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The Acoustic Design of Minimum Diffraction Coaxial Loudspeakers with Integrated Waveguides

Aki Mäkivirta, Jussi Väisänen, Ilpo Martikainen, Thomas Lund, Siamäk Naghian

Genelec Oy, Iisalmi, Finland

Correspondence should be addressed to Aki Mäkivirta (aki.makivirta@genelec.com)

ABSTRACT

Complementary to precision microphones, creating an ideal point source monitoring speaker has long been considered the holy grail of loudspeaker design. Coaxial transducers unfortunately typically come with several design compromises, such as adding intermodulation distortion, giving rise to various sources of diffraction, and resulting in somewhat restricted maximum output performance or frequency response. In this paper, we review the history of coaxial transducer design, considerations for an ideal point source loudspeaker, discuss the performance of a minimum diffraction coaxial loudspeaker and describe novel designs where the bottlenecks of conventional coaxial transducers have been eliminated. In these, the coaxial element also forms an integral part of a compact, continuous waveguide, thereby further facilitating smooth off-axis dispersion.

1 Introduction

Positioning of microphones can determine the outcome of a recording, and small microphone location changes can make the difference between the resulting sound being good or sublime. Microphone placement is based on listening, which in turn requires an equal amount of accuracy. Mixing and mastering are other critical phases where trust in what the engineer hears is essential for setting levels, pan, equalization, effects, and evaluating the sound stage width and other fundamental aspects of the presentation quality. Reliable monitoring affects how well a track or a program translates to other rooms and playback conditions.

Traditional loudspeaker designs place individual transducers on the front baffle of the enclosure. Typically, transducers are stacked vertically to avoid time-of-arrival differences when the listener moves to off-axis locations on the horizontal plane as this is the more typical movement in the monitoring room. For vertically stacked transducers, movement in the up-down direction changes the timing between the transducers, and this can generate audible tonal changes at the crossover frequencies. Such crossover coloration makes subjective evaluation unreliable in directions where the geometry between the transducers changes with listener location or head movement. Head movements are a stabilizing factor used by listeners when evaluating and controlling sound stage and imaging [11]. Coloration can be a confounding factor with loudspeakers used for research also.

Coaxial designs, where several transducers are on the same acoustical axis, do not suffer from the sound colour change problem, and have long been regarded as a potent solution to improve the quality of the loudspeaker as a sound radiator. The fundamental benefit of a coaxial design is that the geometry of the transducer distances to the listening location remains the same when the listener moves off-axis to any direction. Because the relative timing does not change or changes minimally, the magnitude response at the crossover transition remains flat also for the off-axis positions.

Another benefit of coaxial designs is that they can have stable frequency response also when the listener is close to the loudspeaker. This improves near field monitoring as the sound colour created by the loudspeaker remains stable with the changing distance to the loudspeaker.

Near field monitoring can reduce the influence of the room acoustics and improve the maximal SPL of the loudspeaker without evoking nonlinearities in transducers typically occurring at high excursions.

However, current coaxial transducers suffer from problems such as sound-colouring diffraction due to discontinuities between the coaxially located drivers. Particularly two-way coaxial designs can have problems with Doppler distortion, having to operate each transducer over a wide frequency band.

Although a two-way active loudspeaker is the ubiquitous reliable work horse of the industry, a three-way design offers the potential for improving performance in several ways including extended frequency range, better control of directivity, higher output capacity and lower distortion. Particularly for coaxial designs, a three-way construction can also significantly reduce the issue of Doppler distortion in the coaxial transducers.

A three-way design allows better optimization of transducer characteristics (for example sensitivity, linearity, output capacity, directivity, materials and construction methods used) than a two-way design because of the narrower frequency range for each transducer. More optimal crossover frequencies can be chosen to circumvent acoustical constraints in transducers and enclosure characteristics. Physically larger loudspeakers have the surface area needed for a waveguide to enhance directivity control, and achieve a better performance in challenging room acoustics.

While a three-way construction has its strong points, implementing it in a compact enclosure suitable for smaller rooms, is a challenge. Coaxial transducer is used in order to create the surface area needed for a waveguide.

The present paper discusses briefly the history of coaxial transducers before describing the design principles for implementing an acoustically coaxial three-way loudspeaker with a large directivity waveguide. Three design case examples of such a loudspeaker are implemented and tested for performance.

Typically, a coaxial transducer uses two magnet motors – one for the tweeter, the other for the midrange. We describe a coaxial transducer using a single magnet motor with two air gaps, one for the tweeter, one for the woofer. To minimize diffraction, the gap between the tweeter dome and the midrange cone, as well as the midrange cone and the enclosure surface, are bridged with elastic material, creating an acoustically continuous surface shaped to minimize diffraction. The elastic members in the designs may be glued in place, and can introduce acoustically significant steps in the surface of the midrange cone.

