(54) Titre: DETECTEUR MAGNETIQUE
(54) Title: INTEGRATING MAGNETIC SENSOR

(86) Date de dépôt PCT/PCT Filing Date: 1999/06/22
(87) Date publication PCT/PCT Publication Date: 2000/01/20
(45) Date de délivrance/Issue Date: 2008/08/05
(85) Entrée phase nationale/National Entry: 2001/01/08
(86) N° demande PCT/PCT Application No.: GB 1999/001967
(87) N° publication PCT/PCT Publication No.: 2000/003260
(30) Priorité/Priority: 1998/07/09 (GB9814848.9)

(51) Cl.Int./Int.Cl. G01R 33/09 (2006.01)
(72) Inventeurs/Inventors:
MAYLIN, MARK GREGORY, GB;
GORE, JONATHAN GEOFFREY, GB;
SQUIRE, PATRICK T., GB;
ATKINSON, DEREK, GB
(73) Propriétaire/Owner:
QINETIQ LIMITED, GB
(74) Agent: FETHERSTONHAUGH & CO.

(57) Abrégé/Abstract:
An integrating magnetic sensor is described which comprises a sensor element made from a filament of substantially amorphous material which exhibits giant magneto-impedance and means for applying a bias field to the said sensor element so that it operates in the high field section of the giant magneto-impedance response.
An integrating magnetic sensor is described which comprises a sensor element made from a filament of substantially amorphous material which exhibits giant magneto-impedance and means for applying a bias field to the said sensor element so that it operates in the high field section of the giant magneto-impedance response.
INTEGRATING MAGNETIC SENSOR

This invention relates to sensors and in particular provides an integrating magnetic sensor for measuring magnetic fields over appreciable distances.

There are a number of different materials and techniques that can be used to measure magnetic fields. The common factor is that the sensors are in point form i.e. they can only measure the strength of the external magnetic field at the point in the field where they are positioned. Typical examples include magneto-resistant materials, Hall probes and flux gates. Another method for measuring a magnetic field is to use giant magneto impedance. Giant magneto impedance (GMI) is a known property of certain materials and is characterised in that a change in the complex impedance of the sensor occurs at high frequencies of alternating current when it is subject to an applied magnetic field.

If conventional magnetic sensors are used to measure a magnetic field over a large area, there are currently two options. Either the whole area to be assessed has to be covered in sensors or a plurality of sensors placed at intervals in the region to be assessed coupled with mathematical interpolation is required. The first of these options allows the whole magnetic field to be accurately measured but is impractical as a large number of sensors would be required. The second option is the one usually employed. However, this is error prone as only the discrete sections of the field covered by the sensors can be accurately measured. Mathematical interpolation is used in conjunction with the results from the sensors to give an integrated field measurement. Magnetic fields fluctuate so
the accuracy of this integrated field measurement depends on where the sensors have been positioned within the field.

Materials which exhibit giant magneto impedance (GMI) exhibit a large sensitivity in impedance to changes in magnetic field strength when subject to high frequencies of alternating current. The relationship between the impedance of the material and an external magnetic field is complicated. There are two distinct sections to the GMI response: low-field and high field.

If a material exhibiting GMI is produced as an amorphous elongate, the relationship between its impedance and an applied external magnetic field can be exploited. An elongate is hereinafter described as meaning a filament, wire or other object where one dimension of the object is of significantly higher magnitude than the other two which are substantially similar. The magnetic field resultant within the elongate material is characterised in that there are two competing magnetisation directions within the elongate. The magnetic structure of such an amorphous elongate is characterised in that if a cross section is taken through the elongate, the outer part is aligned circumferentially and the central part of the elongate is aligned along the length of the elongate. The proportion of the cross sectional area aligned in each direction depends on the strength of the magnetic field that the elongate is in. As the applied magnetic field is increased, the axial domain grows and this feature results in a change in the inductance of the material. The inductance of a material is related to the magnitude of its impedance, as shown below:

\[ Z = \sqrt{R^2 + \omega^2 L^2} \]
Where $Z$ is the impedance of the elongate, $R$ the resistance of the elongate, $\omega$ the angular frequency of the applied alternating current and $L$ the inductance of the elongate. When these materials are subject to an alternating power supply, a phase difference results between the measured voltage and current. The complex impedance of a material is the complex ratio of sinusoidal voltage to current, as shown below:

$$Z = \frac{V}{I} + jX$$

Where $Z$ is the impedance of the elongate, $V$ the voltage across the elongate, $I$ is the current in the circuit containing the elongate, $X$ the reactance of the elongate and $j = \sqrt{-1}$. Thus, a change in the average value of an applied external magnetic field will result in a change in the resistance and reactance of the material, which consequently affects the impedance. By measuring the voltage and current in a circuit which contains a material which exhibits GMI, the impedance can be calculated and this is related to the average external magnetic field.

The impedance of a material exhibiting GMI has a characteristic shape illustrated in Figure 1. When the applied magnetic field is increased from zero, the impedance of the sensor increases rapidly to a maximum value ($S$) and as the field strength is further increased, the impedance of the sensor decreases monotonically. The GMI response can be measured in either of these two sections and the one chosen will depend on the application the sensor is to be used for. In section A of Figure 1, where the impedance of the material increases as the external magnetic field strength is increased, the material is sensitive to changes in the external magnetic field strength. The magnetic permeability
of the material changes as the field is increased to the saturation point (S). This is the low-field section of the GMI response. Sensors utilising this section commonly operate in closed-loop mode whereby a magnetic field is generated to compensate the ambient magnetic field. In section B, where the impedance decreases from the saturation point (S) as the external magnetic field strength is increased, the wire is magnetically saturated. The magnetic permeability of the material is not sensitive to field changes in this section (B). This is the high-field section of GMI. The sensor described herein utilises this section and operates in open-loop mode whereby the bias magnetic field is of a fixed value.

When a sensor is subject to external magnetic fields below its magnetic saturation point (S) the material is not magnetically saturated and so the magnetic permeability of the material will change as the external magnetic field changes. The result of this is that sensors operating in section A can get distorted results. The reason for this is explained as follows. If the sensor is considered as a line of small, discrete sections each measuring a local part of the external magnetic field, some of these discrete sections will register a different magnetic field strength than the external magnetic field strength. As the sensor is not magnetically saturated the magnetisation of discrete sections of the elongate will be affected by adjacent sections of the elongate. This results in a distortion in the measured external magnetic field strength. The inaccuracies in measured external magnetic field strength resulting from the change in magnetisation of the sensor along its length are dependant on the magnetic field the sensor is measuring. If a GMI sensor is operated in a low field section (section A), an accurate measurement
of a magnetic field is not possible if the sensor is longer than a certain length, the maximum length being determined from the sensitivity of the magnetic permeability of the material being used. Point sensors manufactured out of materials exhibiting GMI in closed loop configuration, operating in section A i.e. below the magnetic saturation point of the material, have been produced using amorphous wires 1mm long and 50μm in diameter. United Kingdom patent application no. 2 313 918 published on 10 December 1997 discloses such a sensor.

If a GMI sensor is operated in the high-field section (section B), the material is magnetically saturated, so the permeability of the material is not affected by changes in external magnetic field strength. This means that the limitations on the length of the sensor that can be used in the closed loop configuration, low field section, do not apply. The discrete sections of the sensor do not cause local distortions in the magnetic field of the sensor as the magnetic permeability of the sensor is not affected by the magnitude of the external magnetic field. Therefore accurate readings for the external magnetic field strength can be determined.

An important aspect of elongate GMI magnetic sensors operated in the high field section of the GMI response section is that they integrate the magnetic field response. If the sensor is considered as a line of small, discrete sections each measuring the magnetic field local to it, the impedance response of the whole sensor is the sum of all the discrete section impedances. This gives an average magnetic field strength for the externally applied magnetic field. As the discrete sensors operated in the high field section do not experience a change in magnetic permeability as the external applied magnetic field strength changes,
every maximum and minimum in the external applied magnetic
field is measured along the length of the elongate. The
total impedance response is the sum of these elemental
impedances, giving a representative average value of the
applied magnetic field.

