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APPLICATION OF LINEAR MAGNETIC LOSS MODEL OF FERRITE TO INDUCTION CAVITY SIMULATION *

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Abstract

A linear, frequency independent model of the rf properties of unbiased, soft ferrite has been implemented in finite-difference, time-domain, electromagnetic simulation code AMOS for the purposes of studying linac induction cavities. The simple model consists of adding a magnetic conductivity term ($\sigma_m H$) to Faraday's Law. The value of σ_m that is appropriate for a given ferrite at a particular frequency is obtained via an rf reflection experiment on a very thin ferrite toroid in a shorted coaxial line. It was found that in the frequency range 100 to 1000 MHz, the required value of σ_m varies only slightly (< 10%), and so we approximated it as a frequency independent parameter in AMOS. A description of the experimental setup and the technique used to extract the complex μ from the measurements is described. The model has been used to study the impedances of the DARHT induction cavity, and comparisons between these experimental measurements and AMOS calculations is presented. Implementation of a frequency dependent version of this model in AMOS is being pursued, and a discussion of this effort is given.

Introduction

Ferrite can play an important role in damping RF modes in induction linac acceleration modules [1]. In the frequency range of interest for the induction cells of the Advanced Test Accelerator (ATA) and the Experimental Test Accelerator – II (ETA-II), which is 100 – 1000 MHz, skin depths in the (unbiased) soft ferrite typically used in induction cores are a few centimeters, and thus relatively thin slabs may be placed at strategic locations in a cell to effectively lower the Q's of troublesome modes. In order to quantify the effect that ferrite has on the impedances of cavity modes using a time-domain code such as AMOS [2], it is necessary to have an electromagnetic model of ferrite that accounts for the lossy nature of the material. For incident fields that result in large swings in the magnetization in the ferrite, the appropriate model is nonlinear and will in general depend on the history of the sample. However, for incident fields that produce only small perturbations on the magnetization, a linear, tensor permeability is appropriate [3]. When the sample has zero net magnetization (virgin sample), there is no preferred direction in the material, and the tensor collapses to a scalar. In the remanent state in soft ferrites there is a preferential direction that depends on the recent bias history of the sample, and this will lead to small off-diagonal elements in the tensor. For the purposes of this work we have *postulated* that the permeability may be characterized by a scalar in the absence of an applied field. Experimentally this appears justified for the samples we considered as there were negligible differences between the results for virgin ferrites and samples in a remanent state.

To represent the complex scalar permeability, $\mu = \mu' - i\mu''$, of unbiased ferrite in the time domain, we add a magnetic conductivity term to Faraday's Law, i.e.,

$$-\nabla \times \vec{E} = \sigma_m \vec{H} + \mu' \dot{\vec{H}}, \qquad (1)$$

where σ_m is the magnetic conductivity, which is related to the imaginary part of μ by

$$\sigma_m = \omega\mu'' = \omega\mu_o\mu_r'', \qquad (2)$$

where μ_o is the free-space permeability. In general, σ_m is a frequency dependent parameter, and to incorporate this characteristic into AMOS requires a significant extension to the standard finite-difference, time-domain algorithm. While this type of capability is the object of some interest in the simulation community [4], an efficient algorithm for general frequency dependencies is not yet available, and for this effort we assume that σ_m is independent of frequency. It was found experimentally that its value did not change significantly over the frequency range under investigation (100 MHz – 1 GHz), although outside this range the frequency dependence does become important. The variation in μ_r' is larger than the variation of σ_m over the frequency range, but as it is small as compared with either μ_r'' or ϵ_r over most of the range, its variation is relatively unimportant.

Experiments on Small Ferrite Cores

To obtain values of σ_m that are representative of the ferrites used as induction cores, reflection measurements were made on thin samples, from which the complex permeability and σ_m could be deduced. The experimental setup is illustrated in Fig. 1. The ferrite samples used in the experiments were thin toroids of rectangular cross section that had an outside diameter of 3.1 cm, an inside diameter of 1.9 cm, and had axial thicknesses of 1 mm and 2 mm. The samples were heated above the Curie temperature (130°C for the ETA-II ferrite, and 205°C for the ATA ferrite) and then cooled to room temperature prior to making the measurements to ensure that they were in an unmagnetized state.

