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FLUXGATE SENSOR WITH A SPECIAL RING-CORE

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Abstract: In the proposed design of a ring-core sensor, three windings, namely the exciting, the sensing and the compensating ones are applied directly on a special ring-core. The core is also wrapped with an additional winding that controls the so-called virtual air-gap. The virtual air-gap enables the sensor sensitivity to be adjusted in wide range. In the paper the design and test results of the proposed sensor are presented**.**

Keywords: fluxgate, magnetic field sensor

1. INTRODUCTION

There are many kinds of design of fluxgate sensors of magnetic field, beginning with the simplest single-core ones currently almost not used in practice due to the high level of the first harmonic of the magnetizing current occurring in the output signal, and ending with double-core ones (e.g., Förster and Vaquier type sensors), where the odd harmonics of the magnetizing current in the output signal are heavily attenuated [1-4].

Sensors with ring cores feature high sensitivity and low contents of odd harmonics of the magnetizing current in the output, and are more resistant to mechanical stresses than sensors built around cores of other shapes. Due to the mentioned virtues ring-core based sensors find wide application. Optimal design solutions are still sought for [4, 5]. For example, sensors based on oval cores may be found in use [5]. Sensors are manufactured using different technologies from classic ones to those employed in integrated circuits and micromechanics.

2. SPECIAL RING-CORE

The galvanically separated transformer-fluxgate based AC and DC transducers are built around a specially designed permalloy-made core. The underlying idea of the design was to replace the classic double-core DC transducers by those based on a single core. The core is stacked up from punchings (Fig. 1) made from thin permalloy. The punching itself is composed of 16 linked toroids that are arranged along the circumference of a circle, which creates a new toroid of specific shape at the same time.

The core magnetizing winding is threaded through holes in the small toroids. In Fig. 2 a part of the special ring core with magnetizing field lines is shown. As may be seen, the field lines close on themselves within the small toroids.

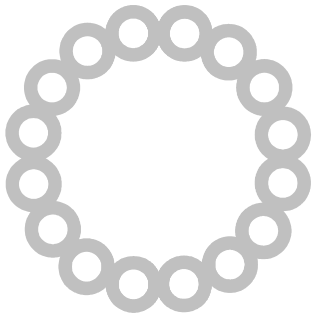

Fig. 1. A special ring-core punching

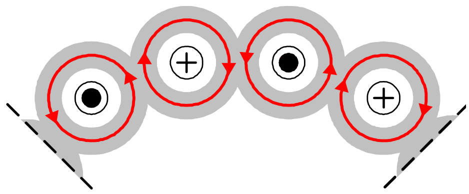

Fig. 2. A part of the special ring-core with magnetizing field lines

The specific shape of the core makes it possible to magnetize not only the whole core, but also a portion of it by threading the magnetizing winding through selected small toroids.

The above mentioned property of the core renders it suitable not only for fluxgate-based DC transducers, but also for fluxgate-based magnetic field sensors.

The following sensor types can be built around the core:

- those where the core is stacked up from whole punchings,
- those using the core with an actual air-gap,
- those using a portion of the core,
- those using the core with a virtual air-gap.

Tests carried out on sensors that utilize the full punching showed that directional properties of the sensor depend on the core anisotropy, the precision of core making, and on the magnetizing current intensity [6]. The properties can be stabilized by introducing an actual air-gap [7] into the core or by introducing a virtual air-gap [8].

3. FLUXGATE SENSOR WITH A VIRTUAL AIR-GAP

The design of the sensor is shown in Fig. 3. In the classic design of a ring-core based sensor, only the magnetizing winding is applied on the core [1-5]. The sensing winding, and possibly the feedback one, are wound on a solenoid that embraces the core. In the design presented in this paper, all three windings are applied directly on the core.

The virtual air-gap is produced by a DC flow through an additional control winding N_v. The current flow controls the magnetic permeability of that portion of the core through which the winding N_v has been threaded, thus creating an area of reduced permeability, i.e. a virtual air-gap.

