Journal of Magnetism and Magnetic Materials 193 (1999) 332–336

# On the vectorial calibration of a vibrating sample magnetometer for thin film measurements

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**Abstract**

A calibration method for the biaxial vector Vibrating Sample Magnetometer (VSM) is proposed to reduce the so-called 'cross talk' error, often observed during angular measurements on magnetic thin films. The coil system of the biaxial vector VSM consists of two sets of coils, one for each of the two co-ordinate axes. The method takes into account that each coil set is sensitive to all components of the magnetisation vector and moreover that the sensitivity to the components parallel and perpendicular to the film plane can be different. A correction for demagnetisation should be used to compensate the fact that the sample used for the calibration cannot be fully saturated with an applied field at angles close to the normal of the film plane. Curve-fitting on the sensitivity curves is used to reduce noise. These procedures result in a calibration which reduces the cross talk by a factor 4–8 depending on the coil configuration and the size and shape of the samples used. 

*Keywords:* Calibration; Vector VSM; Cross talk; Thin film; Demagnetisation; ME-tape

## 1. Introduction

The vector VSM is an essential tool for the analysis of thin film magnetic recording media. Measurement of the magnetisation vector is used for angle dependent measurements, magnetic anisotropy measurements and the determination of the intrinsic magnetic behaviour. Measuring the magnetisation vector in the $xy$-plane (the rotation plane of the sample) requires a biaxial coil system consisting of two coil sets, as shown in Fig. 1, one coil set for each co-ordinate. For angle dependent measurements of the magnetisation vector in thin films an angular calibration of the system is required. The commonly used (conventional) calibration method for a biaxial vector VSM consists of two parts:

- The X-coil (coil set with axis parallel to the applied field) calibration is performed by measuring the signal on the X-coils for every angle of interest while rotating a Ni-sample, with known magnetic moment, at a high field.
- The Y-coil (coil set with axis perpendicular to the applied field) calibration is done with the same sample in a zero field or with a perpendicular magnetised remanent sample. For every angle of interest the signal on the Y-coil is measured and after that the remanent sample is rotated back 90° to measure the magnetic moment on the calibrated X-coils.

This calibration method, which is in some form used in many (commercial) vector VSMs, is in principle incorrect due to a number of invalid assumptions:

(a) The coil system being equally sensitive for both in plane and perpendicular magnetisation components. The results from the calibration of the in plane component of the magnetisation are also used for the measurement of the component perpendicular to the film plane, while the shape of the stray fields resulting from each component is totally different.

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0304-8853/99/$ – see front matter 
PII: S0304-8853(98)00451-X

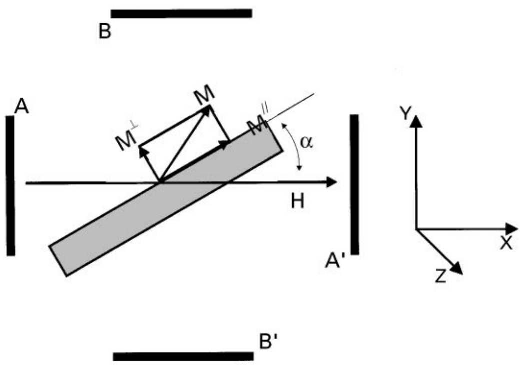


Fig. 1. Topview of sample within the biaxial coil system, consisting of coil sets A and B. $M$, $M_{//}$, $M_{\perp}$ and $\alpha$ are shown in relation to the sample.

(b) Orthogonality of the coil system. One set of coils is considered to have its sensing direction exactly perpendicular to the other set.
(c) The coils being perfectly aligned with the external magnetic field. One set has its axis exactly aligned with the applied field while the axis of the other set is perpendicular to the field.

One of the errors resulting from these invalid assumptions is an undesired contribution to the signal of a magnetic moment perpendicular to the measuring direction. This is often considered as an error, sometimes referred to as 'cross talk' [1], which is getting increasingly important when the sample size approaches the sample-coil distance, especially when angle dependent measurements are performed. This cross talk problem leads to errors in the magnetisation vector of up to 15% in magnitude and 8° in angle in a configuration where the size of the square sample is half the coil distance.

