β AND ELECTROMAGNETIC TRANSDUCTION

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16 June 2004

When reviewing transducer specifications, transducer models and/or test results, you always seem to see the term **B*l***, sometimes referred to as the **B*l*** product or the force factor. Occasionally, the **B*l*** product is represented as a function of the voice coil position, **B*l*(*x*)**. **B*l*(*x*)** is identified as a large signal nonlinear transducer parameter. This term, **B*l***, implies that the more turns there are on the voice coil bobbin the better. Ironically, like so many other transducer and loudspeaker design topics, the **B*l*** product is confusing and counter intuitive to say the least.

In practice and without respect to the power amplifier's current capacity, I will show that the fewer the number of turns the better! How can this be you ask? Let me investigate this heresy with you.

Equations

Starting with the voice coil design equation, $\mathbf{R_e} = \frac{\rho l}{\mathbf{S}}$ (Ω), where $\mathbf{R_e}$ is the DC resistance of the voice coil, ρ is the resistivity of the voice coil wire (Ωm); **S** is the cross-sectional area of the voice coil wire (m^2) and l is the length of the voice coil wire (m). This relationship is intuitive. The larger the diameter of the voice-coil wire, the lower the DC resistance. The longer the voice-coil wire the higher, the DC resistance for a given wire material and inherent resistivity.

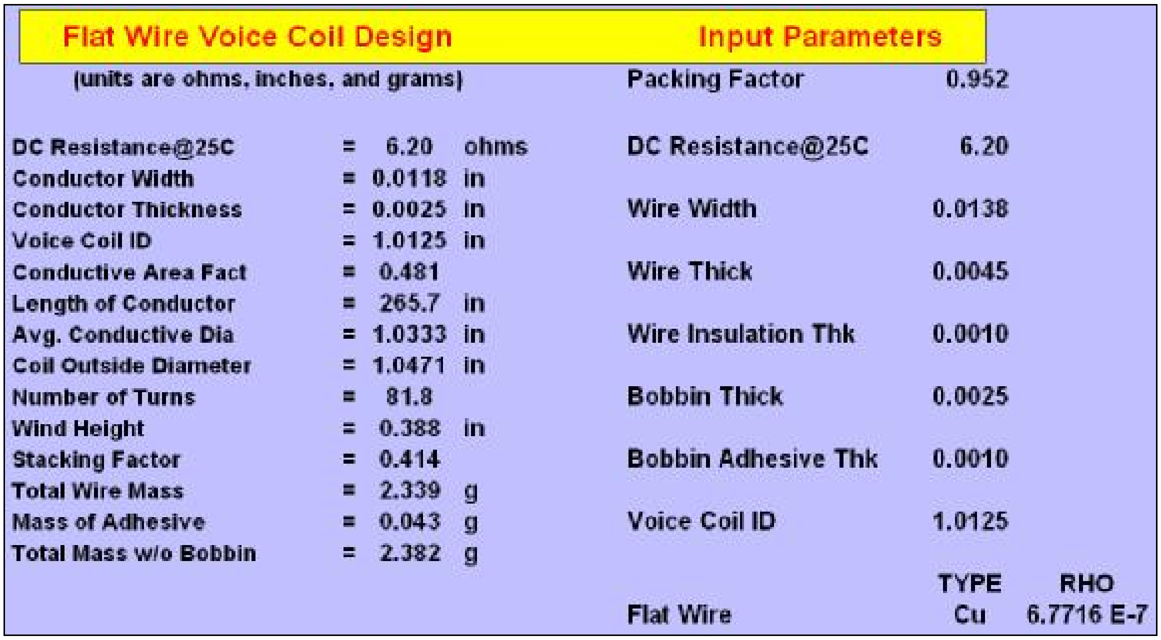
Now consider the input signal from our power amplifier assuming that the power amplifier is an ideal voltage source. This simply means that you can apply the linear equation known as Ohm's law, $\mathbf{V} = \mathbf{R_e I}$ (V), where **V** is the input voltage and **I** is the input current (A).

