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Orthogonal Fluxgates

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1. Introduction

Fluxgates are vectorial sensors of magnetic fields, commonly employed for high resolution measurements at low frequencies in applications where the sensor must operate at room temperature.

Fluxgates are usually classified in two categories: parallel and orthogonal fluxgates. In both cases, the working principle is based on a magnetic core periodically saturated in opposite directions by means of an excitation field. The measured field is superimposed to the excitation field and it alters the saturation process.

The basic structure of the orthogonal fluxgate and its difference to parallel fluxgates is illustrated in Fig. 1. The parallel fluxgate (Fig. 1-A) is composed, in its most common form, of a magnetic ring or racetrack core periodically saturated in both directions by the ac magnetic field H_{ex} generated by the excitation coil. The output voltage is obtained with a pick-up coil wound around the core. Even harmonics arise in the output voltage when an external magnetic field H_{dc} is applied in the axial direction. The sensor is called a *parallel* fluxgate because the excitation field H_{ex} and the measured field H_{dc} lay in the same direction. More details about parallel fluxgates can be found in (Ripka, 2001).

Orthogonal fluxgates are based on a similar principle, but they have a different structure, as shown in Fig. 1-B.

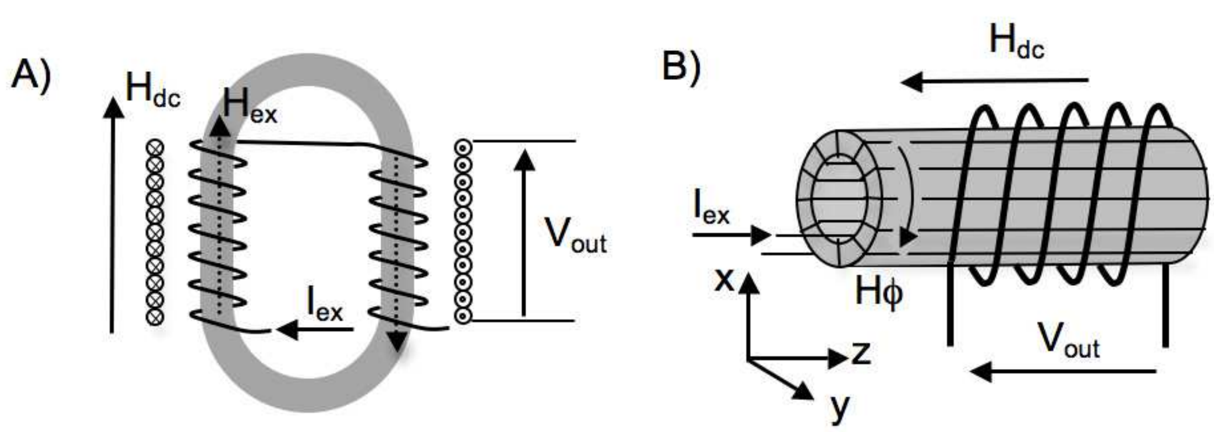

Fig. 1. Structure of parallel (A) and orthogonal (B) fluxgates.

The core is a cylinder of soft magnetic material, with a toroidal excitation coil wound around it. The excitation current flows through the toroidal coil generating excitation $H\phi$ in the circumferential direction. The core is periodically saturated in the circumferential direction by $H\phi$ in opposite polarities. Finally, the output voltage is obtained with a pick-up coil as it was in the parallel fluxgate. Once more, when the external field H_{dc} is applied in the axial direction, even harmonics arise in the output voltage. In this case, the sensor is called an *orthogonal* fluxgate because the measured field H_{dc} is orthogonal to the x-y plane where the excitation field $H\phi$ lays.

Orthogonal fluxgates have been originally proposed in (Alldredge, 1952), both with a cylindrical core and a wire-core. Later, Schonsted proposed an orthogonal fluxgate based on a magnetic wire wound in a helical shape around a conductive wire carrying an excitation current (Schonsted, 1959). Several years later, orthogonal fluxgates appeared again in (Gise & Yarbrough, 1975) where the authors proposed an orthogonal fluxgate with a core obtained by electroplating a Permalloy film on a 6.3 mm diameter glass cylinder after the deposition of a copper substrate. The sensor showed large hysteresis, and it was later improved in (Gise & Yarbrough, 1977) with a core composed of a 3.2 mm diameter copper cylinder and of an electroplated shell on it. An orthogonal fluxgate based on a composite wire, manufactured with a conductive core and electroplated magnetic thin film (about 1 μm thick), was also proposed in (Takeuchi, 1977) after which orthogonal fluxgates were almost forgotten.

From the early years, indeed, parallel fluxgates have been always preferred to orthogonal fluxgates because they usually offer better performances, especially lower noise. Thus, the mainstream of research and development focused on parallel fluxgates.

The development and improvement of techniques for the production of microwires obtained in the last decades (Vázquez et. al, 2011) have made it now possible to manufacture soft magnetic wires with an extremely narrow diameter (50-100 μm) and high permeability. Thanks to this, the principle of the orthogonal fluxgate has been rediscovered. For example, an orthogonal fluxgate sensor based on a glass covered Co-based alloy with a very narrow diameter was proposed in (Antonov et al., 2001) and a similar sensor with a Permalloy/copper wire was used as the core with a 20 μm diameter (Li et al., 2004).

Orthogonal fluxgates based on a microwire gained new popularity mainly due to the rising requests for miniaturized sensors of magnetic fields.

2. Working principle

A detailed explanation of the working mechanism of orthogonal fluxgates is given in (Primdahl, 1970) for the basic tubular structure proposed in (Alldredge, 1958).

Let us consider a tube of soft magnetic material as shown in Fig. 2a, exposed to a sinusoidal excitation field in the circumferential direction $H\phi$ (generated by a toroidal coil - not shown to simplify the drawing) and to an axial field H_Z. The material is assumed to be isotropic with a simplified MH loop shown in Fig. 2b; the magnetization M lies between H_Z and $H\phi$ in order to satisfy the minimum energy condition.

The axial field is assumed to be much lower than the saturation field H_S, therefore during the part of the period when $H\phi<H_S$ the core is not saturated. Under these conditions, when $H\phi$ increases, then both the angle α and the amplitude of M also increase, while the component of M in the axial direction M_Z does not change because H_Z is constant. However, when $H\phi$ reaches the amplitude where the total field is $H_{tot}=H_S$, then the core gets saturated; if $H\phi$ further increases, then the amplitude of M does not increase anymore and the only effect of $H\phi$ is to rotate M along the circumference which describes the saturation state (Fig. 2c). Under this condition M_Z is not constant anymore but it starts decreasing as the M reaches the saturated state (Fig. 2e). As a result, a variation of the magnetic flux occurs in the axial direction and a voltage is induced in the pick-up coil (Fig. 2d).

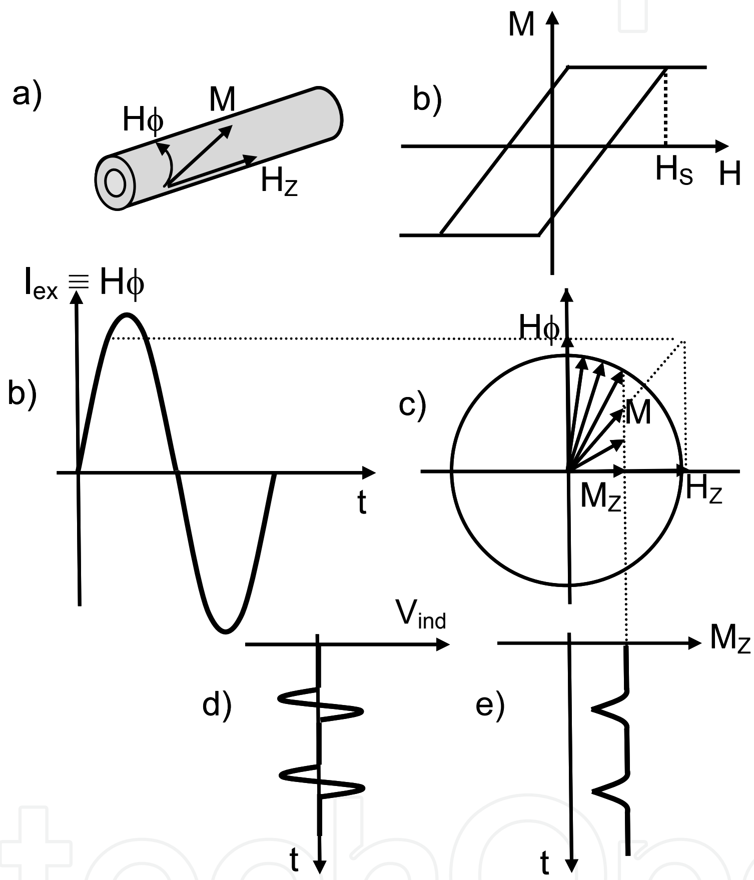

Fig. 2. Working principle of orthogonal fluxgates.

