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THE BENEFICIAL COUPLING OF CARDIOID LOW FREQUENCY SOURCES TO THE ACOUSTICS OF SMALL ROOMS

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1 INTRODUCTION

Since the early days of high fidelity, the reproduction of low frequencies has always been an area that attracted researcher's interested. Apart from the sheer joy the physical impact of proper low frequency reproduction can deliver, low frequencies form the foundation upon which music is built. They also contain sonic clues that carry information about the acoustical size of the recording venue.

The reproduction of low frequencies in listening rooms, studios, or home cinemas depends not only on the loudspeaker used but also on the acoustic conditions of the room itself. Due to the low density of room modes in this frequency range, the sonic reproduction quality is strongly determined by the mode's distribution in frequency and their damping. A change of either the damping or the modal distribution usually requires substantial structural measures. Since in most circumstances one or the other parameter cannot be changed, the LF-source itself (and here in particular its radiation characteristic) and its position in the room remain the only variables open to changes.

The target is an even frequency response in the preferred listening area. This requires an even excitation of all a room modes, provided they are evenly distributed. The excitation of a mode depends on the LF-source's position in the room and its transducer characteristic. Besides the modal coupling of loudspeaker and listener, specular reflections, or so-called image sources, also affect the LF-transfer function.

2 Theoretical considerations

The following section is taken from Olson [1], since it represents a comprehensive overview of the different kinds of gradient sources. Of particular interest are the bi- and unidirectional first order gradient sound sources, while the zero-order gradient sound source (omnidirectional source) is included only for reasons of completeness. For each source type the mathematical description of the on-axis transfer-function and the radiation characteristic is introduced and visualised.

2.1 Omnidirectional source (monopole)

The omnidirectional source consists of a single point source radiating sound in all directions with equal amplitude. The normalised transfer function $|H(w)|$ and the polar directivity pattern $|R(T)|$ are given in Fig. 1. This source is later used to create the two first order gradient sources.

The omnidirectional polar directivity pattern makes the monopole a pressure source. As such it imprints a pressure change on all air particles surrounding the source.

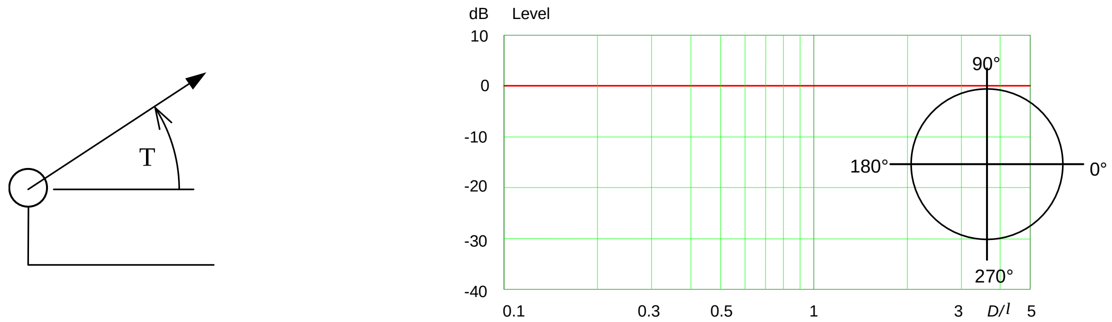

Fig. 1 Schematic, normalised frequency response |*H(w)*|, and polar directivity pattern |*R(T)*| of an omnidirectional source.

2.2 Bidirectional source (dipole)

A bidirectional source (or dipole) is constituted by two omnidirectional point sources spaced at a distance *D* and operating with 180° phase difference. The line connecting the two point sources is referred to as the *dipole-axis*. The normalised transfer function |*H(D/l)*| and the polar directivity pattern |*R(T)*| are described in formula (1) and (2), while the corresponding functions are shown in Fig. 2.

