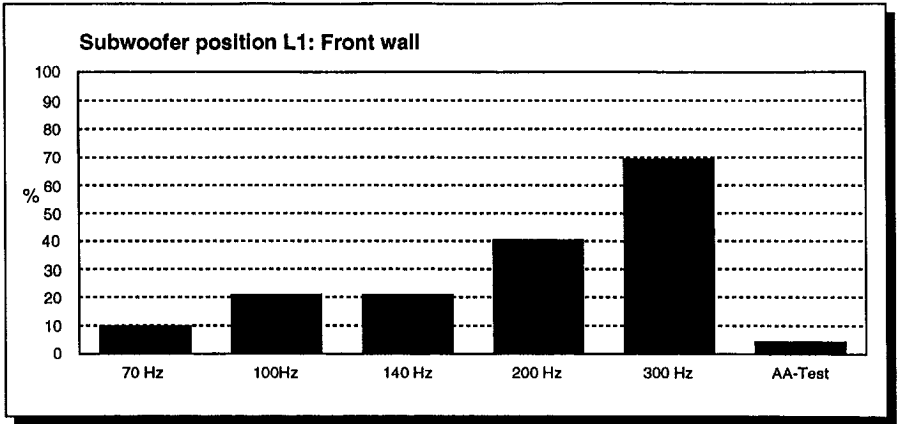


Fig. 5: Average Values

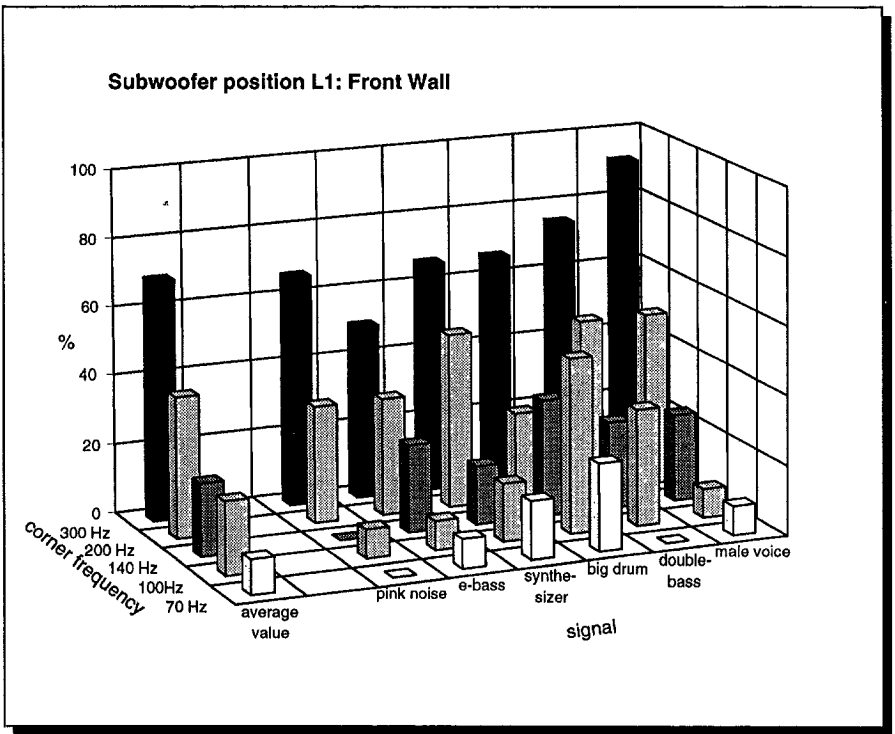


Fig. 6: Individual Signals

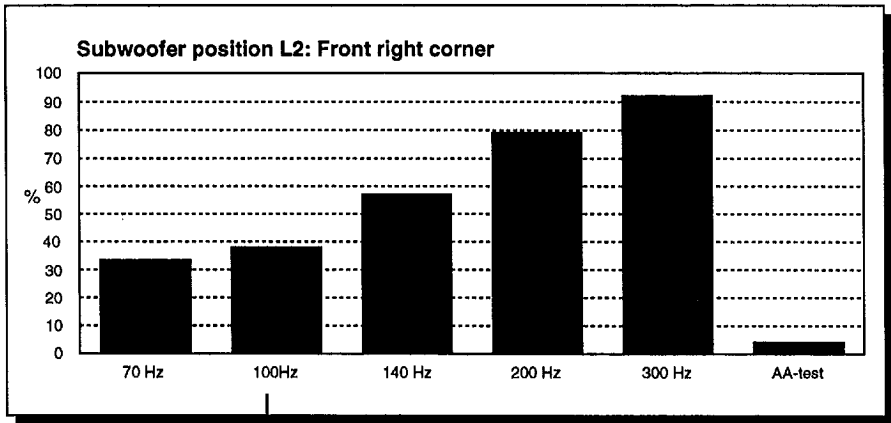


