PROJECT RYU

Contents

0. Introduction

In designing loudspeaker motors we usually try to avoid saturation along the magnetic path. This means we need to properly size the steel pieces to keep the magnetic flux density below the saturation value. We will start with the input data for our design and usually this is desired flux density in the gap B_g, voice coil diameter d_{vc}, voice coil height h_{vc} and desired voice coil excursion in one way X_{max}.

We should also consider the motor type, either underhung or overhung as part of the input data for our design and such we can determine first the magnetic gap height:

1. Underhung

$$h_g = h_{vc} + 2X_{max} \qquad (1)$$

2. Overhung

$$h_g = h_{vc} - 2X_{max} \qquad (2)$$

1. Magnetic Path

For the remaining of this article I will refer mostly to field coil powered motors but the ideas expressed can be applied to permanent magnet motors as well. In figure 1 we have the axisymmetric section through such a motor. We can see the magnetic path by following the red lines representing the magnetic flux in this example. The direction is given by direction of current in the field coil but we don’t have to be concerned with this aspect in this article.

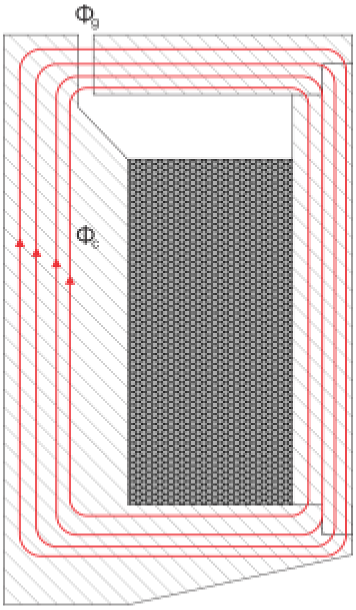


Figure 1. Axisymmetric section of Field Coil Motor

In figure 1 Φ_c represents the magnetic flux through the steel parts or core and Φ_g represents the magnetic flux through the gap. However Gauss law dictates that:

$$\Phi_c = \Phi_g \qquad (3)$$

and since:

$$\Phi_c = B_c A_c, \Phi_g = B_g A_g \qquad (4)$$

results:

$$B_c A_c = B_g A_g \qquad (5)$$

where B_c is the flux density through steel piece, A_c is the cross section area of steel piece perpendicular to magnetic flux, B_g is the flux density through the air gap and A_g is the cross section area of the gap.

The last equation while simple, it is also quite meaningful. It states that unless the area of the gap and the area of the steel through which magnetic flux passes, are equal, then the flux densities through these different areas will be different. This is very important since we need to keep B_c below the saturation value for that particular steel. It also states that since the area of the steel around the gap through which magnetic flux passes is very close to the magnetic gap average area, the flux density in the gap can not be grater than the saturation value for that particular steel because B_c cannot be grater then B_{sat}.

Generally we can say:

$$B_c = \frac{B_g A_g}{A_c} < B_{sat}, A_g = \pi d_{vc} h_g \qquad (6)$$

$$B_c = \frac{B_g \pi d_{vc} h_g}{A_c} < B_{sat} \qquad (7)$$

or better put using our input data:

$$A_c > \frac{B_g}{B_{sat}} \pi d_{vc} h_g \qquad (8)$$

2. Sizing the Steel Parts

To avoid saturation, the area of steel through which magnetic flux passes must satisfy the Equation 8. Now let;s examine what this means for each of the steel parts of a field coil motor.

1. The center pole piece

   Figure 2 shows a section of the center pole piece with red line representing the magnetic flux direction. We can see that the cross section area corresponding to magnetic flux varies, getting smaller towards the top but for now let’s determine the diameter for the thicker section.

