In-Plane Vector Magnetometer Employing a Single Unbiased Magnetoresistor

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Abstract—**This paper extends previous work, where a single barber-pole magnetoresistor (MR) was employed for measuring simultaneously two magnetic field components. The present work differs from the previous one in employing a single unbiased MR, which is simpler and less expensive. The present arrangement, like the previous one, relies on a rotating excitation method. A specially devised elliptically rotating field is employed for this purpose. The latter causes the material magnetization to rotate uniformly when there is no external field present. The presence of an external magnetic field is detected by measuring the time shifts of the resulting MR ac output zero-crossings. Despite the similarity between the present system and its previous counterpart, the sensitivities of detection of the present arrangement are equal for the two orthogonal components of the externally measured field. It is also interesting that the intensities of the sinusoidal excitation fields in the present case are equal. However, the excitation coils are not perpendicular to each other as they were in the previous barber-pole case.**

Index Terms—**Barber-pole magnetoresistor, Barkhausen noise, elliptically rotating bias, magnetoresistance, unbiased magnetoresistor, Stoner-Wohlfarth theory, thin-ferromagnetic films.**

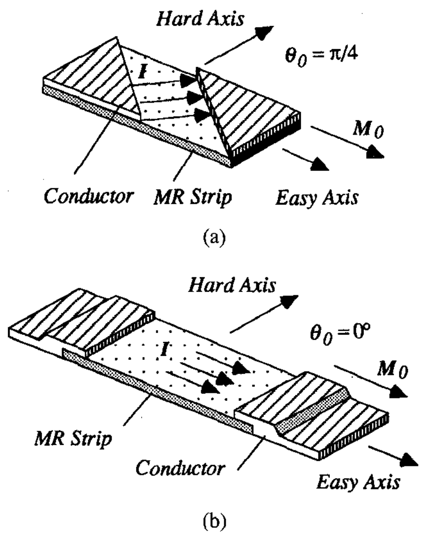

Fig. 1. Magnetoresistors. (a) Geometry of a barber-pole magnetoresistive element. (b) Unbiased magnetoresistor. [θ_0—the angle between the quiescent magnetization (M_0) direction and the current through the magnetoresistive strip.]

I. Introduction

It has been shown that a single anisotropic barber-pole magnetoresistor (MR) can be used as a precise and sensitive in-plane vector magnetometer [1]–[4]. According to the method [1], a single barber-pole MR [see Fig. 1(a)] is excited by an in-plane rotating field, which continuously saturates the MR material. An appropriate elliptical polarization of the rotating excitation field is able to compensate for the anisotropy influence on the magnetization rotation. As a result, it enables uniform rotation of the MR magnetization [1], [2]. Let us assume that the x- and y-directions coincide with orthogonal components of an external in-plane magnetic field [see Fig. 2(a)]. Furthermore, the x- and y-components are chosen to be along the easy and hard MR axes correspondingly. It is interesting that the resulting MR ac output is insensitive to the y external field when the rotating magnetization reaches the hard axis direction, and it is insensitive to the x external field when the magnetization reaches the easy axis direction [1]. The ac part of the MR output crosses zero at these moments. This is due to the barber-pole arrangement that causes the angle (θ_0) between the current flow in the MR strip and the direction of quiescent magnetization [see Fig. 1(a)] to be biased to 45°. At the instances when the MR ac output crosses zero, it is affected exclusively either by the x external field component or exclusively by the y external field component alternatively. Fig. 3(a) shows that in this case, information about external field components is included in the phase shifts between zero-crossings of the MR ac output and zero-crossings of the corresponding excitation fields. Furthermore, this figure demonstrates that the measurement processes of the external x and y field components are mutually independent. The detection procedure relies on measuring the delays between the corresponding zero-crossing instances. This detection procedure can be achieved by a well-known simple electronic realization.

