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An Improved Chevron Configuration for the Detection of Magnetic Field Vectors

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ABSTRAK

Suatu bentuk konfigurasi Magnetoresistive Recording Heads (MRH) yang terubahsuai adalah diperihalkan di sini. Dua MRH selaput-nipis, berperisai, jenis menegak telah dipincang di kawasan lelurus dengan serentak, menggunakan suatu serpihan kecil magnet kekal. Pemincangan tersebut memutarkan vektor pemagnetan M_s setiap MRH tersebut sebanyak 45° daripada vektor arus J yang menatijahkan orientasi konfigurasi Chevron sebanyak 90°. Konfigurasi begini adalah paling berkesan untuk mengesan vektor medan dalam aplikasi seperti pengesanan tanpa-musnah struktur ira dan perubahan kehilangan dalam keluli elektrik, dan untuk penstoran lebih banyak maklumat dalam cakera magnet.

ABSTRACT

A modified version of Chevron type Magnetoresistive Recording Heads (MRH) sensor is described. Two shielded ferromagnetic thin-film vertical-type MRH are biased at the linear region simultaneously using a small piece of permanent magnet chip. The biasing rotates the magnetisation vector M_s of each MRH through 45° with respect to their respective current vectors J resulting in an effective Chevron orientation of 90°. This configuration is shown to be most effective to detect field vectors in applications such as non-destructive detection of grain structures and loss variation in electrical steels, and in packing more bits of information in magnetic disc storage.

Keywords: magnetoresistive recording heads (MRH), chevron, magnetic field, non-destructive detection, magnetic disc storage, grain structures, electrical steel.

INTRODUCTION

Magnetoresistive Recording Heads (MRH) have been widely used over the past two decades. This is largely due to their proliferation in magnetic storage discs and tapes (Davies and Middleton 1975). There are, however, many other useful commercial applications of MRH, such as magnetic card readers, bubble domain detectors (Almasi *et al.* 1971), coin validation systems (Kwiatkowski and Tumanski 1986), and security systems.

It can be shown that the resistivity of a ferromagnetic thin film MRH is given as (Thompson *et al.* 1975)

$$\rho = \rho_o + \Delta\rho_{max}(1 - \sin^2\theta) \tag{1}$$

where ρ_o is the isotropic resistivity acting transverse to the direction of the MRH strip, $\Delta \rho_{max}$ is the maximum change of resistivity in the MRH, and θ is the angle the magnetisation vector makes with the direction of the constant current vector J flowing through the device. It can be seen that this behaviour is quadratic and hence non-linear.

It can also be shown that this resistivity can be represented as (Hunt 1971)

$$\rho = \rho_o + \Delta\rho_{max}\left(1 - \frac{H_y^2}{H_o^2}\right) \tag{2}$$

When a bias field H_B is applied to the device to linearise its characteristics then, neglecting quadratic terms since they are small

$$\Delta\rho = \left[\frac{2H_B\Delta\rho_{max}}{H_o^2}\right]H_y \tag{3}$$

or

$$\Delta R = \left[\frac{2H_B\Delta\rho_{max}l}{twH_o^2}\right]H_y \tag{4}$$

where l, t and w are the length, thickness and width of the device respectively; H_o is the anisotropy acting to restrain the M_s along the length of the device; and H_y is the external field applied across the width of the device.

With the constant current I passing through the device the change in resistance can easily be detected as a change in voltage, $\Delta V = I \, \Delta R$.

This has been the basis of the application of the MRH, i.e. detection of the change in resistivity of the device inside a varying magnetic field.

In most applications, the device merely detects the magnitude of the field without taking into account the relative orientation between the external field and the device. However, when the device is linearly biased it becomes sensitive to changes in the orientation of the external field. Several applications have stemmed from this behaviour, one of which is the detection of the grain structures in grain-oriented electrical steels (Mohd Ali and Moses 1989).

