

A Low-Diffraction Concentric Acoustic Combiner for Two-Way Loudspeakers

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Abstract—A novel acoustic combiner for two-way loudspeakers uses an annular acoustic transmission line to couple woofer sound pressure to a tweeter waveguide, concentrically aligning high and low frequency sources without significant diffraction. Operating principles of the combiner are analyzed with an acoustic transfer-matrix model and finite element analysis. The combiner is implemented in a loudspeaker, and its nonlinear performance is compared with conventional two-way coincident coaxial and noncoincident loudspeakers. The combiner achieves a smooth directivity pattern in all off-axis planes and significantly lower levels of high frequency intermodulation distortion than the conventional coincident coaxial loudspeaker tested.

I. INTRODUCTION

The exact ideal radiation pattern for a loudspeaker is not entirely agreed upon, but there is significant evidence that a loudspeaker exhibiting a smooth on-axis and off-axis magnitude response is generally preferred in small rooms [1]. A loudspeaker with an off-axis tonality that deviates minimally from the on-axis tonality allows sound quality to be maintained for a variety of listening positions. Stereo image localization is improved when the tonality of the direct sound is similar to that of early reflections [2], which originate from a loudspeaker's off-axis radiation.

In live sound reinforcement applications, early reflections from room boundaries are less of a concern, but smooth directivity is still important since the majority of listeners are located off-axis.

It is possible to achieve a smooth polar frequency response within one plane (typically chosen to be the horizontal plane) in a conventional, noncoincident two-way loudspeaker, often using a high frequency waveguide to match the directivity patterns of the tweeter and woofer at the crossover frequency. However, due to the spacing between the woofer and tweeter, two-way loudspeakers exhibit poor polar responses in other planes (typically the vertical plane) because the woofer and tweeter become out of phase off-axis at the crossover frequency [3]. Lowering the crossover frequency and minimizing the distance between the tweeter and woofer can somewhat improve tonality uniformity in the vertical plane but at the cost of large-signal performance. A lower crossover frequency stresses the tweeter, leading to increased distortion [4], and a small woofer is required to minimize woofer-tweeter center-to-center spacing, which limits low frequency output.

Coaxial loudspeakers and multiple-entry horns are two approaches that integrate the low frequency sources into the

high frequency waveguide to minimize the effective spacing between the woofer and tweeter.

When a tweeter's high frequency wavefront interacts with a discontinuity in the tweeter's waveguide, a portion of the incident wave is diffracted, acting as a secondary high frequency source [5]. The outputs from the two high frequency sources (the incident and the diffracted wave) separated in space create an interference pattern, generating peaks and dips in the polar frequency response.

Coaxial loudspeakers place the tweeter at the center of the woofer to avoid vertical plane crossover point nulls. Some coaxials place the tweeter in a fixed waveguide located in front of the woofer cone, but high frequencies wrap around the waveguide to reflect off the woofer cone, interfering with direct sound from the horn and causing uneven directivity. More commonly, "coincident" coaxials place the tweeter behind the woofer cone, using the woofer cone as a high frequency waveguide. When designed carefully, these can achieve relatively smooth directivity in all planes but exhibit undesirable nonlinear behavior because movement of the woofer cone modulates the high frequency radiation pattern [6], [7]. The woofer surround and motor gap also act as discontinuities in the tweeter waveguide, causing diffraction [6]. Simultaneously optimizing the woofer geometry to act as a high frequency waveguide and as a low frequency radiator is a difficult task and often results in a compromise that is not optimal for either function.

Multiple-entry horns, commonly used in live sound reinforcement, resolve the vertical plane nulls of noncoincident loudspeakers by sharing a large horn across multiple drivers operating over different frequency ranges [8]. Multiple-entry horns struggle to achieve a smooth mid and high frequency polar response due to diffraction occurring at the multiple entry points to the horn. Reducing this diffraction requires shrinking the size of the low frequency entry points which increases the compression ratio on the low frequency drivers, leading to distortion and limited output [9], [10].

