Contribution to the Ring-Core Fluxgate Theory

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Abstract

Existing theories for open-core fluxgate are not fitting experimental results in the case of ring-core sensors. Simple description based on transfer functions which takes into account the interaction between two half-cores is presented. Measured inner loops and dynamical transfer functions justified this approach. Flux-evaluating fluxgate was proposed for simple instruments. Its main advantage is its insensitivity to excitation current field parameter variations, but it has a threshold level of about 100 nT in present time. Methods of calibration and noise evaluation of sensors are also mentioned.

1. Introduction

Ring-core fluxgate has been widely used since the end of the sixties. Although its sensitivity is lower than that of the open-core type of fluxgate (due to demagnetisation), it has been demonstrated that ring-core design can lead to a very low-noise sensor with better long-term stability. Many theories have been proposed in order to explain the operation of ring-core sensors. Analyzing a ring-core as two half-cores and applying a classical description leads to formulae disagreeing with the experimental results. The introduction of demagnetisation yields better results, but the complexity of such analysis grows as time variations of permeability cannot be neglected [1], so far voltage induced in sense winding we must write:

$$E_i = -NA\frac{H(1-D)}{(1+[\mu(t)-1]D)^2}\frac{d\mu(t)}{dt}\,\mu_0$$

where H is the measured field, D is the demagnetisation factor, N is the number of turns of the sensing coil, A is the area of the core and $\mu(t)$ is the relative permeability.

A new view of fluxgate mechanism was introduced by Narod and Russel [2]. Instead of flux modulation by the driving current they consider equivalent modulation of sense winding inductance. In quantitative analysis they suppose rectangular excitation current waveform, so that $L(t)$ can acquire only two values. We consider their approach to be sophisticated but restricted to very low values of H, for which $L(t)$ can be taken as constant. But the question under what circumstances was it possible to saturate one segment of a ring-core while another part remained unsaturated is as yet unsolved.

Our analysis brings a new attitude to this problem. It is a semi-quantitative description based on a simple approximation of a dynamic loop and derivation of the transfer function similar to that made by Gordon [3]. The main asset of our description is that we take into account the interaction between two segments of a ring core. Here two different magnetisation loops in a ring-core fluxgate are considered:

(1) the "inner" loop, for the toroidal excitation field H_{exc} characterised here by maximum permeability μ;

(2) the "outer" loop for the homogeneous measured field H which has maximum permeability μ'

$$\mu' = \frac{\mu}{1+(\mu-1)D}.$$

Figure 1 indicates the derivation of the transfer function for a given H. (Piecewise linear approximation of hysteresis loop.) Let us consider the excitation field growing from zero. For $H_{exc} = H_1 = H_{sat} - H$, half-core 1 falls into saturation, while half-core 2 is unsaturated. At that moment the ring-core is magnetically "broken", the magnetic resistance of sensor seen from the excitation winding rapidly increases, permeability changes from μ to μ'. Both half-cores are saturated for $H_{exc} = H_2$. We derived the shape of the transfer function for different values of H.

A series of experiments on several types of ring-core sensors was performed in order to verify the theory. Waveforms of flux in various parts of the sensor core were obtained by integrating voltage induced in the measuring windings. Here results for sensor AT-1 are presented. This is a fluxgate sensor with an oval-shaped closed core (an amorphous $Co_{75}Fe_5B_{20}$ material produced by the Physical Institute, Dresden, GRD) with 20 turns of strip 30 μm thick and 2 mm wide. It is easy to make the sensor even in an oval shape which was selected for its higher sensitivity and ease of measurement because there is no need for high-temperature annealing. It has, however, higher noise level and poorer long-term stability than the classical ring-core sensor made from crystalline materials.

Static inside loops Φ_1 vs. H_{exc} for different H may be seen in Fig. 2. Permeability falling when the half-core 2 is saturated can easily be seen. The last curve for $H = 900$ A/m shows that when H is sufficiently high to saturate the whole sensor even for $H_{exc} = 0$, permeability is μ' only during the whole working cycle.

A dynamic hysteresis loop Φ vs. H_{exc} for excitation frequency of 1 kHz is shown in Fig. 3. From the dynamic transfer function sense coil flux vs. H_{exc} one can see [Fig. 4(a, b)] that the slope is much lower than that of the hysteresis loop, in correspondence with the derivation (Fig. 1). The distance between two peaks is $2H_c$ for lower fields and grows for $H > H_{sat}$. Fig. 5(a, b) shows corresponding waveforms in a time domain.

