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Practical considerations for subwoofer arrays and clusters in live sound reinforcement

Adam J. Hill

Department of Electronics, Computing and Mathematics, University of Derby, UK

a.hill@derby.ac.uk

ABSTRACT

The central theories behind low-frequency directionality with subwoofer clusters and arrays are well-known, but there are practical considerations that are essential to understand. This paper highlights key areas such as: the acoustic center, directionality of so-called omnidirectional sources, performance stage effects, and inter-unit decorrelation methods, primarily through the use of hemi-anechoic measurements with secondary analysis via electroacoustic simulations.

1 Introduction

It is quite often the case in live sound reinforcement that engineers are required to limit low-frequency sound outside audience areas. While directional subwoofers are available from various manufacturers, many sound reinforcement companies utilize omnidirectional subwoofers. Without special configuration of these units, low-frequency sound energy will radiate outside audience areas at considerable and often unacceptably high levels.

While the theory behind achieving directional low-frequency with multiple omnidirectional units is well-known, there has been little previous research into practical issues surrounding these techniques (previous work focuses mostly on mathematical theory and electroacoustic simulations).

Practical issues such as apparent directivity of omnidirectional subwoofers, the issue of acoustic center shift, source orientation, performance stage effects and inter-unit signal decorrelation are addressed here, largely by inspection of hemianechoic measurements, supplemented by electroacoustic simulation, when necessary.

2 Single unit/cluster polar response

It is essential to understand the polar response of the individual sources utilized within a subwoofer system before proceeding to combine multiple sources to form clusters or arrays. Polar response information is typically provided by manufacturers. Expanding upon this information, individual sources are commonly clustered together, so that they're acoustically coupled, effectively forming a single source when observed in the far-field. Techniques related to source clustering are well-known and are largely based on the seminal work of Olson [1].

Within this section, various basic polar responses of single sources and source clusters are investigated.

2.1 Omnidirectional

Subwoofers commonly employed within live sound reinforcement generate a so-called omnidirectional polar response, due to a single drive unit (or multiple drive units physically mounted within the same face of an enclosure). Naturally, it is expected that the omnidirectional response will degrade with increasing frequency, as the enclosure becomes acoustically larger with decreasing frequency wavelength, causing lobing due to diffraction.

To investigate this, a d&b audiotechnik B6 subwoofer [2] was modeled in a free-field using d&b ArrayCalc software [3]. The predicted sound energy coverage and subwoofer polar response are shown in Figs. 2.1 and 2.2, respectively.

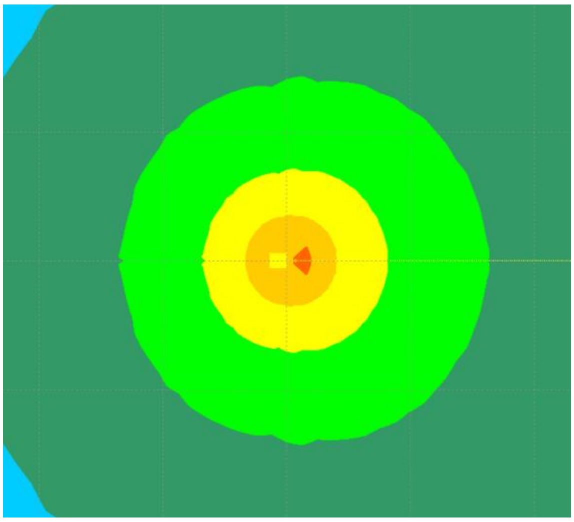

Fig 2.1 Predicted sound energy coverage of a d&b B6 subwoofer at 40 Hz (grid line spacing is 5m and color contours are spaced at 6 dB) [3]

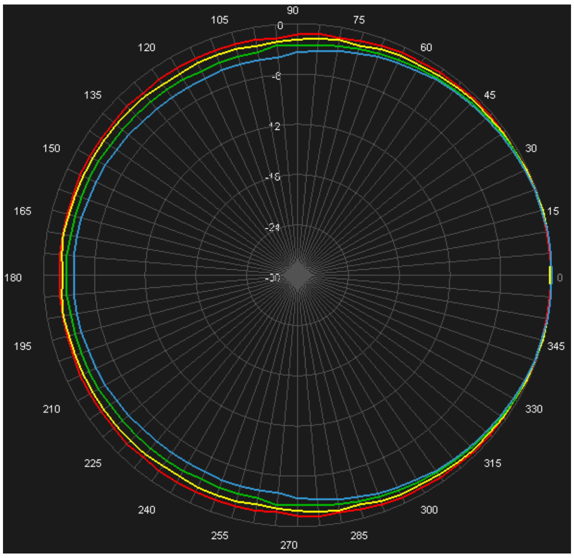

Fig 2.2 Predicted polar response of a d&b B6 subwoofer at 40 Hz (red), 63 Hz (yellow), 80 Hz (green) and 100 Hz (blue) [3]

A d&b B6 subwoofer was then measured in a hemi-anechoic chamber with 50 m^2 floor space and a cut-off frequency of 100 Hz, in accordance with ISO 26101. While the 100 Hz cut-off seemingly disqualifies the chamber for testing a subwoofer, formal testing results for ISO 26101 indicate compliance down to 50 Hz, as long as measurements are made within 2 m of the room center.

With this is mind, a measurement radius of 2 m was used with 30° resolution. The loudspeaker was centered for the measurements (Fig. 2.3).

