

▶ Inductance et al. – A Closer Look at AC, Part 1

By Steve Mowry

The DC electromagnetic nonlinear mechanisms within electrodynamic audio transducer motor assemblies are fairly widely understood; however, the nonlinear AC mechanisms are typically ignored during the simulation and design phase of new transducer development. The inductance is a result of the voice coil's linkage to the AC magnetic flux. It is the behavior of this time-dependent AC flux within the motor assembly that is the focus of this article.

I will update my nonlinear model and present new information on S.M. Audio Engineering's voice-coil-emulating command files. Extensive use of graphic solution contour plots, plotted command file data output together with the equivalent circuit model are intended to shed new light on this classic electromagnetic field's topic. In the process, I discuss the new and important topics of dynamic permeability and skin effect. I will show that the inductance and inductance-related phenomena are significant sources of nonlinear behavior from within the motor assembly.

The SI unit of inductance is the "henry" (H). The equivalent electromagnetic, electric, and electromechanical units are respectively contained in equation 1.

$$(H) = \left(\frac{V_S}{A} \right) = \left(\frac{Wb}{A} \right) = \left(\frac{Nm}{A^2} \right) \quad (1)$$

If the rate of change of current in a circuit is 1A per second and the resulting electromotive force is 1V, then the inductance of the circuit is 1H. The henry is named after Joseph Henry (1797-1878), a Scottish-American scientist. During

his lifetime, he was considered one of the greatest American scientists since Benjamin Franklin. While building electromagnets, he discovered the electromagnetic phenomenon of self-inductance.

The following discussion is from a technical engineering paper, *Nonlinear Quasi-dynamic DC and AC FEM for Electro-dynamic Audio Transducer Motor Assembly Simulation*, prepared as documentation for a PC OPERA 2d training seminar that I conducted on August 30, 2006, at Advanced Sound Products, in Malaysia. I have attempted to present the concepts in as friendly a format as possible.

MOTOR ASSEMBLY MODEL

I will present an equivalent circuit to illustrate the voice coil within the motor assembly in **Fig. 1**.

MODEL VARIABLES:

B_l is the DC force factor (Tm).

B_l is the AC force factor (Tm).

$\dot{\phi}$ is the rate of change of the time varying AC flux (Wb/s).

r is the radius (m).

l is the length of the voice coil wire (m).

μ is the magnetic permeability (H/m).

σ is the electrical conductivity of the material (1/ Ω m).

J is the eddy current density (A/m²).

E is the electric field (V/m).

v is the input voltage from the power amplifier (V).

i is the current in the voice coil (A).

R_e is the DC resistance of the voice coil (Ω).

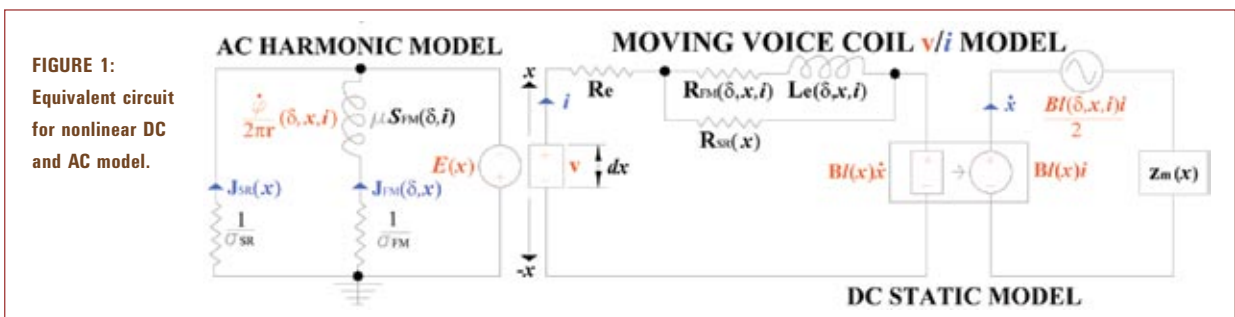


FIGURE 1:
Equivalent circuit
for nonlinear DC
and AC model.

