

# ***THE UNDER HUNG VOICE COIL MOTOR ASSEMBLY REVISITED IN THE LARGE SIGNAL DOMAIN***

BY STEVE MOWRY

The under hung voice coil can be defined as a voice coil being shorter in wind height than the magnetic gap height. There are only a handful of transducer manufacturers utilizing this approach today. The major reason for this is that, although well known for motor linearity, magnetic gap efficiency is considered to be too low for a cost effective transducer design. This may or may not be totally accurate; however, we shall discover other issues associated with under hung designs.

Suppose we compare two 8 or 10 in. low frequency transducer motor assembly designs in the large signal domain where  $\mathbf{B}l(\mathbf{x})$  and  $\mathbf{L}_e(\mathbf{x},f)$  are the large signal motor parameters. In doing this we shall define another large signal parameter,  $\mathbf{X}_{\max}$ , such that  $\mathbf{X}_{\max}$  is the peak displacement of the voice coil where  $\mathbf{B}l(\mathbf{X}_{\max}) = 0.82 \mathbf{B}l(\mathbf{0})$ . The amplitude modulation of  $\mathbf{B}l(\mathbf{x})$  at peak displacements of  $\mathbf{X}_{\max}$  will result in approximately 10% distortion, including IM and THD.

DC Resistance@25C	=	6.40	ohms
Conductor Length	=	727.5	in
V C Section Width	=	0.0217	in
Voice Coil Outside Dia	=	1.8974	in
Voice Coil Avg. Dia	=	1.8767	in
Wind Inside Diameter	=	1.8560	in
Number of Turns	=	123.4	
Turns on 1st Layer	=	62.2	
Stacking Factor	=	0.606	
Inner Wind Height	=	0.728	in
Outer Wind Height	=	0.717	in
Average Wind Height	=	0.722	in
Total Wire Mass	=	8.17	g
Adhesive Mass	=	0.37	g
Total Mass w/o Bobbin	=	8.53	g

**Figure 1. 2-Layer Voice Coil Model.**

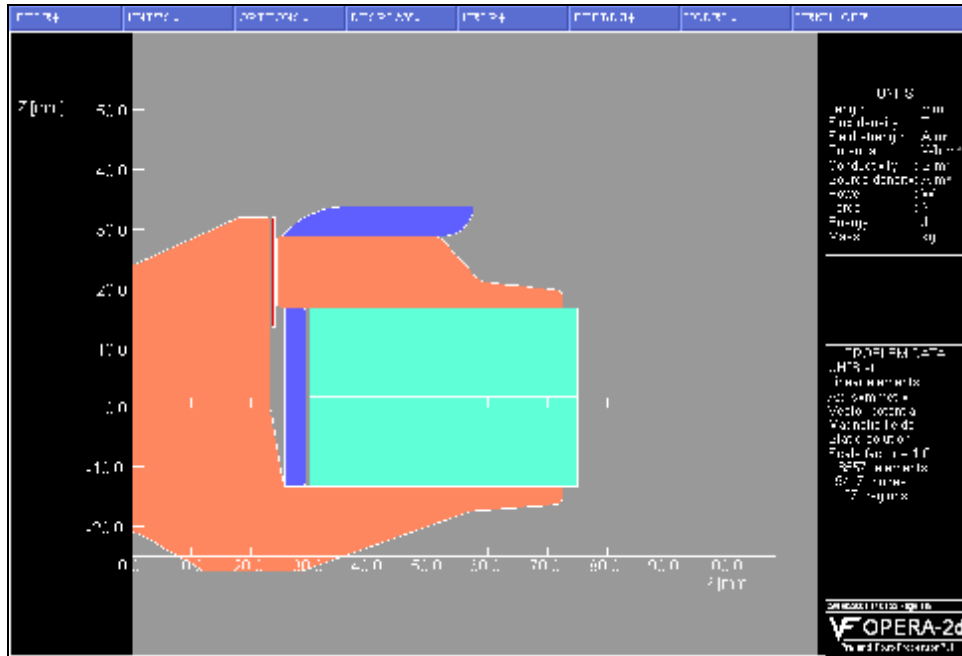
DC Resistance@25C	=	6.40	ohms
Conductor Length	=	727.5	in
V C Section Width	=	0.0602	in
Voice Coil Outside Dia	=	1.9743	in
Voice Coil Avg. Dia	=	1.9152	in
Wind Inside Diameter	=	1.8560	in
Number of Turns	=	120.9	
Turns on 1st Layer	=	22.7	
Stacking Factor	=	0.656	
Inner Wind Height	=	0.265	in
Outer Wind Height	=	0.207	in
Average Wind Height	=	0.236	in
Total Wire Mass	=	8.17	g
Adhesive Mass	=	0.25	g
Total Mass w/o Bobbin	=	8.42	g

**Figure 2. 6-Layer Voice Coil Model.**

The two voice coils defined in figures 1 and 2 are identical with regards to the length of copper magnet wire; however figure 1 illustrates a 2-layer voice coil while figure 2 illustrates a 6-layer voice coil.

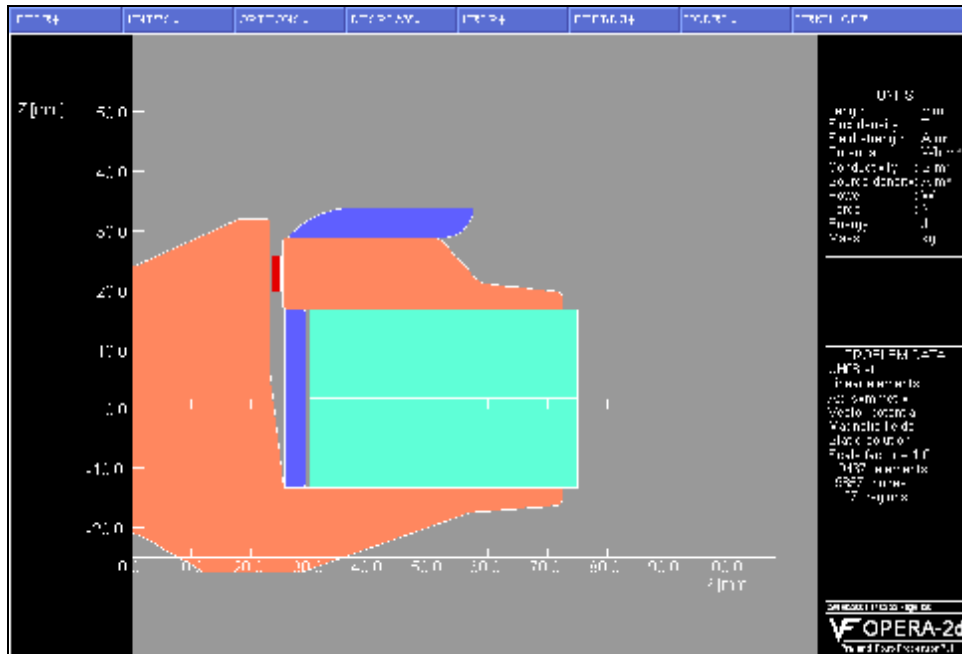
Hopefully, we will discover some meaningful characteristics of the under hung motor design approach. Unfortunately, the author takes no responsibility for the analysis results contained within this article. Continue please but at your own risk.

Let's create two similar motor assembly geometry models for our finite element analysis, utilizing the voice coils in figures 1 and 2 respectively. We shall use VECTOR FIELDS OPERA 2d and SM Audio Engineering's proprietary voice coil command files to perform nonlinear DC static, restart nonlinear AC harmonic, and coupled linear steady state thermal motor assembly finite element analysis simulations. When using computer aided engineering (CAE) software tools, it seems to be more assuring to have a baseline design, to which we can respectively compare and contrast. This sometimes referred to as a 'sanity check'.



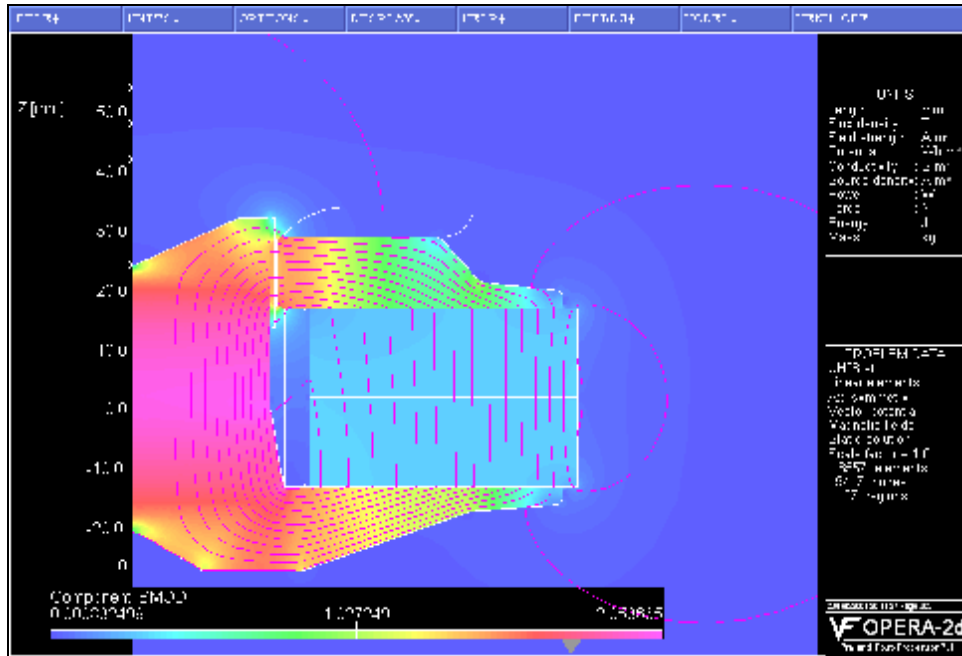
**Figure 3. Axi-Symmetric Over Hung Motor Assembly Geometry.**

Notice that in figure 3, the pole piece is approximately the same height as the top of the voice coil wind. This seemed to result in reasonably symmetrical linking of the over hung voice coil to the distribution of the DC magnetic flux lines about the mid point of the front plate thickness, 12 mm. This can be observed in figure 5, below.



