Micromagnetic Calculations of Eddy Currents with Time-Varying Fields

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***Abstract*: This paper extends a recently presented program for solving the eddy current problem in a cylindrical geometry, by investigating the effect of time-varying fields. When the applied field is turned off, wall motion slows by several orders of magnitude, but since the wall energy can be reduced by reducing the length of the wall, it continues to move, albeit much more slowly. Reversing the applied field has the effect of nucleating the opposite kind of wall which propagates inward and eventually annihilates the previous wall.**

***Keywords*: Micromagnetism, Eddy Currents, Domain wall**

I. INTRODUCTION

Several micromagnetic programs have been developed to compute the effect of eddy currents in ferromagnetic materials [1], [2], [3], [4]. We have developed a one dimensional model micromagnetic program to solve for the dynamic magnetization in conducting cylinders as a test bed for determining the accuracy of these programs [5], [6].

We consider an infinite cylinder of a material having uniaxial magneto-crystalline anisotropy, with easy axis parallel to the axis of the cylinder. The initial magnetization is also parallel to the cylinder axis, but at time t=0 an oppositely directed magnetic field is applied. The applied field nucleates a concentric Bloch wall on the surface of the cylinder, which propagates towards the center. The wall motion produces eddy currents, which in turn generate magnetic fields that shield the interior of the cylinder and retard the wall motion.

The simulation solves the coupled magneto/electro-dynamic system by interleaving micromagnetic and eddy current computations. We assume that the micromagnetic dynamics are much faster than the relaxation of the eddy currents, so the micromagnetic step is handled by direct energy minimization. With this technique there is no precession, which in conjunction with the problem geometry insures that there are no self-magnetostatic (demagnetization) fields.

The particular results reported in this work were obtained using the following parameter values, chosen for illustrative purposes rather than to mimic any physical material: cylinder radius R = 9.5x10^{-4} m, saturation magnetization M_s = 10^{7} A/m, magneto-crystalline anisotropy K_u = 10^{-4} J/m^3, exchange coupling A = 3x10^{-4} J/m, conductivity σ = 0.1 S/m, and base time unit 2.08x10^{-3} s.

II. PULSE RESPONSE

After applying a magnetic field long enough to propagate the wall half-way to the center, we turned the applied field off. At first it appeared that the wall had stopped, as shown in Fig. 1. It is seen that when the wall is almost still the wall energy is smaller than when it is moving. Closer examination showed that it was still moving inward but much more slowly. This type of phenomena has been observed in single crystals [7].

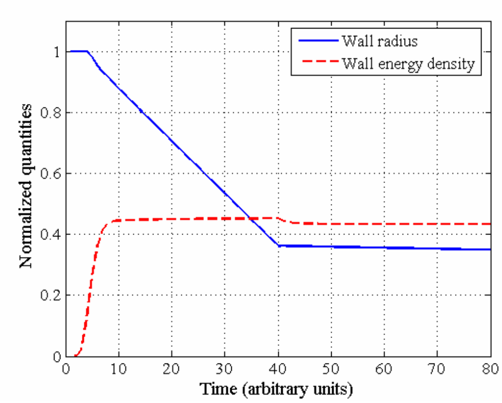

Fig. 1. Normalized wall position and wall energy as a function of time due to a pulse input field.

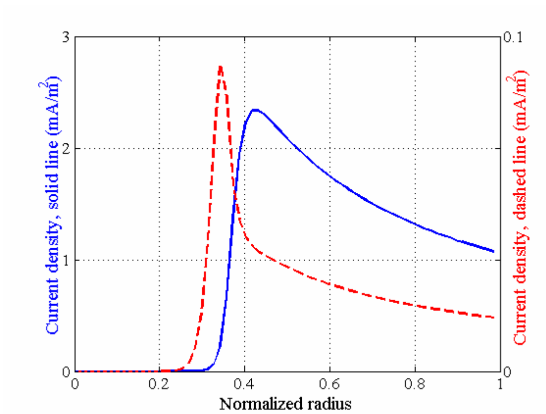

Fig. 2. Current density just before (solid line) and just after (dashed line) applied field is turned off.

Examination of Fig. 2 shows that just before the field was turned off the current pulse peak was 2.4 mA/m^2, and three time steps after the pulse was turned off the current pulse peak was .09 mA/m^2, indicating that the wall had slowed down by a factor of 26 but was still moving.

