



THE BALANCED MODE RADIATOR (BMR)

TIM WHITWELL
TECTONIC AUDIO LABS, INC.

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 manufacturing techniques. However, many of the component parts of a modern day loudspeaker are still very similar to those used in the original 1920s prototype.

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.

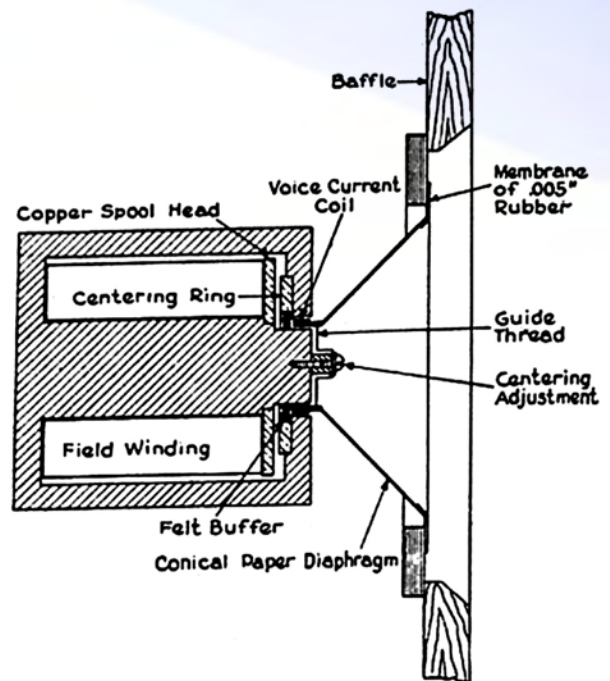


Figure 1. Original embodiment from Rice and Kellogg.

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

CONVENTIONAL DIAPHRAGM LIMITATIONS - BREAKUP

Although many variants of diaphragm exist, they almost all require a curved geometry to achieve their stiffness – a conical section. 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 to remain rigid against the surrounding air while 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. Consequently, the designer must 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. As a result, the diaphragm is no longer pistonic – different regions of the diaphragm are vibrating in opposite directions (see [Figure 2](#)).

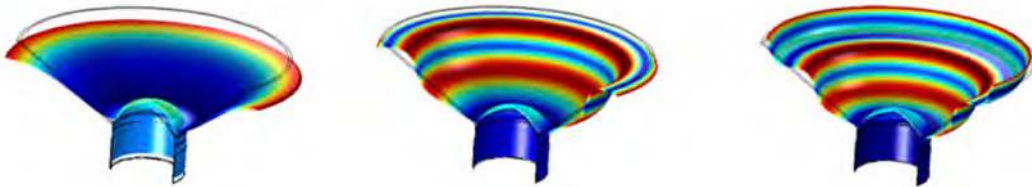


Figure 2. Cone breakup modes.

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](#)).

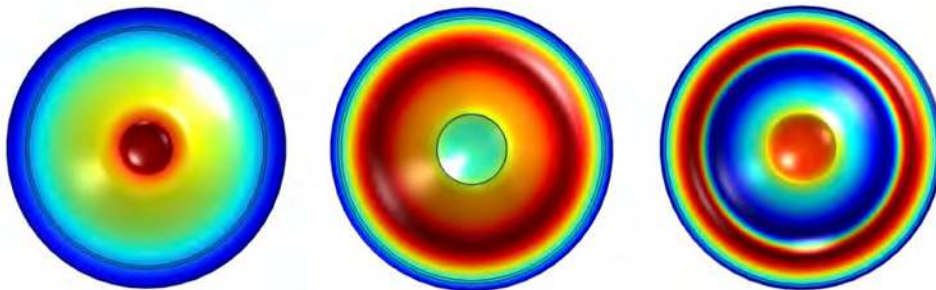


Figure 3. Cone breakup modes. Color-field represents axial displacement vector with red and blue color indicating movement towards and away from the viewer respectively.

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 traveling through the air medium. From [Figure 3](#), we can see that breakup causes the diaphragm to produce 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, it creates a local compression of the air (positive pressure). Whereas the outermost region (blue ring) is moving away from us, and it creates a local rarefaction of the air (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).

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 to leave the residual negative component in the far field.

