A BALANCED MODAL RADIATOR (BMR)

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1 INTRODUCTION

It has long been a desire amongst loudspeaker engineers to be able to create a loudspeaker that behaves like a perfect point source. In its absence, the common prototype for most loudspeakers is a rigid disc, often described as a "piston". This is partly because the acoustical behaviour of such an object has been known for a long time, and was known to Rayleigh [1] in 1896. Although many attempts have been made to make such a radiator, its realisation still leaves the question – what is the optimal size? To have good directivity the piston should be small, but to generate low frequency power it should be large.

The work described in this paper focuses on the proposition that there might be an alternative to the rigid piston prototype, and investigates whether such a prototype could be turned into a practical loudspeaker.

It is traditional to consider the loudspeaker as approximating to "perfect point source", for the purpose of design and analysis, whilst accepting the real limitations of such practical devices. This often means making the diaphragm suitably stiff in order to confine the resonances to higher frequencies and then using appropriate means to limit their unwanted effects. However, analysis shows that there is an alternative, which does approximate to a point source, but its theoretical nature does not suggest an obvious practical device. Using this prototype, a flat diaphragm loudspeaker has been developed which has both wide directivity and a substantially flat on-axis response.

2 THE FREE DISC

For a modal object, the total response is made up of the sum of the outputs from all the individual modes. In the case of a flat disc, the on-axis pressure is a sum of the pistonic response and the modal contributions. In using a free disc, the modal contributions have a zero mean volume velocity, so they do not contribute to the on-axis response.

If we now apply an "ideal force" to this disc, that is a force which acts at a point and has no mass or damping, we can convert it into and "ideal loudspeaker". This loudspeaker has a substantially flat on-axis frequency response and wide directivity, indicated by a smooth extended power response.

Unfortunately, for all practical purposes, a force always has mass and normal voice-coils have finite diameters, rather than delivering a force at a point. The action of driving the disc at a given diameter, with a mass associated with it, unbalances the free disc and gives rise to errors in both the pressure and power responses.

3 FEA MODELLING

In order to evaluate the free disc case, as well as the proposed solutions it was decided to use the numerical methods of Finite Element Analysis (FEA) and the Boundary Element Method (BEM). In combination, these techniques can be used to calculate the complete responses. Using a fully coupled model, a series of axisymmetric Finite Element Analyses were run using PAFEC [2]. Shell elements were use to model the diaphragm. The far field region was modelled using a boundary element formulation, and an intermediate region of fluid finite elements connected the structure to the boundary elements. Any possible ill-conditioning from the coupled boundary region was eliminated by using the Burton-Miller formulation. Both on-axis pressure and radiated acoustic power were evaluated for a range of frequencies from 100 Hz to 10 kHz (the acoustic power is a convenient way to gauge the overall directivity of the device in a single curve). No structural damping was used in any of the analyses.

3.1 Basic model

The disc used in the FEA model was 1mm thick aluminium, 144.7mm in diameter. A monolith avoids most of the concerns over the shear limitations that a composite might have, and the disc size was chosen to have four modes in the band of interest. The basic mesh is shown in **Figure 1**. A parameterised approach allowed changes to the model to be made readily, and facilitated automatically meshing to new parameter sets.