Unfortunately, the method proposed in [1] and reviewed in the previous paragraph cannot be directly applied to an unbiased MR [Fig. 1(b)]. The ac output signal of an unbiased MR reaches its extreme values when magnetization direction arrives at the easy or at the hard axes directions [Fig. 2(b), Fig. 3(b)]. Furthermore, one can generalize and say that several of the effects that are noticed in the barber-pole MR case as occurring at zero-crossings of the MR ac output signals [Fig. 3(a)] occur in the unbiased MR case at the maxima and minima points [Fig. 3(b)]. This 45° shift in

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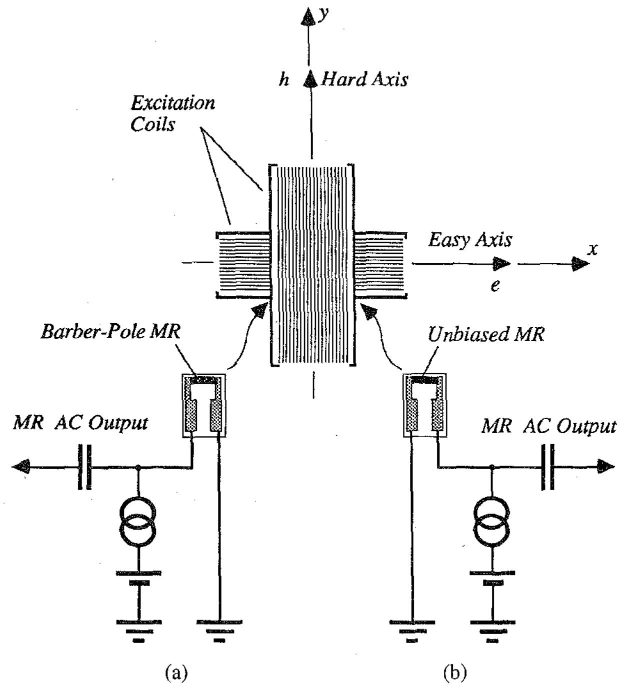

Fig. 2. Schematic diagram of the experimental setup for exciting magnetoresistors by rotating field as was proposed in [1]. (a) Excitation of barber-pole magnetoresistor. (b) Excitation of unbiased magnetoresistor.

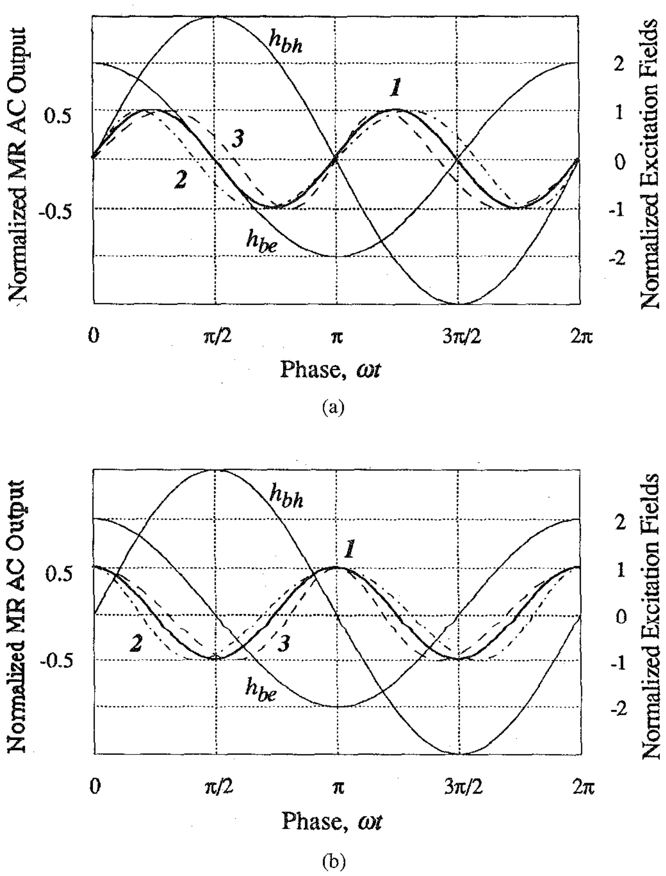

Fig. 3. The theoretically obtained outputs (normalized MR ac output versus time) of magnetoresistors employing rotating excitation method described in [1]. (a) Output signals of barber-pole magnetoresistor. (b) Output signals of unbiased magnetoresistor. The outputs are obtained for different values of dc external field: 1—$H_{mx} = 0$; 2—$H_{mx} < 0$; 3—$H_{mx} > 0$; 1-3—$H_{my} = 0$.