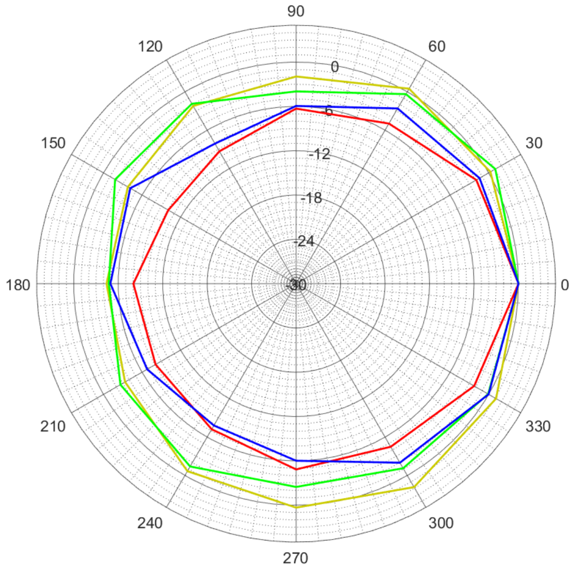

Fig 2.3 Measured polar response of a d&b B6 subwoofer at 40 Hz (red), 63 Hz (yellow), 80 Hz (green) and 100 Hz (blue)

The measurements apparently indicate that reality isn't in line with the software predications. Luckily, this isn't an accurate observation. It is essential to understand that at low-frequencies, enclosure diffraction causes the loudspeaker's acoustic center to shift forward in space. This has been well-researched and documented by Vanderkooy in [4,5].

With this in mind, the subwoofer's acoustic center at low-frequencies was approximated as 35 cm in front of the loudspeaker front baffle (it is important to note that acoustic center is frequency-dependent, hence the necessary approximation) and the loudspeaker was positioned so that the acoustic center coincided with the room center (Fig 2.4).

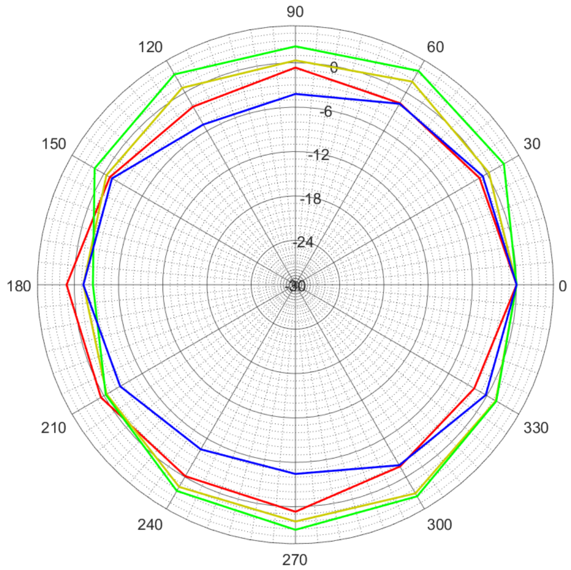

Fig 2.4 Measured polar response of a d&b B6 subwoofer at 40 Hz (red), 63 Hz (yellow), 80 Hz (green) and 100 Hz (blue) with a 35 cm acoustic center shift

While the relative levels between frequencies aren't precisely in agreement with the software, the general polar responses are in rough agreement. The inaccuracies seen at 40 Hz are likely due to the hemi-anechoic chamber not quite supporting measurements at 2 m (as discussed previously).

The important practical point here is that the acoustic center must always be taken into consideration when measuring subwoofers. Otherwise, measurements will appear to contradict expectations, which is incorrect. The acoustic center shift can be seen quite clearly in the software predictions shown in Fig. 2.1, which is encouraging.

2.2 Bi-directional (figure eight)

While omnidirectional subwoofers are sufficient for many applications, there is an increasingly common demand for directional low-frequency at events in order to limit sound levels on stage as well as in neighboring areas.

While many manufacturers produce subwoofers which achieve directional polar responses within single units, it is of great value to be able to achieve directionality with multiple omnidirectional sources arranged in a coupled cluster.

The theory relating to this is well-known and documented [1,6,7,8], however, much of the previous work specifically looking into live sound reinforcement [6,7,8] is based on mathematical theory and electroacoustic simulations.

The first step towards subwoofer directionality is achieving a bi-directional, or figure eight, polar response. Following Olson's gradient loudspeaker theory [1], this can be achieved by placing two omnidirectional subwoofers in line with one another. The rear subwoofer must have reverse polarity.

Instead of measuring the d&b B6 subwoofer, as in the previous section, a dB Technologies DVA S10 DP subwoofer [9] was used since four of these sources were available at the time of testing (four identical sources are required in Section 2.4). The two subwoofers were positioned facing forwards with a front-to-front spacing of 1.5 m. The cluster was centered in the room (Fig. 2.5).

The measured polar response isn't as expected. The errors are due to not accounting for the acoustic center. Taking this into account, the cluster was shifted back 37 cm (the approximated acoustic center for the dB Technologies DVA S10 DP) and re-measured (Fig. 2.6).

With the acoustic center considered, the polar responses are as expected. This indicates that acoustic center must be considered when deploying subwoofer clusters in practice.

