DYNAMIC PINNING IN THIN-FILM SPIN-WAVE RESONANCE*

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Since the direct observation of spin-wave resonance in thin films,[1] the nature of surface spin pinning has been the object of considerable interest.[2-6] Identification of the various spin-wave modes and the values derived for the exchange constant which are determined from these resonances[1,7,8] depend strongly upon the assumptions made concerning the pinning. The usual models invoke either the Néel surface magnetic anisotropy[2,3] or the presence of an antiferromagnetic layer[4] to give a static pinning condition at the surface of the ferromagnetic film. Our recent experiments indicate, however, that surface spin pinning can be explained by assuming that there exists on the film a thin surface layer in which the magnetization differs from that in the body of the film. Under most conditions the resonance frequency of the uniform precession mode in this surface layer will differ from that in the body of the film, and since the spins are exchange coupled at the interface, the excitation of the uniform precession mode of oscillation will be suppressed. However, those spin-wave modes that satisfy the appropriate boundary conditions at the interface can exist. There is, then, a dynamic pinning at this interface.

These considerations apply when the static magnetic field, H, is oriented in any direction with respect to the normal of the film except for one particular angle. At this critical angle the uniform precession resonance condition of the surface layer is the same as the uniform precession resonance condition of the body of the film, and the magnetization in all of the layers may be excited as a unit in the uniform precession mode. Such a model is supported by observations made on a number of Permalloy (80% Ni-20% Fe) and cobalt films and by data reported elsewhere.[9,10] In all cases, the spin-wave modes disappear at a predictable critical angle as the static field is turned away from the normal to the film (Fig. 1).

Inspection of the dispersion relation [Eq. (1)] shows that this critical angle should increase for an increase in the microwave frequency. This was also observed. The results are shown in Figs. 2 and 3 where the magnetic field separation, δH, between the various modes and the lowest-order mode is plotted. These data were obtained at 9.6 kMc/sec (Fig. 2) and 14.6 kMc/sec (Fig. 3) for a vacuum-deposited Permalloy film 2700Å thick. The saturation moment $4\pi M$ was 8.16 kilogauss. The general features of Figs. 1-3 can be explained along the lines indicated.

The dispersion relation in thin films including the angular dependence is given by the expression[11]

$$(\omega/\gamma)^2 = [H\cos\phi - 4\pi M\cos\theta + (2Ak^2/M)\cos\theta]^2 + [H\sin\phi + 4\pi M\sin\theta + (2Ak^2/M)\sin\theta] \times [H\sin\phi + (2Ak^2/M)\sin\theta], \quad (1)$$

where H is the magnetic field, M is the magnetization, A is the exchange constant, and ϕ and θ are the angles between the normal to the film and the directions of the magnetic field and the magnetization, respectively. The magnetic equilibrium condition further relates ϕ and θ by the con-

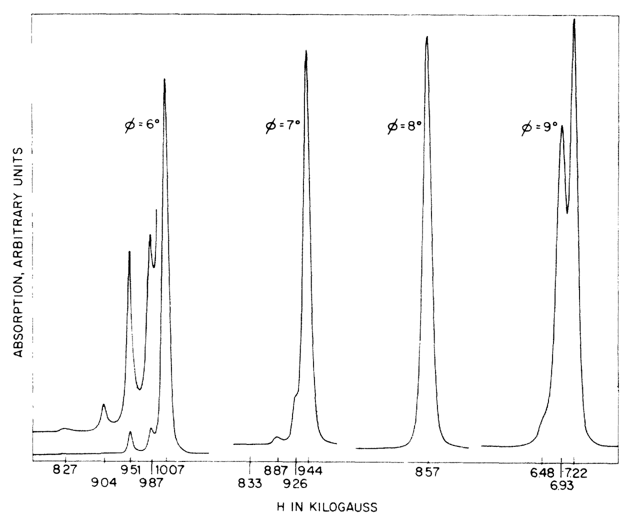

FIG. 1. Data obtained at different angles between the film normal and the magnetic-field direction demonstrating the collapse of the spin-wave spectra at the critical angle; $2\pi\omega = 9.60$ kMc/sec.

