OPTIMISATION OF DDS-CONTROLLED LOUDSPEAKER ARRAYS USING A HYBRID PSM-BEM MODEL

Evert Start & Gerald van Beuningen   Duran Audio BV, Zaltbommel, The Netherlands

1 INTRODUCTION

Using Duran Audio's Digital Directivity Synthesis (DDS) technology, introduced five years ago[1], any desired 3D array response can be synthesised. Starting from a pre-defined array set-up and desired SPL distribution at the boundaries (including the audience area) of a (fictive) hall, the optimum output filters for the array elements (channels) can be calculated. After this optimisation, the output filters can be uploaded to all units in the array.
In order to simulate the 3D pressure response of a DDS-driven array a simple Point Source Model (PSM) is used, that is described in many text books[2]. In the PSM each loudspeaker in the array is modelled as a directional point source, positioned in free space. In other words, the PSM assumes that the sound field (magnitude and phase of the acoustic pressure in all directions) of a loudspeaker is unaffected by the presence and the relative positions of the other cabinets in the array. As a benefit of this approach, identical loudspeakers in the array can be modelled with the same free field directivity function. Moreover, measurements on a relatively small loudspeaker cabinet (i.e., not in an array) can be done quite easily in an anechoic room.
This free field assumption yields accurate results for higher frequencies, but for lower frequencies deviations between the predicted and measured array response may occur. Due to changes in the radiation impedance ('baffling' or 'coupling' effect) and cabinet diffraction, the response of a loudspeaker in an array differs slightly from its free field response (i.e., single cabinet response). Although these deviations are usually small, they can become more problematic for an accurate simulation of LF cardioid arrays.
To improve the PSM, the spectral and directional characteristics of each loudspeaker at its actual position in the array should be known. However, due to the large array dimensions and unlimited number of variations in array set-up, anechoic far field measurements of each loudspeaker at any position in array are practically impossible.
Using the acoustic Boundary Element Method[3] (BEM), it is possible to accurately model diffraction and coupling effects for low and mid frequencies. The BEM is based on the Helmholtz integral formulation; given the discrete distribution of the normal component of the particle velocity at the boundaries of a radiating object, the sound radiation can be calculated in all directions outside the object. Unfortunately, direct implementation of the BEM into the DDS algorithm would lead to dramatically increased computation times. Therefore, a computationally efficient, hybrid PSM-BEM approach is developed.

2 THE PSM-BEM MODEL

2.1 Principle

The idea behind the PSM-BEM approach is the following. The array is modelled as a set of directional point sources. But, in contrast to the PSM, the spectral and directional behaviour of each point source is no longer given by the measured free field response of the loudspeaker in a single cabinet, but is described by BEM-calculated directivity data of the loudspeaker in the actual array set-up.
Using the BEM, it is relatively easy to calculate a library of directivity data of a single loudspeaker used in various array set-ups. If the particle velocity distribution at the surface of a single cabinet is known (or measured), far field balloon data can be calculated for any array set-up. A prerequisite is that the volume velocity of a moving loudspeaker cone is unaffected by the presence of other (radiating) loudspeakers. Since the velocity of the cone is almost completely dictated by its driver, i.e., is highly independent of the radiation resistance, this is a valid assumption.

2.2 Goal and application

In this research the PSM-BEM approach is applied to modular bass arrays consisting of large Target, B-215 cabinets. Each vented bass reflex enclosure has two 15'' woofers and four bass ports. Any pre-defined array set-up (e.g., simple bass stacks, cardioid stacks or endfire arrays) can be DDS-optimised using the DDA software.
Currently, the directional behaviour of DDS-optimised bass arrays can be modelled quite accurately using the AXYS Digital Directivity Analysis (DDA) software. However, the effect of array size on the response of the woofers in the array is not taken into account. Also, the increasing front-to-back ratio of the array for increasing array dimensions is not modelled. In many situations these shortcomings in the model are acceptable. However, larger and unacceptable deviations between the predicted and the actual response are found with modular cardioid bass arrays. The predicted LF sound cancellation behind the array isn't found in practice. This can be explained by the fact that small modelling errors in the complex directivity function of the individual loudspeakers lead to major errors in the resulting cancellation behind the array.

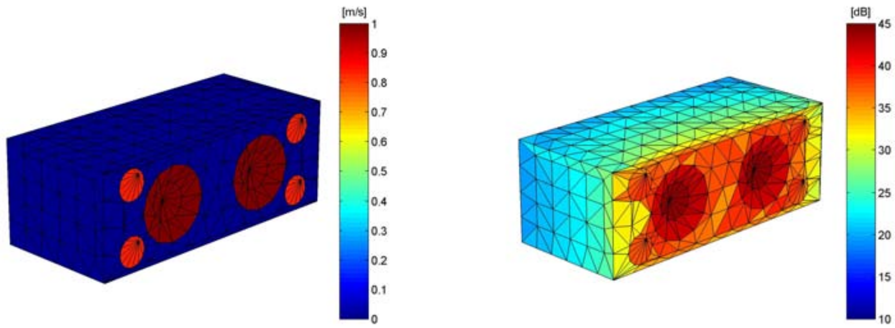
3 BEM MODELLING

3.1 Procedure

In order to calculate the sound field of a radiating object by the BEM, a few steps are necessary. First the closed surface of the radiator is approximated by a finite element model consisting of a large number of finite boundary elements. Next, the normal component of the particle velocity at each boundary element must be known or measured using a velocity probe (Note: starting with the particle velocity is called a Neumann boundary value problem). The next step is to calculate the pressure distribution on the surface by solving the so-called discrete Helmholtz Integral Equation (HIE). The pressure and normal velocity are considered as constant over each boundary element (collocation method). After this, the sound field in the entire outer space can be calculated with the help of the exterior HIE by an integration over the surface.
Although various BEM software packages are commercially available, for our purposes a finite element mesh generator and the necessary BEM algorithms have been implemented in a proprietary MATLAB routine.