R_{FM} is the resistance related to the eddy current losses within the steel (Ω).

R_{SR} is the resistance related to the eddy current losses within the shorting ring (Ω).

L_e is the total self inductance of the voice coil (H).

S_{FM} is the cross-section of the steel (m^2).

x is the position of the voice coil (m).

v is the velocity of the voice coil (m/s).

dx is the voice coil wind height (m).

z_m is the lumped equivalent mechanical impedance (Ω) related to moving mass M_{ms} , nonlinear termination stiffness $K_{ms}(x)$, and termination losses R_{ms} .

δ is the skin depth of the "AC skin effect" (m).

The skin effect as it affects eddy current is essential to understanding inductance and the other AC effects. The skin

depth δ for a sinusoidal signal is defined in equation 2.

$$\delta(i) = \frac{1}{\sqrt{\pi f \sigma \mu(i)}} \quad (2)$$

where f (Hz) is the frequency of the AC current, i . I will show that the skin depth has a nonlinear current dependence related to the dynamic permeability.

In **Fig. 1**, the segment on the left, the AC harmonic model, is attached to ground and thus it does not change position. However, the large right-hand segment represents the moving voice coil within the magnetic gap and does change position, x . There are no physical wires and/or connections from the left segment to the right-hand segment. Nor are there any mechanical terminations. There are two magnetic fields interacting with the voice coil, the primary DC, and the secondary

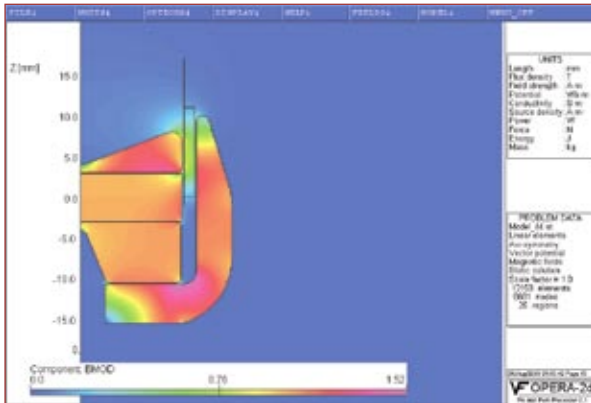


FIGURE 2: Contour plot of $|B|$, the magnitude of the DC flux density.



FIGURE 3: Plot of quasi-dynamic simulation of $BI(x)$ and $\beta(x)$.

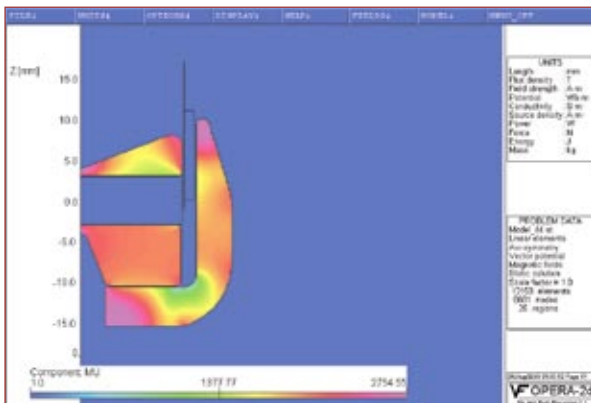


FIGURE 4: Contour plot of the relative DC permeability, μ_r .