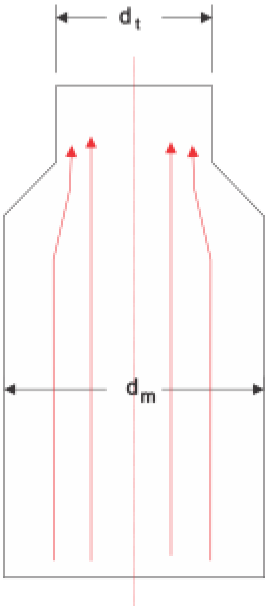


Figure 2. Section of central pole piece

$$A_c = \pi(\frac{d_m}{2})^2 \qquad (9)$$

From Eq 3

$$\pi(\frac{d_m}{2})^2 > \frac{B_g}{B_{sat}}\pi d_{vc}h_g \qquad (10)$$

$$d_m > \frac{\sqrt[2]{\frac{B_g}{B_{sat}}d_{vc}h_g}}{2} \qquad (11)$$

d_t from figure 2 will be determined by voice coil diameter and gap width but it is not as big a factor as d_m because the field lines will not pass through the top section. Magnetic flux will steer towards the gap and thus the area will be very close to the gap area as shown in figure 3. In Eq 6 we have the expression for gap area but in reality that area is larger because of flux bulging out in the gap (flux lines marked a in figure 3) and not strictly following the geometrical path we would like it to. To what extend the difference is depends heavily on the geometry. But this also means it will take more flux to saturate that area so it is safe to assume the gap area as in Eq 6.

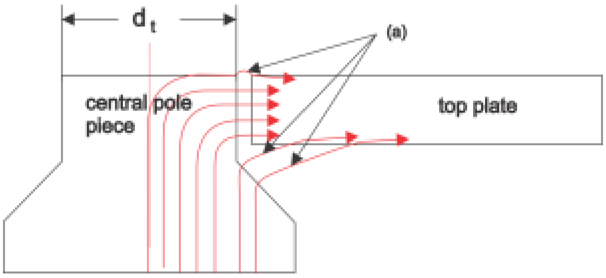


Figure 3. Detail of magnetic gap region

2. Bottom plate

In figure 4 we can see the path the magnetic flux takes through the bottom plate. We can also observe that the flux travels through a disc which means that the diameter increases the further it goes. If the thickness of the bottom plate is constant it will mean the area through which flux passes through increases from the center of the motor towards the outer diameter. While the increase will not hurt the magnetic flux, it is a waste of material and will add extra weight to the motor.

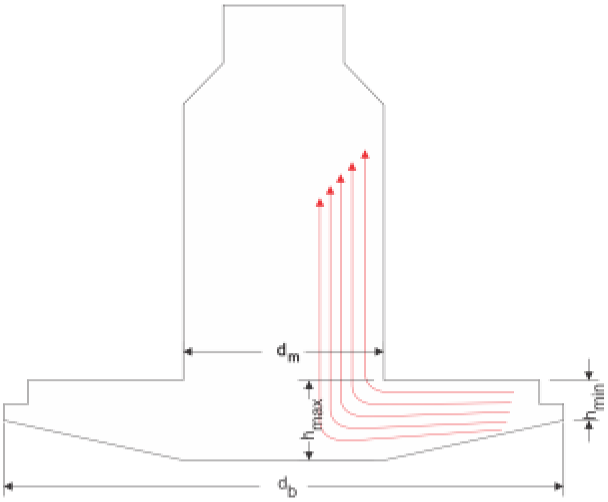


Figure 4. Central pole piece and bottom plate

To size the bottom plate it is best to start from the center. The center pole piece with diameter d_m meets the bottom plate and the flux lines turn about 90 degrees and start passing through the bottom plate. We can thus define the center area as:

$$A_{bp_c} = \pi d_m h_{max} \qquad (12)$$

where A_{bp_c} is the center area of the bottom place.

According to Eq 8:

$$\pi d_m h_{max} > \frac{B_g}{B_{sat}} \pi d_{vc} h_g \qquad (13)$$

$$h_{max} > \frac{B_g}{B_{sat}} \frac{d_{vc}}{d_m} h_g \qquad (14)$$

In figure 4 d_b is the bottom plate diameter. If we want to keep a constant area trough the bottom plate we can easily see that:

$$\pi d_m h_{max} = \pi d_b h_{min} \qquad (15)$$

thus:

$$\frac{h_{max}}{h_{min}} = \frac{d_b}{d_m} \qquad (16)$$

3. Steel Ring

The steel ring piece can be identified in figure 5. This piece can be an actual ring or it can be made using multiple steel rods. Its purpose to the provide a path for magnetic flux between the bottom plate and the top plate. The steel rods will allow for better cooling of the field coil but will concentrate the flux around them in the bottom and top plate so in terms of avoiding saturation it is my opinion not to tapper the the bottom plate's thickness as discussed in previous section. So basically keeping h_min same as h_max.

