APPLICATION NOTE

8600 Series Vector Vibrating Sample Magnetometer (VVSM)

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In this application note, a vibrating sample magnetometer with the vector option (VVSM)—or biaxial VSM—is described, which, in addition to standard hysteresis loop measurements, provides for measurement of the angular dependence of the vector components of the total magnetization. The VVSM also provides for indirect measurement of torque curves for anisotropy constant determinations. Two sets of sensing coils are employed to measure the components of $\boldsymbol{M}$, from which M_{II}—the component parallel to the applied field H, and $M_{\perp}$—the component perpendicular to H are deduced. The torque density exerted on the sample by the applied field is

$$\tau = \mu_o \boldsymbol{M} \times \boldsymbol{H} = -\mu_o M_{\perp} H \boldsymbol{k}.$$

In this note, we will discuss the theory of operation and measurement methodology and present results for samples exhibiting both in-plane (IP) and out-of-plane (OOP) anisotropy.

Lake Shore
CRYOTRONICS

Introduction

Anisotropy is a basic property of magnetic materials.[1,2,3] The magnetization tends to lie in certain preferred directions, and the energy of a ferromagnetic material includes an anisotropy term $E_a(\theta,\phi)$ where the angular coordinates (θ,ϕ) define the direction of magnetization. The anisotropy can be intrinsic, related to atomic scale interactions which define easy directions in the crystal (magneto-crystalline anisotropy), or it can be related to the energy of the sample in its own demagnetizing field (shape anisotropy). Magnetic anisotropy is a very important parameter in a broad range of magnetic materials used in a host of technical and commercial applications.

The usual method for anisotropy determinations is torque magnetometry, which directly measures the macroscopic torque exerted by an applied field on the magnetization of a sample that is not precisely aligned with the field. Although torque magnetometers enjoy the advantage of high sensitivity and accuracy, they are unsuited to other magnetic measurements of interest, e.g., major and minor hysteresis loops, remanence curves, first-order-reversal-curves (FORCs), etc. A normal or single-axis VSM measures only M_{II}, the component of the magnetization parallel (or longitudinal) to the applied field, while the VVSM[4,5,6,7,8,9,10,11,12] measures both M_{II} and $M_\perp$, the magnetization component perpendicular (or transverse) to the applied field. $M_\perp$ is directly related to the macroscopic torque, and hence the VVSM provides information that is essentially identical to that provided by a torque magnetometer.

Theory: anisotropy constants from vector magnetization data

The anisotropy is obtained in a manner very similar to torque magnetometry, the difference being that instead of measuring torque directly, which is the product $HM_\perp$, one obtains the transverse magnetization $M_\perp$, and the longitudinal magnetization M_{II} from the components M_y and M_x, respectively, measured by the vector magnetometer coils. These experimental quantities are related to the torque and anisotropy constants. The formalism is as follows.

The energy of the system is given by the sum of anisotropy and magnetic potential energies,

$$E_T = E_a + E_p$$

In the case of uniaxial symmetry we have,

$$E_a = K_o + K_1 sin^2\theta + K_2 sin^4\theta + ...$$

Where θ is the angle between $\boldsymbol{M}$ and the easy direction of magnetization of the sample, and K_o is constant and independent of angle. The potential energy is given by $-\mu_o \boldsymbol{M} \cdot \boldsymbol{H}$, hence

$$E_p = -\mu_o MHcos(\Psi - \theta)$$

where Ψ is the angle between H and the easy direction of magnetization (see figure 1). If $K_2 << K_1$

$$E_T \approx K_o + K_1 sin^2\theta - \mu_o MHcos(\Psi - \theta) \tag{1}$$

At equilibrium the total energy is minimized, which requires that $dE_T/d\theta = 0$, hence

