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Offset drift in orthogonal fluxgate and importance of closed-loop operation

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In this paper we show an up-to-now unexplained source of offset drift affecting the fundamental mode orthogonal fluxgate. After a sudden change or removal of the magnetic field, we observe an offset transient which lasts units to hundreds of seconds. We exclude the thermal origin of such transient as well as the electric origin in the pick-up coil resonance circuit or sensing amplifiers. We prove that this transient has magnetic origin, since it depends on both the amplitude and the duration of the pulse of magnetic field applied to the sensor which can be expressed as magnetic energy. We conclude that operating the fundamental mode orthogonal fluxgate in a closed feedback-loop is useful by suppressing this transient behaviour by keeping the core in a (almost) zero field, however when switching the magnetometer sensor on/off, this transient has to be taken into account.

I. INTRODUCTION

Orthogonal fluxgates in fundamental mode [1] have been shown since early 2000s to provide very low-noise [2–6] vectorial measurements of quasi-static magnetic fields. Magnetometers based on annealed wire core [7, 8] with precisely designed excitation and signal conditioning circuits have shown noise levels below $1 \text{ pT}/\sqrt{\text{Hz}}$ at 1 Hz and a noise floor which can reach $350 \text{ fT}/\sqrt{\text{Hz}}$. Such low noise makes it possible to measure very weak magnetic fields, such as those generated by the human heart [9, 10]. However, in all cases, these noise levels were achieved some time after the magnetometer started up, while its output has a first order transient until reaching a stable value. The same transient has been observed when the sensor is placed in magnetic shielding for noise measurements. This is not uncommon for fluxgate magnetometers, but it seems more pronounced for the orthogonal fluxgate. In this paper, we investigate the origin of such a transient, since it could lead us to a more detailed understanding of the mechanism underlying the performance of orthogonal fluxgate in fundamental mode. Moreover, since the effect is in the scale of seconds to a minute, it might give us more insight into the origin of the excess ultra-low-frequency noise of the orthogonal fluxgate in fundamental mode.

II. EXCLUDING THE THERMAL RESPONSE OF THE AMORPHOUS WIRE

For our fluxgate, we have used Co-rich amorphous wire ($[\text{Co}_{94}\text{Fe}_6]_{72.5}\text{Si}_{12.5}\text{B}_{15}$) (CoFeSiB) with $120 \mu\text{m}$ diameter. Our first reasonable assumption was based on the fact that the saturation magnetization M_S of this type of material depends on temperature. In an orthogonal fluxgate, the excitation current flows through the wire and could lead to a non-negligible increase in its temperature due to the Joule effect, leading to a drop in saturation magnetization M_S . If we consider the working principle of the orthogonal fluxgate in fundamental mode [11], we find that the voltage is proportional to the derivative of the projection of saturation magnetization M_S on the axis of the wire core; thus:

$$v_{out} = -N \cdot \frac{\partial \phi_Z}{\partial t} = -N \cdot \frac{\partial}{\partial t} S_w \mu_0 M_S \sin \left(\text{atan} \left(\frac{H_Z}{H_{exc}} \right) \right). \quad (1)$$

where N is the number of turns of the pick-up coil, S_w is the axial cross-section of the wire at the active part of the wire core where the fluxgate mechanism occurs, M_S is the saturation magnetization, H_Z is the axial field, and H_{exc} is the circumferential field generated by the excitation current.

As the temperature changes, either because of the Joule effect of the wire's excitation current or because the sensor is moved to another location (e.g., shielding) with a different temperature, we can expect a change in the output of the magnetometer because of temperature-dependent M_S . To investigate this hypothesis, we must first analyze the dependence of M_S on temperature. To do so, we measured the amorphous wire's circumferential hysteresis loop at 1 kHz in an oven wherein the temperature was monitored by a Pt100 sensor. The hysteresis loop was obtained by averaging the loop for 20 seconds. The wire reached saturation state for a current as low as 40 mA . We measured the hysteresis loop both while the temperature rose from 27°C to 62°C and while it fell, which took place over a much longer time period (about 6 hours). This length of measurement is necessary to homogenize the temperature in the oven and minimize the temperature gradient between the Pt100 sensor and the amorphous wire. The temperature should also not significantly change while the hysteresis loop is averaged for 20 seconds; indeed, the fastest rate temperature of change was 0.08°C in 20 seconds, which was sufficiently low.

Fig. 1 shows the dependence of the saturation flux Φ_S (which is proportional to the saturation magnetization M_S by a geometrical factor) on the temperature for both the warming and the cooling process. We can observe a small hysteresis, probably due to the fact that the warming curve is faster.