II. CONFIGURATION OF THE COMBINER

The proposed combiner's half-section is shown in Figure 1. An acoustic transmission line (TL) is used to couple the woofer's output to the tweeter's waveguide. The TL is annular and wrapped around the high frequency waveguide. The combiner is designed so that high frequencies originating from

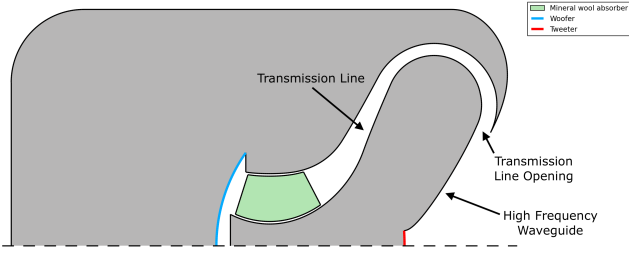


Fig. 1: Half-sectional drawing of the proposed combiner.

the tweeter that enter the TL are absorbed and minimal high frequency energy exits the channel.

The combined cross-section of the waveguide and TL has a C^1 continuous cross-sectional area for a wavefront originating from the tweeter to reduce high frequency diffraction off the TL opening. This requires that the TL opening be oriented parallel to the wall of the waveguide, facing the tweeter.

The woofer end of the TL is filled with mineral wool, acting as a porous absorber [11] for frequencies above ~ 5 kHz. Between 1.5 kHz and 5 kHz, the woofer moves to actively cancel high frequency reflections off its cone. The sound pressure required from the woofer to cancel the high frequency wave reflected by the woofer cone can be represented by an LTI transfer function and is purely a matter of designing the appropriate crossover. Below the crossover point at 1.5 kHz, the woofer plays alone through the TL to produce midrange and bass.

Concentric placement of the radiating elements avoids off-axis nulls at the crossover frequency in all planes.

The narrow radial width of the TL opening suppresses radial resonance modes within the TL, and the axisymmetric design suppresses circumferential modes. Only 0.88 dB of tweeter sound power is lost to the TL due to the narrow TL opening. The junction where the TL meets the waveguide can be well-approximated as a plane wave port since the tweeter wavefronts entering the TL and the woofer wavefronts exiting the TL are both nearly flat in the meridional plane.

The compression ratio of the woofer S_d/S_{TL} is only 2:1. By designing the combiner geometry and crossover such that very little high-frequency sound pressure exits the line, the total cross-sectional area of the combiner's TL can be made much larger than low frequency entry points in typical multiple-entry horn designs, which are typically kept very small to minimize diffraction.

III. PRINCIPLES OF OPERATION

A. Virtual Impedance Matching

For illustrative purposes, the combiner can be represented using the 1-dimensional two-port acoustic network model in Figure 2.

To avoid high frequency diffraction off the TL opening, the effective specific impedance at the TL opening to a wavefront originating from the tweeter must match the outwards specific

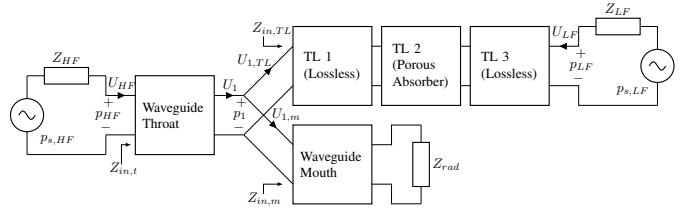


Fig. 2: Two-port acoustic network model of the combiner.

impedance of the waveguide mouth at the axial position where the TL opening lies.

The porous absorber inside the TL produces a well-matched condition at the TL opening for frequencies above approximately 5 kHz. Below 5 kHz, the lumped input impedance at the TL opening (with the woofer muted) is the lumped woofer acoustic impedance, transformed by the TL, which results in a severe specific impedance mismatch between the waveguide mouth and TL opening due to the inherently high acoustic impedance of a woofer.

By treating the woofer as an active load, the effective specific impedance looking into the TL opening can be lowered below 5 kHz to match the local specific impedance of the waveguide mouth at the TL opening, i.e. “virtual impedance matching.” The following shows how the 1-dimensional model is used to find an analytical solution for the woofer sound pressure required to eliminate high frequency reflections at the TL opening.