$$K_1 sin(2\theta) = \mu o\ MHsin(\Psi - \theta). \tag{2}$$

The expression on the left is the torque $\tau = -dE_a/d\theta$ exerted on the magnetization M by the crystal, and the expression on the right is the torque exerted on M by the applied magnetic field. Since $Msin(\Psi - \theta) = M_\perp$, the transverse magnetization,

$$K_1 sin(2\theta) = \mu_o M_\perp H.$$

When $M_\perp$ is a maximum, $sin(2\theta) = 1$. Hence,

$$K_1 = \mu o\ M_\perp^{max} H \tag{3}$$

Measurement of $M_\perp$ as a function of angle Ψ therefore allows determination of the anisotropy constant K_1 and torque τ. In the 8600 Series VVSM the angle Ψ is varied by rotating the sample relative to the magnetic field.

An alternative method of extracting a value for K_1 and also a value for K_2 is by fitting the torque curve to a Fourier series. All data in the torque curve is then used to calculate the anisotropy, not just the peak value.

Keeping terms in the energy to order $sin^4\theta$, the torque is:

$$\tau(\theta) \approx (K_1 + K_2)sin(2\theta) - 2K_2sin(4\theta) \qquad (4)$$

K_1 and K_2 can both be extracted by least-squares fitting the torque curve to this function. If the magnitude of the Fourier components for 2θ and 4θ are $\tau_{2\theta}$ and $\tau_{4\theta}$ respectively, then $K_2 = -\tau_{4\theta}/2$, $K_1 = \tau_{2\theta} - K_2$. If we only keep terms to order $sin^2\theta$ in the energy, then $K_1 = \tau_{2\theta}$.

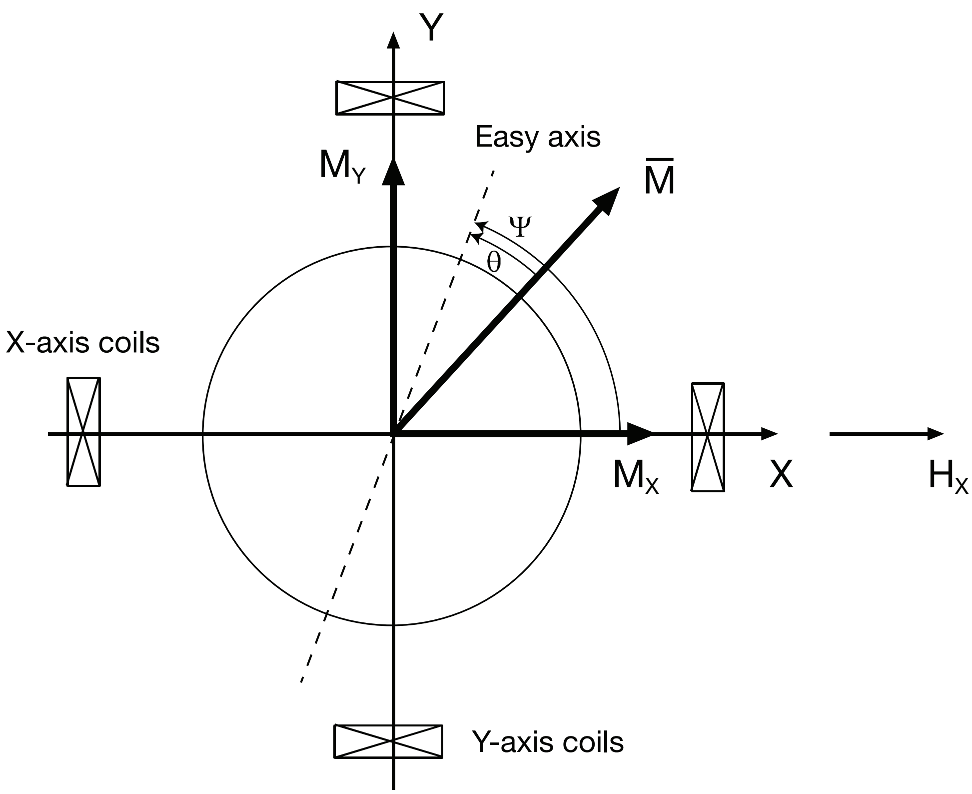

Figure 1: Schematic top view of the vector VSM.

