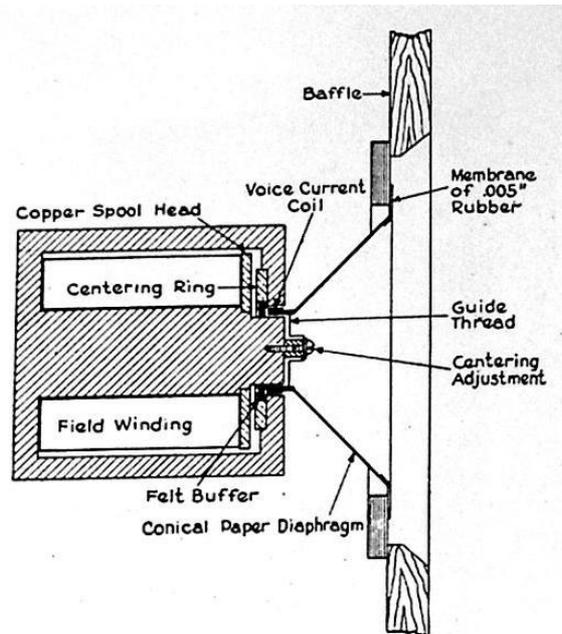


# Explanation of the Balanced Mode Radiator (BMR)

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## Introduction

Ever since the first drive unit design (patented by Rice and Kellogg in 1925), loudspeaker drive units have been steadily evolving with improved materials, refined motor design and modern manufacture techniques. However, many of the component parts of a modern day loudspeaker are still very similar to those used in the original 1920s prototype.



**Figure 1. Original embodiment of Rice and Kellogg. Source: Rice, Chester W. and Edward W. Kellogg, "Notes on the Development of a New Type of Hornless Loudspeaker," Transactions of the American Institute of Electrical Engineers 44, 1925**

Of all these components it could be argued that the most critical is the diaphragm as it provides the interface between the induced mechanical vibrations and the resulting acoustic pressure waves that we hear.

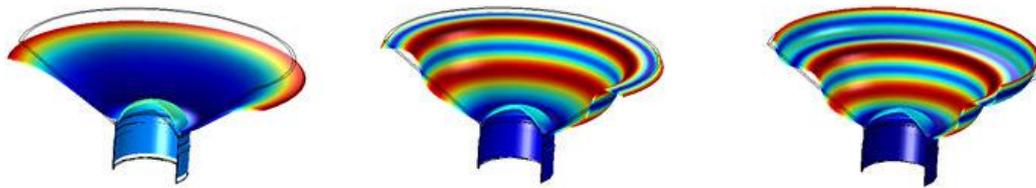
Balanced Mode Radiator (BMR) technology provides a novel approach to diaphragm design that addresses two significant limitations of conventional cone diaphragms: "breakup" and "power beaming." In doing so, BMR drive units confer a number of key improvements to loudspeaker fidelity.

## Conventional Diaphragm Limitations - Breakup

Although many variants of diaphragm exist they almost all require a curved geometry to achieve their stiffness – a conical section. Simply put a sheet of paper is very light and floppy, but when rolled into a cylinder or cone the structure becomes much stiffer in the direction parallel to the axis of rolling. This is a clever way of making a light, floppy diaphragm material stiff enough so that it remains rigid against the surrounding air whilst being forced back and forth by the voice coil.

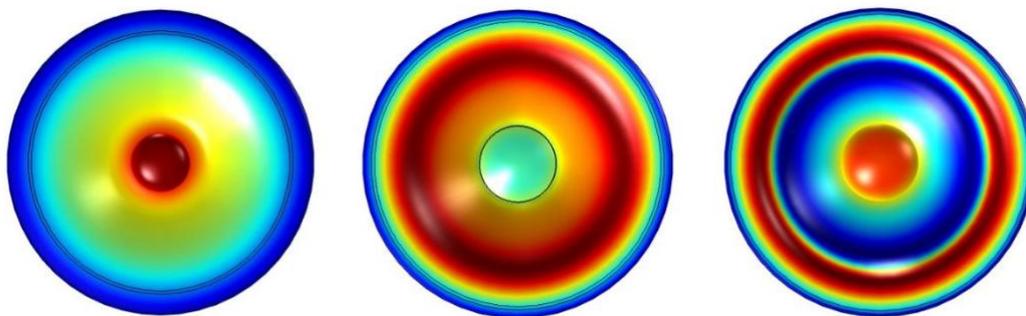
Unfortunately, there is no known practical material that is light enough to give reasonable efficiency while providing a completely rigid, pistonic surface across the whole of the audible range. The consequence of this is that the designer has to deal with the phenomenon known as breakup.