In the above application, a pair of thin-film monolithic ferromagnetic horizontal type MRH (known as the Chevron) configured at 120° to each other, was adapted as the sensor detecting the field on the surface of a magnetized Grain-Oriented Electrical Steel. Because the relative orientation of the magnetization vector M_s and the current vector J running through a linearly biased MRH is 45°, the effective angle of the Chevron becomes 30°, instead of 120°.

Even though satisfactory computation of the resultant field vectors has been achieved in the above investigation this configuration is by no means ideal, as the Chevron angle of 30° makes it less sensitive to changes in directions of field orientation, particularly at small angles. Moreover, the computation of the resultant magnetic field vector from the readings of each member of the Chevron is also more intensive because it involves a large number of terms. This factor is critical when a large array of data detected from the surface of the electrical steel is to be processed in real-time.

The resultant vector detected by a Chevron pair is given as (Mohd Ali and Moses 1988)

$$H = 2\sqrt{\left[\cos^2\theta°(H_A + H_B)^2 + \sin^2\theta°(H_A - H_B)^2\right]} \tag{5}$$

$$\alpha = \mathrm{Tan}^{-1}\left[\left(\frac{H_A - H_B}{H_A + H_B}\right)\mathrm{Tan}\,\theta°\right] \tag{6}$$

where H_A and H_B are the fields detected by the two sides of the MRH pair respectively constituting the Chevron.

For the Chevron employed in Mohd Ali and Moses (1989), the resultant magnitude and direction of the field detected by the Chevron are given as

$$H = 2\sqrt{\left[\cos^2 75°(H_A + H_B)^2 + \sin^2 75°(H_A - H_B)^2\right]} \tag{7}$$

$$\alpha = \mathrm{Tan}^{-1}\left[\left(\frac{H_A - H_B}{H_A + H_B}\right)\mathrm{Tan}\,75°\right] \tag{8}$$

DERIVATION OF THE MAGNITUDE AND ANGLE OF APPLIED FIELD

In the present investigation, a pair of vertical-type ferromagnetic MRH was biased simultaneously in such a way that the relative angle between the individual magnetization vector M was 90°. With this configuration, it could be shown that the response of the two MRHs is as follows:

$$H_A = H \sin(45^\circ - \alpha) \tag{9}$$
$$H_B = H \sin(45^\circ + \alpha) \tag{10}$$

Expanding and adding

$$H_A + H_B = 2H(\sin 45^\circ \cos\alpha) \tag{11}$$
$$H_B - H_A = 2H(\sin 45^\circ \sin\alpha) \tag{12}$$

Therefore

$$\alpha = \mathrm{Tan}^{-1}\left[\frac{H_B - H_A}{H_A + H_B}\right] \tag{13}$$

The computation of the field in equation (Mohd Ali and Moses 1988) reduces to

$$\begin{aligned} H &= 2\sqrt{\cos^2 45^\circ(H_A + H_B)^2 + \sin^2 45^\circ(H_A - H_B)^2} \\ &= \sqrt{(H_A + H_B)^2 + (H_A - H_B)^2} \\ &= \sqrt{2(H_A^2 + H_B^2)} \end{aligned} \tag{14}$$

This equation is simpler than that obtained in equation 7.

This paper describes an investigation to confirm that the sensitivity of the MRH is with respect to the M_s, and that the best configuration of the MRH pair for the computation magnetic field is 90° obtained by arranging the two MRHs parallel. A possible application in increasing the packing density of magnetic disc recording in computer systems is also described.

EXPERIMENTAL PROCEDURES

Two vertical-type thin-film ferromagnetic MRHs (Ni-Fe 81:91 % by wt) were employed in this investigation. The MRHs have dimensions of: length = 1mm, width = 20μm, and thickness = 0.4 μm. A dc current of 2mA was passed through each device independently, to convert the change in resistivity when the MRH is subjected to an applied field, to a change in voltage which could be observed, after some signal conditioning.