Fig. 7: Average Values

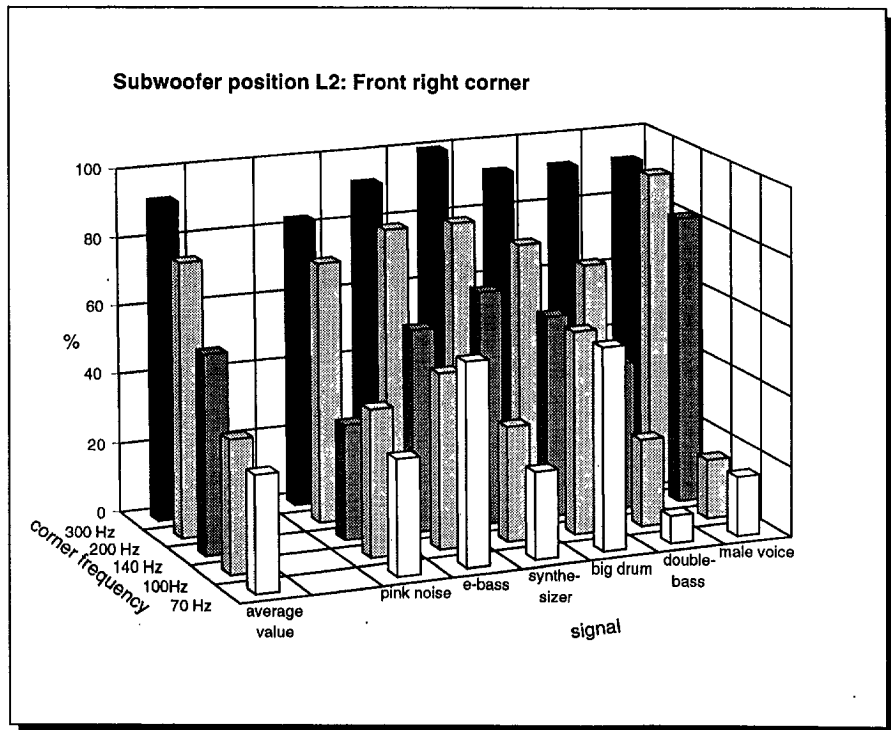


Fig. 8: Individual Signals

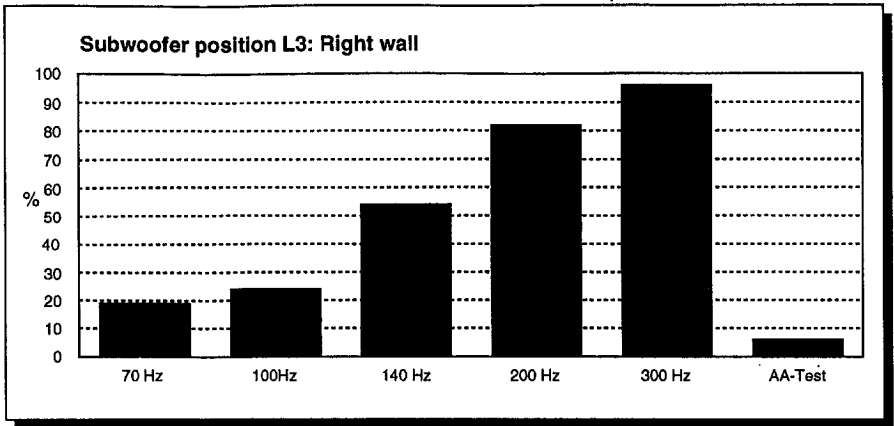


Fig. 9: Average Values