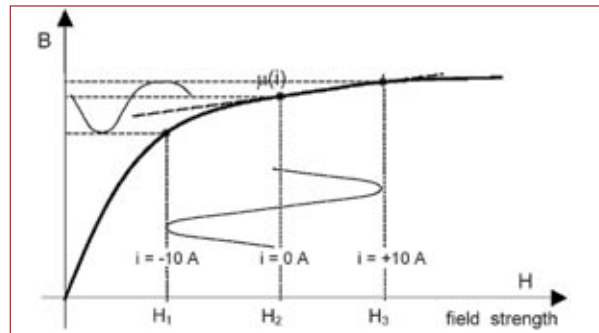


FIGURE 5: Illustration of the nonlinear dynamic permeability of steel, $\mu(i)$.

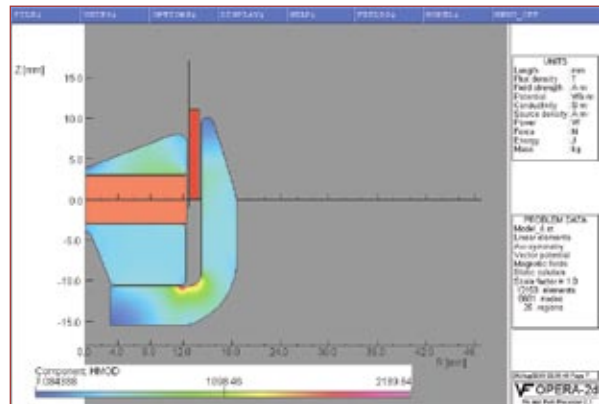


FIGURE 6: Contour plot of the DC Field strength $|H|$ within the steel only.

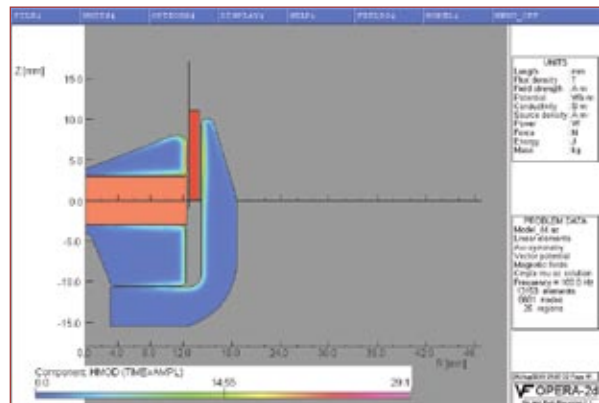


FIGURE 7: Contour plot of AC field strength $|H(24)|$ at 100Hz within the steel only.

AC magnetic fields.

THE DC PROBLEM

I will begin with the DC problem. This is straightforward. The nonlinear DC problem can be defined by the nonlinear force factor, $Bl(x)$, equation 3.

$$\frac{F}{i}(\mathbf{x}) = Bl(\mathbf{x}) \left(\frac{N}{A} \right) \text{ or } (Tm) \quad (3)$$

$F(x)$ (N) is the force. This force and thus the force factor vary with the voice coil position, x (**Fig. 3**). B is the DC flux density, where the DC flux density times the cross sectional area S (m^2) is the DC flux, ϕ (Wb), equation 4.

$$B \cdot S = \phi \quad (4)$$

Figure 4 contains a contour plot of the solution for the magnitude of the DC flux density, $|B|$ (T or Wb/m²).

Figure 3 illustrates the command file simulation of the DC force factor, $Bl(x)$ and $\beta(x)$,

$$Bl(\pm X_{max}) = 0.82Bl(0) \quad (5)$$

The DC command file implements equation 6; N is the number of turns of wire on the voice coil bobbin.

$$Bl(\mathbf{x}) = \frac{Nd\phi(\mathbf{x})}{dx} = \frac{N[\phi(\mathbf{x} + dx/2) - \phi(\mathbf{x} - dx/2)]}{dx} \quad (6)$$

The derivative is a moving difference in flux with respect to the voice coil wind height divided by the wind height!

