ABOUT THE BENEFITS OF MULTIPLE LOW FREQUENCY CARDIOIDS IN SMALL ROOMS

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1 INTRODUCTION

A uniform steady-state low frequency room response is bound to an even excitation of the room's eigenmodes. Although still under dispute [1], this quantity appears to be a widely accepted measure for good bass reproduction in small rooms and is therefore used in this paper.

Consider a typical 5.1 multichannel setup, where all main channels are utilized in full-range mode. Due to the spatial distribution of the lf-sources fairly complex mode excitation patterns are observed. Additional problems arise from the summation of the five lf-signals at the listening position, because each speaker has a different position and phase relation relative to the other speakers. The scenario gets more complex when a single LFE-channel is added to the system, because now each speaker interferes with the LFE-channel in the crossover region.

In this paper the benefits of multiple lf-cardioids when used in an array configuration are explained. Measurements are presented that show how multiple cardioid subs help to balance the lf-room response across an increased listening area, a prerequisite in modern home theatre installations. The results of subjective experiments on correlated versus decorrelated lf-sources are used to give generalised recommendations on the use of stereo or multichannel bass configurations.

2 5.1 SETUP

In Fig. 1 the speaker positions for the six sound sources of a 5.1 listening setup according to the ITU 775 recommendation are shown. Due to manifold constrains on the producer's side in the studio as well as on the consumer's side in his home theatre or listening room, the recommended conditions are rarely put into practice.

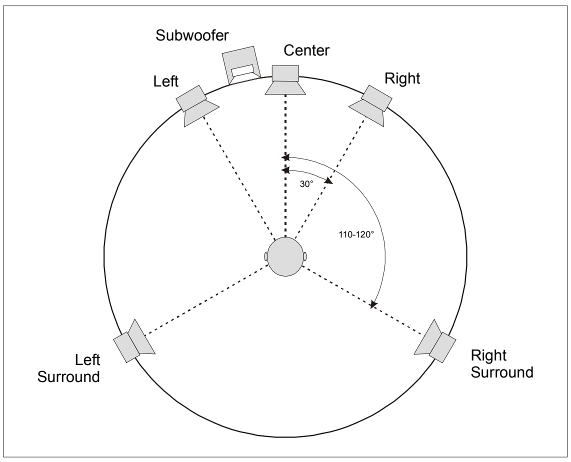


Fig. 1 Loudspeaker positions according to ITU-R recommendation 775 (Rev1) [2].

Often the user is forced to accept severe deviations from the advised scheme due to the shape of the listening room, the furniture the room is equipped with or the used equipment. The following list comprises some of the more frequently observed conditions:

- Five or six places of mode excitation
- Sources with differing bandwidth/transfer function characteristics
- Listening area too larger compared to positioning radius of sources
- Individual sources fed with uncorrelated lf-signals (stereo/multichannel bass-signals)
- Practical limitation enforced by differing standards. Variable delay: available for DVD-video and DVD-audio, but not provided for SACD.

In an earlier study [7] the authors compared the mode coupling properties of monopolar, dipolar, and cardioid lf-sources. The cardioid turned out to be the most flexible (and therefore most usable) low frequency source, because of its low sensitivity to rear wall reflections and the position-independent mode excitation properties. The different ways a cardioid-like radiation pattern can be generated and the acoustic properties of cardioid lf-sources are covered in previous publications [4],[5],[6].

3 MODAL DECAY FOR MONOPOLE AND CARDIOID

The modal coupling properties of a monopole and a cardioid were examined using a series of measurements taken in 5.0x4.0x2.6m sized reverberation chamber. The source positions and the source orientation relative to the room are shown in Fig. 2.