$$|H(D/l)| = 2\cdot\sin\left(p\,\frac{D}{l}\cdot\cos(q)\right) \quad (1)$$

$$R(q) = \sin\left(p\,\frac{D}{l}\cdot\cos(q)\right) \quad (2)$$

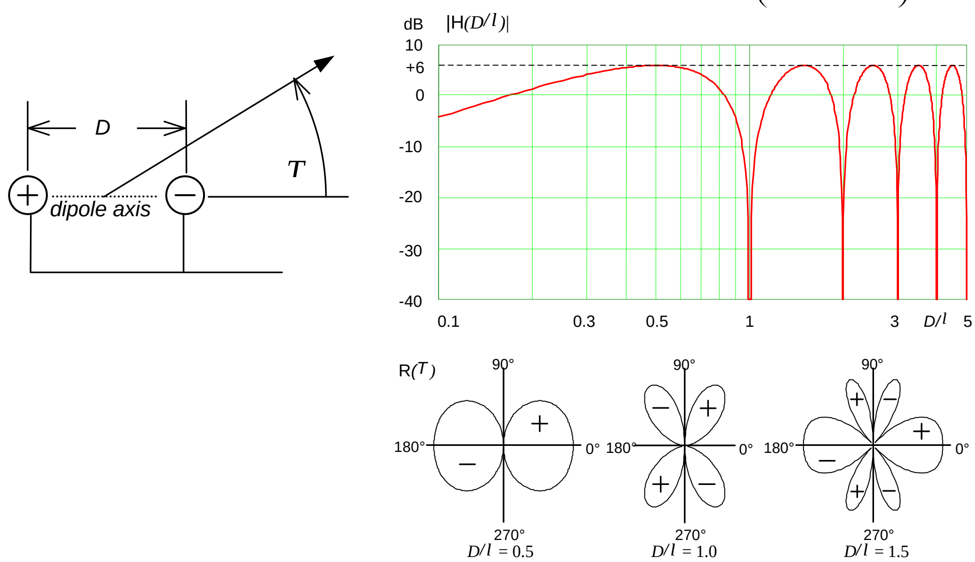

Fig. 2 Schematic, normalised frequency response |*H(D/l)*| for *T* = 0, and polar directivity pattern |*R(T)*| of a bidirectional source.

Typical dipole characteristics comprise a 6dB/oct. decay for frequencies *D/l* < 0.5 and locale minima of |*H(D/l)*| at *D/l* = 1,2,3,…N. The depicted polar plots show clearly that for frequencies *D/l* > 0.5 the dipole develops a multi-polar radiation characteristic with the number of lobes increasing by *4D/l*. The polar directivity for frequencies *D/l* < 0.25 is a dipole, while the bidirectional operating range is restricted to frequencies *D/l* < 0.7. Increasing the distance *D* between the two point sources lowers both, the lower as well as the upper limit of the bidirectional operating range.

The ideal dipole is infinitesimally small and acts as a gradient source. As such it imprints a velocity change on the surrounding air particles along the dipole axis, thus it is a directional dimension.

2.3 Unidirectional source (cardioid)

A unidirectional radiation characteristic is achieved by time-delaying one of the two point sources in Fig. 2. The cardioid-axis is the connecting line between the two point sources. If the time-delay is equivalent to the travel distance between the two point sources, the unidirectional pattern becomes a cardioid. The transfer function and directivity pattern for a cardioid are shown in Fig. 3 together with the analytical description.

$$|H(D/l)| = 2 \cdot \sin\left(p \frac{D}{2l} \cdot (1 + \cos(q))\right) \quad (3)$$

$$R(q) = \sin\left(p \frac{D}{2l} \cdot (1 + \cos(q))\right) \quad (4)$$

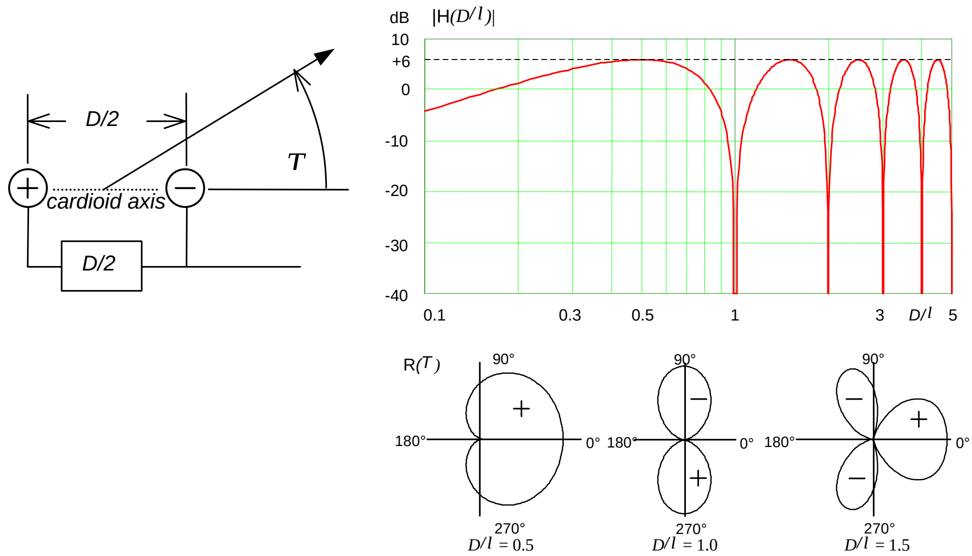

Fig. 3 Schematic, normalised frequency response |*H(D/l)*| for *T* = 0, and polar directivity pattern |*R(T)*| of a unidirectional source.