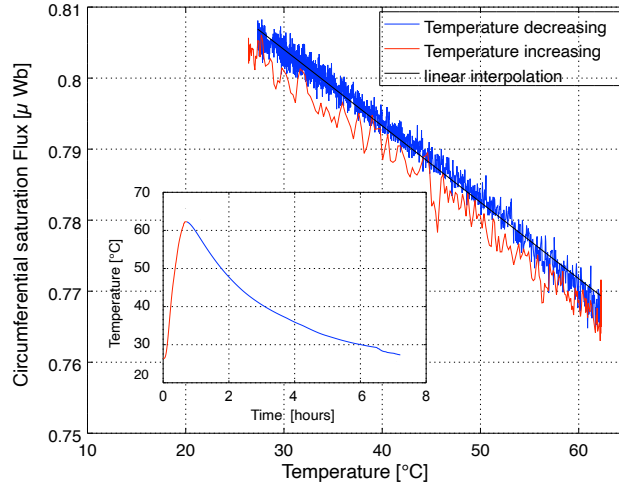


FIG. 1. Dependence of the circumferential saturation flux (proportional to M_S) on the temperature. In the inset: temperature vs. time during the measurement.

In terms of the cooling curve, we obtained a rate of change of M_S of $-0.133\%/K$. The next step is to determine the temperature rise caused by the excitation current in the wire. To do so, we first characterized the dependence of the resistance of the wire R_{wire} on the temperature. This was done simultaneously with the measurement of the hysteresis loop, albeit indirectly. We used the value of the resistance that is necessary to suppress the resistive component of the voltage on the wire before integration to obtain the magnetic flux [12]. As the temperature rises, the value necessary to obtain a correct hysteresis loop also increases. Fig. 2 shows the dependence of R_{wire} on temperature: it is linear, as expected, and we estimate the rate of change to be $0.02\%/K$. Then we measured the actual effect, i.e., the dependence of the resistance on the current, by injecting a current into the wire and measuring its resistance. As expected, the dependence of R_{wire} on the current was parabolic (Fig. 3). Knowing the dependence of resistance on temperature from the previous experiment, we can estimate the mean temperature rise of the wire for the actual excitation parameters, and thus the change of saturation magnetization M_S . A typical excitation current for our fluxgates is 40 mA AC added to 50 mA DC , which results in just over 57 mA RMS value (which should be considered for thermal effects). In the worst-case scenario, when turning the magnetometer on, we experienced a change of current from 0 to 57 mA RMS , which, according to Fig. 2, brings a change of resistance of 0.0157% . Since R_{wire} has a rate of change of $0.02\%/K$, this means that the excitation current in the wire itself causes an increase in temperature of less than 0.8°C . Such a change of temperature causes a change in the saturation magnetization of -0.1% . Such change is, however, two orders of magnitude lower than what we had observed in the transient of the magnetometer output (units and up to 10% of the offset). While the excitation current actually warmed up the wire, causing a drop in M_S , we derived that thermal effects were not the cause of such large transient.

III. THE EFFECT OF EXPOSURE TO LARGE AXIAL FIELD

Having ruled out the thermal effects, we now investigate another possible cause of the transient on the magnetometer output, which may be the presence of a large magnetic field in the wire core of the fluxgate that can magnetize the inner section of the wire, which is not saturated by the excitation current [13]). To test this hypothesis, we performed two experiments. First, we exposed the sensor to a geomagnetic field of approximately $+20\ \mu\text{T}$. We turned the (open-loop) magnetometer on and allowed it to stabilize for about 50 minutes. Then we moved the sensor to a four-layer shielding, and the output voltage of the magnetometer showed a very slow transient that appeared to stabilize at a voltage of 0.2 V (corresponding to 183 nT). Then we extracted the sensor from the shielding and exposed it again to the geomagnetic field for just 4 minutes, albeit this time in the opposite direction, namely to $-20\ \mu\text{T}$. After inserting the sensor into the shielding again, we noticed that the transient, aiming once more at 0.2 V , was now reversed (Fig. 4). Not only that, but the transient appeared faster. This indicates that the transient had a magnetic origin depending on the value of the magnetic field that was applied to the magnetic wire and on the duration of that exposure.