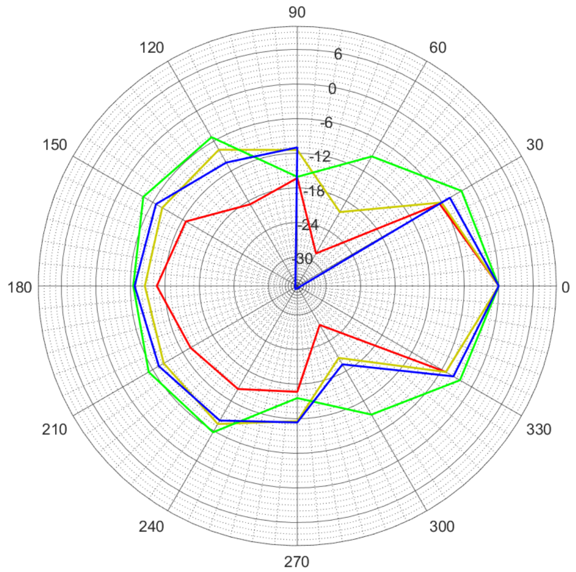

Fig 2.5 Measured polar response of the dBTech S10 subwoofer bi-directional cluster at 40 Hz (red), 63 Hz (yellow), 80 Hz (green) and 100 Hz (blue)

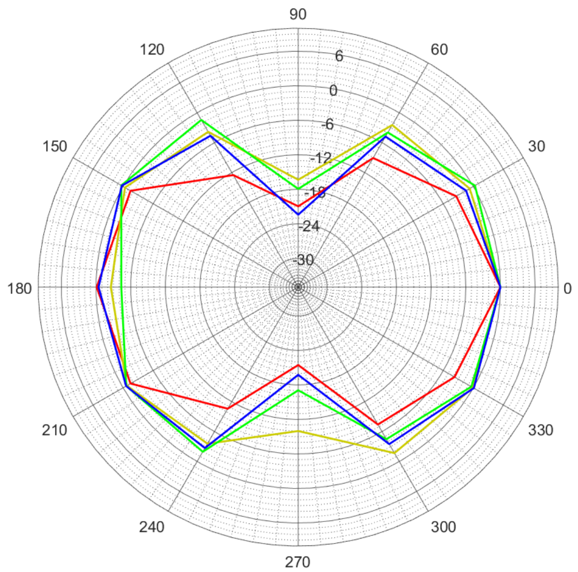

Fig 2.6 Measured polar response of the dBTech S10 subwoofer bi-directional cluster at 40 Hz (red), 63 Hz (yellow), 80 Hz (green) and 100 Hz (blue) with a 37 cm acoustic center shift (units facing forward)

Lastly, the effect of subwoofer orientation must be inspected since, as shown previously, these subwoofers aren't truly omnidirectional. In this instance, the rear subwoofer was rotated 180°, so that the units were facing opposite directions. The cluster was centered in the room (since acoustic center shift will be equal and opposite) with 1.5 m spacing (Fig. 2.7).

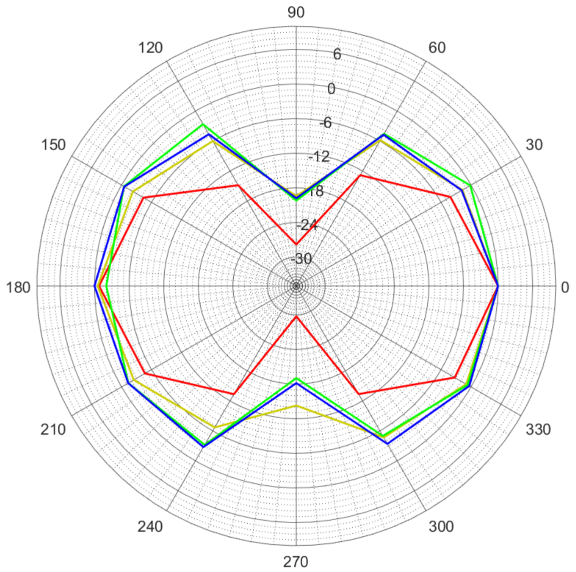

Fig 2.7 Measured polar response of the dBTech S10 subwoofer bi-directional cluster at 40 Hz (red), 63 Hz (yellow), 80 Hz (green) and 100 Hz (blue) (units facing opposite directions)

This configuration provides a much stronger bi-directional pattern and removes the acoustic center consideration, as the opposite shifts from the units cause the acoustic center of the cluster to remain centered in the room.

This highlights another important practical consideration for live sound reinforcement subwoofers: it's essential to remember that omnidirectional subwoofers aren't actually omnidirectional. Source orientation is essential.

2.3 Unidirectional (cardioid)

While achieving a bi-directional pattern is an interesting exercise, it's of little use in live sound reinforcement. Typically, a unidirectional (e.g. cardioid) response is required to direct sound towards the audience and away from the stage.

Following gradient loudspeaker theory [1], a cardioid response is achieved by applying electronic delay to the rear unit in the two-subwoofer cluster from Section 2.2. The amount of delay should be directly related to the unit spacing (1.5 m, in this case, giving 4.37 ms delay). The ideal cardioid response is at the frequency which has a quarter wavelength of 1.5 m, which is 57.17 Hz. (Fig. 2.8). The front-to-rear rejection is given in Table 2.1.