With regards to the force acting upon the moving assembly, you know that the input or Lorentz force can be defined as $\mathbf{F} = \mathbf{B}l\mathbf{I}$ (N), where **B** is the flux density in the magnetic gap (T). The input power from the amplifier is simply the product of the voltage and the current, $P = \mathbf{VI}$ (A). You also can define the power input in terms of current and resistance, $P = \mathbf{I}^2\mathbf{R_e}$ (W) by again applying Ohm's law. In doing this you can relate power to force by substituting the equation for force into the equation for power in terms of current, $P = \frac{\mathbf{F}^2\mathbf{R_e}}{(\mathbf{B}l)^2}$ (W). Now you can identify and define a term that I refer to as BETA, $\boldsymbol{\beta} = \frac{(\mathbf{B}\boldsymbol{l})^2}{\mathbf{R_e}}$ (N^2W^{-1}). This is convenient because you divide out the DC resistance and then use **β** as the true figure of merit for evaluating the performance of a motor assembly–regardless of the nominal impedance, which tends to be less than objective in many instances. **β** is no stranger, for $\mathbf{Q_{es}} = \frac{\mathbf{1}}{\boldsymbol{\beta}}\sqrt{\frac{\mathbf{M_{ms}}}{\mathbf{C_{ms}}}}$ and $\mathbf{dB_{SPL}}$ goes as $\mathbf{10log_{10}}\boldsymbol{\beta}$, double **β** and you get +3dB; half **β** and you get –3dB.

Now substitute the voice-coil design equation into the definition of **β**, where $\boldsymbol{\beta} = \frac{\mathbf{B^2}\boldsymbol{l}^2\mathbf{S}}{\rho \boldsymbol{l}} = \frac{\mathbf{B^2Vol_C}}{\rho}$ (N^2W^{-1}). This is an important relationship that tells you that what is most desirable is to maximize the volume of conductor, $\mathbf{Vol_C}$ (m^3), within the magnetic gap. What happened to ***l*** ? I will get to that shortly.

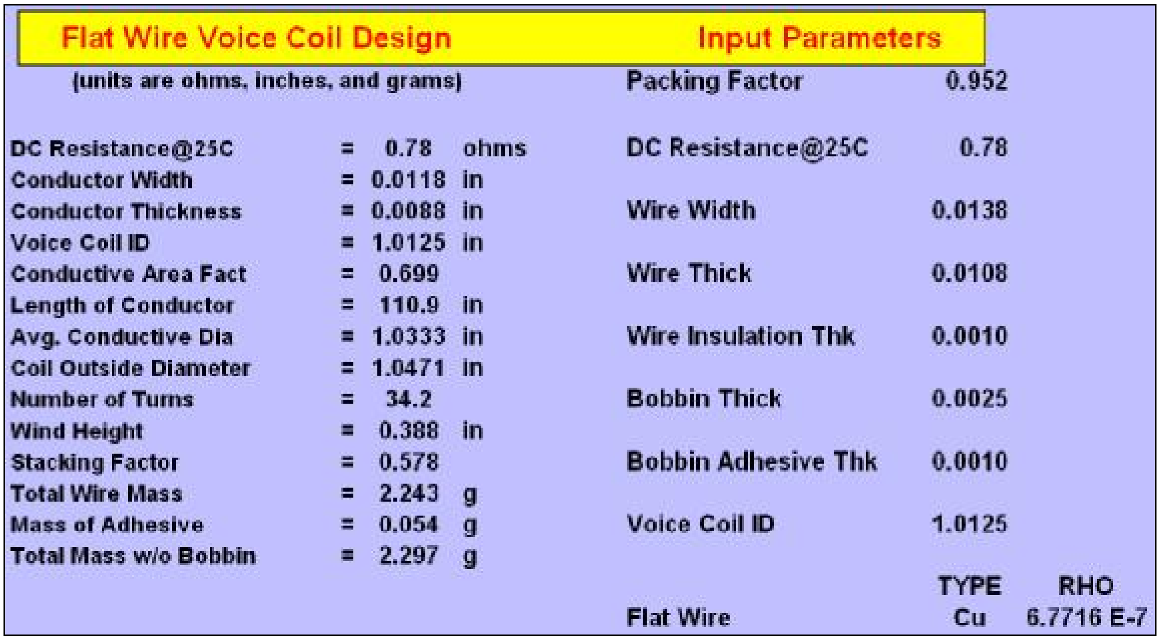
Simulations

Here are two voice coil simulations. The first voice coil (Figure 1) is for an 8Ω transducer for home Hi-Fi applications, and the 1Ω voice coil (Figure 2) is for automotive applications.