Finally, the paper presents the concept of acoustically concealing multiple woofers under the waveguide, enabling the creation of a large continuous front baffle surface for mid and high frequencies. The two woofers spaced to the ends of the enclosure lay under the waveguide and acoustically combine to create controlled directivity in bass frequencies. The proposed woofer system enables physically compact enclosures where horizontal and vertical radiation characteristics can be made similar. The enclosure can be manufactured using different casting technologies, such as in die casting or injection molding.

2 Acoustic benefits of coaxial design

The coaxial transducer arrangement has acoustic benefits. A multiway loudspeaker has two transducers reproducing sound simultaneously across the crossover range of frequencies. Conventional multiway designs have transducer locations distributed across the front baffle. The summation of the outputs from any two transducers is usually designed to be in phase in the primary listening direction (acoustical axis). When the two outputs are in the phase the system output remains flat. For off-axis locations, the two transducers are not in phase because the distances to the transducers have changed from the design geometry (Figure 1). This can produce audio coloration which changes when the listener moves further off-axis. Placing transducers coaxially can reduce or eliminate such coloration.

Crossover performance is further improved by time-aligning the two coaxially constructed transducers at the crossover frequency, with the benefit of maintaining the time domain waveforms. This is particularly important for those transducer constructions where the physical height of the tweeter and midrange transducers are significantly different.

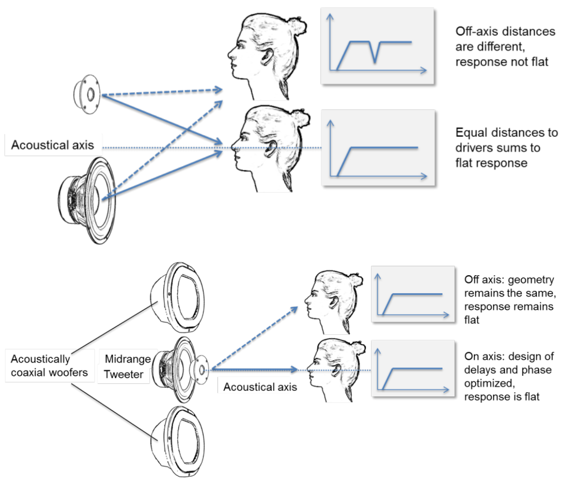

Figure 1: Avoiding off-axis coloration in coaxial system design (bottom) over the conventional vertical stacking (top).

3 Evolution of the coaxial transducer

The idea of implementing a multiway transducer system coaxially is not new. Already in the 1940s, Altec Lansing launched the '601' coaxial transducer [1] with a section horn tweeter coaxially located in a 12 in woofer. This was followed closely by the Tannoy Dual Concentric design [2,3]. By the 1970s, with the introduction of UREI 813, the three-way coaxial loudspeaker became popular in audio monitoring [4].

Figure 2: Altec Lansing 601 coaxial transducer, showing a fixed multicell tweeter horn in the apex of the woofer cone.

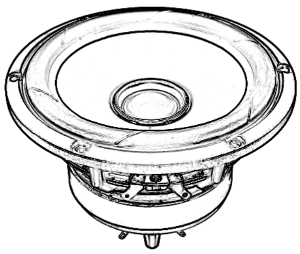

Figure 3: Example of a coaxial transducer with the woofer cone forming the waveguide surface for the tweeter dome; also here the tweeter is surrounded by a fixed edge and there is a gap (opening) between the tweeter and the woofer cone inner edge.

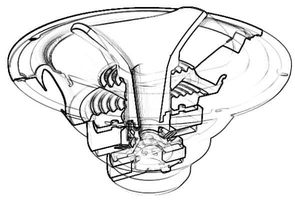

Figure 4: Example of a coaxial transducer with a tweeter in a fixed horn structure installed in the apex of a woofer.

When the woofer works down to bass frequencies (two-way systems) the woofer cone displacement becomes large and this can generate a Doppler shift in the audio radiated by the tweeter. As the woofer cone is making a harmonic movement, this Doppler shift varies harmonically. This leads to a system where low frequencies tend to modulate high frequencies, causing relatively large intermodulation distortion.

When the woofer cone surface forms the waveguide for the high frequency radiator (concentric transducer, Fig. 3), inter-modulation distortion tends to be larger than for constructions with a fixed horn located in the apex of the woofer (Fig. 4). The intermodulation can be reduced by directing low frequencies to a separate woofer transducer, using the coaxial transducer as a midrange-tweeter radiator. The intermodulation distortion problems typical for these designs can be significantly reduced with a physically displaced woofer in a three-way arrangement [5].