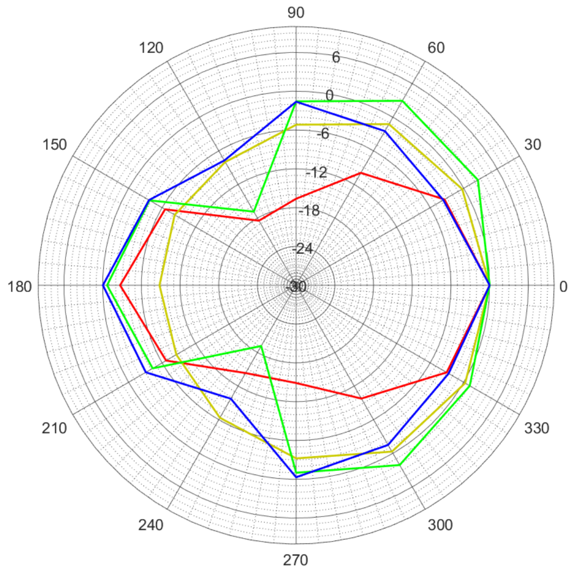

Fig 2.8 Measured polar response of the dBTech S10 subwoofer cardioid cluster at 40 Hz (red), 63 Hz (yellow), 80 Hz (green) and 100 Hz (blue) (units facing opposite directions outward, 4.37 ms delay)

Delay (ms)	40 Hz	63 Hz	80 Hz	100 Hz
4.37	2.71 dB	8.82 dB	0.69 dB	0.04 dB
6.53	2.94 dB	5.41 dB	3.82 dB	4.14 dB

Table 2.1 Front-to-rear rejection for the two-unit cardioid cluster (outward facing units) due to inter-unit delay

This isn't sufficient, as there is negligible rejection at higher frequencies. Again, it's essential to consider the acoustic center shift for each subwoofer. If the units are facing away from one another, the assumed 37 cm shift from both will cause the acoustic spacing of the units to go from 1.5 m to 2.24 m. This requires the delay to be increased to 6.53 ms (Fig. 2.9). The resulting front-to-rear rejection achieved is given in Table 2.1, as before.

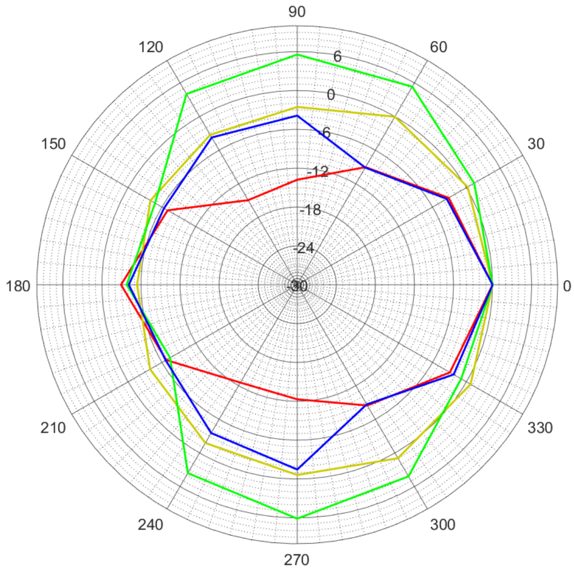

Fig 2.9 Measured polar response of the dBTech S10 subwoofer cardioid cluster at 40 Hz (red), 63 Hz (yellow), 80 Hz (green) and 100 Hz (blue) (units facing opposite directions outward, 6.53 ms delay)

While this is an improvement, the front-to-rear rejection isn't ideal for practical purposes. Considering that gradient loudspeaker theory assumes point source behavior for each individual unit, there is an issue when applying this theory to real subwoofers. The forward moving sound energy is greater than the rear-moving sound energy for each individual unit. This results in imperfect interactions between the units, thus reducing the effectiveness of the cardioid configuration when the units are in opposite directions (as is the case here).

Furthermore, the 1.5 m spacing dictates that above 57.17 Hz, cardioid behavior isn't expected. Considering the acoustic center shift (which gives an effective unit spacing of 2.24 m), the ideal frequency is reduced to 38.38 Hz, as evidenced by the results in Figs. 2.8 and 2.9. The expected polar response at twice the ideal frequency (76.56 Hz) is a figure eight pattern rotated 90° [1]. This pattern emerges in the 80 Hz and 100 Hz responses in Fig. 2.9.

To overcome these problems, the inter-unit spacing must be reduced and the units should be reoriented so that they are both facing forward. In this case, the minimum front-to-front spacing that could be achieved was 0.85 m. Now that the two units are facing the same direction, the acoustic center shift will be equal, so the only further consideration should be to ensure the acoustic center of the cluster is centered in the room. With this configuration, the inter-unit electronic delay was 2.48 ms, corresponding to 100.88 Hz as the ideal frequency for a cardioid pattern (Fig. 2.10).

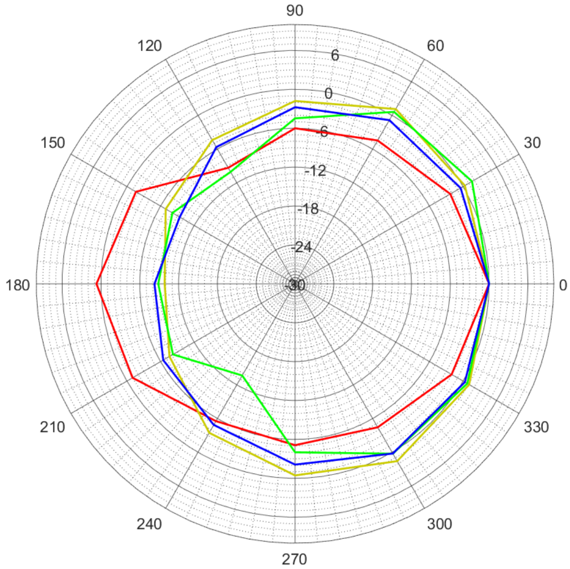

Fig 2.10 Measured polar response of the dBTech S10 subwoofer cardioid cluster at 40 Hz (red), 63 Hz (yellow), 80 Hz (green) and 100 Hz (blue) (both units facing forward, 2.48 ms delay)

Aside from 40 Hz, the other frequencies give improved front-to-rear rejection as compared to the previous configuration and maintain similar polar responses. The anomalous result at 40 Hz is partially due to the close spacing of the units. The quarter wavelength of 40 Hz is 2.14 m, which is over 2.5 times greater than the physical unit spacing. This causes the effect of the cardioid configuration to be limited. The front-to-rear rejection vs. frequency is given in Table 2.2.