3.2 Single bass cabinet

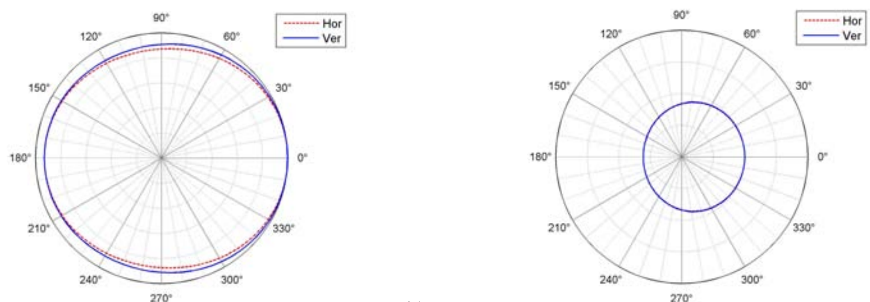
The BEM procedure described in the previous section is first applied to a single bass cabinet. It is assumed that the particle velocity is only non-zero in front the loudspeaker cone (and bass port) and zero elsewhere on the hard surface of the cabinet. Further, the normal velocity is assumed to be constant over the surface of the cone and the opening of the bass port.
The complex (amplitude and phase) ratio between the normal velocity (as a function of frequency) near the cone and at the exit of the ports was measured using a pressure gradient microphone. The results were used as input for the BEM. From the normal velocity data the sound pressure at the surface of the bass cabinet was calculated. As an example, the measured normal velocity (amplitude only) and the calculated SPL at 100 Hz are shown in Figure 1a and b.



a) b)

Figure 1: Measured normal particle velocity (a) and calculated SPL (b) at the surface of a single bass cabinet at 100 Hz.

Using the normal velocity and pressure data, the far field complex 3D directivity balloons for each 1/3-octave band (50-630Hz) were calculated. As an example, the 100 Hz magnitude and phase polar diagrams are shown in Figure 2a and b.



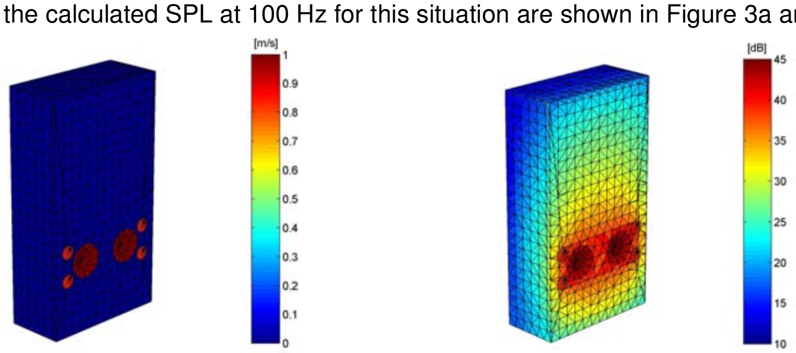
a) b)

Figure 2: Polar diagram of the magnitude (a) and phase (b) behaviour of a single bass cabinet (magnitude diagram: 6 dB/div, phase diagram: 90°/div).

By using on-axis sensitivity data of the single cabinet (measured in free field), the BEM results can be calibrated and a full loudspeaker model can be obtained which can be used for further modelling.

3.3 Bass cabinet as part of an array

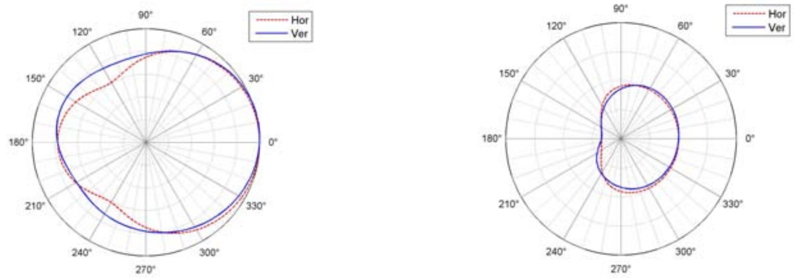
The measured normal velocity data of the single cabinet can also be used to calculate the response of one bass unit as a part of a vertical array of five cabinets. In this example, the second cabinet from below in the array is active, the other units are muted. The measured normal velocity (amplitude only) and the calculated SPL at 100 Hz for this situation are shown in Figure 3a and b.



a) b)

Figure 3: Measured normal particle velocity (a) and calculated SPL (b) at the surface of an array of five bass cabinets at 100 Hz (only second lowest cabinet is active).

The 100 Hz magnitude and phase polar diagrams are shown in Figure 4a and b, respectively.



a) b)

Figure 4: Polar diagram of the magnitude (a) and phase (b) behaviour of one bass cabinet as part of an array of five cabinets at 100 Hz (magnitude diagram: 6 dB/div, phase diagram: 90°/div).