In order to produce a GMI sensor operating in an
open loop configuration, a fixed bias field is produced
around the elongate. The magnitude of the required bias
field is determined from the impedance characteristics of
the elongate when related to external magnetic field
(Figure 1). The bias field strength is chosen as a value
above (S), the magnetic saturation point. To ensure that
the sensor can operate in negative external magnetic fields
as well as positive external magnetic fields, the bias field
is conveniently chosen as a value near the mid point of the
high field section of the GMI response section (B) because,
as a person skilled in the art will realise, this will
reduce the chance of the GMI sensitive material experiencing
an inverse in its GMI response and thus function in the low-
field section of the GMI response.

There are a number of ways to produce the bias
field. A solenoid winding placed around the elongate may be
used, but sensor performance can be affected. If a solenoid
driven by a power supply is used, noise from the power
source can affect the results obtained. If the solenoid is
driven by a battery source drifting of the reading can occur
when the battery power becomes low.

A more effective solution is to incorporate a
permanent magnetic sheath around the elongate. This may be
done by incorporating a suitable magnetic material into a
polymer sheath and covering the amorphous elongate with said
sheath. The amount of magnetic material required depends on
the strength of the desired bias field. One such material is Nd₅Fe₁₄B, although other examples will be obvious to those skilled in the field.

The present invention is directed towards the provision of a magnetic sensor element characterised in that the sensor is elongate, operates under a bias field and utilises the high field section of the GMI response, thus eliminating the need for a multitude of elemental sensors and the need for mathematical interpolation of an external magnetic field between sensors which can introduce errors in the results obtained.

This invention consists of a magnetic sensor for measuring a magnetic field characterised by an elongate element comprising a substantially amorphous material which exhibits giant magneto-impedance (GMI) and bias means for applying a bias field to said element so that it operates in the high field section of the GMI response.

The invention also resides in a method of measuring a magnetic field which comprises exposing to said field an elongate sensor element comprising a component made of a substantially amorphous material which exhibits giant magneto-impedance (GMI), applying a bias field to said component, applying an alternating current to said sensor element and measuring the impedance thereof, the strength of said bias field being such that said component operates in the high field section of the GMI response, whereby to measure said magnetic field integrated along the length of said component.

A bias field can be produced in a number of ways. A preferable method is to place a solenoid winding around the elongate magnetic material. A more preferred method is
to incorporate a permanent magnetic sheath around the elongate magnetic material.

The material used for the sensor is preferably an alloy capable of being formed into an amorphous elongate by a suitable process, for example melt-spinning.

The material used for the sensor is preferably an alloy with a sensitive magneto-impedance response over the range required for the particular application. Examples of materials suitable for use in an elongate magnetic sensor are Co$_{72.5}$Si$_{12.5}$B$_{15}$, and (Co$_{0.94}$Fe$_{0.06}$)$_{72.5}$Si$_{12.5}$B$_{15}$. A small addition of iron to the alloy reduces the magnetostriction of the material so, on the application of a magnetising force, the GMI response of the material is less susceptible to elastic deformation. Chromium and/or molybdenum may also be employed. A particularly preferred alloy has the composition (Co$_{0.94}$Fe$_{0.06}$)$_{72.5}$Si$_{12.5}$B$_{15}$, as this can be produced as an elongate, and exhibits large magneto-impedance so is very sensitive to changes in magnetic field strength.

A more efficient magnetic sensor can be produced by post-production conditioning such as annealing. This improves the metallurgical properties of said elongate by removing residual stresses in the elongate and aligning the magnetic domains in the desired direction thus giving greater magnetisation in that direction and hence a more sensitive sensor.

The impedance of the elongate can be monitored by the use of a bridge circuit, in which the resistive and inductive components of the elongate material are balanced. The real and imaginary output of the bridge circuit can be measured by a lock-in amplifier. A more accurate measurement of the impedance of the elongate can be made by combining the real or in-phase and imaginary or quadrature
components of the bridge output which improves the stability and linearity of the sensor response as a function of applied magnetic field. Thus, in a further embodiment of the invention a bridge circuit is used with the elongate. A more accurate sensor can be produced if the real and imaginary components of said bridge circuit are combined.