Several solutions have been proposed to minimise the cross talk problem. Richter [2] introduces a phenomenological correction for the cross talk based on the mean values of magnitude and orientation of the magnetisation, which is a good approximation if the deviations are small. Other methods minimise the effect of the invalid assumptions by adjusting the design of the detection system; Bernards [1] uses an extra set of 4 coils in addition to an 8-coil set-up, Samwel et al. [3] avoid the rotation of the sample in respect to the coils and take the different sensitivities for different components into account.

In contrast to the methods above, the calibration method introduced here is based on the acceptance of the fact that both coil sets are sensitive to all components of magnetisation and that a magnetisation component perpendicular to and parallel with the film plane contribute differently to the signal. The method requires no adjustment of the detection system and can be implemented in the software.

## 2. The calibration method

In the conventional calibration methods two sensitivity functions are used. The fact that each coil set is sensitive to both components of the magnetisation vector leads to four angle dependent sensitivity functions:

$$\begin{bmatrix} V_{\mathrm{A}}(\alpha) \\ V_{\mathrm{B}}(\alpha) \end{bmatrix} = C \begin{bmatrix} S_{\mathrm{A}//}(\alpha) & S_{\mathrm{A}\perp}(\alpha) \\ S_{\mathrm{B}//}(\alpha) & S_{\mathrm{B}\perp}(\alpha) \end{bmatrix} \begin{bmatrix} M_{//} \\ M_{\perp} \end{bmatrix}, \tag{1}$$

where the definition of angles and vectors is given in Fig. 1, $M$ is the magnetic moment in [A m$^2$], $\alpha$ is the angle between sample and applied field, $S$ is the normalised [unitless] sensitivity, $C$ is the calibration factor in [V A$^{-1}$ m$^{-2}$] and $V$ is the signal in [V]. The subscripts // and $\perp$ indicate, respectively, the component parallel and perpendicular to the sample while the subscripts A and B refer to the coil sets A and B. The calibration constant $C$ is obtained by measuring the signal induced in coil set A by a Ni-foil with a known magnetic moment at a high field at sample angle $\alpha = \alpha_0$ [deg], the reference angle:

$$C = \frac{V_{\mathrm{ANi}}}{M_{\mathrm{sNi}}} \,[\mathrm{V\,A^{-1}\,m^{-2}}]. \tag{2}$$

The 4 normalised sensitivity functions (2 for each coil set) can be obtained by two measurements:

- rotating a remanent VHS-tape or Ni-foil ($H = 0, M_{\perp} = 0$) giving the signals $V_{\mathrm{Ar}//}(\alpha)$ and $V_{\mathrm{Br}//}(\alpha)$;
- rotating the same sample in saturation ($H = H_{\max}, M_{//} = |M|\cos(\alpha),\ M_{\perp} = |M|\sin(\alpha)$) resulting in the signals $V_{\mathrm{As}}(\alpha)$ and $V_{\mathrm{Bs}}(\alpha)$.

From these four measurement values and Ref. [1] we can calculate the four sensitivity functions, two for each coil set:

$$S_{//}(\alpha) = \frac{V_{r//}(\alpha)}{V_{r0}}, \tag{3}$$

$$S_{\perp}(\alpha) = \left[\frac{(V_{\mathrm{s}}(\alpha)/V_{\mathrm{s}0}) - S_{//}(\alpha)\cos(\alpha)}{\sin(\alpha)}\right], \tag{4}$$

where $V_{\mathrm{r}0} = V_{\mathrm{Ar}}(\alpha_0)$ and $V_{\mathrm{s}0} = V_{\mathrm{As}}(\alpha_0)$ the signals at the reference angle.