The second experiment was performed to confirm any residual thermal effects on the transient. Previously, we had found from the dependence of M_S on temperature that the thermal effect should be negligible. We inserted the fluxgate sensor into the shielding and allowed it to stabilize until the transient was almost exhausted. Then we preheated a block of copper and inserted

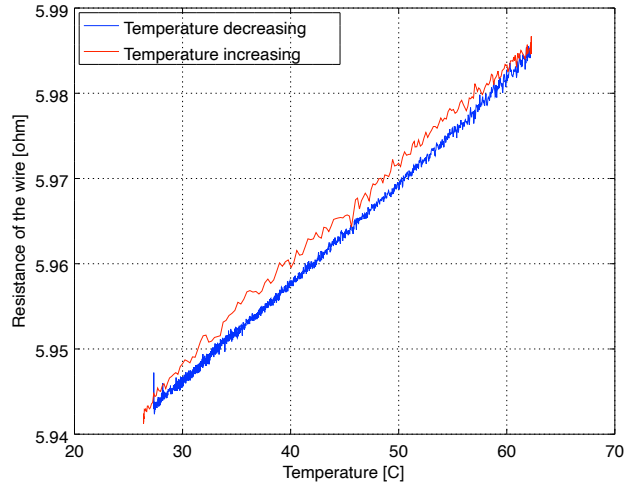


FIG. 2. Dependence of the amorphous magnetic wire resistance on the temperature.

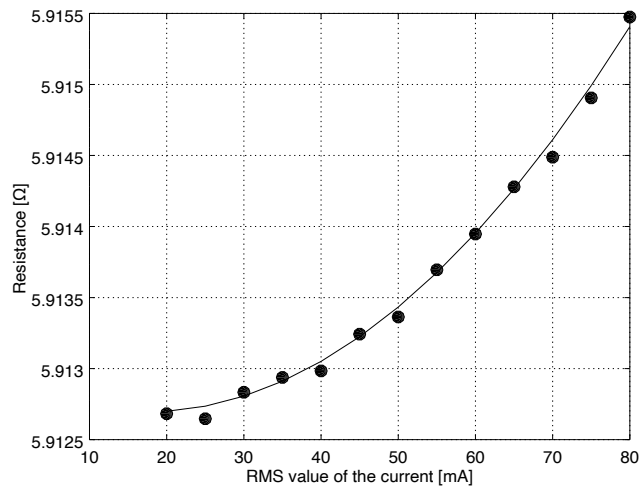


FIG. 3. Dependence of the amorphous magnetic wire resistance on the current.

it into the shielding in the proximity of the sensor to increase its temperature. The temperature was monitored by measuring the voltage on a diode located in close proximity to the wire core and fed by an approximately $10 \mu A$ current source (the magnetic field due to such a small current was negligible). In Fig. 5, we can see the results of this experiment. The temperature, which is almost stabilized at $24.7^\circ C$, rises to over $27^\circ C$ due to the heat provided by the block of copper, and from the time scale, we can reasonably assume that the temperature of the wire core has settled to the same value. However, the output voltage of the magnetometer does not appear to be affected by the temperature, and it continues its initial magnetic transient induced trend. This confirms that the origin of the transient has to be found in the magnetic field applied to the sensor and not in the effect of the saturation magnetization temperature of the fluxgate’s amorphous wire core [14].

This magnetic phenomenon can also explain the transient we observed when the magnetometer was turned on. Also, in that case, the magnetic field applied to the wire core changed. When no excitation current is present in the wire, its whole cross-section is exposed to the axial field. However, once the magnetometer is switched on, the circumferential field generated by the excitation current will reorient the magnetic domains to this direction, although this does not happen instantly. This change in amplitude and direction of the magnetic field can cause a similar transient in the output of the magnetometer.

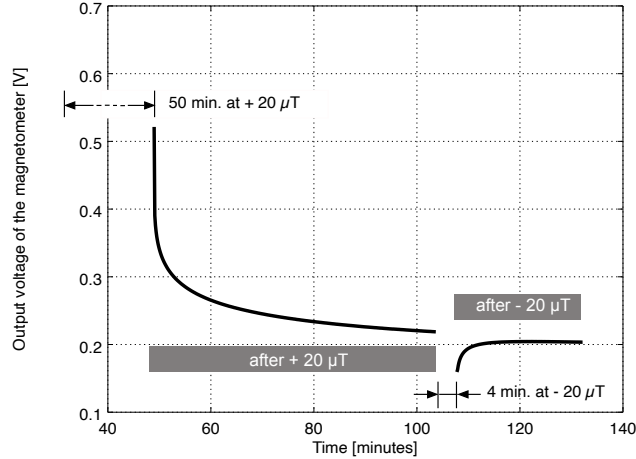


FIG. 4. Transient of the output voltage magnetometer when the sensor is in the shielding after exposing the sensor to $+20 \mu\text{T}$ (in the sensitive direction) for 50 minutes, and after exposing it to $-20 \mu\text{T}$ for 4 minutes.

