Simultaneous Measurement of Two DC Magnetic Field Components by a Single Magnetoresistor

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***Abstract*—The method relies on a special excitation mode which causes uniform rotation of magnetization in the plane of a barber-pole magnetoresistive sensor. It is interesting that the uniform rotation of the magnetization is attained when the excitation field is not uniformly rotating. The rotation of this field should rather be elliptically polarized. The two orthogonal components of an external in-plane measured dc field disturb the uniform rotation of the magnetization in different instances of time. This behavior of the magnetization enables simultaneous but still separate measurements of both external field components by detection of the time shifts between the corresponding zero-crossing points of the sensor ac output and the zero-crossing points of the corresponding orthogonal components of the excitation field. The experimental results confirm the applicability of the method. Possible applications are reviewed.**

I. Introduction

The conventional methods for measuring one component magnetic field by magnetoresistive (MR) sensors are well known [1]. According to these methods one should use several magnetoresistors in order to measure several components of the field simultaneously [2], [3]. Disadvantages of the latter are obvious. Such combined, doubled or tripled MR sensors are correspondingly more complicated, demand a considerable volume and do not allow measurement of all field components in exactly the same position.

This paper deals with a method that enables simultaneous measurement of two components of a magnetic field vector which lies in the plane of a single barber-pole MR sensor. The method relies on a special excitation mode which causes uniform rotation of the sensor's magnetization and enables the sensor output voltage to be sinusoidal. This mode of excitation was already employed by Vicent [4], but he did not make full use of the fact that the resistance of the sensor exhibits two periods of variation for each period of the excitation. This frequency doubling phenomenon is exploited in the present work and enables separate sensing of the two components of an external magnetic field. Reference [4] shows experimentally that a uniform rotation of the magnetization and a sinusoidal voltage in MR thin film can be developed by a saturating and rotating excitation field applied in the plane of this film. The present work shows both analytically and experimentally that this excitation field should be elliptically rotating. Furthermore, we consider the case where an external dc field is added to the excitation. Our analysis of the sensor output behavior shows that the distinct interruptions caused by the orthogonal components of the external field vector enable the simultaneous and yet separate measurement of both these components.

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II. Description of the Method

Let us consider an MR sensor which employs the barber-pole configuration of current electrodes (Fig. 1). The quiescent value of the angle θ between directions of the magnetization $\boldsymbol{M}$ and the current $\boldsymbol{I}$ through the MR strip is about 45° when no magnetic field is applied to the sensor. Transfer characteristic of the MR sensor is described by the equation [1]:

$$\begin{cases} \Delta V_0 = I\,\Delta R_m \cos^2\theta \\ \theta = f(\boldsymbol{H}_a, \boldsymbol{H}_k) \end{cases} \tag{1}$$

where ΔV_0 is the sensor output voltage change; ΔR_m is the change in the MR strip resistance resulting from a 90° rotation of magnetization (from the direction of the current); $\boldsymbol{H}_a$ is a magnetic field applied to the sensor; and $\boldsymbol{H}_k$ is the sensor's anisotropy field. The ac part of the normalized sensor output ($\delta V_0 = \Delta V_0/\Delta V_{om}$) can be described in the following way:

$$\delta V_0 = \cos^2\theta - 1/2. \tag{2}$$

The angle θ can be obtained from the Stoner-Wohlfarth equation [5] that describes the equilibrium between orientation of the magnetization, the field applied to the sensor and the anisotropy:

$$\begin{cases} 0.5\, H_k \sin 2\phi + H_{ax}\sin\phi - H_{ay}\cos\phi = 0 \\ \phi = \theta + \pi/4 \end{cases} \tag{3}$$

where ϕ is the angle between the magnetization vector and the easy axis (Fig. 1); H_{ax} and H_{ay} are the components of a magnetic field applied to the sensor.