Spacing (m)	40 Hz	63 Hz	80 Hz	100 Hz
0.85	-0.69 dB	9.85 dB	8.86 dB	8.28 dB
0.85 (e)	-2.63 dB	3.63 dB	10.19 dB	8.37 dB
1.5	4.58 dB	11.21 dB	9.58 dB	10.44 dB
1.5 (e)	2.23 dB	9.92 dB	6.93 dB	1.21 dB

Table 2.2 Front-to-rear rejection achieved for the two-unit cardioid clusters (forward facing units) due to unit spacing. (e) indicates end-fire configurations

There are techniques other than gradient loudspeakers to achieve cardioid subwoofer clusters. One popular method is commonly referred to as "end-fire". End-fire arrays operate with the same physical configuration as gradient loudspeakers, but the front unit has electronic delay applied to it which corresponds to the propagation time from the rear unit to the front unit. The configuration giving the results in Fig. 2.10 was modified to make it end-fire and was re-measured (Fig. 2.11). The front-to-back rejection data is given in Table 2.2.

As with the gradient loudspeaker approach, the end-fire configuration shows diminishing returns as frequency decreases. In this case, both 40 Hz and 63 Hz show limited rejection, which isn't ideal. The measurements were repeated with 1.5 m front-to-front spacing, for completeness (data given in Table 2.2), showing similar properties to the 1.5 m gradient loudspeaker configuration, where there is improved rejection in the lower frequency bands and limited rejection in the high-frequency bands.

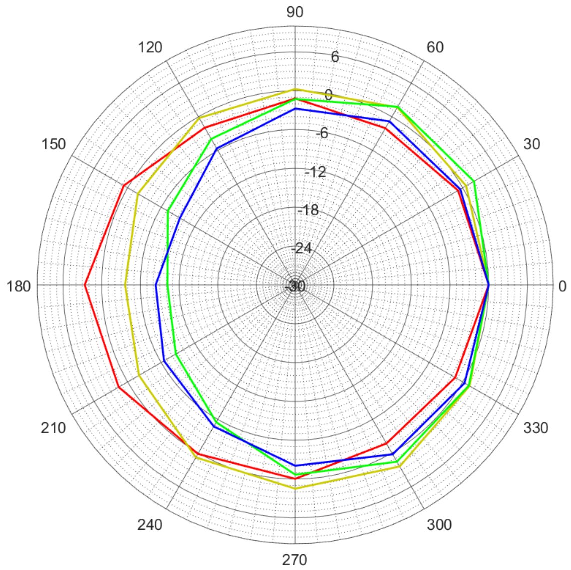

Fig 2.11 Measured polar response of the dBTech S10 subwoofer cardioid cluster at 40 Hz (red), 63 Hz (yellow), 80 Hz (green) and 100 Hz (blue) (both units facing forward, 2.48 ms delay, end-fire)

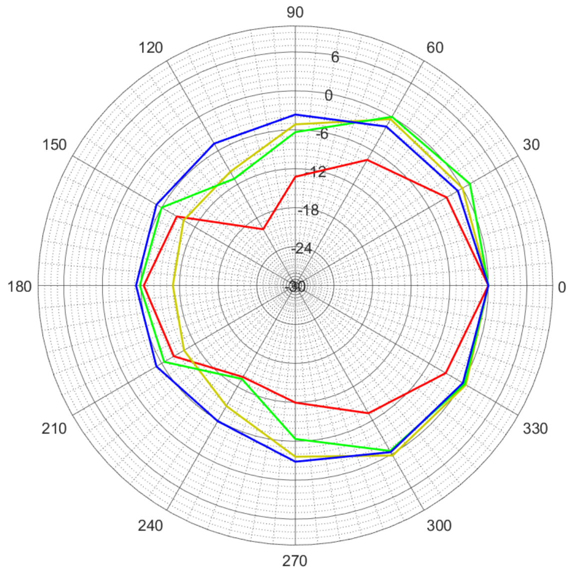

Fig 2.12 Measured polar response of the dBTech S10 subwoofer cardioid cluster at 40 Hz (red), 63 Hz (yellow), 80 Hz (green) and 100 Hz (blue) (stacked units facing opposite directions, 2.10 ms delay)

Lastly, a common approach to achieve a cardioid polar response is to stack subwoofers, where they are facing opposite directions. In this case, the front-to-front spacing was 0.72 m (the depth of the cabinets). The configuration was tested without and with consideration of the acoustic center shift (2.10 ms and 4.26 ms delay, respectively), as shown in Figs. 2.12 and 2.13, respectively. The front-to-back rejection data is given in Table 2.3.

