Crossover design based on median level and phase correction within a listening window

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ABSTRACT

PA and sound reinforcement loudspeaker systems consist, many times, of two or more frequency bands reproduced by horn loaded transducers with phase plugs in front of the drivers, and horn loaded compression drivers. The size, design, and arrangement of these elements inside the cabinet are restricted not only by acoustical reasons but by mechanical constraints, such as weight, gravity center, and the total available volume of the cabinet. Besides, the lack of directivity match at crossover frequencies is usual. Due to its own architecture, it is sometimes difficult or impossible to find a good reference point for crossover design which provides proper crossover and symmetric radiation around this point. In these cases, a crossover design based only on the on-axis responses cannot be optimum in regards to uniformity of coverage. A method based on the alignment at different angles within a listening window to get a representative median level and phase correction, and posterior phase optimization based on maximum average level at crossover frequencies is presented. For certain designs, this method can provide better radiation pattern at crossover, better average level response within the intended listening window, and smoother directivity transitions between ways.

1 Introduction

Loudspeaker systems for PA and sound reinforcement are frequently composed of 2 or more different non-coincident drivers coupled to large horns which can use phase plugs in front of the low-mid cones.

Due to the size and design of the involved drivers and horns, the lack of directivity match, and the front wave shape mismatch at crossover frequencies, the classical approach to crossover design based on a reference point between the involved drivers, time alignment, and level and phase compensation can be really difficult or impossible. Finding a reference point between the virtual sources which provides equal acoustic distance to them and an appropriate point of rotation (P.R.) to get a resultant system with symmetrical polar response is not always possible. In this case, the crossover design based on on-axis alignment provides maximum addition on the reference axis and polar responses aimed to this axis, but symmetry is not always achieved at crossover frequencies, response is poor off-axis, and energy addition at crossover frequencies, computed in a wide listening window, is not optimum.

A method based on the on-axis and off-axis crossover alignments at different angles within a listening window, the calculation of the median level and phase response of the applied correction filters used for these alignments, and the final phase alignment to maximize an average response is presented. The idea behind this method relies on the use of a more representative level correction than the on-axis correction by considering also off-axis level correction within a listening window. Once off-axis level correction is considered, certain misalignment on-axis can provide better average alignment and better off-axis performance. For certain designs, this method can improve the only on-axis based crossover, if we consider the performance of the crossover in a wide listening window. The proposed method is described, and some examples are presented and compared with the traditional on-axis alignment.

2 Literature review

Linkwitz [1] presented in his paper the basics for optimal aiming and coverage of loudspeakers with non-coincident drivers. By using the special properties of two cascaded identical Butterworth filters proposed by R. Riley, and applying proper time compensation, optimum results can be obtained for the ideal case (drivers were considered point sources, therefore phase differences were only due to distance differences between sources and no real radiation pattern was considered).

The effect of crossover type and time alignment on performance of loudspeaker systems has been studied, for example, at [2], [3] in the analog times, showing the impact of different strategies on time and frequency responses. For digital filters, it was analyzed at [4].

Lipshitz and Vanderkooy [5] presented a family of linear phase crossover networks and introduced the lobing error function, which allows the comparison of crossover filters in terms of polar response, considering again ideal sources. Later [6], they showed all-pass crossovers suitable for crossover design with identical phase response for both sections, low and high. Above mentioned Linkwitz-Riley filters are particular cases of this whole class.

D'Appolito [7] showed a special arrangement for two-way loudspeaker systems that can eliminate the lobing error. In a similar way, other clever combinations of loudspeaker arrangements and filtering have been explored to improve the off-axis response of non-coincident drivers, for example at [8].

An analysis of filter performance on real loudspeakers was made at [9], showing the great impact of crossovers on loudspeaker performance. It was shown that the good performance of the filters themselves does not guarantee good loudspeaker system performance. The real acoustical behavior of the drivers involved, level, phase, and directivity must be considered. Crossover design for drivers with non-ideal phase response was analyzed at [10], and digital crossover design was applied to drivers with non-coincident polar responses at [11].

At [12], it was shown that the crossover design affects loudspeaker systems power response using a theoretical model, and some alignments were compared. At [13], the effects on power response of filters and true directivities were investigated.

Other authors presented their results to optimize crossover performance with numerical algorithms, with passive filters [14], or active ones [15][16]. They considered on-axis responses as well as directivity metrics and applied the optimization to real loudspeakers. Also, alignment from a statistical point of view [17] has already been considered.