Flat Wire Voice Coil Design				Input Parameters		
(units are ohms, inches, and grams)				Packing Factor	0.952	
DC Resistance@25C	=	6.20	ohms	DC Resistance@25C	6.20	
Conductor Width	=	0.0118	in			
Conductor Thickness	=	0.0025	in	Wire Width	0.0138	
Voice Coil ID	=	1.0125	in			
Conductive Area Fact	=	0.481		Wire Thick	0.0045	
Length of Conductor	=	265.7	in			
Avg. Conductive Dia	=	1.0333	in	Wire Insulation Thk	0.0010	
Coil Outside Diameter	=	1.0471	in			
Number of Turns	=	81.8		Bobbin Thick	0.0025	
Wind Height	=	0.388	in			
Stacking Factor	=	0.414		Bobbin Adhesive Thk	0.0010	
Total Wire Mass	=	2.339	g			
Mass of Adhesive	=	0.043	g	Voice Coil ID	1.0125	
Total Mass w/o Bobbin	=	2.382	g			
					TYPE	RHO
				Flat Wire	Cu	6.7716 E-7

Figure 1. 8 Ω Nominal Voice Coil Simulation.



Flat Wire Voice Coil Design				Input Parameters		
(units are ohms, inches, and grams)				Packing Factor	0.952	
DC Resistance@25C	=	0.78	ohms	DC Resistance@25C	0.78	
Conductor Width	=	0.0118	in			
Conductor Thickness	=	0.0088	in	Wire Width	0.0138	
Voice Coil ID	=	1.0125	in			
Conductive Area Fact	=	0.699		Wire Thick	0.0108	
Length of Conductor	=	110.9	in			
Avg. Conductive Dia	=	1.0333	in	Wire Insulation Thk	0.0010	
Coil Outside Diameter	=	1.0471	in			
Number of Turns	=	34.2		Bobbin Thick	0.0025	
Wind Height	=	0.388	in			
Stacking Factor	=	0.578		Bobbin Adhesive Thk	0.0010	
Total Wire Mass	=	2.243	g			
Mass of Adhesive	=	0.054	g	Voice Coil ID	1.0125	
Total Mass w/o Bobbin	=	2.297	g			
					TYPE	RHO
				Flat Wire	Cu	6.7716 E-7

Figure 2. 1 Ω Nominal Voice Coil Simulation.

I chose flat rectangular copper magnet wire for our voice-coil examples. In this way you can adjust $\mathbf{R_e}$ while keeping the wind height and the outside diameter constant, only varying the thickness of the voice -oil wire. Therefore, theses two voice coils will conveniently fit into the same motor assembly, the same ID, OD and wind height.

Also, please notice that the 1Ω voice coil has an $\boldsymbol{l}$ of 110.9" (2.82 m), while the 8Ω voice coil has an $\boldsymbol{l}$ of 265.7 inches (6.75 m). Well, the 8 Ω voice coil must result in higher $\boldsymbol{\beta}$, higher $\mathbf{dB_{SPL}}$, and a lower **Q**, right? The answer is a resounding "no"!

Note that the "stacking factors" of the respective coil models in Figures 1 and 2 (41.4% and 57.8%, respectively) are a hint as to what our results will be. Looking at a finite element model, (**FEM**) of the motor assembly that you will utilize to evaluate $\boldsymbol{\beta}$ with respect to these two voice coils.