Although the rejection data implies that the configuration that didn't take the acoustic center into account gives better performance, it's important to inspect the polar responses obtained. The acoustic center configuration gives good coverage ±90°, while the non-acoustic center configuration's coverage patterns fall off sharply off-axis, which isn't ideal for scenarios with wide audience areas. Ultimately, though, stacked configurations appear to provide superior front-to-rear rejection, give as-expected coverage patterns and fit within a small physical footprint; a very important aspect to consider at live events.

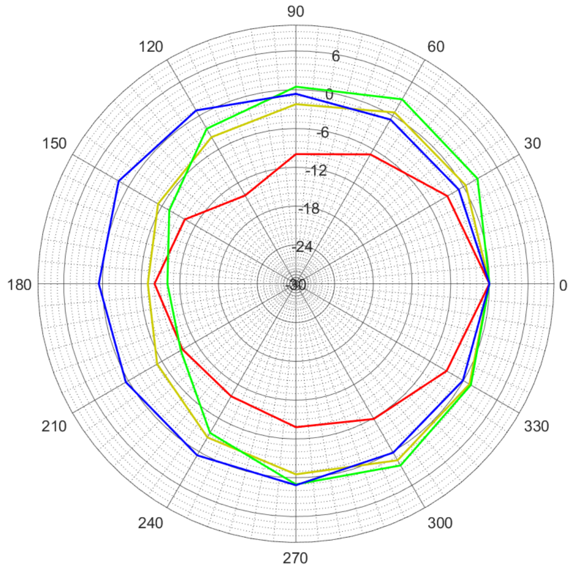

Fig 2.13 Measured polar response of the dBTech S10 subwoofer cardioid cluster at 40 Hz (red), 63 Hz (yellow), 80 Hz (green) and 100 Hz (blue) (stacked units facing opposite directions, 4.26 ms delay)

Delay (ms)	40 Hz	63 Hz	80 Hz	100 Hz
2.10	6.44 dB	10.96 dB	5.83 dB	5.24 dB
4.26	8.08 dB	7.04 dB	10.08 dB	-0.56 dB

Table 3.2 Front-to-rear rejection achieved for the two unit cardioid clusters (stacked, facing opposite directions) due to inter-unit delay

2.4 Steered responses

Expanding from two-unit clusters to achieve bespoke and steered coverage patterns from a subwoofer system is relatively straightforward and was presented in detail in [6]. With this in mind, the theory behind subwoofer clusters won't be repeated here. Rather, a practical application will be presented, since measurements of such systems appear to be absent in most published literature.

Consider the following scenario: an audience wraps around a stage, spanning 270°. An engineer needs to achieve, therefore, 270° of low-frequency coverage while maintaining rejection on stage (the remaining 90°). The subwoofer system should ideally occupy as small a physical footprint as possible.

One method to meet these goals is to use a four-unit cluster [8]. Two approaches were examined: gradient loudspeaker (Fig. 2.15) and end-fire (Fig. 2.16). In both cases, the units were spaced at 0.85 m and the cluster's acoustic center was centered in the room. All units were facing the same direction (Figure 2.14).

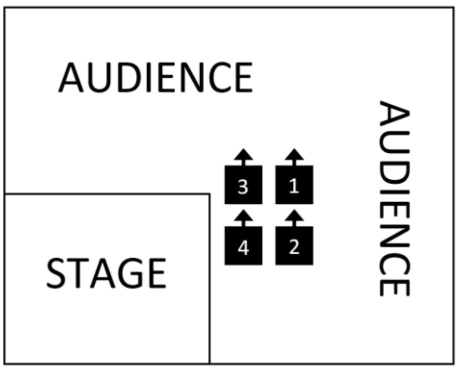

Fig 2.14 Physical configuration for the four-unit cluster (for both gradient and end-fire approaches)

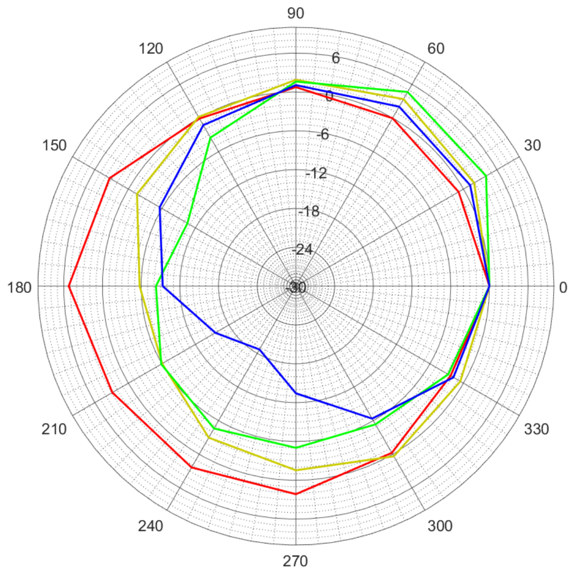

Fig 2.15 Measured polar response of the dBTech S10 subwoofer four unit cluster at 40 Hz (red), 63 Hz (yellow), 80 Hz (green) and 100 Hz (blue) (units facing forward, gradient configuration)