The fixed horn tweeter coaxial designs suffer from diffraction of sound around the mouth of the horn. The sound diffracting around the horn mouth travels to the woofer cone, then reflects backwards and sums with the direct sound with a fixed delay and frequency specific level, creating sound coloration.

4 Elements of a novel coaxial design

There are four primary types of compact three-way loudspeakers.

The first type is the *conventional* non-coaxial transducer arrangement, where individual transducers are arranged in the front baffle of the loudspeaker enclosure, displaced from one another. When three transducers are placed on the front baffle area, there is little surface area left for directivity control particularly in the midrange and woofer frequencies. Crossover coloration problems are typical at the two crossover frequencies in the off-axis directions.

The second type is the *approximately coaxial* arrangement. This places an island containing a tweeter and midrange transducer on top of a woofer. Some approximately coaxial systems stack all three transducers while the transducer axes are not coaxial. Approximately coaxial designs reduce the loudspeaker front baffle needed for transducers. The transducer height differences and the delayed contribution of diffracted audio creates colorations. Directivity matching is problematic and contributes to coloration in off-axis directions.

Two coaxial transducer technologies are used in three-way arrangements. These are the *concentric tweeter-midrange* arrangement and the *horn-loaded tweeter* system.

Certain concentric transducers apply mechanic-acoustic fitting between the tweeter and the midrange to minimize the effect of the acoustic discontinuity and hence the diffraction-related colouring between the tweeter and midrange [12]. The concentric arrangement can show a tendency for intermodulation distortions. It is difficult to optimize the midrange cone shape sufficiently to make the midrange work as a high-performance waveguide for the tweeter. Seating of the midrange cone to the transducer chassis and the joint or gap between the tweeter and midrange can create acoustic diffractions.

The horn-loaded tweeter in a coaxial transducer reduces intermodulation but can add other problems. Some frequency-dependent amount of sound is diffracted around the horn mouth edges. The sound interferes with the direct radiation of the tweeter horn. This creates direction and frequency-dependent variations in the sound pressure level, making it difficult to achieve flat frequency response. The delayed addition of diffracted audio affects the system impulse response. The horn can sustain resonances that in some designs have been addressed using digital signal processing, but it is challenging to completely remove these artefacts.

4.1 Minimized diffraction design

The concentric transducer arrangement is a candidate for reducing the diffraction problems typical in coaxial transducers. To minimize acoustic diffraction in the coaxial three-way design, improvements are needed in order to

- create a coaxial midrange-tweeter transducer with minimized acoustic diffraction
- create an acoustically continuous surface for the tweeter and midrange transducer radiation
- minimize the acoustic impact of having woofer in the enclosure

To avoid acoustic diffractions, the enclosure surface starting from the tweeter is made smoothly shaped, without large edges or openings. The midrange cone is shaped as a part of this form.

4.2 Waveguide design

The waveguide shape is designed using optimization in a physical model (FEM modelling) to enable controlled directivity radiation for the tweeter as well as midrange frequencies.

The waveguide is extended to the ends of the enclosure to minimize the acoustic diffraction at the edges of the waveguide. The enclosure sides are also close to the ending of the waveguide and this further contributes to minimization of the acoustic diffraction at the edges. The edge diffraction was computer optimized using FEM modelling.

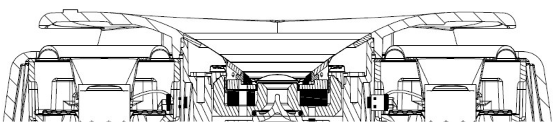

Figure 5: Crosscut view of the concentric transducer arrangement (acoustical axis facing up). Also seen are the radiation cavities for dual woofers with the directivity waveguide extending to cover the woofers.

4.3 Coaxial transducer design

The coaxial transducer contains tweeter and midrange transducers. The midrange cone forms a part of the front baffle waveguide shape. The midrange movement is enabled by elastic sections in the midrange cone. The capacity for movement is optimized by the dimensions of the elastic sections.

The joint from the tweeter to the midrange is created with a ring. The ring surface shape is optimized to minimize diffraction near the tweeter transducer.

The tweeter and midrange share the magnet motor. The motor has two air gaps. The air gap locations and sizes are optimized using modelling to minimize one transducer from affecting functioning of the other due to magnetic field modulation or saturation effects. The back cavity for the tweeter as well as the midrange are optimized for the frequency range and the output capacity needed.