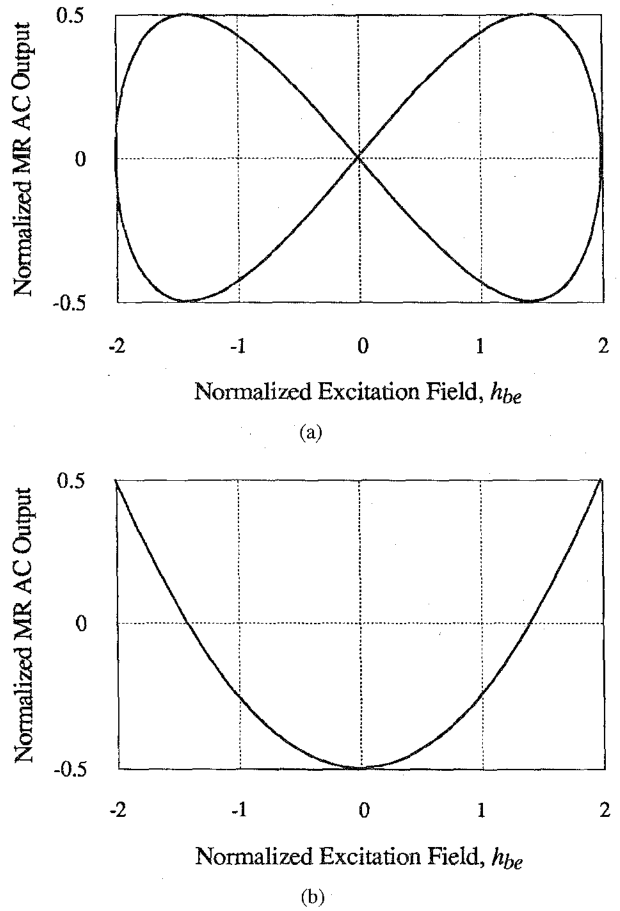

Fig. 4. The theoretically obtained outputs (normalized MR ac output versus normalized easy-axis excitation field) of magnetoresistors employing rotating excitation method described in [1]. (a) Output signal of barber-pole magnetoresistor. (b) Output signal of unbiased magnetoresistor.

MR output behavior results from the 45° change of the angle θ_0 in the unbiased MR case compared with the MR that is biased by the barber-pole arrangement (see Fig. 1). Hence, the points where the MR ac output is affected by one of the external field components exclusively are also at the maxima or the minima of this signal [see Fig. 3(b)]. Detection of time intervals between the MR ac signal peak in this case and the peak of the corresponding excitation field is complicated. The complication of the detection is due to the flatness of the signal at the peaks. However, unbiased MR's are technologically simpler and therefore less expensive than barber-pole MR's. Hence, there is a reason to try to suggest a modified rotating excitation method [1] for the unbiased MR case.

Fig. 3 demonstrates that the different ways by which the output waves of the MR's are shifted as a result of the external field influence do not represent the main difference in behavior between the barber-pole MR output response and the response of the unbiased MR. One can observe that there exists an even more significant difference in noticing that even when there is no external field, the phase difference between the excitation signal and the MR ac output is not the same for the two types of the MR's. This major difference between the MR's is demonstrated by comparing Fig. 4(a) to 4(b). This situation suggests that the behavior of the unbiased MR could

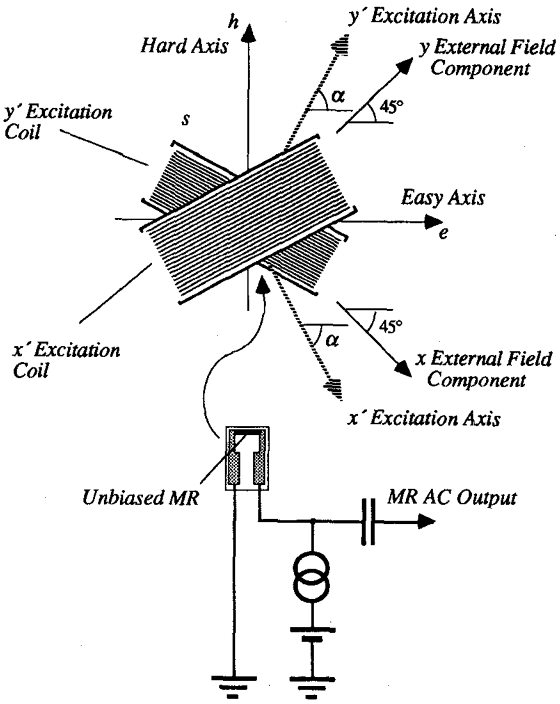

Fig. 5. Schematic diagram of the experimental setup devised for excitation of an unbiased magnetoresistor by rotating field according to the presently proposed method.

