New Method for Extracting Signals Generated by Magnetoresistive Sensors

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Abstract **— A new ac detection technique which reduces the influence of offset, temperature drift and remanence of magnetoresistive sensors is proposed. The technique relies on nonlinearity of the magnetoresistance, permitting mixing of excitation fields of close frequencies and detection of the sensor output signal at the difference frequency. The difference frequency component appears in the output signal spectrum only when an external dc field is applied along the excitation direction. This frequency is located further apart from the excitation frequencies, and this relatively large gap between the frequencies reduces undesirable coupling between the output and excitation circuits and alleviates the filtering problem. Another advantage of the method is due to its potentially better sensitivity (up to nearly two orders), since it enables measuring fields aligned along the sensor easy axis, for which the demagnetizing field is smaller.**

I. INTRODUCTION

Magnetoresistive (MR) sensors permit direct conversion of dc magnetic fields into dc output voltage with no need for pickup coils [1]. This is well suited to applications of relatively low sensitivity, for example, to magnetic memory readout. However, such dc to dc conversion is affected by errors, especially when weak dc or low-frequency fields are measured. In this case the sensors' zero drift and the $1/f$ low-frequency noise of readout electronics reduce the resolution of measurements. The resolution can be improved by introduction of an ac bias technique for extracting the sensor output at a relatively high frequency, for which the zero drift is absent and the $1/f$ noise is insignificant [2] – [5]. Furthermore, ac bias helps to cancel the sensor remanence which can introduce considerable errors when the frequency of the measured magnetic field is below 0.1 Hz [6], [7].

This paper proposes a new ac detection technique that relies on multifield excitation of an MR sensor.

II. MULTIFIELD EXCITATION OF MAGNETORESISTIVE SENSORS

The nonlinearity of the MR sensor transfer characteristic permits mixing of two or more excitation fields of close frequencies and the detection of the sensor output signal at the difference frequency (as was proposed earlier for flux-gate like devices [8]). Lay-out of a typical MR sensor is shown in Fig. 1 (a) where $\boldsymbol{H}_{a\Sigma}$ is the total magnetic field applied to the sensor; $\boldsymbol{H}_k$ is the anisotropy field; θ is the angle between the current $\boldsymbol{I}$ and the magnetization $\boldsymbol{M}$ vectors. The normalized transfer characteristic (relative output voltage change ($\delta V = \Delta V / 2\Delta V_{max}$) vs applied magnetic field) of the MR sensor is described by the equation [3]:

$$\delta V = \cos^2 \theta - 1/2, \text{ where } \theta = f(H_a, H_k)\,. \tag{1}$$

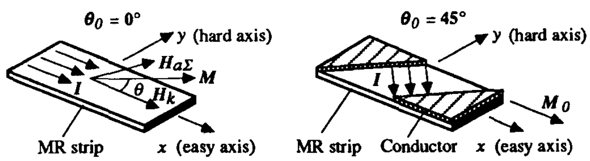
One can see from (1) that the sensitivity $d(\delta V)/d(H_a)$ is a maximum near $\theta = 45°$. There are various modifications of MR sensors where the quiescent value of the angle θ is obtained about 45° (the quiescence is attained when no external field is applied to the sensor). We consider an MR sensor that employs a barber-pole configuration of current electrodes [3] shown in Fig. 1 (b). The operating principle of this sensor permits compensation of a dc component in its output. This is obtained by connecting four diagonally opposed elements similar to the one in Fig. 1 (b) as a differential system (electrical bridge) [3]. Such a differential barber-pole MR sensor is best suited to realizing the proposed method, because its hard-axis (h.a.) and easy-axis (e.a.) transfer characteristics are of purely odd symmetry. These characteristics can be approximated by power series which contains terms with only odd powers:

$$\delta V = a_1 (H_a/H_k) + a_3 (H_a/H_k)^3 \ldots \tag{2}$$

Let us assume now that a differential barber-pole MR sensor is excited in the same direction by two magnetic fields ($\boldsymbol{H}_{a1}, \boldsymbol{H}_{a2}$) of different but close frequencies f_1 and f_2 ($f_1 > f_2$):

$$H_a = H_{a1} + H_{a2} = H_{am1} \cos 2\pi f_1 t + H_{am2} \cos 2\pi f_2 t\,. \tag{3}$$

Equation (2) can be rewritten as follows, when an external unknown dc magnetic field $\boldsymbol{H}_{ex}$ is applied to the sensor along the excitation direction:



(a) a simple MR element. (b) barber-pole MR element.