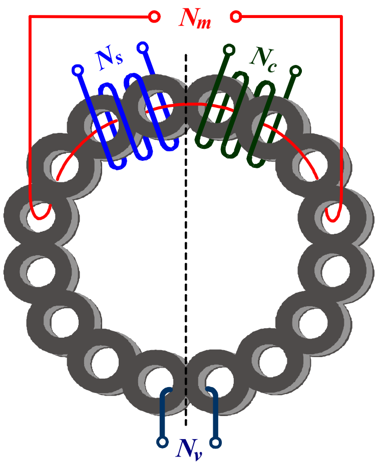

Fig. 3. Sensor with a virtual air-gap, which is produced by an extra winding N_v

The winding has been applied in the following way. The magnetizing winding N_m has been threaded through 8 toroids arranged along the circumference of a circle. Next, the sensing winding N_s and the compensating one N_c have been applied on that part of the core, which bears the magnetizing winding N_m. In addition, the winding N_v that has to control magnetizing of the virtual air-gap has been threaded through two holes in the core.

As indicated in Fig. 3 the windings are so arranged on the core that full geometric symmetry be imparted to the sensor.

The transducer co-operates with a typical automatic DC comparator, which includes a magnetizing generator, a phase sensitive detector driven by the second harmonic of the magnetizing current, and an output amplifier. The comparator is supplemented by a current source to energize the N_v winding that creates the virtual air-gap by means of the current flow I_v. The sensor operates in a closed-loop feedback circuit, which results in extending the range of operation and in weakening the nonlinearity being inherent in magnetic circuits. The corresponding block diagram is depicted in Fig. 4.

The operation principle of the sensor is the following. The sinusoidal magnetizing current I_m affects the magnetic permeability of the core and brings it into deep saturation. Because of saturation, the external magnetic field threading the core at that time does not change its internal magnetic flux. However, when the core is not saturated, i.e. in the magnetizing current zero-crossing area, the core flux generated by the external field does increase. This results in inducing an U_s voltage with a dominating second harmonic of the magnetizing current in the sensing winding N_s. After having been amplified U_s is passed to a phase-sensitive detector driven by the second harmonics of the magnetizing voltage. The detector output voltage, after averaging, drives the output amplifier, which forces a current flow I_c in the compensating winding N_c such that the voltage across the sensing winding N_s be equal to zero. This current represents the output of the sensor.

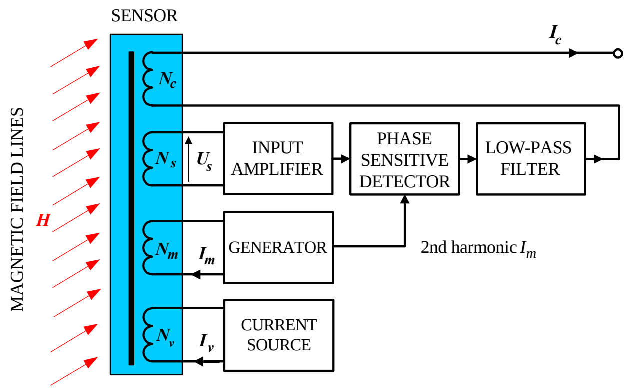

Fig. 4. Block diagram of the sensor with virtual air-gap

As an illustration of the sensor operation, Fig. 5 shows an oscillograph record of the magnetizing current I_m and that of the voltage U_s being induced in the sensing winding.

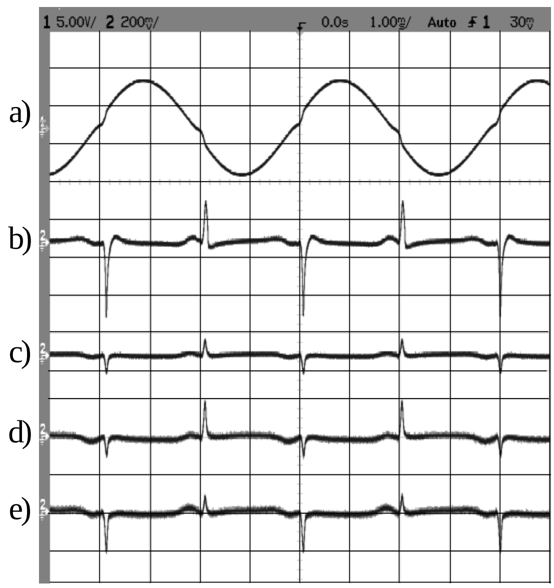

Fig. 5. Temporal variation occurring in the sensor: a) the magnetizing current I_m, b) U_s voltage for $I_v = 0$ and c) for $I_v = 1A$, d), e) U_s voltage for $I_v = 1A$ and for different field line directions (+ and –) when $H = 280A/m$

When the responses shown in Fig. 5.b and Fig. 5.c are compared, it is apparent that the air-gap control current I_v affects the voltage U_s across the sensing winding N_s. This manifests itself in limited amplitude of impulses and their symmetry. In Fig. 5.d and Fig. 5.e a distinct effect of the magnetic field direction on the voltage U_s response may be noted.