Breakup occurs when the wavelength of mechanical bending/flexural waves in the diaphragm becomes similar to the dimensions of the diaphragm. This causes resonant modes (standing waves) to form in the diaphragm which means that the diaphragm is no longer pistonic – different regions of the diaphragm are vibrating in opposite directions (see figure 2).



**Figure 2. Cone breakup modes**

Viewing the cone from face-on and looking at the vector of cone displacement gives a clearer picture of how different regions of the cone are moving in different directions (figure 3).



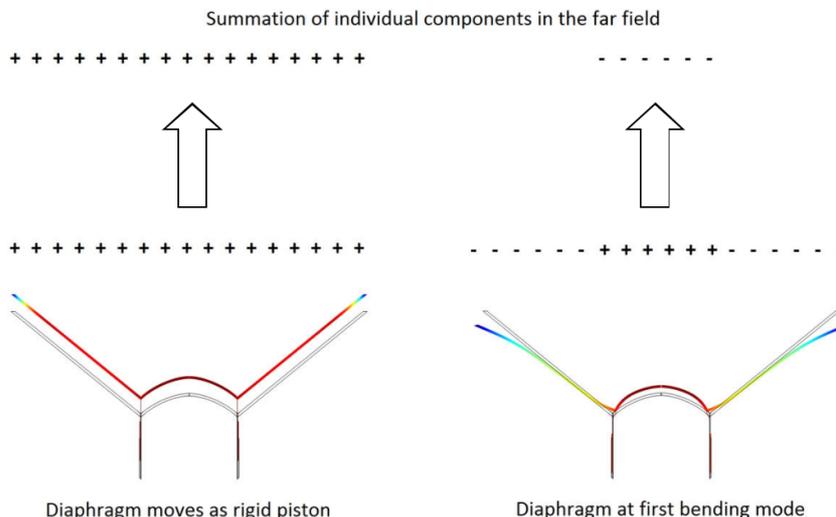
**Figure 3. Cone breakup modes. Colour-field represents axial displacement vector with red and blue colour indicating movement towards and away from the viewer**

When the diaphragm moves towards us we say it “compresses” the air in front of the diaphragm, and when it moves away from us it “rarefies” the air in this region. These compressions and rarefactions are the nature of sound waves travelling through the air medium. From figure 3 we can see that when breakup occurs the diaphragm produces local compressions and rarefactions that vary across the surface of the diaphragm.

For example, looking at the left hand image in figure 3 the central region (red circle) is moving towards us, thus creating a local compression of the air (positive pressure) whereas the outermost region (blue ring) is moving away, creating a local rarefaction (negative pressure).

As these regions of different pressure propagate through the air and encounter each other, they interact with positive and negative pressures cancelling each other out.

The net radiated pressure (in the far field) from the diaphragm is a summation of these positive and negative pressures (see figure 4).



**Figure 4. Compression and rarefaction (positive and negative pressure) produced by rigid diaphragm (left) and diaphragm undergoing breakup at 1<sup>st</sup> mode (right). The top row shows the net summation of pressure from each diaphragm.**

From figure 4 the rigid movement of the diaphragm (left image) creates a strong net pressure in the far field. However, the diaphragm undergoing breakup (right image) creates a much weaker pressure

in the far field as the positive pressure has been cancelled out by the negative pressure, just leaving the residual negative component in the far field.

A cone diaphragm breakup is generally not well controlled and large peaks and dips occur in the frequency response. These peaks and dips are perceived as unnatural emphasis to regions of speech and music signals, giving the sound a “nasal” or “honking” characteristic for example.

To prevent these peaks and dips from becoming audible, a low-pass filter is required to roll off the response from the drive unit prior to the onset of breakup, limiting its useable bandwidth. To cover the full audible range, it is therefore necessary to add a tweeter (see figure 5).



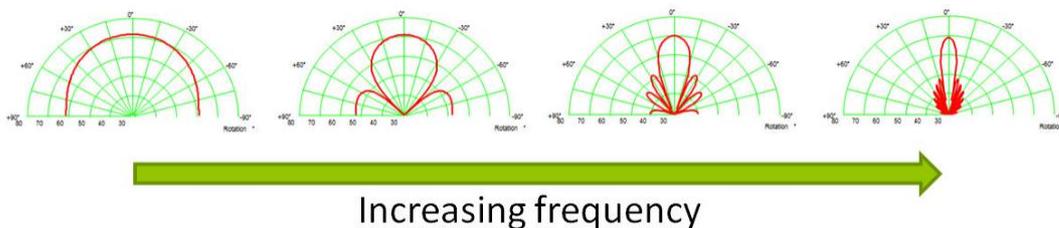
**Figure 5. On-axis response of cone diaphragm speaker. Only part of the frequency range is useable, the region where breakup occurs (red) must be filtered away.**

### Conventional Diaphragm Limitations - Power Beaming

Even if a wonder material with high inherent stiffness and sufficiently low mass to push breakup out of the audible range was discovered tomorrow, there still would remain another limiting effect of cone diaphragms: “power beaming.”