be made similar to that of the barber-pole one by devising a proper method for phasing the excitation fields. This method should provide the same figure for the unbiased MR as the one shown in Fig. 4(a). The development of the corresponding excitation method relies on the Stoner–Wohlfarth theory.

II. Theory

We found that the unbiased MR could be appropriately excited by simply modifying the excitation arrangement (see Fig. 2) proposed in [1] for driving a barber-pole MR. The modified arrangement (see Fig. 5) is due to a surprisingly simple idea. It seems that the new excitation arrangement requires a different orientation of the excitation coils such that their axes x' and y' possess two equal angles α in relation to the MR easy axis (see Fig. 5). This differs from the previous barber-pole MR excitation arrangement, where the excitation coils axes coincided with the MR easy and hard axes (see Fig. 2). It can be shown that in order to produce the appropriate elliptical excitation needed in the present case, the presently sinusoidal excitation fields should be in quadrature and their amplitudes should be equal, namely

$$\begin{cases} h_{bx'} = h_{bm} \cos \omega t \\ h_{by'} = h_{bm} \sin \omega t \end{cases} \tag{1}$$

where $h_{bx'} = H_{bx'}/H_k$ and $h_{by'} = H_{by'}/H_k$ are normalized excitation fields, $h_{bm} = H_b/H_k$ is the normalized amplitude of these fields, H_k is the MR material anisotropy field, and ω is the angular excitation frequency. This differs from the previous case, where the excitation intensities were different. Furthermore, it can be shown that the appropriate choice for the x- and y-directions of the two orthogonal components of an external measured field should be both 45° in relation to the easy axis (see Fig. 5). The latter arrangement enables the behavior of the output signal of an unbiased MR to be similar to that of a barber-pole MR as is shown in Figs. 3(a) and 4(a). According to Fig. 4(a), we would like the ac output of the unbiased MR to cross zero, when one of the excitation fields is zero. The other excitation field is at this moment at its maximum. The amplitude and direction of this field define the direction θ of magnetization in the unbiased MR material, and, therefore, it determines the MR output. The ac part of the normalized MR output ($\delta v = \Delta v/\Delta V$ peak-to-peak) can now be written as follows, when taking into account the fact that in an unbiased MR [see Fig. 1(b)], the current direction is along the easy axis:

$$\delta v = \cos^2 \theta - 1/2. \tag{2}$$

According to (2), $|\theta|$ should be equal to 45° when the MR ac output crosses zero. Taking into account the Stoner–Wohlfarth equation [5] (with reference to the coordinates e, h in Fig. 5)

$$\tfrac{1}{2} \sin 2\theta + h_{be} \sin \theta - h_{bh} \cos \theta = 0 \tag{3}$$

one obtains that the excitation field components should satisfy the following relation in order to maintain the angle $\theta = \pm 45°$:

$$\pm h_{bh} = \pm h_{be} + \frac{\sqrt{2}}{2}, \quad \pm h_{bh} = \mp h_{be} + \frac{\sqrt{2}}{2}. \tag{4}$$

The e and h excitation field components for the instances when one of the fields $h_{bx'}$ and $h_{by'}$ is zero are as follows:

$$\begin{cases} h_{be} = h_{bm} \cos \alpha \\ h_{bh} = h_{bm} \sin \alpha. \end{cases} \tag{5}$$

Equations (4) and (5) assist in obtaining the expression that relates the amplitude of the excitation fields to the angle α

$$\begin{cases} h_{bm} = \dfrac{1}{2 \cos (\alpha + \pi/4)} \\ \pi/2 > \alpha > \pi/4. \end{cases} \tag{6}$$