Let us consider now the case (Fig. 2) where $\boldsymbol{H}_a$ field is the sum of a rotating excitation field $\boldsymbol{H}_b$ and an external unknown dc field $\boldsymbol{H}_u$:

$$\begin{cases} H_{ax} = H_{bx} + H_{ux} \\ H_{ay} = H_{by} + H_{uy}. \end{cases} \tag{4}$$

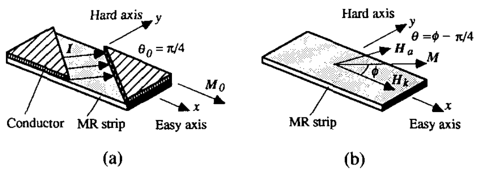


Fig. 1. Barber-pole magnetoresistor. (a) Geometry of a barber-pole magnetoresistive element. (θ_0: the angle between the quiescent direction of the magnetization and the current through the magnetoresistive stripe; M_0: the quiescent magnetization). (b) Magnetization in a magnetoresistive stripe.

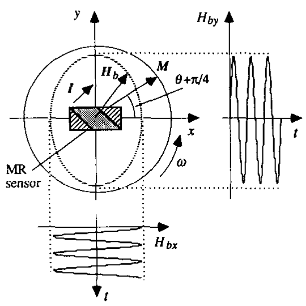


Fig. 2. Excitation of a barber-pole magnetoresistive element by saturating and rotating magnetic field. (External magnetic field is absent.)

It is also assumed that the excitation field rotates elliptically (Fig. 2) and its magnitude is sufficient to saturate the sensor:

$$\begin{cases} H_{bx} = H_{bxm} \cos \omega t = aH_k \cos \omega t \\ H_{by} = H_{bym} \sin \omega t = bH_k \sin \omega t. \end{cases} \tag{5}$$

In these equations both constants $a = H_{bxm}/H_k$ and $b = H_{bym}/H_k$ should be larger than 1 to obtain the condition of the sensor saturation. According to (4) and (5) and after simple trigonometric transformations, (3) can be rewritten as follows:

$$\begin{aligned} b\,[\sin \omega t + H_{uy}/bH_k] \cos (\theta + \pi/4) \\ - a\,[\cos \omega t + H_{ux}/aH_k] \sin (\theta + \pi/4) \\ = \cos (\theta + \pi/4) \sin (\theta + \pi/4). \end{aligned} \tag{6}$$

It will now be shown that a simple form of the exact solution of this equation can be found at least in the two following cases:

1) when external magnetic field is absent,
2) when external magnetic field is present but the sensor output equals zero.

Let us assume for a moment that the solution of (6) can be written as follows:

$$\tan (\theta + \pi/4) = \frac{\sin \omega t + H_{uy}/bH_k}{\cos \omega t + H_{ux}/aH_k}. \tag{7}$$

According to (2) and (7), the sensor output can be calculated in the following way:

$$\delta V_0 = \cos^2 \left(\arctan \frac{\sin \omega t + H_{uy}/bH_k}{\cos \omega t + H_{ux}/aH_k} - \pi/4 \right) - 1/2. \tag{8}$$

In order to check the correctness of (7) and therefore the correctness of (8) one should substitute (7) in (6). Such substitution shows that (7) and (8) are correct at least in the two following cases:

1) when $H_{ux} = 0$ and $H_{uy} = 0$ and $b = a + 1$; (9)
2) when either $\sin \omega t + H_{uy}/bH_k = 0$ or $\cos \omega t + H_{ux}/aH_k$ 0; $b = a + 1$. (10)

It is easy to see now that the first case (9) corresponds to zero value of the external magnetic field. The ratio of amplitudes of the orthogonal components of the excitation field can be obtained from (5) and (9) as follows:

$$H_{bxm}/H_{bym} = a/b = a/(a + 1). \tag{11}$$

Hence the excitation field should be elliptically polarized. It is easy to see, according to (8), that the second case (10) corresponds to zero-crossing points of the sensor output (δV_0).