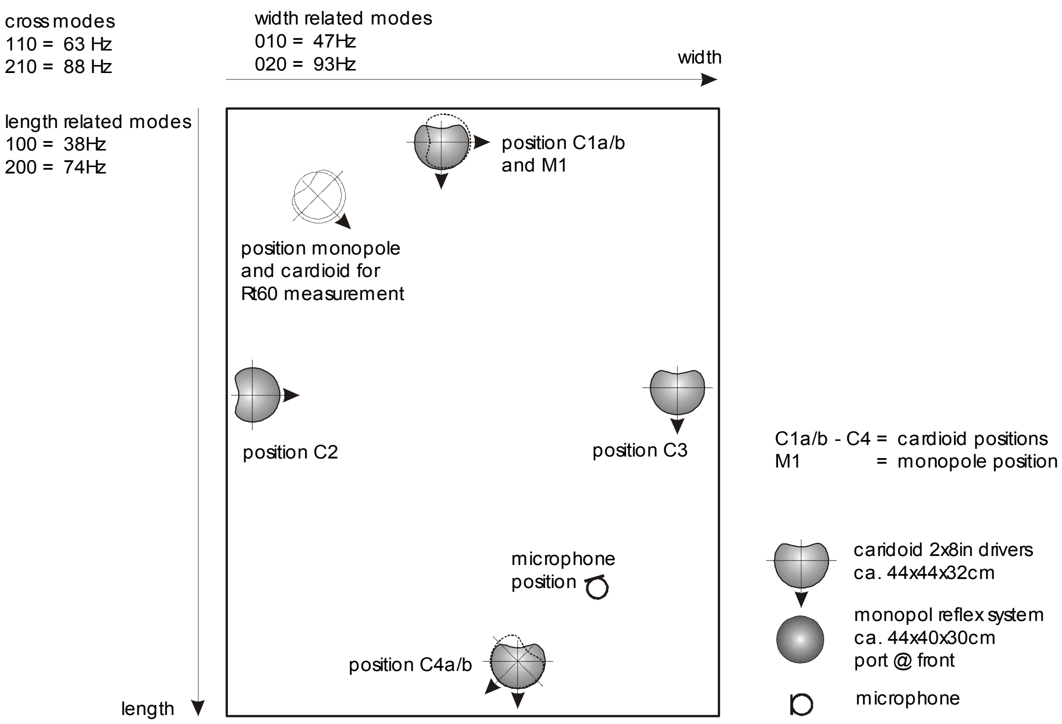


Fig. 2 Position, orientation, and number of cardioid subwoofers as used during the measurements.

To investigate the decay times of individual room modes the position and orientation for each source type was chosen such that good excitation of all modes was ensured. Low frequency absorbers were fitted in the reverberation chamber to reduce the variance of the expected decay times. Than the decay times at distinct individual room modes were determined for each of the three configurations: single monopole, single cardioid, and four cardioids. The positions and orientations of the four cardioids setup were previously determined such that they yield the best mode excitation pattern. The results of this investigation are shown in Fig. 3.

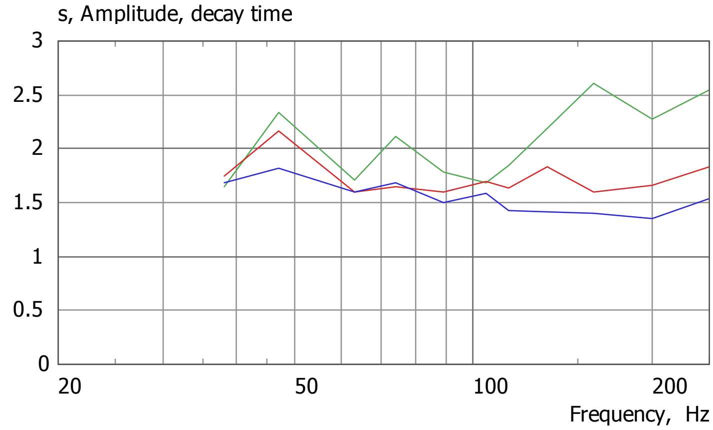
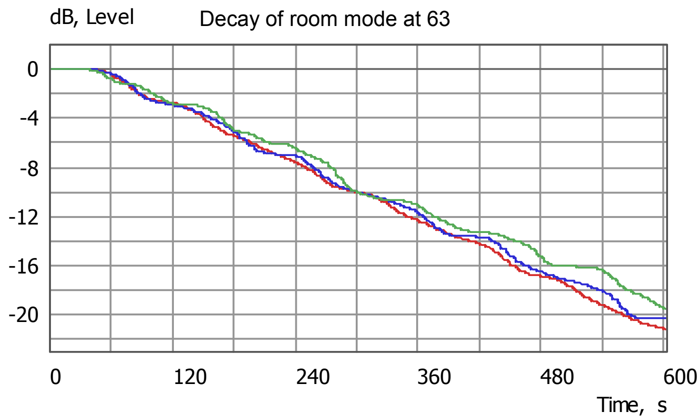


Fig. 3 Decay times as function of mode frequency for each of the following configurations: ***1x monopole***, ***1x cardioid***, and ***4x cardioids***.