At low frequencies, when the wavelength in air is greater than the dimension of the diaphragm, the diaphragm radiates uniformly in all directions. However, at higher frequencies when the wavelength in air is equal to or less than the dimension of the diaphragm, destructive interference occurs between different points on the diaphragm causing the radiation pattern to gradually narrow.

As the frequency rises, the radiation narrows to a beam directly in front of the diaphragm. The direct on-axis sound pressure level (SPL) can remain at a uniform level at these higher frequencies, but off-axis (at angles to the sides) the level drops significantly due to the destructive interference. An example of this power beaming is shown in figure 6.



**Figure 6. Directivity pattern narrowing with increasing frequency for a cone diaphragm.**

This power beaming effect also sets a limit on the maximum useable frequency range of a given cone diaphragm. As in the case of cone breakup, it is necessary to add a tweeter to ensure full frequency coverage.

## Enter the BMR

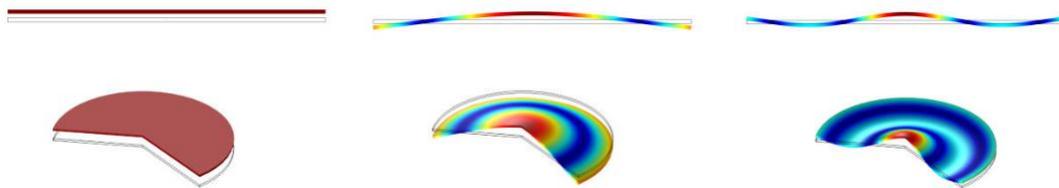
The Balanced Mode Radiator (BMR) was invented about ten years ago (see US patent no. 7,916,878) at New Transducers Ltd (NXT) and built on the world leading expertise in bending wave physics that the company had amassed through development of the Distributed Mode Loudspeaker (DML) technology. However, the operation of a BMR is quite distinct from that of a DML.



**Figure 7. Tectonic TEBM65C20F 3 1/2 inch Balanced Mode Radiator**

### Start by Considering the Free Disc

The starting point is a free, circular disc that naturally has a number of circular modes across the frequency range. The first three modes are shown in figure 8 (note that the rigid piston type movement is usually called the zeroth mode).

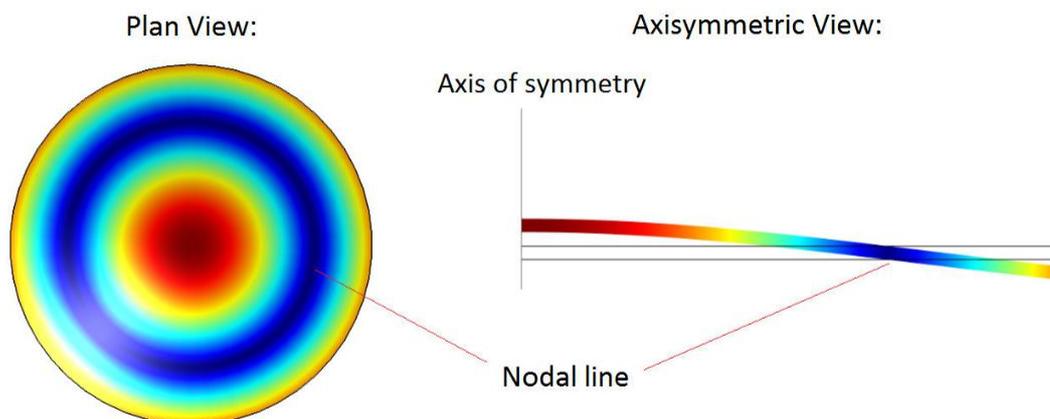


**Figure 8. Zeroth, first and second modes of a free disc. Cross-sectional view (top) and 3D cut view (bottom).**

A free, flat disc such as this, if driven by a perfect force (i.e. one with no mass or damping), exhibits ideal acoustic characteristics of a flat on-axis sound pressure response and a smooth, extended sound power response. *\*Note: sound power response (SWL) is a summation of the pressure responses at each angle surrounding the loudspeaker.*

The reason for the flat on-axis response is that the output from the circular modes perfectly cancels on-axis. This is because the areas of the disc moving in opposite directions are equal, so the pressures exactly cancel out.