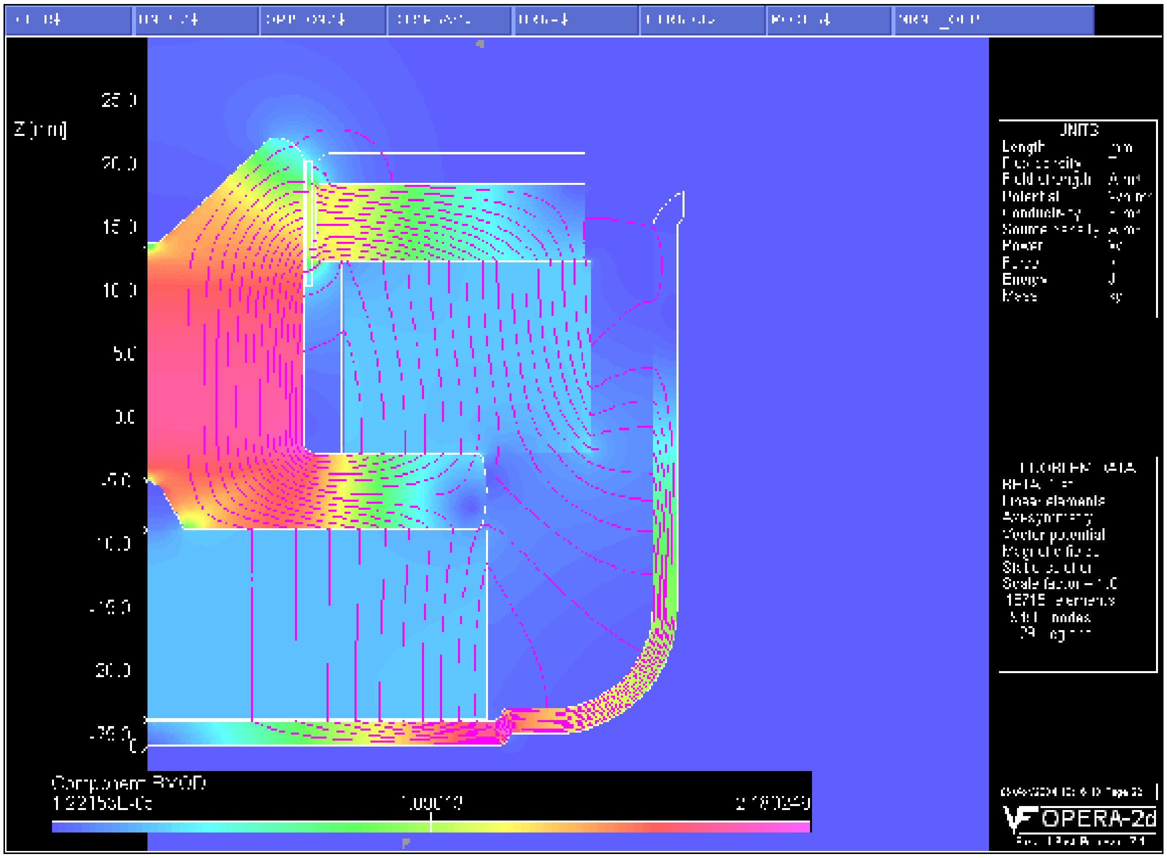


Figure 3. Contour Plot of |B| with the DC Flux Lines Overdrawn.

Figure 3 contains the graphic output for the DC solution of finite element analysis (**FEA**). Now using a voice coil emulating command file, sweep the two voice coils through the magnetic gap and compare the results (Fig. 4).