The MRHs (labelled as MRH_A and MRH_B) were biased simultaneously by means of a ferrite permanent magnet chip, sandwiched between the two MRHs with double-sided tapes, as shown in *Fig. 1.* The MRHs were arranged parallel because linear biasing is anticipated to rotate the M_s through 45° such that the final configuration would thus be at right angles to each other. The biasing was performed inside a solenoid excited from the 50 Hz ac power supply from the mains, and the hysteresis loop was observed on the oscilloscope. Linear biasing was deemed to have been obtained when the zero field region of the loop was linear over a sufficient field range.

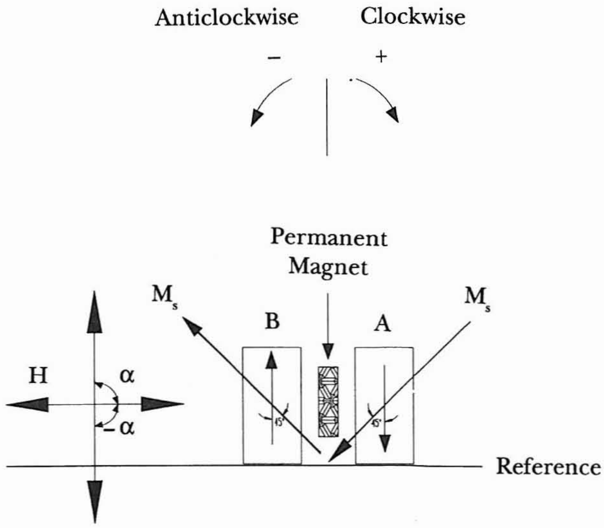


Fig. 1. Schematic representation of the MRHs, being biased simultaneously by a permanent magnet chip inside an applied field. The resulting orientation of the M_s is shown to be at right angles

The pair of MRHs were then mounted on the axis of a graduated rotatable stage placed at the centre of the solenoid. The MRHs were then rotated at 15° intervals, through clockwise (+) and anticlockwise (-) sense; this simulates the rotation of the applied field around the Chevron. As the Chevron is rotated clockwise, say, the magnetic field vector turns into the upper half of the circle, which in the convention adopted here, is referred to as positive angle. Likewise, anti-clockwise rotation of the Chevron results in a negative angle of orientation of the applied field.

The positive peak responses of the two MRHs taken at zero angle position were plotted against the relative orientation of the applied field, with respect to the horizontal axis reference.

RESULTS AND DISCUSSION

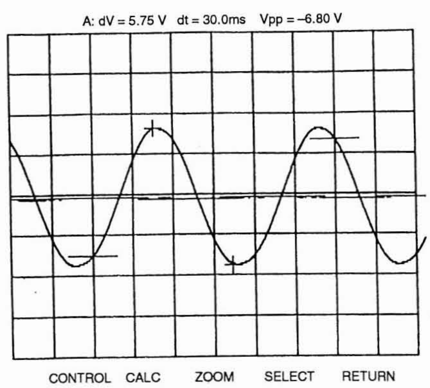
When the Chevron pair is subjected to an external ac field, the resistivity of the MRH changes in response to the applied field. As the Chevron is rotated on its axis inside the field, the amplitude of the voltage detected fluctuates according to the relation, $H = H_a \sin(45^\circ + \alpha)$, where H is the detected field, H_a is the applied field, and α is the angle of orientation of the applied field. A sample of the waveforms obtained from the MRHs is shown in *Fig. 2(A-H)* for α at 0°, +/- 45°, +/-90°, +/- 135° and –180°. These are the positions where significant changes in the detected field occur.

At the initial position, the peak responses of the two MRHs were considered equal even though they were actually opposite in phase. The peak values were taken as positive in both cases and this was taken as the datum for subsequent readings.