This balanced movement of the free disc is key to understanding the operation of a BMR. Let's look at the first mode shape in more detail (figure 9).



**Figure 9. First bending mode of free disc**

Each mode of order “n” has n nodal lines. In figure 9, which shows the first mode, we can see a single, circular nodal line. In the axisymmetric view the nodal line appears as a point. Note that the axis of symmetry is the centre of the disc.

A nodal line indicates a line where there is zero velocity, and on either side of the nodal line the disc moves in opposite directions.

If we calculate the area of the circle within the nodal line in figure 9 and compare this with the area of the ring outside of the nodal line, we find that they are equal. This also applies equally to all of the higher modes.

Therefore, the contributions from each moving area give rise to equal and opposite pressure and neatly cancel out on-axis. Referring back to figure 4, in the case of the free disc there are always equal amounts of “+” and “-“ adding up to a net of zero.

However, off-axis the regions do not cancel out because— now looking from an angle— you are always closer to one type of movement region than the other(s).

We can think of the disc as having two superimposed types of vibration: a piston motion and a modal vibration. On-axis the output from the modal vibration is perfectly cancelled, producing a smooth response from the residual piston component. Off-axis the output from the modal component is added to the piston component, improving the radiated sound power.

The free disc is all well and good as a theoretical example, but we have to have a means of imparting energy to the disc. How do we drive it?

### *Breaking the Free Disc*

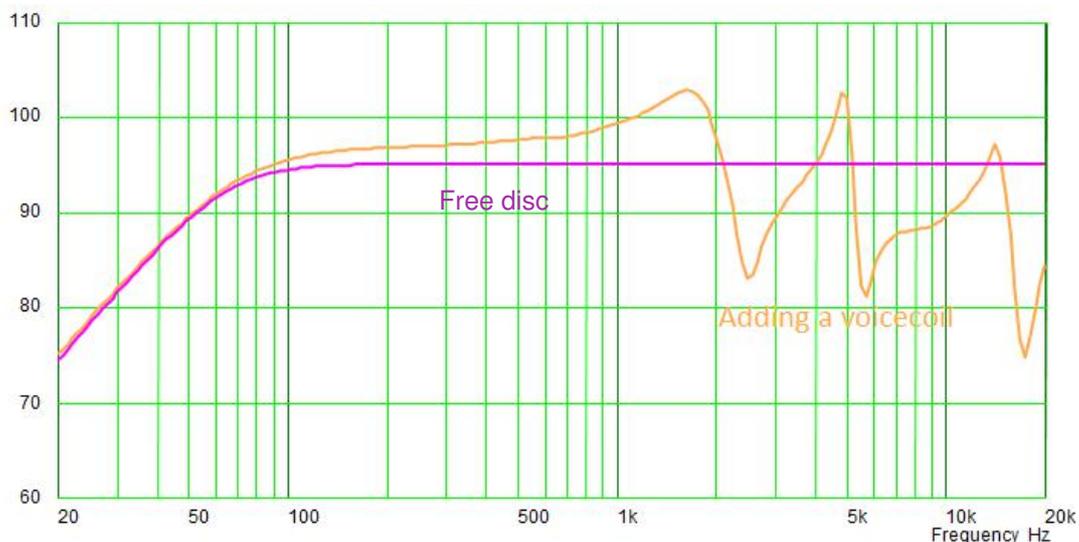
So far we have considered only a “perfect force” (i.e. one with no mass or damping) for driving the disc. Unfortunately, we do not have access to such a perfect force.

The usual method is to attach a voice coil to the disc, immerse the coil in a suitably orientated magnetic field, and then pass an electrical current (the signal) through the coil generating a Lorentz force on the coil that varies according to the signal.

The problem is that when the voice coil is added it disrupts the neat way that the free disc positioned its nodal lines so that all the areas moving in opposite directions were equal.

Another way of looking at this is to consider the mass of these regions. Assuming that the disc is isotropic and homogenous, if the areas are equal then the masses of each of the areas are also equal. But if we place a voice coil onto one of the regions the disc must adjust its nodal lines to ensure that the mass distribution is even (technically speaking we say that angular momentum is conserved). In doing so the disc areas are no longer equal and so the on-axis pressure from the modes no longer cancels out.

The effect of adding the voice coil is shown in figure 10.