The invention is particularly applicable to accurately measuring magnetic fields. Thus, a particular embodiment of the invention comprises a sensor incorporating the elongate element hereinbefore described. The invention may be used in magnetic surveying equipment, magnetic signature control equipment, geomagnetic measuring equipment, security tagging control such as for clothing in shops and perimeter fencing.

A plurality of sensors can be used to produce a non-integrating sensor. If elongates according to the invention of different length are incorporated together and the measured fields compared, then the investigation of the change in magnetic field strength over the area can be conducted differently. A number of average external magnetic field strengths each covering the portions of the field analysed by different elongates will be produced. These average magnetic field strengths can be compared to give a non-integrated result. Thus, instead of an average magnetic field strength over the whole area investigated, a series of absolute values for the magnetic field strength can be obtained. The positions of these absolute values in relation to the sensors can be determined and related back to the area investigated.

By way of example only, a number of embodiments of the invention will now be described with reference to the accompanying drawings, of which:
Figure 1 is a plot of impedance versus magnetic field for a material exhibiting a GMI response;

Figure 2 shows a schematic of the GMI sensor configuration;

Figure 3 is an illustration of a bridge circuit suitable for balancing the resistance and reactance of the elongate sensor;

Figure 4 illustrates the effect of different voltage frequencies on the GMI response of an amorphous elongate;

Figure 5 illustrates the effect of annealing on the GMI response of an amorphous elongate; and

Figures 6a and 6b illustrate the bias field profiles of two examples of biasing means for use in the invention.

Figure 1 shows the relationship of the impedance of an elongate to the external applied magnetic field strength. The GMI response changes when the technical saturation point (S) is reached. As the field is increased beyond this saturation point, there is an inversion in the GMI characteristic. At external applied magnetic fields below the technical saturation point (S), the impedance of the material increases as the external magnetic field increases (A). As the externally applied magnetic field strength increases above the technical saturation point (S), the impedance of the material decreases as the external magnetic field strength increases (B). The GMI response is therefore preferably measured in either external magnetic field strengths below or above the technical saturation point. Section A, the low-field section, is more suitable
for operation where small ranges of magnetic field are encountered and high sensitivity is required. Whereas section B, the high-field section, is more suitable for operation where larger ranges of magnetic field need to be measured with less sensitivity.

Figure 2 shows a schematic of the GMI sensor configuration. A sensing elongate material (1) is encased in a coil or sheath (2) which produces a bias field around the elongate.

Figure 3 shows an example of a suitable bridge circuit, where the resistance (R) and reactance (X) of the sensor (1) are balanced by $R_1$ and $L_1$. The resistance and reactance of the elongate are measured before the bridge circuit is set up to give values for $R_1$ and $L_1$. $R_2$ and $R_3$ which comprise the other two arms of the bridge circuit are of equal value. $R_4$ is the source resistance from the function generator. For the purposes of this study $R_2$ and $R_3$ were given values equal to the sum of $R$ and $R_4$.

Example 1 - A 20cm length of amorphous elongate was used ((Co$_{0.94}$Fe$_{0.06}$)$_{12.5}$Si$_{12.5}$B$_{15}$). The elongate GMI response was determined at various excitation voltage frequencies to find the frequency at which maximum impedance sensitivity occurred. The results are shown in Figure 4. The figure shows the effect of 4 different voltage frequencies on the elongate impedance. The voltage was kept at 0.4V for all the frequencies. At low voltage frequencies (100KHz and below), the GMI response is low and the sensitivity of impedance to magnetic field strength is also low. At voltage frequencies of 1MHz, the sensitivity of the impedance of the elongate to magnetic field strength is at a maximum. At voltage frequencies above 1MHz, the sensitivity of the elongate impedance begins to reduce and there is more
noise in the curve. This noise makes it harder to characterise the impedance-magnetic field strength relationship. A voltage excitation frequency of 1MHz was found to be optimum. There is little noise in the curve and the change in impedance as the external magnetic field strength is changed is at a maximum.