Since the excitation field is sinusoidal the saturation is reached twice per period (i.e. in both the positive and negative directions). This means that the induced voltage will contain even harmonics of the excitation frequency, wherein the second harmonic is generally extracted by means of a lock-in amplifier to obtain the output signal. The amplitude of the induced voltage depends on M_Z, which in turn is determined by H_Z. Finally, the amplitude of the even harmonics gives us a measurement of the axial field H_Z.

If the direction of H_Z is reversed M_Z becomes negative and the phase of the induced voltage is shifted by π rad. This means that the orthogonal fluxgate is able to distinguish between positive and negative fields; usually, the real part of the second harmonic is used as an output signal in order to take into account the phase of the voltage and to obtain an anti-symmetrical function, which allows to discriminate the sign of the field.

2.1 Gating curve

A gating curve is usually measured in order to understand how the flux is gated within the core of a fluxgate. We now consider a real MH loop as in Fig. 3b (without the simplification used in Fig. 2) and we derive the B_Z-$H\phi$ curve that describes the gating occurring in the orthogonal fluxgate core. The amplitude of the peaks in the gating curve is proportional to H_Z since they correspond to M_Z out of saturation. Moreover, the position of the peaks is not constant. For a higher H_Z the saturation is reached for a lower value at $H\phi$, causing the distance between the peaks to decrease (Fig.3).

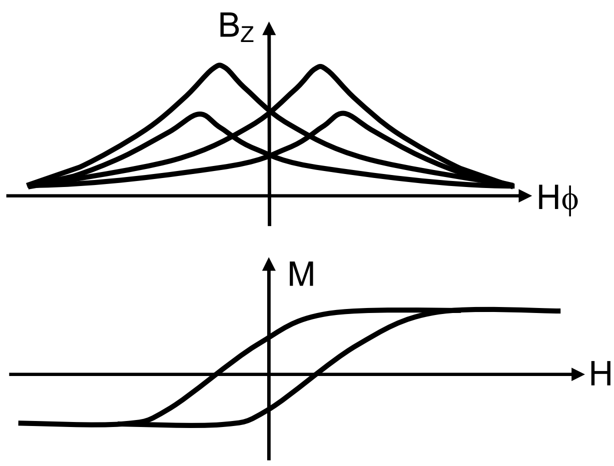

Fig. 3. Gating curves of an orthogonal fluxgate.

The peaks of the gating curve become negative for $H_Z<0$ while no peaks appear when $H_Z=0$. This means that the voltage induced in the pick-up coil is null for no measured field. This becomes extremely important when the sensor is operated in feedback mode with its working point kept around zero. In this case, the output voltage will be always around zero, making it possible to use high gain amplification to increase the signal-to-noise ratio.

2.2 Effect of anisotropy

We must highlight that the model described above applies only if the magnetic core is isotropic or if it has circumferential anisotropy. In case of non-circumferential anisotropy the direction of magnetization M is determined not only by $H\phi$ and H_Z but also by the anisotropy. In this case, the angle θ of M is obtained by minimizing the total energy of M, taking into account the field energy of $H\phi$ and H_Z as well as the anisotropy energy (Jiles, 1991).

Non-circumferential anisotropy can in fact deviate the magnetization from the circumferential plane and give rise to an output voltage even for a zero measured field, significantly changing the gating curves. In such cases, a more detailed model that takes into account the effect of anisotropy should be used (Butta & Ripka, 2008b).

We should also note that in magnetic wires, the anisotropy direction and strength can significantly change according to geometric parameters and manufacturing methods. A detailed characterization of the core's circular and axial magnetic properties is, therefore, always necessary before applying any model to the sensor.

3. Wire-core orthogonal fluxgates

As previously mentioned, the availability of microwires suitable for the fluxgate cores gave new popularity to the orthogonal fluxgate principle.

Fig. 4 shows the structure of an orthogonal fluxgate based on a magnetic wire core. The excitation current I_{ex} is injected to the magnetic wire and generates a circumferential field $H\phi$ while a pick-up coil is wound around the wire as usual.

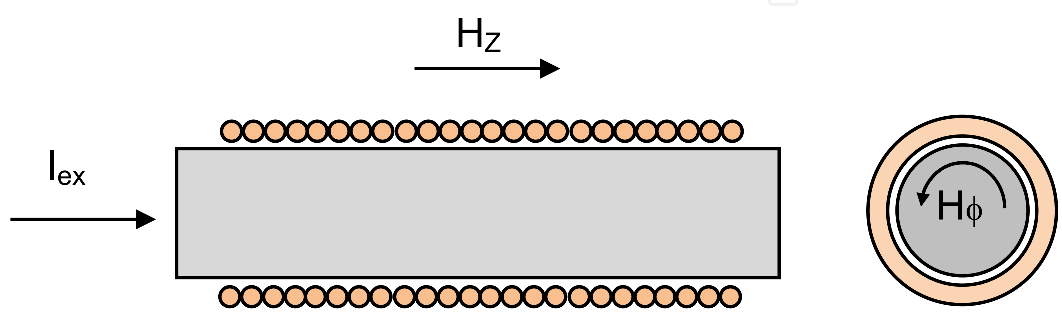

Fig. 4. Orthogonal fluxgate based on a magnetic wire.

In this structure, the excitation coil is not required because the excitation field is generated by the current flowing through the wire. Therefore, the structure of the sensor is extremely simplified and the manufacturing of the sensor becomes easier. Even more importantly, the lack of an excitation coil makes it possible to significantly reduce the dimensions of the sensor. This plays strongly in favor of orthogonal fluxgates, because it makes them suitable for current applications where high miniaturization is required.

Fluxgates based on a microwire became popular also because during the last years the production techniques of magnetic wires have been subject of deep investigation. For example, in (Li et al., 2003) the effect of a magnetic field is shown during the electrodeposition of the NiFe film on a copper wire. By properly tuning the magnetic field's amplitude and direction it is possible to control the anisotropy direction (particularly useful for optimization of sensitivity and offset of the sensors) as well as to improve film uniformity, softness and grain size. Moreover, it has been shown that it is possible to strongly reduce the coercivity of electroplated Permalloy films as well as to increase their permeability by using pulse current instead of dc current for the electroplating process (Li et al., 2006).

Uniformity of the film is improved by a Cu seed layer sputtered on the Cu wire before electroplating because it minimizes the roughness of the surface, helping to reduce the coercivity. The effect of film thickness on the grain size, and finally on the coercivity, has also been studied in (Seet et al., 2006) where it is shown that grain size is lower for larger thickness. However, it is recommended to keep current density constant during the electroplating because if we use a constant current as the thickness increases, the current density decreases, and this is shown to increase the grain size.

3.1 Spatial resolution

Besides the lack of an excitation coil, one of the main advantages of wire-core fluxgates is the diameter of the wire, usually very narrow (several tens of μm). A narrow diameter is advantageous not only for miniaturization, but also for improvement of spatial resolution in magnetic field measurement. Let us consider, for instance, a magnetic field H_Z with constant gradient along the x direction, as shown in Fig. 5. Parallel fluxgates must use either a ring or a racetrack core to reduce the demagnetizing factor and compensate voltage peaks for zero measured fields. Such core has two sensitive sections in the measurement direction (namely A and B in Fig.5, left) which sense different fields H_{ZA} and H_{ZB}. The total field measured by the parallel fluxgate will be the average of H_{ZA} and H_{ZB}.