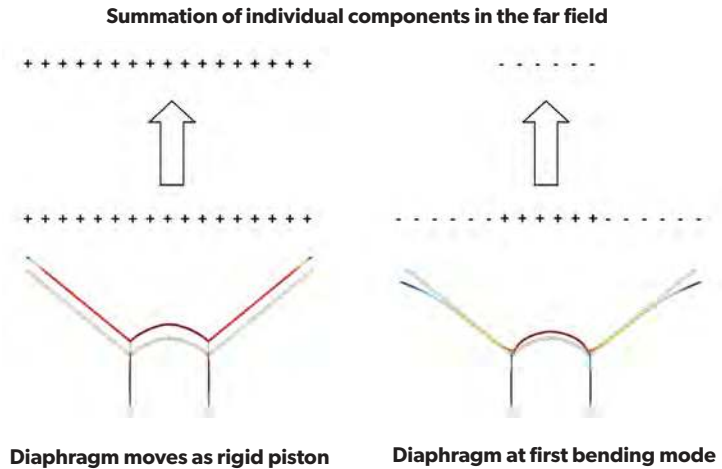


Figure 4. Compression and rarefaction (positive and negative pressure) produced by rigid diaphragm (left) and diaphragm undergoing breakup at 1st mode (right). The top row shows the net summation of pressure from each diaphragm.

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 an unnatural emphasis to regions of speech and music signals, and they give 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; this limits its usable bandwidth. To cover the full audible range, it is therefore necessary to add a tweeter (see Figure 5).

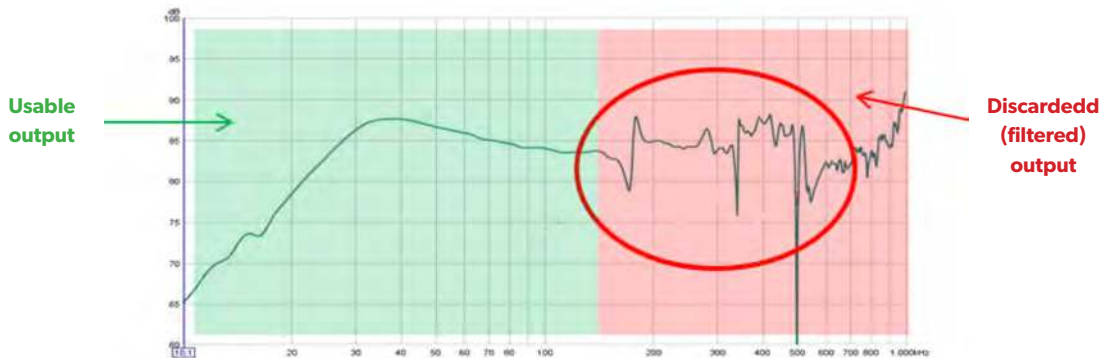


Figure 5. On-axis response of cone diaphragm speaker. Only part of the frequency range is usable, the region where breakup occurs (red) must be filtered away.

CONVENTIONAL DIAPHRAGM LIMITATIONS — POWER BEAMING

Even if a wonder material with high inherent stiffness and sufficiently low mass to push cone 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 circumference 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. This causes 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 the off-axis (at angles to the sides) sound pressure level drops significantly due to the destructive interference.

An example of this power beaming is shown in [Figure 6](#).

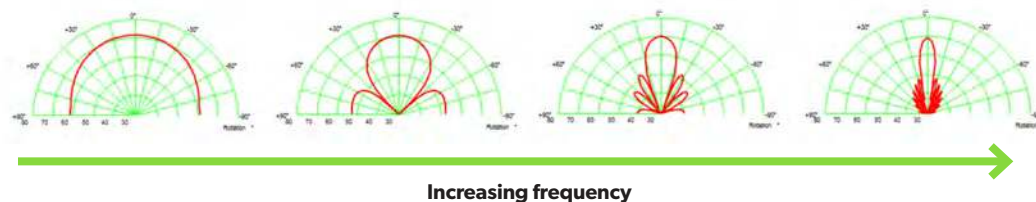


Figure 6. Directivity pattern narrowing with increasing frequency for a cone diaphragm.

This power beaming effect also sets a limit on the maximum usable 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 10 years ago (see US patent no. 7,916,878) at New Transducers Ltd (NXT). It was 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 BMR28 (render)

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).