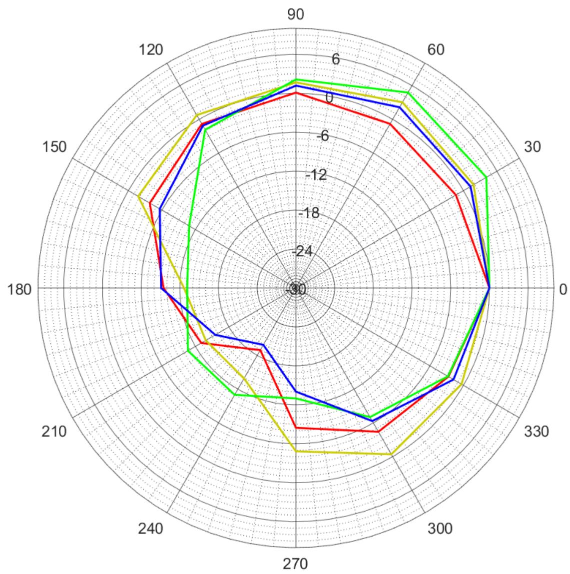

Fig 2.16 Measured polar response of the dBTech S10 subwoofer four unit cluster at 40 Hz (red), 63 Hz (yellow), 80 Hz (green) and 100 Hz (blue) (units facing forward, end-fire configuration)

The gradient configuration had units 1 and 2 in the same configuration as with the two-unit cardioid configuration. Units 1 and 3 made up another cardioid configuration, while unit 4 had reverse polarity to unit 1 to create a figure eight pattern.

The end fire configuration had unit 1 delayed to match the arrival times from units 2 and 3. Unit 4 was delayed with inverted polarity to create a figure eight pattern with unit 1.

The end-fire version of this configuration is quite clearly superior to the gradient loudspeaker approach, in that it achieves between 12 – 18 dB rejection in the stage area, while providing near consistent coverage in the audience area over all frequencies. The gradient loudspeaker configuration proves less effective as frequency decreases, which is largely due to the close spacing of the units.

3 Additional considerations

The discussion contained within the previous section focused on the practical considerations of deploying individual subwoofers or clusters of subwoofers. There are numerous additional practical considerations when implementing subwoofer systems at large-scale live events.

3.1 Horizontal and vertical arrays

As is the case with most live events, a single subwoofer or subwoofer cluster won't be sufficient in covering the entire audience, both in terms of coverage pattern and, more importantly, mean output level. It is therefore necessary to use horizontal or vertical arrays of single subwoofers or clusters to ensure adequate audience coverage.

The theory behind this follows conventional line array theory which requires units to be within one-half wavelength of each other to ensure coupling. This is investigated in detail in terms of ground-based horizontal subwoofer arrays in [6], where numerous configurations are examined.

An increasingly-common implementation of subwoofer systems at large-scale live events is the flown vertical array. These arrays are typically flown side-by-side or behind the main sound systems (either left/right or center cluster). While there are a number of benefits to this approach (simple time-alignment with main PA, less equipment around the stage, more uniform propagation distance throughout the audience, etc.), there are also some issues.

One issue is if left/right vertical arrays are implemented, then there will be coherent interference between the left and right arrays (providing there is no decorrelation applied to the arrays. This is discussed in Section 3.3).

Aside from the coherence issue, engineers also need to consider the vertical polar response of these arrays. If left unprocessed, a flat-hung vertical array will give good coverage directly in front of it, but poor coverage towards the audience area (Fig. 3.1).

This is why engineers must time align the individual units within the array to a point in the audience area. This typically corresponds to a few milliseconds of delay applied to each subwoofer, starting at the second-to-top unit in the array and working downwards. This focuses the sound energy towards the audience, giving a more effective subwoofer system (Fig. 3.2).

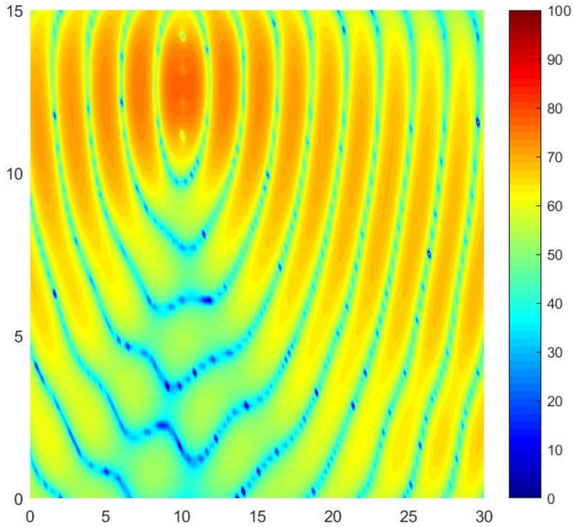

Fig 3.1 Vertical coverage pattern of a flown veritcal array (four units with one meter spacing) with no processing (x- and y-axes are length and height of the venue (m), respectively)

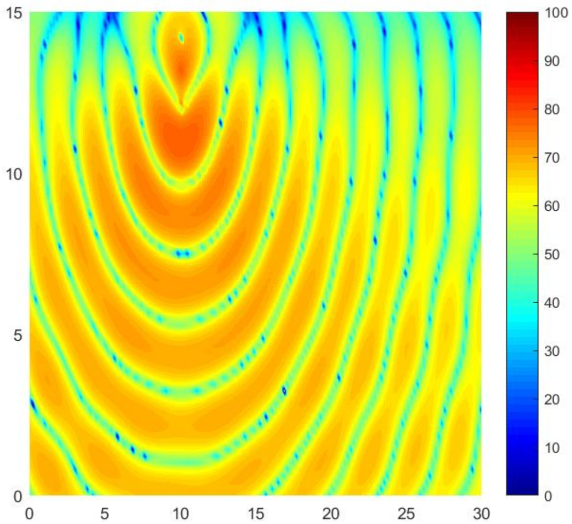

Fig 3.2 Vertical coverage pattern of a flown veritcal array (four units with one meter spacing) with time allignment to 20 m into the audience (x- and y-axes are length and height of the venue (m), respectively)

3.2 Performance stage effects

When implementing a ground-based subwoofer system, it is important to understand that the system isn't operating in a free-field (as is largely assumed within most manufacturer software and other published literature on the subject). There are reflective surfaces in close proximity to the subwoofers, which have the potential to influence the system's coverage pattern.