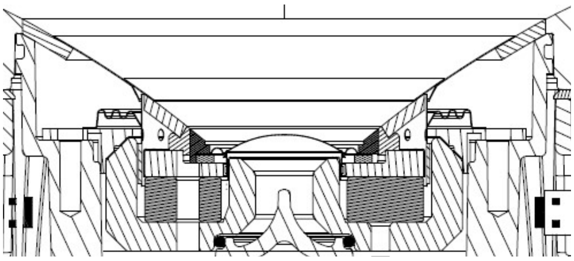

Figure 6: Crosscut view of the concentric transducer showing the magnet motor shared by the tweeter and midrange transducers and the elastic sections of the midrange cone enabling the midrange to be shaped into a part of the directivity waveguide (acoustical axis facing up).

4.4 Woofer cavity design

Two oval (racetrack-shaped) woofers are located under the front baffle shaped as a waveguide (see Fig. 5 and 7). Woofer radiation happens through openings, one for each woofer.

The front baffle creates a cavity over the fronts of the two woofers (see Fig. 9). This cavity has natural resonance frequencies that depend on its volume and shape. The resonances store energy and create colorations and changes in the time domain response of the system.

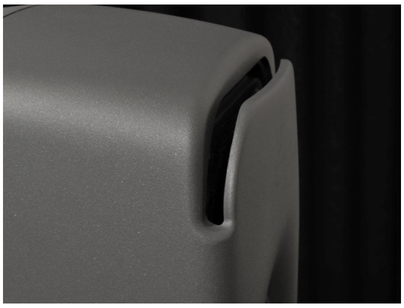

Figure 7: Acoustically concealed woofers radiate low frequency through acoustically optimized openings in the ends of the front baffle; this enables the whole front baffle to be used as a waveguide.

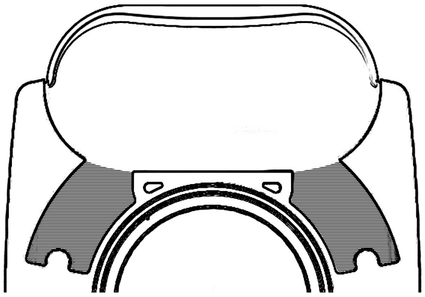

Figure 8: Principle of the woofer cavity and the joined volume filled with absorbent for resonance control (dark grey shaded areas) under the surface of the directivity waveguide; one oval woofer space shown.

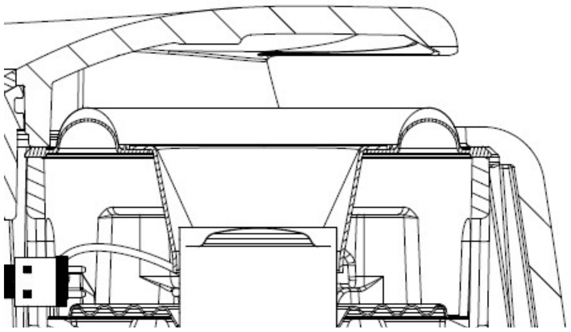

Figure 9: Crosscut detail of the woofer transducer under the surface of the directivity waveguide (acoustical axis facing up).

The cavity resonances in the operational range can be avoided by designing the cavity dimensions suitably. The resonances can also be damped acoustically using absorbing material placed in joined volumes with the cavities for the cases where some resonant tendency remains (see Fig. 8).

The size and shape of the opening of the front cavity has a strong influence on the nature of the cavity resonance. The opening is optimized to minimize the resonance and at the same time to minimize the acoustic diffraction at higher frequencies that the opening may cause.

4.5 Composite dual-woofer design

Two spaced woofers are built into the front baffle of the enclosure (see Fig. 10 for the principle). They are recessed in cavities, allowing the enclosure front to extend as an acoustically continuous surface (see Fig. 9).

Because the two woofers are spaced at a certain distance from each other, they create increased acoustic directivity along the axis of displacement. The woofers are fed with the same audio signal. The distance between the woofers has been selected such that the directivity of the woofer system matches the directivity of the coaxial tweeter-midrange system at the midrange-to-woofer crossover frequency.

The two woofers have oval racetrack shape. The longer dimension of the woofer transducer is selected so that this creates a matching directivity along the smaller dimension of the front baffle, on the axis orthogonal to the woofer displacement axis (see Fig 10). The directivity control waveguide is designed to match the directivities of the dual-woofer system at the crossover frequency.

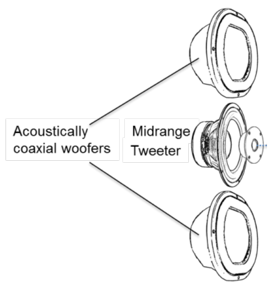

Figure 10: Dual woofer system creating an acoustically coaxial woofer transducer in relation to the tweeter-midrange coaxial transducer.