We use now (8) to simulate the waveforms of the sensor output. Fig. 3 shows the waveforms obtained for the elliptically polarized excitation field ($a = 1$, $b = 2$) and for different values of external field H_u. First we check the case where external field in the sensor plane is absent. According to (7), the sensor's magnetization rotates uniformly in this case and, according to (8), a purely sinusoidal output at an angular frequency 2ω is obtained:

$$\delta V_0 = 0.5 \sin 2\omega t. \tag{12}$$

The even zero-crossing points of this output signal are defined by $2\omega t = 2\pi n$ where $n = 0; 1; 2$, etc. The odd zero-crossing points are defined by $2\omega t = \pi(2n + 1)$. The even zero-crossing points coincide with zero-crossing points of the H_{by} bias field (Fig. 3). The odd zero-crossing points coincide with zero-crossing points of the H_{bx} bias field. However, when external field in the sensor plane differs from zero then, according to (8), the locations of the odd zero-crossing points are affected exclusively by the H_{ux} field and the locations of the even zero-crossing points are affected exclusively by the H_{uy} field (Fig. 3). The time shifts between the corresponding zero-crossing points of the sensor output and the zero-crossing points of the corresponding orthogonal components of the excitation field can be obtained from (5) and (8) for the case $\delta V_0 = 0$, and either $H_{bx} = 0$ or $H_{by} = 0$:

$$\begin{cases} |\Delta t_x| = |t(\delta V_0 = 0) - t(H_{bx} = 0)| = |\arcsin (H_{ux}/aH_k)|/\omega \\ |\Delta t_y| = |t(\delta V_0 = 0) - t(H_{by} = 0)| = |\arcsin [H_{uy}/(a + 1)H_k]|/\omega. \end{cases} \tag{13}$$

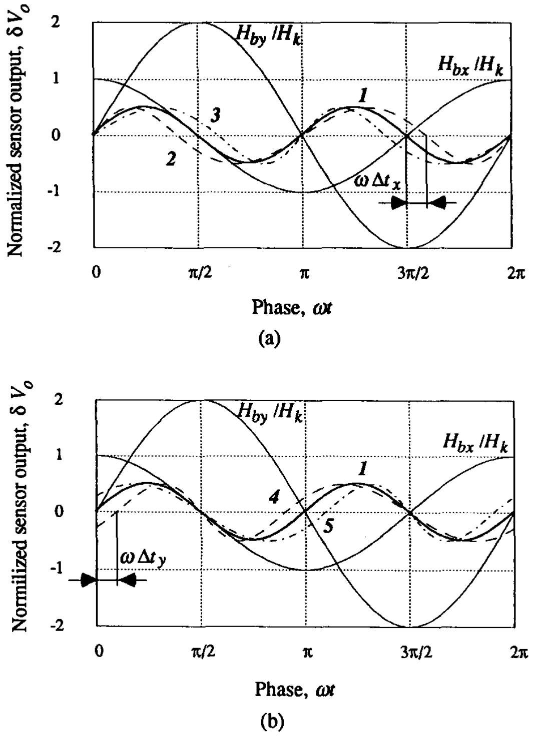


Fig. 3. The theoretical outputs of the magnetoresistive sensor employing rotating excitation. The outputs are obtained for different values of dc external field. (a) $H_{uy} = 0$; *1* – $H_u = 0$; *2* – $H_{ux} < 0$; *3* – $H_{ux} > 0$. (b) $H_{ux} = 0$; *1* – $H_u = 0$; *4* – $H_{uy} < 0$; *5* – $H_{uy} > 0$.

For $H_u << H_k$ these equations can be simplified:

$$\begin{cases} |\Delta t_x| \approx |H_{ux}/\omega a H_k| \\ |\Delta t_y| \approx |H_{uy}/\omega(a+1)H_k|. \end{cases} \tag{14}$$

The error in this case is less than 1% for $H_u < 0.24\, aH_k$. The signs of the time shifts Δt_x and Δt_y in (13), (14) are determined by the signs of the corresponding external field components and the phases of the zero-crossing points of the corresponding orthogonal component of the excitation field (Fig. 3). Namely,

$$\begin{cases} \Delta t_x > 0, \text{ when } H_{ux} > 0 \text{ and } \omega t = \pi/2 + 2\pi n; \text{ or } H_{ux} < 0 \text{ and } \omega t = 3\pi/2 + 2\pi n \\ \Delta t_x < 0, \text{ when } H_{ux} < 0 \text{ and } \omega t = \pi/2 + 2\pi n; \text{ or } H_{ux} > 0 \text{ and } \omega t = 3\pi/2 + 2\pi n \\ \Delta t_y > 0, \text{ when } H_{uy} > 0 \text{ and } \omega t = \pi + 2\pi n; \text{ or } H_{uy} < 0 \text{ and } \omega t = 2\pi n \\ \Delta t_y < 0, \text{ when } H_{uy} < 0 \text{ and } \omega t = \pi + 2\pi n; \text{ or } H_{uy} > 0 \text{ and } \omega t = 2\pi n. \end{cases} \tag{15}$$