By comparing the results in figure 2 and 4, it can be verified that the front-to-back ratio for the array situation is about 4 dB larger compared to the single unit situation. Also the phase difference increased by approx. 50°. It is also noticeable that the vertical directivity pattern becomes slightly asymmetrical for the array situation. This can explained by the asymmetrical positioning of the active cabinet in the array, yielding different diffracted wave contributions around the upper and lower edge of the array.
Besides changes in the directional behaviour, BEM calculations also show that the size of the array and the position of the active cabinet in the array also affects the sensitivity. To illustrate this, the unfiltered on-axis sensitivity (i.e., response @1m for a 2.83V input at the loudspeaker clamps) of a single cabinet (in free space) is compared with the calculated response of one active cabinet in an array of five (for different positions of the active one in the array: ‘1 of 5’ is the lowest unit, ‘2 of 5’ the second lowest, etc.). The results are shown in Figure 5.

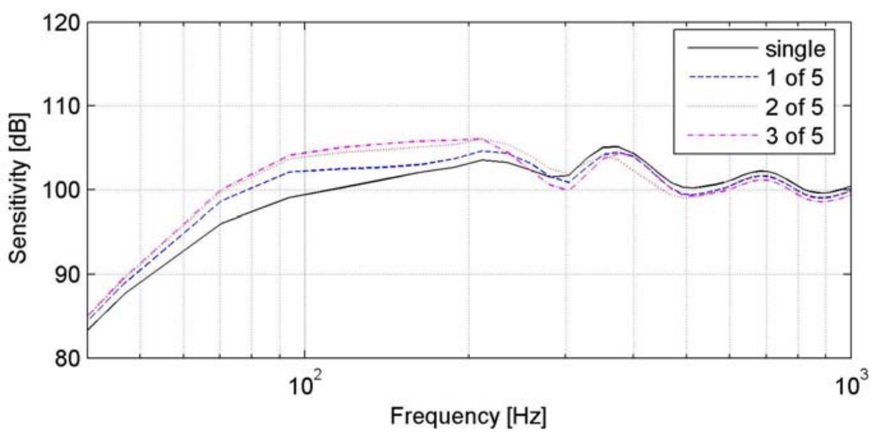


Figure 5: BEM-modelled sensitivity of an unfiltered single bass cabinet compared with the sensitivity of one active cabinet in an array of five (for different positions of the active one in the array).

4 VALIDATION OF THE PSM-BEM MODEL

In order to verify the validity and accuracy of the proposed PSM-BEM model, measurements have been done on DDS-optimised bass arrays in an anechoic room. Using the DDA software, DDS-optimisations and predictions were done using the current PSM and the new PSM-BEM loudspeaker modelling.

4.1 Array set-ups

Two different array set-ups have been tested; A 'standard' bass array and a 'cardioid' bass array, both consisting of five cabinets.

4.1.1 Standard bass array

The standard bass array is a simple stack of five B-215 cabinets, as shown in Figure 6a. The total array height is approx. 2.2 m.

a) b)

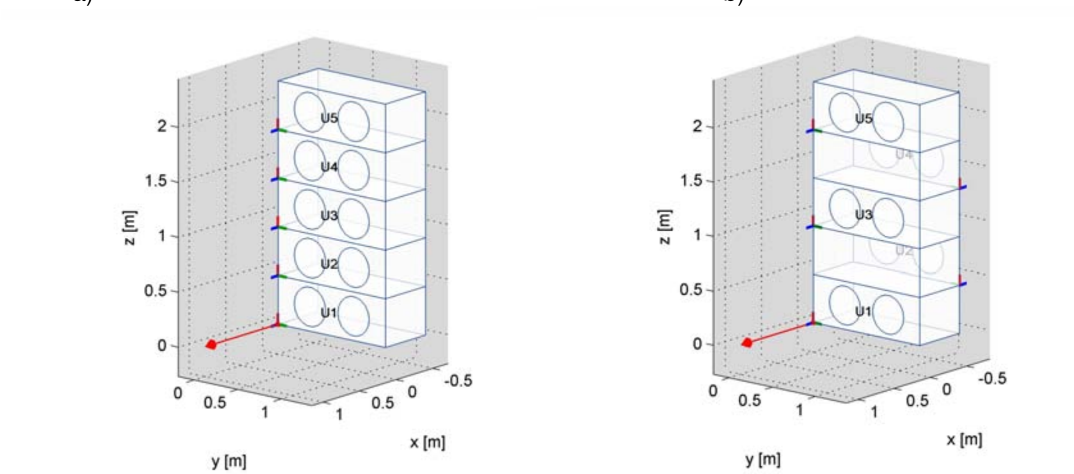


Figure 6: 'Standard' bass array set-up (a) and 'cardioid' bass array set-up (b).

Two DDS-optimisations have been done for this set-up, with different directivity models:

1. Identical free field PSM-model for all cabinets.
2. Unique PSM-BEM model for each cabinet.

Using this set-up, only the front lobe can be optimised in DDA. The back lobe is fully defined by the shape of the front lobe and the directional behaviour of the individual cabinets.

4.1.2 Cardioid bass array

The cardioid bass array also consists of five cabinets, but in contrast to the standard set-up, the second and fourth unit are reversed (i.e., back to front), as shown in Figure 6b.
Using this set-up, three optimisations have been done, with different directivity models:

1. Identical free field PSM-model for all cabinets.
2. Unique PSM-BEM model for each cabinet.
3. Identical PSM-BEM model for all cabinets. The '3 of 5' directivity model of Unit 3 is applied to all cabinets.