Measurement methodology

A schematic top view illustration of the VVSM is shown in figure 1 with the different angles defining the directions of magnetization and applied field. One pair of sensing coils are parallel to the applied field and sense the magnetization component longitudinal to the field $M_{II} = M_x$. A second set of coils is mounted at right angles to the applied field and senses the magnetization component transverse to the field $M_{\perp} = M_y$. Hence the VVSM may be used to measure anisotropy in the xy-plane. Sample rotation, Ψ, in the xy-plane is achieved by rotating the sample about the z axis via a computer-controlled motor attached to the VSM head. For measuring IP anisotropy, a sample is mounted to a bottom mount sample holder so that the applied field is parallel to the sample plane. For measuring OOP anisotropy, a sample is mounted to a side mount sample holder so that the orientation of the applied field can be varied from parallel (IP) to perpendicular (OOP) with respect to the sample plane. The easy and hard axis of magnetization of either IP or OOP samples may be determined by measuring M_x and M_y as a function of angle at remanence $(H = 0)$. Figure 2 shows M_x and M_y as a function of IP angle from 0° to 360° for a magnetic tape with IP anisotropy. At remanence, $M_y = 0$ and $M_x = maximum$ when the easy axis is aligned with the x-axis coils (i.e., parallel to the applied field direction). Alternatively, $M_y = maximum$ and $M_x = 0$ when the easy axis is aligned with the y-coils (i.e., perpendicular to the applied field direction).

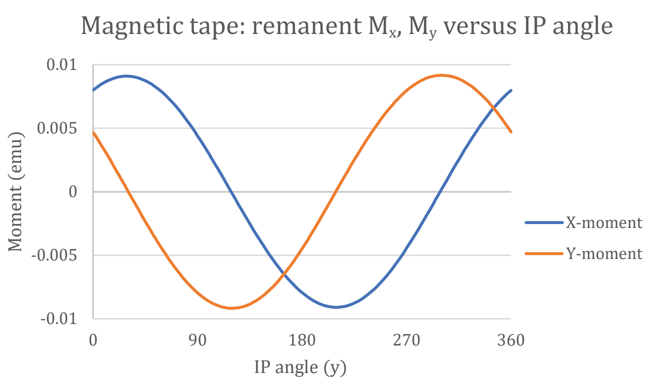

Figure 2: M_x and M_y as a function of IP angle from 0° to 360° for a magnetic tape at $H = 0$.

Examples

1. Out-of-plane (OOP) anisotropy

Figures 3 and 4 show the major hysteresis loops, $M_x(H)$ and $M_y(H)$, respectively, as a function of OOP angle for a magnetic tape. The loops were measured to applied fields of ±6 kOe (0.6 T) as a function of OOP angle (Ψ) from 0° $(H \,||\, tape\ plane)$ to 90° $(H_{\perp}\ tape\ plane)$ in 15° increments.

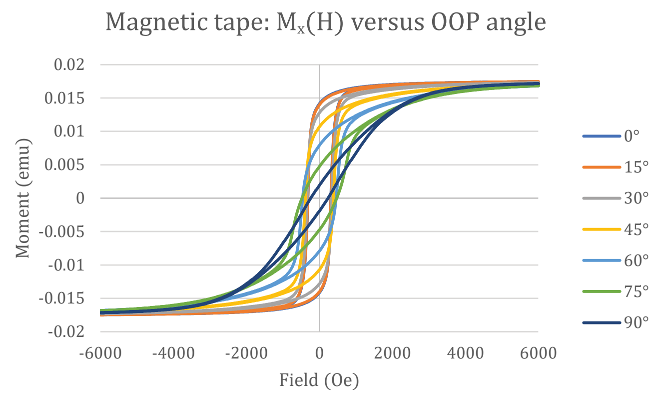

Figure 3: $M_x(H)$ versus OOP angle for a magnetic tape.

