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Magnetic Responses and Processes in Ideally Soft Magnetic Materials

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I. Introduction

Ideally soft magnetic material does not have crystalline anisotropy and internal imperfections. There is a good candidate for our ideally soft magnetic material to be iron, the most important soft magnetic material. Magnetization pattern of the soft magnetic material satisfies the condition $\nabla \cdot \vec{M} = 0$ almost everywhere in the bulk and its stable configuration is determined from minimization of the demagnetization energy. Several domain configurations for cylindrical shaped materials are well-known from minimization of involving energies[1]. The main difficulty for the cylindrically shaped magnetic material is the avoidance of the exchange singularity near the cylindrical axis of the material[2]. The cavity has to be placed along the axis of the cylinder to avoid the large exchange energy unless a small domain with the magnetization along the axis is placed at its center.

II. Magnetic processes and responses

When large current and external field are applied along the cylindrical axis, magnetic configuration at its cross section is expected as shown in Fig. 1. The magnetization inside the central domain is along the axis and the one in the outside domain has only the $\hat{\theta}$-component for the charge-free configuration. The main reasons having the $\hat{\theta}$-component of the magnetization are that the applied current forces the magnetization to be perpendicular to the axis and that the total energy is minimized by eliminating any surface charge at the center of the magnetic material. The size of the central domain is determined with the computation among involving energies. Magnetic processes and ac responses as functions of external fields and currents can be obtained by minimizing the total energy which consists of exchange E_{ex}, demagnetizing E_D, and magnetostriction energies E_{st}, and energies from current E_I and external field E_H. The total energy is expressed as a function of the averaged $\hat{z}$-components (along the cylindrical axis) of the magnetization, $m=M_S\phi/\phi_s$:

$$E_{tot} = E_H + E_D + E_{ex} + E_I + E_{st}$$

$$= -AM_sH_o\frac{\phi}{\phi_s} + 2\pi ADM_s^2\left(\frac{\phi}{\phi_s}\right)^2 + \frac{A_{ex}}{2}A\ln\frac{\phi_s}{\phi} + \pi\sigma\left(\frac{\phi}{\phi_s}\right)^{1/2} + \frac{4\sqrt{\pi}}{3}M_s\left(\frac{I}{c}\right)\sqrt{A}\left(\frac{\phi}{\phi_s}\right)^{3/2} + A\frac{40Y\lambda^2}{27}\frac{\left(1-\frac{\phi}{\phi_s}\right)\frac{\phi}{\phi_s}}{\left(\frac{2\phi}{3\phi_s}+1\right)^2} \quad (1)$$

The exchange energy consists of the domain wall energy $\pi\sigma(\phi/\phi s)^{1/2}$ and the energy inducing from the rotated magnetization of the outside domain $\frac{A_{ex}}{2}A\ln\frac{\phi_s}{\phi}$. The wall energy is assumed as half of a 90° domain wall energy. The magnetostriction energy is induced from varying the size of the central domain.

The effective field defined as $H_{eff} = -\frac{\partial E_{tot}}{A\partial m}$ has to be zero at equilibrium[1]. The external field obtained from the above relation becomes

$$H_o = 4\pi M_sD\frac{\phi}{\phi_s} - \frac{A_{ex}}{2AM_s}\frac{\phi_s}{\phi} + \frac{\pi\sigma}{4AM_s}\sqrt{\frac{\phi_s}{\phi}} + \frac{2I_{amp}}{10}\sqrt{\frac{\pi\phi}{A\phi_s}} + \frac{320Y\lambda^2(-\frac{\phi}{\phi_s}+\frac{3}{8})}{81M_s(\frac{2\phi}{3\phi_s}+1)^3}. \quad (2)$$

The relation between the external field and the averaged $\hat{z}$-components of the magnetization in the cross section with applied currents is shown in Fig. 2. When the external field is large, competition among the demagnetizing, external, exchange fields and fields from applied currents dominate. On the other hand, for the small external field, the exchange and magnetostriction fields become important and these fields make the central domain not disappear completely.