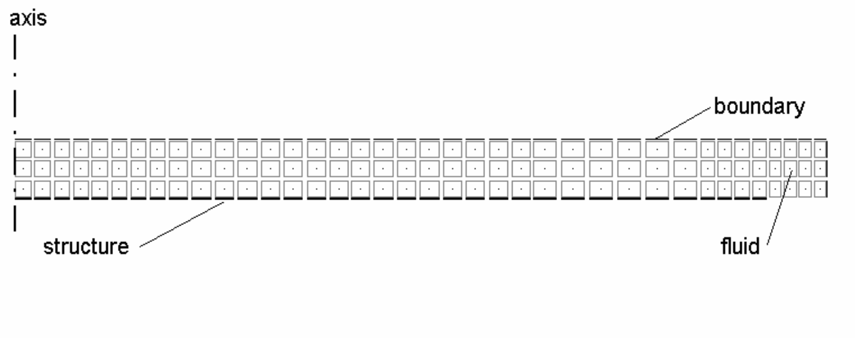

Figure 1: Mesh of axisymmetric FEA model

3.2 Ideal voice-coil

The first model was used to confirm the expected behaviour of a rigid piston, set into an infinite baffle, by driving the centre of a disc with a mass-less force. All the structural freedoms were repeated, constraining the disc to be a piston. Results, shown in **Figure 2** are as expected, with a flat on-axis response and a falling power response, indicating beaming at high frequencies. The turnover point confirms that the power response is dictated by the overall diameter of the piston.

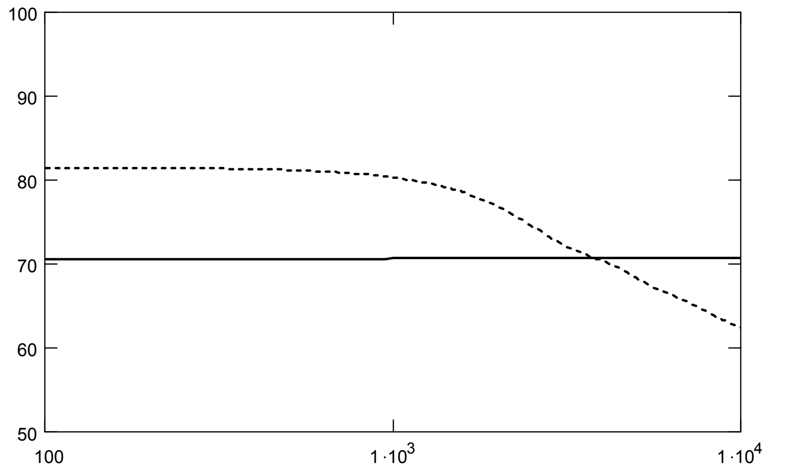

Figure 2: Piston driven with mass-less point force. Solid line: dB SPL (on-axis sound pressure level), Dotted line: dB SWL (sound power level), versus log(frequency).

When the repeated freedoms are removed, then the disc becomes a modal radiator and, using an otherwise identical model, and has the response shown in **Figure 3**. The on-axis pressure remains substantially flat, but the fall-off in sound power has been dramatically improved. It can be seen clearly that the panel size no longer controls the directivity. However, there are panel modes visible in the simulation results, partly because the model uses no mechanical damping.

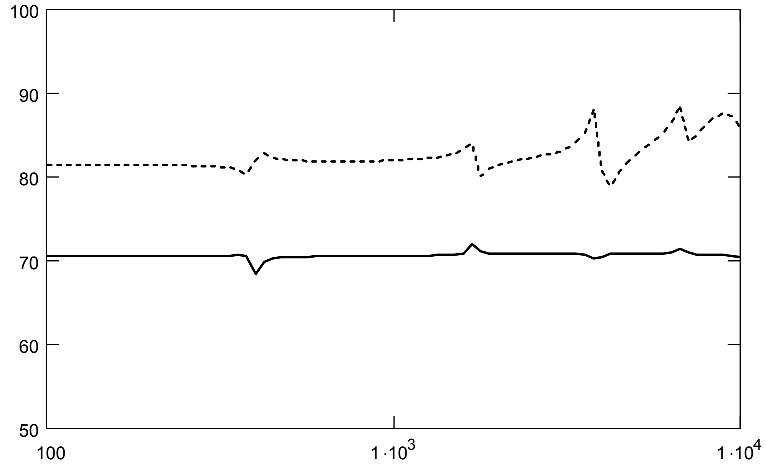

Figure 3: Modal disc driven with mass-less point force. Solid line: dB SPL. Dotted line: dB SWL

For all practical loudspeakers, the force would be supplied by a voice-coil with a finite diameter, depending upon the design and power handling requirements. Prior art would indicate that a good place to position the voice coil would be on the nodal circle of the first bending mode, which is at a diameter ratio of 0.68. As with the previous case of a point force, the mass is still set to zero and the result is shown in **Figure 4**.