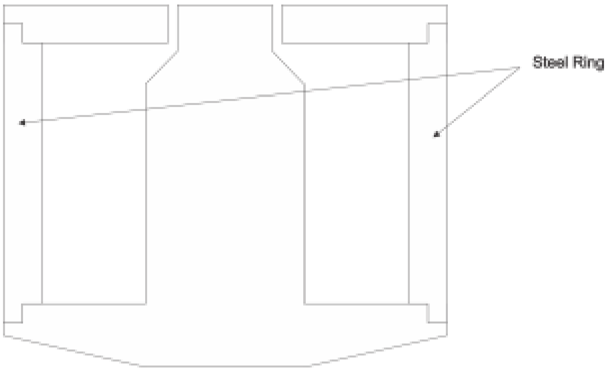
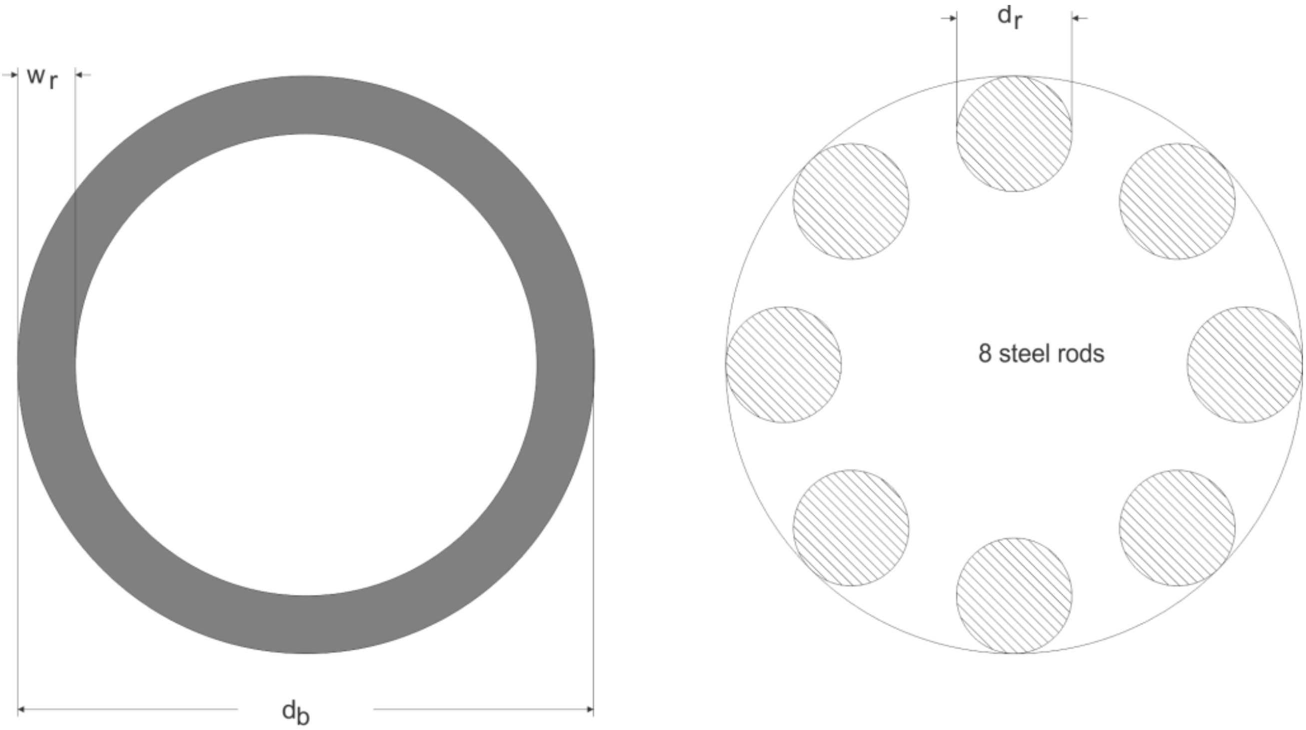


Figure 5. Field Coil Motor structure section showing steel ring

The area perpendicular to the magnetic flux vector is represented in figure 6 for both cases using a ring or multiple rods. For the first case, in next calculations we shall keep the outer diameter of the ring equal to that of the bottom plate d_b and we shall determine the thickness or width of the ring w_r as depicted in figure 6.a.