III. Square Wave Response

If instead of turning off the field as in the previous section, the field was reversed, a new wall of the opposite type was generated at the surface as shown in Fig. 3. This new wall propagates inward and eventually annihilates the previous wall leaving a saturated sample.

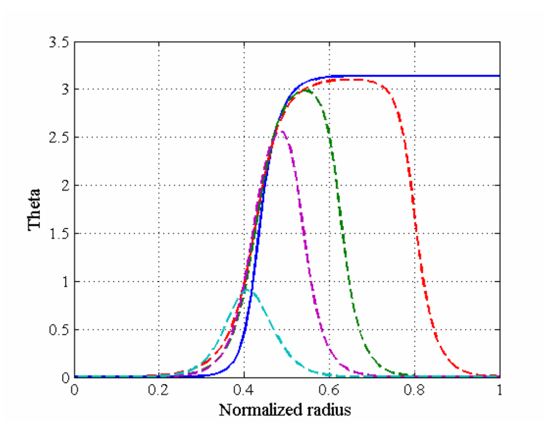

Fig. 3. The angle of the magnetization just before (solid line) and after (dashed lines) the applied field was reversed showing the annihilation of the domain wall.

If we plot the position of the inner wall as a function of time, shown in Fig. 4, we see that there is a slight tendency to reverse when the applied field is reversed (at time 40). However, the motion of the outer wall reduces the field at the inner wall, by the effect of the eddy currents, so that it effectively stops. A plot of the magnetostatic field (eddy current field plus applied field) inside the material, shown in Fig. 5, illustrates that the effect of the applied field in the interior is greatly reduced by the outer eddy currents.

Plotting the total wall energy as a function of time shows that when the field is reversed, the energy increases because a new wall is formed.

We note from Fig. 6 that for a stationary wall the anisotropy energy density and the exchange energy density are virtually equal, as is known to be the case for uncurved Bloch walls. However, for a wall moving at a constant velocity, as shown in Fig. 7, the exchange energy density is larger. We attribute this to a reduced wall thickness resulting from the applied field pushing the wall inward while the eddy current field pushes the wall outward.

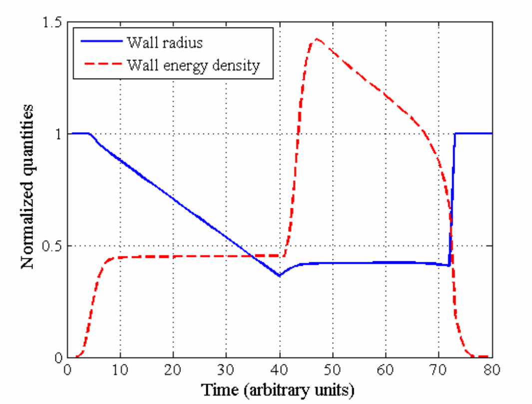

Fig. 4. The position of the inner wall and the total wall energy as a function of time. The field is reversed at time index 40.

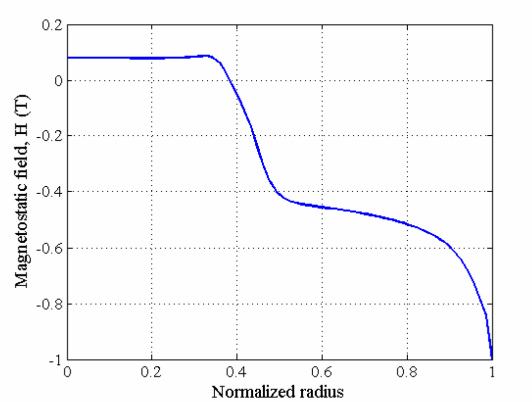

Fig. 5. The magnetostatic field in the material after the applied field is reversed.

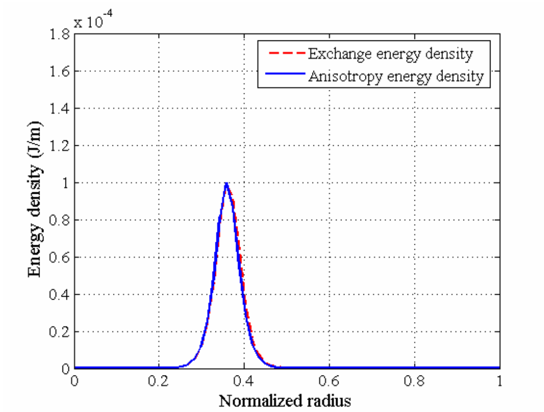

Fig. 6. Energy density after applied field is turned off. (Note that the two curves are virtually identical,)