Fig. 1. Geometry of MR sensors.

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$$\delta V = A_0 + A_1 H_a + A_2 (H_a/H_k)^2 + A_3 (H_a/H_k)^3 , \tag{4}$$

where $A_0 = a_1(H_{ex}/H_k) + 3a_3(H_{ex}/H_k)^3$, $A_1 = a_1 + 3a_3(H_{ex}/H_k)^2$, $A_2 = 3a_3(H_{ex}/H_k)$ and $A_3 = a_3$. Analysis of (3) and (4) shows that the difference frequency $(f_1 - f_2)$ component appears in the spectrum of the output signal only when a dc external field is applied to the sensor, since only then does a square power term appear in the transfer characteristic (4). The normalized amplitude (δV_{diff}) of the difference frequency component can be evaluated according to (3) and (4) as follows:

$$\delta V_{diff} = 3a_3 H_{ex} H_{am1} H_{am2} / H_k^3 . \tag{5}$$

III. Analysis of the Sensor Performance for Two Different Modes of Excitation

A. Evaluation of Sensitivities for the Hard-Axis and Easy-Axis Modes of Excitation

It has already been assumed that both the excitation fields and the external field are applied to the MR sensor along the same direction. The h.a. of the sensor as well as its e.a. can be chosen as directions of these fields.

1) *The hard-axis mode of excitation:* In this case one can use the following analytical expression for the transfer characteristic of the differential barber-pole MR sensor [3]:

$$\delta V = (H_a/H_k) \sqrt{[1 - (H_a/H_k)^2]} . \tag{6}$$

This characteristic can be approximated by (2) where $a_1 = 1$ and $a_3 = -0.6$ (Fig. 2 (a)). According to (5) and assuming that $H_{am1}/H_k = H_{am2}/H_k = 1$, the amplitude of the difference frequency component of the sensor output is equal to

$$\delta V_{diff}(y) = 1.8\, H_{ex}/H_k . \tag{7}$$

2) *The easy-axis mode of excitation:* There is no explicit expression for the MR sensor transfer characteristic (Fig. 2 (b)) in this case. However, its qualitative behavior can be interpreted with the help of the Stoner-Wohlfarth astroid model [9]. The astroid model of the multifield e.a. excitation is shown in Fig. 3 (a). This model allows a simple procedure for obtaining the direction of $\boldsymbol{M}$ when H_a is given. The direction of magnetization can be found in this case by drawing a tangent to the astroid critical curve through the coordinates of total applied field $\boldsymbol{H_{a\Sigma}} = \boldsymbol{H_a} + \boldsymbol{H_{by}}$, where $\boldsymbol{H_{by}}$ is a dc bias field applied to the sensor h.a. Fig. 3 (c) shows that in this case the minor loops of the sensor transfer characteristic do not possess purely odd-nonlinear properties, although the major loop is purely odd-nonlinear.