Parallel fluxgates rarely have a core narrower than 1÷2 cm, limiting the spatial resolution to such level. On the contrary, orthogonal fluxgates have the sensitive cross section of a single wire making it possible to measure the magnetic field H_Z in the single spot, with resolution limited by the diameter. Since typical wires used for orthogonal fluxgates have diameters up to 100 μm, the spatial resolution of orthogonal fluxgates is two orders of magnitude better than conventional parallel fluxgates. To this extent, they were successfully employed for applications such as magnetic imaging. For instance, in (Terashima & Sasada, 2002) a gradiometer based on a wire-core orthogonal flux is presented. The gradiometer is used to measure magnetic fields emerging from a specimen of 3% grain oriented silicon steel, with steps of 50 μm (the diameter of the amorphous wire used as a core is 120 μm). Since the spatial resolution of the sensor is very high it was possible to measure the magnetic field emerging from a single domain, and then graphically represent the domain's topology of the sample.

Parallel fluxgates, based on PCB technology, with an ultra thin core (50 μm) have also been proposed (Kubik et al., 2007). In this case, the spatial resolution is remarkably improved in y direction, but it is still poor in the x direction.

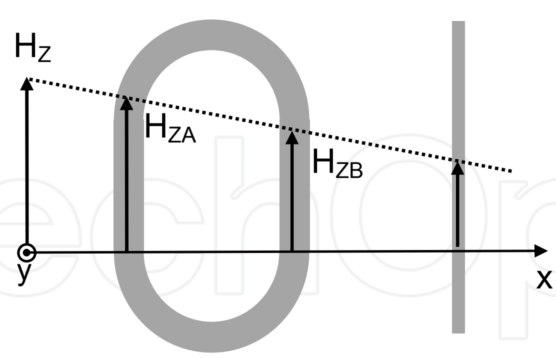

Fig. 5. Spatial resolution in parallel (left) and orthogonal fluxgates (right).

3.2 Excitation field inside the wire

One of the main drawbacks of wire-based orthogonal fluxgates is that the excitation field is not uniform along the distance from the centre of the wire. This comes directly from Ampere's law. Let us consider a magnetic wire with uniform current distribution (i.e. we consider skin effect negligible). The excitation field $H\phi$ increases linearly from radius r=0, the centre of the core, to its maximum at the border of the wire (r=R). If we define H_S as the minimum field to saturate the material[1], we observe that the inner part of the wire, for $r<\sigma$, where $H\phi<H_S$ is not fully saturated. On the contrary, when we use a cylindrical core excited by a toroidal coil, then the whole core is equally saturated.

Saturation is a vital requirement for the proper working of a fluxgate, wherein only the outer saturated shell will contribute to fluxgate mode whereas the inner unsaturated part of the core will not act as a fluxgate. Most important, having the central part of the core unsaturated causes hysteresis in the output characteristic of the fluxgate. Indeed, if we apply an axial magnetic field to the wire this will magnetize the central part of the core in its direction. Since that part of the core is not saturated, the magnetization cannot be restored by the excitation field through saturation in the circumferential direction. The centre of the core will then naturally follow its hysteresis loop.

To this extent, it is very important to achieve the full saturation of the core to avoid the hysteretic behaviour of the sensor. Unfortunately, it is impossible to saturate the wire in its entire cross-section, since this would require an infinite current. Instead, we will always have an inner portion of the wire unsaturated.

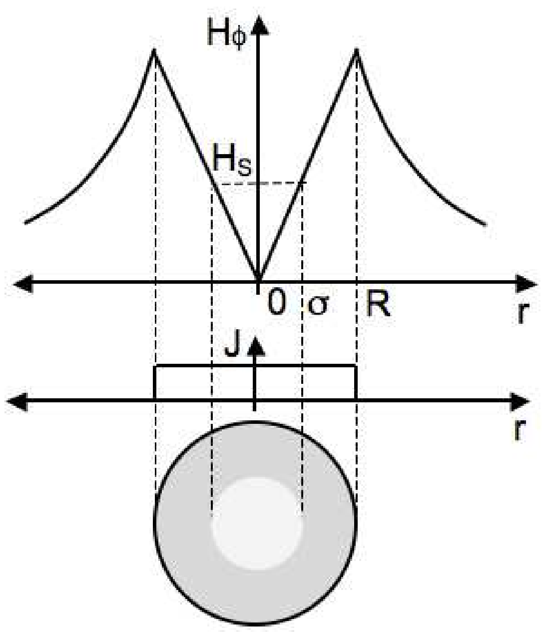

Fig. 6. Magnetic wire with uniform current distribution. The magnetic field increases linearly within the wire and only the outer shell where $H\phi>H_S$ is saturated.

Amorphous wires are often used as cores for orthogonal fluxgates. In this case, the wire has an inner cylinder with magnetization in the axial direction and a shell with radial or circumferential magnetization (Fig. 7) in case of positive or negative magnetostriction respectively (Vázquez & Hernando, 1996).

[1]The saturation field is clearly not a brick wall border. The amount of saturated material asymptotically increases when the magnetic field grows. Therefore, we cannot define a clear border between the saturated and unsaturated state. However, we can define a condition when the core can be considered saturated from a practical point of view. That occurs when any increment of the magnetic field does not cause any significant change in the working mechanism of the fluxgate.

In this case the central part of the core will never contribute to the fluxgate effect, which will be given only by the outer shell. The inner part of the core usually shows a bistable behaviour, which means that its magnetization will switch direction upon the application of an axial field larger than the critical field. A fluxgate base on such wires will be affected by the perming effect (i.e. shift of the sensor's output characteristic after the application of a large magnetic field) due to the switching of the magnetization in the central part of the wire.

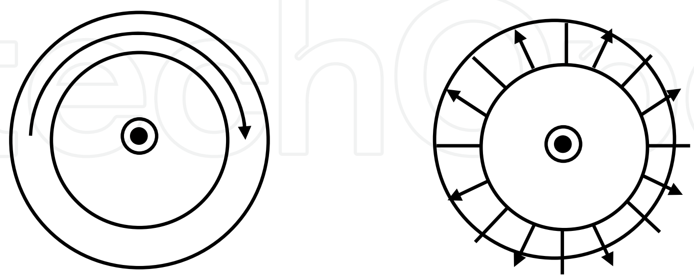

Fig. 7. Cross-section of a magnetic wire with bamboo structure, in case of negative (left) and positive (right) magnetostriction.

3.3 Composite wires

Composite wires have been proposed to solve problems given by the unsaturated inner section of the wire (Ripka et al., 2005; Jie et al., 2006). The main idea involving composite wires is to have wires with non-magnetic cores surrounded by a soft magnetic shell. In this way, we avoid problems such as the hysteresis of the sensor's characteristic and the perming effect, which typically arise if the wire is not fully saturated.

Considering a core composed of a 20 μm diameter copper wire surrounded by a 2.5 μm thick Permalloy layer, the perming error (i.e. shift of offset after 10 mT shock field) is only 1 μT, for an excitation current as low as 20 mA. Moreover, it is shown that the perming error decreases for a higher excitation current, as typically found for bulk core fluxgates, because the core is more deeply saturated.

The most frequently used technique to produce composite wires consists of the electroplating of a magnetic alloy, for example $Ni_{80}Fe_{20}$ (Permalloy), on a copper microwire. The resistivity of copper (~17 nΩ·m) is lower than the resistivity of many magnetic alloys (for instance the resistivity of Permalloy is ~200 nΩ·m). For a typical wire composed of a 50 μm diameter core and surrounded by a 5 μm Permalloy shell, only 3.6% of the total current flows through the magnetic shell. If we operate the sensor with an excitation current low enough to make skin effect negligible, we can assume that the whole excitation current will flow through the copper core. Such simplified configuration is shown in Fig. 8 where the current density J is uniform within the copper core and zero in the magnetic shell. The circumferential magnetic field generated by the excitation current linearly rises until within the copper core ($r=R_c$) and then it decreases as 1/r for $r>R_c$ (i.e. on the magnetic shell). In this case, the outer part of the magnetic layer is excited by a lower field, namely H_m. As far as the excitation current is high enough to make $H_m>H_S$ we can consider the wire completely saturated.

