TAILORING THE TOTAL RADIATION PATTERN OF A GROUP OF LOUDSPEAKERS.

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1 INTRODUCTION

Initially, this paper revises the modelling of the radiation pattern of a group of radiating elements. It then discusses the mostly-poor performance of commercial stand-alone loudspeaker systems when they are arranged in pseudo-arrays. In summary, whenever the spacing between drive units is greater than 1/4 wavelength, the phase interactions between the array elements make it difficult to achieve consistent, lobe-free directionality. The upshot of this poor directionality is significant damage to the tonal balance, clarity and intelligibility at many listening positions.

The second part discusses some specific situations in which we have used custom arrays of direct radiators and horns to shape a system's radiation pattern, in order deliver hi-fi sound quality to listeners with both music and speech. This improvement in quality is beyond the usual enhancement of intelligibility associated with line array systems.

2 COMPUTING THE RADIATION PATTERN OF AN ARRAY

2.1 Complex Summation

This section provides a quick revision of the elements that determine the radiation pattern and frequency response of any array of loudspeakers. The first step is to determine the overall magnitude and phase of each drive-unit's sound pressure response at each frequency and location. A drive-unit's response magnitude is set by its overall level and intrinsic on-axis frequency response, the attenuation associated with distance loss and any tapering filters, and the magnitude of its directional response at each angle. Making up a drive-unit's phase are its intrinsic on-axis phase response and polarity, the phase shifts associated with flight time and tapering filters, the phase of delays or all-pass filters, and the phase of its directional response at each angle.

The magnitude and phase of all the drive-units' sound pressures are turned into complex numbers and summed, and the overall magnitude is then computed to give the overall response of the array. While the literature often gives equations for the directional response of an array in its near or far fields, I generally prefer to work with the elements in the chain that influence directionality, as the response can be computed for any configuration at any location. One advantage of this method is that it does not require any knowledge of the listener's position relative to the array's near or far fields, so long as the listener is in the far field of each drive unit.

2.2 Absence of Polar Phase Data

A potential difficulty with this complex summation method of predicting an array's directional behaviour is that it requires knowledge of the drive-unit's phase at each frequency and polar angle. While this phase response can be measured, it is not yet available in manufacturers' polar data.

Fortuitously, the absence of phase data isn't necessarily a problem, so long as all drive-units in the array are identical and the response is being computed at a location where the off-axis angles to all drive-units are similar [1]. In this context, the computation must be carried out at locations that are away from the very-near-field of the array.

2.3 Where is the Acoustic Centre of a Radiating Element?

Another potential difficulty in predicting the performance of arrays is determining the acoustic centre of a radiating device. From the perspective of array directionality, a drive-unit's acoustic centre is not necessarily the same point as its diaphragm. With direct radiators this issue is relatively simple, but with horns it is not so simple. Fortunately, Ureda [1,2] has confirmed that for purposes of predicting an array's radiation pattern, the mouth of a horn is a useable surrogate for its actual source of energy. This is particularly true at lower frequencies, where the polar patterns of horns in an array overlap and the resulting interference effects are most pronounced.

2.4 The Convolution Model for Array Predictions

The convolution model for predicting array directionality was first documented by Ureda [1]. It makes an array of simple sources using the centre of a horn's mouth or a direct radiator's diaphragm as the position of the source, and applies the device's polar response magnitude to that source. The model is a derivative of the first product theorem [3] which states that the directional factor of an array of identical sources is the product of the directional factor of an array of simple sources with identical geometry and the directional factor of a single element of the array. Closer examination of this theorem reveals that the complex summation method also embodies this concept. In the absence of drive-unit phase information, the complex summation method reduces to the convolution method and can therefore be readily used for prediction of horn arrays.

3 TRAPEZOIDAL ARRAYING IN THE HORIZONTAL PLANE

Common practice is to locate up to four stand-alone systems side by side, with a splay angle between them. Such a practice is predicated on the basis that each speaker radiates sound like a beam of light, and therefore if they are splayed apart, the system's coverage angle must be greater than a single speaker. Figure 1 shows an example from the manufacturer's website.

Fig. 1 Example of simple arraying

With many speakers this practice is dangerous, as it fails to recognise that significant overlap in the radiation patterns of each box occurs over a wide frequency range. This overlap produces severe interference and causes the radiation pattern to narrow, rather than the desired widening. For example, predictions of the polar response of a pair of EV SX300 (nominally 65° x 65° wide) systems were made with the convolution model via the Telex/EVI software ArrayShow. Figure 2 compares the horizontal polar responses between 400 Hz and 2.5 kHz of one SX300 speaker with the predicted polars of two such speakers horizontally splayed at ±25°. (25° is the angle of the enclosure sides). A mental translation of these polars into frequency responses at each angle indicates poor tonality, and although the nulls in this system's measured response are less deep than predicted, they are still significant.[4] It is noteworthy that over most of the region between 0° and ±30°, the polar response of the SX300 pair is essentially narrower than that of a single speaker.