In the largest of the designs (design C), the distance between the centres of the two woofers is 268 mm. The total woofer diaphragm area is close to that of a round 255 mm (10 inch) woofer. The woofers are loaded by a bass reflex enclosure having a reflex port opening to the back of the enclosure. The two openings for the woofers are spaced at a distance of 380 mm. This corresponds to 0.56 wavelengths at the woofer-to-midrange crossover frequency (490 Hz) and gets even smaller in wavelengths when the frequency decreases. As this distance in wavelengths is small, lobing in the radiation pattern due to using two woofers does not occur [7].

The directivity characteristics of the dual-woofer arrangement is in this case similar to a round woofer with a diameter 457 mm (18 inches) along the axis of displacement. Along the perpendicular axis, the woofer directivity is determined by the size of the opening for woofer radiation.

5 Three consolidated designs

Three different sized systems have been designed using the principle of a minimum diffraction coaxial in a waveguide. The main parameters of the three types A, B and C are given in Table 1.

Figure 11: The principle of construction for the system types A-C. The front shows woofer openings at top and bottom of the enclosure and a centered coaxial tweeter-midrange transducer (left); the rear side shows the bass reflex port opening (right).

The main differentiating features are differences in the woofer design and in coaxial tweeter-midrange transducer design. System types A and B use a paper cone woofer while type C uses a honeycomb woofer design with stiff planar diaphragm.

System types A and B have a midrange cone design with separate elastic members in the inner and outer edges of the aluminium cone. System type C uses an aluminium cone covered by an elastic surface, also extending across the inner and outer edges of the cone to allow the elastic joint needed for midrange cone movement.

System types A and B share the single magnet motor design with two air gaps, while the system type C is of a more conventional design with two separate coaxial magnet motors.

		type		
parameter		A	B	C
Enclosure dimensions height width depth	mm	 299 189 212	 350 237 243	 433 312 278
Tweeter diameter	mm	19	19	19
Midrange diameter	mm	90	90	127
Woofer dimensions	mm	130x65	170x90	200x90

Table 1: Overview of the three system types

6 Results

6.1 Directivity control

The low diffraction coaxial transducer seating in the directivity control waveguide of the enclosure front creates a continuous acoustic surface for high frequencies radiated by the tweeter and midrange. The coaxial transducer design has minimal acoustic discontinuity. The large waveguide enables control of directivity across the operating frequency range of the tweeter-midrange system. The waveguide geometry minimizes sound colouring diffractions.

The compact three-way design presents a waveguide surface area equal to that found in large size three-way main studio loudspeakers. In the case of type C, the directivity control (see Fig. 14) exists down to 300 Hz in the larger axis dimension and down to 700 Hz in the smaller dimension.

6.2 Temporal alignment

While it is known that the human auditory system has a frequency-dependent resolution limit to narrow band temporal changes in an audio signal, maintaining accurate temporal relationships is beneficial, when doing so does not cause the smearing of the temporal detail in the signal. Applying filters on the audio signal amounts to convolving the signal with the impulse response describing the filter functions. Convolution tends to increase the total length of the system impulse response.

If the system impulse response becomes excessively long, some early parts of the impulse response can become audible as separate auditory events [8, 9].

In principle, if the relative timing of the audio output remains constant, i.e. if the loudspeaker presents a constant delay to all frequencies, waveforms may be accurately reproduced. While, ideally, the phase relationship between different frequencies should not change during reproduction, the human auditory system is more sensitive to local variation in the system delay at mid frequencies rather than at very low or very high frequencies.

High resolution time-frequency analysis (Figure 13) can be used to study the relative timing of the sound output as well as to understand the length of the system response in time.

In the plots of time-frequency analysis, the system input-to-output delay has been removed and the smallest delay is shown at zero. When signal processing is used to align the time response of the system, the input-to-output latency is sacrificed, especially when aligning the loudspeaker delay down to lower frequencies.

System types A and B use signal processing to realign the mid and high frequencies. For these types, the delay starts growing at bass frequencies where the electro-mechanical delay of the high pass nature of the design is displayed as an increase in the delay. System type C displays the natural minimum phase character of the electro-acoustic design.

The delay for all system types starts growing close to the low corner frequency, mainly due to the combined effect of the woofer mechanical resonance, bass reflex enclosure resonance character and the associated signal processing containing some band limiting filters to control the woofer transducer excursion below the Helmholtz resonance frequencies.

6.3 Multitone distortion

The performance of the proposed design was evaluated against the typical performance of the established implementations of compact three-way loudspeakers in the case of the system type C.

A multitone measurement signal was used. Multitone measurements can give relatively realistic measurements of the overall linearity because the signal is a complex multifrequency signal containing a wide bandwidth and presenting in that sense a load similar to a realistic wideband audio signal. The test signal contained 30 tones distributed evenly on a log frequency scale across the audible range, from 21 Hz to 20 kHz.