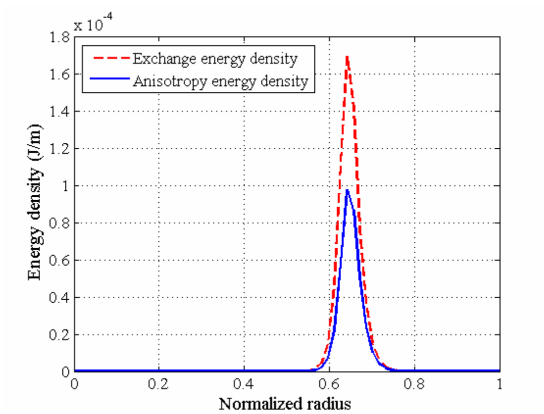

Fig.7. Energy densities for a moving wall.

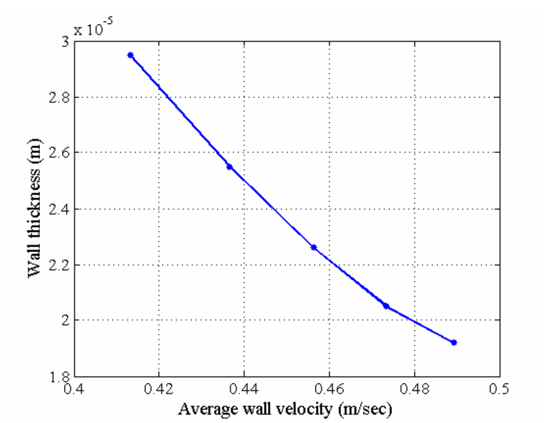

Fig. 8. Wall thickness as a function of average wall velocity.

We have computed wall thickness as a function of average wall velocity as seen in Fig. 8. We see that it is in agreement with the hypothesis.

The wall velocity as a function of time, computed as the velocity of the point at which the magnetization angle is $\theta(R)/2$, is plotted in Fig. 9 for various applied fields. As can be seen from Fig. 10, the wall velocity increases nonlinearly with the applied field. Note that for fields below 0.2 mA/m the wall does not nucleate. The nucleation field and wall velocity are independent properties governed by different phenomena.

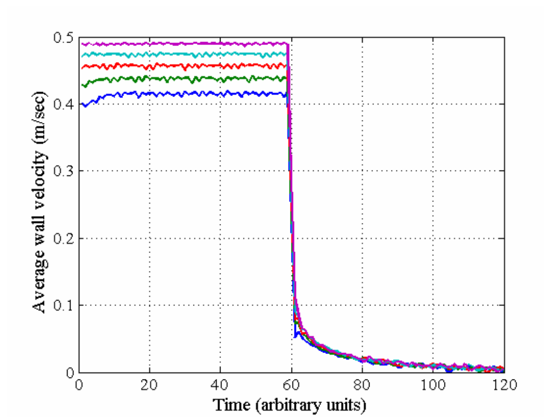

Fig. 9. Wall velocity as a function of time for applied fields (from bottom to top) of 0.2, 0.25, 0.3, 0.35, and 0.4 mA/m.

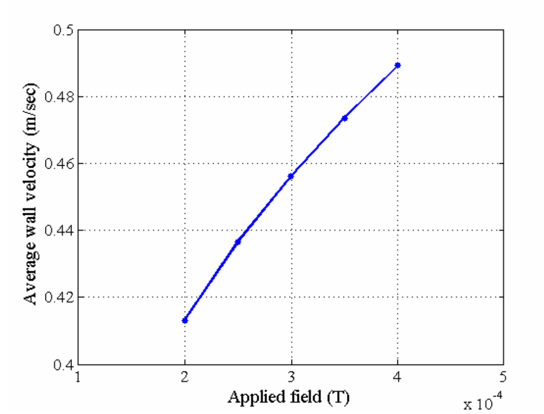

Fig. 10. Average wall velocity as a function of applied field.

IV. Conclusions

We have presented results of a micromagnetic program with eddy currents under the influence of time varying applied fields. We have shown that an isolated cylindrical domain wall will shrink and eventually annihilate in order to minimize wall energy. Changing the polarity of the applied field will nucleate a new domain wall that can annihilate old ones. Also a moving wall is narrower than a stationary wall and the exchange energy density in this case is larger than the anisotropy density.

V. ACKNOWLEDGMENT

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