In this kind of structure, a larger magnetic layer requires a larger excitation current in order to avoid that the outer portion of the magnetic shell becomes unsaturated. Therefore, we must carefully weigh the advantages of lager sensitivity given by a thicker magnetic shell against the disadvantages caused by an increment of current required for the saturation.

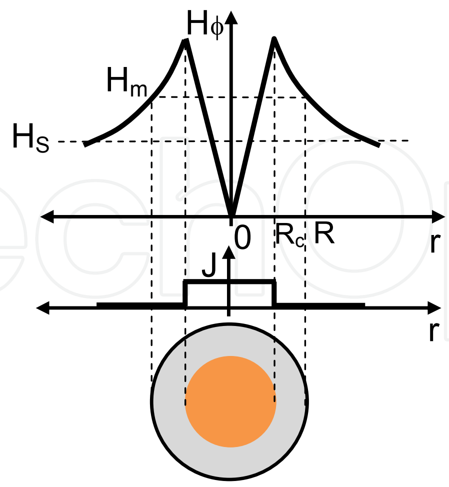

Fig. 8. Composite wire with copper core and magnetic shell. The current flows entirely through the copper core so that the magnetic shell is fully saturated.

Skin effect, however, is not always negligible, especially when the sensor is operated at a high frequency in order to increase the sensitivity. In this case, the excitation current drains from the copper core to the magnetic shell, reducing the magnetic field in the magnetic shell. Depending on the actual current distribution, the magnetic field can strongly change. Numerical simulation is usually employed in order to predict the current distribution within composite wires (Sinnecker et al., 2002). The penetration depth strongly depends on the conductivity of both the conductive core and the magnetic shell as well as on the permeability of the latter. Therefore, a general value for a limit frequency to avoid draining the current to the magnetic shell cannot be given. Numerical simulation is suggested to predict current distribution within the wire.

Finally, designers of orthogonal fluxgates should carefully choose their operating frequency. On the one hand, a higher frequency increases the sensitivity, which contributes to the reduction of noise, whereas on the other hand, a higher frequency can cause parts of the wire not to be completely saturated, incrementing the noise (besides the hysteresis and perming effect). The excitation frequency should be chosen as a compromise between these two opposite effects.

3.4 Glass insulation

A more complex structure has been proposed by (Butta et al., 2009a) to overcome the problem of the current draining to the magnetic shell due to the skin effect. This is carried out by putting a glass layer between the copper core and the magnetic shell. The glass layer provides electrical insulation, helping thus to keep the excitation current flowing entirely within the copper core, regardless of the operating frequency. Even if the skin effect should occur in the copper core, given Ampere's law, this does not affect the magnetic field generated from the copper's diameter.

In order to manufacture a composite structure with glass insulation between the copper and the magnetic shell, glass coated copper wires are used as a base. Following this procedure, a small nm thick gold layer is applied on the glass coating by means of sputtering. Finally, the electroplating of magnetic alloy is performed on the gold seed layer.

By using such structure the saturation current can be strongly reduced. In (Butta et al., 2009a), the saturation current is reduced by a factor of 3.

4. Micro orthogonal fluxgate

As already mentioned, the lack of an excitation coil is one of the main advantages of orthogonal fluxgates, because it strongly simplifies its structure, making high miniaturization possible.

The first attempt made in order to reduce the dimensions of an orthogonal fluxgate was carried out in (Zorlu et al., 2005) where a sensor is based on a wire composed of Au core (20 µm diameter) covered by a 10 µm thick FeNi electroplated layer. The total diameter of the wire is therefore 40 µm, and the length varies from 0.5 to 4 mm. The output voltage is picked-up by means of two planar coils fabricated on a Pyrex substrate by means of sputtering, photolithography and patterning.

The response of the sensor has a large linear range for excitation current, which can be as low as 50 mA (at 100 kHz), showing that the wire is saturated for such low current. If the current is further increased to 100 mA the linear range reaches ±250 µT, and sensitivity reaches 4.3 V/T. A higher current than the minimum current necessary to saturate the core is also useful against the perming effect. While perming shift after ± 50 µT shock field is 16 µT for 50 mA excitation current, it drops down to 2 µT for 100 mA excitation current.

Orthogonal fluxgates based on a microwire, however, can hardly be manufactured at lower dimensions. The microfabrication of the sensor becomes more suitable for micro sensors, especially for mass production. In (Zorlu et al., 2006) a microfabricated orthogonal fluxgate is presented wherein the core is manufactured in three steps. First, a Permalloy bottom layer is electroplated on the Cr/Cu seed layer previously applied on the substrate, then the central copper core is electroplated in the middle and finally Permalloy is electroplated on the three open sides of the copper creating a closed loop of Permalloy around the copper. The resulting structure is composed of a rectangular shape core (8 µm x 2 µm) and a copper nucleus surrounded by a 4 µm Permalloy layer (the total dimensions of the structure is 16 µm x 10 µm). The length of the core is 1 mm. The dimension of the core was finely adjusted thanks to the high precision of photolithography.

Also in this case, the flux is picked-up using two planar coils formed in the substrate under the core (2 x 60 turns). The sensor has a large linear range (±200 µT) but rather low sensitivity, around 0.51 V/T for a 100 mA excitation current at 100 kHz. Thus, the resulting noise is higher than typical orthogonal fluxgates (95 nT/√Hz at 1 Hz). One of the problems of such configuration is that the planar coils cannot properly pick-up the flux as a concentric coil. Clearly, further investigation is necessary to understand whether a different configuration of the coil can significantly increase the sensitivity and then reduce the noise.

5. Multi-wire core

One of the main drawbacks of orthogonal fluxgates based on magnetic wires is low sensitivity, mainly due to cross-sectional areas lower than traditional parallel fluxgates or orthogonal fluxgates based on bulk tubular cores.

In order to increase the sensitivity, multi-core sensors have been proposed wherein the core is composed of multiple magnetic wires closely packed, each of them excited by a current with equal amplitude and frequency. The wires are also not electrically in contact along their length. In case of amorphous wires, a thin glass coating (typically 2 μm) provides insulation between them. For composite Cu/Py wires a small nm layer of epoxy is added to the surface of the wire to assure insulation.

In (Li et al., 2006a) the sensitivity of a multi-wire core fluxgate with tuned output was measured for cores with a different number of wires and it was found to increase exponentially; for instance, a 16 wire core has sensitivity 65 times higher than the sensitivity of a single wire. Later on it was demonstrated (Li et al., 2006b) that such growth of sensitivity was not simply caused by the increase of ferromagnetic material composing the core. Let us consider a sensor having a single wire core and a sensor based on a two-wire core whose total cross-sectional area is comparable to the area of a single wire. In such a case, the sensitivity is higher for the two-wire core despite the cross sectional area being similar to the single sire core. It is shown that the increment of the sensitivity becomes linear if the wires are kept far enough (5 time the diameter). This suggests the cause of the exponential increment of sensitivity for multi-wire cores is the magnetic interaction between the wires.

An increment of sensitivity is, however, useless if the noise also increases. Further investigation (Jie et al., 2009) has proven that orthogonal fluxgates with a multi-wire core do not only have higher sensitivity but also lower noise. It is interesting to note that the noise is lowest for configurations where the wires are arranged in the most compact way, because the mutual interaction between the wires is stronger the closer they are. Therefore, multi-wire cores are convenient both in terms of sensitivity and in terms of noise.

Later (Ripka et al., 2009) suggested that the exponential increment of the sensitivity to the number of wires is due to the improvement of the quality factor of the tuning circuit. This was then confirmed in (Ripka et al., 2010) where the anomalous increase of sensitivity is explained to be due to changes of parametric amplification caused by changes in the quality factor of the tuning circuit.

The total cross-sectional area is clearly higher for multi-core fluxgates and, therefore, the spatial resolution is worse than the single wire core. However, we should consider that the sensitivity increases exponentially, meaning that the sensitivity per unit of area is higher in multi-wire cores. In any case, if we consider a 16 wire core, the spatial resolution decreases by a factor of ~4, depending on the geometry of the configuration. This is still one order of magnitude better than sensors based on bulk cores.

Another advantage of a multi-wire core is the mutual compensation of spurious voltages if wires are connected in an anti-serial configuration. As an example, two-wire core has 0.34 nT/√Hz noise at 1 Hz.