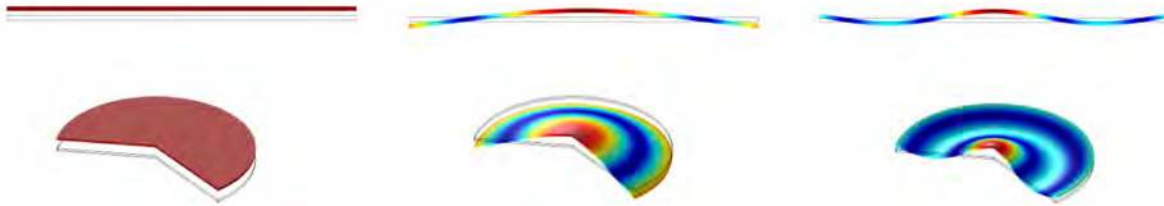


Figure 8. Zeroth, first, and second modes of a free disc. Cross-sectional view (top) and 3D cut view (bottom).

If driven by a perfect force (i.e. one with no mass or damping), a free, flat disc such as this exhibits ideal acoustic characteristics of a flat on-axis sound pressure response and a smooth, extended sound power response.*

The output from the circular modes perfectly cancels on-axis and produces a flat on-axis response. 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).

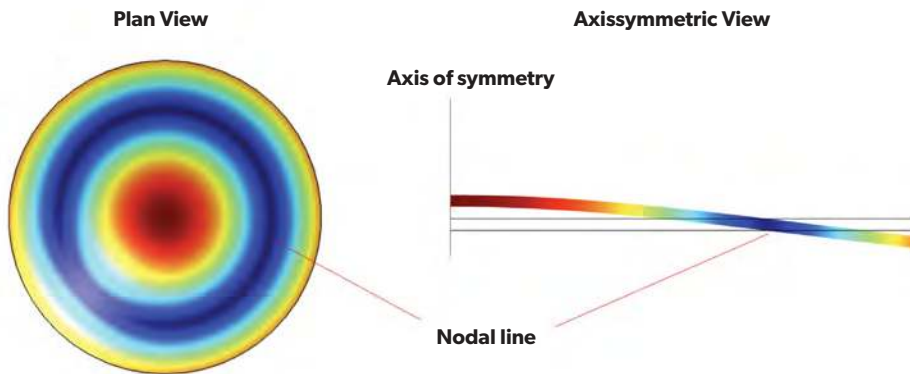


Figure 9. First bending mode of free disc.

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 center 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.

*Note: sound power response (SWL) is a summation of the loudspeaker pressure responses at each angle, weighted by their individual projected area fraction on a hemisphere.

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 concept applies to all of the higher modes in the same way.

Therefore, the contributions from each moving area give rise to equal and opposite pressure, and they 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). This is illustrated in [Figure 10](#).

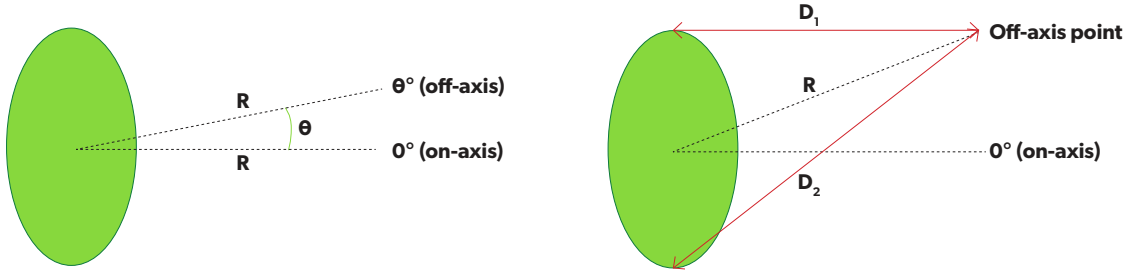


Figure 10. Left image describes what is meant by on and off-axis. Right image shows example distances to the off-axis point from opposite sides of the disc ($D_1 < R < D_2$).

We can think of the disc as having two superimposed types of vibration: a piston motion and a modal motion. 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, and the radiated sound power is improved. This is shown in [Figure 11](#).