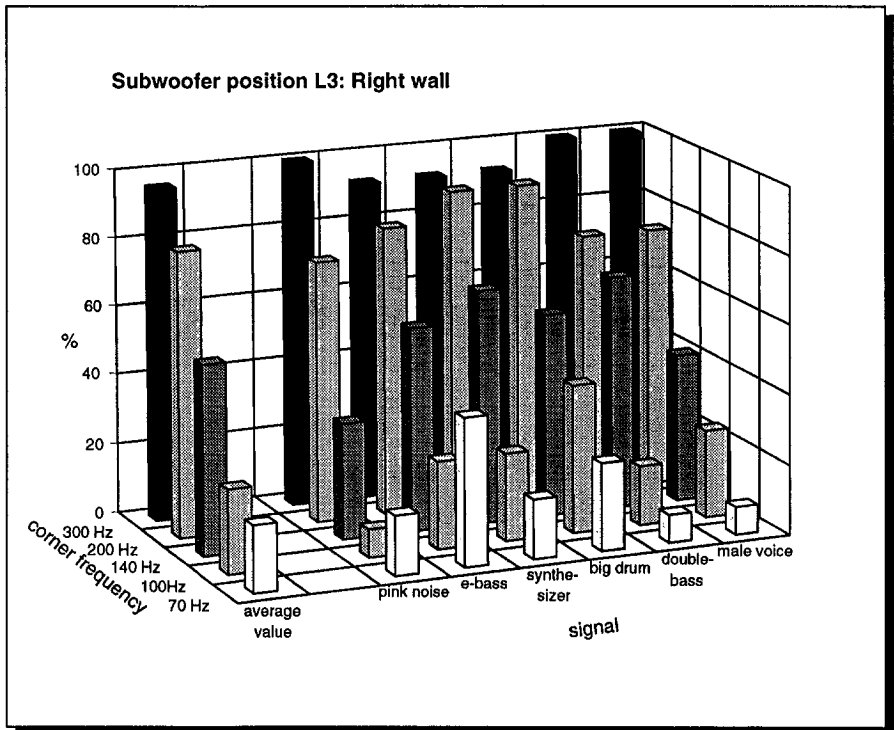


Fig.10: Individual Signals

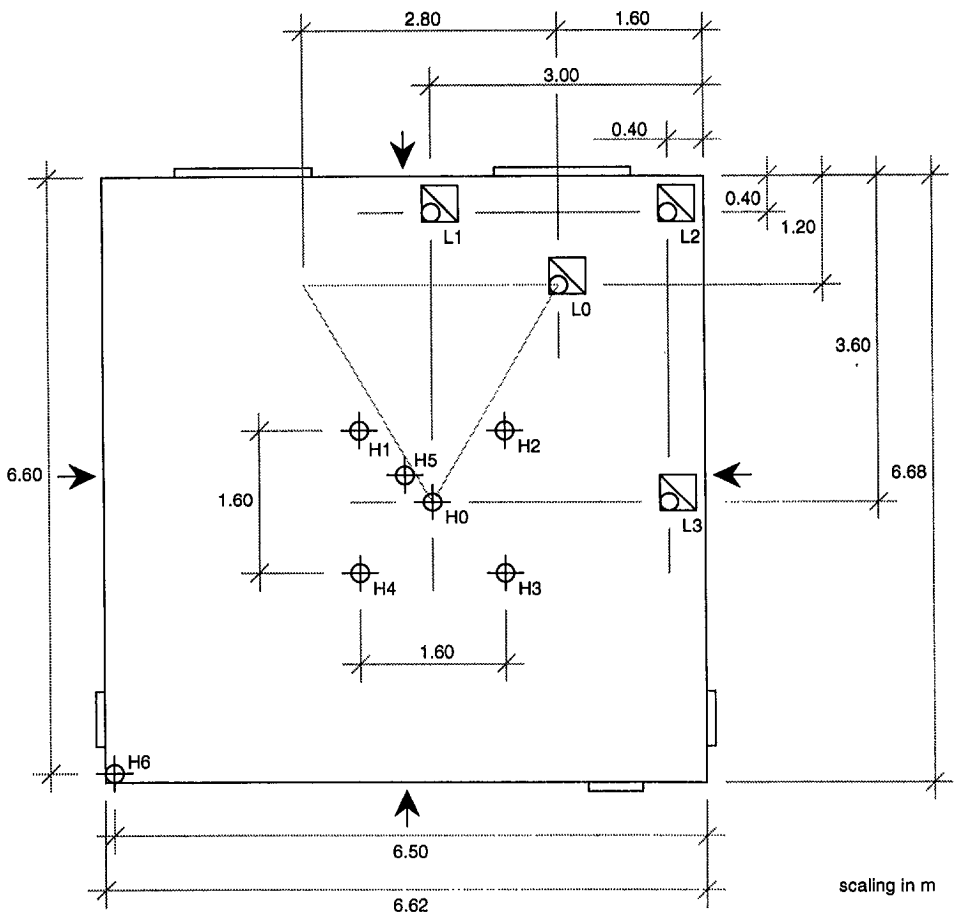


Fig. 11: Plan of Listening Room for Acoustic Measurements

