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Method for Determining the Measurement Direction of Magnetic Field Sensors

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This paper presents a method for determining angular deviations of magnetic field measurement sensors using changes in the instantaneous value of the magnetic field sweeping the applied sensors. Helmholtz-like compensation coils were used to determine the angles and eliminate the constant component of the magnetic field inside a magnetically shielded room, ensuring the generated field's uniformity. The preliminary measurements and analysis made measuring the relative angles of sensors' deviations possible using an external magnetic field generated by three pairs of coils. The paper shows that the applied solution allows for determining the angles between the sensors with an accuracy of up to several degrees, which can be used to analyze magnetic fields in measurements where the angular deviation of the magnetic field sensors changes depending on the tested object.

topics: fluxgate, optically pumped magnetometer (OPM), direction of the magnetic sensor

1. Introduction

The magnetic field is a vector field, which means that its measurement depends not only on the intensity of the field generated by the source but also on the geometry of the measuring system. The distance of the sensors from the field source affects the induction value measured using magnetic field sensors. The field induction value decreases proportionally to the square of the distance between the source and the sensor. As already mentioned, the magnetic field is a vector field. Therefore, the mutual orientation of the sensor concerning the magnetic field lines also affects the measured magnetic induction values.

Magnetic field sensors, such as fluxgate [1] or *optically pumped magnetometer* (OPM) [2–4], measure the value of the magnetic field induction in a specific axis and direction, which gives the measurement result in the form of the projection of the induction vector onto the sensor's measurement axis at a given measurement point.

In the case of measurements of magnetic activity of tissues, e.g., magnetoencephalography [5], magnetocardiography [6], magnetomyography, etc., magnetic field sensors are placed as close as possible to the expected signal source. Differences in the anatomy of individual people may cause deviations of the measurement axis from the adopted reference system. Using flexible caps [5] or mounting bands can lead to deviations and changes in the orientation of sensors relative to the assumed normal surface (e.g., sphere, cylinder) and changes in their mutual position and orientation.

A method for determining the deviation of sensors using compensation coils was developed to determine the mutual orientation of the measuring axes of magnetometers.

2. Materials and methods

2.1. Methodology

The presented method uses compensation coils that allow for changing the constant value of the magnetic field induction in an area with a volume of about 1 m^3. The magnetic field with the most uniform distribution in this space is generated using pairs of Helmholtz-like coils in three directions (see the diagram of our coils in Fig. 1). Due to slight differences in the size of the coils, the supply current was selected individually for each pair so that each generated a magnetic field with the same induction value when powered from a voltage source with a constant value.

In each of the three directions, a magnetic field is generated with a given course and peak-to-peak values (Fig. 1). Changes in the magnetic field are generated sequentially in each direction. A square

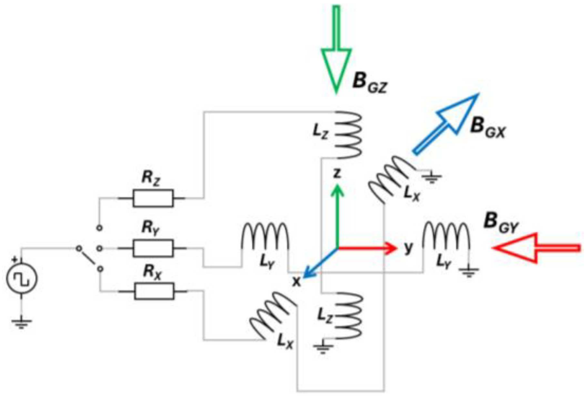

Fig. 1. Diagram of the extortion field generation system used.

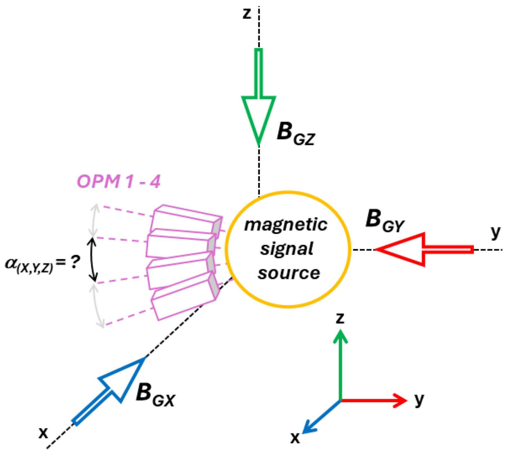

Fig. 2. Diagram of the methodology of the developed solution for determining the angle between OPM 1–4 sensors.

