Fluxgate effect in twisted magnetic wire

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Abstract

In this paper a novel kind of fluxgate is presented. The sensor is based on helical anisotropy of the ferromagnetic layer, electrodeposited on copper wire. The saturating field is provided by current flowing in the wire, and the output voltage is measured directly at the terminations of the wire. Therefore no coils are necessary, making possible high miniaturization of the sensor. The effect has been tested twisting the wire: the second harmonic is shown to be strongly dependent on the applied torsion. Consideration on the practical use of the sensors are finally presented.

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1.Introduction

Fluxgates are the most precise vectorial magnetic field sensors. They are used when field resolution better than 1 nT is required and/or in systems which require high precision. Linearity as high as units of ppm is necessary, if the magnetometer is used to detect small disturbances in large background DC magnetic field.

The basic principle of fluxgate sensor is unchanged from 1930’s. The excitation field should bring the whole sensor core volume into deep saturation. Only then the sensor output is stable without remanence (also called perming effect) \cite{1}. This makes fluxgates preferable to other sensors such as GMI, which do not saturate the ferromagnetic core. The hysteresis curve of fluxgate sensor and the excitation waveform (usually squarewave voltage) should be very symmetrical – then in zero measured field the output voltage contains only odd harmonics. The measured DC field causes non-symmetry of the magnetization and creates even harmonics. The amplitude of the 2nd harmonic voltage for required 100 pT resolution is typically 160 dB below the voltage at the 1st harmonics. This makes unacceptable requirements on the dynamic reserve of the electronics. There are two ways how to suppress the large unwanted signal geometrically: either to use double-core sensors or make the excitation perpendicular to the sensing coil.

The orthogonal fluxgate usually works at 2nd harmonics. A “fundamental-mode orthogonal fluxgate” \cite{2,3} should use large dc current bias, which makes the sensor unpractical.

For practical applications which require highest miniaturization the main disadvantage of fluxgate sensors is the presence of coils. A first step to simplify the structure was done with orthogonal type fluxgate: the excitation current can flow through the core, so that no excitation coil is required. Unfortunately a pick-up coil is still necessary for the detection of the second harmonic component of the core flux.

In this paper we present a novel type of fluxgate which does not require any coil, making its practical application much easier.

The core used for this coil-less fluxgate is a copper wire covered by a layer of magnetic alloy, which has been already used for conventional orthogonal fluxgate \cite{4}. We found that a second harmonic component of the voltage between the terminals of the wire depends on the axial magnetic field. Using this voltage as an output, the fluxgate needs no coil at all.

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By a series of measurements with two types of twisted wires we show that this new effect is caused by helical anisotropy. The conditions necessary for the proper operation of the sensor and a feasibility of practical applications are discussed.

2. Sensor structure

The first sensor is composed by a 50 µm diameter copper wire covered by a layer of electrodeposited ferromagnetic material. The wires have been produced by S. Atalay and F.E. Atalay, and it has been fully characterized in [5]. The ferromagnetic layer is 10 µm thick polycrystalline Co_{18.97}Ni_{49.60}Fe_{31.43}. The total length of the wire is 3.8 cm. During characterization of the sensor we observed unsymmetrical circular hysteresis curves in the presence of DC axial field (Fig. 1). This was indication of a strong off-diagonal component of the permeability tensor [6].

One of the possible sources of this component is helical stress-induced anisotropy. In order to examine the effect, we intentionally twisted the wire in both directions. The wire has been soldered at the ends to a twisting device which allowed us to apply a twisting angle to the wire. One of the two terminations of the twisting device was mounted on a sleight: in this way we could adjust the distance between the termination to fit the wire length. The wire was suspended and was in contact only to the termination of the twisting device, therefore the only mechanical stress applied on the wire was the torque produced by the twisting device at its terminations.

We injected an alternating current \( I_{\text{wire}} (f = 30 \text{ kHz}) \) into the wire and we measured the voltage \( U_{\text{wire}} \) between its terminations, while applying a twisting torque (Fig. 2).

The current \( I_{\text{wire}} \) saturates the ferromagnetic layer in circular direction. \( I_{\text{wire}} \) is provided by a sinewave generator whose internal resistance was 50 Ω, approximately 100 times bigger than the wire’s impedance. Therefore the waveform generator acted as a sinewave current source.

Fig. 3 shows the dependence of the 2\text{nd} harmonic of \( U_{\text{wire}} \), measured by the a SR 760 DSP lock-in amplifier, on the external field \( B_{\text{ext}} \) applied by the Helmholtz coil.

The dependence shows a wide linear part in the range between -100 µT to 100 µT, making the sensor suitable for measurement of magnetic field in that range.

Fig. 2 – Structure of the sensor.

Fig. 3 – 2\text{nd} harmonic of \( U_{\text{wire}} \) [V] vs. external magnetic field \( B_{\text{ext}} \) [µT], \( I_{\text{wire}}=55 \text{ mA}, 30\text{kHz}, \text{twisting angle 30}^\circ \).

We can therefore define a new kind of orthogonal fluxgate: in this sensor the 2\text{nd} harmonic, proportional to external magnetic field, is not extracted from the voltage
induced in the pick-up coil, but directly from the voltage $U_{wire}$ measured at the terminations of the wire. We will call this novel kind of sensor coil-less fluxgate.

The sensitivity of the coil-less fluxgate has been measured for several values of current $I_{wire}$, while changing the twisting angle. The resulting relation between the sensitivity and the twisting angle is shown in Fig. 4.