Because the front and back woofers are physically positioned at different depths (i.e., x-coordinate in Figure 6b) in the array, the front and the back lobe can be optimised independently in DDA. Using the DDS-optimisation algorithm in DDA it is possible to obtain a large front-to back ratio (i.e., a cardioid-like behaviour) while maintaining a high array output at the front.

4.2 DDA predictions

Before the two bass arrays set-ups were tested, the output filters for each channel in the array were DDS-optimised and the total response was predicted in DDA. The desired SPL distribution for the defined (fictive) space is shown in Figure 7. In front of the array a high SPL is defined over a distance of 30 m, while behind the array a negligibly low SPL is desired.

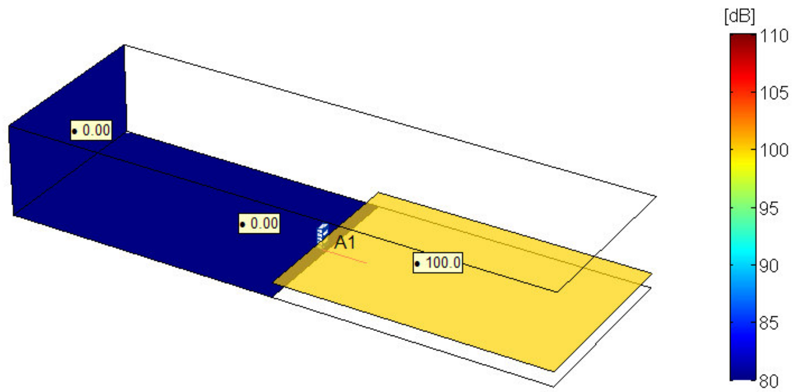


Figure 7: Desired SPL distribution for both the 'standard' bass array and the 'cardioid' bass array set-up.

4.2.1 Standard bass array response

As an example, the 63 Hz response (1/3-octave) for the standard set-up using the PSM-BEM models of the cabinets is shown in Figure 8.

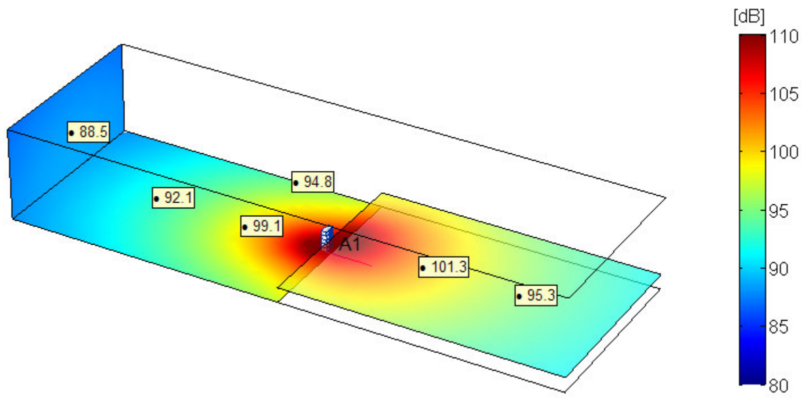


Figure 8: Predicted SPL distribution at 63 Hz (1/3-octave) for the 'standard' bass array using the PSM-BEM models of the cabinets.

The predicted SPL distribution shows an almost omni-directional behaviour of the array at low frequencies.

4.2.2 Cardioid bass array response

The 63 Hz response (1/3-octave) was also predicted for the cardioid set-up using the PSM-BEM models of the cabinets (see Figure 9).

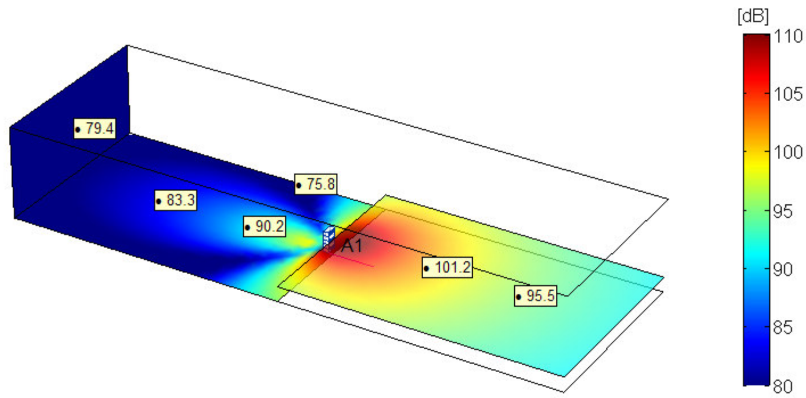


Figure 9: Predicted SPL distribution at 63 Hz (1/3-octave) for the 'cardioid' bass array using the PSM-BEM models of the cabinets.

By comparing Figure 8 and 9, it is clear that a significant overall reduction of the backward radiation can be predicted using the DDS-optimised cardioid array set-up. For slanting angles behind the array, the reduction is even stronger than at more perpendicular angles. This means that the array shows more or less a hyper-cardioid behaviour at this frequency.

4.3 Measurement results

In order to verify the predictions, horizontal and vertical directivity patterns were measured in an 10x10x10m anechoic room for the array set-ups described in section 4.1.1 and 4.1.2. The entire array of five cabinets could be rotated on a big rotation wheel with 5° steps. The distance of the microphone to the rotation point (centre of the array) was 5.75 m. In each direction, the impulse response of the array was measured using WinMLS (sweep method).
To compare the measured polar diagrams, impulse responses were simulated at exactly the same positions on a circle around the array.