The comparison of a single monopole with a single cardioid (both placed at same position) indicates, that the cardioid produces shorter decay times even at low frequencies. Theoretically a cardioid generates 4.8dB less acoustic power output than a monopole. This explains why the decay times are considerably shorter at higher frequencies but reconcile towards lower frequencies, since the cardioid radiation pattern is disturbed by the room boundaries.



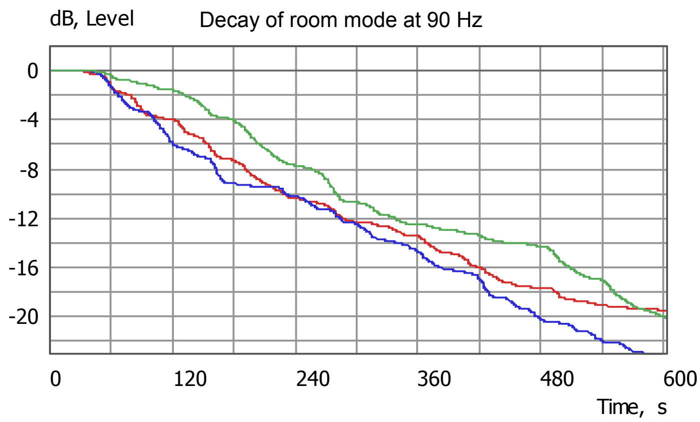


Fig. 4 Schroeder curves calculated from measurements taken in the reverberation chamber utilising ***1x monopole***, ***1x cardioid***, and ***4x cardioids*** at 63Hz and 90Hz.

Fig. 5 Schroeder curves calculated from measurements taken in the reverberation chamber utilising ***1x monopole***, ***1x cardioid***, and ***4x cardioids*** at 160Hz.

The modal decay times are further reduced when four cardioid sources are used instead of one. The Schroeder curves in Fig. 5 illustrate this trend at three exemplary mode frequencies (63Hz, 90Hz, 160Hz). At the lowest mode frequency (63Hz) the Schroeder curves for all three source-configurations look very similar, while at higher mode frequencies they deviate more and more in favour of the four cardioid configuration. This trend indicates, that with increasing frequency the acoustic power output of the cardioid decreases towards its theoretical limit of –4.8dB when compared to the monopole. Previous tests [6] have shown that the cardioid's physical dimension, its shape, and acoustic design affect the radiation properties at low frequencies.

4 MODE EXCITATION FOR MULTIPLE CARDIOIDS

Based on the results of the previous paragraph further investigations were carried out to quantify how the variance of the transfer characteristic depends on the number of cardioid subs. For this series of measurements all source were equalised to yield the same free field frequency response. The single sources were positioned in-between the left front main speaker and the centre, while the configuration shown in Fig. 2 was used in the four cardioid setup. The following graphs illustrate the transfer functions measured for a single monopole, a single cardioid, and four cardioids.

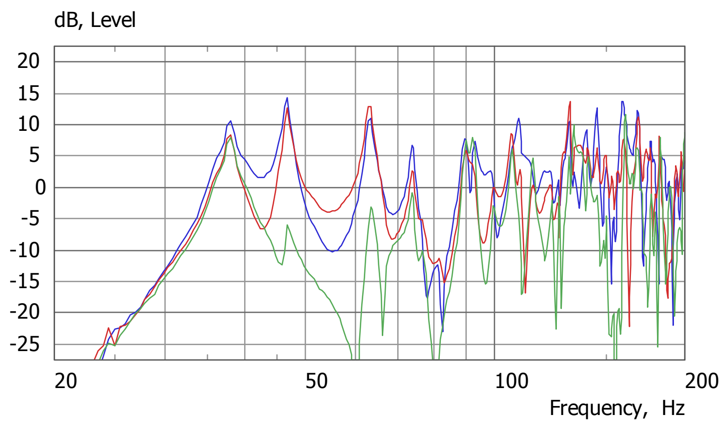


Fig. 6 Transfer function measured in reverberation chamber for ***1x monopole***, ***1x cardioid***, and ***4x cardioids***.