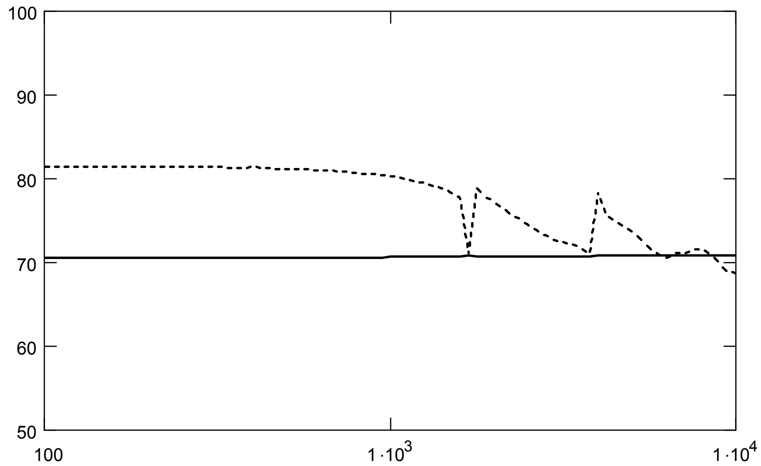

Figure 4: Modal disc driven with mass-less coil, Solid line: dB SPL. Dotted line: dB SWL

The uniform sound pressure is preserved, and the sound power falls off at high frequencies, but noticeably less than in the piston case (compare this result with **Figure 2**), confirming that the power response is now related to the voice-coil size **not** the panel diameter.

3.3 Practical voice-coil

When the ideal voice-coil is replaced with a practical example (which has mass and damping), as well as adding a roll surround, then the disc is unable to behave like the free disc prototype. The result is a loudspeaker which has an uneven on-axis response and a poor power response. It has been customary to treat these designs with some form of applied damping in order to make them useable. To show this effect, the next two figures show the previous model with 2-gram coil (**Figure 5**), and then an 8-gram coil (**Figure 6**).

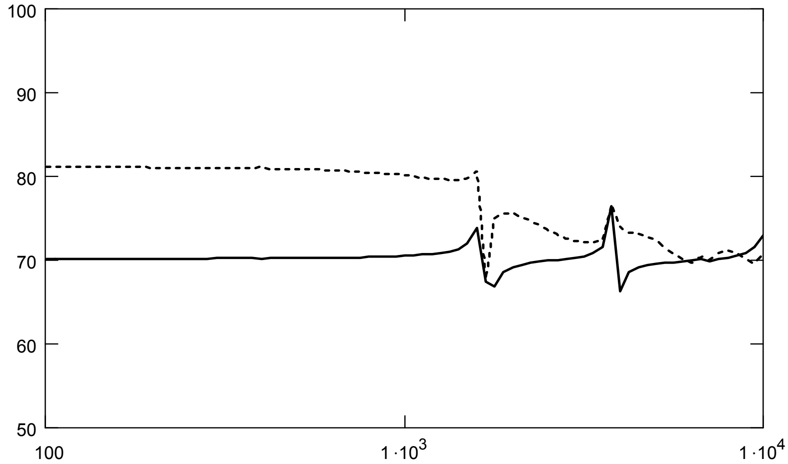

Figure 5: Modal disc driven with a 2 gm coil, Solid line: dB SPL, Dotted line: dB SWL