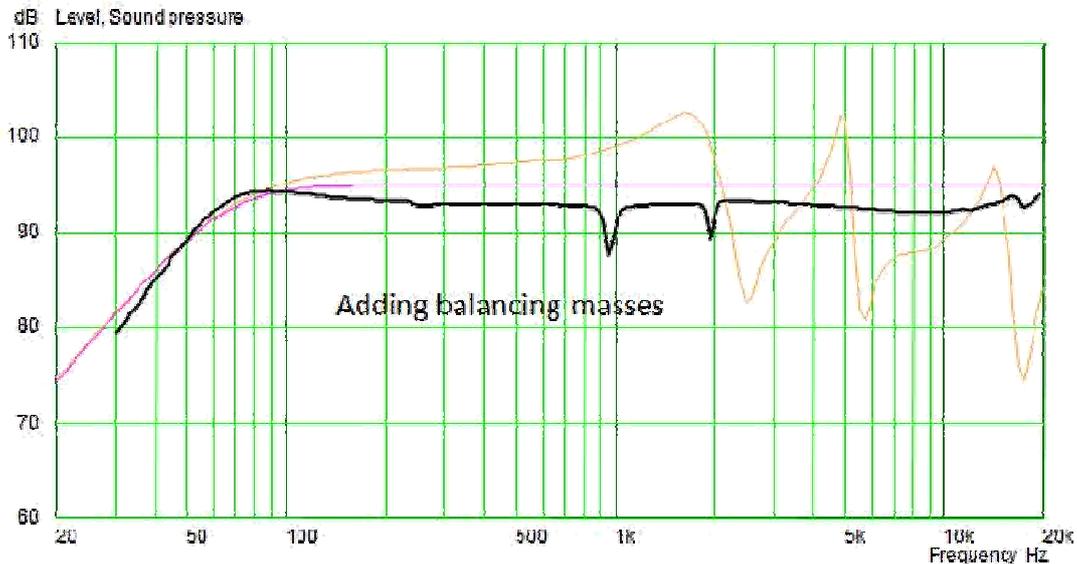


**Figure 10. On-axis response of free disc and with voice coil added**

Adding the voice coil has unbalanced the disc vibration modes and the on-axis frequency response is now uneven.

## Re-Balancing the Disc

This is where BMR design principles come in. We can compensate for adding the voice coil by placing additional ring masses of a scaled value at specific locations on the disc. Thus the unbalancing effect of adding a voice coil can be countered and the behaviour of the free disc recovered – the disc has been re-balanced as shown in figure 11.



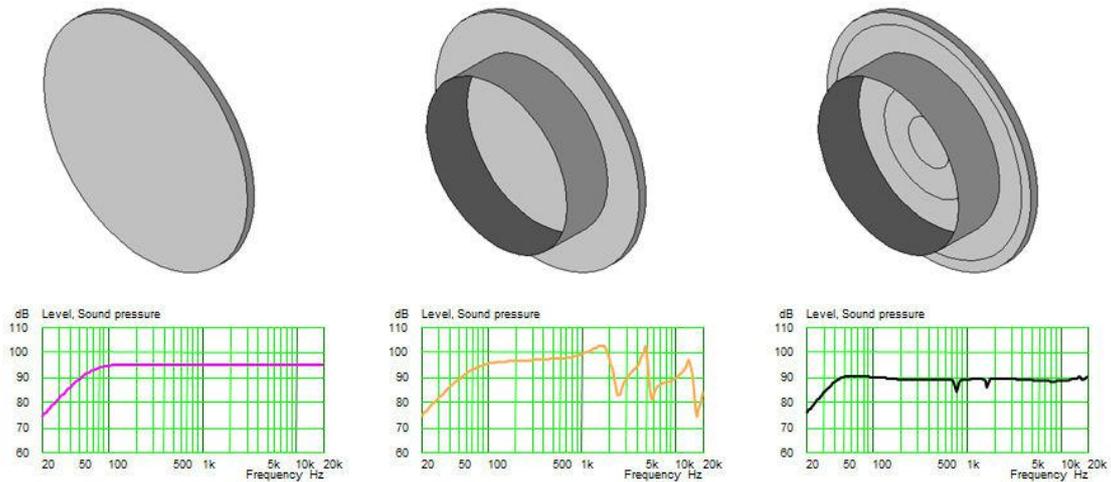
**Figure 11. Recovering the free disc behaviour by adding balancing masses.**

The disc still experiences break-up modes, but now through the BMR rebalancing principles the areas of the parts of the disc moving in one direction exactly balance the areas moving in the opposite direction. The process is summarized in figure 12.

Theoretical ideal

Adding a voice coil

Adding ring masses



**Figure 12. Summary of the BMR balancing method and results**

## Going a Little Deeper – Mode Fixes

The number of mode fixes required for a given BMR design depends on the number of modes that occur within the operating band of the drive unit. So how do we determine the number of modes that occur within a given bandwidth?