Finally, we must be careful about the interaction that may occur between the wires if closely packed. This might cause hysteresis in the response of the sensor for low field measurements (Ripka et al., 2010).

6. Fundamental mode

Orthogonal fluxgates have been ignored in the past because they have higher noise than parallel fluxgates. This, in fact, moved the mainstream of research to focus on parallel fluxgates, since noise is one of the most important parameters for high precision magnetometers (other parameters such as linearity or sensitivity can be compensated to a large extent by proper design of electronics or sensors). Despite the fact that orthogonal fluxgates have recently gained new popularity due to their high spatial resolution and simple structure, their noise is still an issue for these kinds of sensors. Micro fluxgates are reported to have noise around units of nT/√Hz at 1 Hz, while wire core orthogonal fluxgates typically have 100÷400 pT/√Hz noise at 1 Hz. Without substantial reduction of noise, orthogonal fluxgates cannot be considered competitive to parallel fluxgates.

An important step forward in the field of noise reduction in orthogonal fluxgates was made by Sasada, who proposed to operate the sensor in fundamental mode rather than in second harmonic mode (Sasada, 2002a).

6.1 Working mechanism

The structure of the sensor is identical to the wire-core orthogonal fluxgate; however a dc bias is added to the excitation current. The output voltage induced in the pick-up coil in this case will be at a fundamental frequency.

In order to understand the working mechanism underlying fundamental orthogonal fluxgates we can refer to Fig. 9. Since a dc bias is added to the excitation current, the resulting excitation field in the circumferential direction turns out to be as follows:

$$H\phi = H_{dc} + H_{ac} \sin(2 \cdot \pi \cdot f \cdot t)$$

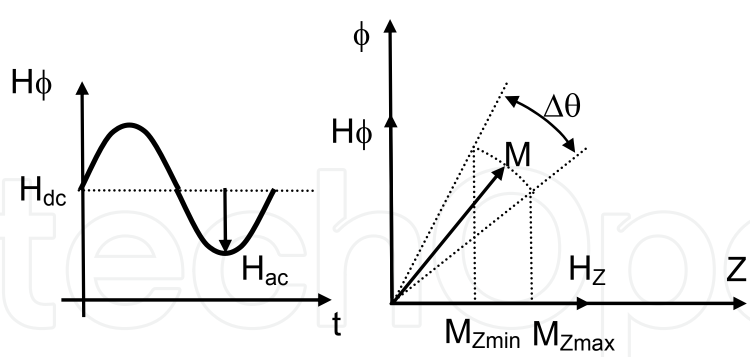

Fig. 9. Schematic diagram of the working mechanism of orthogonal fluxgate operated in fundamental mode.

The dc bias must be large enough to make the excitation field unipolar. As a result, magnetization won't reverse its polarity, as for a symmetrical bipolar excitation current with no dc bias. The magnetization M will oscillate between ±Δθ/2 in order to always satisfy the minimum energy condition, taking into account the field energy of Hϕ and H_Z as well as anisotropy energy. In traditional fluxgates without the dc bias, the magnetization is reversed from positive to negative saturation and vice versa each period, thus the output voltage contains mainly a second harmonic. On the contrary, in the fundamental mode orthogonal fluxgate the dc bias does not allow the magnetization to reverse polarity but only to oscillate with the same frequency f of $H\phi$. Therefore, the output voltage induced in the pick-up coil by time varying M_Z (component of M in Z direction) will be sinusoidal at a fundamental frequency.

At this point, we should point out that this sensor must be, after due consideration, classified as a fluxgate sensor, despite some similarities with other sensors. The magnetic flux within the core is indeed still gated; the sensor works at best, returning a linear and a bipolar response when the excitation field is large enough to deeply saturate the core, as typically found in fluxgates. The only difference between traditional fluxgates without dc bias and fundamental mode orthogonal fluxgates is that the flux is gated only in one polarity rather than in both polarities.

6.2 Offset

So far we have not discussed the effect of anisotropy on the output voltage. The anisotropy contributes to determine the position of magnetization. For instance, if $H_Z=0$ the resulting M_Z is null only if $\alpha=\pi/2$ (i.e. if anisotropy is circumferential). Contrarily, if the anisotropy is non circumferential (i.e. $\alpha<\pi/2$, as in Fig. 10) then M_Z will be non-zero even for $H_Z=0$ and M will lie between $H\phi$ and K_u ($\alpha<\theta<\pi/2$). As a result, the output voltage due to time variation of M_Z will be non-zero despite $H_Z=0$. This means that the sensor's response will show an offset anytime the anisotropy is not circumferential.

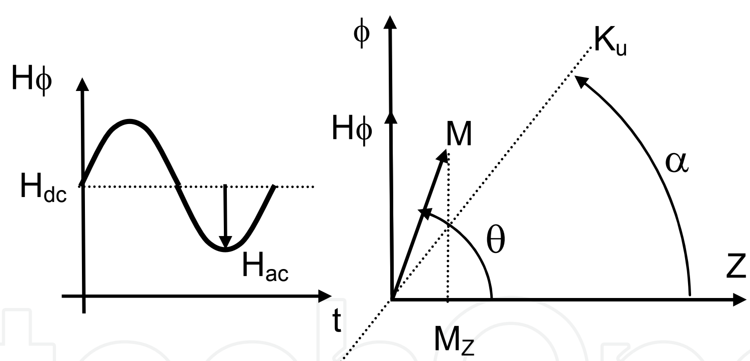

Fig. 10. Non-circumferential anisotropy in a magnetic wire used as core for fundamental mode orthogonal fluxgates.

Unfortunately, non-circumferential components of anisotropy are typically found both in amorphous wires and composite Cu/Py wires. The output offset is therefore always expected in fundamental mode orthogonal fluxgates. In order to suppress the offset, a technique is proposed in (Sasada, 2002b). Sasada's method is based on the fact that the sign of the characteristic is reversed if the dc bias becomes negative, while the offset is unchanged. For $H_Z=0$ the magnetization M will oscillate around θ_0' for positive dc bias and around θ_0'' for negative dc bias (Fig. 11). The projection of M on the Z axis will be identical because $\theta_0''=\theta_0'+\pi$ and H_{ac} makes M rotate in the opposite direction according to the bias sign.

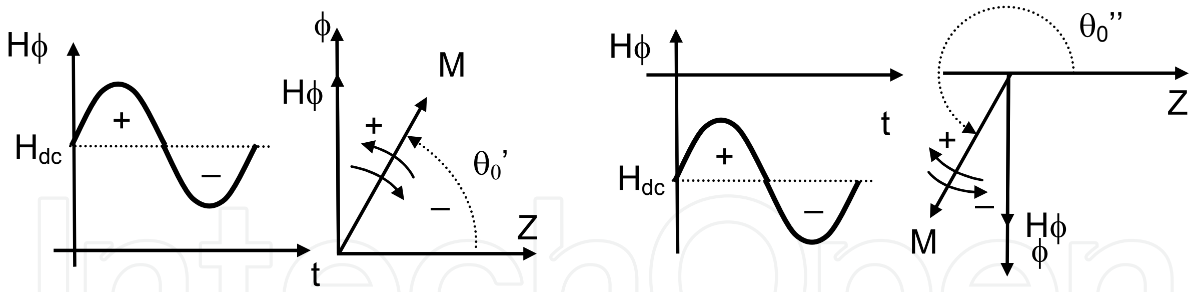

Fig. 11. Diagram of fundamental mode orthogonal fluxgates with positive and negative dc bias. The signal sensitivity is inverted changing the sign of dc bias but the offset is unchanged.

In order to suppress the offset we can periodically invert the dc bias and subtract the signals obtained with the positive and the negative bias. Since the sensitivity is reversed, by subtracting the characteristics we sum up the signals whereas the offset is cancelled given the fact that its sign is unchanged for both the positive and the negative bias.

The bias can be switched at a frequency much lower than the excitation frequency. For example, (Sasada, 2002b) suggests to invert the sign every 25 periods of excitation current. In this way we can reduce the effect of sudden transition from a saturation state to an opposite saturation state which could negatively affect the output noise of the sensor. To avoid the effect of bias switching on the noise we can exclude the period right before and after the transition. This can be easily done digitally (Weiss et al., 2010) or analogously using a fast solid state switch before the final low pass filter (Kubik et al., 2007).