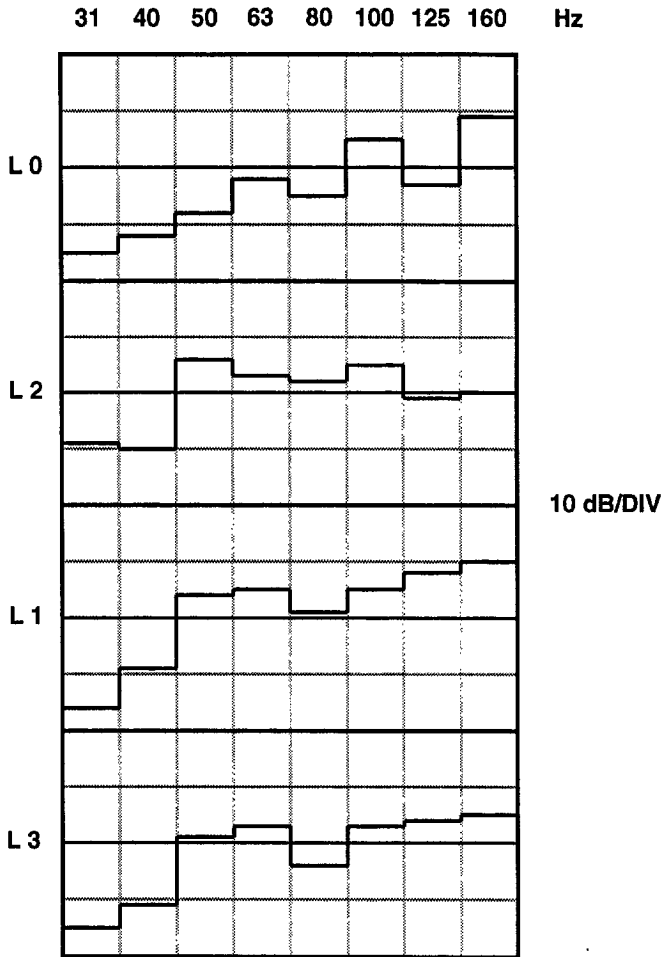


Fig. 12: Frequency Response Curves at Reference Listening Position H0

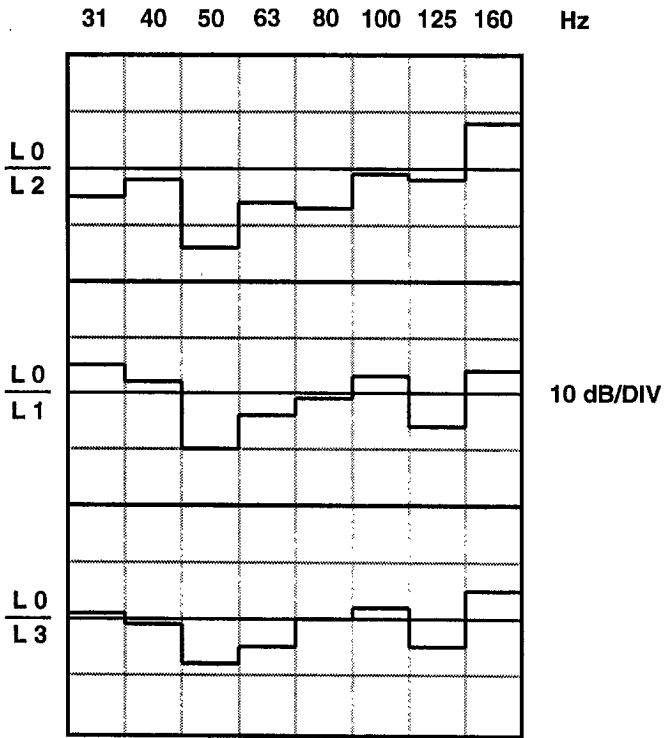