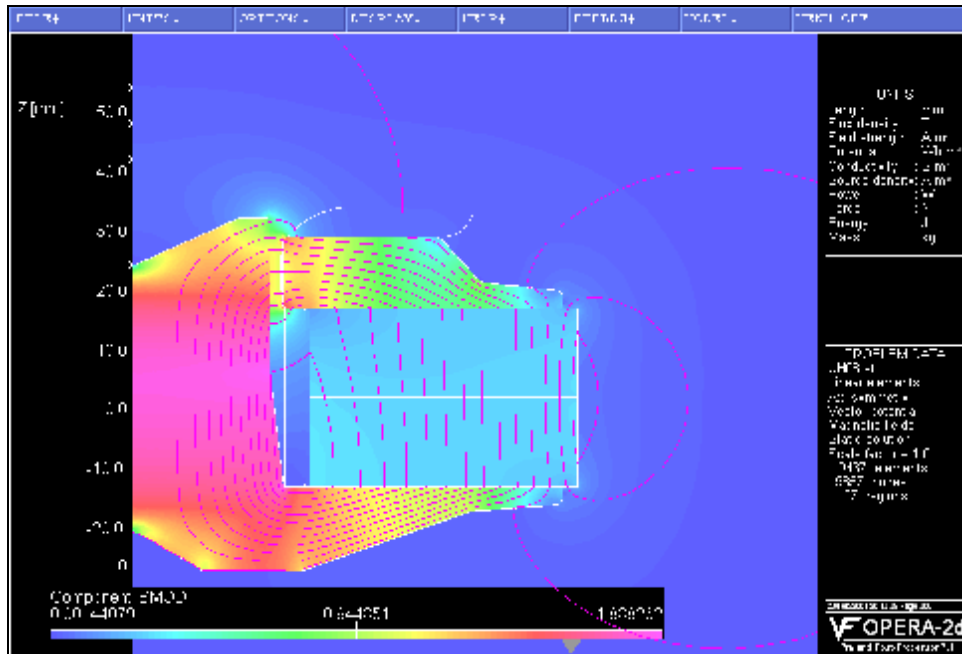
**Figure 4. Axi-Symmetric Under Hung Motor Assembly Geometry.**

The two models illustrated in figures 3 and 4 are identical with the exception of a 6 mm lowering of the pole base OD chamfer to allow additional clearance for the long voice coil in the under hung motor assembly and the respective front plate ID's. Magnetic gap clearances with regards to the voice coils were held constant. The front plate and back plate/pole piece are 1010 annealed steel; the magnets are Ceramic 5 material; the cheating rings are aluminum; the segment of the baskets is also aluminum. We have created the two motor assembly geometry models. Now let's solve the DC electromagnetic problems.



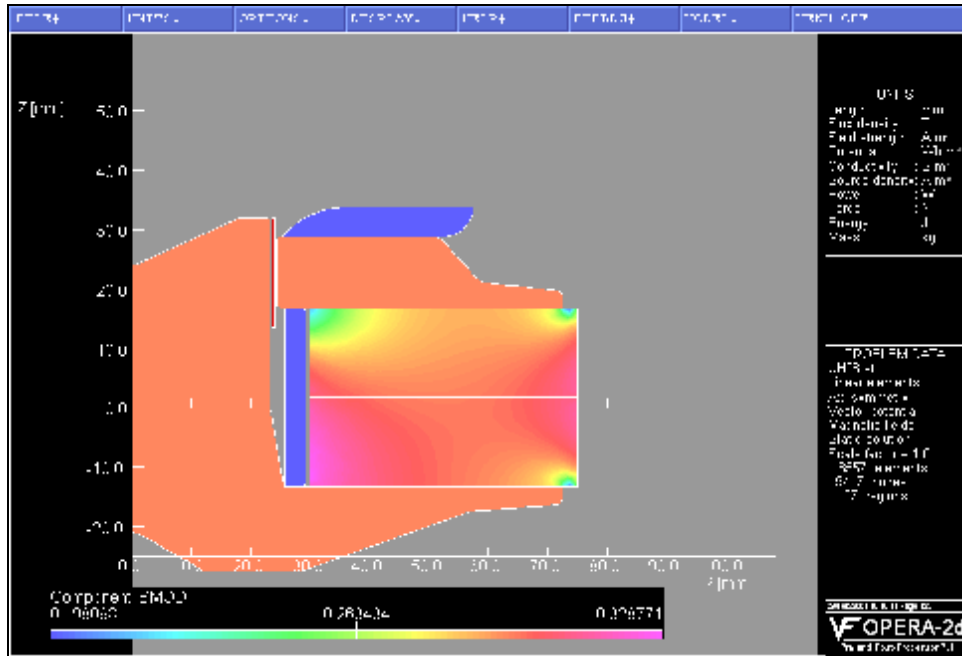
**Figure 5. Contour Plot of  $|B(r,z)|$  with the DC Flux Lines Overdrawn from the DC Finite Element Model of Over Hung Motor Assembly.**

Figure 5 illustrates that the motor assembly seems to be reasonably well designed. There are some typical losses of flux and the peak flux density in the pole is very high at 2 Tesla, 20,000 Gauss. This is a typical design limit.

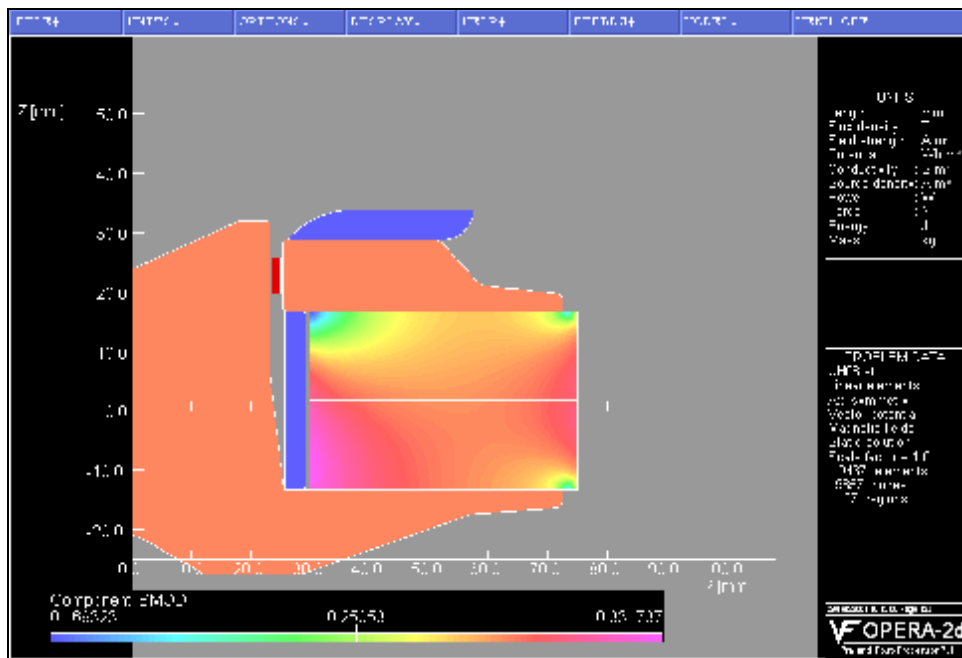


**Figure 6. Contour Plot of  $|B(r,z)|$  with the DC Flux Lines Overdrawn from the DC Finite Element Model of Under Hung Motor Assembly.**

In figure 6 the contour plot illustrates the peak value of  $|B|$  is about 8% lower. This is a result of a small increase in OD flux loss and a reduction of the operating point of the magnets. We are a little farther down on the BH curve for Ceramic 5 due to the increased magnetic gap width required to accommodate the 6-layer under hung voice coil. Let's look at this by comparing figures 7 and 8.

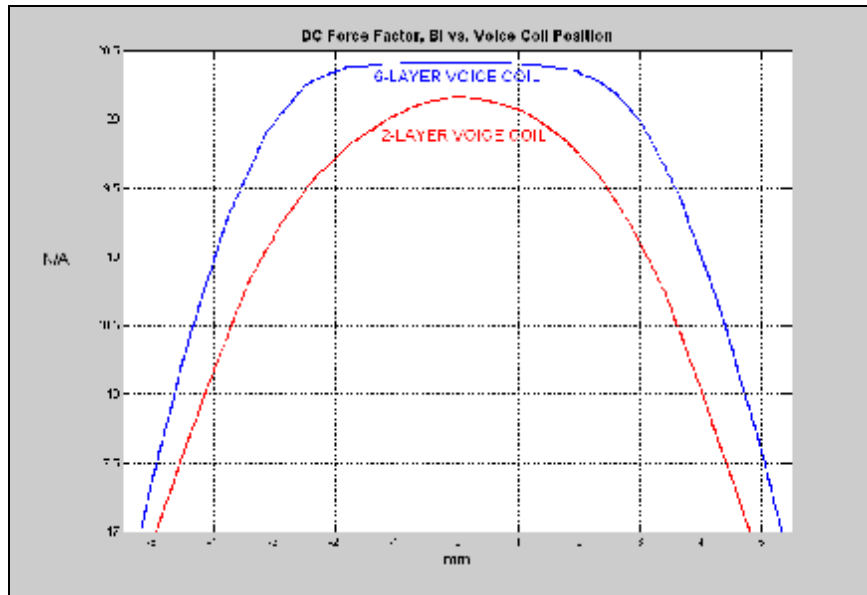


**Figure 7. Contour Plot of the  $|B(r,z)|$  within the Magnets only for the Over Hung Motor Assembly.**



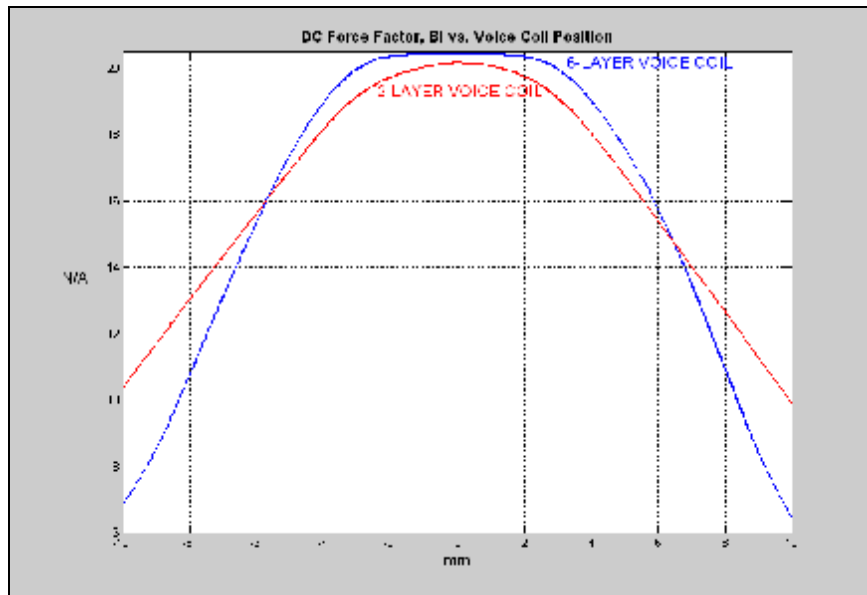
**Figure 8. Contour Plot of the  $|B(r,z)|$  within the Magnets only for the Under Hung Motor Assembly.**