![Fig. 4 - Sensitivity of the coil-less fluxgate vs. twisting angle, $I_{wire}=55\text{mA}$, 30 kHz.](image)

It is clear that the 2$^{nd}$ harmonic in $U_{wire}$ is due to the twisting torque applied to the wire. An experiment has been realized, measuring the 2$^{nd}$ harmonic response for both positive and negative twisting angles, without changing the reference phase of the lock-in amplifier. It has been clearly observed that inverting the direction of the twisting angle makes also the 2$^{nd}$ harmonic response changing sign: for negative angles we obtained 2$^{nd}$ harmonic dependence on $B_{ext}$ with negative slope (Fig. 5). This result suggests that the 2$^{nd}$ harmonic in $U_{wire}$ is caused by helical anisotropy of the ferromagnetic layer, caused by mechanical stress associated with twisting torque.

![Fig. 5 – The sensor characteristics for twisting angle of -30, 0, and + 30 deg.](image)

The saturation of the core in orthogonal direction is a necessary condition for the achievement of a linear characteristic of the coil-less fluxgate. If $I_{sat}$ is lower than the saturation current $I_{sat}$ the 2$^{nd}$ harmonic response is affected by perming effect, making the sensor useless. Therefore it is crucial to use a current amplitude higher than $I_{sat}$. It has been observed that the twisting torque influences also $I_{sat}$. Fig. 6 shows the dependence of $I_{sat}$ on the twisting angle. We can therefore derive that applying a torsion on the wire makes the coil-less fluxgate working properly, giving rise to a 2$^{nd}$ harmonic (which increases for higher twisting angle), but it has also the drawback of increasing the saturation current requirement.

![Fig. 6 – Dependence of the saturation current $I_{sat}$ on the twisting angle, $f=30\text{kHz}$.](image)

### 3. Wire with thinner layer

We performed similar measurement on the similar wire, provided by X.P. Li, whose ferromagnetic layer was much thinner, typically 2 µm. They have shown a similar behaviour: also in this case the 2$^{nd}$ harmonic increases when we apply a torsion to the wire terminations. In this case the sensitivity was ten times smaller, which is reasonable if we consider the lower thickness of the magnetic layer.

The main advantage of using electrodeposited wires with thinner ferromagnetic layer is that they require much smaller saturation current. In this case we could achieve saturation of the wire at 7-8 mA, 30 kHz, which could be acceptable for practical applications.

It has been also observed that this kind of wires with thinner ferromagnetic layer show a non-zero sensitivity even without any applied torque. In this case we can deduct that the helical anisotropy was built-in during the production of the wires. In any case twisting the wire further increases the sensitivity.

### 4. Considerations on the practical use of the sensor

It is worth to be highlighted, that the field-dependent 2$^{nd}$ harmonic is only one component of the total voltage $U_{wire}$. In order to evaluate the feasibility of 2$^{nd}$ harmonic extraction we applied a constant field $B = 125 \mu T$ to the coil-less fluxgate and we evaluated the ratio of the 2$^{nd}$ harmonic amplitude over the total voltage $U_{wire}$ peak-peak. We chose the peak-peak amplitude because we are interested in the maximum gain we can use while amplifying the signal without saturating the electronics; in this case the peak-peak value is much more significant than the RMS value,
especially taking into account that $U_{wire}$ is not sinusoidal at all (the ferromagnetic layer is saturated) – Fig. 7.

Fig. 7 – Waveforms for $B = 250 \, \mu T$: excitation current $[A]$ (upper trace), output voltage $[V]$ (lower trace). Excitation current 24 mA, 10 kHz. Twisting angle 20 deg.

In Fig. 8 we can see the dependence of the 2nd harmonic at 125 $\mu T$, in percent of $U_{wire}$ p-p on the twisting angle ($I_{wire}=55mA$, 30kHz, thicker wire). The 2nd harmonic increases while increasing the torsion, as we have shown previously. Indeed the p-p amplitude of $U_{wire}$ only slightly decreases, twisting the wire.

We can observe from Fig. 8 how we can easily achieve a signal whose 2nd harmonic is $\approx 3\%$ of peak-peak amplitude. Such a level of 2nd harmonic is not too demanding, since it can be extracted using usual techniques.

Fig. 8 – 2nd harmonic of $U_{wire}$ in % of $U_{wire}$ peak-peak, vs. twisting angle. Excitation current 55 mA, 30 kHz. $B_{ext}$ 125 $\mu T$.

Similar calculation, performed on the wire with thinner alloy layer, gave as a result a lower percentage of the 2nd harmonic in $U_{wire}$. Nevertheless, a 1% 2nd harmonic can still be achieved even with this thinner wire.

It should be noticed that the best performance can be obtained using four terminals connection for the sensing wire. The exclusion of the connection cables from the measurement of the voltage reduces the resistive component of the $U_{wire}$. This gives a lower peak-peak $U_{wire}$ amplitude while does not affect the 2nd harmonic, which only depends on the magnetic properties of the alloy layer. It should be advisable to design the next generation of coil-less fluxgate using a core whose material has the lowest possible contact resistance, in order to maximize the performance of the sensor.

We must consider that the results shown in this paper have been achieved from measurement performed twisting the wires as low as possible; typically we measured all the parameters for each position, then we changed twisting angle. After several times we twisted the wire in alternating directions, it irreversibly changed its parameters probably due to the plastic deformation and changes in its structure.

5. Conclusion

In this paper we have presented a new kind of fluxgate realized with electrodeposited ferromagnetic wires. We have proved that the second harmonic of the voltage at wire’s termination depends on the torsion applied to the wire.

The sensitivity and the linear range achieved with this sensors are good enough to consider it feasible for a wide range of practical applications. If we also consider that lack of coil makes possible high miniaturization, the development of this sensors seems to be really promising.

Next step will be the development of coil-less fluxgate with shorter wire ($\approx$ mm) and built-in helical anisotropy.

References


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