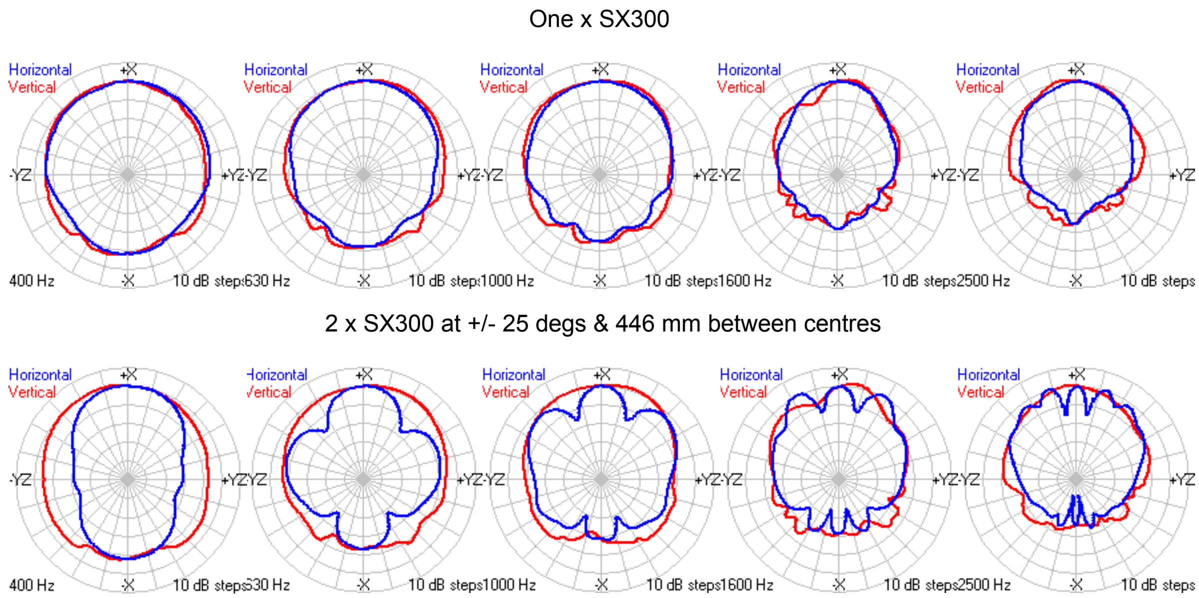


Fig. 2 Comparison of polar responses of one SX300 box with two arrayed SX300 boxes.

In a reasonable acoustic environment, speech sounds adequate through this type of array, but when vocals and a live band are reproduced, its ragged frequency response makes it hard to obtain good vocal projection and clarity without making the vocals unduly loud in the mix. I believe this generic arrangement of boxes is often the bane of sound systems in churches, pubs and small gigs, and that culturally, we have become accustomed to its poor sound.

In hostile acoustic environments where there is substantial late-arriving energy from distributed loudspeakers and/or high RTs, there can be serious implications of this type of array. The nulls in the direct-field response can greatly reduce the clarity ratios at the critical mid-range frequencies with the consequent loss of intelligibility. Regrettably, there are numerous examples of clusters of JBL, EV, Meyer, EAW boxes and other brands, many of them specified or certified by acoustic consultants, which have both poor tonality and poor clarity due to this interaction.

3.1 EASE 3.0

Unfortunately, this behaviour is not always observed in the software EASE 3.0. We compared the polar performance of a cluster of three MSL4 speakers using the Meyer MAPP software and EASE 3.0. In both cases, we formed the cluster with the wire frames of each speaker box just touching at their backs. The MAPP results showed deep phase cancellation nulls with the overall trends showing strong similarity to ArrayShow’s results. In contrast, the EASE polars for the cluster showed little evidence of the nulls. Investigations showed that the acoustic centre of the MSL4 data in EASE 3.0 was considerably inside the wire frame, thereby reducing the inter-speaker distances.

3.2 Two Techniques to Reduce Polar Damage

Introducing a 10ms delay into one box in the SX300 pair array helps somewhat as shown in Figure 3. This delay swamps the difference in the propagation delays, causing the cancellations to be at intervals of approximately 50 Hz, rather than in the 400 Hz to 800 Hz region. While the tonality will be much improved, the polars are now unsymmetrical above 630Hz. Spacing the boxes apart by 1.5 m helps considerably as shown in Figure 3, and is probably the best simple solution.

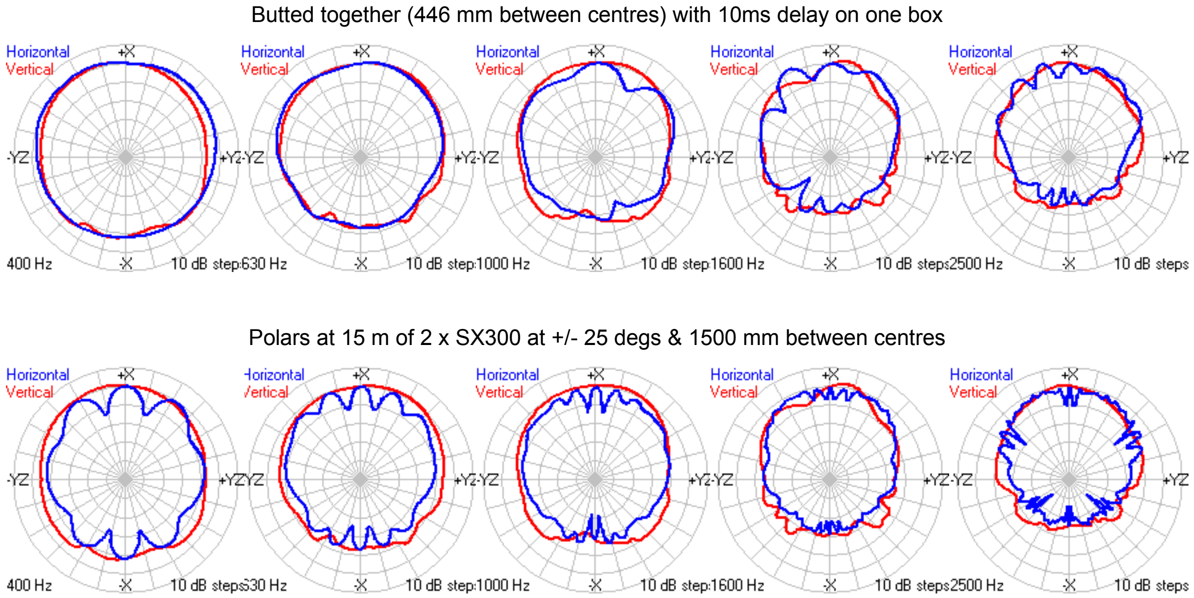


Fig. 3 Effects on polar responses of 10 ms delay on one box and increasing the inter-box spacing.