Fig. 13: Difference Sound Pressure Levels

Diaphragm \varnothing

Chassis \varnothing

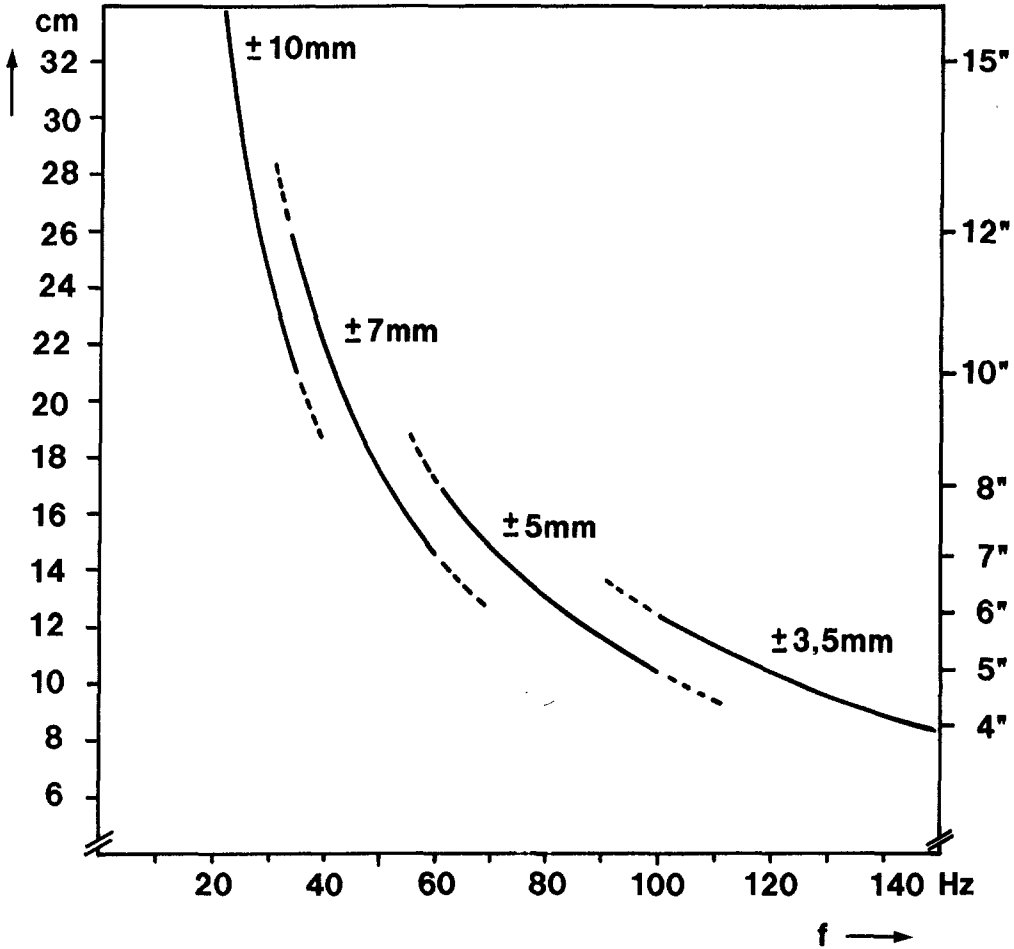


Fig. 14: Approximate Diaphragm Size to Produce a Sound Pressure Level of 98 dB in 1 m