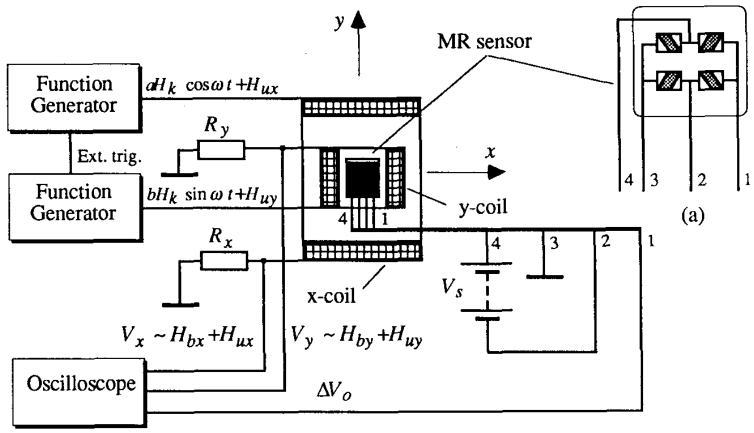
III. Experimental Results

We have used for experiments a commercially available differential thin-film barber-pole MR sensor of type KMZ 10 A made by Philips [2]. The operation principle of this MR sensor permits compensation of a dc part in its output. This is obtained by connecting four diagonally opposed elements similar to the one in Fig. 1(a) as a differential system (electrical bridge) shown in Fig. 4(a). The scheme of the experimental set-up is shown in Fig. 4(b). Two orthogonal coils were used for ac and dc biasing along the sensor axes. The supply voltage of the sensor was set about $V_s = 8.5$ V. The frequency of the rotation of the excitation field was chosen 1 kHz.

The sensor anisotropy field H_k was measured to be about 780 A/m. The purely sinusoidal sensor output and therefore the uniform rotation of the magnetization were obtained for the following amplitudes of the excitation field components: $H_{bxm} = 2$ kA/m and $H_{bym} = 2.8$ kA/m. The relationship between these experimentally obtained amplitudes of the excitation field components is in well agreement with theoretical relationships (9), (10) where $a = H_{bxm}/H_k \approx 2.6$, $b = H_{bym}/H_k \approx 3.6$ and $b \approx a + 1$. Experimental outputs of the MR sensor excited by this elliptically rotating field are shown in Fig. 5. Fig. 6 demonstrates good conformity between the experimental and the theoretical responses of the MR sensor.

IV. Conclusions

This paper shows both theoretically and experimentally that it is possible to use special techniques of excitation and detection to make a single barber-pole MR element to be sensitive to two orthogonal components of an in-plane magnetic-field vector. We employ saturating and elliptically-rotating magnetic field to obtain uniform rotation of the sensor's magnetization. The needed relationship between the two orthogonal components of the elliptically polarized excitation field was found by employing the Stoner–Wohlfarth equation. External dc field which is added to the sensor excitation causes time shifts between the corresponding zero-crossing points of the sensor ac output and the zero-crossing points of the corresponding orthogonal components of the excitation field. The exact dependencies of these time shifts on the intensities of the orthogonal components of an in-plane external magnetic field were also found according to the Stoner–Wohlfarth equation. The nonlinearity associated with measurements performed by employing the method is less than 1% when the external field components are less than a quarter of the sensor's anisotropy field. The sensitivity of the method increases when the magnitude of the induced anisotropy field in the MR material is reduced. MR sensors which are used for relatively low-sensitivity applications do not usually employ an ac excitation. Anisotropy field in such sensors is artificially emphasized to obtain reliable returning of magnetization to its quiescent position. One of the advantages of the proposed method is that the sensitivity of an MR sensor



(b)

Fig. 4. Experimental set-up. (a) Structure of the differential barber-pole magnetoresistive sensor; (b) Schematic diagram of the experimental set-up. Note that the external magnetic field in the present experiments – H_u is generated by employing the dc bias facilities of the function generators.