4 DIFFICULTIES FOR DIRECTIVITY WITH MULTIPLE BOXES

We investigated the feasibility of producing a desired polar pattern using an array of commercially available D&B C7 full-range boxes. These speakers were initially chosen for an auditorium in the UK on the basis of their ready acceptance by sound operators. Modelling with EASE 3.0 using power sum showed that to cover the auditorium above 2kHz from -10° to -85° (below horizontal) required three forward-facing and two side-fill boxes. Our goal was to provide constant directivity over the full frequency range and to use the three vertical boxes to minimise radiation towards the ceiling and stage.

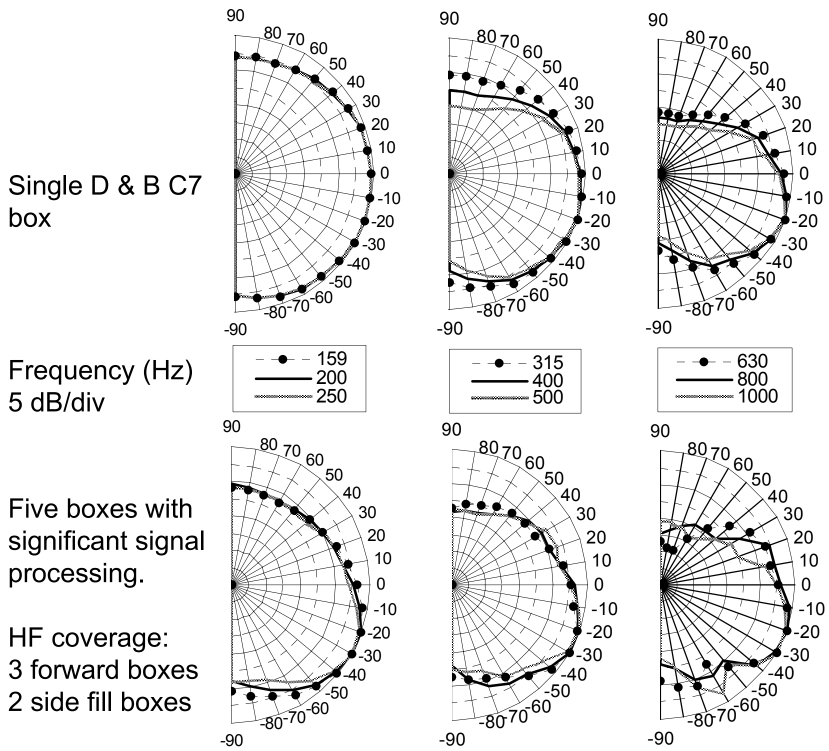


Fig.4 Comparison of polar responses for single C7 box with processed array of five C7 boxes

Achieving the predicted polar response shown in Figure 4, required the following signal processing for the array: 2 x 2nd order low-pass filters, 1 x 2nd order high-pass filter, 2 x notch filters, 3 x delay, and 3 x all-pass filters (2 x 1st order, 1 x 2nd order). Although we spent considerable time on this design, the final polar consistency was inadequate, and it seems that an array of off the shelf boxes with signal processing is unable to achieve constant directionality.

5 NARROWING A HORN'S DIRECTIONALITY

Due to their limited size, mid-range horns do not usually exhibit constant directivity over their frequency range. The use of a second horn can improve the directional consistency in one plane. The Bose 4402 LT device comprises of a mid-range and high-frequency horn. To increase its vertical directivity at low-mid frequencies, a second 4402 is inverted and butted up against the first so that the mid-range horns touch. The high-frequency horn of the second 4402 is unused, as this would corrupt the polar response. To make the low-mid directivity similar to that at 1 kHz, a second order low-pass tapering filter (f_{res} = 500 Hz with Q = 0.6) and a notch filter are applied to the second horn. A compensating signal delay of 0.9 ms is also applied to the first horn to prevent the tapering filter's group delay from steering the overall pattern. Figure 5 compares the vertical polars of a single 4402 horn with those of the two-horn system.