The measured reflection coefficient (magnitude and phase) for the 1 mm thick samples of ETA-II and ATA ferrites are shown as functions of frequency in Fig. 2. The permeability is obtained by inverting the expression for the

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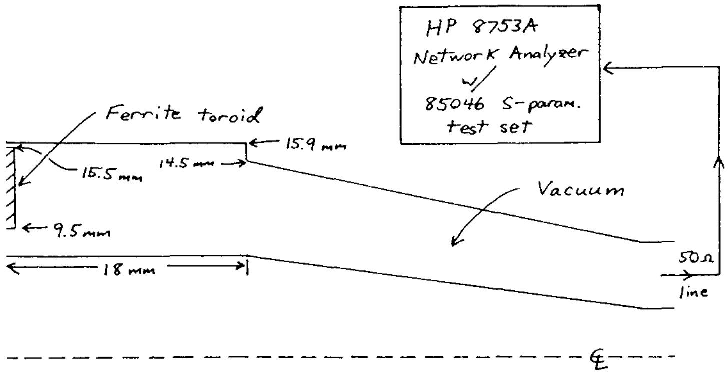

Fig. 1. Schematic of reflection experiment setup. Geometry is cylindrical, concentric about dashed centerline. 1 mm thick ferrite toroid is shown; experiments were also done on 2 mm thick samples. Effects of radial discontinuity and small impedance mismatch accounted for with calibration run.

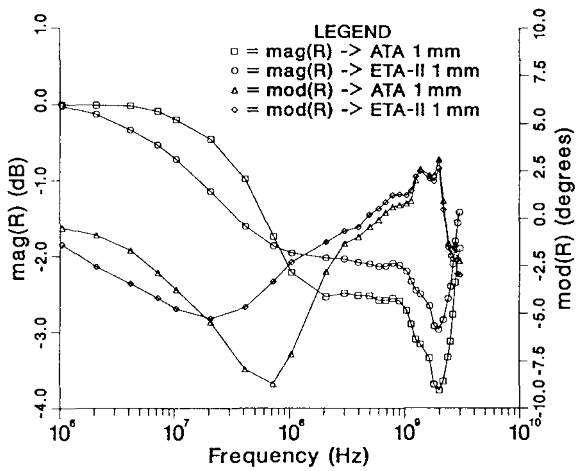

Fig. 2. Measured reflection coefficients, normalized by the reflection realized when no ferrite is present, for 1 mm thick samples of the ATA and ETA-II ferrites.

normalized reflection from a slab, of thickness $\Delta = 1$mm, backed by a short,

$$R = \frac{\left[\left(1+\exp^{-i2k\Delta}\right) - \eta_r\left(1-\exp^{-i2k\Delta}\right)\right]\exp^{i2k_o\Delta}}{\left(1+\exp^{-i2k\Delta}\right)+\eta_r\left(1-\exp^{-i2k\Delta}\right)}, \quad (3)$$

where $\eta_r = \sqrt{\mu_r/\epsilon_r}$ is the relative wave impedance of the ferrite, k is the wave number in the ferrite, and k_o is the free space wave number. R as shown in Eqn. (3) has been normalized by the reflection obtained when no material is present.

A first estimate of μ_r is obtained using the small argument ($|2k\Delta|^2 \ll 1$) expansion of Eqn. (3), i.e.,

$$\mu_r \approx 1 + \frac{1-R}{i2k_o\Delta}, \quad (4)$$

and then this value is refined using a numerical search. Values of μ_r for the ETA-II and ATA ferrites are shown in Fig. 3. The curves show a broad resonance or relaxation at low frequencies, and then a second resonance around 2 GHz. These two features have been attributed to domain wall motion and to spin rotation within domains, respectively [5]. Values of σ_m derived from the ferrite permeability are shown in Fig. 4. Note that they are relatively constant between 100 MHz and 1 GHz, and that there are only small differences between the values derived from the 1 mm samples and those taken from the 2 mm samples. These small differences may result from variations between samples, or from an inaccurate value for the permittivity. For both the ATA and ETA-II ferrites, the permittivity was taken to be $\epsilon_r = 13$, and assumed to be independent of frequency.

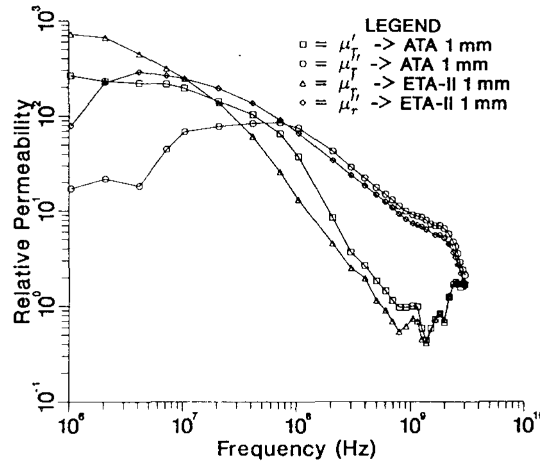

Fig. 3. Values of μ_r derived from the measured reflection data using Eqn. (3). Values shown have been modified (multiplied by the ratio of short area to core area = 1.3) to account for the incomplete coverage of the shorting plane by the ferrite.