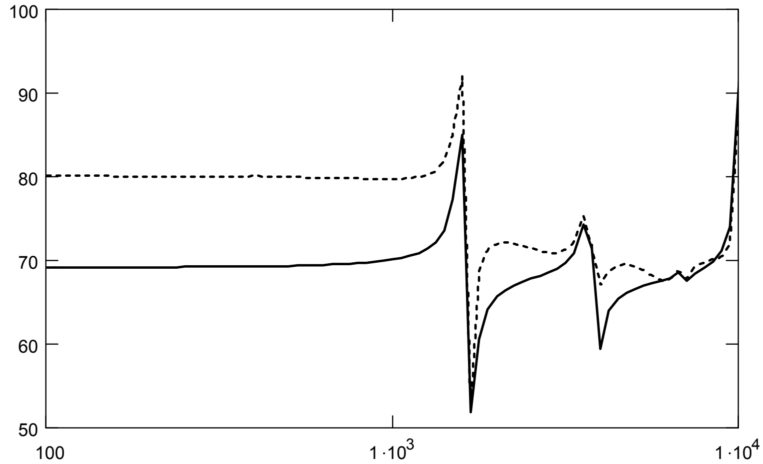

Figure 6: Modal disc driven with an 8 gm coil, Solid line: dB SPL, Dotted line: dB SWL

4 BALANCING THE MODES

Adding a practical voice-coil has “spoiled” the naturally flat response by distorting the mode shapes. The authors formed the hypothesis that if the original mode shapes could be restored, then the desirable acoustic properties of the free disc would also be restored.

4.1 Adding balancing masses

In an attempt to recover the free disc modes shapes that had been distorted by adding mass, it was proposed that additional masses might be used to balance the necessary mass of the voice coil. But, how could a number of modes be considered simultaneously, since the nodal circles would change positions for every mode shape?

In order to balance a number of modes in the operating frequency range we need to determine a set of average nodal positions. These average nodal positions are those which encompass the highest mode order of interest and **all** the lower order modes.

By evaluating the real part of panel’s mechanical admittance Re (Ym) it is possible to determine the average nodal positions. In the case of the first bending mode, this is shown in **Figure 7**.

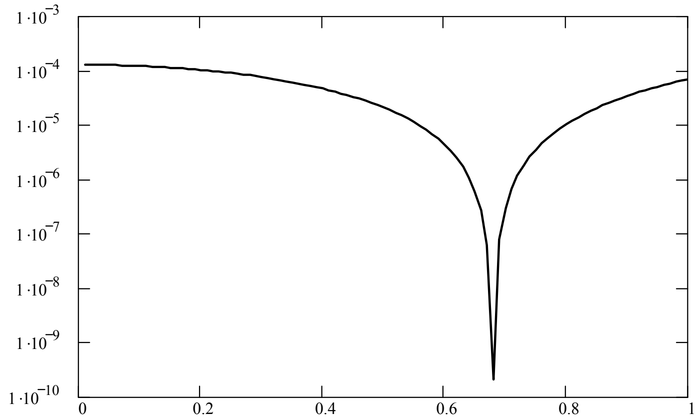

Figure 7 Real part of Ym, for the first disc bending mode, Re (Ym) s/Nm versus relative radial position.

The admittance curve exhibits a clearly define dip at the 0.68 ratio, confirming the expected result when only the first bending resonance is present.

Compare this with **Figure 8**, which is the result of adding a second bending resonance into the admittance calculation. Although both the first and second modes contribute to the admittance, the dip from the first mode has almost completely disappeared.

This result gives an indication of how we might rebalance our disc which was unbalanced when the mass of the voice-coil was introduced. Since the two dips in **Figure 8** represent regions of low velocity, if two scaled masses could be added at these two positions, then the second mode shape would be preserved. Not only that, but these two masses would form a couple which would also satisfy the admittance curve for the first mode. This technique can be extended to any mode order, and adding masses at the “average nodal positions” of the highest mode automatically recreates the free disc mode shapes at this mode and **all** the lower modes.

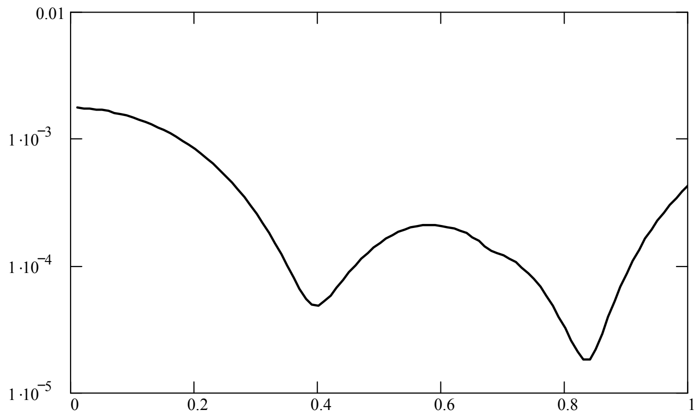

Figure 8 Real part of Ym, for the first two disc bending modes, Re (Ym) s/Nm versus relative radial position.