In the second part of the calibration, the calibration sample is supposed to be saturated, but even at 3 Tesla the VHS-tape or Ni-foil used cannot completely be saturated at angles close to the normal of the film plane ($80° < \alpha < 100°$) due to sheet-demagnetisation. Therefore a demagnetisation correction will be needed:

$$S_{\perp}(\alpha) = \left[\frac{(V_{\mathrm{s}}(\alpha)/V_{\mathrm{s}0}) - S_{//}(\alpha)\cos(\alpha - \beta)}{\sin(\alpha - \beta)}\right], \tag{5}$$

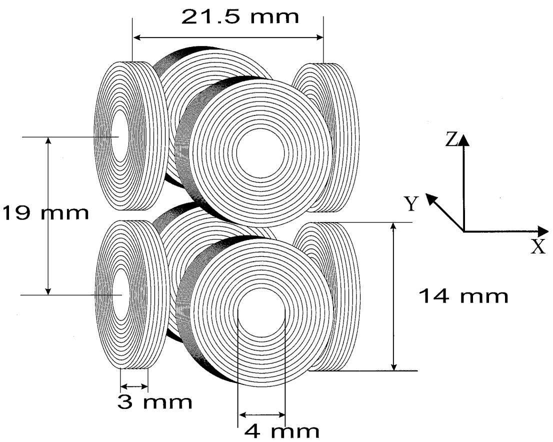


Fig. 2. The applied biaxial coil system for the vector VSM.

where the correction angle $\beta$ is given by

$$\beta = \frac{\sin(2\alpha)}{(2H/M_S) + 2\cos(2\alpha)} \quad [\text{rad}]. \tag{6}$$

Another method to get the perpendicular sensitivity functions is from a rotating remanent perpendicular sample (such as a thin film Ba-ferrite sample with a perpendicular anisotropy) rather than a saturated sample with in plane anisotropy. The formula for the perpendicular sensitivity curves (Eq. (4)) of each coil set will then simplify into

$$S_{\perp}(\alpha) = \frac{V_{r\perp}(\alpha)}{V_{r\perp 0}}. \tag{7}$$

An angle correction for the demagnetisation will not be needed in this case. However using two different samples for the angular calibration can result in a poorer result when the reproducibility of the sample position is not accurate enough.

## 3. Results

As a verification for the calibration procedure a remanent single-layered ME-tape with a magnetic anisotropy tilted approx. 21° out of the film plane is rotated in a zero magnetic field, so that both the in plane as well as the perpendicular component of the magnetisation are available and constant during this measurement. Any fluctuations of the magnitude and angle of $M$ with the film plane are of course an error. The calibration and measurements were performed with samples of $10 \times 10$ mm in a coil setup as shown in Fig. 2. In this case the sample size was large in comparison to the coil distance. In cases where the sample size is relatively small the results may be less dramatic.

Table 1
Comparison of the results of the various tests on the vectorial calibration method

| Coils-set up | Calibration sample 1 | Calibration sample 2 | Calibration method | Demagn.angle corr. | Curve-fitting | $\Delta\varphi$ (deg) | $\Delta\lvert M\rvert$ (%) | $\Delta M_{//}$ (%) | $\Delta M_{\perp}$ (%) |
|---|---|---|---|---|---|---|---|---|---|
| A | VHS-rem | VHS-sat | Conv. | No | No | 7.9 | 14.5 | 15.9 | 32.1 |
| | | | New | No | No | 4.0 | 5.9 | 6.7 | 16.0 |
| | | | New | Yes | No | 3.9 | 5.2 | 6.9 | 13.4 |
| | | | **New** | **Yes** | **Yes** | **2.2** | **4.9** | **6.1** | **9.3** |
| | Ni-rem | Ni-sat | Conv. | No | No | 7.7 | 13.7 | 15.0 | 32.2 |
| | | | New | Yes | Yes | 5.0 | 11.5 | 13.0 | 22.0 |
| | VHS-sat | Ba-ferrite-rem | Conv | No | No | 7.3 | 16.3 | 15.7 | 11.6 |
| | VHS-rem | Ba-ferrite-rem | New | No | Yes | 2.5 | 4.5 | 6.2 | 9.3 |
| B | VHS-rem | VHS-sat | Conv. | No | No | 11.0 | 16.2 | 19.2 | 42.4 |
| | | | New | No | No | 3.0 | 7.1 | 8.1 | 12.0 |
| | | | **New** | **Yes** | **No** | **1.2** | **2.1** | **2.4** | **4.6** |
| | | | New | Yes | Yes | 1.4 | 2.6 | 3.1 | 5.5 |
| | Ni-rem | Ni-sat | Conv. | No | No | 10.1 | 17.9 | 19.2 | 38.5 |
| | | | New | Yes | Yes | 3.2 | 10.0 | 10.8 | 18.3 |
| | VHS-rem | Ba-ferrite-rem | New | No | Yes | 2.8 | 5.6 | 6.3 | 9.9 |