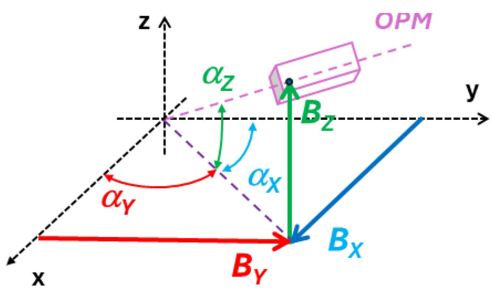

Fig. 3. Diagram of the extortion field generation system used.

waveform with a specified number of cycles and frequency within the measurement band of the sensors is used in the measurements. The rectangular waveform is successively switched in the X, Y, and Z directions, according to the arbitrarily established coordinate system adopted for the coil system.

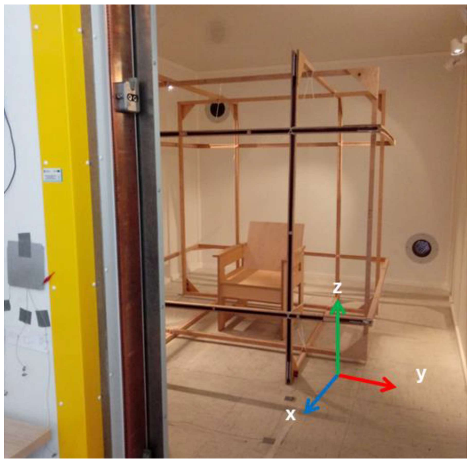

Fig. 4. The compensation coil system placed in the magnetically shielded room, which was used in the experiment with the coordinates system shown.

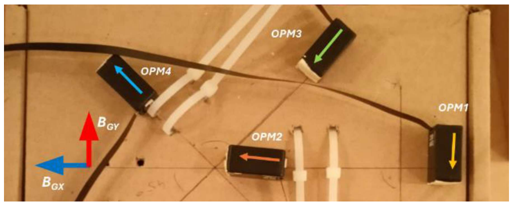

Fig. 5. Photo of the arrangement of the OPM sensors used in the tests of the developed technique, together with the coordinate system concerning the coils generating the excitation and the directions of the OPM sensors' measurements.

The direction of the sensor measurement axis is determined based on the registration of changes in the magnetic field in each of the sensors, with these changes forced in three directions (Fig. 2). Then, based on the observed changes and the value of the field generated by the coils, the angle of the sensor's deviation from the field generated in the coils is determined.

Based on the values of the peak-to-peak changes in the magnetic field observed in each sensor, the angle of the sensor's deviation from the field generated in the coils is determined. Since the field's value generated by the coils in each direction was measured during calibration, it can be taken as a reference value. The magnetic induction recorded by the sensors depends on the angle of the sensor's deviation from the direction of the field generated in the coils. This relationship can be determined for each angle component using equation

$$\alpha_X = \arccos\left(\frac{B_X}{B_{GX}}\right), \qquad (1)$$

in which B_X is magnetic induction measured in the sensor with the change generated on the X-axis, B_{GX} — magnetic induction generated by the coils along the X-axis, α_X — the angle of deviation of