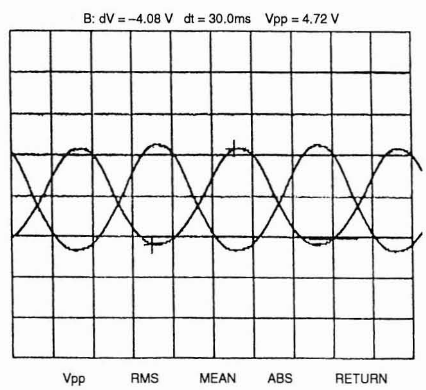
As the pair is rotated clockwise (positive angle), MRH_B increases steadily until 45° when the response is at its maximum. At the same time, the response of MRH_A diminishes to zero. This is due to the configuration of the biased pair as shown in *Fig. 1.* As the Chevron rotates in the clockwise direction, the magnetisation vector M_s of MRH_B gradually approaches the angle 90° with respect to the applied field, at the angle α = 45°. This is the position of maximum sensitivity following the relationship, $H_B = H_a \sin(45^\circ + \alpha)$, as stated in equation 5, where H_B is the field detected by MRH_B. In this case, α is considered positive when the Chevron is rotating clockwise, as α lies in the positive half of the circle.

This behaviour is summarized in *Fig. 3* showing the peak values of the MRH waveforms, against the orientation of the applied field, α.

It can be seen that after +/- 45°, the response of one of the MRHs turns negative (i.e. MRH_A at +45° and MRH_B at -45°). This comes about because the output of that MRH which diminished to zero, changed phase by 180°, so that the peak value of the waveform when measured at a fixed point in



A (α = 0°)



B (α = 45°)