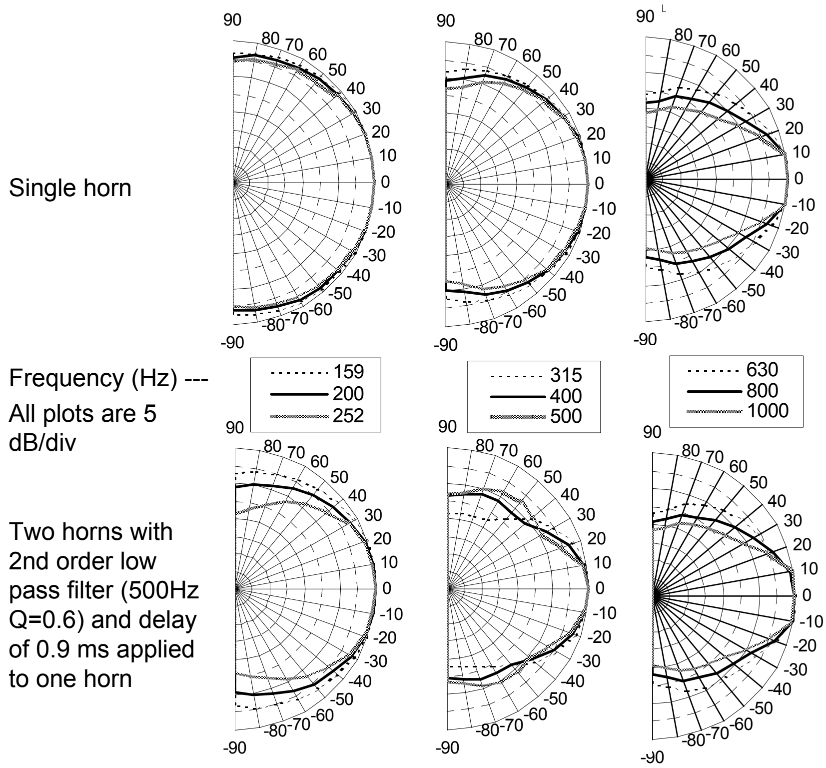


Fig. 5 Increasing the directionality of a 4402 mid-range horn

6 THE BENEFITS OF "IN BETWEEN" ARRAYS

While the use of line arrays to enhance intelligibility in highly reverberant environments is well understood, the benefits of line arrays in other applications is not so well appreciated. One limitation of line arrays that use only direct radiators is their restricted coverage and frequency response at high frequencies. By combining a high-frequency horn and a line array, a number of advantages result over many other types of speakers for both speech and music:

- Constant directivity horns readily provide a wide and well-controlled radiation pattern at frequencies above 1kHz, where it is difficult to get a wide, lobe-free pattern with arrays of cone drivers. (The narrowing directionality of cone drivers at high frequencies, and the cancellations from the unavoidably-large spacing between drivers in terms of wavelength at high frequencies means that multiple units cannot be used to achieve a wide pattern.)
- The radiation pattern of the line array can be shaped at most frequencies to match that of the high-frequency horn, producing a more consistent frequency response across the listening area. (Because of reduced directionality in the lower mid-range, many sound systems have

poor tonal balance in areas close to and below the speakers. If the directionality is constant between 40 Hz to 15 kHz, then the sound is on the way to true hi-fi for all listeners. However, even producing a constant directionality over the range 200 Hz to 12 kHz is difficult.)

- When the horn's orientation and directivity compensates for distance loss and the array's pattern matches the horn, a consistent sound level is produced over the listening area.
- Removal of high frequency demands from the cone drivers allows them to be chosen for a more extended low-frequency response and maximum sound pressure level.

The other benefits of line arrays are still available:

- Minimisation of late-arriving sound, particularly in the 300Hz to 800Hz region from reverberant colouration or a ceiling reflection.
- Beam steering (with only the horn being tilted) for architectural situations in which slim, vertical or horizontal lines are easier to integrate.
- A reduction in the amount of early and late sound arriving at live microphones.
- Enhanced psycho-acoustic localisation of a live sound source at low mid frequencies.

While large-scale line array systems such as JBL Vertec or LAcoustics VDOSC, or Meyer MD3 offer the above benefits, the sheer size and cost of these systems makes them unsuitable for many situations, and the absence of good commercial "in between arrays" necessitates custom designs. Examples of three custom systems that the author has designed are now discussed.

6.1 Australian Parliamentary House of Representatives

"In between" arrays have recently been successfully used in the public galleries of the Australian Parliamentary House of Representatives. Architectural constraints dictated that a) only vertical elements could be used, and b) loudspeakers could only be located in the corners, forcing listeners to be between 2 and 15 m from the speakers. Although the lower gallery areas are absorptive for early reflections, late reflections from the hard, high ceiling would be strongly evident to listeners due to the relative absence of early arrivals. The system uses a vertical beam-steered line array of nine Vifa 125 mm low frequency drive units and an EV HP94 high-frequency horn tilted down at 17°. A Tannoy ICT 125 mm driver provides infill for listeners in the first 1.5 m immediately below the array/horn system. Figures 5 and 6 show the situational context and layout of the arrays.

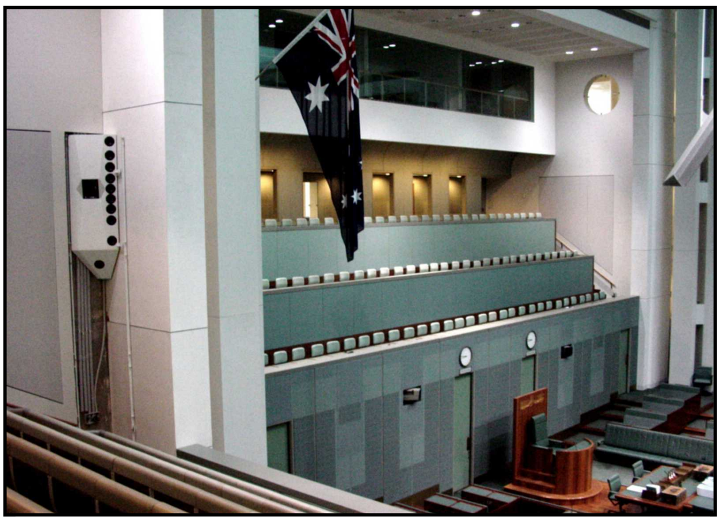


Fig. 5 Location of system in Government gallery (NB decorative grille has been removed)

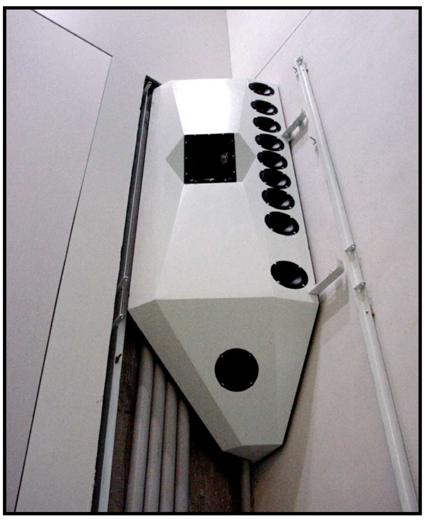


Fig. 6 The system showing drivers and articulated baffle

The HP94's orientation was first selected for optimal coverage, and by designing the array's vertical directionality across the voice range to match that of the horn, the system provides consistency above 315 Hz of level, frequency response and the minimisation of ceiling reflections. This design was undertaken using least-squares optimisation of the tapering filter parameters and inter-driver distances. In addition, the system can deliver moderately high SPLs to reproduce a loud male voice at 15 m with an Equivalent Acoustic Distance [5] of 2 m. (This translates to L_{peak} of 124 dB @ 1 m).