The relation between H and the height of the transfer function (i.e. the change in sense-winding flux during one cycle of excitation current) is linear over a wide range. For understanding this mechanism it is useful to look on fluxgate as the instrument which gates sense-winding flux Φ by an excitation current. In the case of a one-core sensor, the minimum and maximum flux is determined mainly by H_{exc}. Due to symmetry, these high-level half-core fluxes Φ_1, Φ_2 are

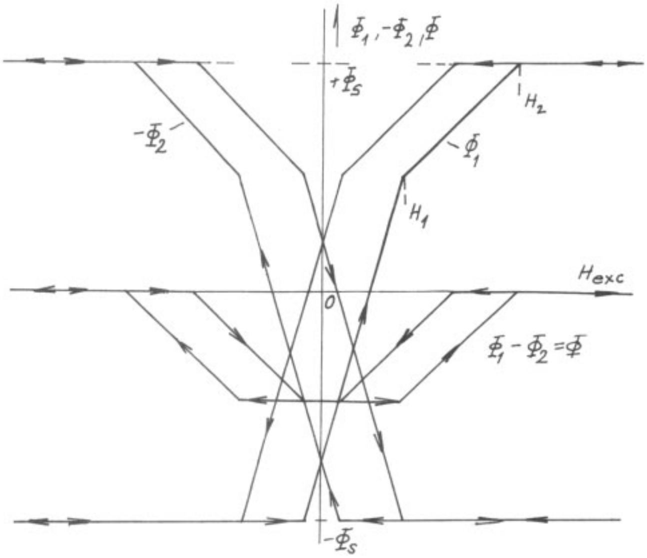

Fig. 1. Derivation of the transfer function for given H.

compensated in ring-core, so Φ is proportional to $\mu_0 H$ when both half-cores are saturated and to $\mu' H$ when the core is unsaturated (see Fig. 1).

This leads to a new non-selective method of output signal evaluation: $\Phi(t)$ is reconstructed from the induced voltage by a fast integrator and then peak-to peak detection is performed. This method could be called Flux-Evaluation Fluxgate (FEF). The main disadvantage is the presence of the threshold level. Due to the asymmetry of the ring-core the mutual inductance between the exciting and the sense winding is nonzero, so Φ_1 or Φ_2 feeds through, causing the signal of exciting frequency f_{exc} in the induced voltage V_i. By the proper core setting this threshold level can be lowered to 100 nT with a good long-term stability. Figure 6(a) indicates the signal below the threshold level (in this case equal to sensor offset of about 10 nT). In Fig. 6(b) is the signal slightly higher than the threshold level: two peaks of Φ are growing in each a half period of I_{exc}, making peak-to-peak value growing. For large $H > H_{sat}$ ring-core is magnetically broken

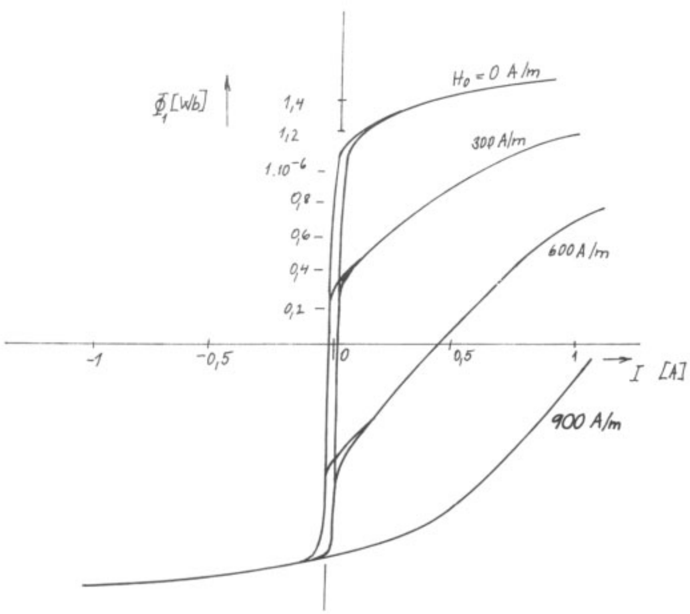

Fig. 2. Static inside loops for various H.