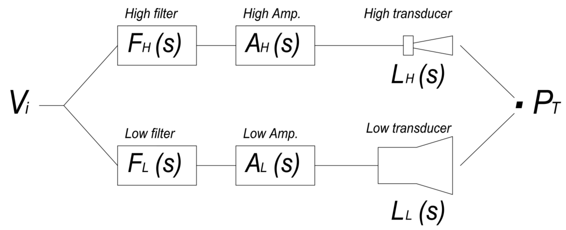

Figure 1. 2-way bi-amplified loudspeaker system block diagram.

In general, a lot of bibliography can be found about crossover design, but most covers the theoretical approach to the problem, with ideal sources, and reduces the problem to the intrinsic behavior of the combination of the filters themselves. This generates some misunderstanding by non-specialized public who confused the properties of the electrical filters applied in a crossover design (High filter and Low filter at Figure 1) with the final acoustical behavior of the electroacoustic crossover, that is, the combination of electrical filters, amplifiers, transducers, cabinet, and horns. The loudspeaker system's total pressure is the sum of the pressure radiated by each driver, and the transfer function of each band is the product of the transfer function of all involved subsystems in this band:

$$P_T = P_L + P_H = F_L(s)\ A_L(s)\ L_L(s) + F_H(s)\ A_H(s)\ L_H(s)$$

As mentioned before, only a few papers deal with crossovers for true loudspeakers, with unpaired directivities, level, and phase. And sometimes, previously mentioned optimization algorithms act as black boxes, providing good results but little information about why they work.

3 Proposed method

Traditional on-axis crossover alignment is based on on-axis responses measured in front of a "privileged" reference point between non-coincident drivers. But finding this appropriate point can be hard or impossible. The acoustic center of each driver is different and can move with frequency [18], and finding an acoustic center for the system which provides symmetric radiation for the involved drivers is sometimes not possible. As showed by [19], 3D complex measurements (level and phase) of the different ways of a loudspeaker system can be measured with a microphone aligned with a point of rotation under the conditions stated there. For crossover design purposes at mid frequencies, this P.R. can be simply chosen at the center of the cabinet if complex responses are considered. The proposed method works with 3D complex response balloons for the low and high sections, and calculates, first, proper filters to provide Linkwitz Riley 24dB/oct acoustic LPF and HPF level response for each band, and flat response for the combined responses at each measured angle. The final level correction to be applied to each band is calculated as the median value of the levels of the calculated filters within a listening window in the plane of the drivers (horizontal plane in the following examples, $\Phi = 0$). As the chosen listening window gets wider, more correction is applied to compensate for the level drop at large off-axis angles and the median level response provides more representative correction than the solely on-axis correction.

Regarding to phase alignment, the starting point for phase correction of each band is the median value of the phase of the calculated filters within the same listening window in the driver's plane. The median value level and phase of the calculated filters relies on the ideas described at [20][17][21], adapted to calculate median values. As optimum alignment within a 3D listening window is desired, fine tune of phase is done. The phase of the HF filter is modified with a phase shift from -180º to 180º with 10º steps in the crossover frequency range and total system's radiation balloon is calculated, looking for maximum addition: at every phase step, the total system response is tested by calculating the weighted [22] average level response within the defined listening window, 3D in this case, to also include vertical radiation. Phase variations which maximize the average level in the listening window are kept and added to the final filter for the HF.

4 Examples

In order to show the improvements the proposed method can provide on certain designs, it has been applied to a large PA loudspeaker system with the design constraints previously explained. This system can be used vertically or horizontally, and the horns can be rotated. In these examples, the system is arranged horizontally to reduce vertical profile and horns are rotated to keep the widest coverages in the horizontal plane. Nominal coverage angle of this loudspeaker system is 90º x 50º. As can be seen at Directivity Index plots, Figure 8 and Figure 12, there is not perfect match of directivity. The listening window considered for crossover design was 45º.