As expected, the monopole exhibits the problematic nature of weak excitation (pressure source placed in pressure node) for all width-related modes (010 and 110). In contrast to this the single cardioid, measured in the same position, shows a noticeably improved excitation pattern, due to proper alignment of its main radiation axis. Now the cardioid's velocity component excites all width-related modes. Further improvement is achieved when four cardioids are used (carefully positioned and adjusted) instead of one.
The variation bandwidth of the four cardioids regarding their modal excitation properties is illustrated in Fig. 7 on the basis of two modes, 110 mode at 63Hz and 200 mode at 74Hz. The six curves were acquired varying the cardioid's orientations, its phase and its level. It becomes apparent that the use of four cardioids sources improves the control of the room transfer function especially in the sparsely modal frequency range. The final result depends upon the correct position and orientation of the cardioids as well as on carefully adjusted level and phase.

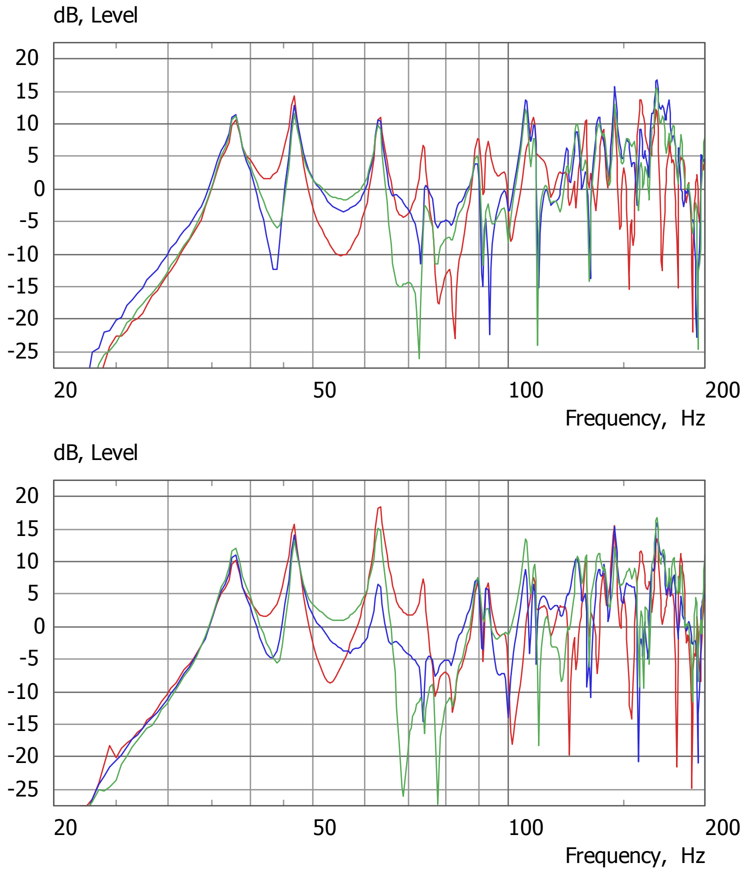


Fig. 7 Variation of modal excitation measured with four cardioid sources at 63Hz (110 Mode) und 74Hz (200 Mode). Changes were generated by varying the cardioid's orientation, their relative phase and level.

The results prove that because of its versatile characteristic a cardioid array can be used efficiently to control the modal frequency range in a room. Consequently, such configuration is well suited to balance out irregularities even in acoustically awkward environments. A welcome side effect of multiple cardioid excitation are the noticeably reduced mode decay times.

Especially for multichannel listening rooms with insufficient damping in the sparsely modal frequency range, multiple cardioids represent a new solution that helps controlling the modal excitation. The quality of the bass reproduction is improved, without the need for costly structural measures.