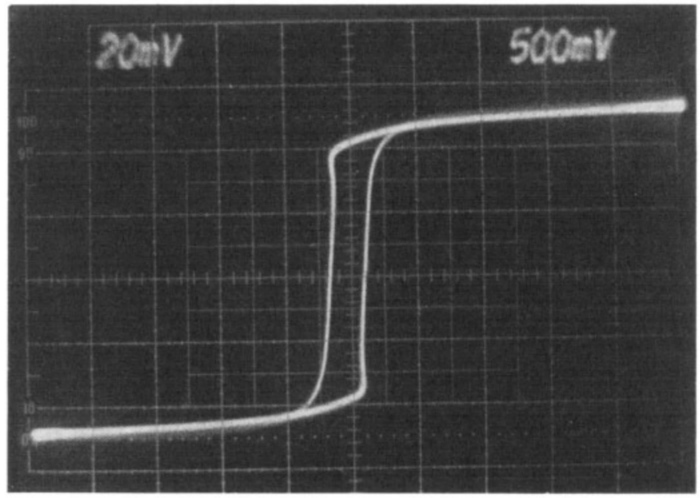

Fig. 3. Dynamic hysteresis loop of sensor PT-1 for $f_{exc} = 1$ kHz.

for the whole period. *P–p* value of Φ reaches its maximum $2\Phi_{sat}$ and does not change.

The output of AT-1 based FEF vs. the measured field characteristics is in Fig. 7. According to the theory, after reaching threshold level the characteristics is linear and for high H it flattens. The useful signal is much stronger than the parasitic one for large H, as seen in Fig. 5.

Because the proper part of the flux is at $2f_{exc}$ frequency, the

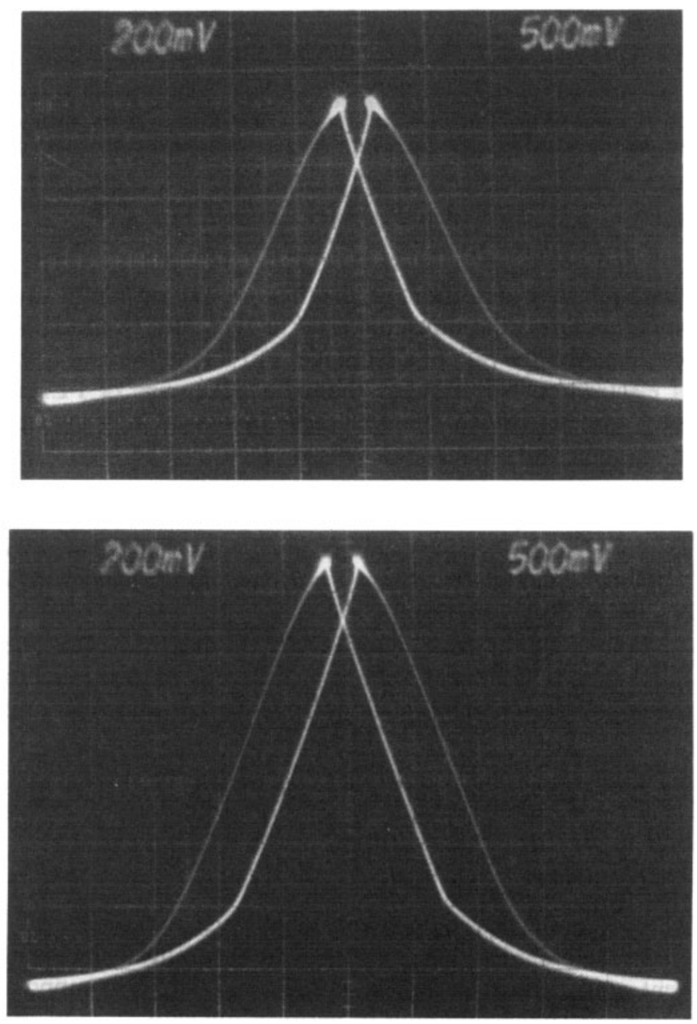

Fig. 4. Dynamic transfer characteristics for (a) $H = 200$ A/m, (b) $H = 400$ A/m.