Being a derivative of the dipole, the cardioid shares the 6dB/oct. slope for frequencies *D/l* < 0.5 and the locale (on-axis) minima of |*H(D/l)*| for *D/l* = 1,2,3,…N. The polar directivity for *D/l* < 0.25 is a cardioid, but sustains a unidirectional shape up to *D/l* < 0.7.

The cardioid originates from the superposition of a monopole and a dipole. Consequently it unites both pressure source and gradient source. A measure for the gradient component is the front-to-back level ratio, where large values indicate a strong gradient component.

3 Basic room acoustic

In the previous section, mathematical descriptions are given for the three sources compared. The results are derived for the source radiating into a free space. In practise, loudspeakers are not used in free space but are placed in a room often closed to adjacent boundaries such as walls. In this section the impact of the room on the loudspeaker-listener-transfer-function is investigated. In particular two effects, the excitation of room modes and the interaction with adjacent boundaries, are examined. Using two simplified models the way the loudspeaker-listener link is affected is explained for each source individually.

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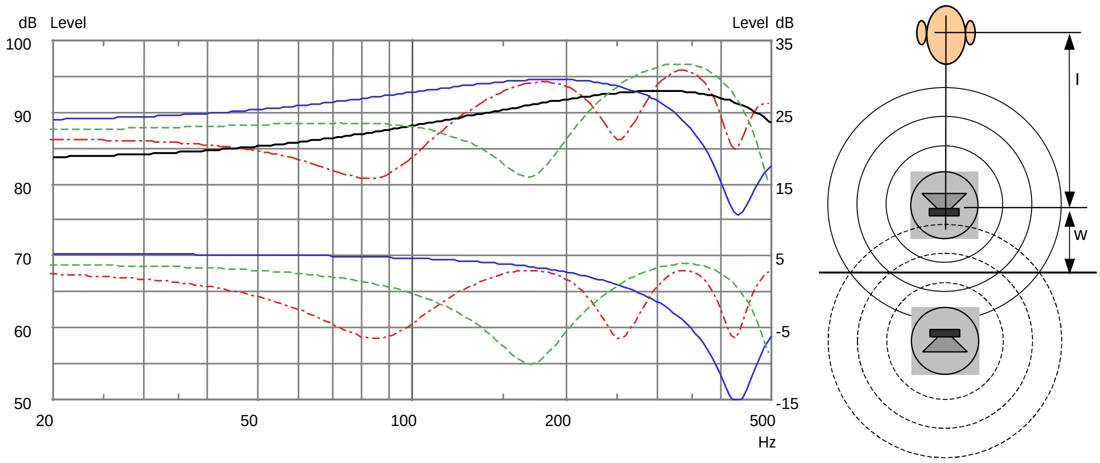

Fig. 4 On-axis frequency response of a monopole in free-field (— black) and with a specular reflection at *w = 0.2m* (— blue), *w = 0.5m* (--- green), and *w = 1.0m* (-.- red). Lower three traces are normalised to free-field-response.

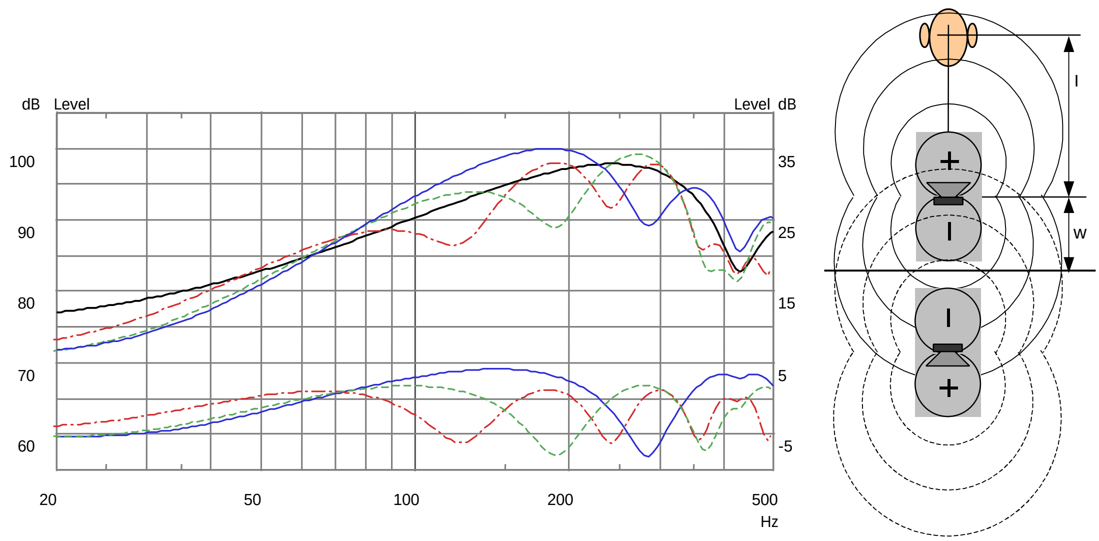

Fig. 5 On-axis frequency response of a dipole in free-field (— black) and with a specular reflection at *w = 0.2m* (— blue), *w = 0.5m* (--- green), and *w = 1.0m* (-.- red). Lower three traces are normalised to free-field-response.