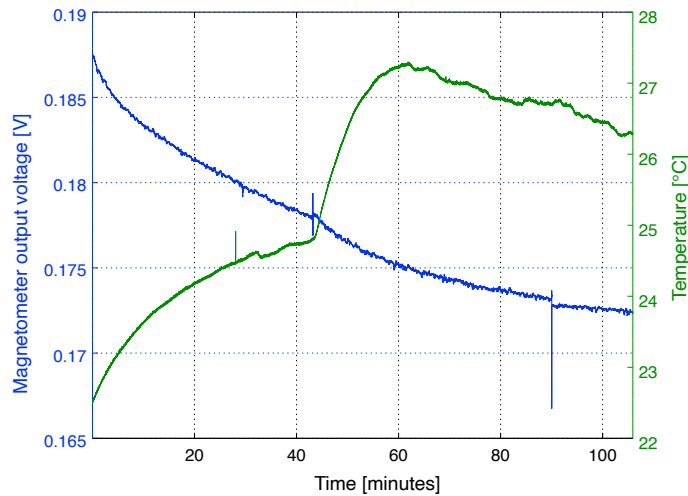


FIG. 5. Output voltage of the magnetometer after the sensor was placed in the shielding. At time=42 minutes the temperature is increased by inserting a block of pre-heated copper in the proximity of the sensor.

IV. DEPENDENCE OF THE SETTLING TIME ON AXIAL FIELD AMPLITUDE AND DURATION

In the previous section, we showed that the origin of the reported transient is in fact magnetic and not thermal, as originally supposed. To understand this phenomenon better, we study this effect by exposing the sensor to different magnetic field pulses of well-defined amplitude and duration. To do so, we placed the sensor inside the shielding and created an artificial axial field B_{ax} in the axial direction of the sensor using an additional coil coaxial with the sense winding (Fig. 6). With a current source, we can control both the amplitude and duration of the applied field B_{ax} .

We again needed to exclude the auxiliary coil that produces B_{ax} from creating sufficient heat to affect the sensor thermally. Therefore, we initially used a large Helmholtz coil (600 mm diameter) far enough to exclude any possible heating of the sensor, and we measured the transient of the output after exposing the sensor to B_{ax} . After that, the experiment was repeated by creating B_{ax} using a coil wound directly on the sensor, and the transient was identical. From this, we can derive that the transient was not affected by any possible heat generated by the auxiliary coil producing B_{ax} . Another possible source of artifact arises from

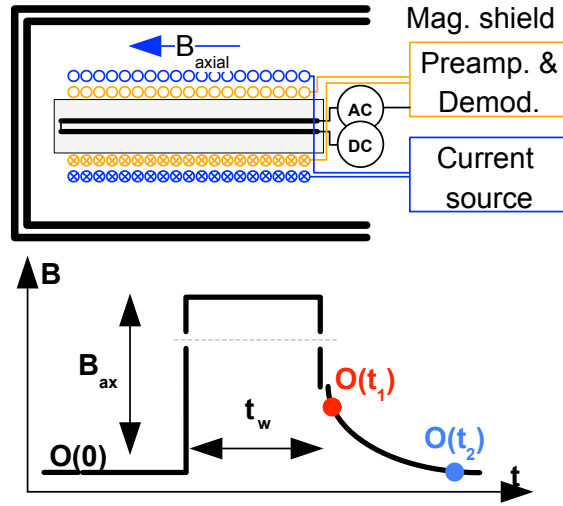


FIG. 6. Set-up for the measurement of the settling time (not to scale). The field B_{ax} was applied for the time t_w , and the two points $O(t_1)$ and $O(t_2)$ were later used to describe the transient.

the magnetization of the shielding where the experiment is performed. In that case, we would rather observe the effect of changing the shielding remanence. To rule out this possible source of error, we repeated the experiment outside the shielding while exposing the sensor in an east-west direction to minimize the geomagnetic field applied to it. Once we moved the sensor back to the shielding, we obtained the same transient, proving that the source of the transient was not the magnetization of the shielding. Yet another possible problem could arise from the fact that the sensor is exposed to a field larger than the maximum field measurable by the magnetometer (in open-loop operation, our range is approximately $1 \mu T$). This could lead to saturation of the input stage of the electronics, causing a transient of the magnetometer output due to the protection diodes' recovery time (which would then have electric and not magnetic origin). Therefore, during our experiments we added a switch that would automatically short the input of the preamplifier when a large field is applied to the sensor.