β is the figure of merit for motor force regardless of the nominal voice coil impedance, equation 7.

$$\beta = \frac{(Bl)^2}{Re} = \frac{B^2 (N2\pi r_{VC})^2 S_W}{N2\pi r_{VC} \sigma_W} = \frac{B^2}{\sigma_W} Vol_W \left(\frac{N^2}{W} \right) \quad (7)$$

where σ_W ($1/\Omega m$) is the conductivity of the voice coil wire and r_{VC} (m) is the radius of the voice coil and S_W (m^2) is the cross-section of the voice coil wire. Then for a given voice coil wire material, copper or aluminum, β depends only on the square of flux density and the volume of conductor, Vol_W (m^3) in the magnetic gap! Remember that $\beta(x)$ is a DC quantity.

PERMEABILITY

Dynamically, current affects the permeability of the steel. This is what I call dynamic permeability, $\mu(i)$ (H/m). To explain the dynamic permeability I must first define the DC permeability μ in equation 8.

$$\mu = \frac{dB}{dH} \left(\frac{Tm}{A} \right) \quad (8)$$

This is the slope of the material BH Curve. This is linear for air and for the magnet up to reasonable temperatures, but for steel the BH Curve is nonlinear (**Fig. 5**). A common way to represent the permeability is relative to the permeability of air, μ_0 . Air is the poorest conductor of magnetic flux known. There are no known insulators of magnetic flux. See **Fig. 4** for the contour plot of the relative DC permeability.

$$\mu_{rel} = \frac{\mu}{\mu_0} \text{ (unit-less) where } \mu_0 = 4\pi 10^{-7}, \text{ the permeability of}$$

air, is a small constant. (9)

The AC problem is restarted from the DC permeability. There is an AC magnetic field with AC flux density, $B(i)$ and AC magnetic field strength, $H(i)$, thus the dynamic permeability shown in equation 10 and **Fig. 5**.

$$\mu(i) = \frac{B \pm B(i)}{H \pm H(i)} \text{ peak-to-peak} \quad (10)$$

Figure 3 illustrates the dynamic permeability phenomenon with regard to a typical nonlinear BH Curve of steel.

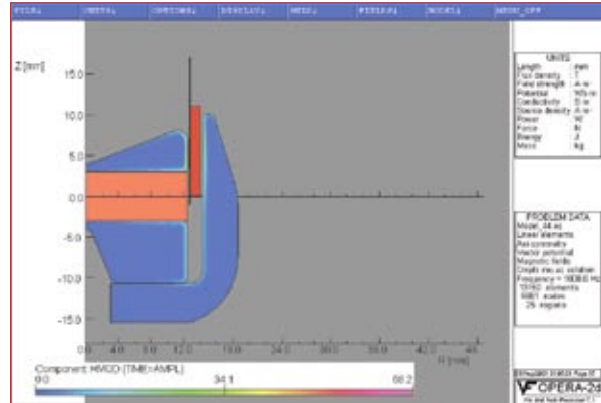


FIGURE 8: Contour plot of AC field strength $|H(24)|$ at 1.0kHz within the steel only.

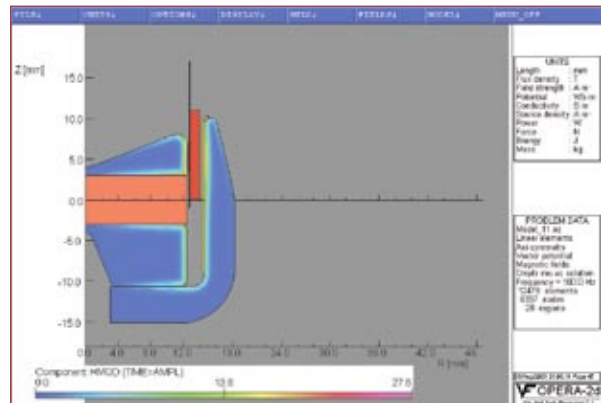


FIGURE 9: Contour plot of AC field strength $|H(24)|$ at 100Hz with shorting ring.