A good starting point is to run what is known as an Eigenfrequency study of the target disc size. An Eigenfrequency analysis is the mathematical way of determining the free mode frequencies (and shapes) of a given structure. This is usually performed using a finite element analysis (FEA) software tool.

In addition to specifying the initial dimensions of the disc, the designer also has to input the material properties of the disc. Young's modulus, density and Poisson's ratio are the key parameters, but also the shear modulus is important. Apart from the density, all of these other parameters are typically matrices specifying the individual moduli in orthogonal directions.

Let's consider an example and try to avoid getting mired in the math. We'll start by considering a 100mm diameter disc and because we want it to be as light as possible (for higher sensitivity) we will initially specify the thickness at 1.0mm. However, as we will see it will be necessary to increase the thickness. Table 1 shows the first six Eigenfrequencies for our disc in two thickness options.

Mode n	Eigenfrequencies (Hz)	
	T = 1mm	T = 2mm
1	716	1430
2	3176	6334
3	7288	14493
4	13035	25826
5	20408	27903
6	27905	40245

**Table 1. Eigenfrequency list for 1mm and 2mm thick discs of diameter 100mm**

The more mode fixes required means adding more mass to the disc, so usually we aim to use up to four mode fixes.

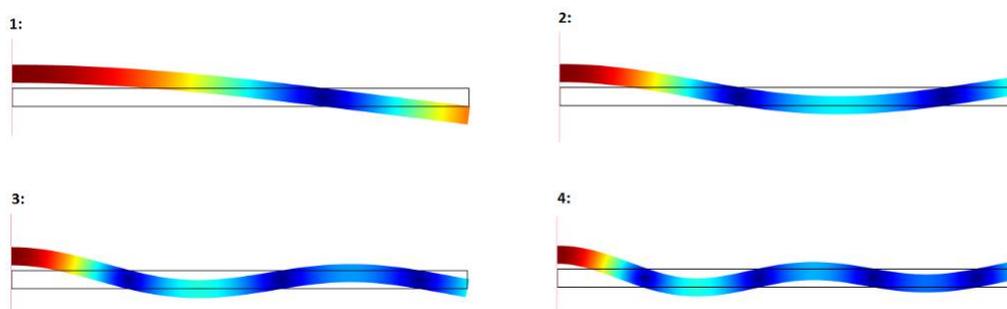
From inspection of table 1 we can see that if our target bandwidth is up to 20kHz we would require four mode fixes for the 1mm disc and three fixes for the 2mm disc. However, it is important to note that once we add the mass of the voice coil and roll surround these frequencies will all shift downwards. It is almost certain that the fifth mode of the 1mm disc (at 20,408Hz) will drop into the operating band, so this disc size would actually require at least five mode fixes.

Looking at the 2mm disc the fifth mode occurs at almost 28kHz. If we opted for a four-mode fix (the fourth mode is at 25,826Hz) we should be okay within our target bandwidth.

There are additional subtleties to be considered with regard to the sound power response at this stage. The details are beyond the scope of this document, but suffice to say that it is recommended to ensure that the frequency of the first mode of the disc occurs just below the point at which the rigid disc would start to beam its power response.

Let's proceed with our 100mm diameter disc, using the 2mm thick option.

Figure 13 shows the first four mode shapes.