You must look close but you can see the reduction in the  $|B|$  within the magnets in figure 8. Both motor assemblies are robust and should withstand  $-30$  to  $-40$  °C. The magnets are very thick,  $2 \times 15$  mm. The goal of this design was high performance within a reasonable package.



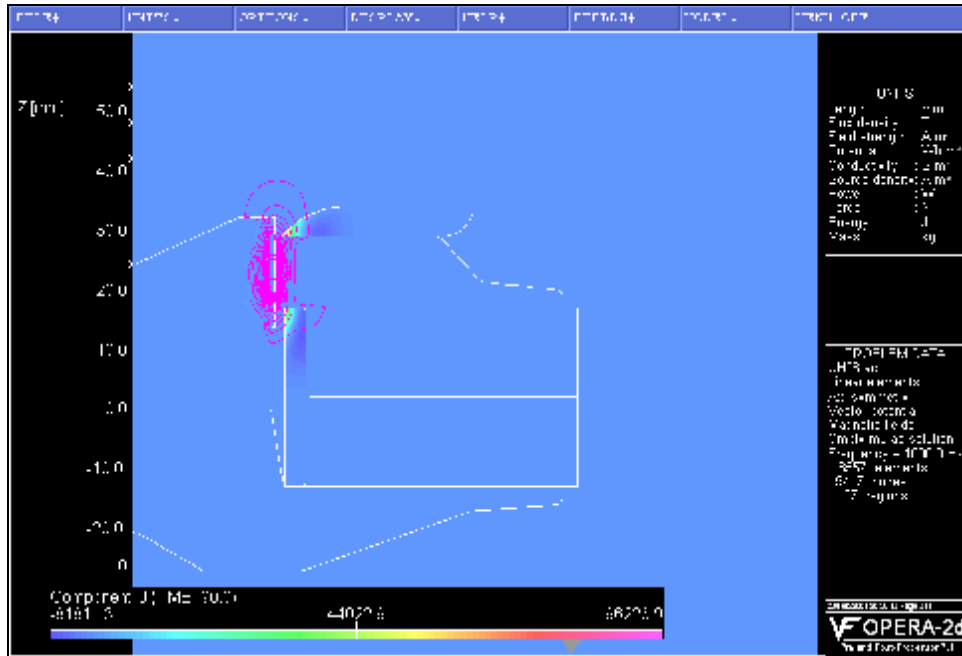
**Figure 7. Simulation of the DC Force Factor,  $B/l$  vs. Voice Coil Position for Approximately  $\pm X_{max}$  Displacements.**

Wow, it looks like the under hung motor assembly is more efficient. How is this possible? Let's look at figure 8 that extends the range of displacement to  $\pm 10$  mm. The over hung voice coil motor assembly, red, has significantly more area under its curve illustrated in figure 8. However, not within the usable displacement range defined by  $\pm X_{max}$ . Figure 7 tells a much different story.



**Figure 8. Simulation of the DC Force Factor,  $B/l$  vs. Voice Coil Position.**

The DC analysis of the under hung motor assembly looks good. Let's apply an AC current density of  $10^5 \text{ Am}^{-2}$  to each voice coil's cross-section and see what happens.

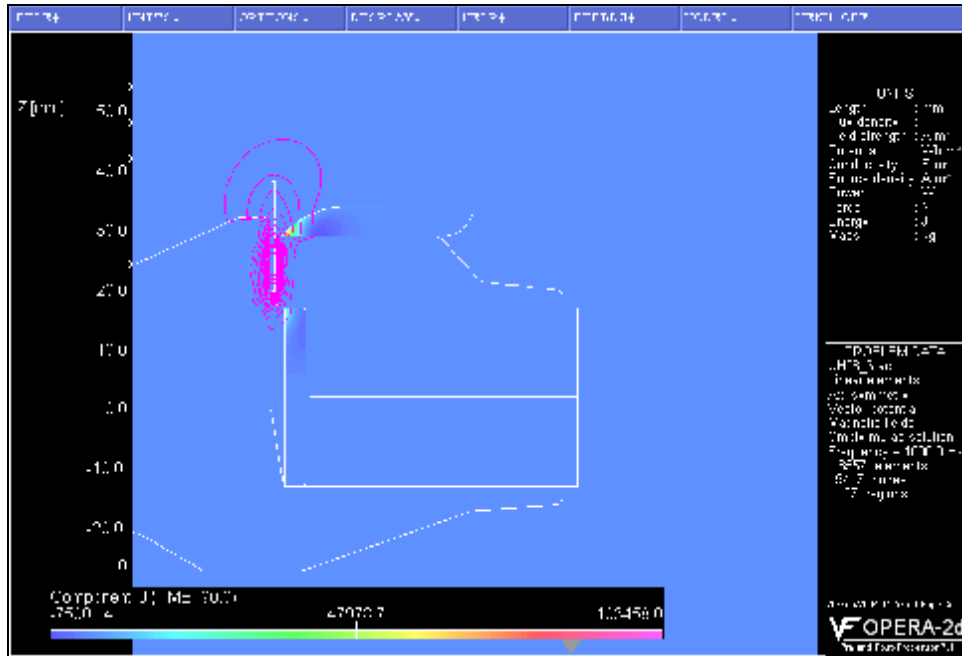


**Figure 9. Contour Plot of the Induced AC Eddy Current Density with the AC Flux Lines Overdrawn for the Over Hung Motor Assembly at the Voice Coil Rest Position,  $x = 0$ , at 1.0 kHz with 1.0 A Input.**

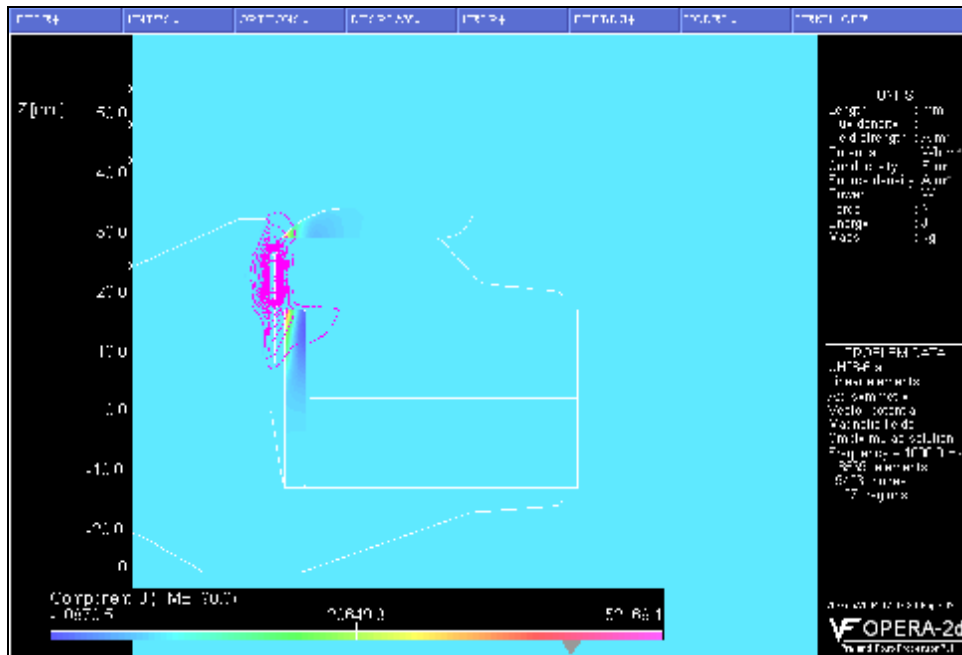


**Figure 10. Contour Plot of the Induced AC Magnetic Field,  $|B(r,z)|$ , for the Over Hung Motor Assembly at 1.0 kHz with 1.0 A Input.**

We see that at 1.0 kHz there is a small induced AC magnetic field within the steel around the voice coil. In figure 9 we also see the induced AC flux lines' paths. The aluminum cheating ring and basket seem to be controlling the induced AC magnetic field. The looping of the AC flux lines within the gap is desirable. Let's move the coil up and down by 6.0 mm and see what happens.