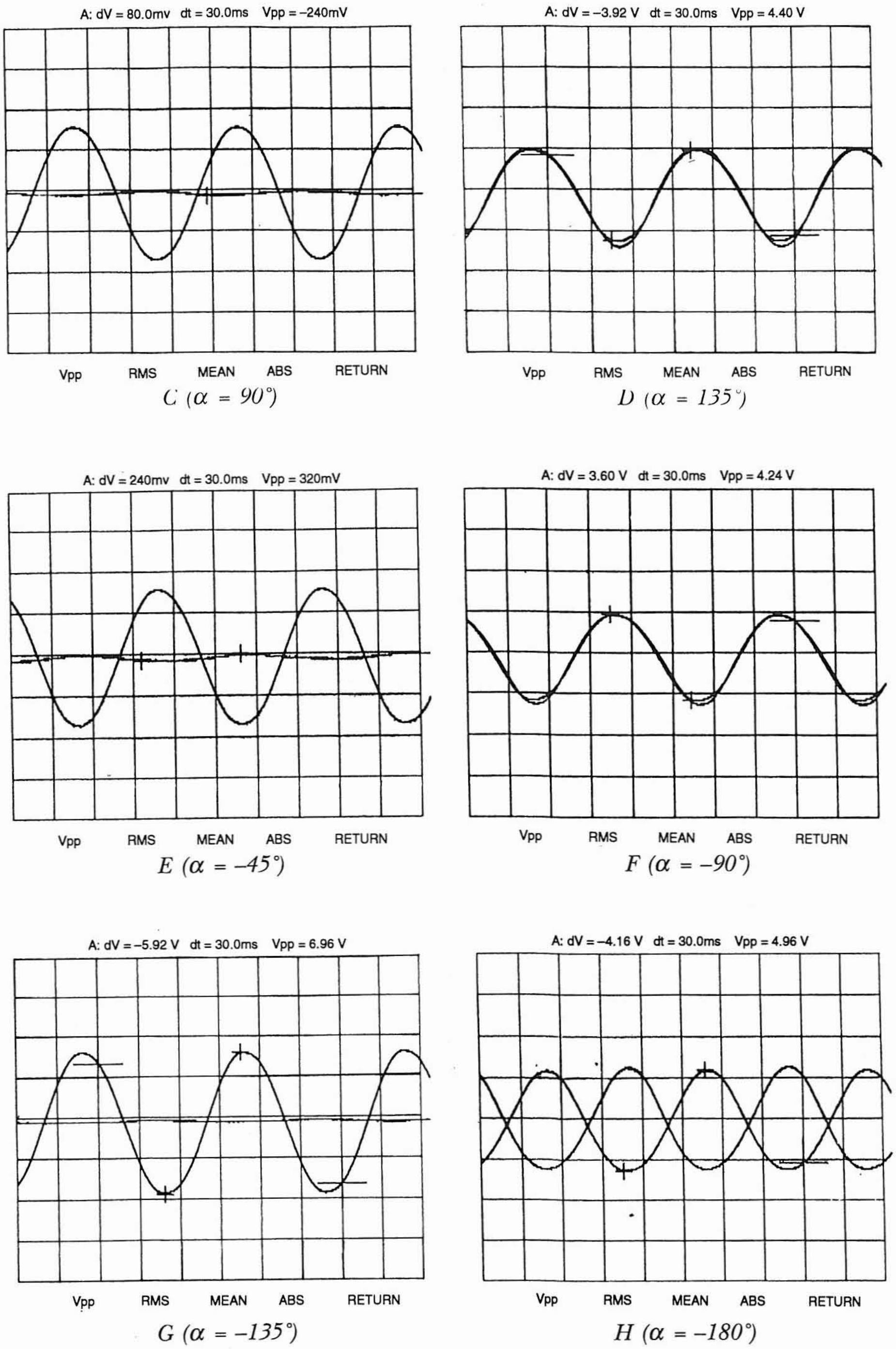


Fig. 2. The waveform traces of the MRHs when rotated inside an applied field (α = 0°, +/−45°, +/−90°, +/−135°, −180°)

time, would be negative. The change of phase happened because, at that critical angle of +/- 45°, the M_s switched to the opposite direction to maintain the position of minimum energy.

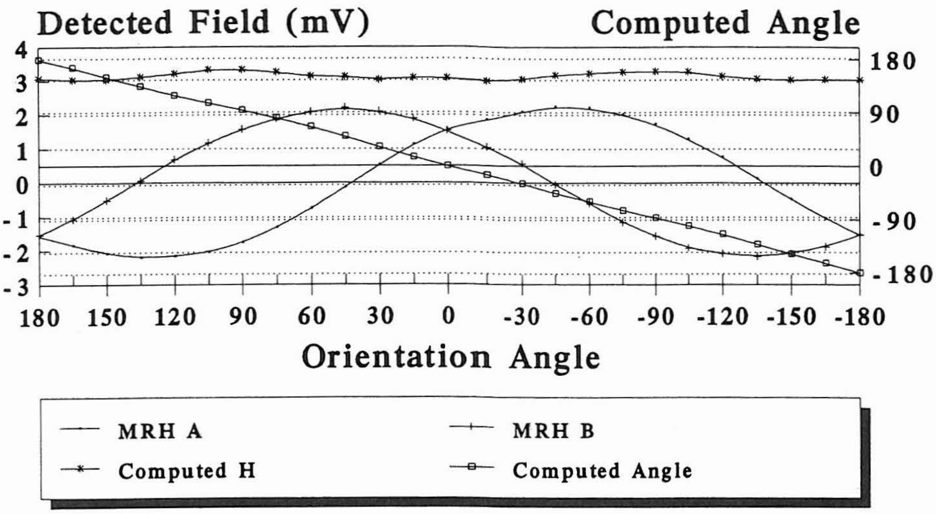


Fig. 3. Detected field and computed angle vs orientation angle

A computation of the resultant magnitude and α of the applied field from equations (13) and (14) shows that the values obtained are fairly constant throughout the whole excursion, since the fields are kept constant throughout the whole experiment. The computed angles also agree with the orientation angle α as seen by the linear relationship (*Fig. 3*). However, at angles greater than +/-90°, a discontinuity in equation 9 occurs. This is taken care of by adding 180° to the term in equation 3.

The stability of the measurement depends very much on the stability of the biasing point. In this investigation, the biasing magnet has been attached temporarily to the Chevron, by means of a double-sided tape or plasticine, to facilitate subsequent reuse. Because of this, the biasing point could displace as the Chevron is moved around, such that the biasing may no longer be linear. This will introduce some errors in the final computation of the resultant field. However this is overcome by taking the mean of 3 sets of readings for each point in the graph.

