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 $\mathbf{M}$, from which $M_{//}$ — 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

$$\tau = \mu_0 \mathbf{M} \times \mathbf{H} = -\mu_0 M_\perp H k.$$ 

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.
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 $HM$, one obtains the transverse magnetization $M_\perp$ and the longitudinal magnetization $M_\parallel$, 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 $\theta$ is the angle between $M$ and the easy direction of magnetization of the sample, and $K_o$ is constant and independent of angle. The potential energy is given by $-\mu_0 M \cdot H$, hence

$$E_p = -\mu_0 MH \cos(\Psi - \theta)$$

where $\Psi$ is the angle between $H$ and the easy direction of magnetization (see figure 1). If $K_2 \ll K_1$,

$$E_T \approx K_o + K_1 \sin^2 \theta - \mu_0 MH \cos(\Psi - \theta)$$

(1)

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

$$K_1 \sin(2\theta) = \mu_0 MH \sin(\Psi - \theta).$$

(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 $M \sin(\Psi - \theta) = M_\perp$, the transverse magnetization,

$$K_1 \sin(2\theta) = \mu_0 M_\perp H.$$  

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

$$K_1 = \mu_0 M_\perp \max H$$

(3)

Measurement of $M_\perp$ as a function of angle $\Psi$ therefore allows determination of the anisotropy constant $K_1$ and torque $\tau$. In the 8600 Series VVSM the angle $\Psi$ 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:

$$\tau(\theta) = (K_1 + K_2)\sin(2\theta) - 2K_2 \sin(4\theta) \quad (4)$$

$K_1$ 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 $2\theta$ and $4\theta$ 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 $M_x = M_x$. A second set of coils is mounted at right angles to the applied field and senses the magnetization component transverse to the field $M_y = M_y$. Hence the VVSM may be used to measure anisotropy in the xy-plane. Sample rotation, $\Psi$, 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).

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 ($\Psi$) from 0° ($H \parallel tape plane$) to 90° ($H \perp tape plane$) in 15° increments.
To derive the torque curve and anisotropy constants from the vector data, $M_y(\Psi)$ was measured as a function of OOP angle from $0^\circ \leq \Psi \leq 360^\circ$ 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.

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 $\pm 16$ kOe (1.6 T) as a function of IP angle ($\Psi$) from $0^\circ$ ($H ||$ easy axis) to $90^\circ$ ($H ||$ hard axis) in 15° increments.

$M_y(\Psi)$ for IP angles ranging from $0^\circ \leq \Psi \leq 360^\circ$ 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 5: Torque curve (dyne-cm) as a function of OOP angle for a magnetic tape at $H = 10$ kOe (1T).

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.

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 \(<60 \mu\text{emu}\). 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 \(\pm 40 \text{ Oe} \) (4 mT) as a function of IP angle (\(\Psi\)) from \(0^\circ\) (\(H \parallel \text{easy axis}\)) to \(90^\circ\) (\(H \parallel \text{hard axis}\)) in \(15^\circ\) increments. These results demonstrate that the 8600 Series VVSM is well suited to measuring both low coercivity, and low moment samples.

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

\[\text{Figure 9: } M_x(H) \text{ versus IP angle for a low moment, low coercivity multilayer NiFe thin film.}\]

\[\text{Figure 10: } M_y(H) \text{ versus IP angle for a low moment, low coercivity multilayer NiFe thin film.}\]
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

13. Sample courtesy D. Adams, Univ. of New Orleans.