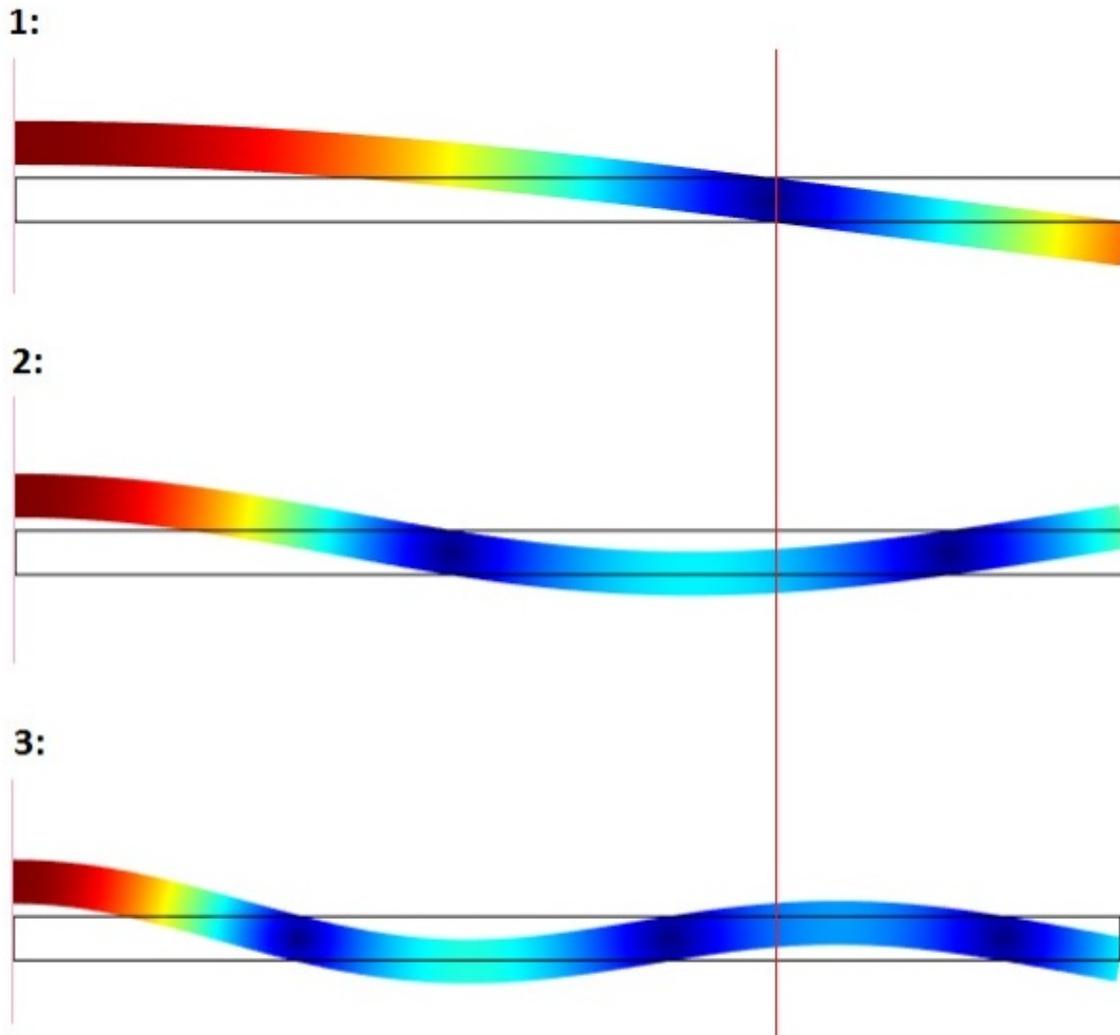


**Figure 13. First four mode-shapes (axisymmetric view)**

As discussed earlier (recall figure 9) each mode of order  $n$  has  $n$  nodal lines (shown by the darkest blue points in figure 13). A nodal line is characterized in that it is a region of the disc that does not undergo translation, rather the disc rotates about these lines (or points when viewed in axisymmetry). A starting point for the position of the voice coil might be the nodal line of the first mode, i.e. at the radius of the dark blue point in the top left image in figure 13.

By "driving" the disc at this nodal line the first mode is suppressed. This seems like a great starting point, and indeed this is an established technique in the prior art for extending the bandwidth before breakup of a given diaphragm.

However, this comes with a penalty. Notice what the disc is doing at this same point in modes 2 and 3 in figure 13. At this point in modes 2 and 3 we are close to an anti-node. This is shown more clearly in figure 14.



**Figure 14. First three modes. Red vertical line indicates the nodal line of first mode.**

What this means is that by driving at the nodal line of the first mode, the first mode is suppressed, but the second and third modes are enhanced.

This is not good. As from table 1 we know that at least the first three modes (and most likely the fourth) will be within our operating band. So are we stuck? Actually this is the point at which, prior to the invention of BMR, engineers were stuck at and could go no further.

To take the next step we will need to consider a concept known as the “admittance” of the disc.

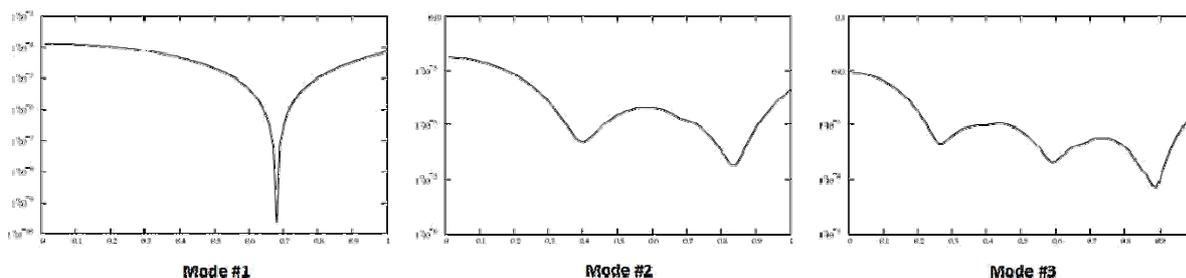
### *Admittance and Average Nodal Positions*

Admittance is a common term in electrical engineering where it is used as a measure of how easily current will flow in a given circuit, and may be defined as the inverse of impedance. In our case we are interested in the mechanics of the disc and fortunately there are direct analogies between concepts in electrical and mechanical (and acoustical) engineering.