The appropriate form of the excitation fields components is as follows in accordance with (1) and (6)

$$\begin{cases} h_{be} = \sqrt{2} h_{bm} \cos \alpha \sin (\omega t + \pi/4) \\ h_{bh} = -\sqrt{2} h_{bm} \sin \alpha \cos (\omega t + \pi/4). \end{cases} \tag{7}$$

Equations (6) and (7) demonstrate that the total excitation field rotates elliptically. Moreover, it can be easily shown that the half-lengths of the ellipse axes are

$$\begin{cases} a = h_{bem} = \sqrt{2} h_{bm} \cos \alpha \\ b = h_{bhm} = \sqrt{2} h_{bm} \sin \alpha. \end{cases} \tag{8}$$

It is interesting that a and b here are related in the same way as their counterparts in [1] and [2]. Indeed, according to (6) and (8)

$$b = a + 1. \tag{9}$$

It means, in accordance with (7) and [1] and [2], that the magnetization of the MR material rotates uniformly. Hence, according to (2), the MR output waveform is a sinusoid whose angular frequency is 2ω (provided that no externally

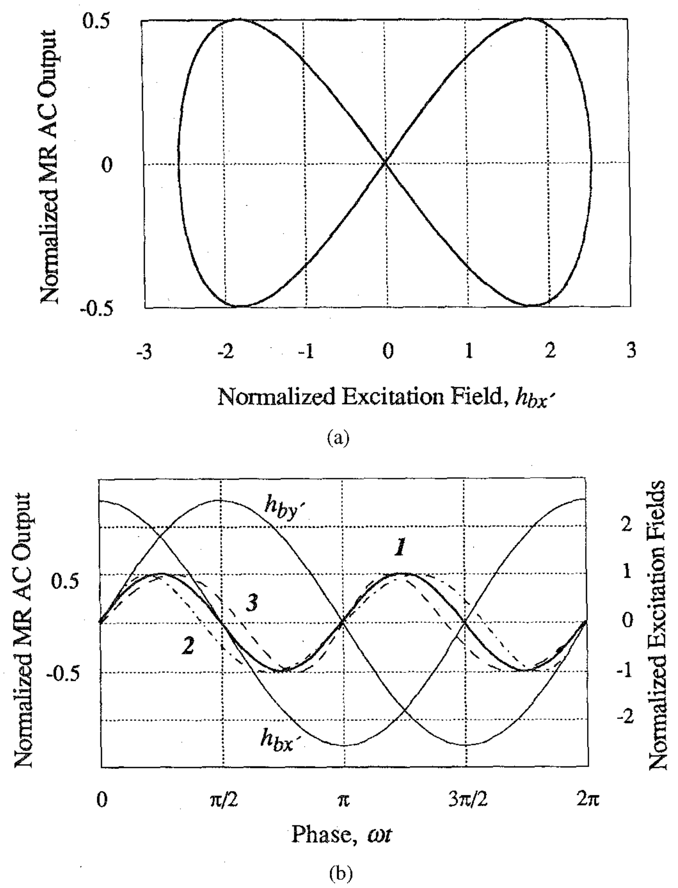

Fig. 6. The theoretically obtained outputs of an unbiased magnetoresistor employing the proposed rotating excitation method. (a) Magnetoresistive output versus the easy-axis excitation field. (b) Magnetoresistive outputs versus time. The outputs are obtained for different values of dc external field: 1—$H_{mx} = 0$; 2—$H_{mx} < 0$; 3—$H_{mx} > 0$; 1–3—$H_{my} = 0$.

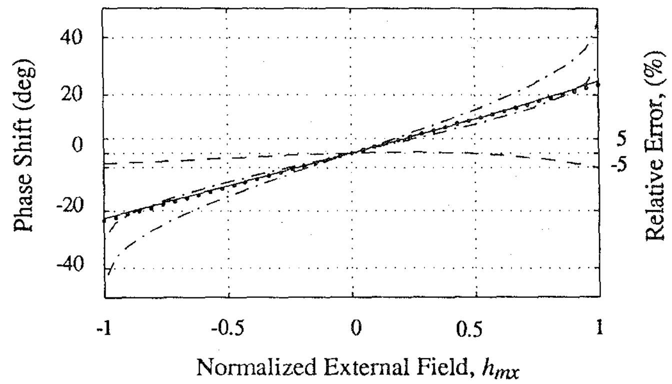

Fig. 7. Theoretical response characteristic (dotted line) of unbiased magnetoresistor employing the proposed rotating excitation method. For comparison we also show the theoretically obtained easy-axis and hard-axis response characteristics (dashed–dotted lines) of barber-pole magnetoresistor employing the rotating excitation method described in [1]. The solid line is a linear approximation of the response characteristic. The broken line represents the relative error of the approximation.