The corner location is potentially disastrous for the line-array's frequency response due to interference from the image sources behind the adjacent walls, but positioning the LF drivers directly against one wall pushes most of the cancellations present in the listening area above the array's crossover frequency. To keep the horn as close as possible to the line-array, whilst minimising damage to the overall frequency response from scattering due to angular structures, a complex series of angled panels was used to provide a relatively smooth baffle transition from the vertically-mounted woofers to the tilted horn. The array's measured low frequency response of -3 dB at 80 Hz, is achieved through 4th order closed box topology [6].

Figure 7 shows the vertical polar pattern of the line-array/horn system. The woofer array begins to lose directional consistency at approximately 1.2 kHz due to the minimum inter-driver distance of 140 mm and therefore crosses over to the horn. The tapering filters consist of 2^{nd} order low-pass filters with a Q of 0.6. These filters, along with beam steering delays, crossover functions and equalisation, and all-pass filters to integrate the infill system are implemented in a Media Matrix X Frame. Each driver uses an individual power amplifier that is located above the gallery ceiling. The frequency responses of the array were measured with MLSSA at a number of angles and found to be within ±2 dB of the predicted responses.

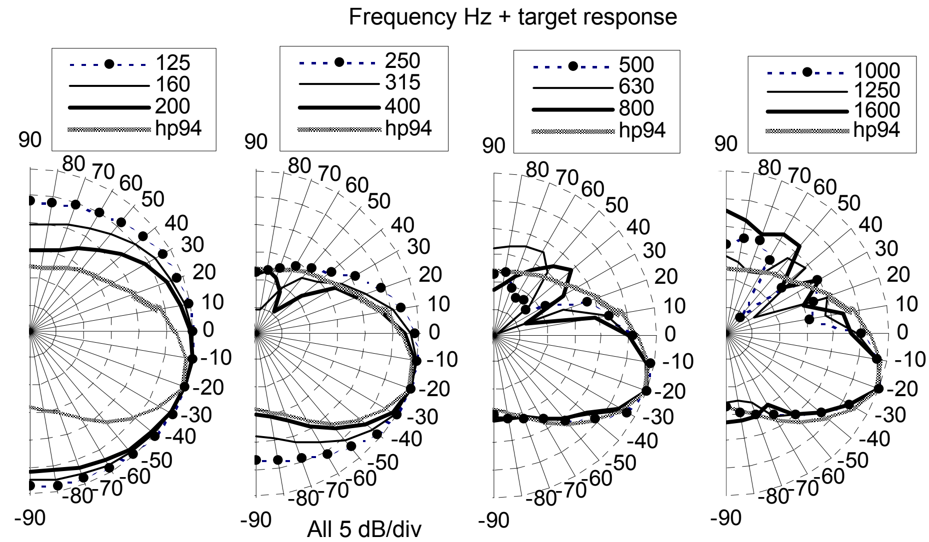


Fig. 7. Vertical polar response of gallery array

6.2 Sydney Opera House Opera Theatre: Dress Circle Low/Mid-Range and Subwoofer Arrays

The loudspeaker system in the Opera Theatre of Sydney Opera House was installed in late 1999 and is characterised by its number of systems that can be considered as "in between" arrays.

A subwoofer line array comprising six 450 mm drive-units provides bass to the entire theatre, while side-by-side arrays of low and mid-range horns form the dress circle centre-channel system in conjunction with a high-frequency horn. Other arrays used in the theatre are mid-range horn arrays for the stalls left and right channels, each comprising three JBL 3215 horns and a mid-range array comprising three 350 mm JBL 1400 Pro woofers for the stalls centre channel.

Two main design targets were addressed in the design of the Dress Circle centre channel system:

- With the speakers mounted in the proscenium wall, 10 dB of isolation was required above 250 Hz to the stalls below the dress circle with minimal irradiation of walls, ceiling and stage.
- Matching of the array's vertical directionality to that of the associated high-frequency horn (JBL2352) to provide a consistent frequency response across the dress circle.

Three main targets were applied to the subwoofer system:

- Compensation by directivity of the distance loss to all areas forward of the orchestra pit.
- Minimal low-frequency sound radiated towards the ceiling to enhance bass "punch".
- Minimal low-frequency sound to reach stage and orchestra pit for feedback and disturbance.

Figure 8 shows a sectional view of the Opera Theatre and the areas covered by each array.