It must be noted that all the proposed techniques require significant modification of the electronics both on the excitation side as well as on the signal conditioning circuit. While this slight complication in the electronics can be bearable for many magnetometers, it could be a non-negligible problem for applications such as portable devices.

6.3 Noise

Orthogonal fluxgates in fundamental mode became very popular thanks to the fact that they have less noise than traditional orthogonal fluxgates. This is due to their operative mode, rather than the sensor itself. In (Paperno, 2004) it is demonstrated how the very same fluxgate (120 μm diameter Co-based amorphous wire surrounded by 400 turn pick-up coil) has 1 nT/√Hz noise at 1 Hz if operated in the second harmonic mode whereas the noise is reduced to 20 pT/√Hz when the fundamental mode is used. In this case, the fundamental mode contributes to reduce the noise by a factor of 50, obtained using the same sensor.

A similar result was obtained in (Paperno et al., 2008) for a fluxgate based on a tubular core manufactured with a 5 cm wide amorphous ribbon wrapped with 8 mm of outer diameter. In this case, both the excitation and pick-up coils are added to the core. When this sensor is operated in a fundamental mode, the noise results as being 10 pT/√Hz at 1 Hz, or 30 times lower than the value obtained in the second harmonic mode.

Therefore, noise reduction given by the fundamental mode can be generalized as it applies to all kinds of orthogonal fluxgates, based on the wire core as well as on bulk tubular core.

This can be easily seen when analyzing the source of the noise. Typically, the noise of fluxgate sensors originates in the magnetic core. The reversal of magnetization from positive to negative saturation (and vice versa) involves domain wall movement, which is the origin of the Barkhausen noise. Since a pick-up coil detects time-variation of flux within the core, the Barkhausen noise will cause noise in the output voltage of the pick-up coil. Therefore, designers of fluxgates have chosen materials for the core, which are not only very easy to saturate but also present very smooth transitions between opposite saturation states.

This source of noise is dramatically reduced when a dc bias is added to the excitation current. If the bias is large enough to keep the core saturated for the whole period of the ac current I_{ac}, then the magnetization is only rotated by I_{ac} (Fig. 9) and no domain wall movement occurs.

Sensitivity, however, should also be considered when calculating the output noise in magnetic units. A higher dc bias I_{dc} can significantly reduce sensitivity, because it increases the angle θ of magnetization M resulting in a lower projection of M on the longitudinal axis (i.e. the magnetic flux in the longitudinal direction is sensed by the pick-up coil). On the contrary, the sensitivity monotonically increases with the ac excitation current I_{ac} (Butta et al., 2011) and therefore an increment of I_{ac} can be useful to reduce the total noise even if a larger I_{ac} could bring the core out of saturation.

The lowest noise of an orthogonal fluxgate in fundamental mode is then obtained selecting a pair of parameters I_{ac} and I_{dc} such that the sensitivity is large enough to minimize the noise but with the minimum value of the total current not too low, so as to avoid significant domain wall movement in the core. The optimum condition for noise reduction is obtained right before minor loops appear in the circumferential BH loop (Butta et al., 2011). Noise as low as 7 pT/√Hz at 1 Hz was obtained by optimizing excitation parameters, using the magnetometer structure proposed in (Sasada & Kashima, 2009).

The noise can be further reduced to 5 pT/√Hz at 1 Hz by using three-wire cores instead of a single wire, in order to increase the sensitivity.

7. Coil-less fluxgates

As previously mentioned, orthogonal fluxgates based on microwires gained popularity due to the absence of the excitation coil, which help to simplify the manufacturing process. To this extent, the wire-core needs only a pick-up coil, which can be easily wound around it with an automatic procedure. However, the presence of a coil, even if it is simply a pick-up coil, can make the sensor unsuitable for applications where high miniaturization is required. A possible solution to this problem is to use planar coils manufactured on a substrate under the fluxgate core as in (Zorlu et al., 2006) although this solution has a more complicated structure, which needs an extra step in the manufacturing process. It would be better to have a fluxgate without any pick-up coil at all. This can be achieved with coil-less fluxgates (Butta et al., 2008a).

7.1 Structure of the sensor

In a coil-less fluxgate, torsion is applied to a composite microwire with a copper core covered by a ferromagnetic layer, while an ac excitation current flows through the wire (Fig.

12). If the excitation current is large enough to saturate the magnetic layer in both polarities and a magnetic field is applied in the axial direction, then even harmonics will arise in the voltage across the terminations of the wire. It was found that a second harmonic is proportional to the magnetic field applied in the axial direction; therefore this structure can be used as a magnetic sensor. Since the output voltage is obtained directly at the terminations of the wire no pick-up coil is required.

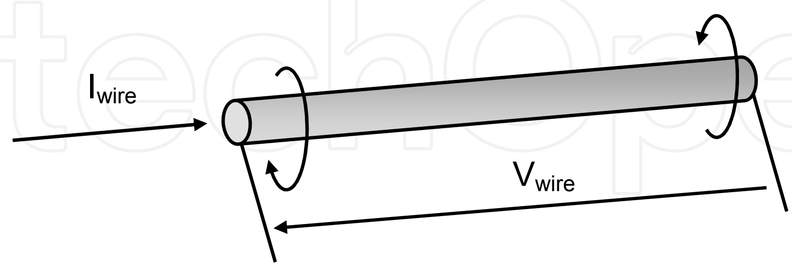

Fig. 12. Coil-less orthogonal fluxgate. The magnetic wire is twisted and the output is obtained at the wire's terminations.

It should be noted that this sensor must be classified, after due consideration, as an orthogonal fluxgate, even if the structure could recall that of magneto impedance (MI) sensors. Indeed, the sensor returns an output signal with linear characteristic only if full saturation of the wires is achieved in both polarities; if saturation is lost the signal vanishes. Moreover, the operative frequency for a coil-less fluxgate is around 10 kHz, whereas MI sensors are operated at MHz range. This means that the physical phenomena occurring within the wire are substantially different. In other words, MI sensors are mainly based on variation of skin effect in the magnetic wire due to a change of permeability caused by the external field (Knobel et al., 2003) whereas in coil-less fluxgates the external field causes linear shifting of a circumferential BH loop, giving rise to even harmonics. The difference between sensors becomes evident when considering their output characteristics. Coil-less fluxgates, have a second harmonic, which linearly depends on the external field with anti-symmetrical characteristic. This allows one to discriminate between positive and negative fields. MI sensors have, on the other hand, impedance, which shows a non-linear symmetric characteristic. In order to be used in a magnetometer, MI sensors must be biased with a dc field (Malatek et al., 2005), so that the working point will move in the descendent branch of the characteristic (the output, however, will only be approximate to a linear function).

7.2 Working mechanism

In (Butta et al., 2008a) it is shown how the sensitivity of a coil-less fluxgate depends on the twisting angle applied to the magnetic wire and how the sensitivity becomes negative if the wire was twisted in the opposite direction. No output signal was instead recorded for no twisting applied to the wire. Therefore, it was assumed that the working mechanism of the coil-less fluxgate took place due to helical anisotropy induced into the magnetic wire by mechanical twisting. This was later confirmed by observing coil-less fluxgate effect also on magnetic wires manufactured with built-in helical anisotropy. In (Butta et al., 2010b) a Permalloy layer is electroplated under the effect of a helical field, obtained as a combination of a longitudinal field imposed with a Helmholtz coil and a circular field generated by a dc current flowing in the wire. In (Atalay et al, 2011; Butta et al., 2010c; Kraus et. al, 2010) helical anisotropy is induced in the wire electroplating the Permalloy under torsion and releasing it at the end of the manufacturing process. The back-stress after such release is responsible for helical anisotropy.

In (Butta & Ripka, 2009b) a model for the working mechanism of the coil-less fluxgate is proposed, based on the effect of helical anisotropy on the magnetization of the magnetic wire, during the saturation process determined by the excitation current.Fig. 13 shows the circumferential BH loop (Ripka et al., 2008) of the magnetic wire with +80 μT, - 80 μT, and 0 μT of the external field applied to the axial direction.