V. STUDY OF THE TRANSIENT BEHAVIOUR- DURATION AND AMPLITUDE OF THE FIELD PULSE

The sensor was tuned at the resonance frequency with an additional capacitor so that we achieved about 1 MV/T sensitivity in the open-loop magnetometer operation. We measured the transient of the magnetometer output after applying $B_{ax} = 8 \mu T$ and $-8 \mu T$ for $t_w = 1, 2, 3,$ and 4 seconds. The results are shown in Fig. 7 for both positive and negative fields, from which we have removed the offset value once it stabilized (around 40 nT for positive pulses and -100 nT for negative pulses), to highlight the transient. We must point out that after applying a pulse of $\pm 8 \mu T$, the offset always returned to the same value (40 nT or -100 nT , depending on the polarity) regardless the duration of the pulse. First, we observed that in the case of a negative field, the transient was reversed, once again confirming the magnetic origin of this phenomenon (any temperature effect would yield the same change). Next, we measured once again the transient after exposure of the sensor to $B_{ax} = 8 \mu T$, albeit after adding a 330Ω damping resistor connected in parallel to the pick-up coil. The purpose of this resistor was to change the quality factor of the resonance circuit to see if this had any effect of the transient. In Fig. 8, we can see that the transient is not affected by the damping resistor, showing that the transient is not even in the relaxation of the tuned circuit.

In Fig. 7, we have plotted not only the transient of the output of the magnetometer for different pulse durations but also the slope vs. time. From a physical point of view, we are interested in the time necessary for the offset to reach a stable condition, and this can be identified as a the time when the derivative of the offset becomes lower than a certain threshold. Since an offset drift corresponds to a low-frequency noise, a different threshold of the derivative of the offset can be chosen as a parameter to define the offset as "stable" when interested in the noise at a different frequency. As we can see in Fig. 7, the longer the time of exposure of the sensor to the $B_{ax} = 8 \mu T$ field, the longer the settling time, which is defined as the time required to reach a value below a specific threshold. This leads us to study the dependence of the settling time on both the amplitude of B_{ax} and

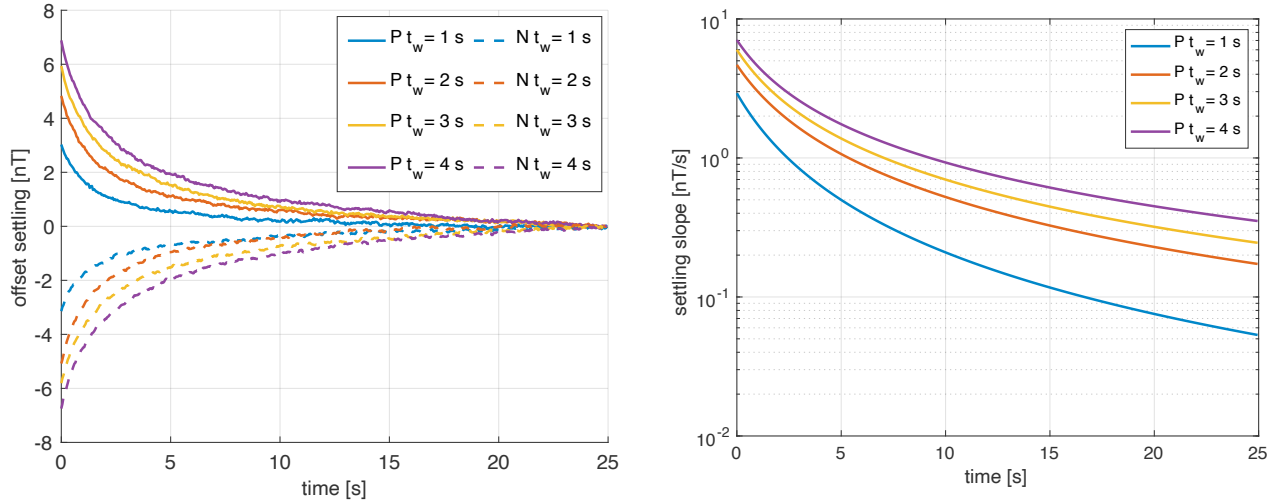


FIG. 7. Left: Offset drift after the application of $B_{ax} = 8 \mu T$ (P) and $-8 \mu T$ (N) for 1, 2, 3 and 4 seconds (the transients have been normalized by removing the final DC offset from each trend). Right: amplitude of the derivative of the offset transients vs. time (for simplicity only for the negative pulses and with filtering).