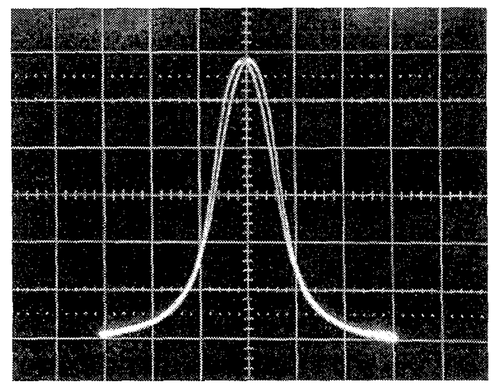

Fig. 8. Output characteristic (MR ac output versus hard-axis magnetic field) of the unbiased magnetoresistor. $X = 1$ (kA/m)/div; $Y = 5$ mV/div.

measured magnetic field is applied to the MR). Fig. 6 shows the theoretically obtained MR output for the case where $\alpha \approx 56.31°, h_{bm} \approx 2.55(a = h_{bem} = 2, b = h_{bhm} = 3)$. One can see from this figure that the zero-crossings of the MR ac output and the zero-crossings of the corresponding excitation fields coincide when external field is zero. Moreover, Fig. 6(b) shows that information about x external measured field component can be concluded from the phase shift between the zero-crossings of $h_{bx'}$ excitation field and the even zero-crossings of the MR ac output. The locations of the odd zero-crossings of the MR ac output are unaffected by this field. Their locations, however, depend on the y external measured field component only. Theoretical relationships between the external measured field components and corresponding phase shifts can be obtained from the following system of equations, obtained by considering (4), (7), and (8):

$$\begin{cases} h_{bh} = h_{be} + \sqrt{2}/2 + \sqrt{2}h_{mx} \\ -h_{bh} = h_{be} + \sqrt{2}/2 + \sqrt{2}h_{my} \\ h_{be} = a\cos(\omega t + \pi/4) \\ h_{bh} = b\sin(\omega t + \pi/4) \end{cases} \tag{10}$$

where h_{mx} and h_{my} are the x- and y-component of a measured external field (see Fig. 5). Fig. 7 shows solution of (10), which has been obtained by numerical methods. This solution is expressed by the relationships $\Delta(\omega t) = f(h_{mx}), \Delta(\omega t) = f(h_{my})$ in Fig. 7. The latter are in fact the response characteristics of an unbiased MR. The response characteristics of a barber-pole MR employing a similar rotating excitation [1] are also shown in this figure. Comparison between these characteristics shows that response characteristics of an unbiased MR possess the advantage of being more linear. A further advantage of the unbiased MR is that by employing the presently suggested arrangement both the x-direction sensitivity and the y-direction sensitivity become equal. It is interesting that the size of the sensitivities possesses a value that lies in between the x- and y-sensitivities of the barber-pole MR.

III. Experiment

We have used for the experiments a 2-mm-long and 20-μm-wide unbiased MR that had been patterned from an ion beam sputtered Permalloy (81% Ni, 19% Fe) film 40 nm thick [6] (see Figs. 1 and 5). The MR characteristic (MR ac output versus hard-axis magnetic field) is shown in Fig. 8. Anisotropy field of the MR material was measured to be about 1 kA/m. Fig. 9 shows results of the MR ac output when excited according to the method developed in [1] [see also Figs. 2, 3(b), and 4(b)]. The latter was developed for barber-pole MR's. Fig. 9 demonstrates that the method [1] cannot be simply employed for an unbiased MR. This is due to the