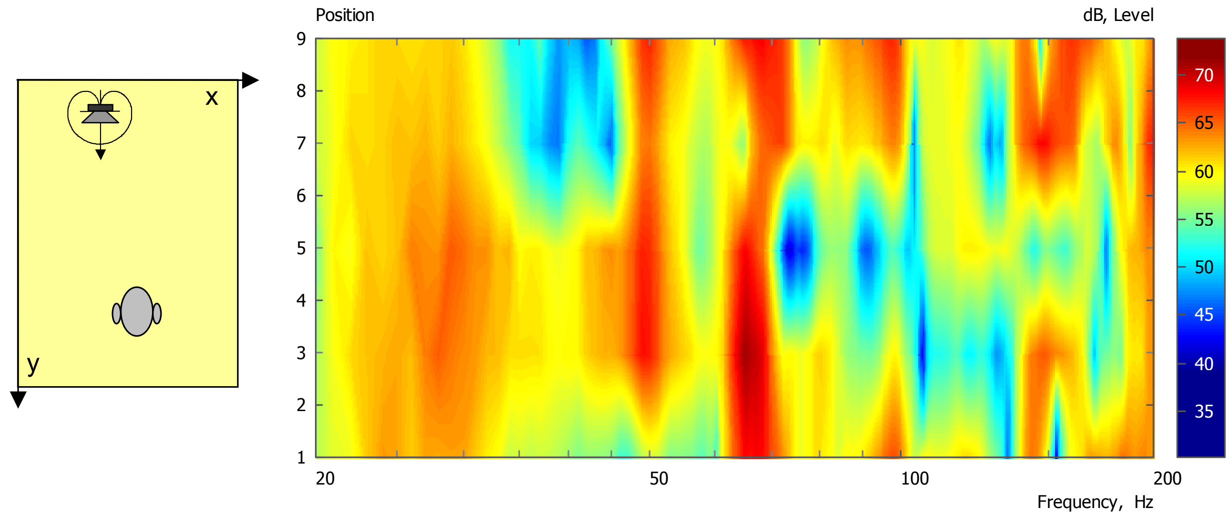


Fig. 8 ***One cardioid sub:*** Contour plot of room transfer function plotted against measurement position (9 meas. positions, listening area ca. 1,5m²)

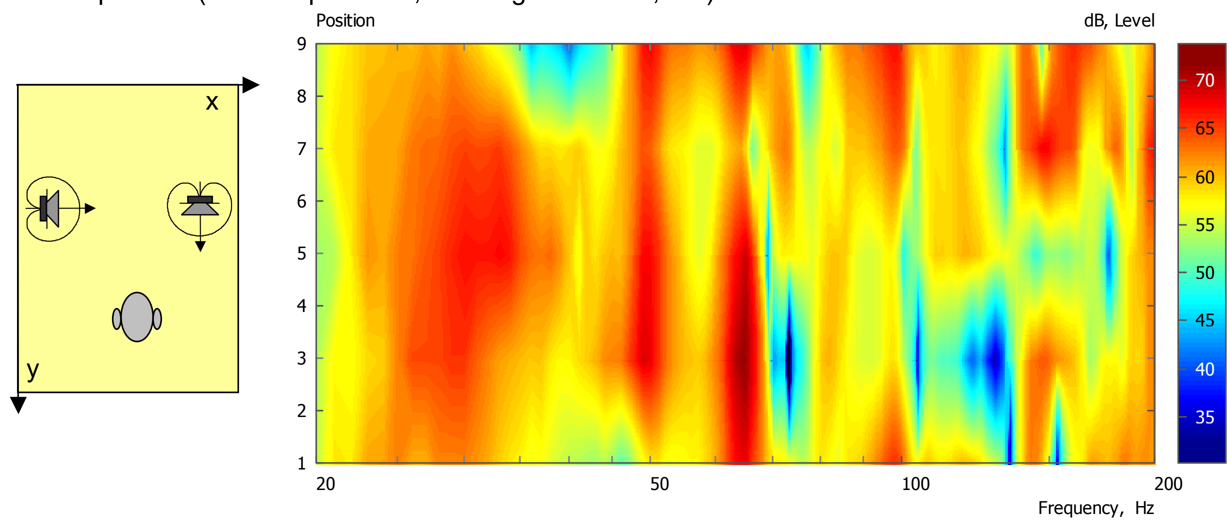


Fig. 9 ***Two cardioid subs:*** Contour plot of room transfer function plotted against measurement position (9 meas. positions, listening area ca. 1,5m²)