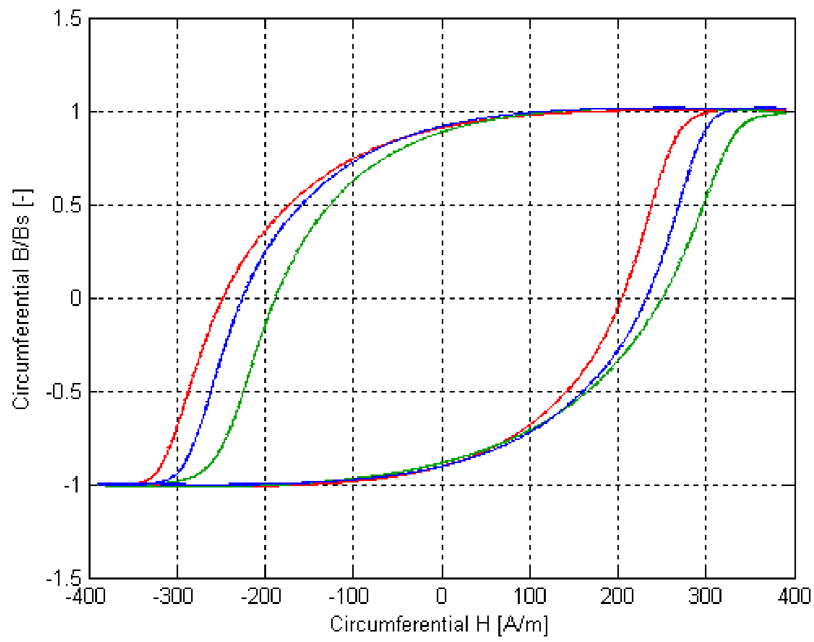

Fig. 13. Circumferential BH of a magnetic wire with applied torsion for 0 μT and ±80 μT field applied in the axial direction. The loop is shifted by the external field.

The circumferential flux is obtained by the integration of the inductive part of the voltage across the wire's terminations V_{wire}. In turn, the inductive component of V_{wire} is obtained subtracting the resistive part of the voltage calculated as $R_{wire} \cdot I_{wire}$. The voltage measured on the terminations V_{wire} will then be the derivative of the circumferential flux; when the magnetization is reversed from positive to negative saturation and vice versa, the voltage peaks appear in V_{wire} in addition to the resistive voltage drop.

Let us consider a microwire with helical anisotropy as shown in Fig. 14, where γ is the angle axis of easy magnetization in regards to the axial direction of the wire Z. As observed in cases of traditional fluxgates, the magnetization is rotated by the excitation field Hϕ, which periodically saturates the wire in the opposite direction. However, the mechanism is now rotated by an angle γ. Therefore, the field responsible for the rotation of M is now the component of Hϕ perpendicular to the easy axis of magnetization, namely Hϕ⊥. The dc axial field also has a component on the perpendicular axis, H_Z⊥, which acts as a dc offset to the ac Hϕ⊥. This implies that the periodical process of saturation caused by the excitation field is shifted by the axial field through its component H_Z⊥. If we observe the circumferential BH loop using Hϕ as a reference, then we observe a shift of the loop under the effect of the axial field as shown in Fig. 13. The sensitivity of the sensor increases together with the increasing anisotropy angle γ because the higher is γ the larger is $H_Z\perp$.

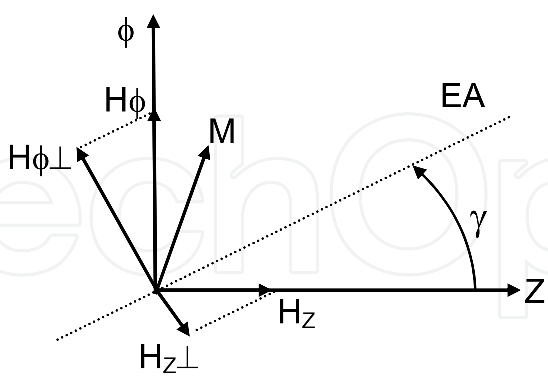

Fig. 14. Working mechanism of coil-less fluxgates.

7.3 Sensitivity

The sensitivity of coil-less fluxgates strongly depends on the amplitude of the excitation current. However, while the sensitivity of traditional fluxgates increases if we use a bigger current, the sensitivity of coil-less fluxgates decreases. This means that the higher the excitation current is, the lower the sensitivity will result (Fig. 15). This can be clearly explained by considering the model of the sensor. By increasing the excitation current, the field energy associated to the circular magnetic field will also increase, causing the magnetization M to be tied more strongly to the excitation field in a circular direction, while the effect of anisotropy energy on the total energy of M will become progressively negligible.

By observing Fig. 15 one might think that the best working condition for coil-less fluxgates is obtained with an excitation current about 42÷43 mA, where the sensitivity is at its maximum. However, the excitation current must be high enough to fully saturate the wire, in order to lower the noise as well as to assure a wider linear range. Since an external field shifts the circumferential BH loop of the magnetic wire (Fig.13), the sensor will keep working regularly as long as the measured field is not too large to move one end of the BH loop out of saturation. If that were to happen, the linearity of the sensor would be lost. Therefore, it is recommended to keep the sensor working at a higher excitation current than the minimum current required to achieve saturation, although still not high enough to avoid significant loss of sensitivity.

Compared to traditional fluxgates a coil-less fluxgate has generally lower sensitivity. This is due to the fact that we pick up the circumferential flux with a virtual one-turn coil. While fluxgates with a pick-up coil can simply multiply the sensitivity by using a large number of turns, this is not possible for coil-less fluxgates.

Typical sensitivity for coil-less fluxgates based on a composite Cu-Permalloy wire is about 10 V/T. This value is significantly higher if a Co-based wire is used. In (Atalay et al., 2010) it is reported that a coil-less fluxgate obtained with a Co rich amorphous wire after 15 minutes joule annealing, which reaches sensitivity at about 400 V/T at 30 kHz. In (Atalay et. al, 2011) a coil-less fluxgate based on a composite copper wire with $Co_{19}Ni_{49.6}Fe_{31.4}$ electroplated shell is proposed. The sensitivity in this case is about 120 V/T at 20 kHz. Further research on different materials will show if even higher sensitivity will be achievable with other alloys.

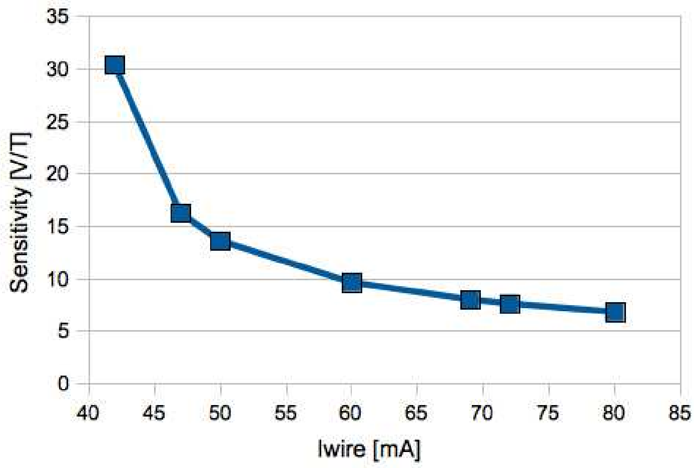

Fig. 15. Output characteristic of coil-less fluxgates for different amplitudes of excitation current I_{wire}. The higher I_{wire} becomes, the lower the sensitivity of the sensor will be.

Sensitivity can be also increased with higher angles of helical anisotropy but we should keep in mind that saturation current also increases, and this will require a higher excitation current.

A drawback of coil-less fluxgates is that low sensitivity cannot be increased by using high gain amplification because the output voltage of the sensor includes large spurious voltage. This component of the voltage does not include a signal but contributes to enlarge its peak value, limiting the maximum amplification. The resistive part of the spurious voltage, due to the voltage drop on the wire's resistance can be easily removed by a classical resistive bridge. However, the inductive component of the voltage, given by the transition of the magnetization from one saturated state to the opposite, will be always present in the output. As previously explained, these peaks will be shifted by the external field to opposite directions, but they will continue to be present in the output. A technique proposed by (Butta et al., 2010a) is presented to remove the inductive peaks and obtain an output voltage that is null for no applied field and whose amplitude increases proportionally to it. The method is based on a double bridge with two sensing elements fed by current in opposite directions. In the output voltage, the positive peaks of the first wire will be compensated by the negative peaks of the second wire and vice versa. The sensitivity of the two wires must clearly point to opposite directions so that the sum of the voltage obtained with the opposite current will be the sum of the two signals rather than their difference.