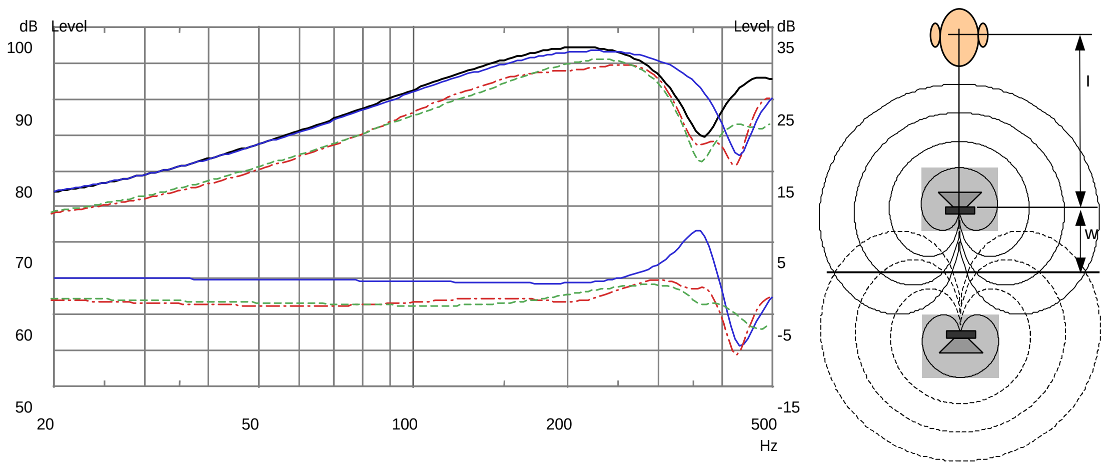

Fig. 6 On-axis frequency response of a cardioid in free-field (— black) and with a specular reflection at *w = 0.2m* (— blue), *w = 0.5m* (--- green), and *w = 1.0m* (-.- red). Lower three traces are normalised to free-field-response.

3.1 Reflection on a single boundary

When a loudspeaker is placed near a solid boundary, some waves, which would otherwise radiate away from the listener, are reflected towards him. The listener perceives the superposition of the direct-radiated and the reflected wave.

This scenario has been simulated using the simulation software AkAbak. The results for each source type are presented in Fig. 4, Fig. 5, and Fig. 6. The distance between listener and source is kept constant at *l = 2m*. The four traces in the upper half of each diagram represent the simulated on-axis frequency response (black) under free-field conditions and with a reflective boundary introduced. The impact of the distance *w* between the source and the boundary on the frequency response is shown for *w = 0.2m, 0.5, 1.0m.* The lower three curves in each diagram show the level difference between the reflective-boundary- and the free-field-condition.

In the frequency range of interest (f<300Hz), the cardioid model used in this investigation has a front-to-back level ratio of 20dB. This marks the lower end of what are feasible values for real-world designs. With increasing front-to-back level ratio the radiation characteristic becomes over sensitive to the level- and phase-balance between front and rear output.

As a direct consequence of the reduced rear radiation, the cardioid's response curves in Fig. 6 show no interference related cancellations. The response dip around 400Hz is related to the separation of the two point sources (0.4m) used in the simulation. In contrast to this both, monopole and dipole strongly interfere with the introduced boundary across all tested distances (see Fig. 4 and Fig. 5). The closer the source is positioned to the boundary, the higher first cancellation shifts in frequency. At very low frequencies (<50Hz) the monopole is boosted up to 6dB while the dipole shows a similar loss in output.

3.2 Mechanisms of mode excitation

As stated earlier the excitation of room modes, especially in the sparsely modal frequency range, has a substantial influence on the achieved sound quality in a room. The three sources have different mode-coupling mechanisms and they are illustrated by means of a two-wall-model in Fig. 7. The monopole is a pressure source and excites modes most strongly when placed at positions of high pressure, so called pressure-antinodes (*x=0*, *x=L* in Fig. 7). This is interpreted as good coupling to the mode. Conversely, poor coupling is obtained when the monopole is placed in pressure-nodes (*x=L/2*). The mode is then weakly excited.

The counterpart of the monopole is the dipole. Good coupling to a mode is achieved at positions with high velocity (pressure-node = velocity-antinode). In Fig. 7 this is the case at the pressure-node *x=L/2*. As pointed out earlier the velocity component is a vector and the dipole-axis needs to be aligned along the travel direction of the mode to obtain maximum coupling. Turning the dipole-axis into an angle less than 90° continuously lowers the mode-coupling until dipole and mode are completely decoupled (90°).