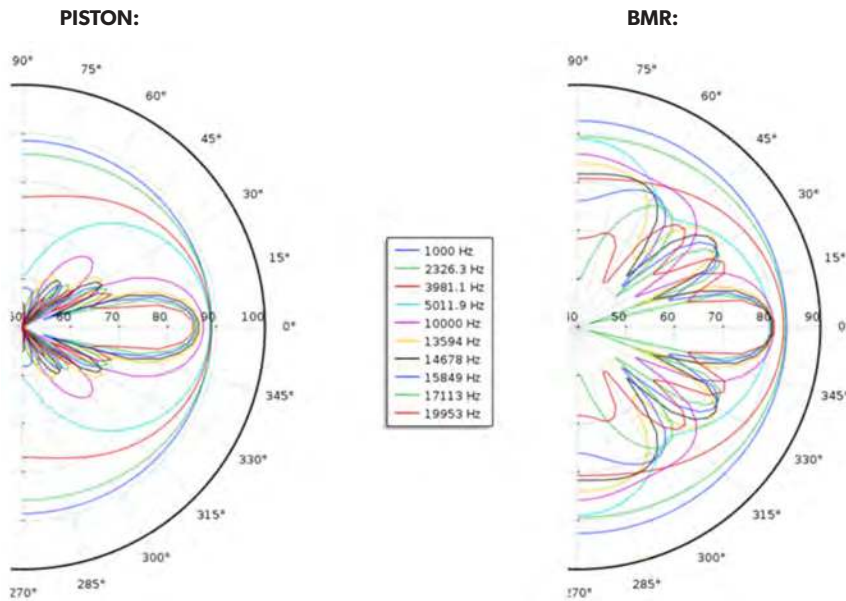


Figure 11. Left image shows polar response curves for a 3.5” piston. Right image shows polar response curves at the same frequencies for a 3.5” BMR.

The free disc is ideal as a theoretical example because there are no components attached to the disc and so the modes can naturally arrange themselves in the optimal manner described above. However, a means of imparting energy to the disc is required. **How do we drive the disc without losing the natural modal behavior?**

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 its mass disrupts the neat way that the free disc positioned its nodal lines so that all the areas moving in opposite directions are 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 (more precisely we say that angular momentum is conserved). In doing so, the disc areas are no longer equal and the on-axis pressure from the modes no longer cancels out.

The effect of adding the voice coil is shown in Figure 12.

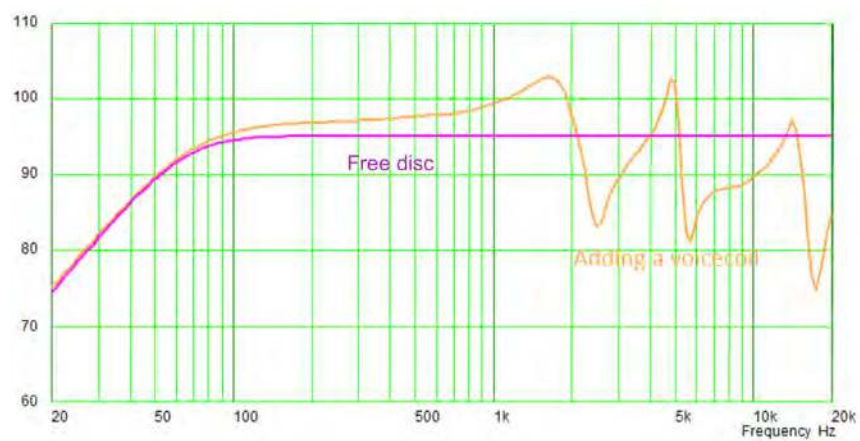


Figure 12. On-axis response of free disc and with voice coil added.

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 enter. 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 behavior of the free disc can be recovered. The disc has been re-balanced as shown in Figure 13.

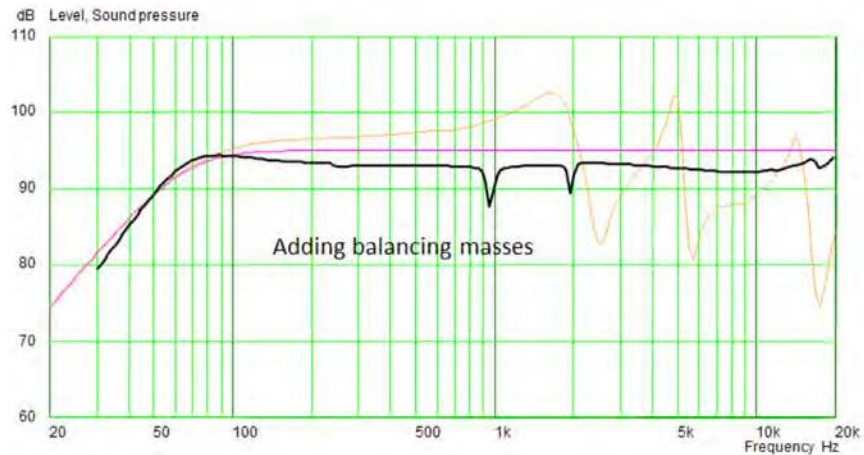


Figure 13. Recovering the free disc behavior by adding balancing masses.