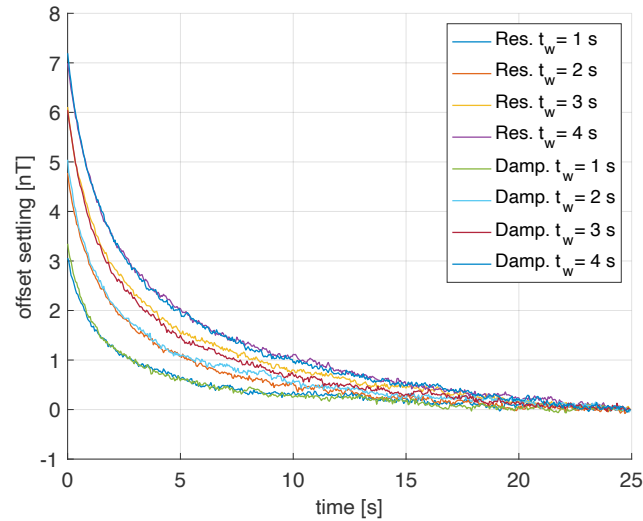


FIG. 8. Offset drift after the application of $B_{ax} = 8 \mu T$ for 1, 2, 3 and 4 seconds without (Res.) and with (Damp.) a 330Ω damping resistance parallel to the pick-up coil to artificially modify the resonance circuit (the transients have been normalized by removing the final DC offset from each trend.)

its duration. Specifically, we defined as the settling time the time necessary for the offset transient to reach a derivative in time less than 0.1 nT/s after exposure to B_{ax} . We tested fields from $1 \mu T$ to $30 \mu T$ and duration times of the pulses t_w from 0.1 to 10 seconds. We observed that the settling time depends on both amplitude and duration of B_{ax} . These results are summarized in Fig. 9, where we can observe the dependence of the settling time on the duration of B_{ax} with the amplitude of the pulse as a parameter.

To better understand this phenomenon, we plotted the values of settling time as a function on a quantity calculated as $\sqrt{t_w \cdot B_{ax}}$, which can be regarded as "magnetic energy". Interestingly, we observed a linear behavior that was consistent for t_w up to 1 second (Fig. 10). This means that for a short time exposure to the axial field, the settling time depends only on the product of t_w and B_{ax} , regardless of the respective amplitude of the factors. This phenomenon deviated, however, especially for t_w of 5 and 10 seconds. The possible reason for this is that the settling time had not yet been reached, since the energy in this case was high.

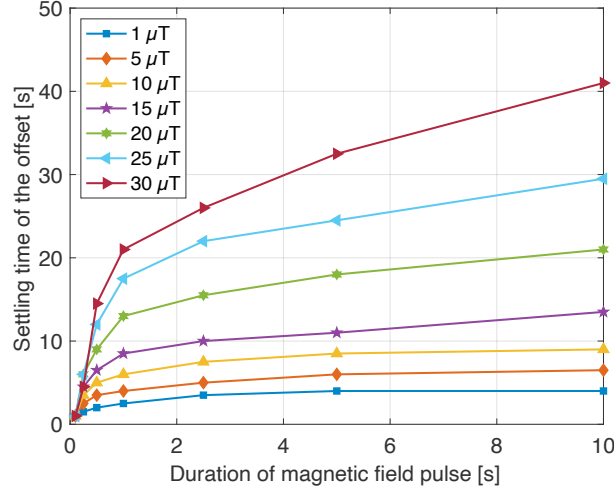


FIG. 9. Settling time of the offset after removal of B_{ax} as a function of the duration t_w of the B_{ax} for different values of the field.

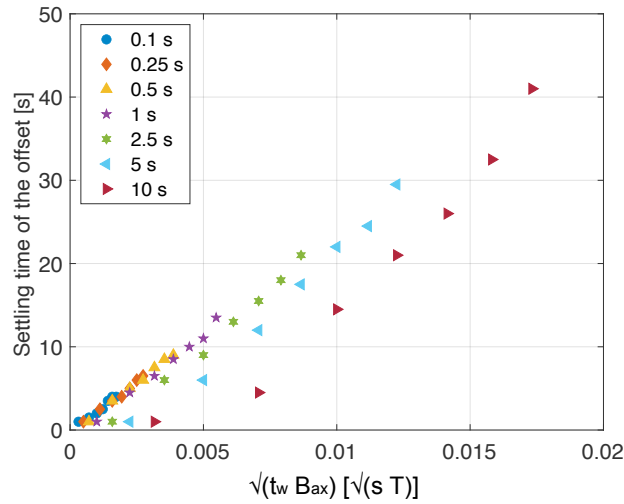


FIG. 10. Settling time of the offset after removal of B_{ax} as a function of $\sqrt{t_w \cdot B_{ax}}$ for different duration of t_w [s]