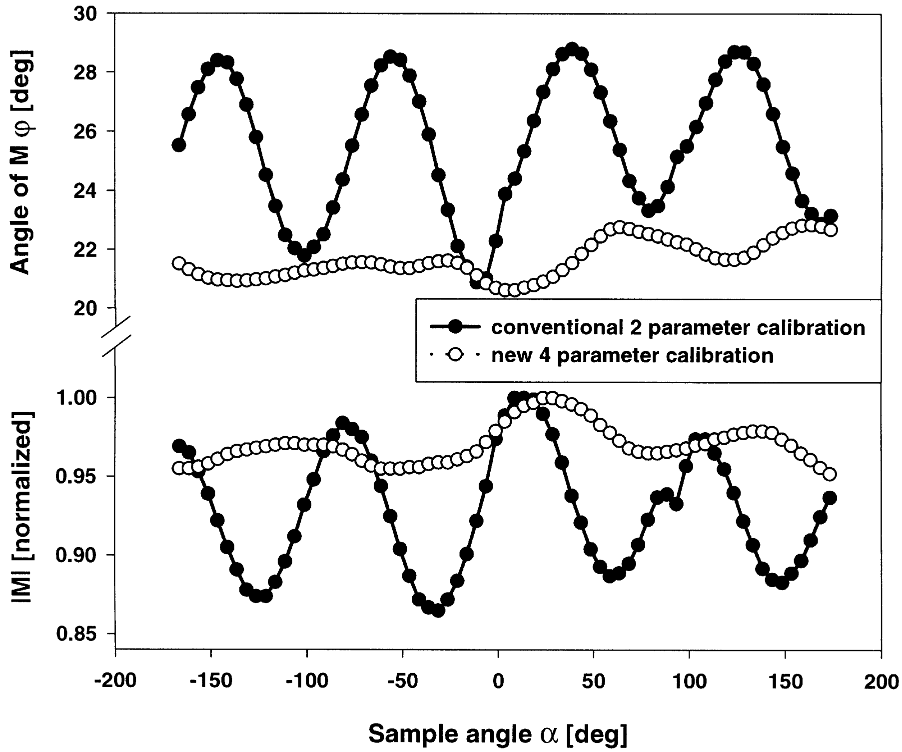


Fig. 3. Comparison between the conventional and new calibration method on a 0° (type A) coil assembly.

In the first 6 columns of Table 1 the tests are listed and in the last 4 columns their results are given:

1. Column 1 gives the two positions of the coil set which were tested:
   A. The conventional setup in which one coil set has its axis parallel and the other set perpendicular with respect to the field direction.
   B. All coils were rotated 45° in respect to the field in the $XY$-plane.
2. The vector calibration has been done with different samples. Sample 1, which is listed in column 2, is used for the in plane sensitivity functions of both coil set A and B in case of the new calibration method. In case of the conventional method it is used for the sensitivity function of coil set B.
3. Sample 2 in column 3 is in the case of the new method used for the perpendicular sensitivity functions of both coil sets, while in the conventional calibration it is used for the sensitivity function of coil set A. The saturated VHS-tape and Ni-foil are rotated at 3 Tesla for the perpendicular calibration. A remanent Ba-ferrite sample with perpendicular anisotropy has also been used to determine the perpendicular sensitivity function.
4. The 4th column shows the calibration method used: the conventional way used in most commercial vector VSMs, or the new approach as proposed in this paper.
5. The 5th column shows whether or not the angle correction for the sheet demagnetisation is used (Eq. (4) or (5)).
6. Further improvement can sometimes be achieved by using curve-fitting for the sensitivity curves using a linear fit of sine and cosine terms. Column number 6 shows whether or not such a curve-fitting routine has been used.
7. The last four columns list the resulting errors as the top–top fluctuations of the angle of $M(\Delta\varphi)$ with the film plane and fluctuations of the magnitude $M(\Delta|M|)$ as well as the in plane $(\Delta M//)$ as the perpendicular $(\Delta M\perp)$ components of the magnetisation vector of the rotated remanent ME-tape as a percentage of their maximum.