4.3.1 Standard bass array response

The measured and predicted polar diagrams for the 'standard' array set-up using the PSM and the hybrid PSM-BEM model are shown in Figure 10 (horizontal direction) and 11 (vertical direction). Note that only the results using the PSM-BEM-calculated output filters are shown. The PSM directivity results are expected to be almost identical, because the output filters are almost identical.
From the measurements it is clear that the PSM-BEM model produces better predictions than the free field PSM (especially behind the array).

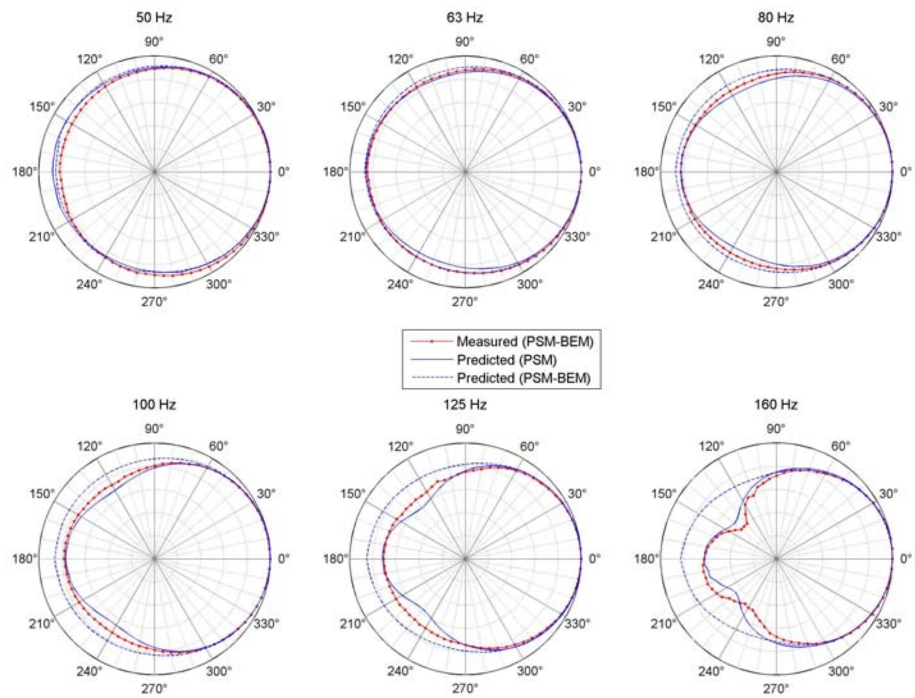


Figure 10: Measured and predicted horizontal polar diagrams for the ‘standard’ bass array set-up at different 1/3-octave band centre frequencies (6 dB/div).

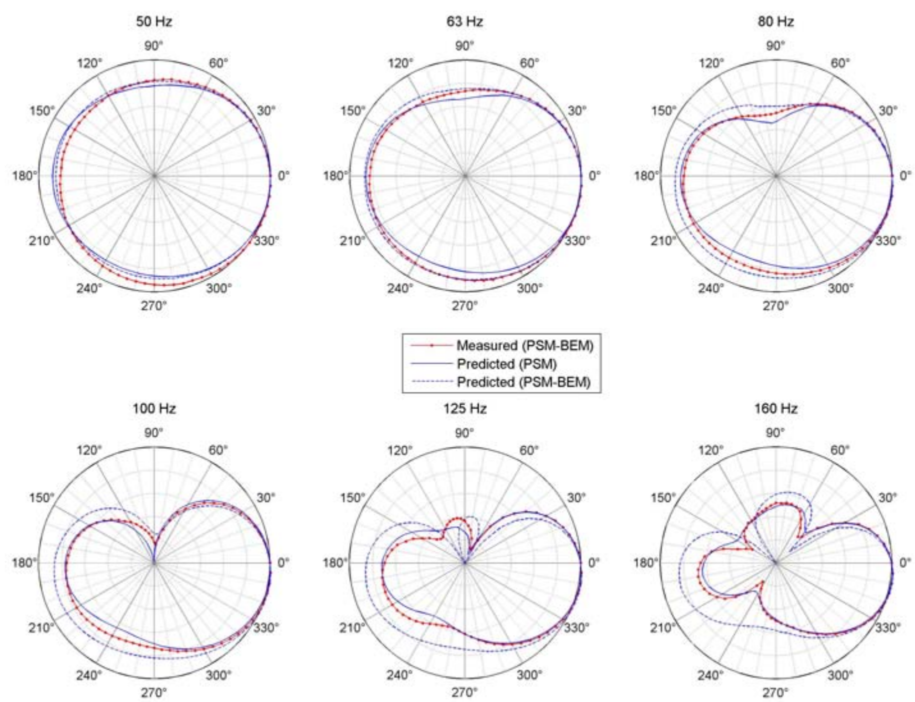


Figure 11: Measured and predicted vertical polar diagrams for the ‘standard’ bass array set-up at different 1/3-octave band centre frequencies (6 dB/div).