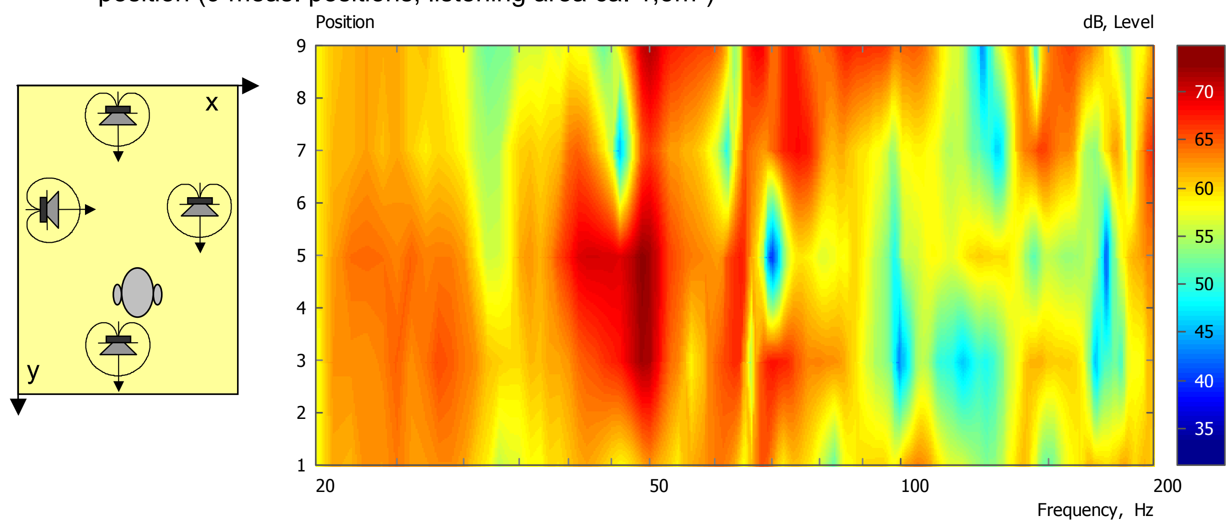


Fig. 10 ***Four cardioid subs:*** Contour plot of room transfer function plotted against measurement position (9 meas. positions, listening area ca. 1,5m²)

5 LEVEL VARIATION ACROSS LISTENING AREA

This work was inspired after studying Welti's AES paper on *"How many Subwoofers are enough?"* [3]. Although Welti used monopolar subs in his analysis, his proposed optimal positions of one sub at each wall's midpoint is identical to the arrangement that works best with cardioid subs. The target functions Welti used in his optimisation were derived from a set of transfer functions that were simulated across a listening area. Here the same approach is taken to investigation the local level variance a cardioid sub array produces across a defined listening area.

From the previous results it is obvious that the observed level variations at within the listening area are somehow related to the number of cardioid subs placed in the room. In order to quantify this relation more precise, the transfer functions of arrangements with one, two, three and four cardioid subwoofers were measured at nine positions. The measurement positions were evenly spread across a 1.5m^2 large listening area.

The measured transfer functions are plotted as colour-coded level-maps, as shown in Fig. 8 - Fig. 10, for configurations utilising one, two and four cardioid subwoofers (the three sub configuration was measured but is not shown). The measurement positions in the colour maps are plotted successively position after position as they were acquired. Areas in-between two measurements are interpolated by the visualisation software (*VACS* [9]). The plot in Fig. 8 shows that a single cardioid subwoofer generates a useful transfer characteristic within its operating range between 20Hz and 100Hz, but only at or near the optimal listening position.Changing the listening position or increasing the listening area causes large deviations of the transfer characteristic.

Adding a second cardioid sub to the configuration whilst moving both subs to either sides of the listening room (see schematic in Fig. 9 and recommend configurations in [3]) greatly reduces level variations within the examined listening area. To achieve this advantageous result the radiating axis of the two cardioids must be orientated normal to each other (90°). This particular configuration improves the excitation of width-related modes (these are modes propagating in x-direction) and thus reduces level variations across the listening area. When a third sub is added into array level variations across the examined listening area are further reduced. Acoustically the integration of the centre and the sub array remains the most noticeable improvement.