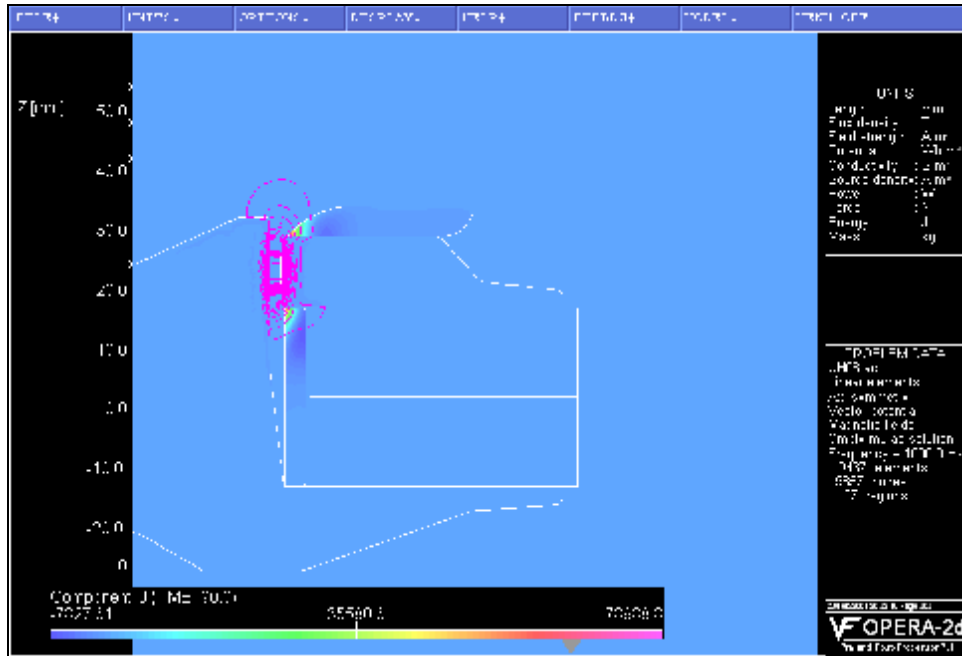
**Figure 11. Contour Plot of the Induced AC Eddy Current Density with the AC Flux Lines Overdrawn for the Over Hung Motor Assembly at the Voice Coil Position,  $x = 6$ , at 1.0 kHz with 1.0 A Input.**



**Figure 12. Contour Plot of the Induced AC Eddy Current Density with the AC Flux Lines Overdrawn for the Over Hung Motor Assembly at the Voice Coil Position,  $x = -6$ , at 1.0 kHz with 1.0 A Input.**

It appears that the paths of the AC flux lines do not change significantly and therefore inductance will change with voice coil position. The flux linkage is changing with position, while the magnetic field remains relatively constant within the steel.

Let's look at the AC harmonic analysis results for the under hung motor assembly.

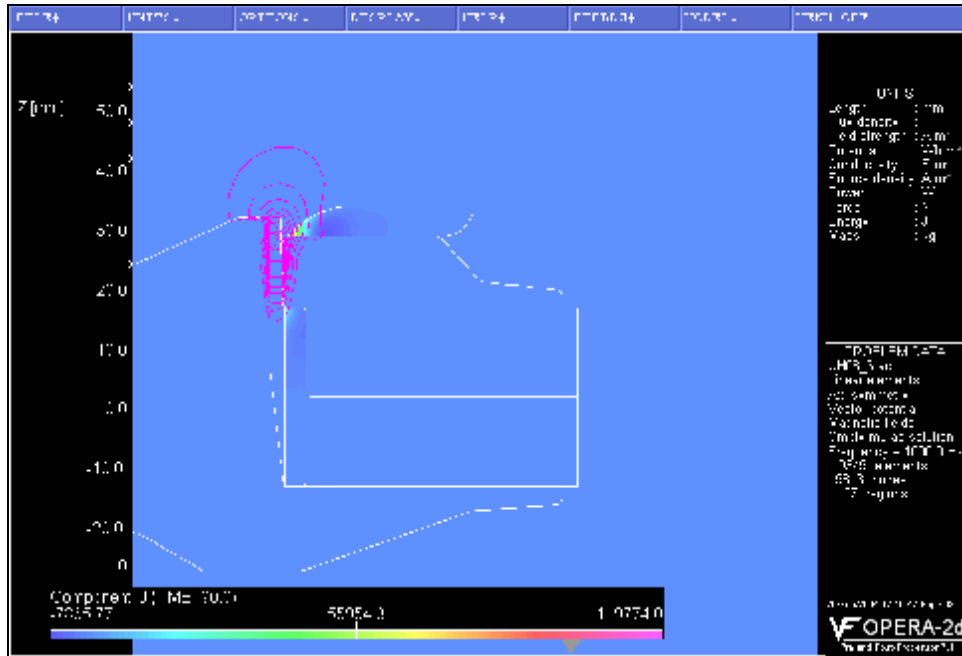


**Figure 13. Contour Plot of the Induced AC Eddy Current Density with the AC Flux Lines Overdrawn for the Under Hung Motor Assembly at the Voice Coil Rest Position at 1.0 kHz with 1.0 A Input.**

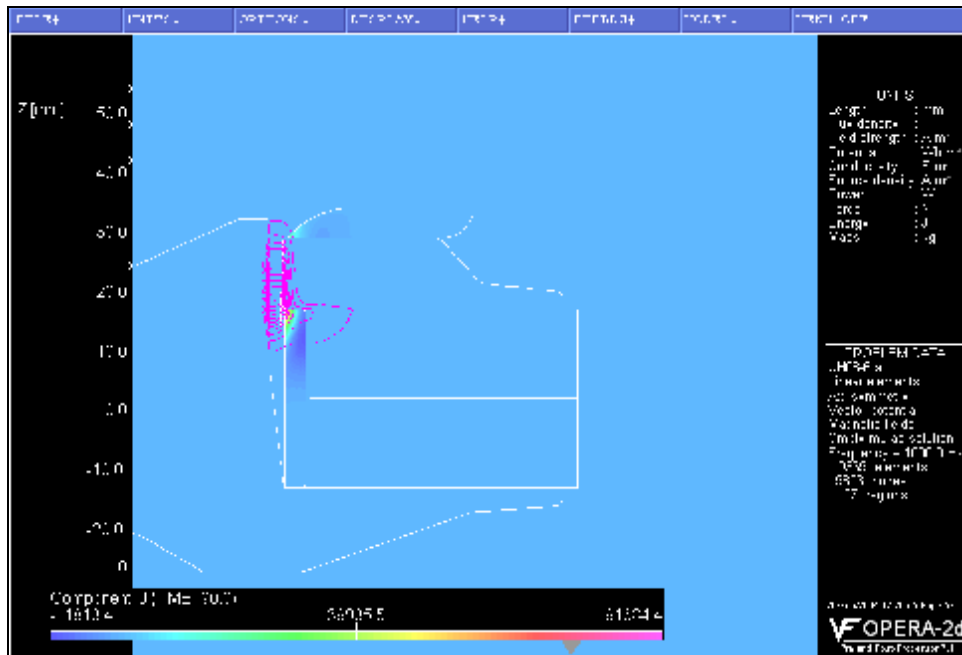


**Figure 14. Contour Plot of the Induced AC Magnetic Field,  $|B(r,z)|$ , for the Under Hung Motor Assembly at 1.0 kHz with 1.0 A Input at the Voice Coil Rest Position.**

The value of the induced AC magnetic flux density,  $|B(r,z)|$ , is 62% greater at 38 Gauss. This could indicate a problem with self-inductance. Let's continue with our investigation of simulation results.



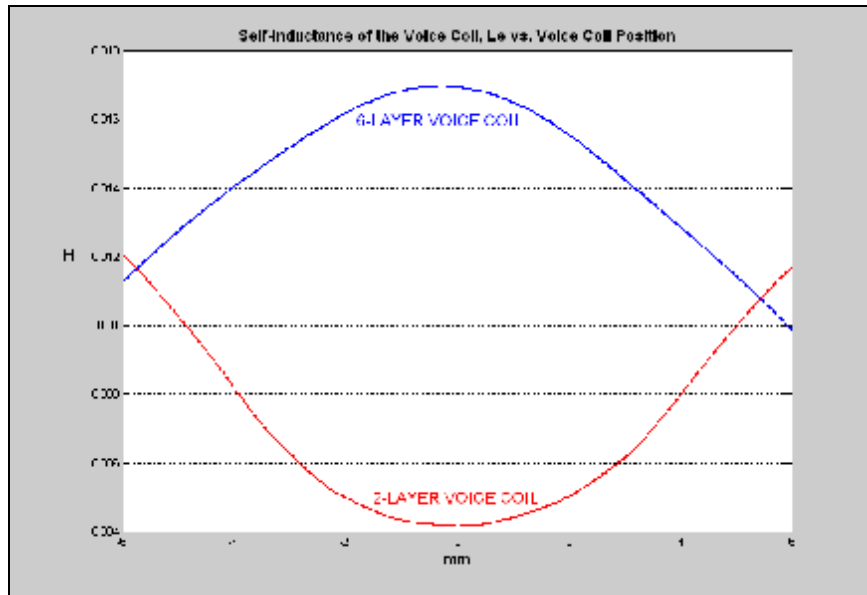
**Figure 15. Contour Plot of the Induced AC Eddy Current Density with the AC Flux Lines Overdrawn for the Under Hung Motor Assembly at the Voice Coil Position,  $x = 6$ , at 1.0 kHz with 1.0 A Input.**



**Figure 16. Contour Plot of the Induced AC Eddy Current Density with the AC Flux Lines Overdrawn for the Under Hung Motor Assembly at the Voice Coil Position,  $x = -6$ , at 1.0 kHz with 1.0 A Input.**

With regards to the short under hung voice coil, the induced AC magnetic field does change with voice coil position and seems to go with the voice to some extent.