When the voice-coil is positioned at one of these “average nodal positions”, either the inner or outer, a second mass can be added at the other location, recovering the response of the free disc up to and including the highest mode balanced.

This method can be adopted for any number of modes, but typically up to 4 or 5 modes would normally be sufficient. For 5-modes, the ratio of lowest to highest modes is 1:27. If the first mode was set at 1 kHz, then the output would be “fixed” up to 27 kHz. Likewise, putting the first mode at 2 kHz would “fix” the device up to 54 kHz.

A 4-mode “fix” would have masses located at four “average nodal positions”, with one of these being the voice-coil. Since we are trying to re-create a free disc, the outer average nodal position is inboard of the disc periphery and it is here that the roll surround would normally be fixed, thus providing the outer balancing mass. The two remaining masses would take the form of rings fixed to the disc’s surface. For a 2 mode “fix” the coil and roll suspension provide all the necessary masses and no extra parts are needed. This is the simplest implementation to make. Unfortunately, any additional masses will always incur some loss of sensitivity, but the characteristics of the on-axis response and power output should be similar to those of a free disc, up to the highest balanced mode. We term this radiator a “Balanced Mode Radiator”, or “BMR” [3].

4.2 Analysis after balancing

The two examples used in **Figure 5** and **Figure 6** were modified to include masses to balance the voice coil mass. The BMR solution to the 2-gram voice coil is shown in **Figure 9**. The 8-gram case might appear to be much more difficult to balance, but the BMR method still works, as shown in **Figure 10**. Both solutions have no structural damping, so that the disc modes can be seen more clearly. The residual damping present in most practical materials typically renders these modes harmless.

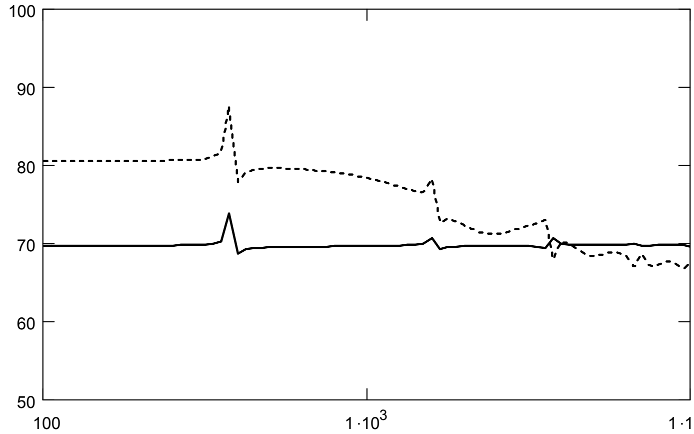

Figure 9: BMR modal disc solution, driven with a 2 gm coil. Solid line: dB SPL. Dotted line: dB SWL

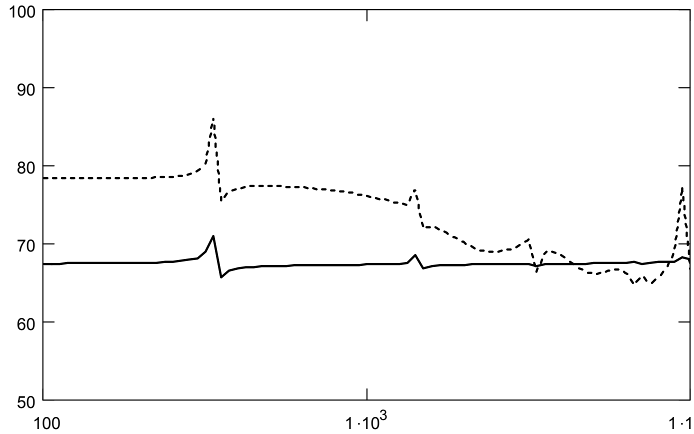

Figure 10: BMR modal disc solution, driven with an 8 gm coil. Solid line: dB SPL. Dotted line: dB SWL