In its final stage the array consists of four subs positioned in the same arrangement as before (see Fig. 10). Only small improvements regarding the level variation within the listening area were found, compared to the three-sub configuration. The main benefit of the four-sub configuration is its flexibility due to the many degrees of freedom. Variation of the position and orientation of each cardioid sub as well as its delay and level give access to a very selective control over distinct modal frequency ranges. Of course, the acoustic integration of the subwoofer array and the five main channels is further improved.

6 MONO OR STEREO BASS ? – THE EFFECT OF DECORRELATION ON THE PERCEIVED LF-SOUND QUALITY

So far it has been assumed that all lf-cardioid sources are fed with identical signals. The signal is derived through summation of the two (or five) main channels with subsequent low-pass filtering. Such configuration can be referred to as "correlated mode". Alternatively each lf-cardioid can be driven by an individual lf-signal that is associated with its position in the room – this is called "decorrelated mode". In this section we compare both alternatives regarding their pros and cons.

The investigation was limited to two individual lf-cardioid sources. The first task was to find a quantifiable measure for "correlated" versus "decorrelated mode", that enabled us to acquire reproducible in-room transfer function measurements. Whilst the "correlated mode" setup was simple since both units were receiving identical signals, the "decorrelated mode" setup took a bit longer. After investigating the low frequency correlation between the left and the right channel of various recordings it was finally decided to generate a pseudo-stereo signal, where one channel's signal is derived from the other channel using two different de-correlation methods.

- 2nd order all-pass filter at 40/60Hz
- 3ms time delay (1m geometrical offset)

As it turned out the results of the two methods did not differ too much. Thus in the following description they will not be differentiated. The two lf-cardioids were placed half way down the left and right side wall of the listening room with their orientation being offset by 90° as shown in Fig. 11.

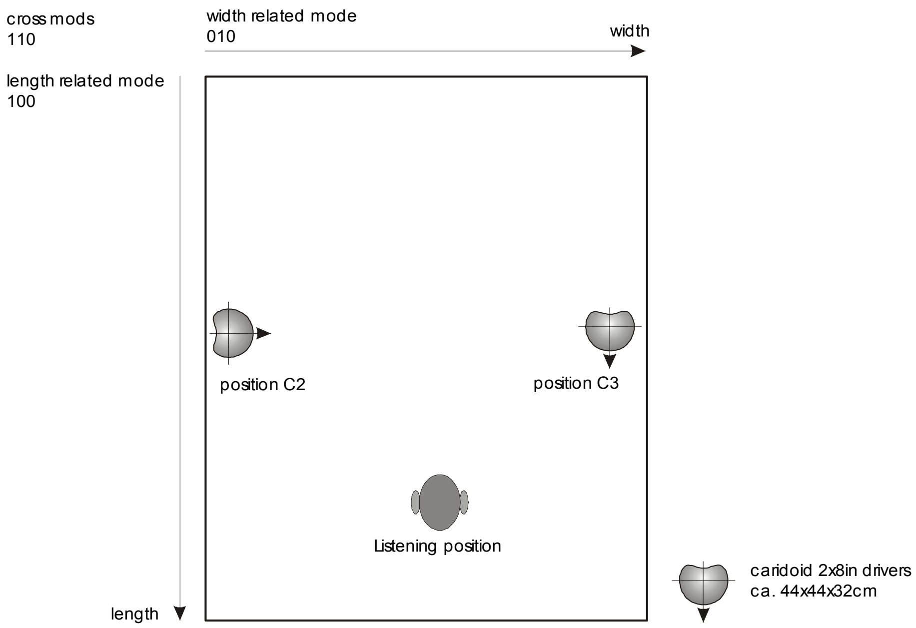


Fig. 11 Positions and orientation of lf-cardioids for measurements and listening experiments on de-correlation.