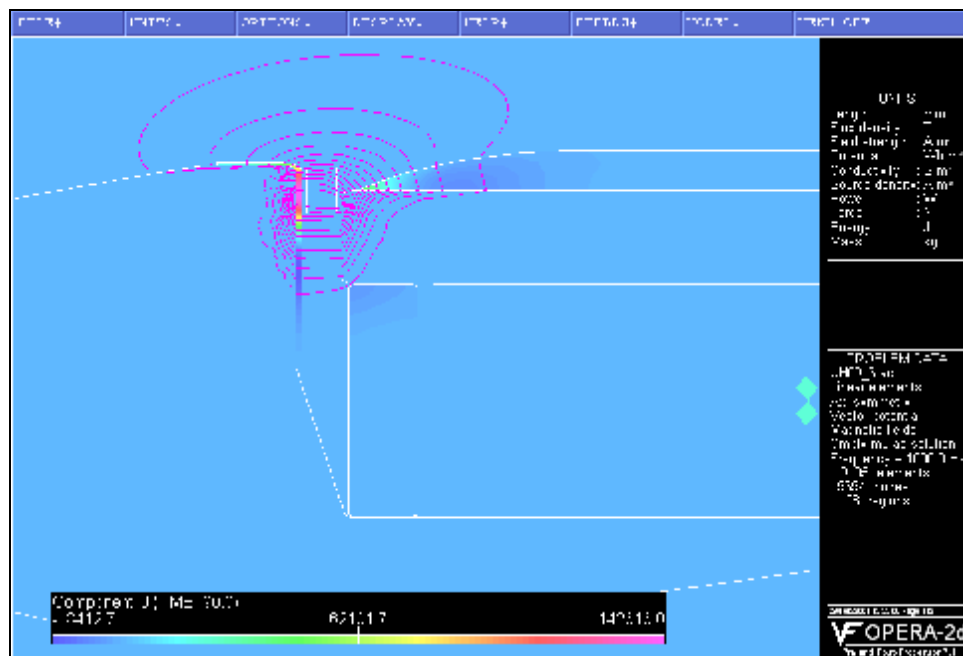
Let's sweep the voice coils through the respective induced AC magnetic fields and plot the results in figure 17.



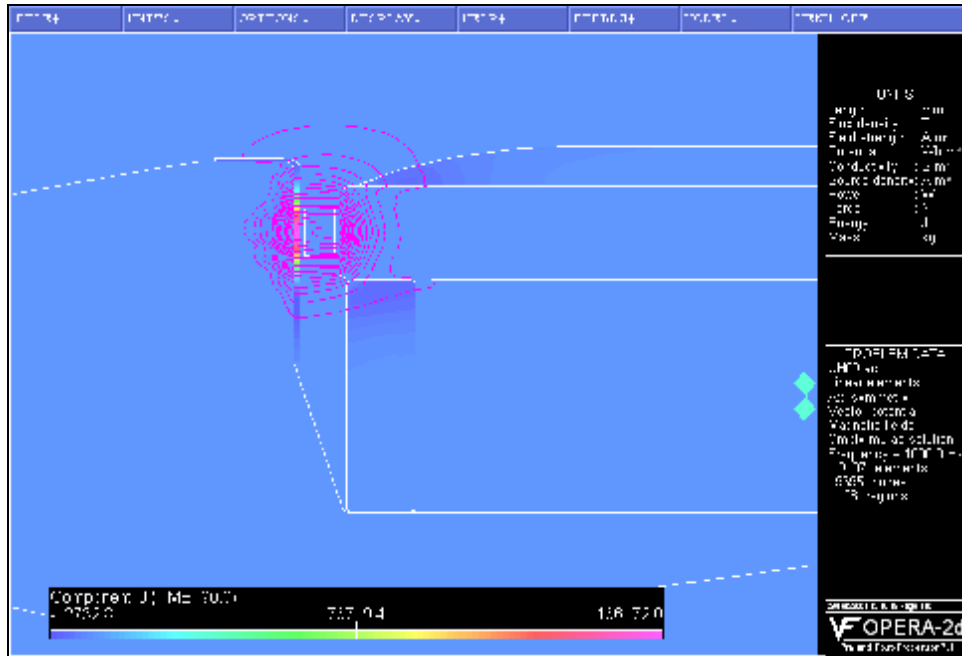
**Figure 17. Simulation of the Self-inductance of the Voice Coils versus Displacement at 1.0 kHz with 1.0 A Input.**

Oh no, the self-inductance of the under hung voice coil is high and amplitude modulation of inductance for both voice coils is also high at 1.0 kHz. Can we fix this? The answer is yes; however, the fix will come at a cost in terms of money and magnetic gap efficiency. Let's try placing a 0.3 mm thick oxygen free copper cap right over the pole piece. Unfortunately, this will reduce the OD of the pole piece by 0.6 mm and increase the annular magnetic gap width by 0.3 mm, resultantly  $\mathbf{B}$  will be reduced. We can get most of the  $\mathbf{B}$  back by substituting Ceramic 8 grade magnets in our under hung design.

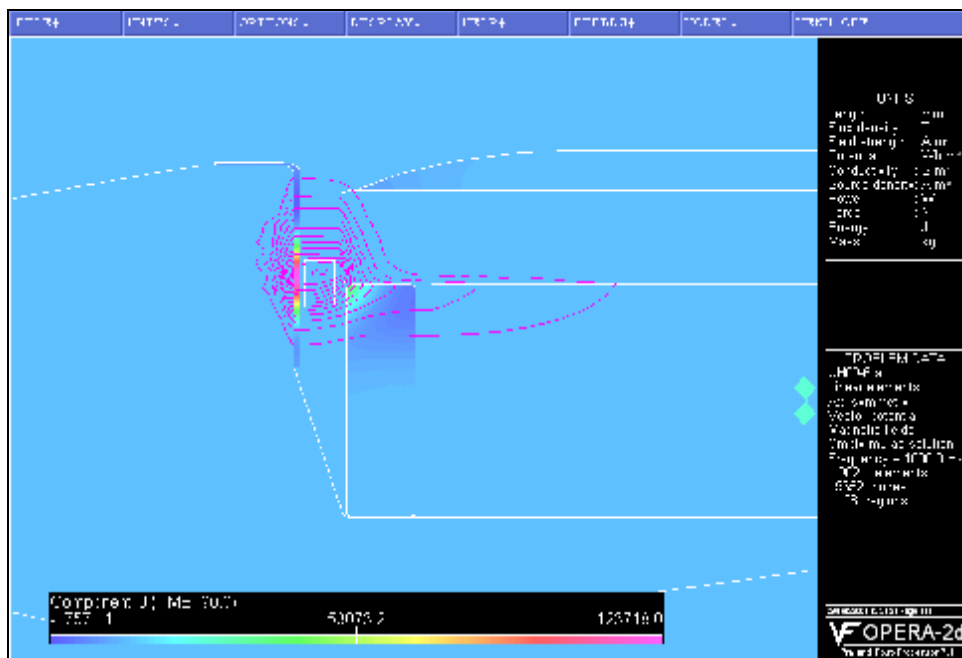
Let's start by examining the AC harmonic analysis of the under hung motor assembly with the addition of the 'copper cap'. We want to reduce the eddy current density within the steel and thus reduce the induced AC magnetic fields. We will zoom in on the magnetic gap for a clearer look at what the copper cap is doing.



**Figure 18. Contour Plot of the AC Induced Eddy Current Density with the AC Flux Lines Overdrawn at 1.0 kHz with the Voice Coil at 6 mm Displacement.**



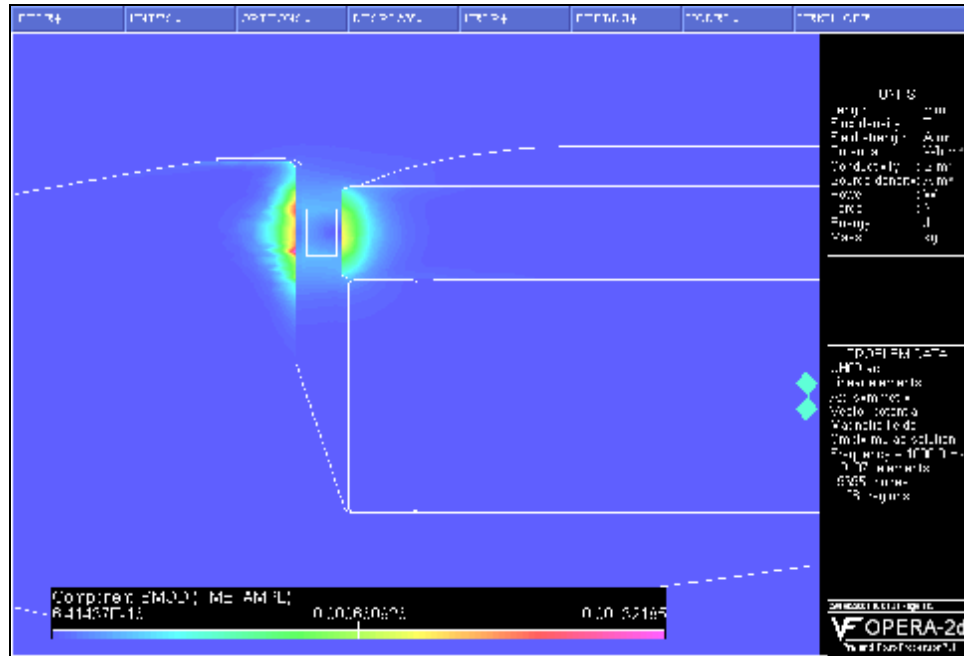
**Figure 19. Contour Plot of the AC Induced Eddy Current Density with the AC Flux Lines Overdrawn at 1.0 kHz with the Voice Coil at 0 mm Displacement.**



**Figure 20. Contour Plot of the AC Induced Eddy Current Density with the AC Flux Lines Overdrawn at 1.0 kHz with the Voice Coil at - 6 mm Displacement.**

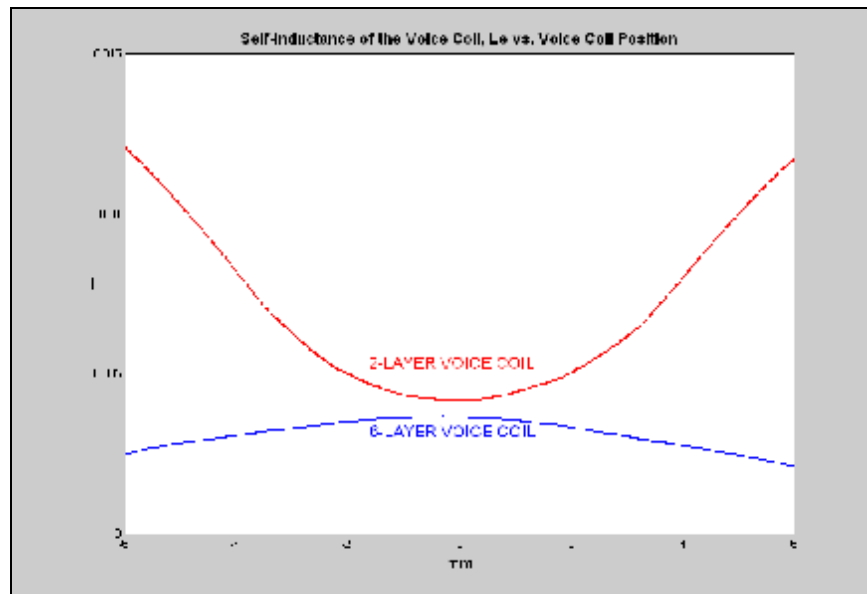
The induced AC magnetic field center seems to follow the voice coil as it is displaced through the gap as indicated by the AC flux lines' paths at 1.0 kHz. This is illustrated in figures 18, 19, and 20. This is typically desirable.