The disc still experiences breakup modes, but now, through the BMR rebalancing principles, the areas of the parts of the disc that move in one direction exactly balance the areas moving in the opposite direction. The process is summarized in Figure 14.

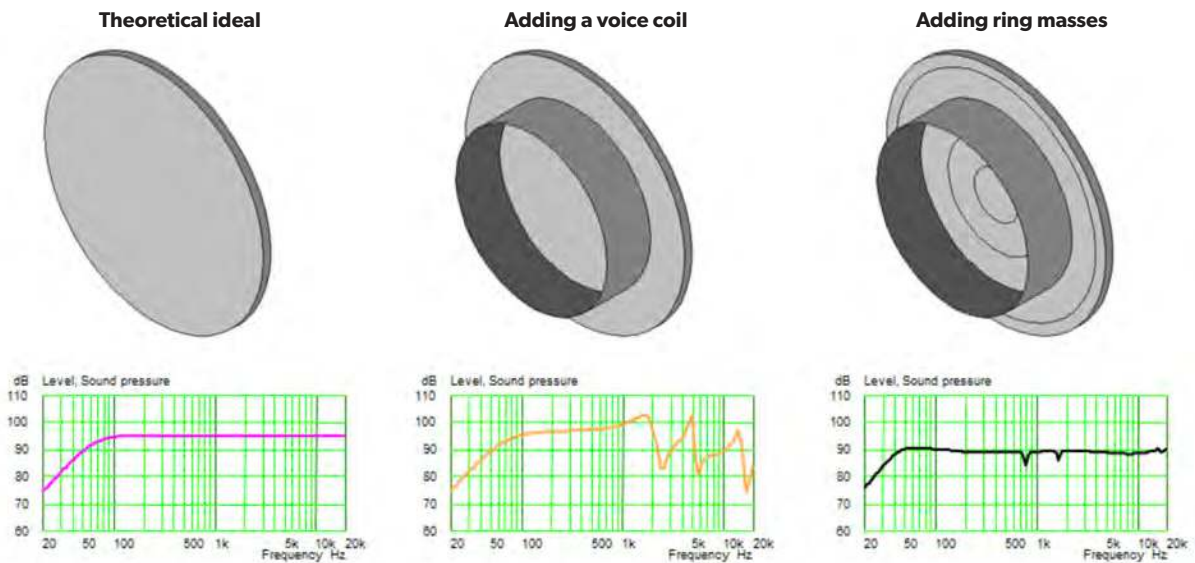


Figure 14. Summary of the BMR balancing method and results.

GOING A LITTLE DEEPER – MODE FIXES

The number of mode fixes required for a given BMR design depends upon 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 inputs the material properties of the disc. Young’s modulus, density, Poisson’s ratio, and shear modulus are key material parameters. Apart from the density, all of these 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. 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 later. Table 1 shows the first six Eigenfrequencies for our disc with two thickness options.

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 this 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.

| 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.

Let's proceed with our 100mm diameter disc, using the 2mm thick option. Figure 15 shows the first four mode shapes.

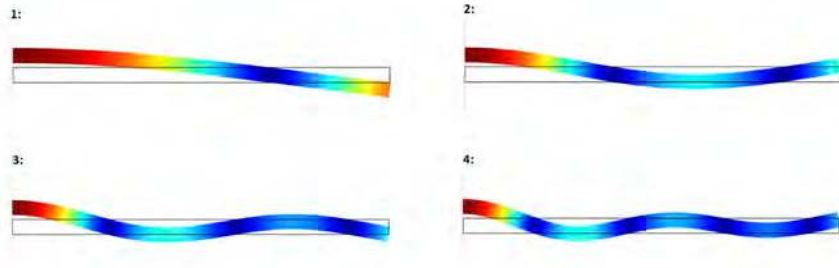


Figure 15. First four mode-shapes (axisymmetric view).

As discussed earlier in Figure 9, each mode of order n has n nodal lines (shown by the darkest blue points in Figure 15). A nodal line is characterized by 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 15. By “driving” the disc at this nodal line, the first mode is suppressed. This seems like a great starting point, and it indeed is an established technique in 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 15. At this location, we are close to an anti-node for modes 2 and 3. This is shown more clearly in Figure 16.

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.