4.3.2 Cardioid bass array response

The measured and predicted polar diagrams for the ‘cardioid’ array set-up using the free field PSM-calculated output filters are shown in Figure 12 (horizontal direction) and 13 (vertical direction). The results show that large deviations occur between the measured and predicted polar responses. For most frequencies the cancelling of the backward radiated energy is predicted too optimistically. Above 100 Hz, the measured front-to-back ratio is even worse than in the ‘standard’ bass array set-up.
The results for the ‘cardioid’ array set-up using the PSM-BEM-calculated output filters are shown in Figure 14 (horizontal direction) and 15 (vertical direction). From the polar diagrams it is clear that the PSM-BEM approach yields much better performance than the free field PSM. The measured results are even slightly better than the predicted ones for most frequencies.
The results for the ‘cardioid’ array set-up using the fixed ‘3 of 5’ PSM-BEM directivity model are shown in Figure 16 and 17. It is remarkable that in this situation the measured values at 180° are much lower than the predicted values. At more lateral directions, the correspondence between measurement and prediction is less good than in the previous situation.

5 SUMMARY AND CONCLUSIONS

A hybrid PSM-BEM modelling approach for the LF and MF loudspeakers in DDS-optimised arrays has been developed. On the basis of free field on-axis measurements of a single cabinet in combination with particle velocity measurements of the loudspeaker cone (and optionally bass-reflex port), a description of the spectral and directional behaviour of a loudspeaker as part of an array can be obtained. In contrast to the free field PSM, diffraction and coupling effects caused by the other cabinets in an array are taken into account. Using this method, it is relatively easy to calculate a library of directivity data of a single loudspeaker used in various array set-ups.
Measurements on standard and cardioid bass arrays confirm that the PSM-BEM predictions are more accurate and perform better than PSM predictions. Now, the predicted back lobe cancellation with cardioid arrays can be really fulfilled in practice.
It is also made plausible that using a unique model of each loudspeakers in the array is not always necessary. Reasonably accurate results can be obtained by using a fixed PSM-BEM model for all identical loudspeakers in an array.
Future research will focus on the effect of a neighbouring, reflecting plane on the spectral and directional behaviour of the array (e.g. bass stack on a floor). Preliminary investigations show that these effects can also be modelled with the PSM-BEM approach, using the half-space formulations of the Helmholtz integral equations.

6 REFERENCES

1. G.W.J. van Beuningen & E.W. Start. Optimizing directivity properties of DSP-controlled loudspeaker arrays. Proceedings of the Institute of Acoustics (Reproduced sound) Vol 22 part 6 (2000), p 17-37.
2. J. Borwick. Loudspeaker and Headphone Handbook. Butterworth & Co. (Publishers) Ltd. (1989)
3. F.P. Mechel. Formulas of Acoustics (2002). Springer Verlag.

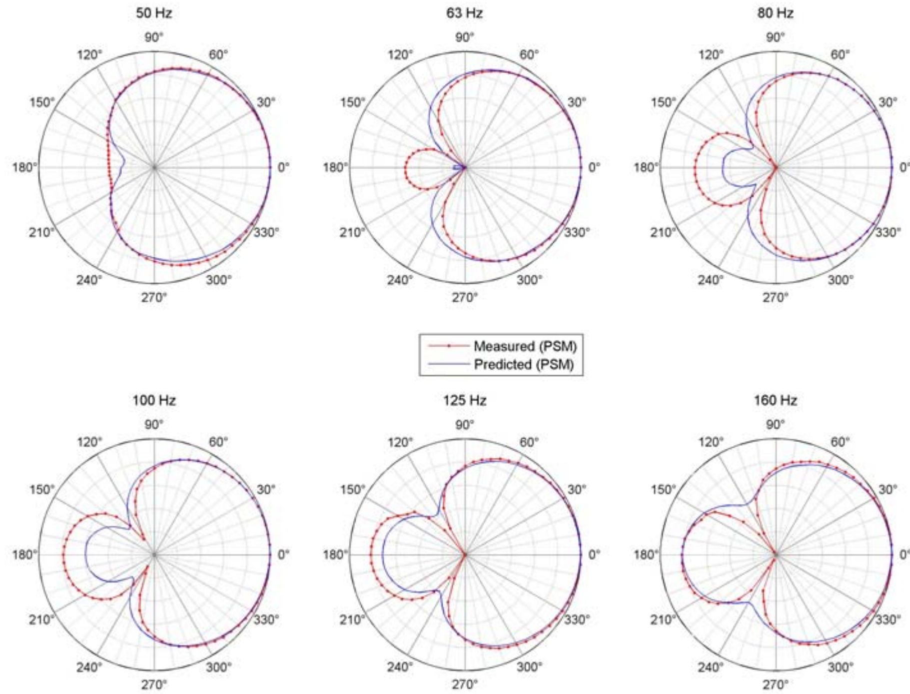


Figure 12: Measured and predicted horizontal polar diagrams for the ‘cardioid’ bass array set-up using the PSM at different 1/3-octave band centre frequencies (6 dB/div).