In figure 21, we can see the AC flux density within the steel in the proximity of the short voice coil,  $|\mathbf{B}(\mathbf{r},\mathbf{z})|$ , is now very small. The copper cap seems to be working.



**Figure 21. Contour Plot of the Induced AC magnetic field,  $|B(r,z)|$ , at 1.0 kHz for the Under Hung Motor Assembly with the Copper Cap.**

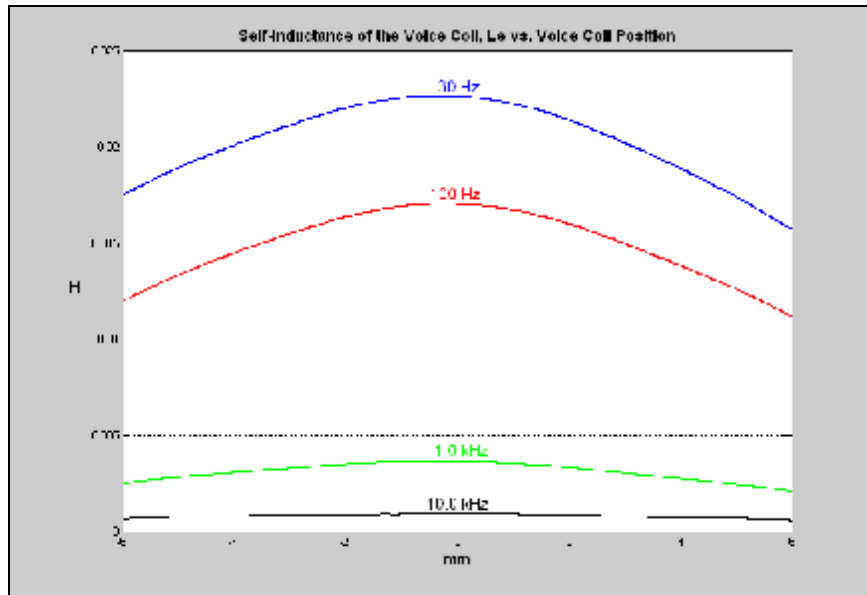
The copper cap has reduced the peak value of the AC magnetic field from 38 Gauss to 13 Gauss at 1.0 kHz. This looks good. Let's sweep the voice coils through the induced AC magnetic fields.



**Figure 22. Simulation of the Self-Inductance of the Voice Coils at 1.0 kHz with 1.0 A Input.**

Ok, that looks much better, very linear and a peak value of  $L_e \approx 3$  mH, but what about  $B_l(x)$ ? Subsequently, figure 25 will show that the under hung motor assembly has slightly less  $B_l(0)$ ; however, this small reduction in peak  $B_l$  actually increases  $X_{max}$ .

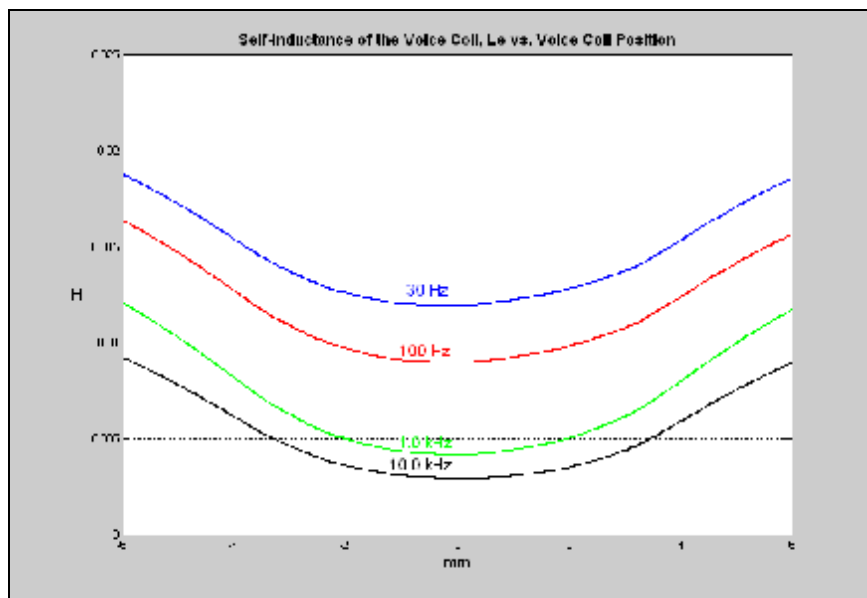
Let's first look at the inductance of the under hung voice coil at several other frequencies.



**Figure 23. Simulation of the Self-Inductance of the Under Hung Voice Coil at 30 Hz, 100 Hz, 1.0 kHz, and 10.0 kHz with 1.0 A Input.**

Figure 23 illustrates the frequency and amplitude modulation of inductance for our under hung motor assembly design. This is about the best we can do. The copper cap is working at high frequencies, but is too thin to work well at low frequencies.

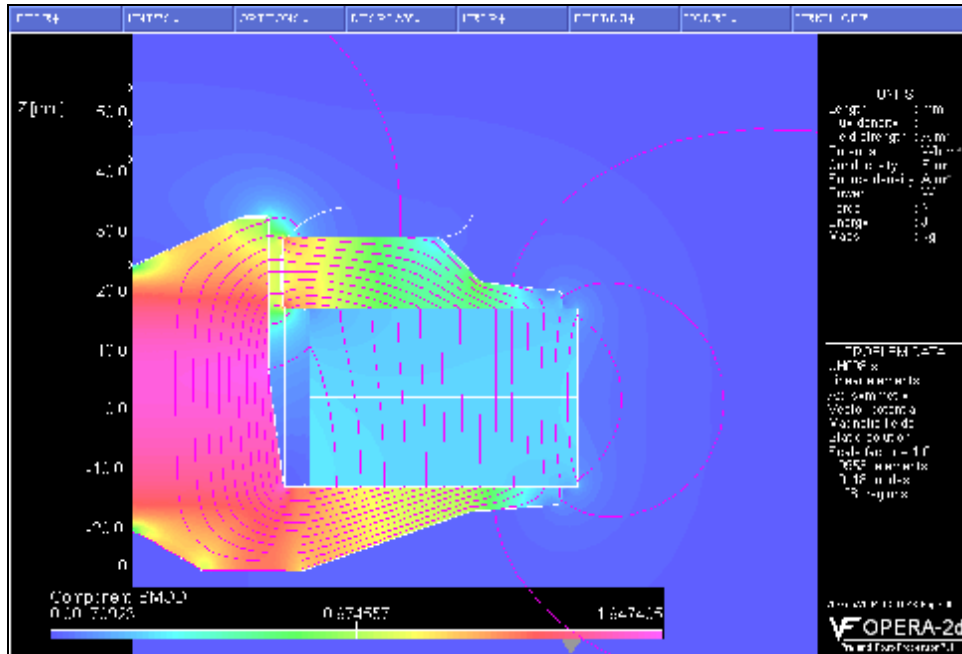
Let's now go back and look at the inductance of the over hung voice coil motor assembly at several frequencies.



**Figure 24. Simulation of the Self-Inductance of the Over Hung Voice Coil at 30 Hz, 100 Hz, 1.0 kHz, and 10.0 kHz with 1.0 A Input.**

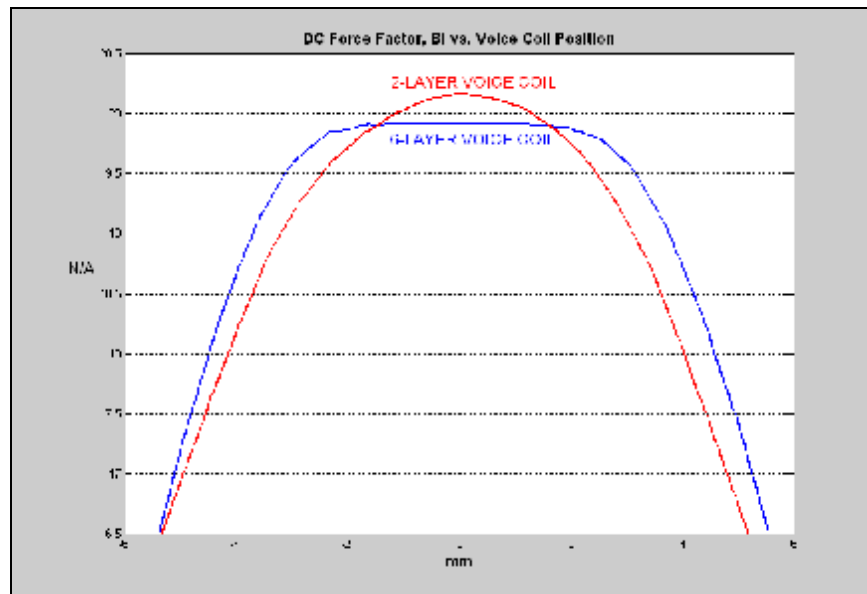
In comparing figures 23 and 24, we see that the under hung voice coil's inductance is well behaved at 1.0 kHz and 10.0 kHz; however the inductance is still quite high at 30 Hz and 100 Hz. These are 120 plus turn coils on a 47 mm bobbin ID. This is about the best we can do.