The cardioid is a combination of a gradient and a pressure source. Thus it obtains good coupling to the mode in Fig. 7 across the whole length *L*, provided the cardioid-axis is aligned along the mode's travel direction. Turning the cardioid-axis reduces the coupling factor.

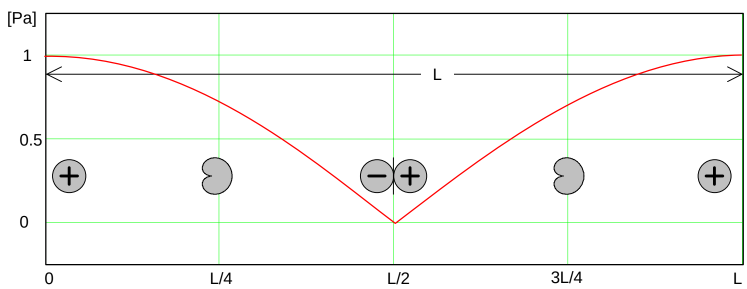

Fig. 7 Pressure distribution of the first order mode between two walls, separated by a distance L. Positions for maximum mode excitation of monopole, dipole, and cardioid.

The one-dimensional model in Fig. 7 has one important limitation that should not be overlooked. Real rooms are three-dimensional, thus the cardioid's position-independent coupling to a mode would disappears for all axial modes propagating in the other two directions. Turning the cardioid-axis to an angle such that its velocity-component couples into x-, y-, and z-direction can fix this problem.

4 Experimental results

In this section the mode-coupling properties of the three described sources are verified on the basis of measurements taken in a 4.0x5.0x2.6m sized reverberation chamber. The transfer functions were measured for three positions A, B, and C as depicted in Fig. 8. The low damping environment of the rev-chamber was chosen, because it emphasises the differences in mode excitation.

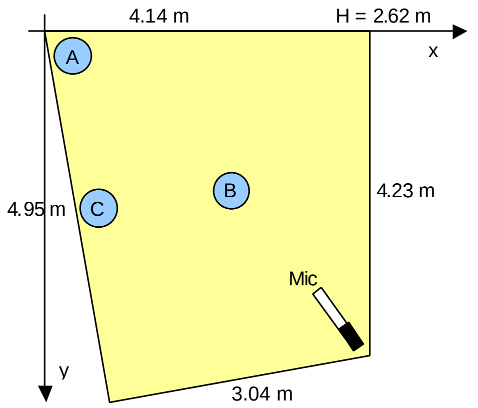

Fig. 8 Dimensions of the reverberation chamber and measurement positions A, B, and C.

The acquired excitation patterns are judged using the first order axial modes in x- (100-mode @ 38Hz) and y-direction (010-mode @ 46Hz). Type, position and orientation (dipole & cardioid) of the sources follow from the sketches to the left of each diagram. The microphone was placed in the lower left corner of the reverberation chamber. All impulse responses were acquired at 5kHz sampling rate with a total duration of 1.2 sec. Individual equalisation was applied to each sources to assure identical on-axis responses under free-field conditions.

4.1 Position and orientation

In Fig. 9 the responses are plotted for corner placement with diagonal orientation of the two gradient sources. As expected the monopole (---) shows good excitation of both modes, as does the cardioid (—), while the dipole suffers from a broad cancellation due to the three adjacent boundaries.

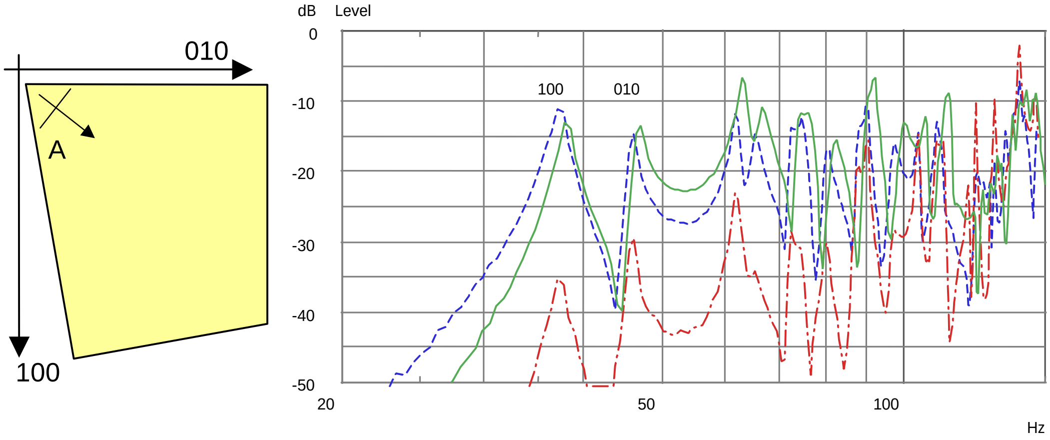

Fig. 9 Room transfer function of monopole (blue ---), dipole (red -.-), and cardioid (green —) at position A with diagonal orientation.