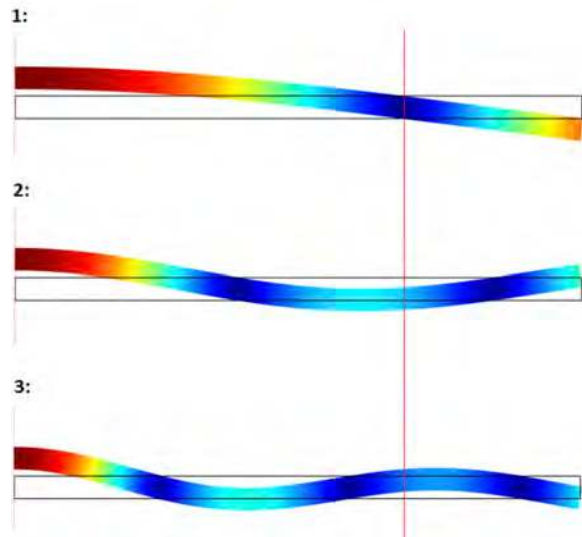


Figure 16. First three modes. Red vertical line indicates the nodal line of first mode.

This is not good. From Table 1, we know that at least the first three modes (and most likely the fourth) occur within our operating band. **So are we stuck?** Actually, this is the point which, prior to the invention of BMR, engineers were stuck 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; it is used as a measure of how easily current will flow in a given circuit, and it may be defined as the inverse of impedance. Fortunately, in the case we are interested in, the mechanics of the disc, there are direct analogies between concepts in electrical, 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 for a given force.

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

Figure 17 shows the disc admittance calculated from the center to the edge for the first three modes.

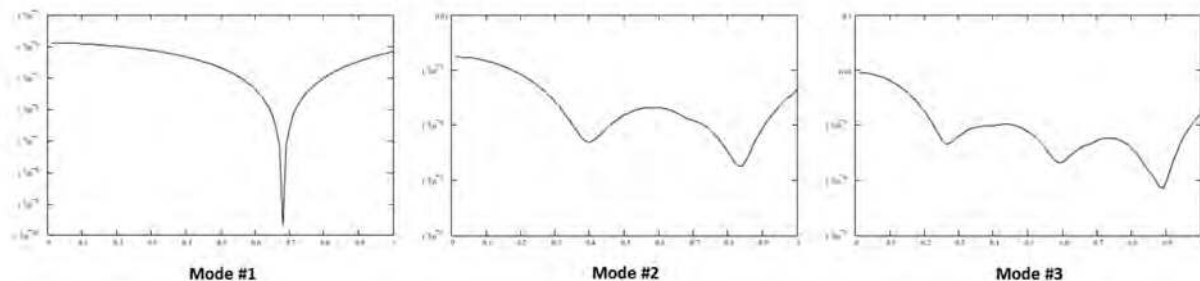


Figure 17. Disc admittance for first three modes.

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 it 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 balanced.

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 17](#). Also see the mode shapes in [Figure 16](#)). 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 is placed at the fourth (outermost) average nodal position. Additional rings of mass are added at the first and third average nodal positions. [Figure 18](#) shows the implementation.

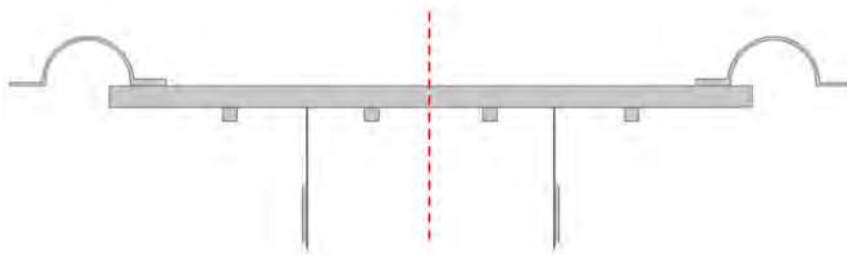


Figure 18. Example configuration of a four-mode-fix BMR. Dashed line shows disc center.

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 18](#), 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 18](#) may appear somewhat complex but note that the only additional components over a conventional system are the two balancing rings. In addition, 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

- Wide dispersion. The extended output off-axis leads to a room-filling sound and improves coverage and intelligibility for multiple listeners.
- The typical requirement for a cross-over in the critical 1kHz – 3kHz region (where the human hearing mechanism is most sensitive) is eliminated.
- Point source integrity is preserved. The sound energy is coming from a single source and not multiple drive units located at different points in space.
- Superb timing from the single acoustic source with no mid-tweeter comb filtering interference effects.
- Flat disc diaphragm eliminates the “shouty” sounding megaphone effect produced by cone shaped diaphragms.
- The flat disc reduces the build height of the drive unit and occupies less of the enclosure volume.





TECTONICAUDIOLABS.COM

(425) 686-7640