The case examples of the different technologies include the typical technologies currently applied in compact three-way loudspeaker designs.

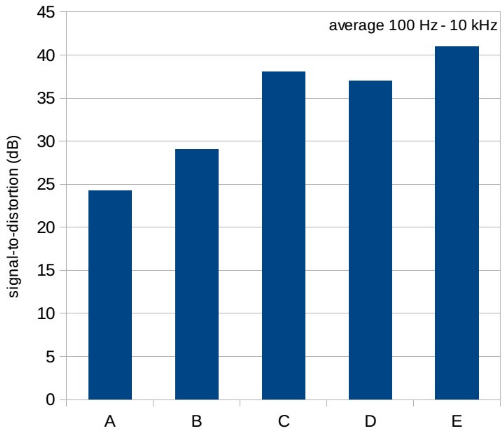

Figure 11: Multitone signal-to-distortion for case examples of the different technologies: (A) concentric, (B) conventional non-coaxial, (C) approximately coaxial, (D) fixed tweeter horn coaxial, and (E) proposed technology.

The technologies were represented by case example products of the concentric type tweeter-midrange system (A), conventional separate transducer arrangement (B), approximately coaxial approach with the tweeter located on an island suspended over the tweeter and a displaced woofer (C), fixed horn-type tweeter coaxial with the midrange transducer (D), and the proposed acoustically coaxial minimum diffraction transducer system (E). It is worth noting that in this case study, technologies A and D were in fact two-way systems, and this may affect the distortion figures for these two cases.

The multitone distortion to audio signal ratio was measured for each of the case examples and the distortion within the frequency range 100 Hz to 10 kHz was considered (Fig. 12). It is worth noting that when the frequency range was limited to 500 Hz to 10 kHz, the results remained relatively the same. The signal level for cases B to E was 89 dB SPL, and for case A 84 dB SPL.

The classic concentric technology is showing tendency for intermodulation distortion and low signal-to-distortion ratio. This may be due to the individual characteristics of the transducer and may not reflect a universal principle.

The conventional separate transducer three-way system did not show a clear advantage in terms of the intermodulation distortion although it has theoretically an advantage over coaxial systems [6].

6.4 Subjective evaluation

To evaluate potential angle-continuous off-axis radiation differences between the three-way monitor technologies labelled as B and E (previous paragraph), a subjective evaluation test was devised.

The DUT is placed in an anechoic room, adjusted for flat frequency response on the acoustical axis. The DUT is rotated using a turntable, while playing an audio signal. The output is recorded using a calibrated microphone. Figure 12 shows the test setup.

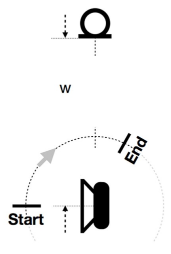

Figure 12: Listening-based test of DUT rotating at a microphone distance of w

Recordings are started with the DUT at -90 degrees relative to the microphone direction, and stopped when the DUT is pointing +10 degrees. The rotation rate is 1.5 degrees per second, and various types of stimuli were applied.

The resulting audio recordings are loudness-normalized per ITU-R BS.1770 [10] and listened to using headphones to eliminate secondary room acoustic influence. Our ears are generally superior to the eyes in recognizing a temporal pattern, so clues to possible differences in performance might be found this way.

Using broadband noise as stimulus, patterns can be readily heard with high quality traditional DUTs (technology B) compared to the coaxial design (technology E), even when the former are oriented as intended. Technology E device produces an artefact-free listening result regardless if they are oriented vertically or horizontally. Both technologies show the systematic change in the frequency balance of the sound due to the higher directivity of radiation in high frequencies. The traditional technology B also exhibits mid frequency range tonal balance variation related to the frequency response changes that are happening because of the time-of-flight changes from multiple drivers when the loudspeaker rotates. Subjects describe the technology B artefacts as "phasing" at the recording distance w = 1.60 m, i.e. not in the nearfield. Consequently, differences may also be audible when loudspeakers are used for sound quality evaluation. The particular loudspeaker representing technology B used in the study is a compact three-way with the tweeter, midrange and woofer not only vertically displaced but also horizontally. This may explain largely the audibility of the midrange tonal balance variation.

The subjective evaluation suggests that a coaxial technology can reduce the complexity of evaluating the sound character by making the loudspeaker more well-behaved and, in that sense, more predictable as a monitoring tool, particularly in compact three-way constructions, where the small baffle area precludes vertical stacking of drivers.

More subjective evaluation studies of multi-transducer loudspeaker designs are being planned.