The most significant reflective obstacle in close proximity to ground-based subwoofers (aside from the ground) is the performance stage. It is common to place subwoofers on, under or in front of a stage. It is therefore essential to inspect the effect a stage may have on a subwoofer system's performance.

An initial investigation into this was carried out in [6] with a more detailed analysis presented in [10]. The conclusion is that if directional low-frequency is desired (whether via a cluster or single directional unit), it is highly disadvantageous to place the subwoofers under or on top of a stage. The reflections and resonances of the stage can almost completely degrade the directionality achieved by the system in a free-field.

Instead, it is recommended that ground-based subwoofers are placed around 1 m in front of the stage to avoid coherent reflections, thus maintaining the desired directional pattern. Furthermore, it is important to avoid acoustically non-transparent stage skirts across the front of a stage. Such skirts provide a reflection that severely compromises both the directionality of the system as well as the mean output level. The key results given in [10] are reproduced for inspection in Table 3.1.

Subwoofer placement	Front-to-rear rejection (dB)
Free-field	11.76 dB
Under stage	3.91 dB*
On top of stage	8.48 dB
In front of stage	12.67 dB

Table 3.1 Measured mean front-to-rear sound pressure level difference
(* modelled data due to stage height restrictions)

3.3 Inter-unit decorrelation

Lastly, a brief note is required on the issue of unit-to-unit signal correlation. This is a major issue engineers face when attempting to achieve consistent sound coverage across a wide audience area. The problem is directly tied to the issue of widely spaced units or clusters. If the spacing is greater than one-half a wavelength at a given frequency, the units will be decoupled and operate as discrete sources [6]. This results in coherent interference across a venue, causing peaks and nulls (which greatly contribute to a position-dependent listening experience, especially at low-frequencies).

The root of the problem lies with the fact that each individual subwoofer is fed an identical source signal (neglecting the delay and polarity inversions used within clusters, which won't affect signal correlation). If there was a way to decorrelate the signal going into each individual subwoofer (or cluster), then this problem would cease to exist.

Traditionally, some sound system engineers process left/right subwoofer signals with slightly different graphic equalization in order to decorrelate the signals between the left and right sides of a sound system. It has been shown experimentally that even slight panning of low-frequency components in a mix serves as a basic means of left/right signal decorrelation in order to make the audience response more consistent [11].

Work is currently underway to provide a more robust version of this method using what is termed diffuse signal processing (DiSP) [12,13]. The core idea behind DiSP is that each subwoofer signal is convolved with a unique temporally diffuse impulse (TDI). These TDIs are generated with a flat magnitude response and a randomized phase response. The generation process takes into account perceptual considerations, as it’s essential to avoid noticeable coloration of the audio signal.

Whether or not DiSP is a viable solution to the subwoofer coherency problem has yet to be seen, but current work is showing promising results. Full optimization and validation of this method is the subject of ongoing research.

4 Conclusions

Applying a few key practical considerations to existing low-frequency directionality theory allows engineers to easily achieve the desired coverage patterns for subwoofer systems at live events. These practical considerations include:

1. Remember that omnidirectional subwoofers aren’t completely omnidirectional. As frequency increases, they exhibit increasingly directional behavior. This is essential to understand when configuring subwoofer clusters.

2. Acoustic center shift is essential to consider when configuring subwoofer clusters (as well as when measuring systems). Applying time delay based on the physical spacing of opposite-facing units will result in a non-ideal polar response. Accounting for the effective increase in spacing due to the equal and opposite acoustic center shifts will provide superior results.

3. Gradient loudspeakers are configured based on a single ideal frequency. Above and below this frequency, results will be compromised (at lower frequencies, this means diminishing front-to-rear rejection, at higher frequencies, this means a completely different polar response).

4. End-fire configurations are also susceptible to inaccuracies at lower frequencies, although they have been shown here to maintain the desired polar response across a wider bandwidth when compared to the gradient approach.

5. When using vertical arrays, it’s essential to time-align the system to a point in the audience. Otherwise, the bulk of the sound energy will be directed away from listeners.

6. The effects of a performance stage on ground-based subwoofer directionality must not be ignored. Placement underneath or on top of a stage should be avoided. Placement in front of a stage allows for the desired polar response of the system to be maintained. Acoustically non-transparent stage skirts should be avoided.

7. Subwoofers spaced at distances greater than one-half a wavelength will operate as discrete sources. Efforts should be made to decorrelate the signals going to each unit to avoid coherent interference. Manual individual equalization, panning or DiSP are useful methods to combat this problem.

8. While further optimization of subwoofer clusters and arrays is certainly possible, it is important to limit complexity. The four-unit steered cardioid configuration given in this work, for example, only requires two independent channels of processing and amplification.

Maintaining this practical, common-sense approach in the deployment of subwoofer systems at live events will result in consistent listening experiences for audience members, will create safe and desirable working environments for performers and stage personnel and (sometimes most important, these days) will limit low-frequency sound energy directed towards other stages at the event and neighboring off-site areas.

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