5 A PRACTICAL BMR

5.1 First example

Previous results in this paper have shown that the high frequency output of a BMR is not governed by the panel diameter, but rather the coil size and number of balanced modes. The geometry of the "average nodal positions" dictates that there are a given number of panel diameters, once the voice-coil size is chosen, although increased disc diameters allow for more modes to be balanced.

In the example used in this paper, the voice-coil was set at 32mm diameter and the simplest BMR implementation, using 2 modes, was chosen. The coil was set at the inner of the "average nodal positions", whilst the surround fixed at the outer position. These ratios are 0.39 and 0.84; setting the overall panel size to 82 mm. **Figure 11** illustrates the loudspeaker construction.

In order to recreate the behaviour of the free disc the surround is not located at the disc edge, and is positioned behind the panel, so that the whole of the disc is able to radiate, reconstructing the complete wave front.

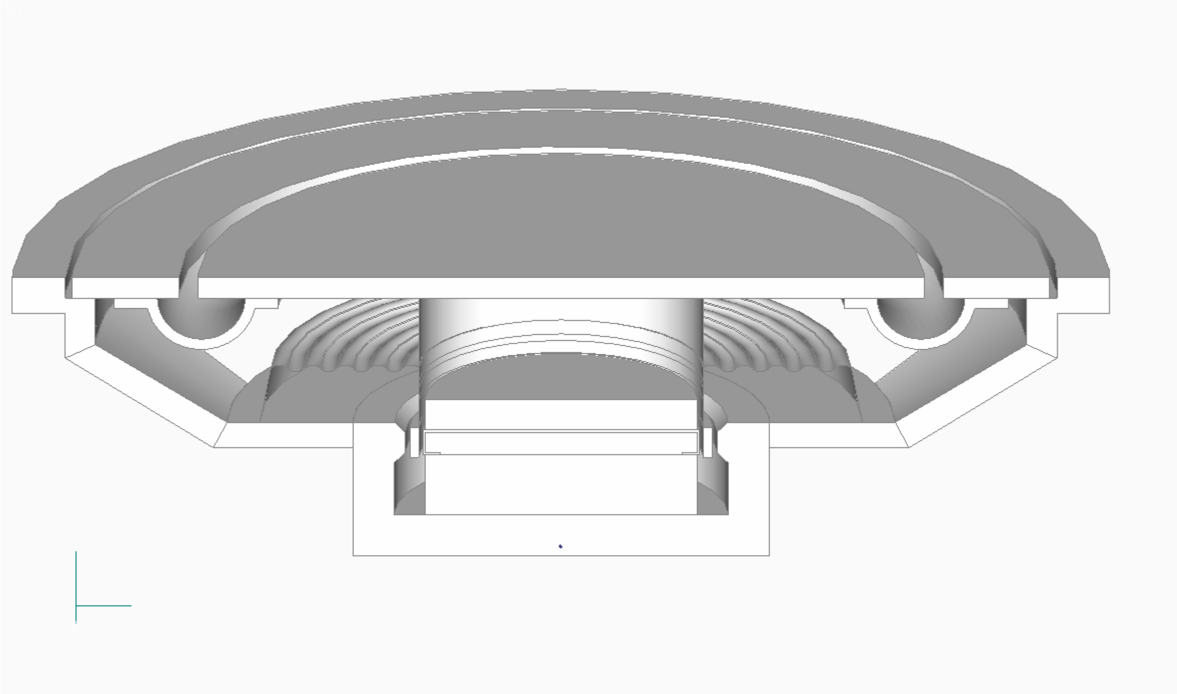

Figure 11: Sectional view of prototype loudspeaker.