Rephrasing the diffraction-free condition, the volume velocity $U_{1,TL}$ entering the TL opening must be proportional to the volume velocity passing through the waveguide mouth $U_{1,m}$, with a ratio defined by the cross-sectional areas of the TL opening S_{TL} and the mouth S_m . The impedance $Z_{in,TL}$ follows from this relationship.

$$U_{1,TL} = U_{1,m} \frac{S_{TL}}{S_m} = U_1 \frac{S_{TL}}{S_m + S_{TL}} \quad (1)$$

$$Z_{in,TL} = \frac{p_1}{U_{1,TL}} = \frac{p_1}{U_{1,m} \frac{S_{TL}}{S_m}} = Z_{in,m} \frac{S_m}{S_{TL}} \quad (2)$$

Given the transfer matrix of the waveguide mouth M_m along with the free-space radiation impedance Z_{rad} , the outward lumped impedance through the horn mouth $Z_{in,m}$ can be found.

$$Z_{in,m} = \frac{A_m Z_{rad} + B_m}{C_m Z_{rad} + D_m} \quad (3)$$

The lumped impedance looking into the waveguide throat $Z_{in,t}$ is found using the throat transfer matrix M_t .

$$Z_{in,t} = \frac{A_t(Z_{in,m} || Z_{in,TL}) + B_t}{C_t(Z_{in,m} || Z_{in,TL}) + D_t} = \frac{p_{HF}}{U_{HF}} \quad (4)$$

The TL transfer matrix $M_{TL} = M_{TL1} M_{TL2} M_{TL3}$ relationship (5) can be chained with the throat transfer matrix relationship (6) using (1), to find the acoustic pressure p_{LF}

and volume velocity U_{LF} in terms of tweeter acoustic pressure p_{HF} and volume velocity U_{HF} (7).

$$\begin{bmatrix} p_1 \\ U_{1,TL} \end{bmatrix} = M_{TL} \begin{bmatrix} p_{LF} \\ -U_{LF} \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} p_{HF} \\ U_{HF} \end{bmatrix} = M_t \begin{bmatrix} p_1 \\ U_1 \end{bmatrix} \quad (6)$$

$$\begin{bmatrix} p_{LF} \\ -U_{LF} \end{bmatrix} = M_{TL}^{-1} \begin{bmatrix} 1 & 0 \\ 0 & \frac{S_{TL}}{S_m + S_{TL}} \end{bmatrix} M_t^{-1} \begin{bmatrix} p_{HF} \\ U_{HF} \end{bmatrix} \quad (7)$$

Applying the throat impedance $Z_{in,t} = \frac{p_{HF}}{U_{HF}}$ gives the acoustic pressure required at the woofer in terms of the acoustic pressure at the tweeter to achieve virtual impedance matching and eliminate diffraction at the TL opening.

$$\begin{bmatrix} p_{LF} \\ -U_{LF} \end{bmatrix} = M_{TL}^{-1} \begin{bmatrix} 1 & 0 \\ 0 & \frac{S_{TL}}{S_m + S_{TL}} \end{bmatrix} M_t^{-1} \begin{bmatrix} 1 \\ \frac{1}{Z_{in,t}} \end{bmatrix} p_{HF} \quad (8)$$

Equation (8) shows that within the 1D model, a woofer pressure exists which eliminates diffraction at the TL opening, i.e. that virtual impedance matching is achievable.

B. Simulation and Crossover Design

The combiner was simulated in free space with an axisymmetric FEA model using the FEniCSx python library [12]–[14].

The woofer's polar response in Figure 3a becomes very irregular above 2 kHz, so the crossover frequency must be below 2 kHz. Note the off-axis deviations of the tweeter's response in Figure 3b between 2 kHz and 5 kHz, which fall within the tweeter's required operating range. Neither driver has a smooth polar response between 2 kHz and 5 kHz, so it appears difficult to design a crossover with desirable off-axis behavior using traditional techniques.

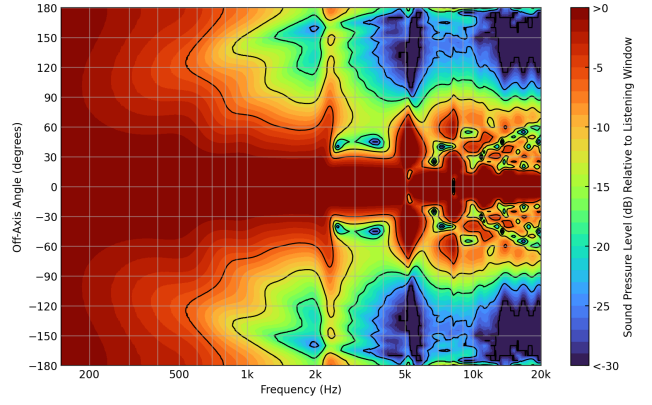
Figure 4(a, c, e) shows the simulated behavior of the combiner with a crossover which forces each of the drivers' Listening Window [15] response into 1500 Hz linear-phase 8th-order Linkwitz-Riley responses. This demonstrates a traditional crossover design.