For both coil setups the calibration with the VHS-tape for both the in plane as well as the perpendicular sensitivity gave the best result. For these calibrations the results of each step are shown while of the poorer performing calibration samples only the conventional and the best

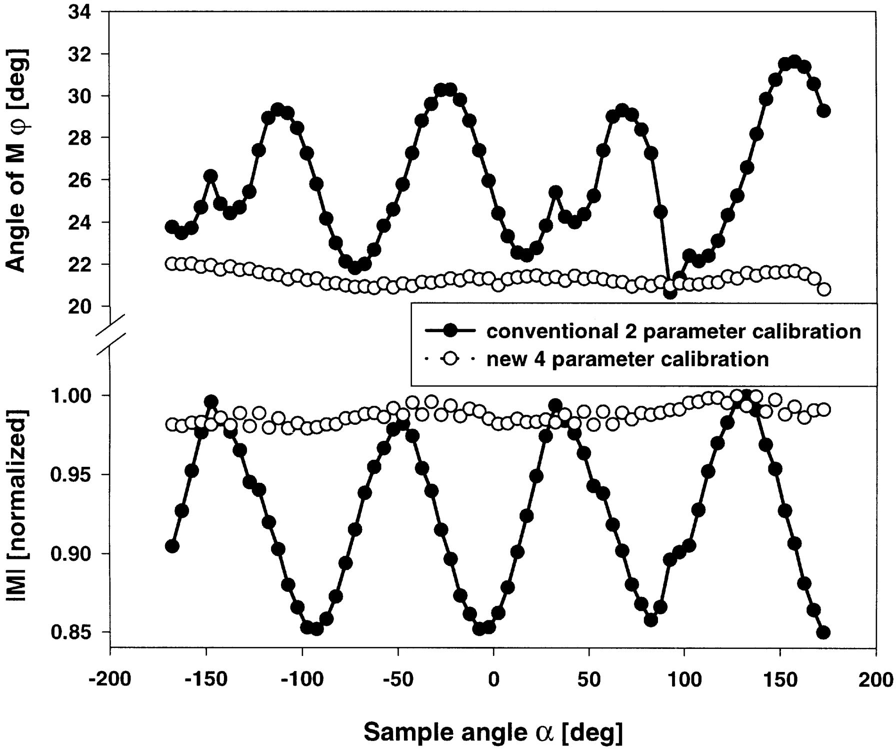


Fig. 4. Comparison between the conventional and new calibration method on a 45° (type B) coil assembly.

results of the new approach are shown. The improvement of the proposed calibration method over the conventional one for both coil setups is clearly shown in Figs. 3 and 4. Later implementation of this calibration method on a DMS VSM at ADE Technologies Inc., showed an improvement on the top–top fluctuations of the magnitude of $M$ from 10% to 4% and of the angle of $M$ from 6.5° to 1.8° using $10 \times 10$ mm samples.

## 4. Conclusions

The application of the proposed calibration procedure reduces the cross talk problem by at least a factor of 2 in cases where the sample size approaches the coil distance, while other improvements like angle correction for the non-saturated calibration sample and curve fitting of the sensitivity functions will yield a decrease of another factor of 2. Using a VHS-tape as an angular calibration sample gives the best results. The angle correction for the Ni-foil is less valid because of the higher magnetisation resulting in a higher demagnetisation. All of these improvements do not involve any hardware modifications and can be implemented in most (commercial) VSMs quite easily by software changes. Another advantage of the new calibration method is its insensitivity to mismatch, misalignment and non orthogonality of the coils. Rotating the coils to an angle of 45° gives a further improvement. In this case the proposed calibration method reduced the cross talk by a factor of 8.

## Acknowledgements

The authors would like to thank Dr. J.G.Th. te Lintelo for the fruitful discussions.

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