The measurements confirmed what has already been discussed in section 3 and 4. If the two lf-sources are driven in the "correlated mode" configuration the control of the lowest room modes is better and thus the modal decay times are shorter than in any of the two "decorrelated modes". On the other hand the measured in-room transfer function reacted quite sensitive to phase or time delay changes applied to one of the two lf-cardioids, when the setup was driven in "decorrelated mode". As the "decorrelation" (phase shift or time delay) between the two lf-sources increases the controlled modal excitation degrades along with increasing decay times of the lowest modes.

In the following listening test this trend was confirmed. When auditioning the "decorrelated mode" setup with dry recordings, that had only little or no natural reverberation (modern pop music) and high lf-energy content, the bass sounded less precise and more blurred, than in the "correlated mode" setup. The situation changed with music that was recorded with a high amount of natural reverberation and low lf-energy content (such as voice/instrumental recordings in churches or large halls). Then a noticeable increase in spaciousness was perceived when changing from the "correlated mode" to the "decorrelated mode" configuration.

Thus the threshold between correlated and decorrelated lf-reproduction is directly linked to the size of the room and its damping. Large rooms with well-damped lf-modes allow for a low "decorrelation threshold". In small and medium sized rooms with higher mode decay times a correlated cardioid array with its beneficial effect on the "mode control" represents the better choice. Here the ability to take control over certain fundamental modes prevails by far any possible gain in perceived spaciousness. Nevertheless, if the transition from correlated to uncorrelated operation is carefully chosen a high level of spaciousness can still be achieved. These results are in good agreement with Griesinger's findings [8] published in 1998.

In a reasonable damped room of small or medium size a cardioid array's surplus in acoustic performance can be utilized in two ways, either, to produce a precise and well-controlled low frequency sound (high degree of correlation among the lf-sources), or to increase the perceived spaciousness on the expense of less control at low frequencies.

Generally speaking, a correlated ".1-channel" represents the preferred setup mode in most multi-channel systems. The well controlled interaction of the ".1-channel" and the five or more main channels ensures a correct integration in the crossover region. Furthermore this crossover frequency also controls the transition from correlated (lf-cardioid array) to decorrelated operation (full-range main channels). The spatially distributed and decorrelated main channels are than responsible for the reproduced spaciousness.

7 CONCLUSIONS

In this paper results of an examination regarding the low frequency transfer characteristic of multiple cardioid subwoofers when used within multichannel systems are presented. The following generalised recommendations have been derived from above findings.

- Five fullrange loudspeaker with identical bandwidth and transfer characteristics offer better conditions for an even modal room excitation than systems using non-uniform loudspeakers. This recommendation is valid independent of the use of the ".1" or LFE-channel. If the ".1" or LFE-channel is used all channels should be fed the same LFE-signal, because of the advantageous "multi-point-excitation".
- The traditional sub-sat-combination with correctly adjusted crossover frequencies still represents a good alternative. Here the mode excitation in the room benefits from the use of multiple monopole subs, provided the sources are positioned in a sensible arrangement. However, in comparison to a cardioid array, the monopoles require more damping at the modal frequencies, while their flexibility regarding the modal excitation is reduced.

The results of this paper show that cardioid sources unite several beneficial properties when compared to conventional low frequency monopoles. Utilising these benefits new solutions for multichannel systems can be developed, some of which are listed below.

- The use of a cardioid to radiate low frequencies in small rooms offers clear advantages over a monopole. First, a more balanced modal excitation is achieved; second, the decay times for singular (sparsely) modes in the room are noticeably shorter. The reduced amount of acoustic energy (-4.8dB) that is coupled into the room's modal system reduces the decay times of the sparsely modal frequency range. Utilising this approach the acoustic design of the room requires less acoustic treatment in the modal range, thus it represents the more cost effective solution.
- The use of multiple cardioid sources configured as an array greatly improves the modal excitation pattern in the room.
- With just two sources good results are achieved in partially damped rooms within a small listening area.
- With four cardioid subs the transfer characteristic becomes more balanced while the evenly covered listening area is increased.
- The four parameters position, orientation, level, and phase/delay of each cardioid sub allows a very subtle and flexible control of the modal excitation in a room.
- In multi-channel systems the crossover frequency between lf-array and main channel speakers controls the transition from correlated to decorrelated operating mode. Thus in

small and medium sized rooms proper adjustment of the decorrelated lf-frequency band can be used to improve the perceived spaciousness.

8 REFERENCES

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