4. SENSOR MODEL TESTS

The sensor under study is characterized by the following parameters:

- the toroidal core being 5 mm thick has been stacked up from 0.1 mm thick permalloy-made punchings,
- number of turns of the windings is:
  - magnetizing $N_m = 10$,
  - sensing $N_s = 240$,
  - compensating $N_c = 120$,
  - controlling the virtual air-gap $N_v = 12$.

The sensor has been tested by its placing in a homogenous magnetic field produced by Helmholtz coils. Using this homogenous magnetic field the transducer has been tested for transduction sensitivity, linearity and directionality.

The tests have pursued the goal to analyze in two angular planes how the compensating current I_c is dependent on the magnetic field direction. It has been adopted that α denotes an angle the sensor is turned through in the plane of permeating magnetic field lines with respect to a conventional zero position.

On the other hand, β is an angle between the sensor's plane and magnetic field lines permeating it. It has been taken that β = 0° means the sensor's plane is situated in parallel to the magnetic field lines. The position of the sensor in relation to the magnetic field lines is depicted in Fig. 6. Accuracy of α and β angles definition: several degrees.

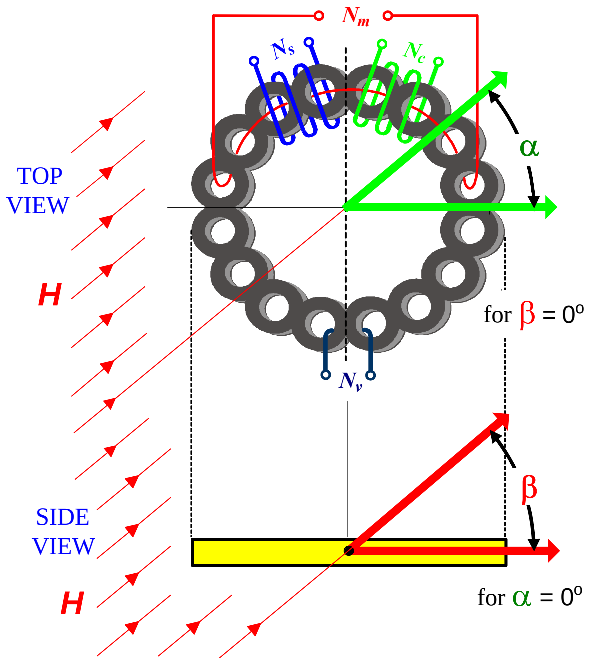

Fig. 6. Arrangement of the sensor in relation to the magnetic field lines

The transducer features high linearity, as the measured linearity error is in the order of some tenths of a percent. The evaluated maximal sensitivity of the sensor for $\alpha = 0°$ and $\beta = 0°$ is equal to around $2{\cdot}10^{-4}$ A/A/m.

Fig. 7 shows how the output compensating current I_c depends on angular arrangement (α) of the sensor in relation to the magnetic field produced by Helmholtz coils.

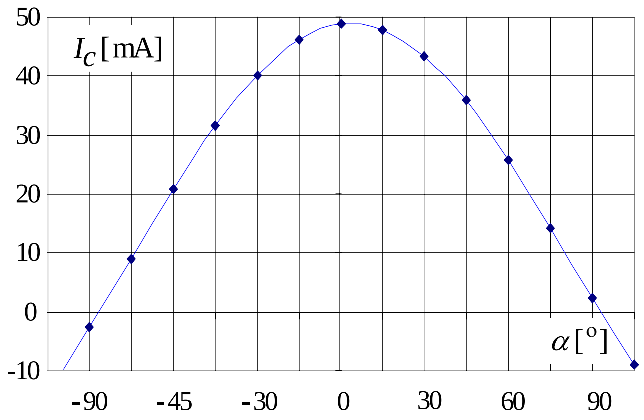

Fig. 7. Compensating current I_c vs. angular arrangement of the sensor in relation to the magnetic field produced by Helmholtz coils for α angle, when $\beta = 0°$

Fig. 8 shows the dependence being analogous to that of Fig. 7 with the difference that α angle represents here the independent variable and $\alpha = 0°$.