Fig. 3 (b) and Fig. 3 (d) demonstrate that purely odd-nonlinearity of both the major loops and the minor loops of the transfer characteristic can be achieved when an additional dc bias field $\boldsymbol{H_{bx}}$ of appropriate value is applied along the sensor e.a. One can see from Fig. 3 (b) that the magnetization rotates from direction $\boldsymbol{M'}$ when coordinates of the total applied field ($\boldsymbol{H_{a\Sigma}} = \boldsymbol{H_a} + \boldsymbol{H_{bx}} + \boldsymbol{H_{by}}$) are inside the critical curve to direction $\boldsymbol{M''}$ when coordinates of this field are outside the astroid. Therefore, there is an intermediate direction $\boldsymbol{M_{dc}}$ for which $\theta_{dc} = 45°$ and according to (1) the sensor output there equals zero. $\boldsymbol{H_{bx}}$ and $\boldsymbol{H_{by}}$ dc biases corresponding to such magnetization direction determine the bias point in Fig. 3 (b). The minor loops are located in this case in the center of the major loop and the complete e.a. transfer characteristic is of purely odd-symmetry (Fig. 3 (d)). This hysteresis-like characteristic can be now approximated by a simple characteristic (2) which is also purely odd and includes the effects of the minor loops and of the initial regions of the major loop saturation. In this simple characteristic $a_1 = 0.8$, $a_3 = 0.5$ (Fig. 2 (b)). According to (5) and assuming that $H_{am1}/H_k = H_{am2}/H_k = 1$, one obtains that the amplitude of the difference frequency component of the sensor output signal is equal to

$$\delta V_{diff}(x) = 1.5\, H_{ex}/H_k . \tag{8}$$

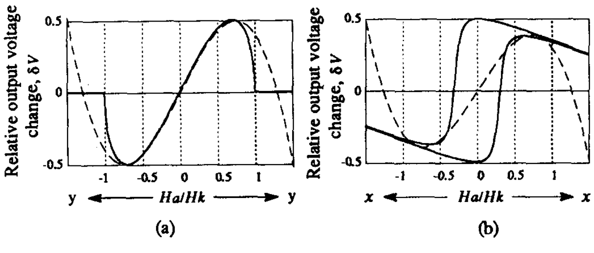

Fig. 2. Theoretical transfer characteristics of differential barber-pole MR sensor (broken lines are approximation curves). (a) hard-axis characteristic. (b) easy-axis characteristic (dc biases H_{bx} and H_{by} of appropriate sizes are applied along the easy axis and along the hard axis of the sensor respectively).

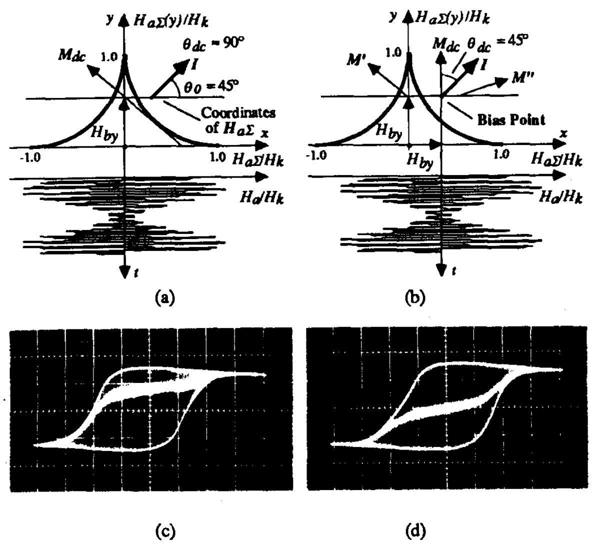

Fig. 3. (a), (b) astroid models of the multifield excited MR sensor. (c), (d) experimental outputs of the MR sensor vs excitation field. X=100 (A/m)/div; Y=50 mV/div. (a), (c) dc bias field H_{by} is applied along the sensor hard axis only; (b), (d) purely odd characteristic is obtained when appropriate dc biases H_{bx} and H_{by} are applied along both sensor axes.

B. Influence of Demagnetizing Field on the Hard-Axis and Easy-Axis Sensitivities of the Sensor

The calculations of the previous section do not consider the dependence of the sensitivity upon the demagnetizing field. Therefore, it is correct to compare sensitivities for the h.a. and e.a. modes of excitation with the sensitivity of the sensor not employing ac bias only when the demagnetizing fields along both hard and easy axes are equal. They are equal, when the MR element is a circular film. However, MR elements are usually made in the form of strips that are very stretched along their easy axes. It increases the resistance of the strips and emphasizes the longitudinal anisotropy. One can employ the following expressions for the magnetic field in the MR material when an MR strip is placed in an external field $\boldsymbol{H_{ex}} = \boldsymbol{H_{ex}(x)} + \boldsymbol{H_{ex}(y)}$ [10]:

$$\begin{cases} H_{ex}'(x) = H_{ex}(x) - D_x M_x = H_{ex}(x) - D_x(\mu_\Delta' - 1) H_{ex}(x) \\ H_{ex}'(y) = H_{ex}(y) - D_y M_y = H_{ex}(y) - D_y(\mu_\Delta' - 1) H_{ex}(y) \,, \end{cases} \tag{9}$$

where μ_Δ' is the apparent incremental permeability of MR material; D_x and D_y are the e.a. and h.a. demagnetizing factors of the MR strip respectively. These demagnetizing factors can be found from [11] assuming that the MR strip is a very slender ellipsoid. Obtaining $D_x \approx 2 \times 10^{-6}$ and $D_y \approx 7.6 \times 10^{-4}$ for a typical MR strip [4] one can calculate according to (9) the ratio of the external field along the h.a. to that along the e.a., for the same values of $H_{ex}(x)$ and $H_{ex}(y)$. Dependence of this ratio on μ_Δ' is shown in Fig. 4. This figure demonstrates that magnetic field, and consequently the sensitivity, along the e.a. of the MR strip can substantially exceed those along the h.a. For example μ_Δ' of 78 Permalloy (traditional MR material) can reach 10^5 [10]. Hence according to (7), (8) and (9) the e.a. sensitivity of the multifield excited sensor can be about 60 times higher than the h.a. sensitivity. As a result, when considering (6), we conclude that the e.a. sensitivity can be about 100 times higher than the h.a. sensitivity of the sensor with no ac bias.

IV. Experimental Results

We have used for experiments a commercially available thin film MR sensor of type KMZ 10 made by Philips. Two orthogonal coils were used for ac and dc biasing along the sensor axes. The supply voltage of the sensor was set about 8.5 V. Amplitude-modulating magnetic field was chosen for realizing the multifield excitation. The carrier frequency of the ac bias field was 10 kHz and the frequency of modulation was 400 Hz.

Experimental output characteristics of the MR sensor employing multifield excitation are shown in Fig. 5 (the output voltage ΔV is measured at the output of a band-pass filter tuned to 400 Hz). The e.a. and h.a. sensitivities of multifield excited sensor are correspondingly about 4 and about 1.8 times higher than the h.a. sensitivity of the sensor with no ac bias. These results are in agreement with the theory described in the previous section. (The ratio $H'_{ex}(x)/H'_{ex}(y)$ can be evaluated to be about 2.5 - 3 according to the internal geometry of the KMZ 10 A sensor.)

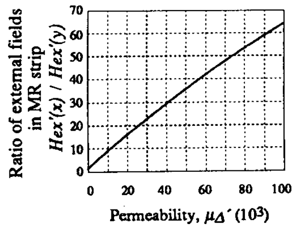

Fig. 4. Ratio of the magnetic field along the easy axis to that along the hard axis vs apparent incremental permeability.

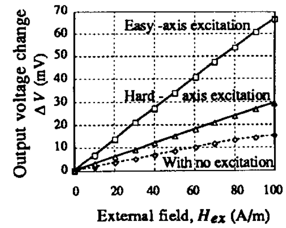

Fig. 5. Experimental output characteristics of the MR sensor.

V. Conclusion

A new ac detection technique is exemplified by the multifield excitation of the differential barber-pole MR sensor. The sensor output is detected at a difference frequency. Modes of the multifield excitation along the e.a. of the sensor as well as along its h.a. are analyzed. It is shown that dc bias fields must be applied along both axes of the MR sensor to obtain a purely odd-nonlinearity of its e.a. transfer characteristic. It is found also that the sensitivity for the e.a. mode of excitation can be up to 60 times higher than that of the h.a. mode of excitation and up to 100 times higher than the h.a. sensitivity of the MR sensor with no ac bias due to the smaller demagnetizing effect along the e.a. It must be emphasized that such amplification of the sensitivity is achieved even though no external flux concentrator was used. Moreover, introduction of the dc biases in the e.a. mode of excitation assists in stabilizing the single domain state and decreasing the Barkhausen noise level [3], [12].

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