Figure 4(b, d, f) shows the simulated behavior of the combiner with a crossover optimized to the following objectives:

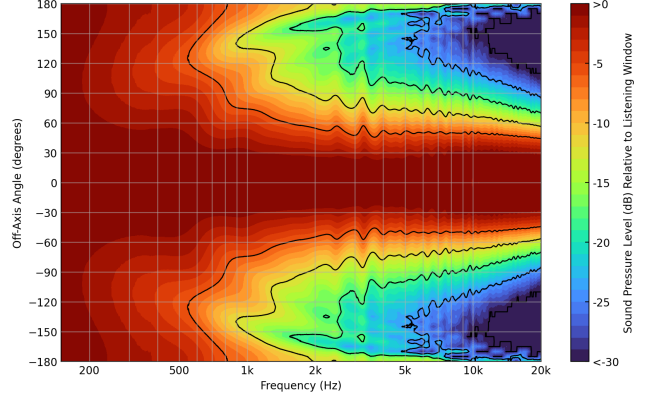
- 1) Smooth frequency response on- and off-axis
- 2) Smoothly, monotonically decreasing output off-axis
- 3) Smooth directivity index
- 4) Flat Listening Window [15] response
- 5) Not exceeding tweeter excursion limits

While neither the tweeter's nor the woofer's individual polar response is smooth from 2 kHz to 5 kHz, a superposition of the two radiation patterns can result in a polar response that is smoother than either driver is individually capable of, as shown in Figure 4(d, f).

By optimizing the crossover in the frequency domain, the woofer sound pressure required to actively absorb the tweeter's sound pressure within the TL can be determined using only the polar frequency responses of the individual drivers.



(a) Contour plot of woofer polar frequency response.



(b) Contour plot of tweeter polar frequency response.

Fig. 3: Simulated individual polar responses of tweeter and woofer in the combiner. Both plots are normalized to the Listening Window response [15].

IV. RESULTS

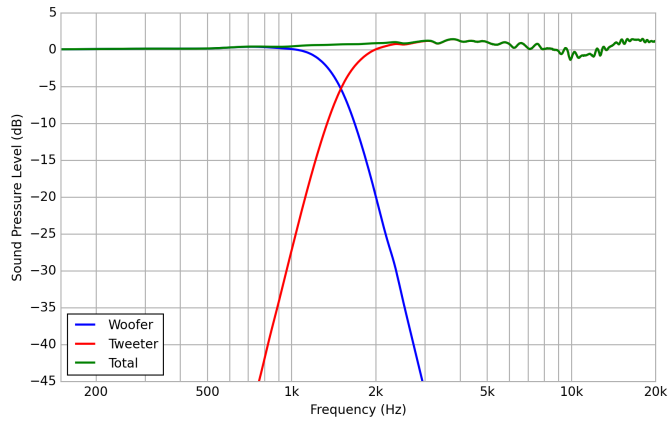
A. Prototype

A prototype loudspeaker using the acoustic combiner was constructed and tested, depicted in Figure 5. The prototype combiner's pseudo-anechoic polar frequency responses of the tweeter and woofer were independently measured using a 7.5 ms gated time window. Each tweeter and woofer frequency response measurement was taken with the other driver's terminals shorted to accurately characterize the mutual coupling between the drivers when actively driven by voltage-source amplifiers.