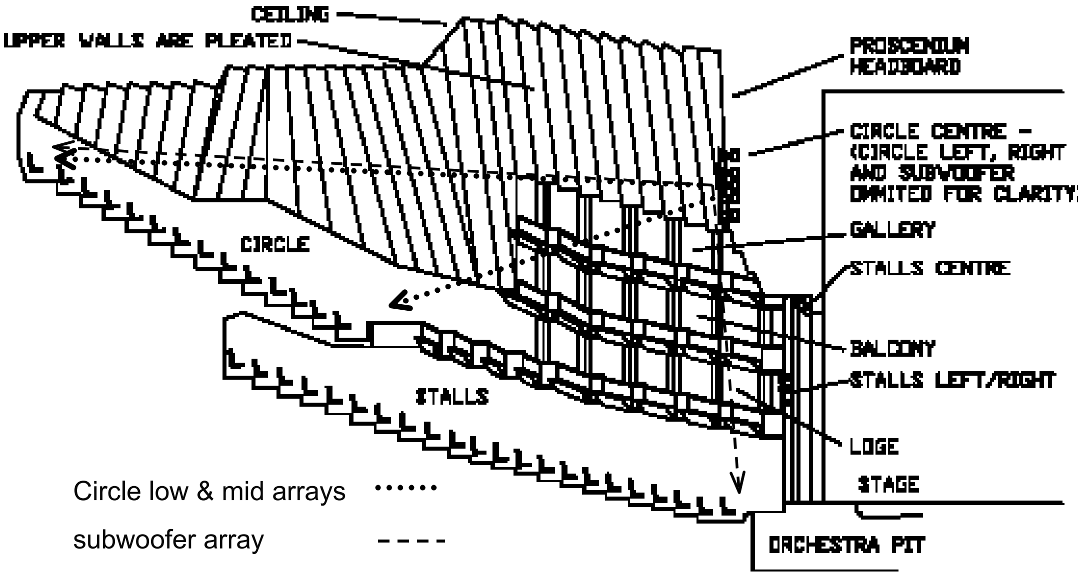


Fig. 8 Sectional view of Opera Theatre showing coverage of low/mid and subwoofer arrays

6.2.1 Implementation of Circle Low/Mid-range Arrays

These two arrays utilised the low and mid horn composite assembly that forms part of the JBL HLA 4895 system. In the HLA system, the low-frequency horn (fed by a 355 mm driver) is located directly below the mid-range horn (fed by a 250 mm driver). Using five horn assemblies that were first rotated 90° and then stacked vertically, two line arrays of low-frequency and mid-range horns were formed side-by-side. Another benefit of rotating the horn assembly by 90° was that the narrower vertical pattern of the horns at upper-mid frequencies minimised irradiation of the side walls of the theatre. Achievement of the required directivity over the full frequency range required a total array height of 3.8 m with the inner three horns being as close as possible. The vertical radiation pattern of the arrays was designed to match that of the high-frequency horn using least-squares optimisation of the tapering filter parameters and inter-horn distances. As these arrays use constant summation type of tapering filters, they do not require equalisation.[7] Figure 9 shows the arrays in situ.

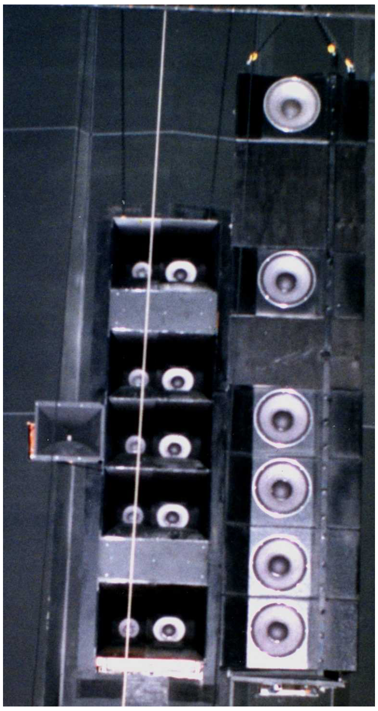


Fig 9. Low, mid and subwoofer arrays with high frequency horn.

Frequency -----

5dB div

Fig 10a Measured polars of test configuration

Fig 10b Predicted polars for test configuration (inner horn @ 0dB)

Fig 10c Predicted polars for designed configuration (inner horn @ +6dB)