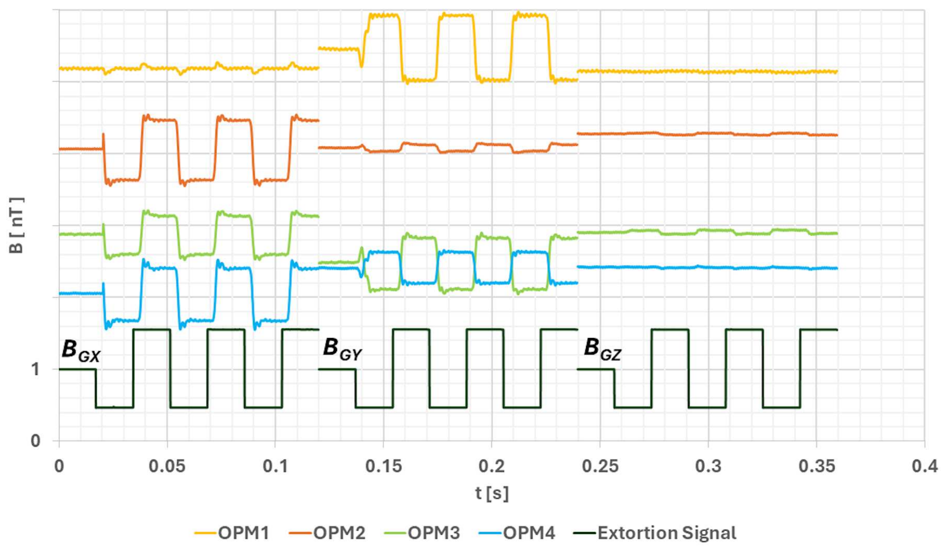

Fig. 6. Waveforms of the extortion magnetic field from specified directions (B_{GX}, B_{GY}, B_{GZ}) and recorded responses in individual sensors (OPM 1–4) in relation to the direction of the forcing field.

the sensor's measurement axis from the X-axis generated by the coils. The angle of deviation from individual axes is determined based on the excitation from the appropriate direction (Fig. 3).

Any parameter of the course of changes in the magnetic field induction can be used to determine the angle. However, in the described solution, the peak-to-peak value of these changes is used. Using the peak-to-peak value allows for independence from field changes resulting from changes in the background magnetic field, which, in the case of amplitude, cause errors in determining the zero value of the field.

Observation of changes in the magnetic field and their measurement using sensors also allows for determining whether the generated field causes the registration of changes in the antiphase or follows the phase of the generated course. This will allow us to precisely determine the sensor's measurement direction.

3. Experimental research

To verify the method in practice, a coil system was used for static reduction of the magnetic field in a magnetically shielded room. The test coils were placed inside the *magnetically shielded room* (MSR). The coil system is shown in Fig. 4.

The OPM sensors were set in the configuration shown in Fig. 5. The image shows the directions of the excitation field using blue and red arrows. The sensors were placed on the XY plane, with different mutual angular deviations.

A measurement sequence of changes in the magnetic field, generated using a microcontroller, was applied to the system prepared in this way. Figure 6 shows the forcing waveform and measurements recorded during each sensor's entire sequence of changes. The microcontroller generated a rectangular waveform consisting of three periods switched successively to the coils in the X, Y, and Z directions. The forcing waveform is marked in black on the graph. The presented data are raw data recorded directly from the sensors without additional processing, such as filtering, averaging, or fitting to a function.

TABLE I

Summary of measurements of angles between sensors based on geometric arrangement and angles determined using the proposed method.

Sensors configuration	Angle values [°]		
	Angles from geometry	Angles measured using the proposed method	Difference
OPM 1–OPM 2	90	95.18	5.18
OPM 1–OPM 3	45	49.92	4.92
OPM 1–OPM 4	135	137.24	2.24
OPM 2–OPM 3	45	45.57	0.57
OPM 2–OPM 4	135	140.76	5.76
OPM 3–OPM 4	90	90.18	0.18

After analyzing the obtained waveforms, the peak-to-peak values were used to determine the angles, calculated based on samples taken just before the generated field change, to minimize the effect of sensor delays.

Table I contains the angles measured based on geometry and the values obtained from measurements using the proposed method. The angles between individual sensors are compared.

A protractor with a scale of 1-degree accuracy was used while constructing the test coil system. To evaluate the results of the method, the angular deviation error was assumed as the sum of the position errors of two sensors, amounting to 2 degrees.

The difference between the values obtained by both methods was calculated to compare the proposed method of determining angles based on changes in the test field with the geometry of the test system.

Analyzing the results presented in the table, it cannot be clearly stated that the differences in the determined angles between sensors obtained by the developed method are within the error limits assumed for the geometry of the sensor layout.

Unfortunately, the results of the method can be influenced by many factors related to the construction of the test system itself and the process of conducting measurements, such as noise in the recorded signal or inaccuracies in the geometry of the forcing coils. The measurement may also be burdened with an error resulting from the inaccuracy of the sensor itself, whose deviation from the measurement axis is unknown.

4. Conclusions

The paper presents the method for determining the deflection angles of magnetic field sensors based on measurements of changes in the induction values recorded by these sensors. Using an external magnetic field with a specific course enabled the determination of angles between the measuring axes of the sensors. The tests and measurements are of a pilot nature, constituting a proof of concept that confirms the validity of continuing work in this direction.

The developed method can have practical application in the measurement of magnetic fields, where the variable geometry of the object causes changes in the angular setting of the magnetic field sensors.

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