5.2 Panel material

The overall behaviour of the BMR is dominated by the overall mass distribution, leaving the panel stiffness to control the frequencies of the modes. These need to be set so that the balanced modes are in the frequency range of interest. The high frequency limit will be controlled by the first un-balanced mode, and the panel shear must be sufficient to prevent this mode from dropping into the operating band.

6 RESULTS

A prototype, as described in section 5, was built and tested. The response curves for 2 V rms into 4 Ω (i.e. a nominal 1 W input) are shown in **Figure 12**. The responses were measured in a small, 2-π anechoic room, the limits of which are indicated by the vertical marker at around 300 Hz. In particular, the irregularity below this frequency is due to acoustic modes in the chamber.

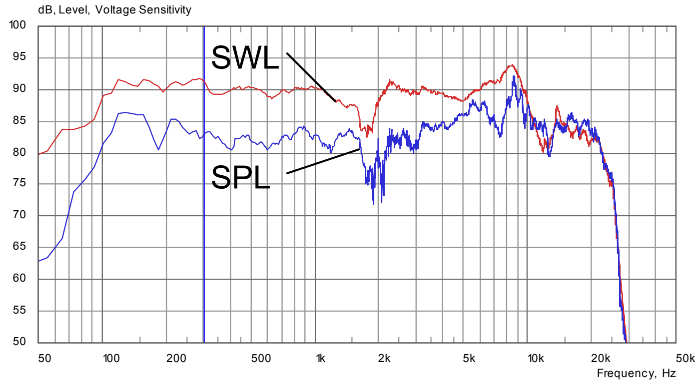

Figure 12: BMR prototype. Top curve is SWL. Bottom curve is on-axis SPL at 1 metre.

This drive unit was built into a 1.6 litre cabinet as a demonstration unit. Some passive filtering was used to equalise the 4-π to 2-π transition, and to adjust the trend of the power response.

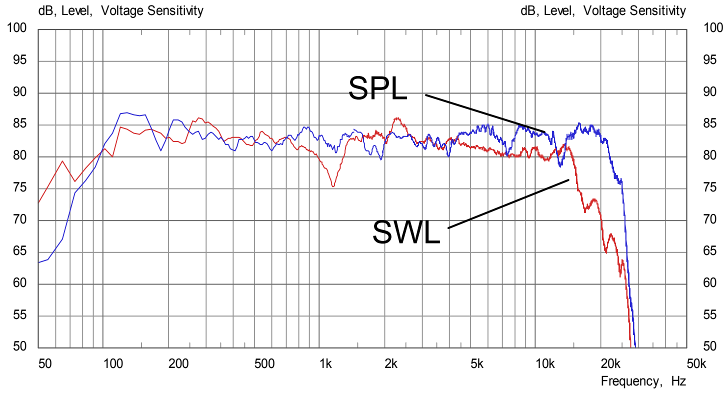

Figure 13: Composite responses for a system using the BMR unit mounted in a 1.6 litre cabinet. Red curve is SWL. Blue curve is on-axis SPL at 1 metre.

Measurements shown in **Figure 13** were obtained by splicing near-field low-frequency and far-field high-frequency measurements together (the level of the SWL curve has been adjusted to overlay the two curves).

7 CONCLUSIONS

The underlying hypothesis, that the mode shapes of a free disc could be recreated by mass-loading a disc at its average nodal positions, was tested using a fully coupled FEA model. The results for a free disc, driven with a mass-less voice-coil, were compared to those of a balanced disc, driven with a practical voice-coil. Re-balancing the disc in this way gives substantially the same response characteristics as the free disc, although adding extra masses will inevitably lower the sensitivity. The measurements of the prototype demonstrate the practicality of this new loudspeaker.

8 REFERENCES

1 J.W.S. Rayleigh, "*The Theory of Sound*", Vol 2, 2nd ed., 1896, reprinted by Dover, New York, 1945, art 302.

2 PAFEC, supplied by PACSYS Ltd. Strelley Hall, Strelley, Nottingham, NG8 6PE, UK

3 The Balanced Mode Radiator is subject to a pending international patent, PCT/GB2005/001352, Bank and Harris.