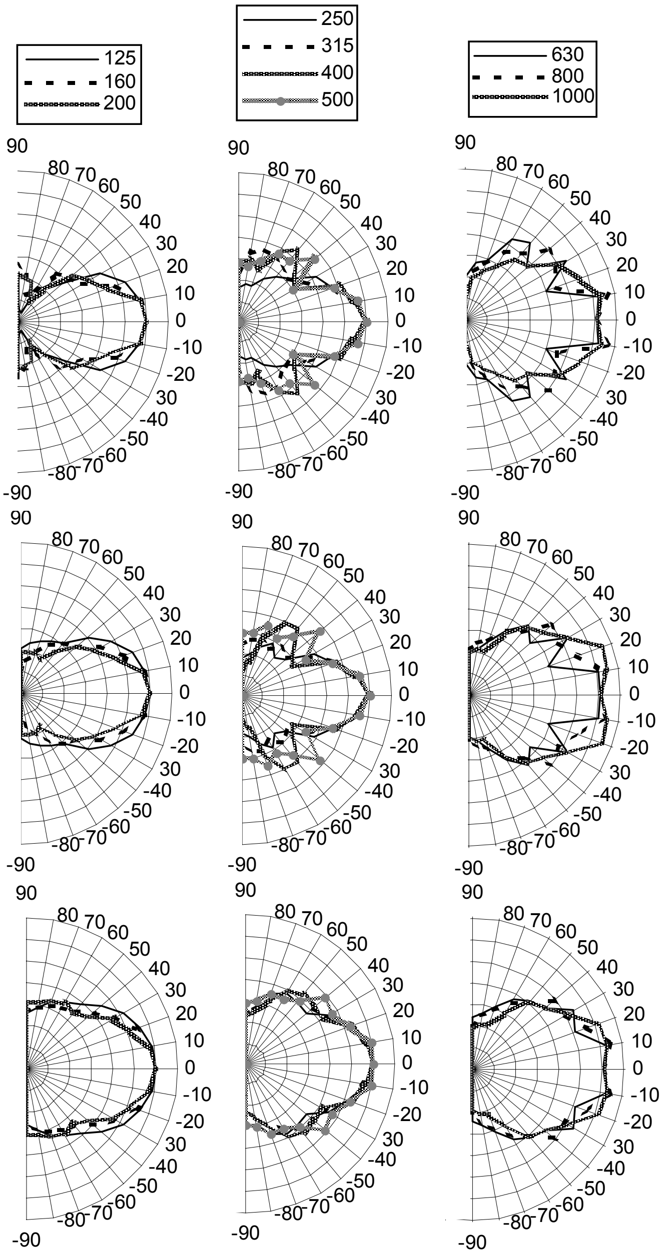


Fig 10 Comparison of measured and predicted polar responses for the 4895 array

These arrays were designed using the convolution method, with the radiation patterns of the 4895 elements taken from JBL data sheets. Before installation, JBL Professional measured the vertical directionality of the array system at Summit Labs in the USA. For various reasons, the test configuration of the array did not match our designed configuration. Comparison of the measured polars in Figure 10a with our predicted polars for the test configuration in Figure 10b shows good agreement. This agreement provided confidence for the as-designed configuration with the smoother polar patterns in Figure 10c. To illustrate the improvement of the frequency response consistency for all listeners that this type of array provides, Figure 11 compares the frequency response at off-axis angles of a single 4895 system with that of the five-element array.

At first glance, this situation would seem to be a prime candidate for the concert type of line array system such as JBL Vertec. Although not available at the time, the cost of such a system would be well beyond this system's budget and the coverage requirements would have resulted in the non-use (and hence wastage) of all but three of the high frequency sections of the Vertec array.

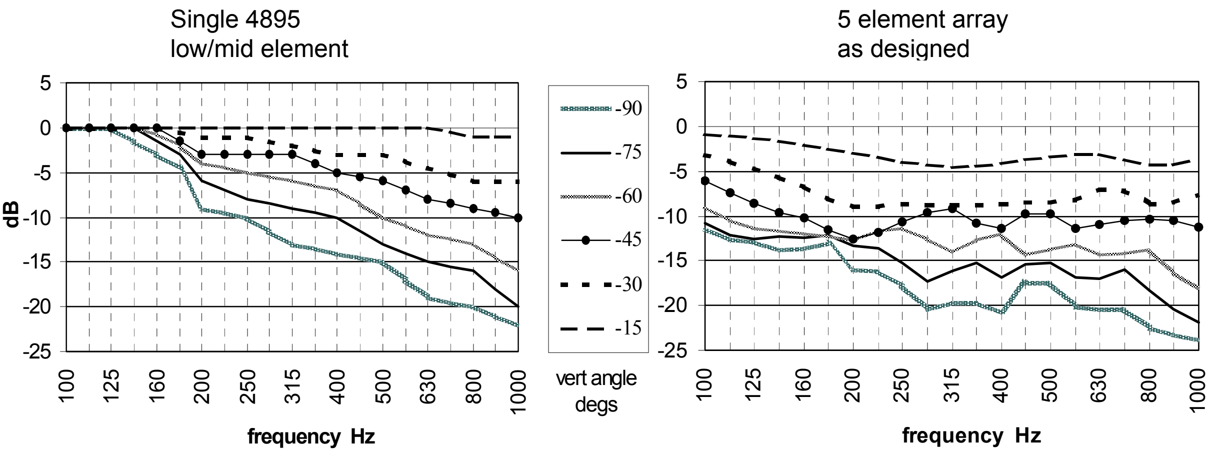


Fig. 11 Off-axis responses relative to on-axis of single 4895 system and tapered array of five 4895 elements

6.2.2 IMPLEMENTATION OF SUBWOOFER ARRAY

The subwoofer system used six JBL 2242 450 mm drive-units, arranged with asymmetrical inter-driver spacings in a 5 m high line array. The predicted polar pattern is shown in Figure 12, with 0° being towards the rear of the dress circle. Distance loss compensation was provided by the directionality below 0°, while directly upward there was an attenuation of at least 12 dB above 63 Hz. A frequency response of -3 dB at 40 Hz is achieved in this very small enclosure size via a non-classical 6th order vented system.

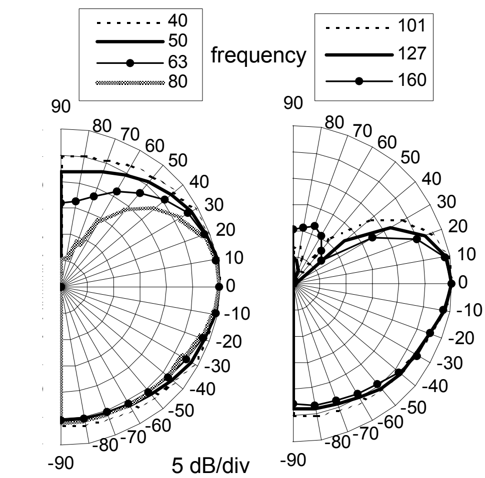
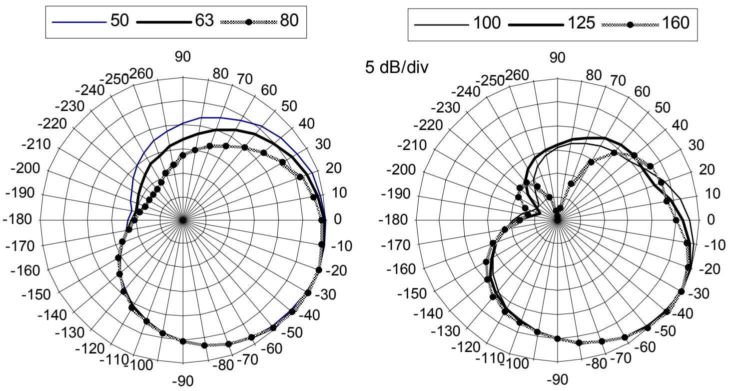