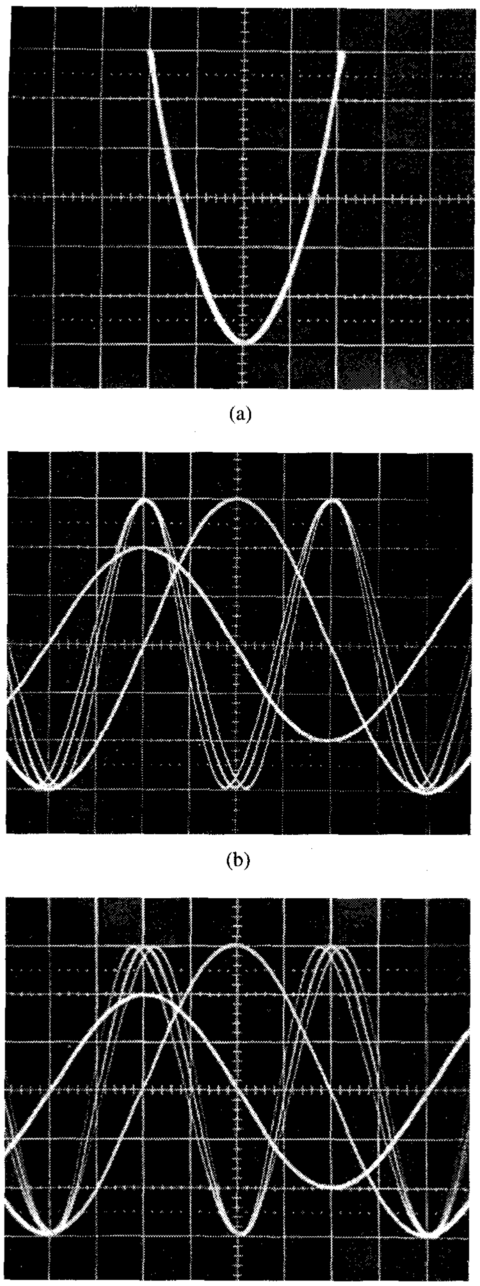

Fig. 9. Experimental outputs of the unbiased magnetoresistor that employs the rotating excitation method described in [1]. (a) Magnetoresistive output versus the easy axis excitation field. $X = 1$ (kA/m)/div; $Y = 5$ mV/div, (b) and (c) magnetoresistive outputs versus time. The outputs are obtained for different values of dc external field: $H_{my} = 0$; $H_{mx} = +440$ A/m (the right trace); $H_{mx} = 0$ (the center trace); $H_{mx} = -440$ A/m (the left trace). $X = 125$ μs/div; $Y = 5$ mV/div. [The traces of representing the lower frequency correspond to the excitation fields. The frequency of the excitation fields is 1 kHz. $Y = 1$ (kA/m)/div.]