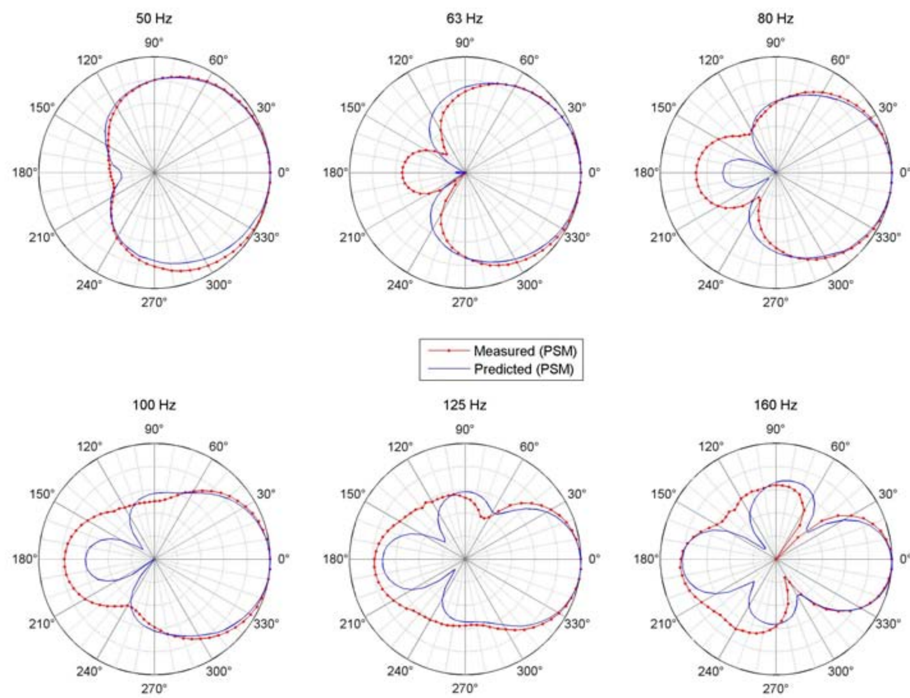


Figure 13: Measured and predicted vertical polar diagrams for the ‘cardioid’ bass array set-up using the PSM at different 1/3-octave band centre frequencies (6 dB/div).

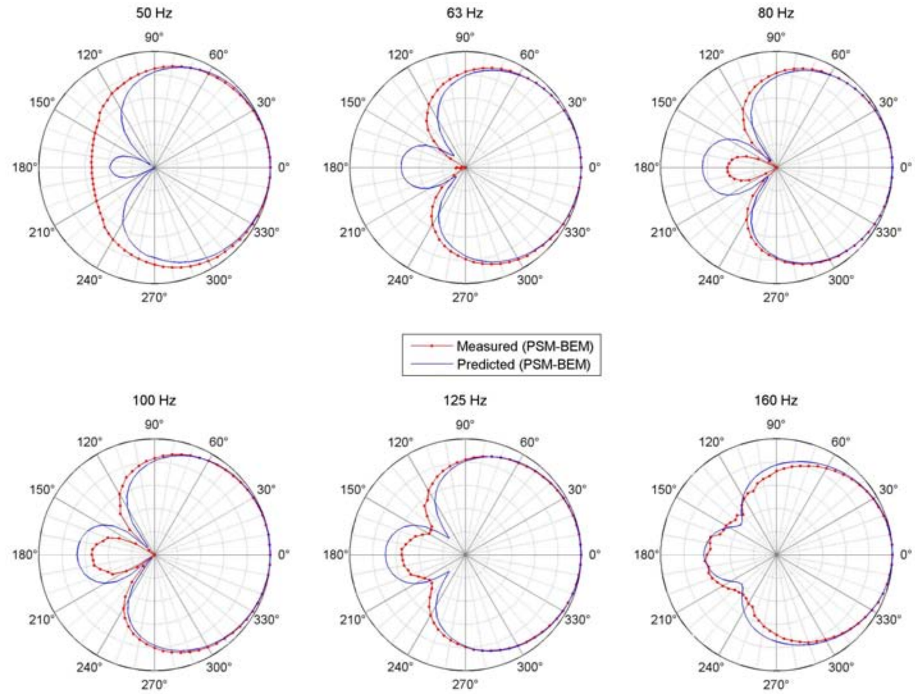


Figure 14: Measured and predicted horizontal polar diagrams for the 'cardioid' bass array set-up using the PSM-BEM model at different 1/3-octave band centre frequencies (6 dB/div).