In Fig. 10 the sources are positioned at the centre of the rev-chamber while the diagonal orientation is maintained. Again the cardioid shows the best coupling of all three sources, followed by the dipole, because of its good coupling to the local pressure-node. The monopole shows poor coupling to both modes.

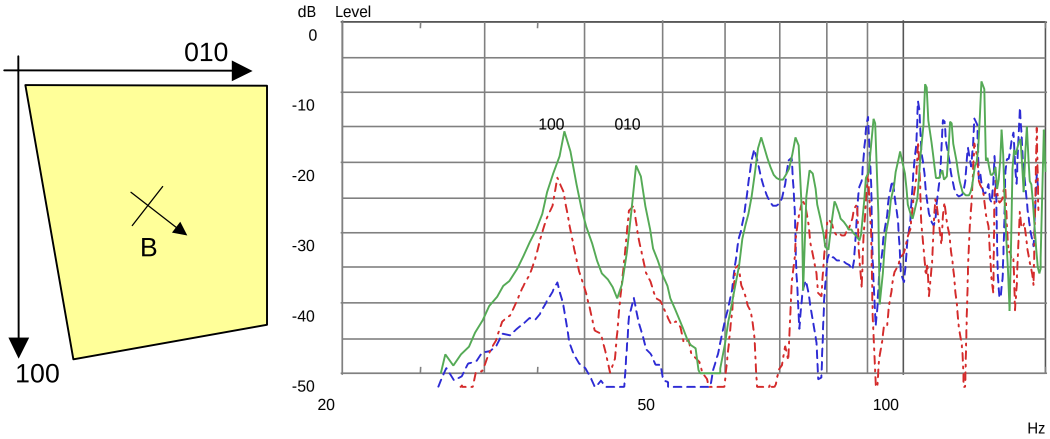

Fig. 10 Room transfer function of monopole (blue ---), dipole (red -.-), and cardioid (green —) at position B with diagonal orientation.

The cardioid's excitation pattern is not affected by moving the sources in position C, half way along the length of the chamber. The strong excitation it achieved in position B (Fig. 10) is sustained. The monopole shows good coupling to the 010-mode but fails to excite the 100-mode since it is placed in its pressure-node. Unsurprisingly, the dipole shows the opposite behaviour.

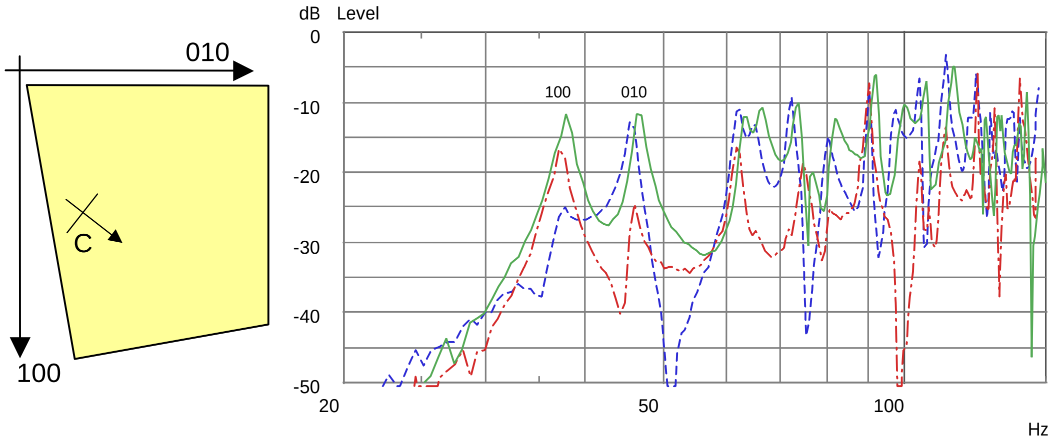

Fig. 11 Room transfer function of monopole (blue ---), dipole (red -.-), and cardioid (green —) at position C with diagonal orientation.

Finally the two gradient sources are orientated along the width of the reverberation chamber (y-axis, Fig. 12). Both show only weak coupling to the 100-mode. While the cardioid actively suppresses the 100-mode by pushing energy into both ends, the dipole just fails to couple into the mode because its dipole-axis is aligned at right-angles to the mode's propagation direction (x-direction). In addition, the rear reflection causes broad cancellation.

These four examples outline the different mode coupling mechanisms of monopole, dipole, and cardioid. Moreover the data underlines the cardioid's advantageous mode-coupling properties. Its excitation pattern shows only small variations when moved across various positions.