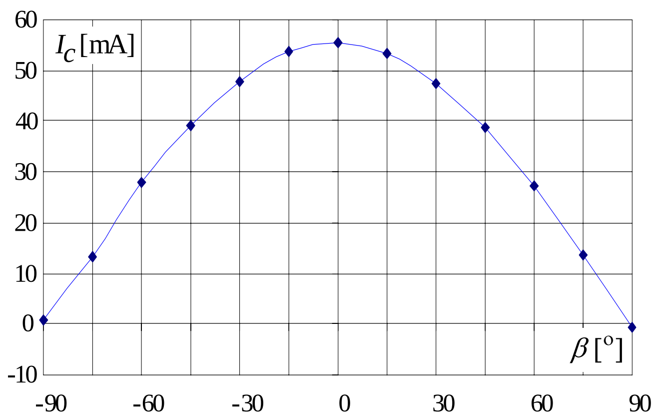

Fig. 8. Compensating current I_c vs. angular arrangement of the sensor in relation to the magnetic field produced by Helmholtz coils for α angle, when $\alpha = 0°$

As may be seen, the dependences shown in Fig. 7 and Fig. 8, have a cosine-like form and are wholly symmetric. Some departure from the cosine form is a result of inaccuracy the angular position of the sensor is set up.

Figure 9 illustrates how the sensor sensitivity depends on the magnetomotive force $\Theta_v = I_v N_v$, which creates the virtual air-gap. Measurements have been made in a magnetic field of 280 A/m.

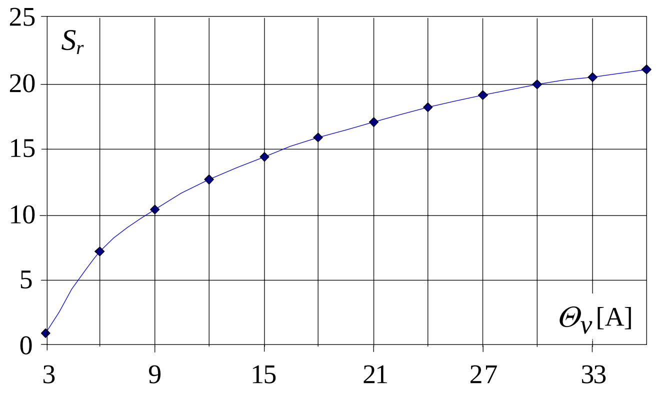

Fig. 9. Relative sensitivity S_r (in relation to its value for Θ_v = 3 A) vs. magnetomotive force Θ_v

As may be seen, the relative sensitivity S_r increases nonlinearly with increasing magnetomotive force Θ_v. For $\Theta_v \leq 3$ A it is considerably lower and then the sensor characterizes instability of the zero level and the sensitivity.

From tests having been carried out the sensor's output may be defined approximately in the following way:

$$I_c \approx \frac{k\ S(\Theta)}{N_c} H \cos\alpha \cos\beta \qquad (1)$$

where

k is a coefficient correcting for the core geometrical dimensions,

$S(\Theta_v)$ is an empirically given coefficient following from the relation between the sensitivity and the magnetomotive force (Fig. 9),

α and β are angles that define the sensor's position in relation to the magnetic field lines (Fig. 6),

N_c is the number of compensating turns.

As may be inferred from (1), the output (compensating) current I_c is directly proportional to the field intensity H and the sensor's arrangement in relation to the magnetic field lines. The current also depends on geometric dimensions of the sensor, the magnetomotive force that produces the virtual air-gap, and also on the number of compensating turns N_c.

5. CONCLUSIONS

The air-gap was introduced to achieve stable properties of the magnetic field sensor that is built around a special core. This, however, leads to an irreversible destruction of the core.

Stable and repeatable directional properties of the sensor may be also obtained by introducing a virtual air-gap instead of a physical one. This is made possible thanks to magnetizing only a portion of the core that is made of punchings of a special shape. Such a solution has the advantage that the value of the virtual air-gap can be controlled through changing the level of magnetizing, which corresponds to changing the air-gap length in the case of a physical air-gap.

Such a design has a beneficial effect on sensor's parameters, in particular on:

- sensitivity that can be varied over a much wider range (up to ~20 times) than in the case of the sensor with unseparated magnetic circuits (up to two-fold [8]),
- directional properties of the sensor that are determined by the position of the virtual air-gap,
- the sensor is characterized by high linearity; the nonlinearity error is in the order of some tenths of a percent,
- the compensating current has a cosine-like dependence on the angles the sensor is situated at with respect to the magnetic field lines.

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