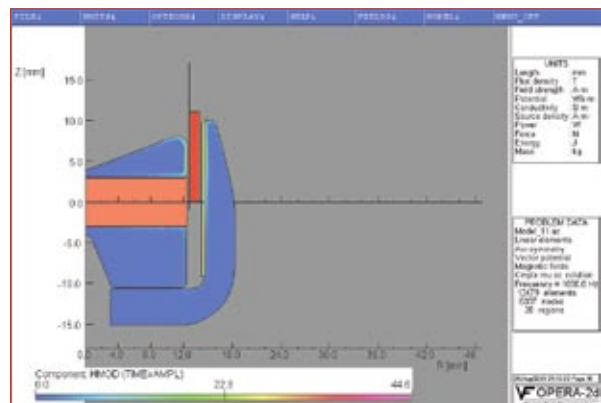


FIGURE 10: Contour plot of AC field strength $|H(24)|$ at 1.0kHz with shorting ring.

Figure 6 illustrates the DC field strength $|H|$ (A/m) within the steel. While **Fig. 7** shows the AC field strength $|H|$ at 100Hz, **Fig. 8** shows $|H|$ at 1.0kHz. **Figures 9** and **10** illustrate the AC field strength H in the steel alone at 100 and 1000Hz, respectively, but with a shorting ring. You can also observe the skin effect in **Figs. 9** and **10**.

It is also an AC $H(i)$ (**Figs. 12-15**) that combines with the DC field strength within the magnet (**Fig. 11**), but the permeability of the magnet is μ_0 (**Fig. 4**). There is also no skin effect and the eddy current is small; σ is low but not zero like air. The flux is coming from the current in the steel. The magnet almost behaves like a large air gap with regard to the

AC problem.

The BH Curve of the “N48H” magnet is linear at room temperature but becomes nonlinear as temperature is increased (**Fig. 16**). The operating point moves about the load line by $\pm H(i)$ as it does with the steel (**Fig. 5**). So by reducing eddy current within the steel, the shorting ring reduces the $|H(i)|$ within the magnet, too.

In next month's issue, Part 2 will continue this look at inductance effects in transducer design. **VC**

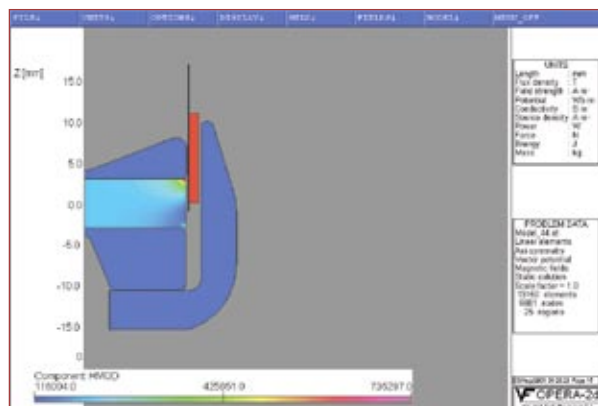


FIGURE 11: Contour plot of the DC field strength $|H|$ within the magnet only.

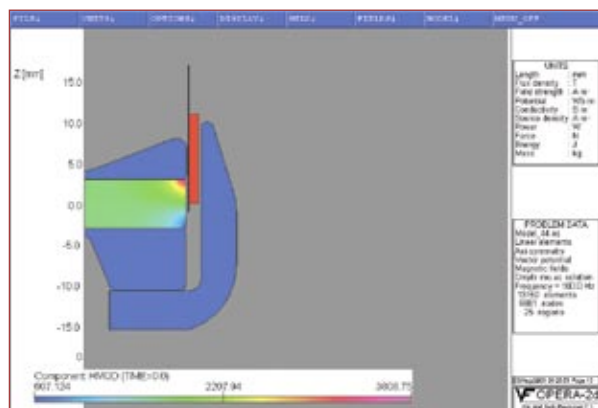


FIGURE 12: Contour plot of $|H(24)|$ at 100Hz within the magnet only.