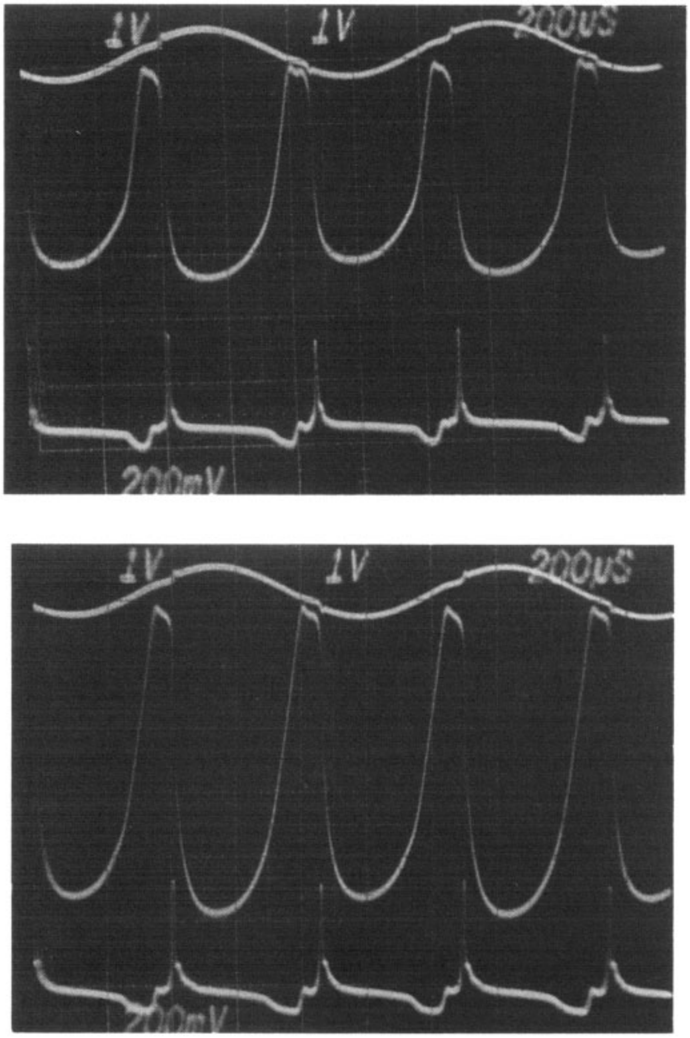

Fig. 5. Waveforms for H = (a) 200 A/m, (b) 400 A/m. Upper trace: I_{exc}. Middle trace: sensing coil flux Φ. Lower trace: induced voltage V_i.

phase-sensitive detection of the flux would be useful and would suppress the threshold level to zero. But this method would cancel the first of advantages of FEF — the simplicity of electronics. Nevertheless the main advantage of FEF is great insensitivity to small changes in the exciting current magnitude and frequency changes. That can be seen from these experimental results:

(1) for the classical evaluation of the 2nd harmonical component of V_i by PSD, 5% change in f_{exc} causes 5% change in the sensitivity and 5% change in I_{exc} magnitude causes 15% change in the sensitivity.

(2) for FEF the same changes were 1% and 0.2%. It is due to the fact, that induced voltage V_i is directly proportional to the slope of I_{exc}, which is obvious from the following relations:

$$V_i = N\frac{d\Phi}{dt} = NA\frac{d}{dt}\mu H = NAH\frac{1-D}{1+(\mu-1)D}\frac{d\mu}{dt}$$

$$\frac{d\mu}{dt} = \frac{d\mu}{dH}\frac{dH}{dt} = k_c\frac{d\mu}{dH}\frac{di_{exc}}{dt}$$

where k_c is the sensing coil constant.

On the other hand Φ_{max} and Φ_{min} are theoretically independent on I_{exc}, because $\Phi_{max} = NA\mu' H$ and $\Phi_{min} = 0$ suppose that I_{exc} is sufficiently high to perform full saturation of the sensor core. Earlier mentioned possiblity to integrate output voltage before phase-sensitive detection may also reduce the

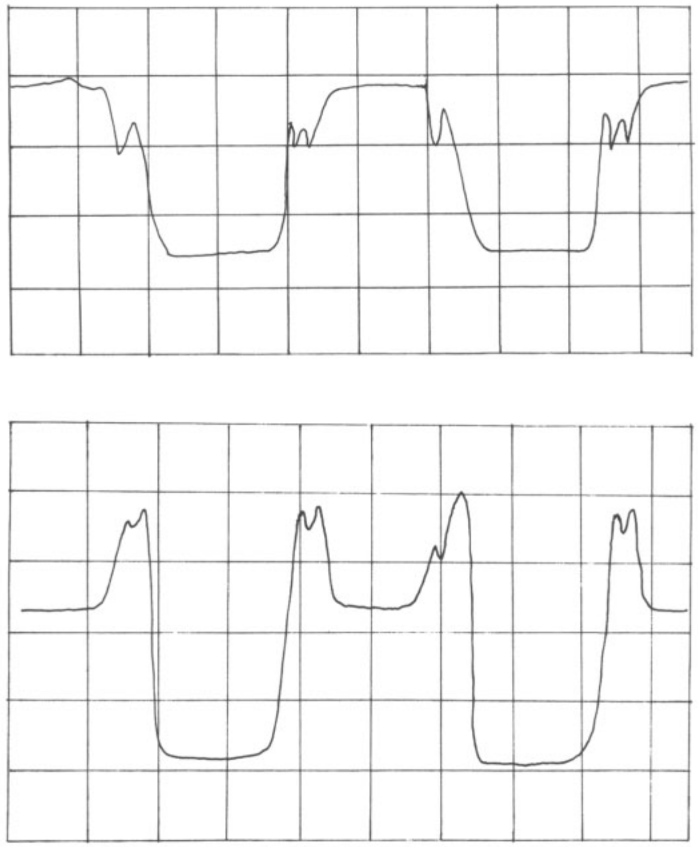

Fig. 6. Sensing coil flux Φ for (a) H = 0 A/m, (b) H = 1 A/m.

sensitivity on the I_{exc} parameter variations and it would be very interesting to verify it.