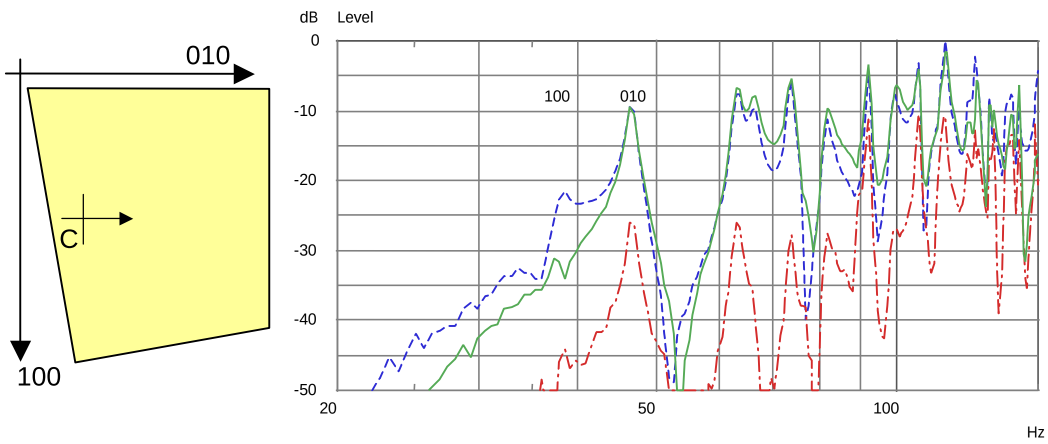

Fig. 12 Room transfer function of monopole (blue ---), dipole (red -.-), and cardioid (green —) at position C with y-orientation.

The cardioid represents the ideal source when an even mode excitation is to be achieved in acoustically difficult situations. An additional degree of freedom is gained from the possibility to change the mode coupling by turning the source, thus making it easier to find a position in the room that suits both practical as well as acoustical demands.

4.2 Different makes of lf-cardioids

The "simplest" construction of a low frequency cardioid is the combination of a monopole and a dipole in a common enclosure. Here, one drive unit is put in a closed box, with a second one sitting on top mounted in an open baffle. A source like this is shown in Fig. 13.a built around two 10"-units accommodated in a closed box with a single 12” unit making up the gradient component. Major drawbacks of this design are the costly enclosure and the use of at least two chassis and amplifiers.

A more economical alternative is the “semi-open-back” enclosure. In its simplest form the rear of an otherwise closed box is replaced with a flow-resistance. The task of this flow-resistance is to delay the rear radiation by a constant phase angle. However, practical trails have shown that a reduction in amplitude is unavoidable. *Musicelectronic geithain* has successfully introduced the “semi-open-back” enclosure in its monitor range, which is proof of the commercial potential of the cardioid.

Fig. 13.a Fig. 13.b Fig. 13.c

Fig. 13 a: Combination of monopole (top) and dipole (bottom) (*wvier, Germany*).).
b,c: Front- and rear-view of the monitor loudspeaker RL901K (*musicelectronic geithain, Germany*). The black openings to the left and right of the electronic section (c) are the two acoustical flow-resistances (pictures taken from [6]).

Regarding its acoustic properties, the main difference between the two cardioid-types is the front-to-back level ratio. When carefully adjusted the monopole/dipole-combination can achieve values up to 40dB, while even carefully designed flow-resistance based cardioids will not achieve values better 20dB. The answer to the question how much front-to-back level ratio is necessary to get most of the advantageous behaviour of the cardioid is answered in Fig. 14.

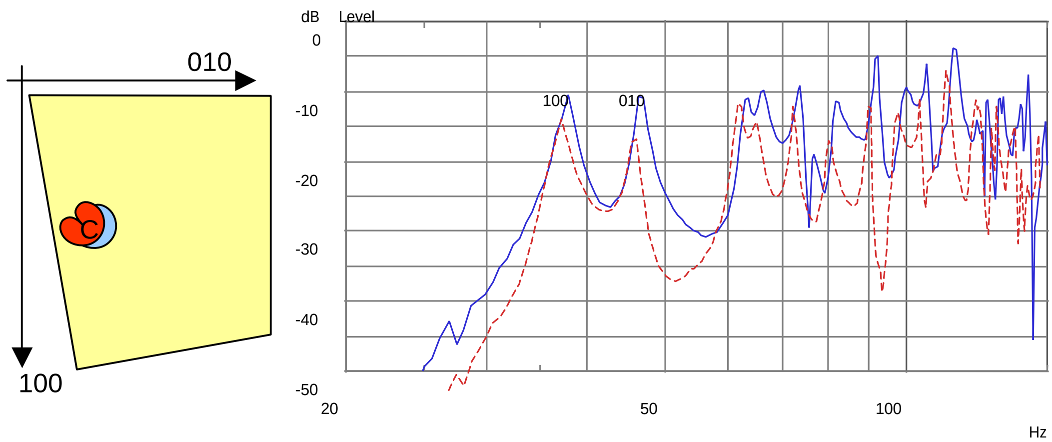

Fig. 14 Room transfer function of two different cardioid-makes in position C with diagonal orientation. “Flow-resistance”-cardioid (blue —) and monopole/dipole-combination (red ---).