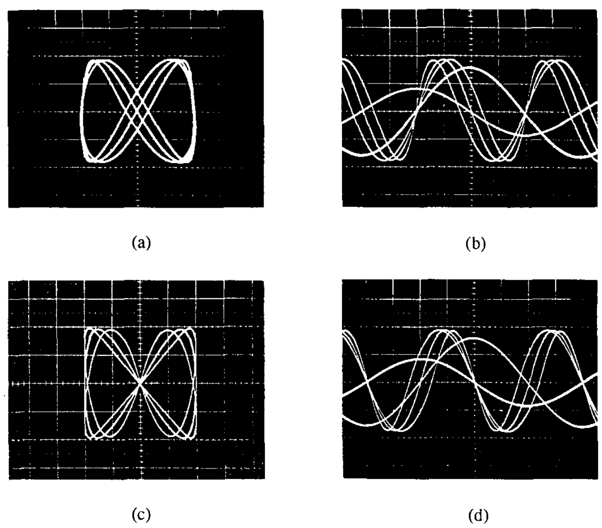


Fig. 5. Experimental outputs of the magnetoresistive sensor employing rotating excitation. (The traces of relatively low frequency correspond to the excitation fields. The frequency of the excitation fields is 1 kHz. H_{bx} bias field is represented by the trace with less amplitude. H_{bxm} = 2 kA/m; H_{bym} = 2.8 kA/m.) (a) and (b) are the experimental outputs versus H_{bx} fields and versus time respectively. H_{uy} = 0. H_{ux} = +630 A/m (the right trace); H_{ux} = 0 (the center trace); H_{ux} = −630 A/m (the left trace); (c), and (d) are experimental outputs vs H_{bx} fields and versus time respectively. H_{ux} = 0; H_{uy} = +950 A/m (the right trace); H_{uy} = 0 (the center trace); H_{uy} = −950 A/m (the left trace). Y = 50 mV/div. (a) (c) X = 1 (kA/m)/div. (b) (d) X = 125 μs/div.

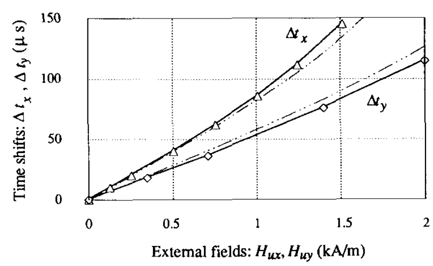


Fig. 6. The experimental (solid lines) and theoretical (broken lines) response characteristics of the magnetoresistive sensor employing rotating excitation. The characteristics represent time shifts between the zero-crossing points vs external magnetic fields.

can be improved by reducing of this induced anisotropy. The performance of the present sensor should not be degraded in this case because the excitation field defines the rotation of the magnetization completely when external field is absent. In other words, the saturating rotating excitation prevents memory effects that are due to previous measurements from affecting the performance. Moreover, introduction of the large excitation field, that saturates the MR material, assists to stabilize the single domain state and decreases the Barkhausen noise level [1], [6]. The proposed method is based on the symmetry of the output characteristic (output voltage vs one of the excitation field components) of the MR sensor (Fig. 5(a), (c)). It has been shown that the existence of an external measured field is reflected in the presently discussed case by loss of the symmetry. As long as the symmetry is not lost under influence of temperature changes or variations of supply voltage, the method is expected to be relatively immuned against such variations.

The proposed technique can be used for a contactless detection of rotation or angle detection and can also perform as two component vector magnetometer. The method appears also interesting because it enables relatively simple processing of the magnetometer output signals. The time shifts associated with the sensor outputs for example can be measured by conventional digital processing methods. Another advantage is that the MR elements together with the planar excitation coils can be fabricated in standard IC-technology, which offers the possibility of combining it with on-chip signal processing circuitry. Hence the method should enable the design of a single solid-state functionally-complete integrated magnetometer with digital outputs.

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