7 Conclusions

We have presented the concept of designing three-way loudspeakers combining compact enclosure size to coaxial tweeter-midrange transducers having minimized acoustic diffraction, seating the coaxial transducer as a part of the directivity control waveguide, and a dual-woofer system. Seating the woofers under the waveguide enables a large continuous, low diffraction front baffle surface for the mid and high frequencies. The two spaced woofers acoustically combine to extend the directivity control to bass frequencies.

These concepts have been applied in the designs of three different sizes of loudspeakers. The performance data confirming the design objectives has been presented. Comparisons with other compact three-way design technologies currently used, including other techniques for implementing coaxial transducers for three-way designs and traditional implementations of high performance three-way loudspeakers, have been reported.

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We are very deeply indebted and grateful to the giants lost, but living in our memories, for idealism, inspiration and skills, during the decade-long development process of these coaxial concepts: Ari Varla and Ilpo Martikainen.

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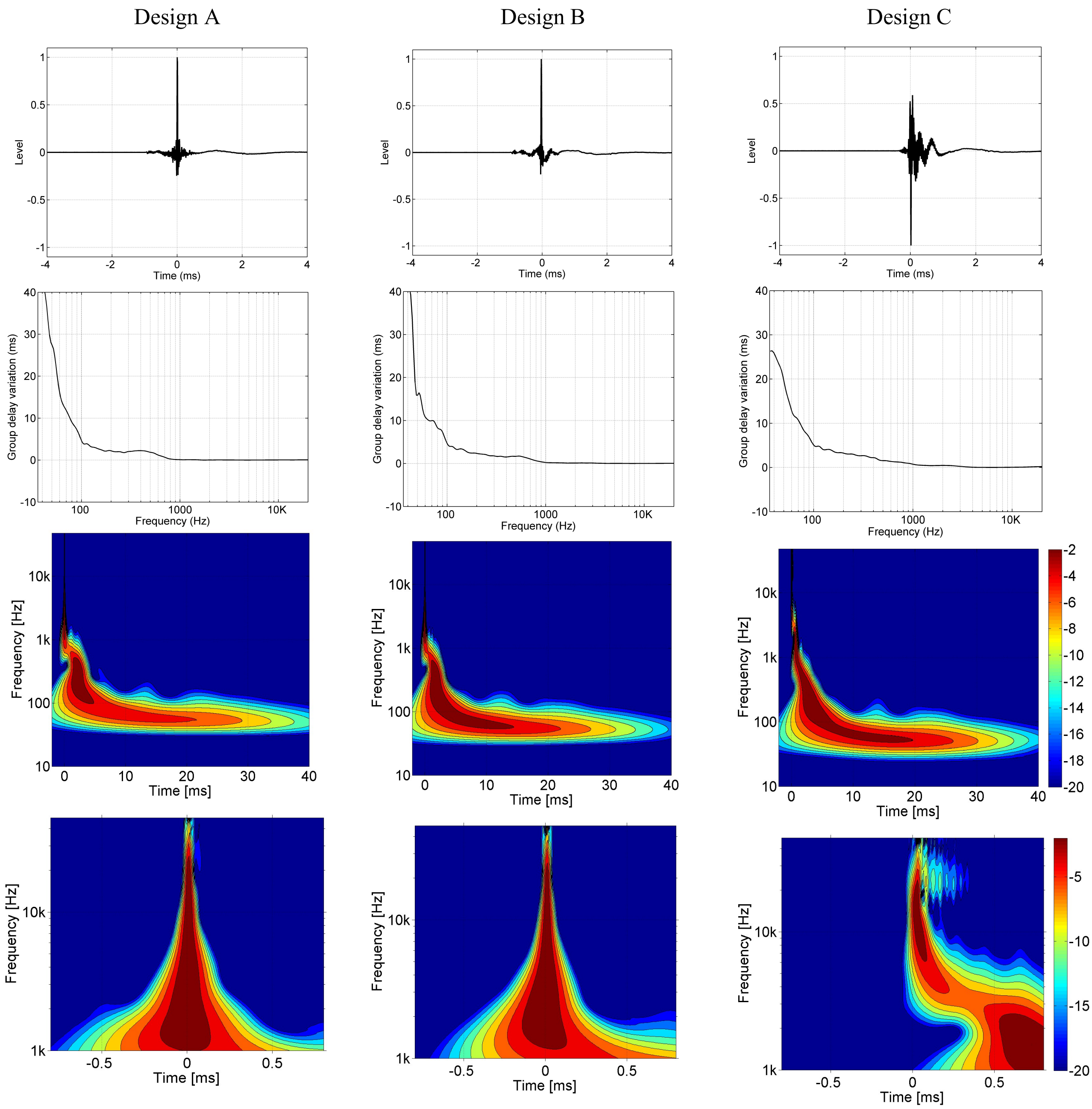

Figure 13: The temporal performance of design types A-C. Impulse response, centered at maximum energy (top row); group delay variation (second row); high resolution (wavelet) time-frequency analysis (third row) and a zoom-in to the first 1.6 ms of the system impulse response (bottom row). Frequency scale extends to 48 kHz. Color indicates sound level in dB, see the right column for the color key.