The near-field frequency responses of both cardioids were adjusted in order to match each other, causing the composite-cardioid to show a higher front-to-back level ratio than the “flow-resistance”-cardioid. But the two traces in Fig. 14 reveal, that this distinction does not affect the excitation pattern. The subtle differences are mainly caused by different enclosure geometries. A high front-to-back level ratio is only advantageous when the cardioid is directly placed in front of a wall. Here possible cancellation caused by the image source is efficiently suppressed.

4.3 Practical considerations

All the presented material gives support to the cardioid as the most versatile low frequency source (regarding mode excitation) of all the three sources examined. The investigation was concluded with a comparative measurement of a monopole, a dipole, and a cardioid LF-source in an ordinary listening room. To guarantee the comparability of the measurements all sources were placed at the same position in the room. Orientation was chosen to give the smoothest response for the dipole and was kept the same for the cardioid. The measurement below confirms the previously found results. In particular, the monopole fails to excite any of the modes between 40Hz and 70Hz. This is a common problem of omnidirectional sources and is frequently observed. However, neither dipole nor cardioid, have any problem exciting the modes in this frequency range.

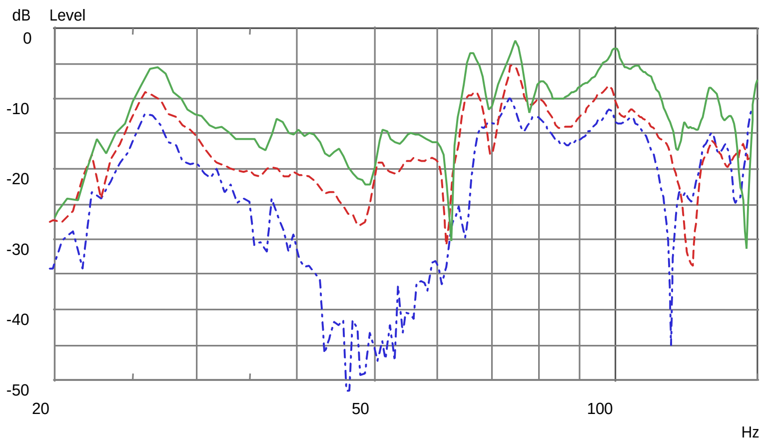

Fig. 15 Transfer function of monopole (---), dipole (-.-), and cardioid (—) measured in ordinary listening room.

5 Conclusions

The conclusions of this study are summarised in the following.

1) A cardioid low-frequency source unifies the physical properties of monopole and dipole. The front-to-back level ratio can be used as a measure for the level balance between two generic sources (monopole and dipole).

2) A cardioid’s reduced rear radiation makes it insensitive to rear boundaries. A front-to-rear level ratio of 10dB is sufficient to secure this advantageous property.

3) A cardioid excites room modes in pressure-nodes as well as velocity-nodes. Therefore its coupling to room modes is far less position dependent than that of a monopole or a dipole. Experiments prove that the cardioid maintains nearly the same mode excitation pattern even when placed in contrary positions (corner vs. centre). Turning the cardioid can help to adjust for an even mode excitation pattern.

4) Utilising a flow-resistance terminated enclosure enables a commercially viable design of a low-frequency cardioid. Front-to-back level ratios between 10dB and 20dB are feasible.

Finally, the author thanks his colleague Uwe Kempe for building and assessing numerous prototypes and his patience when suffering controversial telephone discussions.

6 REFERENCES

[1] Harry F. Olson, „ *Gradient Loudspeakers* “, J. Audio Eng. Soc., pp86-93, Vol. 21, No. 2, 1973.
[2] Gyn Adams, John Borwick, „*Loudspeaker and Headphone Handbook*“, Focal Press 3rd Edition 2001, pp. 353-359.
[3] Lampos Ferekidis & Uwe Kempe, „*Room mode excitation of monopolar and dipolar low frequency sources*“, Preprint no. 4193, 100th AES Convention, Kopenhagen 1996.
[4] Roy F. Allison, „*The influence of room boundaries on loudspeaker power output*“, J. Audio Eng. Soc., pp314-320, Vol. 22, No. 5, 1974.
[5] Siegfried Linkwitz, „*Investigation of Sound Quality Differences between Monopolar and Dipolar Woofers in Small Rooms*“, Preprint no. 4786, 105th AES Convention, New York 1998.
[6] Jochen Kiesler, Interview with Dieter Thomsen, Produktion Partner 5/2002 (german)