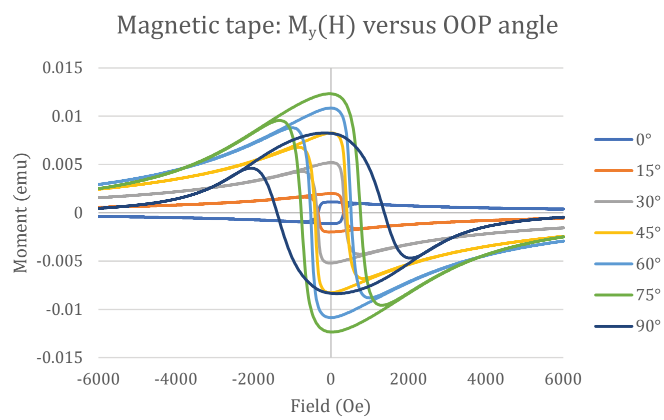

Figure 4: $M_y(H)$ versus OOP angle for a magnetic tape.

To derive the torque curve and anisotropy constants from the vector data, $M_y(\Psi)$ was measured as a function of OOP angle from $0° \leq \Psi \leq 360°$ in 2.5° increments at an applied field of 10 kOe (1 T). The torque curve in dyne-cm derived from the Fourier analysis of the $M_y(\Psi)$ results is shown in figure 5. As discussed in the Theory section, the anisotropy constants K_1 and K_2 are extracted by least-squares fitting the torque curve to equation (4): $K_1 = 12.8 \times 10^{-3}$ *dyne-cm*, $K_2 = -1.0 \times 10^{-3}$ *dyne-cm*.

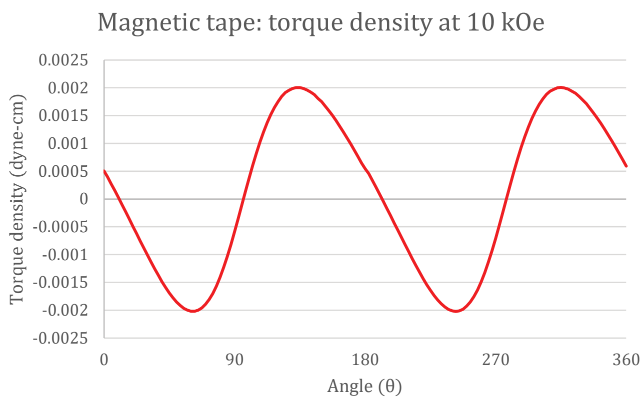

Figure 5: Torque curve (dyne-cm) as a function of OOP angle for a magnetic tape at $H = 10$ kOe (1T).

2. In-plane (IP) anisotropy

a) Uniaxially anisotropic magnetic tape

Figures 6 and 7 show the major hysteresis loops, $M_x(H)$ and $M_y(H)$, respectively, as a function of IP angle for a uniaxially anisotropic magnetic tape. The loops were measured to applied fields of ±16 kOe (1.6 T) as a function of IP angle (Ψ) from 0° *(H || easy axis)* to 90° *(H || hard axis)* in 15° increments.

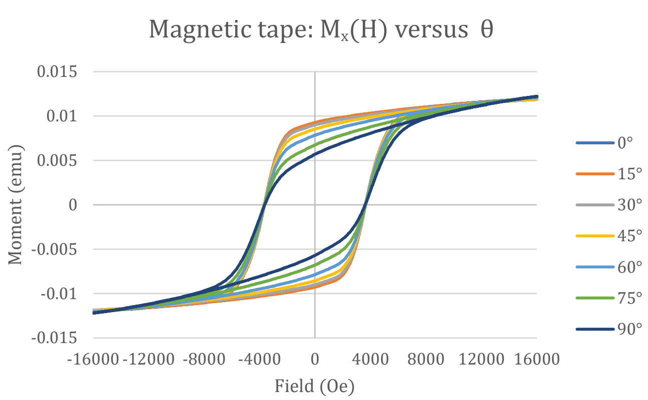

Figure 6: $M_x(H)$ versus IP angle for a uniaxially anisotropic magnetic tape.