7.4 Linearity

A common technique used to improve linearity of magnetic sensors is to operate them in a closed loop mode, by generating a compensation field, which nullifies the measured field (Ripka, 2001). The pick-up coil is usually used for this purpose, because the compensating field must be generated at a low frequency, several orders of magnitude lower than the excitation frequency. Using the feedback mode, the working point of the sensor will always be around zero magnetic field and the output characteristic will be determined by the linear characteristic of the coil.

This method, however, cannot be used for coil-less fluxgates, since it has not a pick-up coil available for the generation of a compensating field (and if we add a compensation coil the sensor would not be coil-less anymore).

Therefore, the linearity of the coil-less fluxgate is an extremely important parameter, because the sensor will be used in an open loop mode. Fortunately, the coil-less fluxgate has a large linear range. In (Butta et al., 2010c) it is shown that a coil-less fluxgate with ±0.5% of full-scale non-linearity error in a ±50 μT measurement range. The non-linearity error is reduced to ±0.2% of full scale if we consider a ± 40 μT range. These values are comparable to the non-linearity of non-compensated parallel fluxgates (Kubik et al., 2009; Janosek & Ripka, 2009).

The high linearity of coil-less fluxgates comes from the working mechanism of the sensor, which is simply based on linear shifts of the circumferential BH loop. Non-linearity might be due to the non-uniformity of the helical anisotropy angle along its length. Further improvements of the manufacturing process can help make the anisotropy more uniform and improve the linearity of the sensor.

7.5 Noise

The noise of a coil-less fluxgate is rather high. For instance, in (Butta et al., 2010c) a coil-less fluxgate is presented which shows 3 nT/√Hz at 1Hz noise. This is much higher than the noise of other orthogonal fluxgates, operated in a fundamental mode, mainly because of low sensitivity. The noise of coil-less fluxgates manufactured with Co-base magnetic wires, which have larger sensitivity, has still not been reported. It can be expected that further improvements of the sensitivity of coil-less fluxgates will contribute to decrease the noise.

8. Comparison

It is important to understand both the advantages and disadvantages of orthogonal fluxgates when we have to select a magnetic sensor for a specific application. Depending on the particular requirements of the measurement system, the best solution can be a parallel or an orthogonal fluxgate. Here we give a list of both advantages and disadvantages of orthogonal fluxgates in order to help the user in choosing the best sensor for his/her purposes.

Advantages of orthogonal fluxgates

- high spatial resolution, limited by the wire diameter (usually around 100 μm);
- lack of excitation coil, which implies a smaller structure;
- easy to manufacture;
- low excitation current (many wires require a few tens of mA to be saturated, whereas parallel fluxgate cores are often saturated with several hundreds of mA).

Disadvantages of orthogonal fluxgates

- higher noise than parallel fluxgates;
- lower sensitivity due to small cross-sectional areas of the wire-core (this can be increased by using a multi-wire core to the expense of the spatial resolution);

- the excitation current flowing directly to the wire-core generates power dissipation within the wire; this can increase the temperature of the wire causing dilatation and finally mechanical stress, which is a typical source of noise.

The following table summarizes several orthogonal fluxgates reported in the literature with their features and obtained performance. The proper choice for structure and operative parameters of orthogonal fluxgates can be made based on the application requirements and available performances summarized here.

	Sasada. 2009	Zorlu, 2007	Paperno, 2004	Fan, 2006	Li, 2006	Goleman, 2007
Principle	Fundamenta l mode	Second harmonic	Fundamental mode	2^{nd} harmonic (tuned)	2^{nd} harmonic (tuned)	Fundamenta l mode
Configuration	U-shaped amorphous wire	Planar Cu/Permallo y structure	Amorphous wire	Cu/Permall oy Wire	16 glass coated amorphous wires	U-shaped amorphous wire
Length	40 mm (20 mm sensitive length)	1 mm	20 mm	9 mm	18 mm	28 mm
Diameter	120 µm	16 µm x 10 µm (squared)	120 µm	20 µm	16 µm	125 µm
N. of turns pick-up coil	2 coils x1000 turns	2 planar coils x60 turns	400	1000	1000	250
Excitation Current	8mA ac + 47 mA dc	100 mA peak sinusoidal	40 mA ac + 40mA dc	10 mA rms sinusoidal	6 mA rms sinusoidal (each wire	4 mA ac + 20 mA dc
Frequency excitation	118 kHz	100 kHz	40 kHz	500 kHz	188 kHz	100 kHz
Sensitivity	350,000 V/T (gain 47)	0.51 V/T		20,000 V/T	850,000 V/T	1,600 V/T
Offset	-0.33V				48.2 mV	
Linear range	±25 µT	±100 µT				
Noise PSD @ 1 Hz	10 pT/√Hz	95 nT/√Hz				0.11 nT√Hz at 10 Hz
Resolution		215 nT	100 pT			
Power consumption		8.1 mW		100 mW		

Table 1. Comparison of several types of orthogonal fluxgates

9. Future development

During this last decade, the research has been focused mainly on issues regarding orthogonal fluxgates, like noise reduction, increment of sensitivity, and simplification of the sensors' configuration and development of wires with new structures.

These efforts strongly improved the performances of orthogonal fluxgates, making this sensor competitive in the field of magnetic measurement at room temperature.

However, even if sensors like orthogonal fluxgates in a fundamental mode already achieved noise levels similar to cheap parallel fluxgates, other issues have to be faced.

Currently, we still do not have extensive information about the long-term offset stability of orthogonal fluxgates as well as the temperature dependence of both offset and sensitivity, which are critical points for many magnetometers.

Another important field, which has to be investigated, is the dependence of the orthogonal fluxgate's performance on the geometrical dimensions of the core. So far, different structures have been proposed, but a comprehensive study that explains the effect of different core sizes on sensitivity and noise has yet to be reported. In particular, the effects of the demagnetization factor have not been properly investigated, mainly due to the fact that the excitation field is applied to a circumferential direction facing a toroidal shape, which is not affected by the demagnetizing effect. Nevertheless, a measured field is applied in the axial direction over a finite length specimen so that the internal field distribution will be affected by the demagnetizing effect. This applies especially to multi-core orthogonal fluxgates. Indeed, when operated out of resonance, the output sensitivity will strongly depend on the distance between the wires, because it affects the demagnetization factor. A detailed study on the core's size dependence of orthogonal fluxgates' parameters will be also useful to optimize the geometry of micro-fluxgates, where the small dimension strongly affects the achieved sensitivity and noise.

Finally, further steps should be made towards developing manufacturing techniques for the production of magnetic wires to be used as the core of orthogonal fluxgates, as a means of assuring mass production of cores with very similar parameters. Such efforts are an important requirement for the industrialization of this type of sensor.

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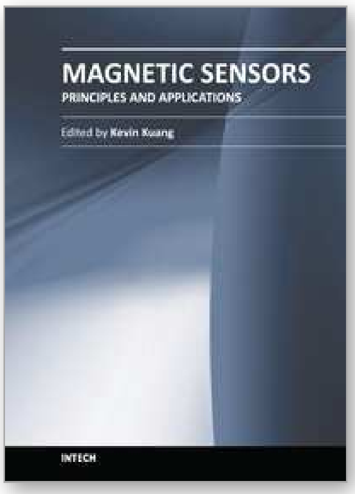

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This book provides an introductory overview of the research done in recent years in the area of magnetic sensors. The topics presented in this book range from fundamental theories and properties of magnets and their sensing applications in areas such as biomedicine, microelectromechanical systems, nano-satellites and pedestrian tracking. Written for the readers who wished to obtain a basic understanding of the research area as well as to explore other potential areas of applications for magnetic sensors, this book presents exciting developments in the field in a highly readable manner.