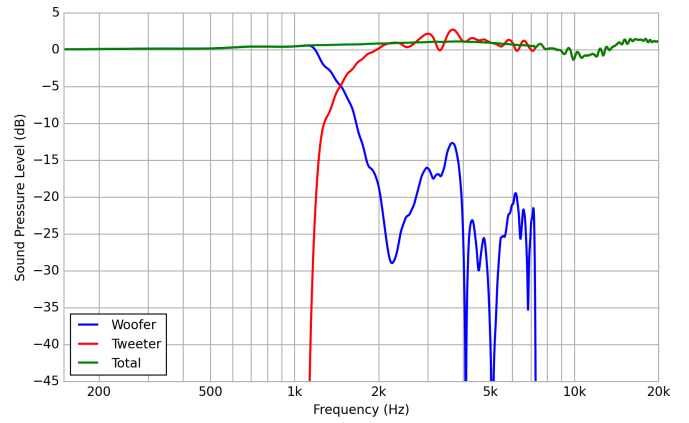
These real-world responses were then used to co-optimize the crossover FIR kernels for the woofer and tweeter with the optimization process described in the crossover design section. Finally, near-field measurements were used to characterize the low frequency response of the prototype combiner, and IIR filters were used to manually tune the desired bass response.

B. Directivity Performance

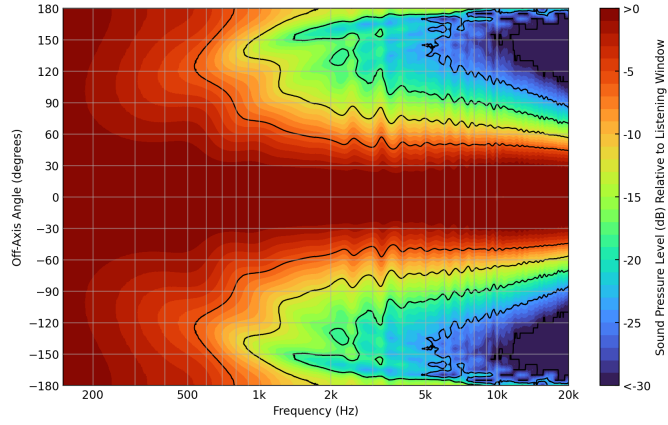
Directivity measurements shown in Figure 6 were taken at 1 m from the center of the front baffle using a MiniDSP



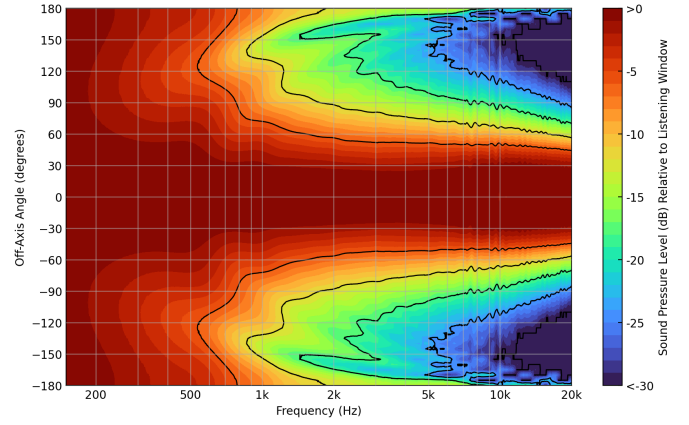
(a) Linkwitz-Riley crossover on-axis acoustic response.



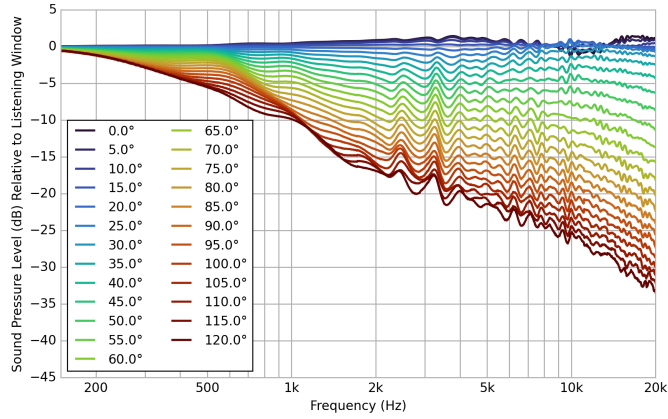
(b) Optimized crossover on-axis acoustic response.