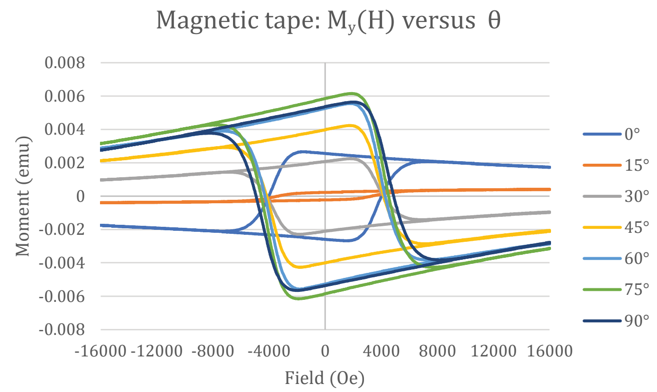

Figure 7: $M_y(H)$ versus IP angle for a uniaxially anisotropic magnetic tape.

$M_y(\Psi)$ for IP angles ranging from $0° \leq \Psi \leq 360°$ in 2.5° increments at an applied field of 25 kOe (2.5 T) was measured, and the torque curve in dyne-cm derived from the Fourier analysis of the $M_y(\Psi)$ results is shown in figure 8. Least-squares fitting the torque curve to equation (4) yields anisotropy constants of: $K_1 = 5.1 \times 10^{-2}$ *dyne-cm*, $K_2 = -6.53 \times 10^{-4}$ *dyne-cm*.

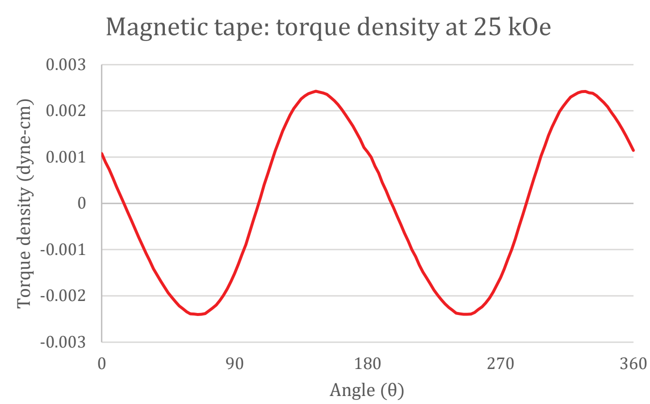

Figure 8: Torque curve (dyne-cm) as a function of IP angle for a uniaxially anisotropic magnetic tape at H = 25 kOe (2.5 T).

b) Permalloy (NiFe) multilayer thin film

The final example is for a magnetically soft (low coercivity) multilayer NiFe thin film[13] with saturation moment of <60 μemu. Each successive layer in the film was deposited with an applied field at a different angle than the previous layer. Figures 9 and 10 show the major hysteresis loops, $M_x(H)$ and $M_y(H)$, respectively, for applied fields of ±40 Oe (4 mT) as a function of IP angle (Ψ) from 0° *(H || easy axis)* to 90° *(H || hard axis)* in 15° increments. These results demonstrate that the 8600 Series VVSM is well suited to measuring both low coercivity, and low moment samples.