Let's look at the new DC model of the under hung motor assembly with the Ceramic 8 magnets and the copper cap, wider magnetic gap.



**Figure 25. Contour Plot of  $|B(r,z)|$  with the DC Flux Lines Overdrawn from the DC Finite Element Model of Under Hung Motor Assembly with the Copper Cap.**

The new DC solution for our under hung design looks very similar to the previous DC solutions. The peak value for the  $|B(r,z)|$  has increased to 1.9 Tesla, 19,00 Gauss. Let's sweep the voice coil through the gap.



**Figure 26. DC Simulation of  $B/l$  verses Voice Coil Position**

With regards to figure 26, we can see that we have lost some peak  $B/l$ ; however, there is still significantly more area under the blue curve than the red curve. The area under the curves is the 'Work' done per Ampere over the operating displacement range,  $\pm X_{max}$ . Well it looks like the under hung voice coil does more work; is more linear; has less inductance and inductance modulation at high frequencies; and has a more  $X_{max}$ . The under hung transducer should sound better but it will cost a little more.

The  $X_{max}$  of our under hung motor design is approximately 5.5 mm compared to 5.0 mm for the over hung motor assembly. This phenomenon is related to the 'fringing' of the

DC flux lines above and below the front plate to effectively increase the magnetic gap height. This can be observed in figure 25.

The small difference in peak  $B$  is insignificant and the under hung design has about 240 mg less moving mass. The bobbin of the under hung voice is 6.2 mm shorter than the over hung voice coil and figure 2 indicates a 110 mg mass difference due to adhesive mass.

Let's take a look at the induced AC force factors at 30 Hz for both the long and the short voice coils.

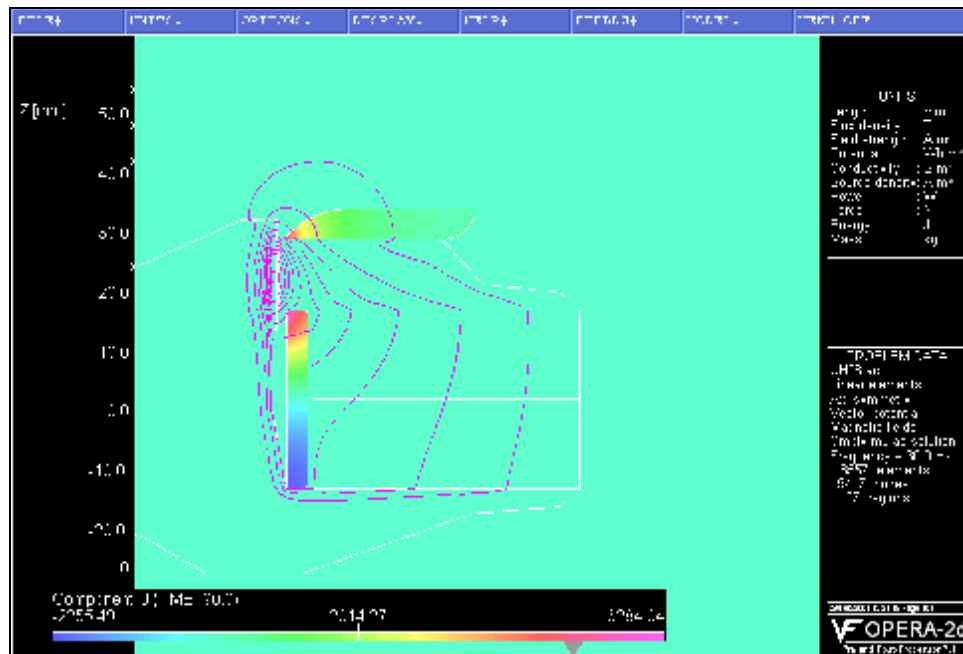


Figure 27. Contour Plot of the AC Induced Eddy Current Density with the AC Flux Lines Overdrawn at 30 Hz with 1.0 A Input and the Voice Coil at the Rest Position for the Over Hung Motor.

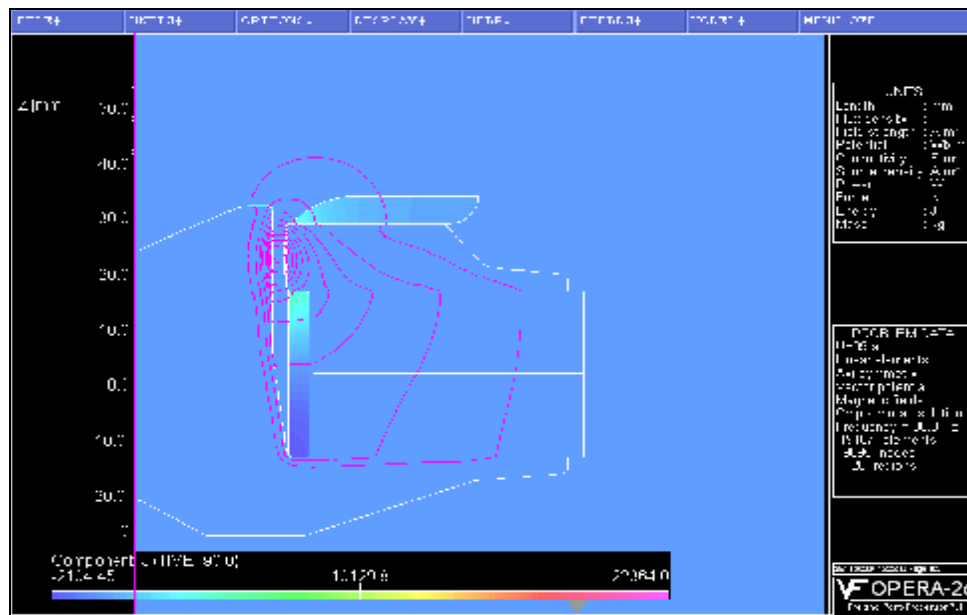
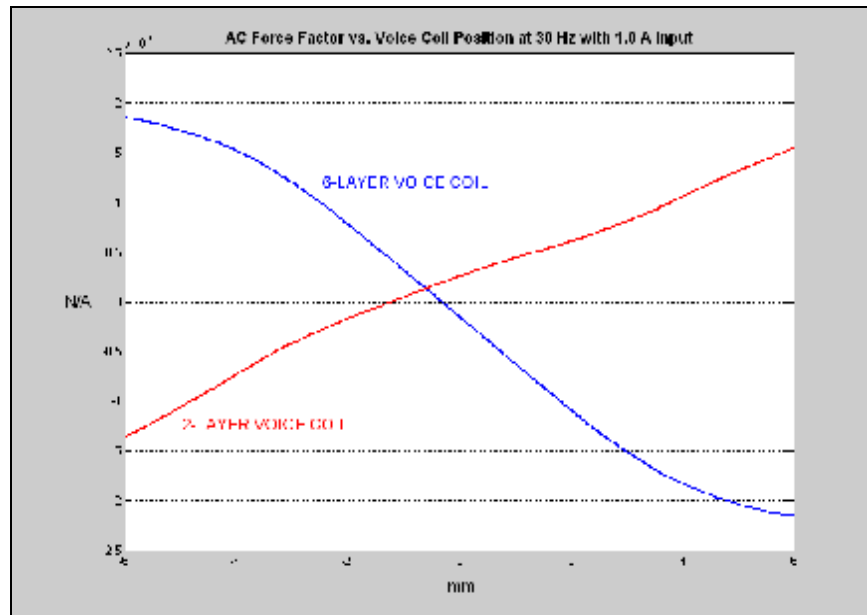


Figure 28. Contour Plot of the AC Induced Eddy Current Density with the AC Flux Lines Overdrawn at 30 Hz with 1.0 A Input and the Voice Coil at the Rest Position for the Under Hung Motor with the Copper Cap.

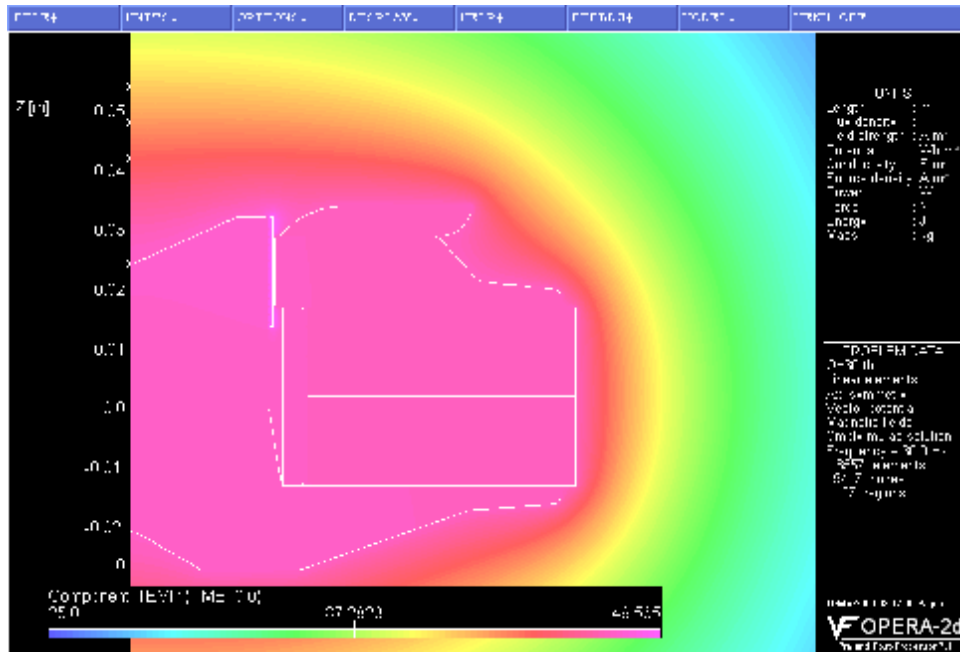
Ok we have our 30 Hz AC models, now let's sweep the voice coils through the AC magnetic fields to simulate the AC force factor. Is it linear and does it pass through the origin? Is there x-y symmetry?