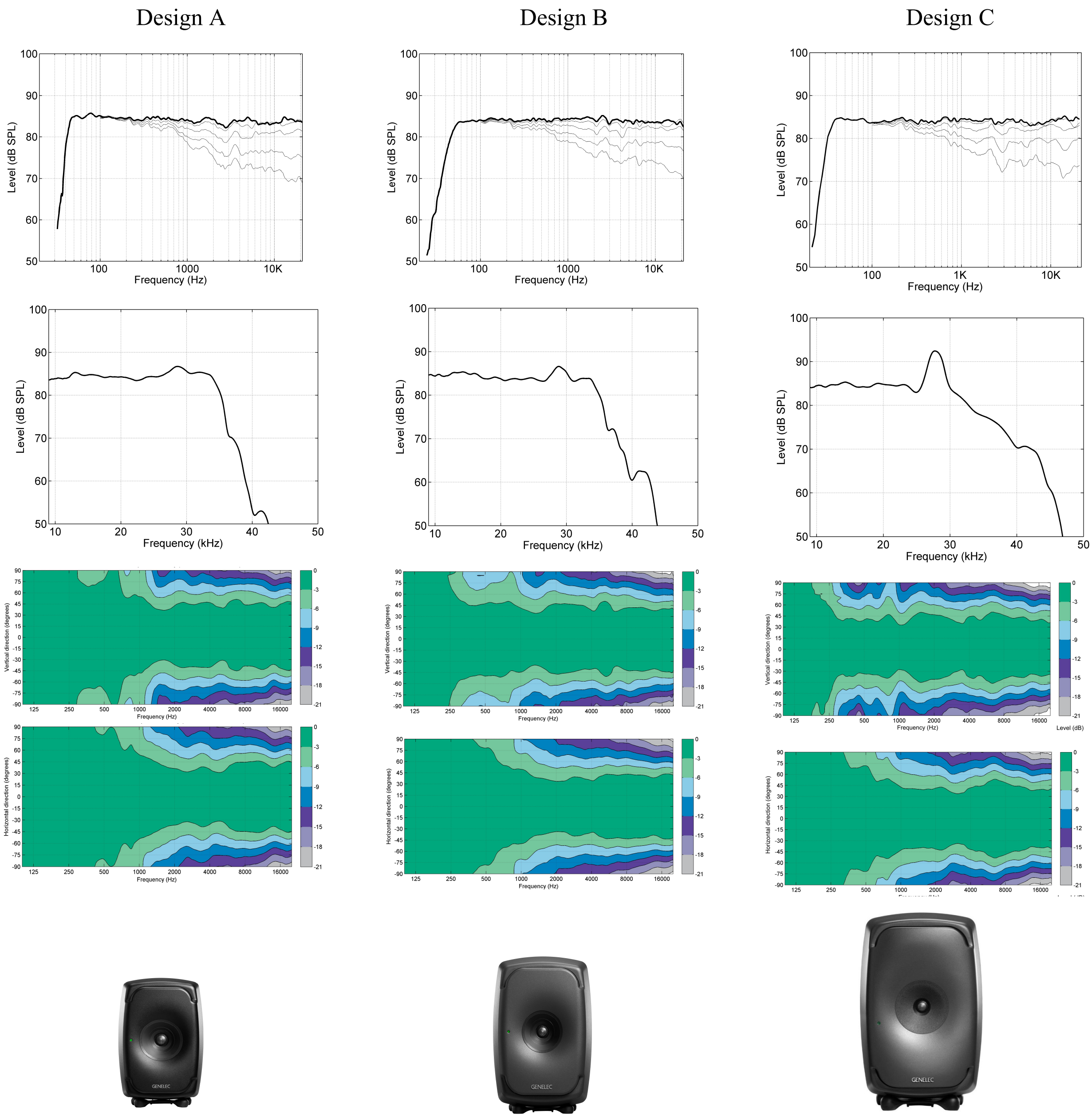

Figure 14: The performance of system designs A-C. Graphics from top to bottom, magnitude responses on the acoustical axis (bold) and in 15, 30, 45 and 60 degrees off axis on the horizontal plane (top); ultrasonic extension of the on-axis response (second down); directivity on the plane with the longer axis, in 3 dB increment from -180 degrees to 180 degrees around the system (third down); directivity on the plane with the shorter axis, similar scaling as in the previous (fourth down).