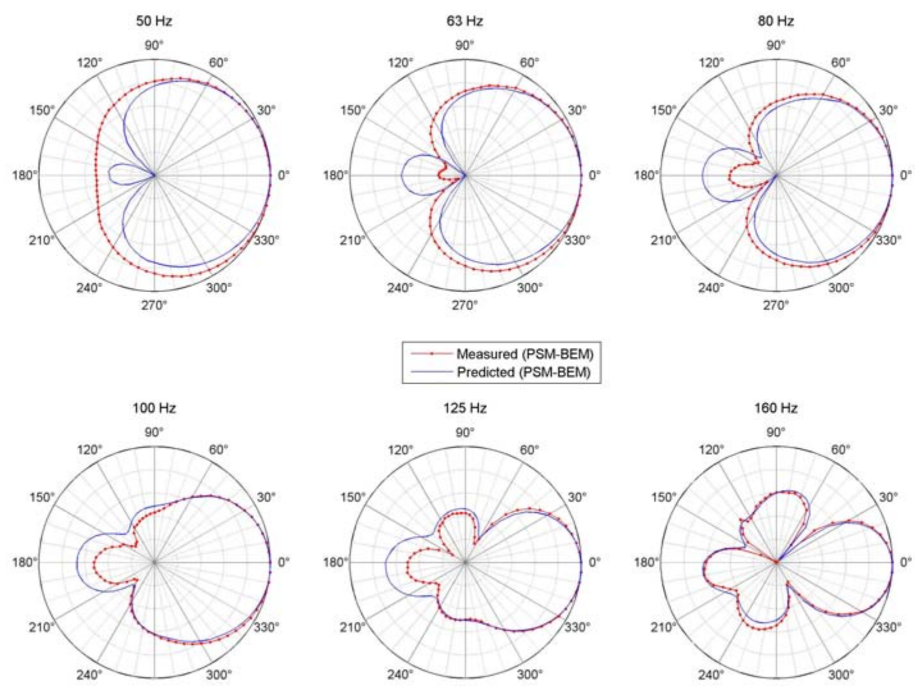


Figure 15: Measured and predicted vertical polar diagrams for the 'cardioid' bass array set-up using the PSM-BEM model at different 1/3-octave band centre frequencies (6 dB/div).

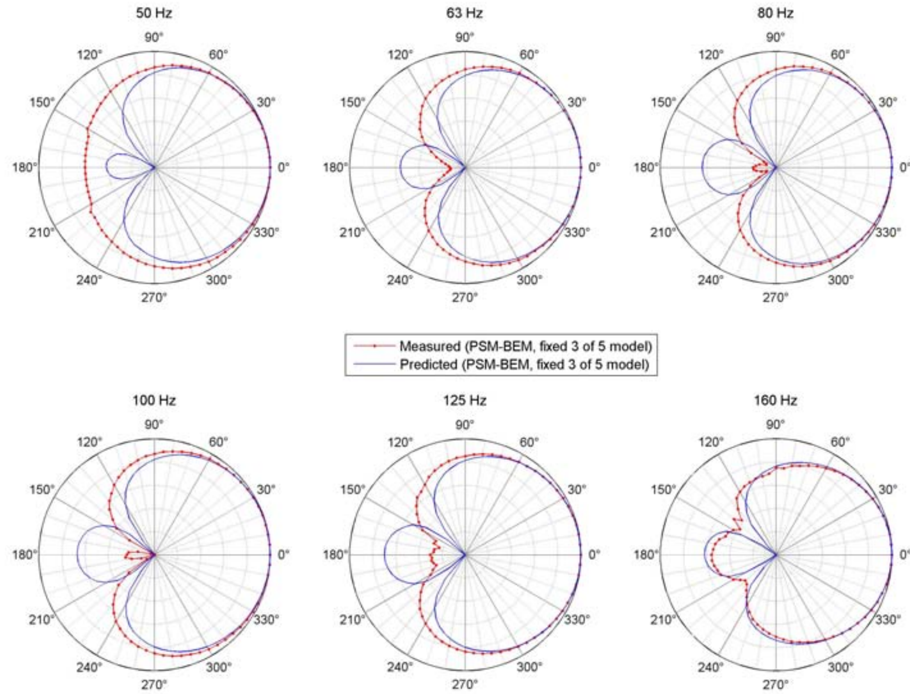


Figure 16: Measured and predicted horizontal polar diagrams for the ‘cardioid’ bass array set-up using the fixed ‘3 of 5’ PSM-BEM model at different 1/3-octave band centre frequencies (6 dB/div).

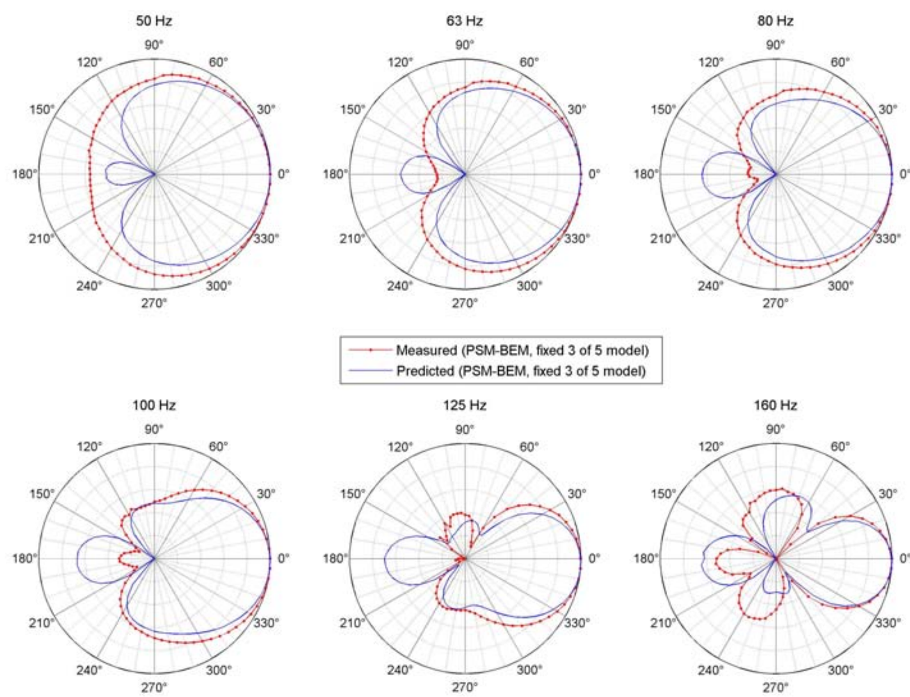


Figure 17: Measured and predicted vertical polar diagrams for the ‘cardioid’ bass array set-up using the fixed ‘3 of 5’ PSM-BEM model at different 1/3-octave band centre frequencies (6 dB/div).