Fig.12 Predicted polar response of the subwoofer array

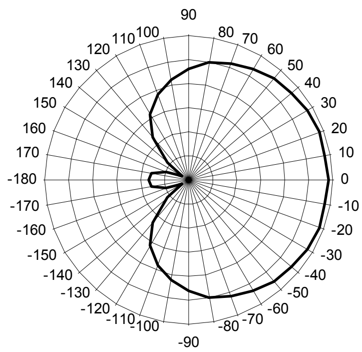
To prevent a notch in the power response from the image source in proscenium wall, the enclosure depth was only 250 mm from the driver baffle to proscenium wall. An offset of 0.3 m between the subwoofer and the rear wall would cause a cancellation at 285 Hz with an attendant 2.2 dB loss at 125 Hz. I believe that many modern system designs fail to consider the cancellations due to image sources.

7 STEERED, DIPOLAR, LINE ARRAY SUBWOOFER

This subwoofer system was recently designed for the main auditorium of the NSW Conservatorium of Music in Sydney. The system was to hang vertically in free space above the front of the stage and retract through a hole in the ceiling of size 600 mm x 700 mm. The directionality of the subwoofer is both steered and shaped to compensate for distance loss in both forward and sideways directions and to minimise rear radiation towards the ceiling and bulk of the stage. Using eight 380 mm JBL 2226 drive-units, the system comprises of two vertical line arrays, each of four drive-units, that are separated horizontally (forward to back) by 600 mm. Both arrays employ signal delays and a combination of vertical driver spacing and tapering filters to produce a frequency-consistent downward beam in the vertical plane. Horizontal control of radiation is provided by the usual dipole elements of the physical offset of the arrays, polarity inversion and the delay of the rear array. Figure 13a shows the array's vertical polar response in the forward direction, while Figure 13b shows its horizontal polar response at 80 Hz. Figure 14 shows the directional balloon at 80 Hz.



a) Vertical



b) Horizontal

Fig. 13 Polar responses of Conservatorium subwoofer a) Vertical b) Horizontal at 80 Hz

Figure 15 shows the predicted frequency response plot in the subwoofer's far field. The frequency-dependant losses from the combination of the dipole arrangement and the tapering filters have been held to a manageable level ranging between 10 dB and 3.5 dB over subwooofer's passband of 40 Hz to 160 Hz. The 109 dB graticule corresponds to the full space sensitivity (1w/1m) of eight. 2226 drivers that are all co-located.

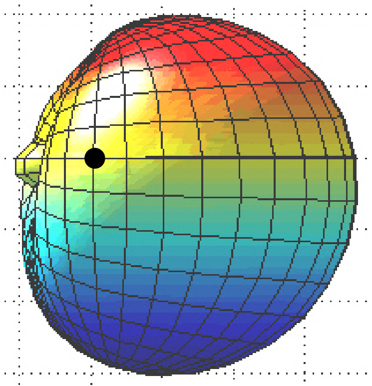


Fig. 14 Radiation balloon of subwoofer at 80 Hz

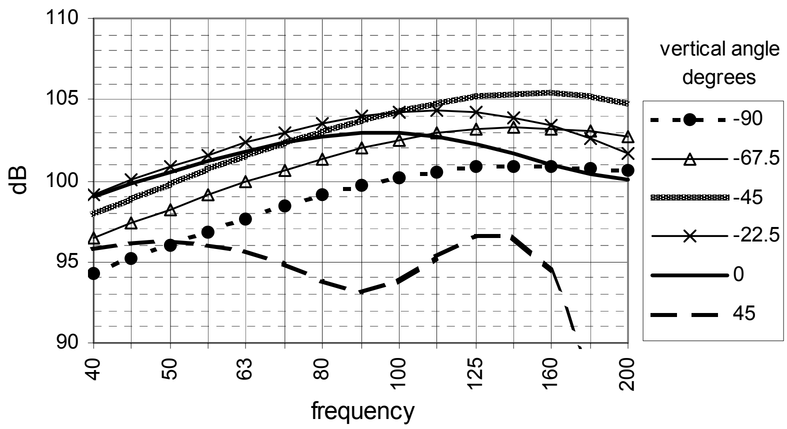


Fig 15 Predicted far field frequency response of subwoofer for 1 watt into each driver and scaled to 1m

8 CONCLUSION

With knowledge of each radiating element's polar magnitude response and complex number theory, current modelling techniques allow prediction of the polar and frequency response of any arrangement of boxes, drivers, or horns.

Despite the market place encouraging the practice, it is difficult to produce constant directionality using clusters of full-range commercial speaker systems and therefore delivery of a constant frequency response and a frequency-consistent clarity ratio over a listening area is compromised. The poor polar performance of two clusters of boxes was illustrated, and an example was given of how a two-horn array with signal processing can provide a useful increase in directivity at low mid frequencies.

By considering the magnitude and phase response of each component in the chain that forms the loudspeaker array, it is possible to design "in between" arrays that provide controlled and constant directionality over the full audio range. The resulting flat frequency response at each listener and the control of clarity ratios allows these array-based systems to deliver sound quality beyond the usual enhancement of intelligibility. In addition, the ability to shape the radiation pattern allows unprecedented flexibility for the architectural integration of loudspeakers.

Examples were given of systems at the Australian Parliament House, Sydney Opera House and the NSW Conservatorium of Music (currently in design) that employ line arrays of direct radiators or horns to achieve a specific radiation pattern that complements the patterns of other elements in those systems.

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