VI. TOWARDS THE ORIGIN OF THE PHENOMENON

Although we have proved that the origin of the transient is magnetic, the actual mechanism that gives rise to such a transient after the removal of an axial field it is still open to question. A similar process of reversal magnetization in amorphous microwires has been studied by Vazquez on iron-rich wires [15]. The effect described in that paper also applies to CoFeSiB wires, such as the one used in this study, under specific circumstances, such as thermal treatment or the application of tensile stress. In our case, the wire had a natural curvature from the manufacturing process that was made straight and soldered to the sensor head holder. The residual stress therefore provided a tensile component to the wire. The application of tensile stress gives rise to a variable switching field of the magnetization that depends both on the stress and length of the wire (due to the demagnetization factor). Vazquez then modeled the total energy of the wire, taking into account the Zeeman, reversed domain walls, and stray field energy. Then it was shown that, after removal of the applied field, some closure domains appeared at the ends of the wire to minimize the energy, and they progressively collapsed along the length of the wire. This effect may sound similar to what we had observed; however, there was a substantial difference, namely that the velocity of propagation was too large (hundreds of m/s) to explain our reported phenomenon. A probable cause in our case may lie in the fact that ferromagnetic wire can actually be regarded as

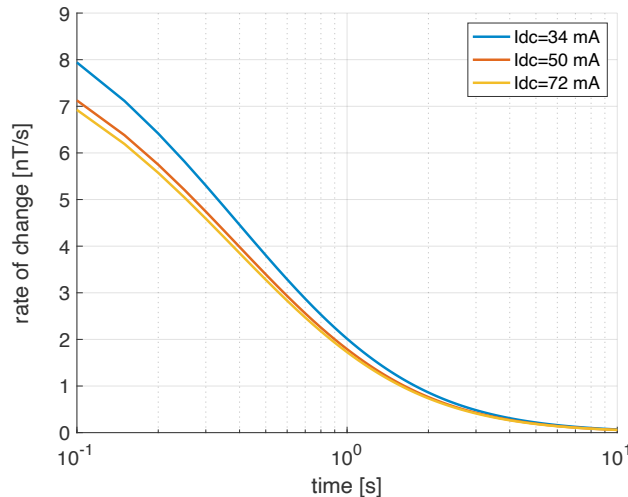


FIG. 11. Settling of the offset vs. time for $I_{ac} = 33$ mA and different values of dc current after exposing the wire to $10 \mu T$ for 1 s

having two different regions. During the operational mode, the wire core is not only exposed to the axial field B_{ax} but also to the circumferential excitation field generated by the excitation current. The wire's outer shell is thus saturated in a circumferential direction, and only the inner part of the wire, which is progressively less saturated as we approach the wire center, is magnetized in an axial direction. There is no clear-cut separation between these two regions of the wire, since the circumferential field monotonically increases as the radius increases. We can at this point speculate that there may be a transitional region between the inner core and the outer shell, where the domains slowly reverse and reorient to minimize the energy after removing the magnetic field from the wire, giving rise to the observed transient. As a preliminary test to verify this hypothesis, we again measured the transient of the output after applying $10 \mu T$ for 1 second, but we changed the excitation current. We performed three experiments, each using 33 mA as the AC component of the excitation current, while the DC component used 34, 50, and 72 mA. The purpose of increasing the DC component of the current was to increase the portion of the wire that was saturated (the depth of the shell), and therefore we should change the volume of the transition region where this phenomenon could occur. Fig. 11 shows that to some extent the transient is indeed faster when the DC component of the excitation current is increased, but our results are not conclusive. More detailed investigation is clearly needed to fully understand this phenomenon.

VII. THE IMPORTANCE OF A COMPENSATING FEEDBACK-LOOP OPERATION

Operating a fluxgate in a closed-loop feedback is a common method used to improve the linearity of a sensor, mainly to extend its linear range when open-loop sensitivity is very high. This study shows that in the case of an orthogonal fluxgate in fundamental mode, it is important to operate the sensor in the closed loop also to minimize the reported effect. As we have already seen, even a small variation in magnetic field (e.g., quickly rotating the sensor on the horizontal plane of the Earth's field) does affect the output of magnetometers by creating decaying transients from one field value to another. This causes a delay in the response of the sensor, which might not be acceptable in some applications. If we operate the sensor in feedback mode, however, the wire core is always exposed to the same value of the magnetic field (ideally zero), even if the measured field changes. Thus, the core of the fluxgate should not experience any transient.