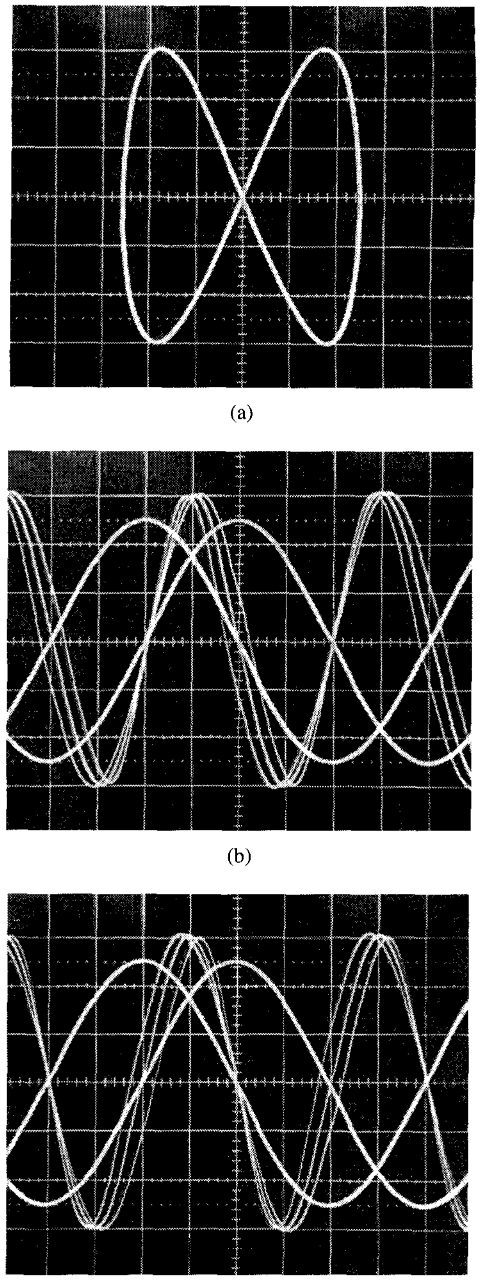

Fig. 10. Experimental outputs of the unbiased magnetoresistor that employs the proposed rotating excitation method. (a) Magnetoresistive output versus the easy axis excitation field. $X = 1$ (kA/m)/div; $Y = 5$ mV/div, (b) and (c) magnetoresistive outputs versus time. The outputs are obtained for different values of dc external field: $H_{my} = 0$; $H_{mx} = +440$ A/m (the right trace); $H_{mx} = 0$ (the center trace); $H_{mx} = -440$ A/m (the left trace). $X = 125$ μs/div; $Y = 5$ mV/div. [The traces representing the lower frequency correspond to the excitation fields. The frequency of the excitation fields is 1 kHz. $Y = 1$ (kA/m)/div.]

fact that the information about the intensity of external field components can be concluded by measuring the shifts between corresponding extremes of the MR ac output. Detection of such shifts is difficult. It is more preferable to detect the shifts between zero-crossings to obtain information about external measured fields.

Fig. 9 shows results of the MR ac output when excited according to the presently developed method (see also Figs. 5 and 6). Angles α between excitation axes and the MR easy axis are chosen to be about 56.31° (Fig. 5). The amplitude of the excitation fields is chosen in accordance with (6) to be about 2.55 times larger than the MR material anisotropy field. Fig. 10 demonstrates that the proposed method enables us to benefit from the advantages of the detection of an externally measured field through the employment of the MR ac output zero-crossings. The present method relies on a rotating excitation

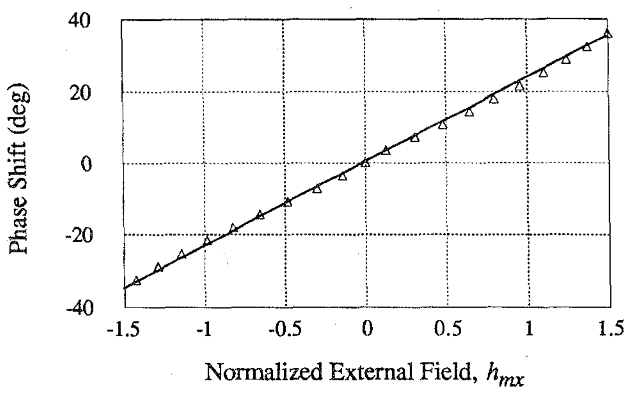

Fig. 11. The experimental and theoretical (solid line) response characteristics of the unbiased magnetoresistor that employs the proposed rotating excitation.

field and is in this respect similar to the rotating excitation field method employed for the barber-pole MR case [1]. Fig. 11 compares the evaluated MR response (an approximation) to the one obtained experimentally.

IV. Conclusion

The present work deals with a relatively simple method that enables the employment of a single unbiased MR for measuring simultaneously two dc or low-frequency magnetic field components. The employment of a single MR for this task was attained previously, when a barber-pole device was used [1]. A rotating excitation field is employed in both cases for ac biasing the sensor. The rotating field in both cases is elliptically polarized. The appropriately special choice of the ellipse axes enables the resulted magnetization rotation in the MR material to be uniform. This characterizes both the present device and also the device that was developed in [1], although the excitation coils in the present case are not orthogonal to each other as was the case previously [1]. The detection of the externally measured field depends in both cases on the time shift between the zero-crossings of the MR ac output and the zero-crossings of the corresponding excitation field. This method simplifies the detection procedure. Moreover, in the present case of the unbiased MR, it enables equal sensitivities to be obtained in both directions. Another advantage of the method is its ability to suppress the Barkhausen noise [3]. This is due to the maintenance of a large rotating excitation field which continuously saturates the MR material. Furthermore, unbiased MR's are simpler and less expensive than barber-pole MR's.

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