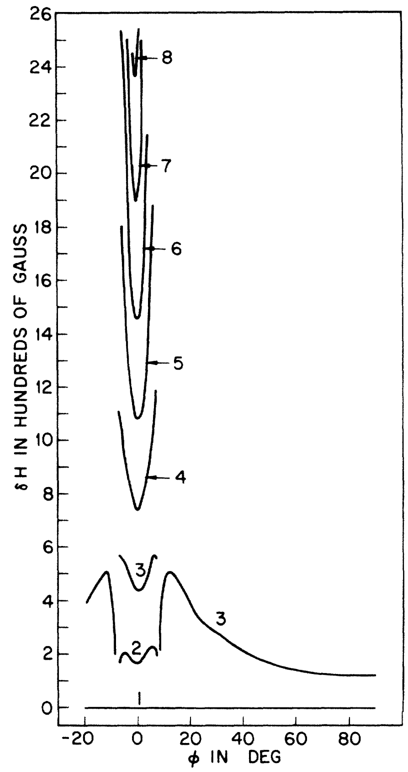

FIG. 2. The dependence of the magnetic-field splittings between the lowest order and the various higher order spin-wave modes as the normal to the film is rotated to some angle φ with respect to the direction of the magnetic field. The Permalloy film is 2700Å thick; $4\pi M = 8.16$ kG, $2\pi\omega = 9.60$ kMc/sec, and $\omega/4\pi\gamma M = 0.424$.

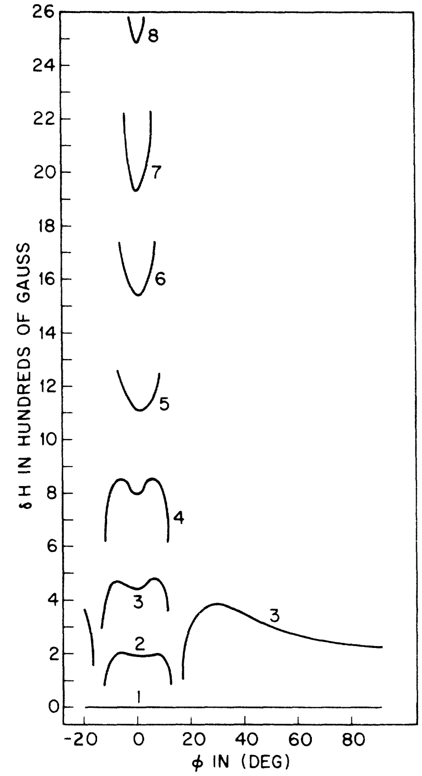

FIG. 3. The dependence of the magnetic-field splittings between the lowest order and the various higher order spin-wave modes as the normal to the film is rotated to some angle ϕ with respect to the direction of the magnetic field. The Permalloy film is 2700Å thick; $4\pi M = 8.16$ kG, $2\pi\omega = 14.67$ kMc/sec, and $\omega/4\pi\gamma M = 0.639$.

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$$H \sin\phi/M \sin\theta = (H \cos\phi - 4\pi M \cos\theta)/M \cos\theta. \quad (2)$$

For complete pinning at the film surfaces the propagation constant k is given by $k = p\pi/d$, where d is the thickness of the film and p is the order of the mode. The angular dependence of the magnetic-field splitting between the modes $p = 1$ and $p = 3$ as calculated from (1) and (2) is shown graphically in Fig. 4.

The modes indicated by the even numbers in Figs. 2 and 3 are weak in intensity and arise from an asymmetry in the pinning condition at the two surfaces.[6] They would not be excited if the surface spins were completely pinned[3] or if the degree of pinning were identical at each surface. The odd-numbered modes are much stronger by comparison, and for perfect pinning they would correspond to spin waves with the indicated number of half-wavelengths equal to the thickness of the film.[3] The calculated magnetic-field splittings

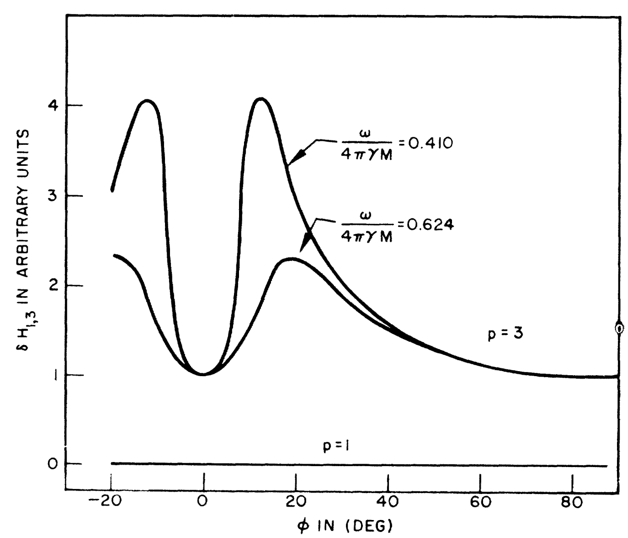

FIG. 4. Calculated dependence of the magnetic-field splittings between the first two spin-wave modes in a thin film where perfect pinning is assumed at each surface.