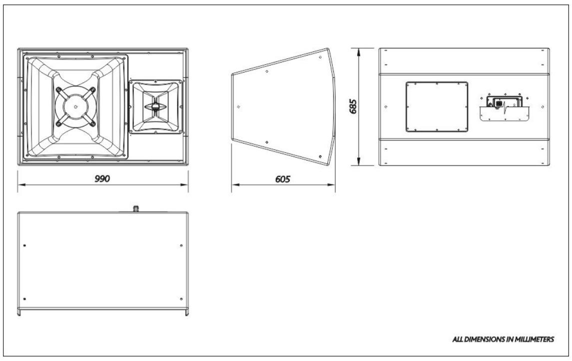

Figure 2. Loudspeaker system dimensions

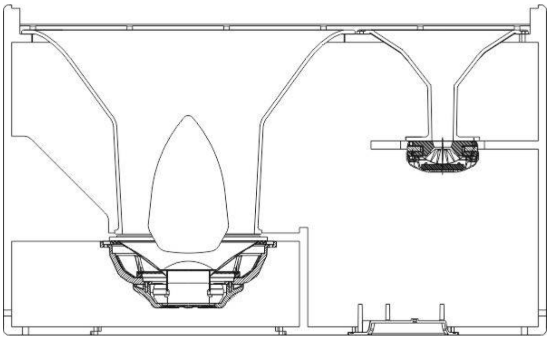

Figure 3. Loudspeaker cross-section

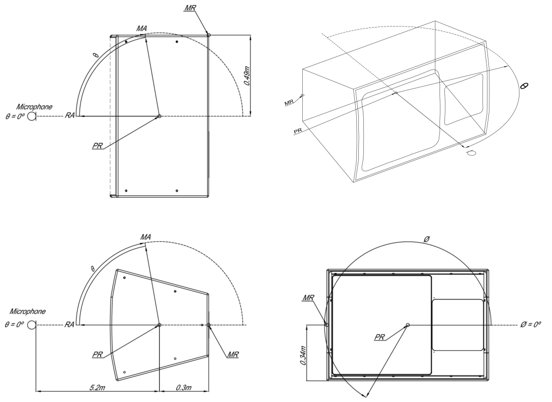

Figure 4. Plan and perspective views showing the Point of Rotation (PR) and Mechanical Reference (MR) – top. Side and front views showing the Point of Rotation (PR) and Mechanical Reference (MR) – bottom.

Two crossovers have been designed at 500 Hz and at 1 kHz in order to show the method when applied to wave lengths comparable to the distance between the sources and to shorter wave lengths.

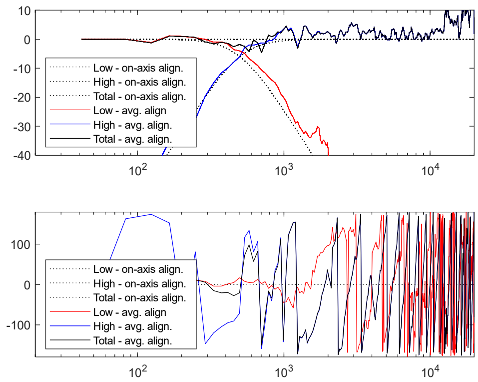

Figure 5. 500 Hz crossovers. Frequency response

Figure 5 and Figure 9 show the on-axis (in front of the P.R.) frequency response of the sound pressure level and its phase. The on-axis approach crossovers were calculated to have Linkwitz Riley 24dB/oct level response and ideal 0º phase response, so they exhibit perfect on-axis summation. The average approach crossovers show no perfect alignment on-axis, although the on-axis response does not deviate too much from a flat level response.

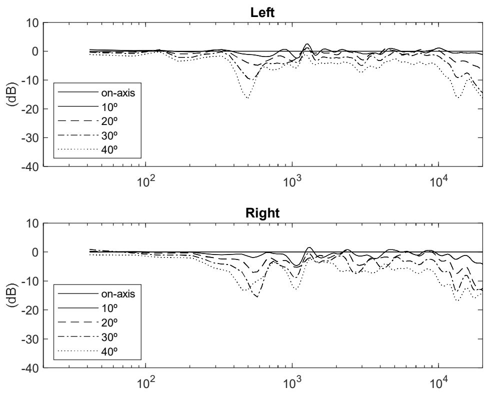

Figure 6. 500 Hz crossover. Horizontal off-axis response. On-axis alignment

Regarding to off-axis performance, comparing Figure 6 to Figure 7, and Figure 10 to Figure 11, it can be seen that strong off-axis cancellations are reduced, providing a more even coverage. The only drawback is that maximum level is achieved off-axis at certain frequencies. The nominal 90º horizontal coverage of the system is better kept at the average crossovers.

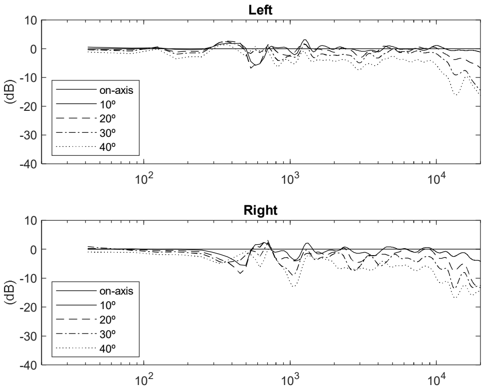

Figure 7. 500 Hz crossover. Horizontal off-axis response. Average alignment

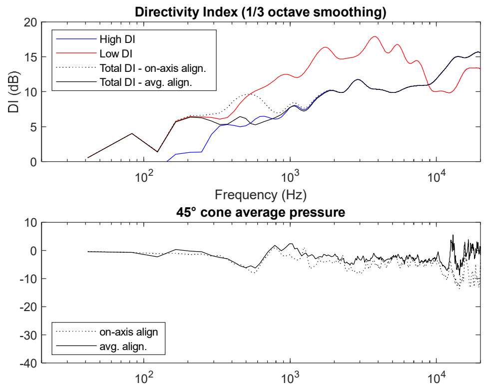

Figure 8. 500 Hz crossovers. DI and cone average pressure

Figure 8 and Figure 12 show that the DI with average crossover approach is lower and the transition from one way to the other is more continuous. The average pressure level within the intended listening window is higher with the average approach and clearly smoother and more continuous in the 1 kHz case.