The mechanical admittance is given by the ratio of velocity to force at a given point on the radius of the disc. Essentially we can use the admittance function to tell us how much velocity is imparted at a point on the disc if we apply a given force at that point.

A nodal line causes a minima in the disc admittance. Remember a nodal line cannot translate (move vertically), only rotate, so there is no translational velocity generated at a node regardless of the force imparted.

Figure 15 shows the disc admittance calculated from the center to the edge for the first three modes.



**Figure 15. Disc admittance for first three modes.**

Now for the magic. It transpires that by suitably weighting the contribution from each mode and adding them all together the “average nodal positions” are determined.

By balancing the disc for the highest mode-fix required, the lower order modes are also automatically fixed. This was a revelation and forms a key basis of the BMR invention.

The problem has essentially been turned on its head. Previous attempts to expand the bandwidth of a diaphragm started with the first mode and worked upwards. We saw in the previous section that this approach does not work. The principles of BMR tell us the opposite; start with the highest mode and the lower modes are naturally taken care of.

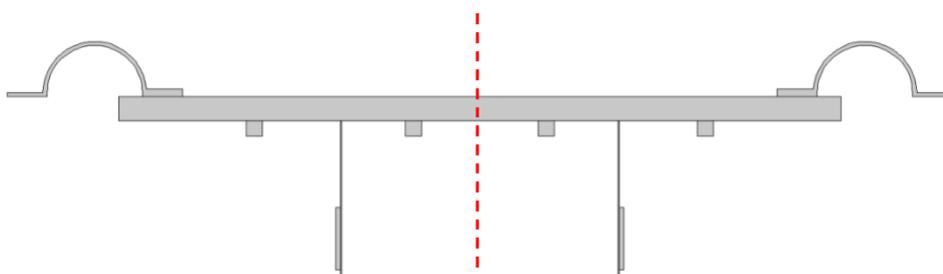
These average nodal positions are the locations at which we will place our driving force (voice coil), roll surround and balancing masses.

### *Configuration of a BMR*

Now we are ready to construct our BMR by adding the voice coil, roll surround and any additional balancing masses (rings) at the appropriate positions.

An important observation we can now make is that the center and edges of the disc are never nodal lines; they are always antinodes (maxima in the admittance curves in figure 15. Also see the mode shapes in figure 14). This is important because usually the roll surround is attached to the edge of the diaphragm. However, as the edge is always an antinode for a BMR it should always be left free – the roll surround is mounted inboard, at the outermost average nodal position.

Let’s return to our example of the 100mm diameter disc with a four-mode fix. In this case the voice coil is placed at the second average nodal position and the roll surround at the fourth (outermost). Additional rings of mass are added at the first and third average nodal positions. Figure 16 shows the implementation.



**Figure 16. Example configuration of a four-mode-fix BMR. Dashed line shows disc centre.**

Typically, the voice coil is specified first to satisfy other key requirements of the drive unit such as DCR, power handling and excursion range. Once the mass of the voice coil is known the appropriate masses of the roll surround and balancing rings can be calculated. As is shown in figure 16 the thickness of the inner flange of the roll surround can be adjusted to achieve the correct mass for this component.

The object shown in figure 16 may appear somewhat complex, but note that the only additional components over a conventional system are the two balancing rings. The only other key differences are that a flat disc has been used for the diaphragm instead of a cone, and the relative locations of the components have been set according to the average nodal positions.

In following these principles of BMR design the drive unit will radiate sound with flat on-axis pressure and wide directivity, just like the ideal acoustic object - the free disc.

### *Features and Benefits*

1. Wide dispersion. The extended output off-axis leads to a room filling sound with improved coverage for multiple listeners.
2. The requirement for a cross-over in the critical 1kHz – 3kHz region is eliminated.
3. Point source integrity is preserved as all the sound energy is coming from a single source, not multiple drive units located at different points in space.
4. Superb timing from the single acoustic source, and no mid-tweeter comb filtering interference effects.
5. Flat disc diaphragm eliminates the “shouty” sounding megaphone effect produced by cone shaped diaphragms.
6. The flat disc also reduces the build height of the drive unit, occupying less of the enclosure volume.

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