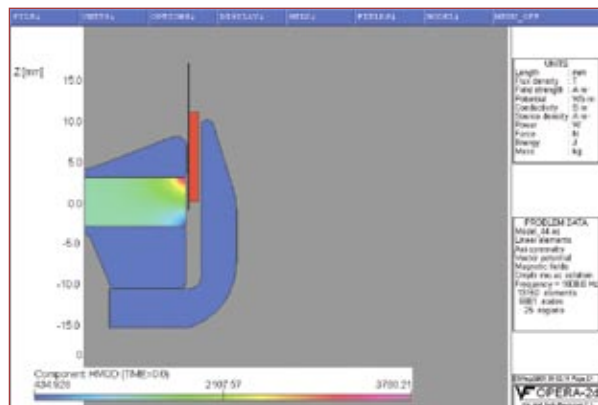


FIGURE 13: Contour plot of $|H(24)|$ at 1.0kHz within the magnet only.

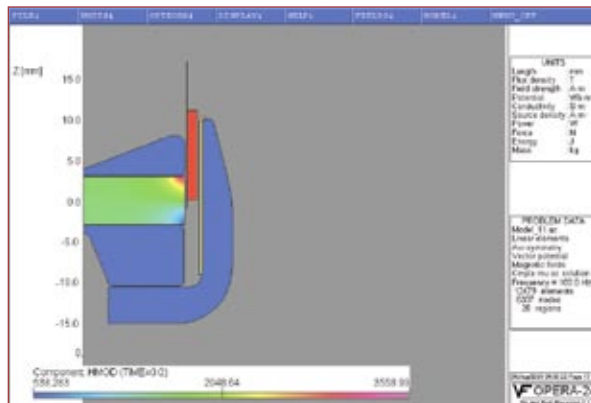


FIGURE 14: Contour plot of $|H(24)|$ at 100Hz with shorting ring within the magnet only.

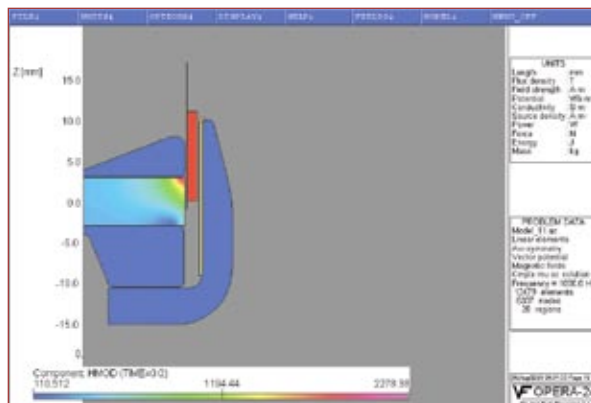


FIGURE 15: Contour plot of $|H(24)|$ at 1.0kHz with shorting ring within the magnet only.

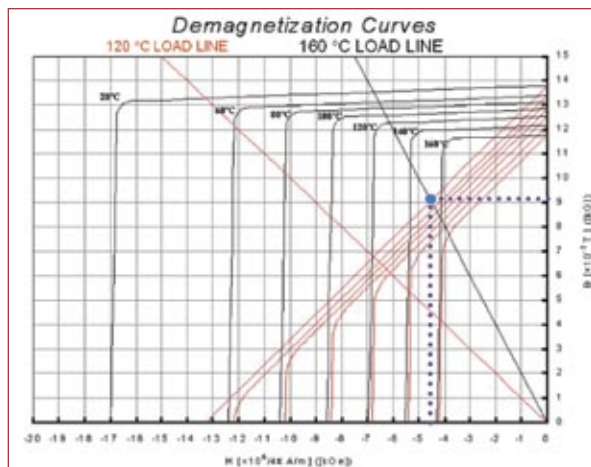


FIGURE 16: Temperature dependent N48H BH curves.