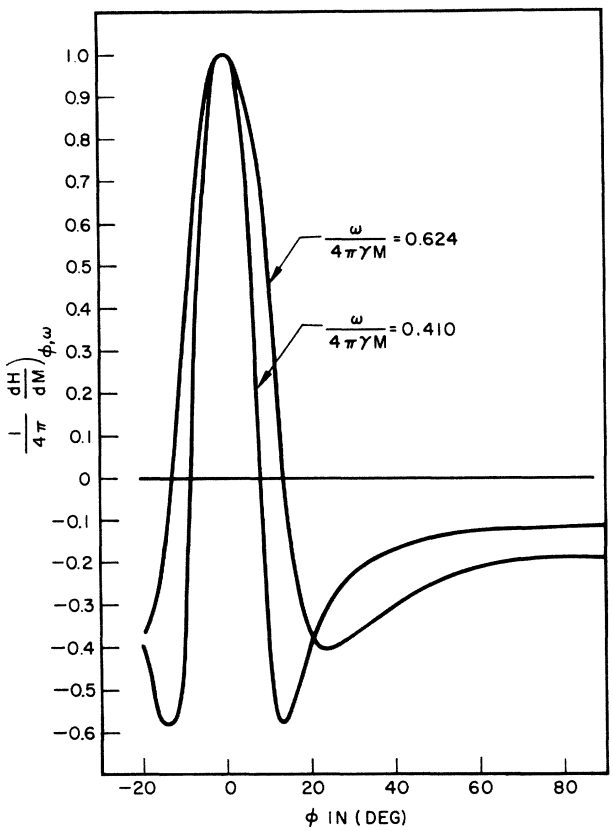

FIG. 5. Calculated angular dependence of the magnetic-field differences between the uniform precession modes of two films having a small difference in their magnetization for the two conditions $\omega/4\pi\gamma M$ equals 0.410 and 0.624.

between the modes $p=1$ and $p=3$ for complete pinning shown in Fig. 4 and the experimental splittings for the first and third modes shown in Figs. 2 and 3 are in qualitative agreement except for a region near $\phi=8^\circ$ in Fig. 2 and $\phi=13^\circ$ in Fig. 3, where the spectra collapse to a single line (Fig. 1).

With these critical angles in mind consider the difference, δH, between the magnetic fields supporting the uniform precession mode ($p=0$) in two films in which the magnetization differs by δM. The angular dependence of $(\partial H/\partial M)_{\phi,\,\omega}$ is shown in Fig. 5. When $\omega/4\pi\gamma M=0.410$ (9.60 kMc/sec), both layers will support the uniform precession mode in the same external field H, only near $\phi=8^\circ$; when $\omega/4\pi\gamma M=0.624$ (14.67 kMc/sec), uniform precession is supported only near $\phi=13$. These are just the angles at which the singularities in the spin-wave spectra were observed. Furthermore the relative field splittings at $\phi=90^\circ$ in Figs. 2 and 3 may indicate that the spin pinning, in general, may depend on the value of $(\partial H/\partial M)_{\phi,\,\omega}\delta M$ (Fig. 4, $\phi=90^\circ$). The second mode in Figs. 2 and 3 is not shown beyond the critical angle as the decrease in field splitting, δH, between the first and third modes and the increase in the linewidth of these modes override the weak intensity of the second mode.

The essential feature of our model is that the effective internal field must differ by a small amount in the two regions. The difference in the magnetization of the surface layer, giving a slightly different demagnetization field, is only one way to produce this effect. A different state of strain in the surface layer through the magnetoelastic effect or a change in an anisotropy field that is perpendicular to the film will produce the same results. The oxidation of the film surface previously shown to effect spin pinning may involve one of these interactions rather than the exchange anisotropy as suggested.[6]

The disappearance of the higher-order modes at small values of ϕ and the singularity in the resonance spectrum at the predicted angle give support to our model consisting of a film with a surface layer of different magnetization which is exchange-coupled to the body of the film. The surface spins are not pinned by a static boundary condition[2-6] but rather by a dynamic condition where the surface spins are free to precess but unable to support the uniform precession mode under the same external field conditions required for that mode in the interior of the film.

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[11]This expression, equivalent to those used in references 8 and 9, is derived from the equations of motion for the magnetization.