(a) (b)

Figure 6. Steel Ring (a) and Steel Rods (b) Top View

Lets call d_i ~~the~~ inner diameter of the ring:

$$d_i = d_b - 2w_r \qquad (17)$$

Area for steel ring in Fig 6.a would be:

$$A_r = \pi \frac{d_b^2 - d_i^2}{4} \qquad (17)$$

Following Eq 8:

$$\frac{d_b^2 - d_i^2}{4} > \frac{B_g}{B_{sat}} d_{vc} h_g \qquad (18)$$

$$d_i > \sqrt[2]{d_b^2 - 4\frac{B_g}{B_{sat}} d_{vc} h_g} \qquad (19)$$

$$w_r > \frac{d_b - \sqrt[2]{d_b^2 - 4\frac{B_g}{B_{sat}} d_{vc} h_g}}{2} \qquad (20)$$

Then for steel rods in Fig 6.b Eq 8 would be:

$$N\left(\frac{d_r}{2}\right)^2 > \frac{B_g}{B_{sat}} d_{vc} h_g \qquad (21)$$

$$d_r^2 > \frac{B_g}{B_{sat}} d_{vc} \frac{4}{N} h_g \qquad (22)$$

$$d_r > 2\sqrt[2]{\frac{B_g}{B_{sat}} \frac{d_{vc} h_g}{N}} \qquad (23)$$

where N is the number of steel rods, $N = 8$ in Fig 6.b

4. Top Plate

Top plate behavior is similar to the bottom plate but the thickness of the plate near the gap is given by the gap height h_g as shown in Figure 7. There are cases when the thickness is tapered towards the outer diameter but usually it is constant to make mounting on the speaker frame easier.

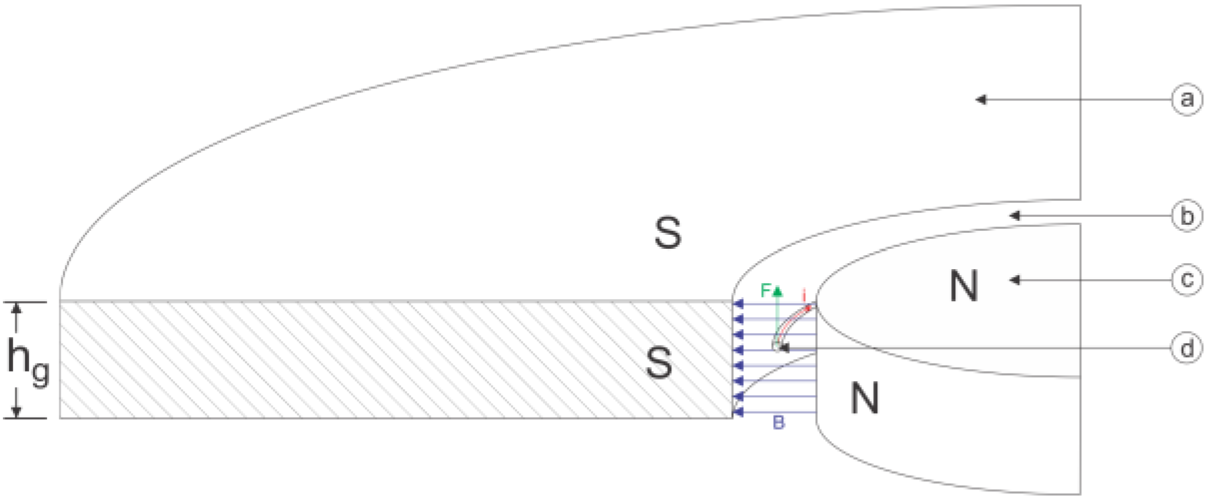


Figure 7. Representation of Magnetic Gap (b) with Top Plate (a), Central Pole Piece (c) and Voice Coil (d)

With a constant thickness, at the outer edge of the top plate, the B_c value will be smaller than B_g as the area though which magnetic flux passes, $\pi d_p h_g$ is larger. Moving towards the gap the area becomes smaller as the diameter decreases towards d_{vc} and thus B_c approaches B_g.

If tapering is desired then Eq 16 should be applied in this case as well.

3. Conclusion

Through simple calculations we can determine rough dimensions of the loudspeaker motor in order to avoid magnetic saturation of the steel in the magnetic circuit. These values can be a starting point and then refined with the use of advanced numerical methods. We also identified the restrictions around the magnetic gap and the limit imposed by the saturation value of the material. For typical 1010 Steel $B_{sat} = 1.85T$, for 1006 Steel $B_{sat} = 2.13T$ and for Hyperco50 Alloy $B_{sat} = 2.4T$.

We can see the importance of using steel materials with high saturation values to lift the limits imposed on the gap. This is also the reason why in some designs only in the region around the gap high quality steel is used and for the rest of the motor’s structure a lower grade is chosen to keep the costs down.