2. The calibration and noise evaluation

In our standard laboratory we used the Helmholtz coils for the high-fields calibration. For small H we used either the

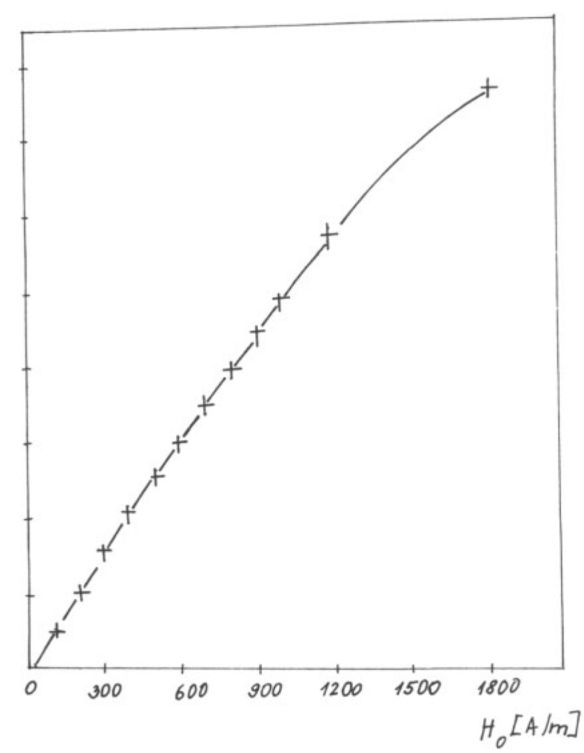

Fig. 7. Output of flux-evaluating fluxgate vs. measured field.

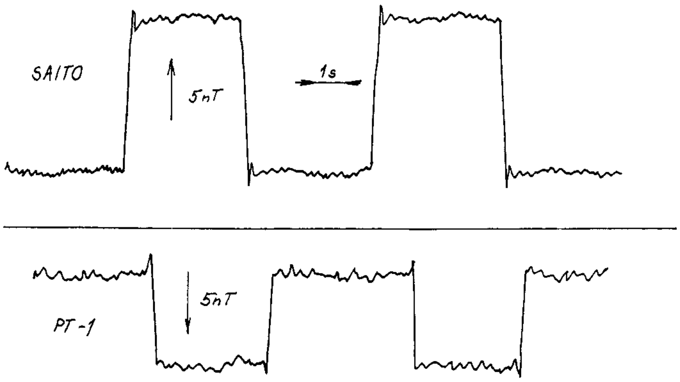

Fig. 8. Noise measured in MAVACS. (a) Sensor Saito, (b) sensor PT-1.

ferromagnetic or active shielding. The former one was convenient to use but it had a slow drift of the field about 1 nT/min in case of our double permalloy cylindrical shielding due to the relaxation effects. For the latter one the Earth's field compensating system MAVACS (developed by Geofyzika Brno), based on a rotation sensor. It is placed in a magnetically silent laboratory in Průhonice. Long-term zero stability is 0.1 nT, noise 30 pT *p–p*. The example of the results is shown in Fig. 8. Measured sensors are:

(a) PT-1 developed in our department – core material Py 79, 50 μm thick, 6 mm width, 6 turns;

(b) the sensor developed by T. Saito described in Ref. [4].

3. Conclusions

The dynamic transfer functions can be useful not only for understanding the processes in the sensor core, but also in developing new sensors and adjusting sensors and their electronics. We are currently developing a PT-1 based magnetometer with autocalibration abilities and we are trying to increase the stability of the sensor. It would be possible and desirable to test also some other fluxgate developed in another laboratory in MAVACS system to compare performance.

References

1. Burger, J., IEEE Trans. Magn. **8**, 791 (1972).
2. Narod, B. and Russel, D., IEEE Trans. Magn. **20**, 592 (1984).
3. Gordon, D., Lundsten, R. and Chiarodo, R., IEEE Trans. Magn. **1**, 330 (1965).
4. Saito, T., J. Geomag. Geoelectr. **32**, 649 (1980).