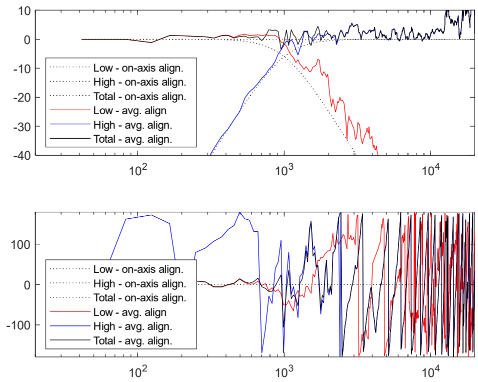

Figure 9. 1000 Hz crossovers. Frequency response

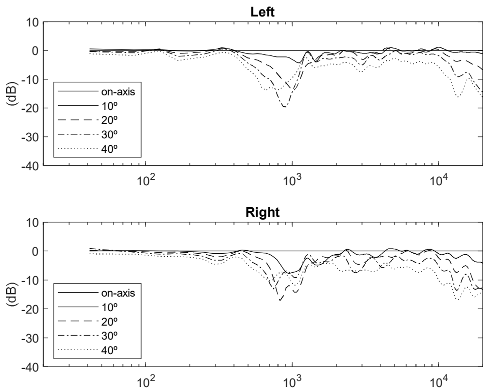

Figure 10. 1000 Hz crossover. Horizontal off-axis response. On-axis alignment

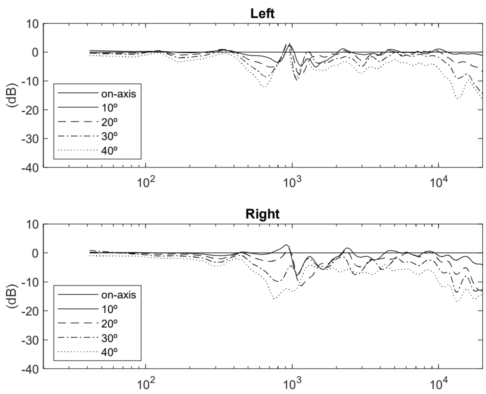

Figure 11. 1000 Hz crossover. Horizontal off-axis response. Average alignment

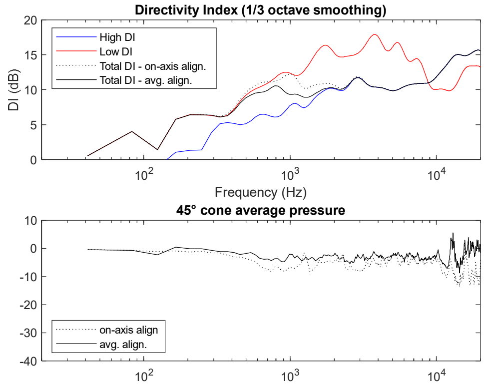

Figure 12. 1000 Hz crossovers. DI and cone average pressure

5 Conclusion

This paper has shown that, for non-ideal loudspeaker systems with non-coincident drivers, a crossover design based on a statistical approach can outperform the traditional on-axis crossover alignment in terms of uniformity of coverage, DI continuity and cone average SPL. The proposed method, based on median value level and phase filters, and optimum alignment to maximize the average level within a listening window, can be used at loudspeaker systems when strong cancellations off-axis have to be avoided in the intended listening window, for example at outdoor PA systems where these cancellations in the voice range can compromise intelligibility.

Further research with listening tests is needed to establish the perception of non-perfect on-axis alignment against better off-axis response, both at on-axis and at off-axis listening positions. Because in this kind of loudspeaker systems, completely asymmetrical, perfect on-axis alignment gets imperfect as soon as the listener moves from the reference axis, from the author's point of view, good subjective acceptance is expected.

Other important considerations about crossover design, such as driver over-excursion, power handling and amplifier power consumption, have not been covered in this paper, which is focused on radiation optimization. In this regard, the proposed technique can be more demanding as more power is applied to the drivers in the crossover region.

Acknowledgments
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