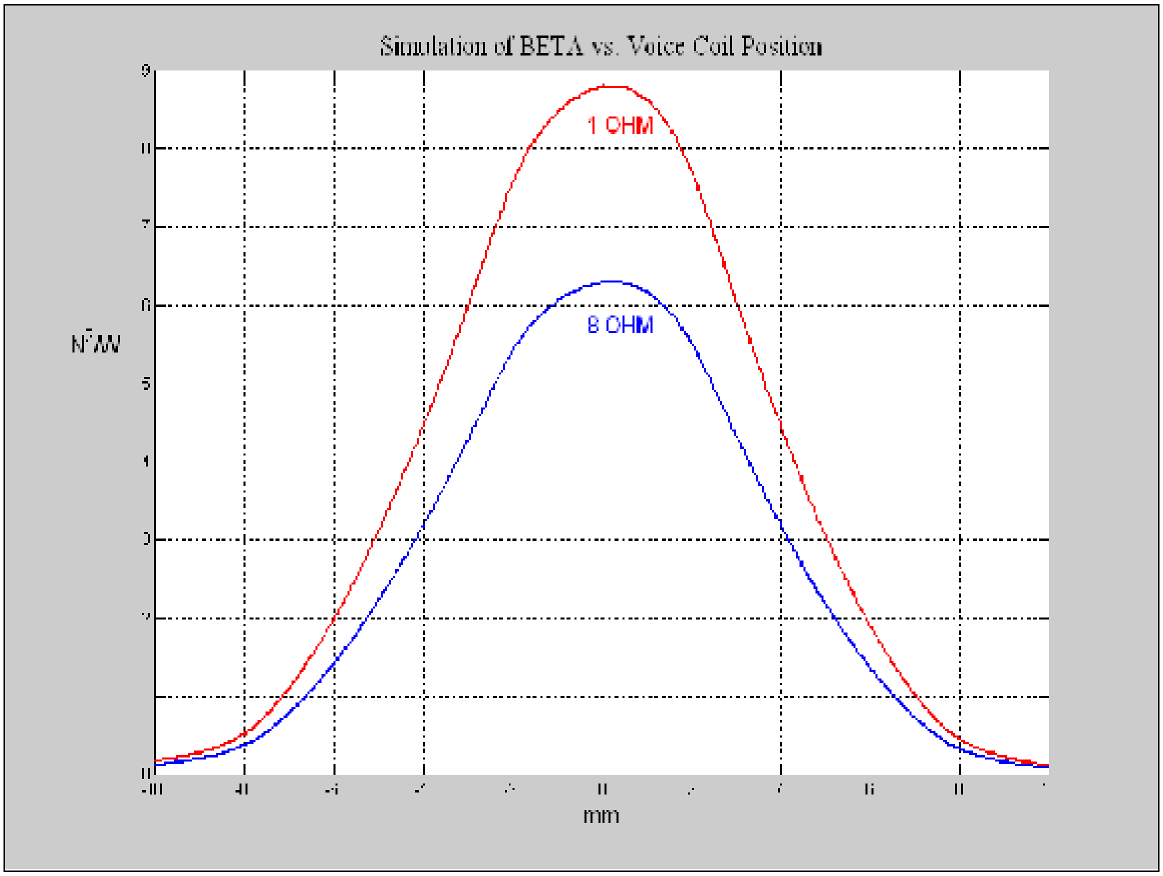


Figure 4. Plot of the Simulation of β(x) vs. Voice Coil Position.

Surprising as it may seem the 1Ω voice coil within an identical motor assembly is much more efficient. In terms of Power for 1.0 W input, the 1Ω transducer will have +1.5 dB more output. In terms of voltage for 2.83V input, the 1Ω transducer will have +6 dB more output! Perhaps what is more important is the fact that you now have a figure of merit for motor assembly performance evaluation that is not dependent on the DC resistance or the nominal impedance of the transducer, **β**.

Additionally, the electrical quality factor ($\mathbf{Q_{es}}$) of the 1Ω transducer will be approximately 28% lower than the 8Ω transducer. The moral of this story is that things are not always as they appear, and you should look at $\mathbf{Vol_C}$ and not just ***l***. Wire insulation and adhesive are the enemy.

Automotive applications were mentioned for the 1 Ω transducer; however, a low impedance transducer is also suitable for arrays. Resistance adds in series. Remember the BOSE 901 and 802? The transducers utilized in those systems featured a DC resistance of 0.8Ω with flat rectangular magnet wire. I wonder why?

That's the Phuket Report,
Steve Mowry

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