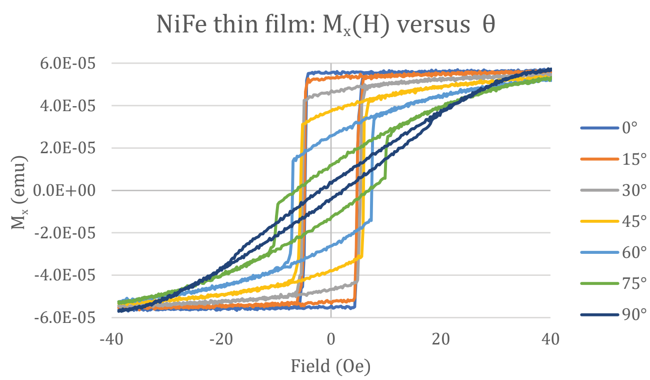

Figure 9: $M_x(H)$ versus IP angle for a low moment, low coercivity multilayer NiFe thin film.

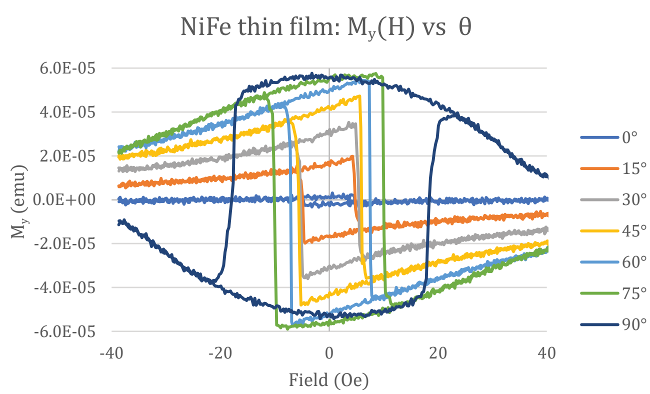

Figure 10: $M_y(H)$ versus IP angle for a low moment, low coercivity multilayer NiFe thin film.

$M_y(\Psi)$ for IP angles ranging from $0° \leq \Psi \leq 360°$ in 1° increments at an applied field of 20 Oe (2 mT) was measured, and the torque curve in dyne-cm derived from the Fourier analysis of the $M_y(\Psi)$ results is shown in figure 11. Least-squares fitting the torque curve to equation (4) yields anisotropy constants of: $K_1 = 3.29 \times 10^{-4}$ *dyne-cm*, $K_2 = -6.17 \times 10^{-5}$ *dyne-cm*.

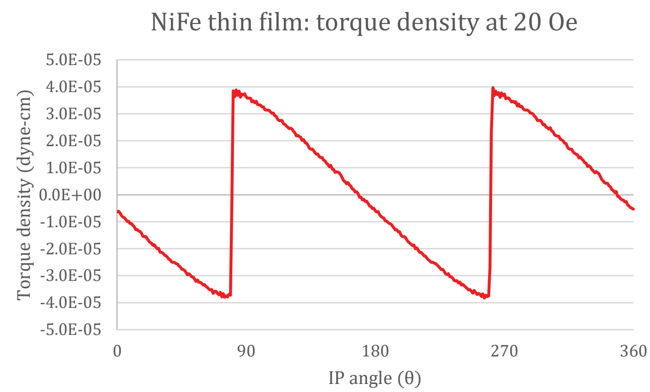

Figure 11: Torque curve (dyne-cm) as a function of IP angle for NiFe thin film at H = 20 Oe (2 mT).

Summary

In this application note, we have presented the 8600 Series vector VSM, which in addition to major and minor hysteresis loop measurements, remanence curves, first-order-reversal-curves (FORCs), etc., also provides for measurement of the angular dependence of the vector components of the total magnetization for magnetically anisotropic materials. We have discussed the measurement methodology and the theory of operation as it relates to using the vector VSM to derive torque curves and anisotropy constants. We have presented typical measurement results for magnetic tapes exhibiting both in-plane and out-of-plane anisotropy, and a multilayer magnetic thin film with in-plane anisotropy.

References

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