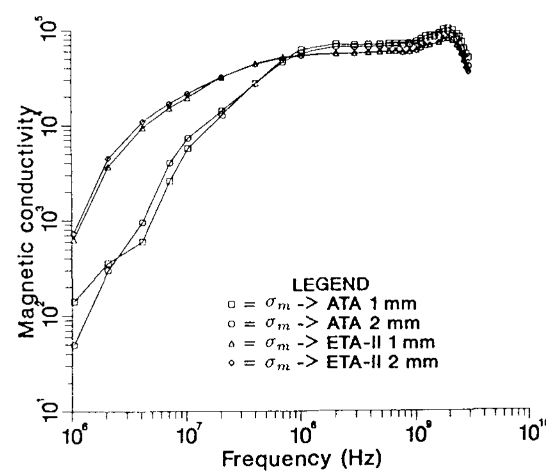

Fig. 4. Values of σ_m derived from the permeabilities shown in Fig. 3 using Eqn. (2).

Induction Cells: Simulation and Experiment

The first prototype induction module (called the Mod 0 cell) of the Dual Axis Radiographic Hydrodynamics Test Facility (DARHT) accelerator has recently been fabricated, and RF impedance measurements have been made on this cell with a partial ferrite load (see Fig. 5). The ferrite used in the DARHT prototype is identical to the ferrite used in the ATA induction modules, and for this comparison the power feed lines have been removed from the cell and the remaining holes were plugged. These modifications have the effect of making the cell rotationally symmetric, which then allows a direct comparison between the experimentally measured impedances and the AMOS predictions. The ferrite properties that were used in the

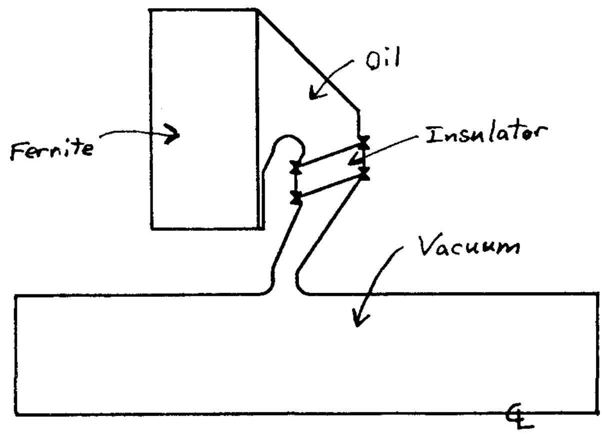

Fig. 5. Geometry of DARHT prototype cell with power feed lines removed. Cell is rotationally symmetric about centerline. Shown with partial ferrite load.

simulation were obtained from the small core experiment on the ATA ferrite, which yielded values of $\mu_r' = 1.0$ and $\sigma_m = 7.4 \times 10^4 \Omega/\mathrm{m}$. The experimental and calculated values are in good agreement, as shown in Fig. 6. Additional measurements are currently being taken on the SNOMAD and ETA-II accelerator modules, and these data will be compared against AMOS simulations to provide additional information about the model.

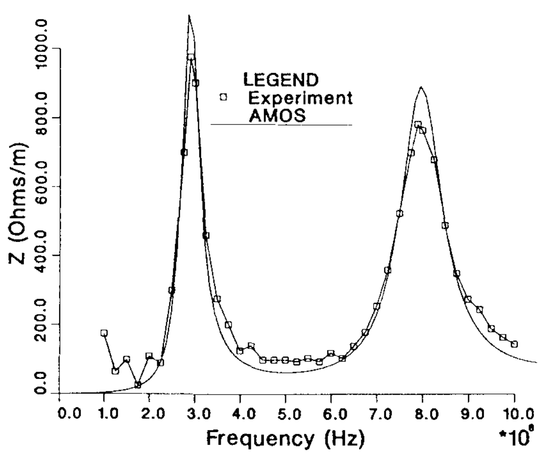

Fig. 6. Measured and calculated transverse (dipole) impedances vs. frequency for DARHT prototype cell.

If impedance data outside the given frequency range had been required, the values of σ_m would change significantly, and the material could no longer be treated as non-dispersive in a spread-spectrum calculation. In general, time-domain modeling of dispersive materials requires a convolution, which, in the case of a frequency dependent permeability, takes the form

$$\vec{B}(t) = \int_{\tau=0}^{t} \mu(t-\tau)\vec{H}(\tau)d\tau. \qquad (5)$$

This equation is very expensive from a computational standpoint because it requires previous values of $\vec{H}$ for evaluation. Work is ongoing to alleviate the computational burden by representing σ_m in a form for which the convolution can be computed as a running sum, thereby eliminating the need to store previous values of $\vec{H}$.

Conclusions

A simple, linear model of the RF behavior of lossy soft ferrites has been implemented in the electromagnetic simulation code AMOS. The model represents the RF magnetic losses via a magnetic conductivity term in Faraday's Law. The value of σ_m that is appropriate for the ferrite of interest is obtained by making 1-D reflection measurements on thin samples. The model has been validated by using it to simulate the reflection experiments, and also by measurements made on the DARHT accelerator induction module. The current incarnation of the model is frequency independent; however, work is underway to incorporate the measured frequency dependence of the permeability to enhance the frequency range of applicability of the model.

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