To verify that this problem is solved by operating the sensor in feedback mode, we performed the following experiments, and their results are shown in Fig. 12. First, we exposed a sensor to $20 \mu T$ for 120 seconds on its axial direction while operated in open loop and then removed the axial field and observed a typical transient of the output of the magnetometer. Next, we repeated the same experiment while operating the sensor in feedback mode by choosing the closed-loop option of the magnetometer. The compensating field was created by a 500 turn, single-layer coil wound directly over the pick-up coil. A layer of Kapton tape was used between the pick-up coil and compensating coil. The total length of the compensating coil was 80 mm. In this case, the magnetic core of the fluxgate was constantly exposed to zero field, since the sensor was being operated in closed loop. We exposed the sensor again to $20 \mu T$ for 120 seconds and observed the output of the magnetometer after the removal of the axial field. In this case, the transient of the output disappeared. This shows that operating the sensor in feedback mode does indeed suppress this phenomenon.

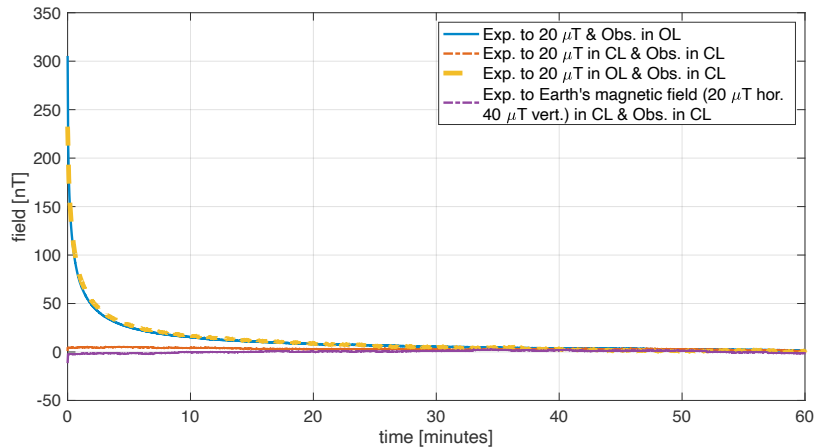


FIG. 12. Offset transient of the magnetometer observed after exposing it to $20 \mu T$ for 120 seconds in open-loop [OL] (blue curve), in closed-loop [CL] (orange curve), in open-loop while applying the magnetic field and then in closed-loop after removing it (yellow curve). The purple curves shows the output of the magnetometer operated in close-loop after exposing it to the Earth magnetic field.

To provide additional evidence of the role of the feedback in suppressing the transient of the output, we performed the following experiment. We exposed the sensor one more time to $20 \mu T$ for 120 seconds while operating in open-loop. Then we removed this field and simultaneously switched the magnetometer to closed-loop. In this case, we again observed the typical large offset transient. This confirmed that the transient of the offset had been caused by the fact that the field was exposed to an axial field when left in open-loop, and the feedback could no longer compensate for the problem once the offset had been generated because the closed-loop would simply follow the offset transient. With this experiment, we show that the feedback mode, when constantly applied, suppresses the offset transient because it nulls the magnetic field applied to the sensor when the axial field is $20 \mu T$.

We then performed a final experiment whereby we operated the sensor in closed-loop and exposed it to the Earth's magnetic field (with a horizontal component of $20 \mu T$ and a vertical component of $40 \mu T$). Then we inserted the sensor in shielding, still keeping the magnetometer in closed-loop. Again, in this case, we did not observe a large transient of the offset. This result indicates that it is enough to compensate for the magnetic field in the axial direction to suppress the problem of the large offset transient, and it is not necessary to have a three-axial feedback system.

This experiment proves the importance of using the feedback mode operated magnetometer with this type of orthogonal fluxgate, even if no improvement in linearity is required.

VIII. CONCLUSIONS

In this paper we have proved that the offset drift in an orthogonal fluxgate operated in fundamental mode when the magnetometer is turned on is not due to change of temperature as initially assumed but, on the contrary, it has magnetic origin. We have proven it by showing that the current flowing in the wire does not increase the temperature of the wire enough to cause a change of offset due to temperature. We have also excluded external sources of temperature change (for instance when moving the sensor to the shielding) since they don't change the transient of the offset. On the contrary, we have shown that the transient of the offset is caused by the magnetic field applied in axial direction, most probably because the inner part of the magnetic wire is not saturated by the excitation current and it the external axial field can magnetize it. Finally we have shown that this problem is solved by operating the sensor in feedback mode, since the total magnetic field applied to the core of the sensor in axial direction is kept at zero and the core of the wire has no opportunity to be magnetized in axial direction.

ACKNOWLEDGMENTS

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