However, in applications for detecting the surface field of grain-oriented electrical steels as described in [1], the vertical type MRH is not suitable, because it detects the vertical component of the surface field only, which only occurs at grain boundaries, and not the body of the grain areas. In order to detect the horizontal component of the surface field a pair of horizontal MRH should be used instead.

For this type of application where the medium is sensitive to external field interference, the most appropriate type of biasing is obviously the self-biasing technique (barber-pole or anisotropy) where the biasing is performed by rotating the current vector with respect to the anisotropy, or vice versa.

CONCLUSIONS

An improved geometry for the detection of field vectors has been presented. Arranging two MRHs parallel to each other, and simultaneously biasing them at the linear region, results in an orthogonal configuration, whereby the magnetisation vectors M_s are effectively lying at 90° to each other. This is the ideal configuration for vector sensors.

With this configuration, the computation of the magnitude and direction of H is more efficient, compared with configurations at other angles.

If a self-biasing pair of MRH is arranged in this manner, an efficient field detector could be obtained in applications such as the non-destructive detection of grain structures in grain-oriented electrical steel (Mohd Ali and Moses 1989).

This technique could also be used to pack more bits of information in the magnetic disc or tape storage. The information could be encoded suitably using the technique popular in digital modulation such as Quadrature Amplitude Modulation (QAM) whereby each bit is modulated using Quadrature Phase Shift Keying (QPSK) and Amplitude Modulation (AM). A separate inductive recording head would be needed to store the information in the magnetic medium.

The information to be stored in the magnetic storage medium is grouped into a 4-bit group (nibble) first. The actual combination of the 4-bit group of information would magnetise the medium into appropriate direction and magnitude (*Fig.4*).

For example, if the information is 0110, then the storage is in the direction of 135°, with the magnitude below the threshold set in the system. If the information is 1101, then the storage is in the direction of - 90°, with the magnitude set higher than the threshold.

The two recording heads would record their appropriate components; i.e. for 0110, recording head A would have 0 field, and recording head B maximum field strength. Likewise, for 1101 recording head A would record with half of its field strength and recording head B would also have the same field strength. However, the phase of the recording head B would be 180° to that of recording head A.

Hence, each range of angles and amplitude of the fields detected by the Chevron carry 4-bits of information instead of just one bit. This

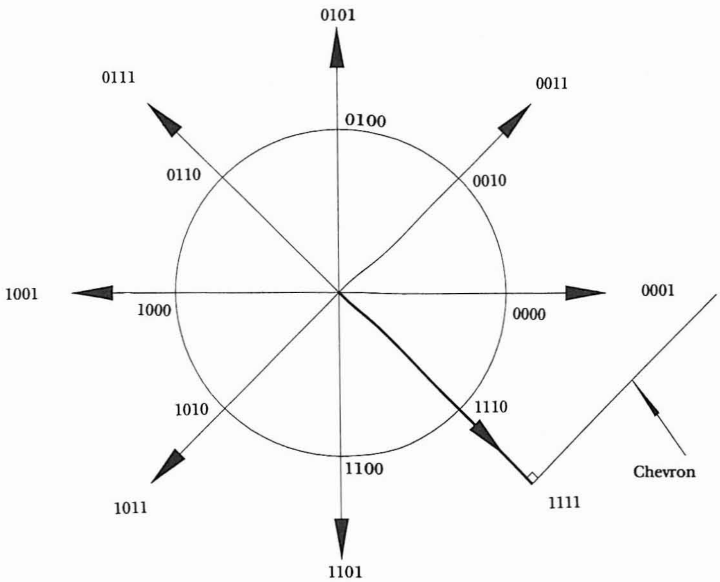


Fig. 4. Encoding technique to increase the packing density of magnetic storage.

advantage would of course be at the expense of increased processing time due to source and channel encoding required. More experiments are needed to investigate its feasibility and to evaluate its performance against factors such as access time, processing time, and costs. Performance of the system in the presence of noise should also be evaluated.

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