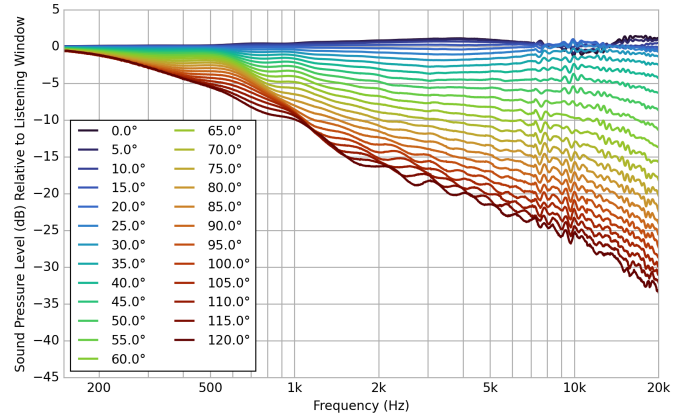
(c) Linkwitz-Riley contour plot.



(d) Optimized crossover contour plot.



(e) Linkwitz-Riley polar frequency response plot.



(f) Optimized crossover polar frequency response plot.

Fig. 4: A comparison of the directivity behavior of the Linkwitz-Riley crossover (a, c, e) vs. optimized crossover (b, d, f). Contour plots and polar frequency response plots are normalized to the Listening Window response [15].



Fig. 5: Prototype loudspeaker using the acoustic combiner.

UMIK-1 calibrated microphone and complex smoothed to 1/48 octave.

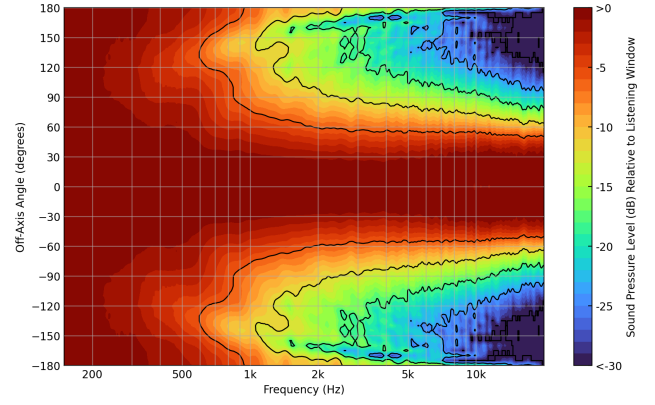
Figure 6a shows the prototype combiner's -6 dB beamwidth (horizontal and vertical) is held at $\pm(55 \pm 5)$ degrees from 2 kHz to 20 kHz and smoothly transitions to a monopole pattern below 2 kHz.

Figure 7 shows the CTA-2034-A dataset for the prototype loudspeaker, demonstrating smoothness in the Early Reflections, Sound Power, and Sound Power Directivity responses.

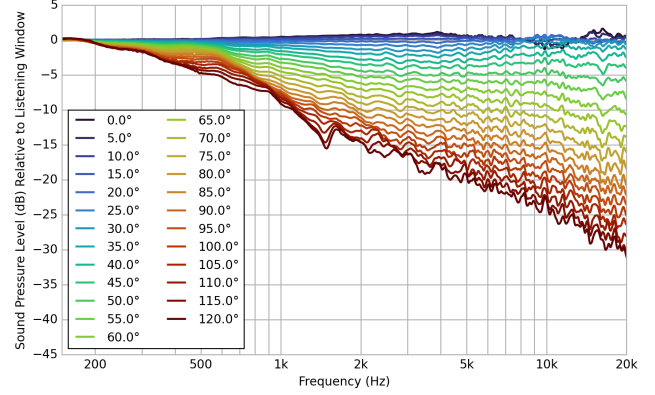
C. Nonlinear Performance

The prototype combiner's large-signal behavior was compared to two similar loudspeakers: a two-way coincident coaxial loudspeaker and a noncoincident two-way bookshelf speaker. All three loudspeakers have nominally 130 mm (5.1 in) diameter woofers operating in sealed cabinets, 25.4 mm (1 in) diaphragm tweeters and a 1500 Hz crossover frequency.

Transfer function modulation with respect to woofer cone position was measured using a two-tone sweep adapted from the swept-sine deconvolution method of Farina [16]. A fixed "bass" tone f_1 is played while "voice" tone f_2 is linearly swept ($f_1 = 20$ Hz, 53 dB@1 m; $f_2 \in [1500, 20000]$ Hz, 80 dB@1 m) at a rate of 332 Hz/s. The bass tone level corresponds with a peak-to-peak woofer excursion of approximately 2.0 mm. The signal recorded from the loudspeaker was deconvolved with the inverse of the f_2 component of the stimulus to temporally separate the high-order impulse responses associated with each sum ($f_1 + f_2$) or difference ($f_2 - f_1$) intermodulation distortion (IMD) product. Each impulse response within the deconvolved signal was individually gated at 7.5 ms to produce a pseudo-anechoic IMD measurement. This measurement procedure was repeated every 10 degrees across the loudspeaker's horizontal and vertical planes from -90 degrees to $+90$ degrees. Each measurement was weighted according to the spherical area element for each



(a) Contour plot of the prototype combiner.