The magnetic stiffness with zero frequency is calculated to be

$$\frac{1}{\chi_{ex}} = \alpha(0) = \frac{\partial H_o}{\partial m} = 4\pi D + \frac{A_{ex}}{2AM_s^2}\left(\frac{\phi_s}{\phi}\right)^2 - \frac{\pi\sigma}{4AM_s^2}\left(\frac{\phi_s}{\phi}\right)^{3/2} + \frac{I_{amp}}{10}\sqrt{\frac{\pi}{A}\frac{\phi_s}{\phi}} + \frac{80Y\lambda^2(\frac{16\phi}{3\phi_s}-7)}{81M_s^2(\frac{2\phi}{3\phi_s}+1)^3}. \quad (3)$$

Also, the magnetic viscosity solved with the eddy current calculation for the cylinder is $\omega\beta(0) = 4\pi^2\sigma_c / c^2 \log(\phi_s / \phi)$. The ac susceptibility as a function of driving frequencies is then given by

$$\chi_{ex} = \chi' - i\chi'' = \frac{\alpha(0)}{\alpha(0)^2 + (\omega\beta(0))^2} - \frac{i\omega\beta(0)}{\alpha(0)^2 + (\omega\beta(0))^2} \quad (4)$$

Calculations of the field dependence of χ' for a frequency, 700 Hz, and three choices of current along the axis are shown in Fig. 3. Our model suggests the sharper increases in χ' for low fields. A large external field is necessary to make the central domain disappear. χ'' can also be solved as functions of external fields and frequencies. For inverting the magnetization of the central domain, the magnetic singularity has to be propagated along the cylindrical axis.

III. Conclusion

Ac magnetic responses based on the simple model are calculated as functions of driving frequencies and external fields. These magnetic responses are very similar with the ones measured with a {100} iron whisker[3]. We do not measure the ac responses with a cylindrically shaped material. It is a challenging problem to make a cylindrically shaped whisker without defects. However, we can predict and explain its ac magnetic response with our model.

IV. Reference

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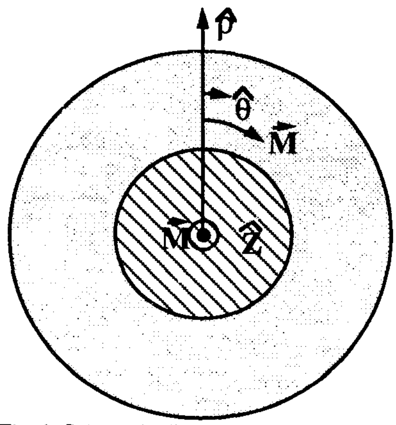

Fig. 1. Schematic diagram for our calculation.

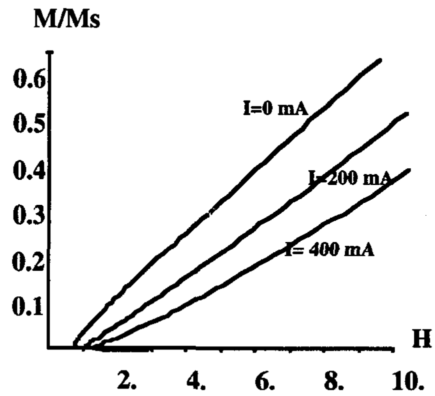

Fig. 2. Calculated relation between the magnetization and external field while applying different currents.

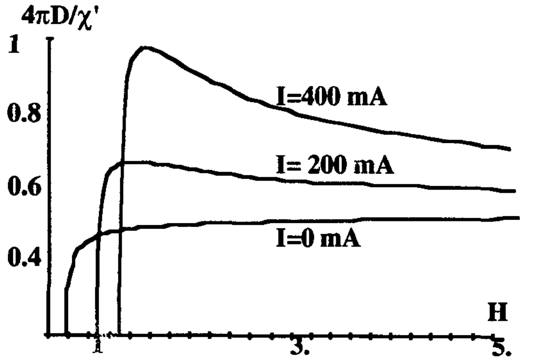

Fig. 3. Calculation of the field dependence of c' for three current along the axis.