**Figure 29. Simulation of the AC Force Factors versus Voice Coil Position at 30 Hz with 1.0 A Input.**

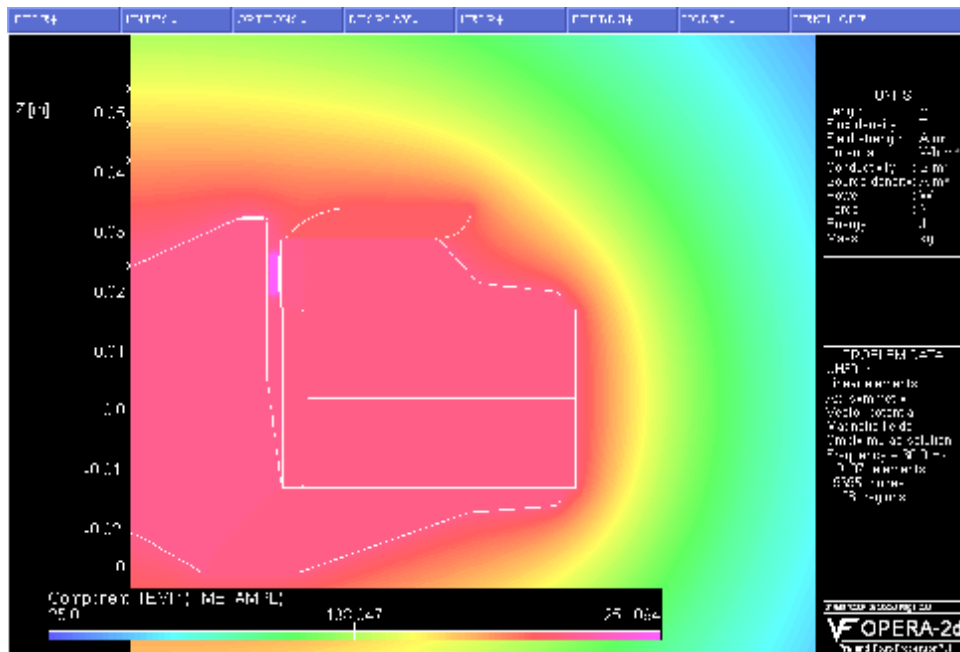
The AC force factors are small and quite linear over the operating displacement range; however, as we saw in figure 27, the AC magnetic center is shifted into the motor for the over hung design. The under hung motor assembly also has a shift of the AC magnetic center into the motor, but it is small. This is illustrated in figure 28. The AC force factor will modulate with the DC force factor and can induce a DC offset, depending on drive level and frequency. This is quite important in under hung designs. The DC force factor is so linear that the voice coil may have trouble finding its effective or dynamic magnetic center, while in the case of the over hung motor assembly there is a clear DC magnet center. This was illustrated in figure 26. Resultantly, the suspension for the under hung transducer must be carefully designed and can help to correct any induced DC offset. The transducer suspension for the under hung motor assembly must also control the voice coil displacement such that the voice coil does not encounter 'lockout' of magnet gap. Simply put, we must prevent the short voice from completely leaving the effective magnetic gap.

Ok everything looks good but what about the relative voice coil operating temperatures? This could be a design issue. Let's take a look.



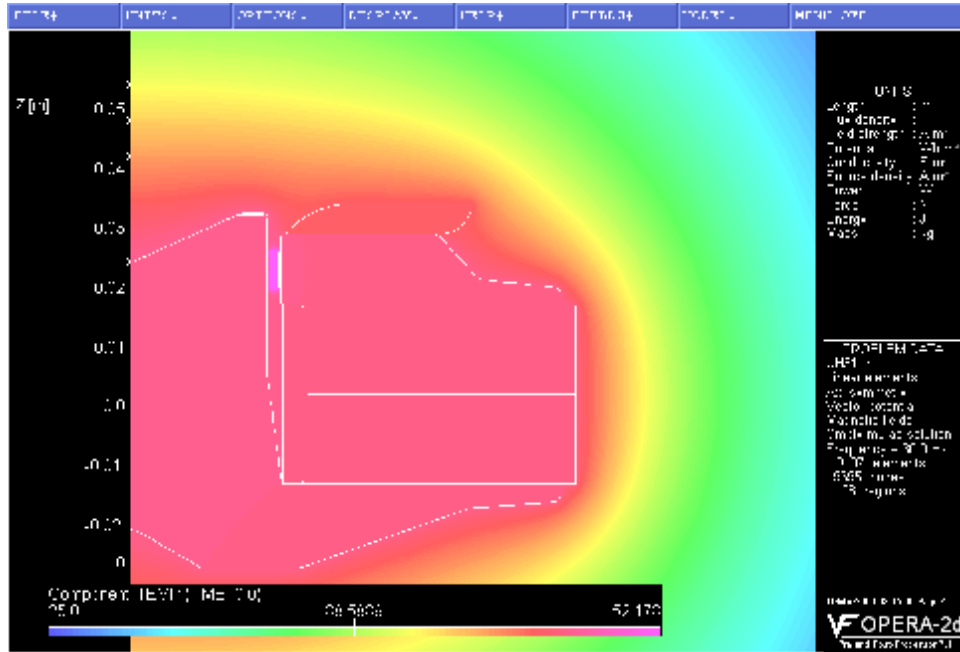
**Figure 30. Contour Plot of the Steady State Operating Temperature, °C, of the Over Hung Motor Assembly with ~ 40 W<sub>rms</sub> Input.**

In figure 30 we see that the over hung voice coil's operating temperature is about 150 °C for 40 Watts input. The long voice coil appears to have good thermal conductivity with respect to the motor structure.



**Figure 31. Contour Plot of the Steady State Operating Temperature, °C, of the Under Hung Motor Assembly with ~ 40 W<sub>rms</sub> Input.**

Oh no in figure 31, we see that the voice coil is too hot. We must reduce the input current density. Let's reduce the input current by 25% and the resultant power input by 50%, 3 dB.



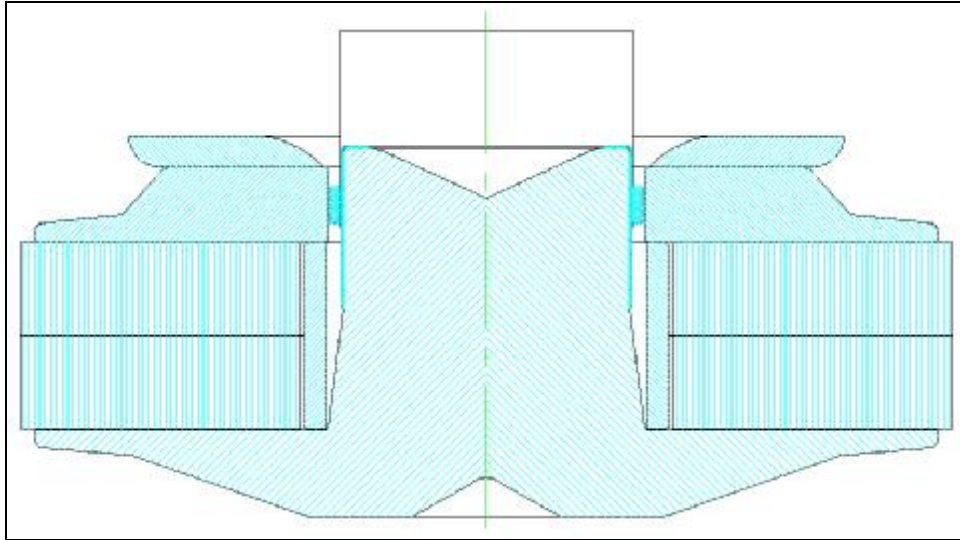
**Figure 32. Contour Plot of the Steady State Operating Temperature, °C, of the Under Hung Motor Assembly with ~ 20 W<sub>rms</sub> Input.**

Ok that's better. This was to be expected. The long, 18.3 mm, voice coil can dissipate double the power of the short 6.0 mm voice coil. Based on previous generalized theories relating to voice wind height and power handling we should have lost 5 dB ( $10\log_{10}(18.3/6.0) \approx 5$ ); however, we lost 3 dB in power handling. This is not trivial and frankly represents the major limitation with under hung voice coil motor assembly designs. We cannot fix this. There will be more thermal compression in the under hung design; however, there is also the question of whether the transducer will be thermally limited or displacement limited. That question cannot be fully answered until we have completed the transducer design and chosen the enclosure. The answer lies within the system application, the loudspeaker system.

If we recap what we observed in this example, we can summarize in the following:

1. Low DC magnetic gap efficiency was not found to be a design issue;
2. Short voice coils within tall magnetic gaps tend to be more self-inductive than over hung voice coils;
3. Short voice coils will operate at a higher temperature than tall voice coils for the same input power;
4. Under hung voice coil motor assemblies have a more linear DC force factor over a given displacement range than over hung motor assemblies;
5. Wide magnetic gaps tend to increase the effective magnetic gap height and potentially  $X_{\max}$  by increasing the DC magnetic fringing field above and below the front plate;
6. Under hung motor assemblies will inherently cost more than under hung designs.

Now that we have completed our analysis, it's DXF out and mirror within our CAD program. The under hung motor assembly drawing is illustrated in figure 33, below.



**Figure 33. Cross-Sectional Assembly Drawing of Under Hung Voice Coil Motor.**

The motor assembly investigated and shown above is high performance with regards to linearity and the large signal parameters  $\mathbf{B}I(\mathbf{x})$  and  $L_e(\mathbf{x},f)$  have been simulated. It should be somewhat obvious by now that without the command files to evaluate FEA solution results, the capabilities of OPERA or any other electromagnetic modeling software package alone are limited.

In closing, we have observed that the voice coil operating temperature and the related thermal compression along with high self-inductance of short voice coil motor assemblies are real issues regarding under hung voice coil motor designs. Magnetic gap efficiency seems to be at best a secondary issue.

Steve Mowry