(b) The prototype combiner's polar frequency response from 0 to 120 degrees.

Fig. 6: Contour plot (a) and polar frequency response (b) of the prototype combiner. Both are normalized to the Listening Window response [15] and smoothed to 1/48 octave. Contour lines are drawn at 6 dB intervals.

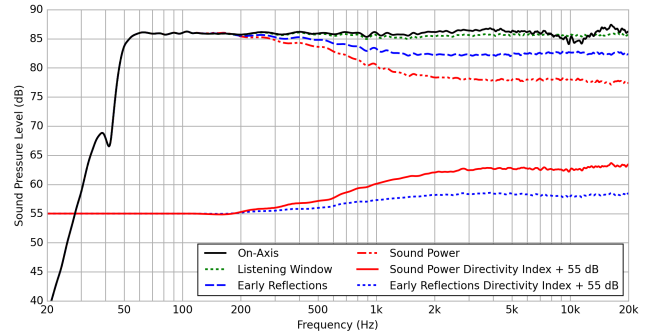


Fig. 7: The CTA-2034-A report [15] of the prototype combiner loudspeaker, using spherical area Sound Power weights.

angular bin to estimate the forward-radiating sound power of both the 2nd-order IMD and the f_2 fundamental. The ratio of 2nd-order IMD sound power to fundamental sound power is plotted in Figure 8.

Large-signal measurements were taken at 1 m from the center of the front baffle of each loudspeaker using an NTI

M2010 microphone and complex smoothed to 1/48 octave.

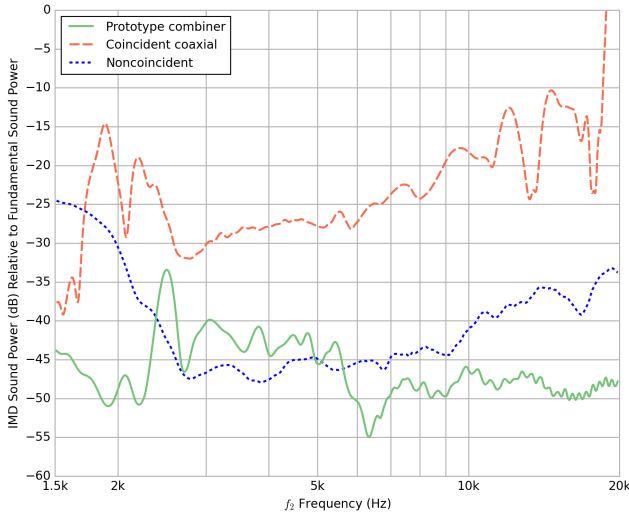


Fig. 8: The 2nd-order IMD sound power of the coincident coaxial, noncoincident, and prototype combiner across off-axis angles from -90 to $+90$ degrees horizontal and vertical, normalized to the fundamental sound power response.

In Figure 8, the prototype combiner exhibits much less high frequency transfer function modulation than the coincident coaxial loudspeaker, demonstrating how the combiner successfully decouples woofer cone motion from the tweeter's radiation pattern. The combiner has comparable levels of high frequency transfer function modulation to the noncoincident bookshelf loudspeaker.

V. CONCLUSION

An acoustic combiner for achieving low-diffraction radiation in two-way loudspeakers is presented. The combiner uses an acoustic transmission line to couple woofer output to a tweeter's waveguide without introducing physical discontinuities. The combiner allows for greater flexibility in driver selection, relaxing the design constraints associated with low-diffraction coincident coaxials.

The directivity smoothness of the combiner is comparable to that of modern, low-diffraction coincident coaxial loudspeakers [6], [17] and significantly exceeds that of existing multiple-entry horn designs [18], [19]. Simultaneously, the high frequency intermodulation distortion of the combiner is comparable with a noncoincident design and is considerably lower than in the traditional coincident coaxial tested.

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