Example 2 - The effect of annealing the amorphous elongate was investigated. Figure 5 shows the affect of annealing on \((\mathrm{Co}_{0.94}\mathrm{Fe}_{0.06})_{72.5}\mathrm{Si}_{12.5}\mathrm{B}_{15}\). The graph shows the effect of annealing from no annealing (the as quenched state) to 60 minutes at 472°C, on the impedance response to external magnetic field strengths. By annealing the elongate material, the impedance-magnetic field strength curve is altered to a more uniform and so more easily characterised response. Annealing can improve the sensitivity of the elongate materials response to external magnetic field strength.

Example 3 - In order to produce a bias field along the length of the elongate, a solenoid was produced that encompassed the amorphous elongate. The solenoid was made significantly longer than the elongate such that a constant bias field along the elongate was achieved.

Example 4 - An alternative means of producing a bias field was achieved by incorporating 20% fraction of a magnetic material - \(\mathrm{Nd}_2\mathrm{Fe}_{14}\mathrm{B}\) - into a polymer material, which was subsequently formed into a sheath to encompass the amorphous elongate. Figure 6a shows the calculated variation in bias field strength along the length of the elongate material when covered by the magnetic sheath. Along the central portion of the elongate (0.05-0.15 on the x-axis of the graph), a uniform bias field has been generated. At the ends of the elongate, the bias field is
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non-uniform. To overcome this non-uniformity of the bias field, the filling fraction of the magnetic material in the polymer sheath can be modified. Figure 6b shows a more uniform bias field profile, achieved by reducing the fraction of permanent magnetic material at the ends of the polymer sheath.

Example 5 - By incorporating the features explained in examples 1, 2 and 3 i.e. a voltage frequency of 1MHz, annealing the elongate and producing a uniform bias field, in an amorphous elongate of (Co0.94Fe0.06)72.5Si12.5B15, a 20cm long magnetic sensor with a sensitivity of 10-20nT with a field measurement range of ±500μT was made.
CLAIMS:

1. A magnetic sensor characterised by an elongate sensor element comprising a component made of a substantially amorphous material which exhibits giant magneto-impedance (GMI) and bias means for applying a bias field to said component so that it operates in the high field section of the GMI response.

2. A magnetic sensor in accordance with claim 1 in which said bias means comprises a solenoid winding.

3. A magnetic sensor in accordance with claim 1 in which said bias means comprises a permanent magnetic material.

4. A magnetic sensor in accordance with any of claims 1 to 3 wherein the amorphous material is an alloy comprising substantially cobalt, silicon and boron.

5. A magnetic sensor in accordance with claim 4 wherein the amorphous material also includes one or more of the elements iron, chromium and molybdenum.

6. A magnetic sensor in accordance with any of claims 1 or 4 wherein the amorphous element has the composition \((\text{Co}_{0.9}\text{Fe}_{0.6})\text{Si}_{12.5}\text{B}_{13}\).

7. A magnetic sensor in accordance with any one of claims 1 to 6 wherein the sensor element has been annealed.

8. A magnetic sensor in accordance with any one of claims 1 to 7 including a bridge circuit for measuring the impedance of the sensor element.

9. A magnetic sensor in accordance with claim 8 wherein the in-phase and quadrature components of the bridge
circuit output are combined to improve the stability and
linearity of the sensor response.

10. A magnetic sensor for measuring an external
    magnetic field strength comprising at least two elongate
    sensor elements as claimed in any of claims 5 to 9.

11. A method of measuring a magnetic field which
    comprises exposing to said field an elongate sensor element
    comprising a component made of a substantially amorphous
    material which exhibits giant magneto-impedance (GMI),
    applying a bias field to said component, applying an
    alternating current to said sensor element and measuring the
    impedance thereof, the strength of said bias field being
    such that said component operates in the high field section
    of the GMI response, whereby to measure said magnetic field
    integrated along the length of said component.

12. A method according to claim 11 using a sensor
    according to any one of claims 2 to 10.

FETHERSTONHAUGH & CO.
OTTAWA, CANADA

PATENT AGENTS
Fig.1.
(PRIOR ART)