net volume

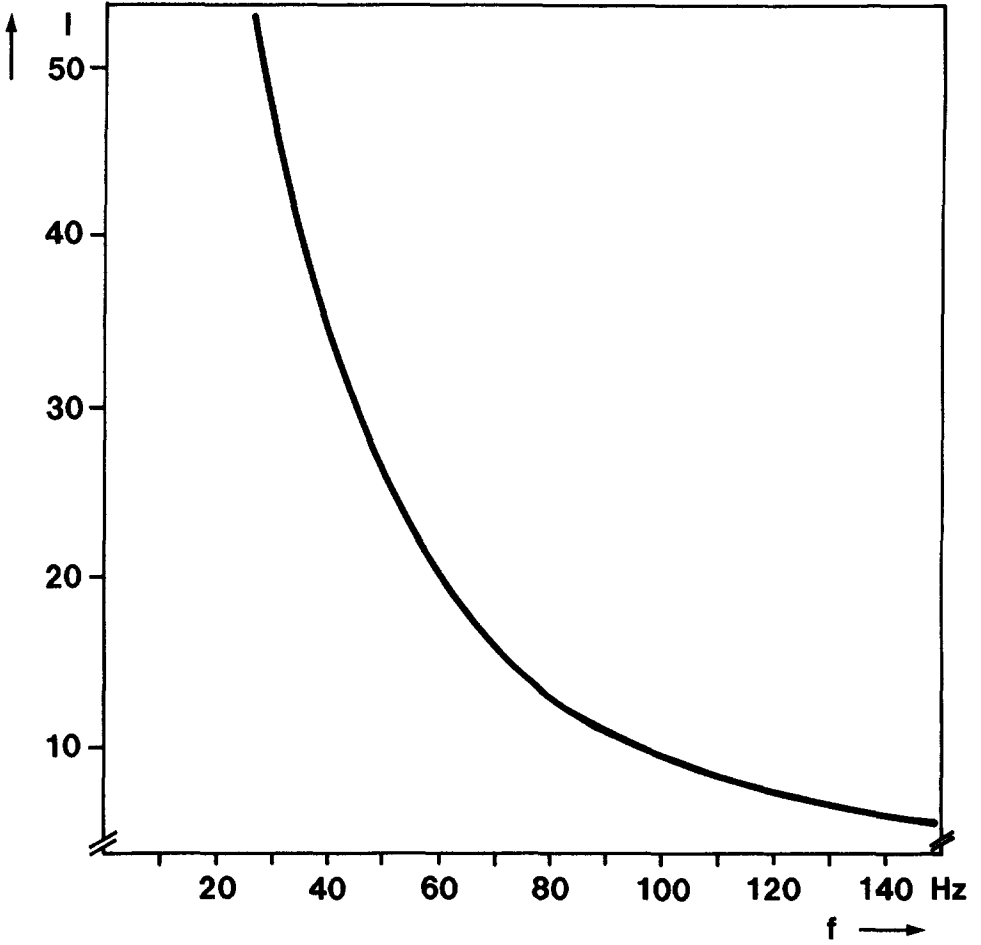


Fig. 15: Approximate Net Volume of a Loudspeaker Box as a Function of the Lower Cutoff Frequency