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Project of Absolute Three-Component Vector Magnetometer Based on Quantum Scalar Sensor

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Abstract

A project of vector magnetometer of new kind based on optically pumped quantum M_x-sensor placed in symmetrical magnetic coils system is proposed and mathematically proved. The device uses a new method of the fast precision measurement of three Earth magnetic field (EMF) vector components providing absolute accuracy of the order of 0.1 nT at 0.1 s sampling rate. Absoluteness here implies that the process of measurement changes the measured parameter, i.e., field component value, no more than by the value determined by the sensitivity of scalar sensor. The short-term resolution of the method is determined by the M_x-sensor sensitivity.

1. Introduction

There are different systems using for measuring magnetic field vector a scalar sensor placed into the coil system, (i.e., Fairweather 1972). Particularly, it is well known that any component of magnetic field can be measured by measuring the field scalar value – provided that two orthogonal components are compensated down to zero with a special magnetic coils system. This method does not require high compensation accuracy, since according to vector addition rules the contribution of small residual orthogonal component is to high extent suppressed in the presence of a big non-compensated component.

However it is difficult to build a real three-component device based on this method because the compensation of any field component requires relatively strong compensating magnetic field; therefore, procedures of measuring of three field components by this method must be separated in space or in time. Besides, a very fast scalar magnetometer is needed in order to follow field jumps arising when switching from one component measurement to another.

The main point of the method proposed here lies in creation of a system of compensating fields around the sensor, harmonically changing in such a way that the total field vector in the sensor would rotate, keeping its length, around the initial field direction and during each rotation cycle would pass through three different points, two components of the field in each compensated with high accuracy and third component not compensated at all so it can be measured.

As a scalar device we propose cesium or potassium optically pumped magnetometer registering oscillating signal of transverse magnetization of the atoms in the cell – so-called quantum M_x-magnetometer, characterized with high accuracy and speed.

The suggested method is applicable to wide field range, though its application for precise measuring of EMF components is most obvious, because of EMF high homogeneity and relatively small variations.

The mathematical model of the magnetometer based on these principles was built and the behavior of the device was modeled numerically. Numerical modeling shows that using standard Cs sensor with 20 nT resonance linewidth one can achieve about 0.015 nT r.m.s. sensitivity in each field component at 0.1 s sampling rate, accompanied by 0.1 nT absolute accuracy – provided that coil constants do not vary by more than 100 ppm and coil axes directions do not vary by more than 0.6".

2. Description of the Method

The scalar quantum sensor is supposed to be placed in the center of a symmetric three-component system of magnetic coils. The system is oriented so that both the principal diagonal of the cube inscribed into the system of coils and the symmetry axis of the sensor are directed along the Earth magnetic field $\mathbf{H}_0$. The coordinate system we choose is rigidly bound to the axes of the coil system, so all three components of the Earth magnetic field vector in this coordinate system are initially equal in magnitude: $H_X = H_Y = H_Z = |\mathbf{H}_0| / \surd 3 = H_0$.

The field H_{ACi} in each coil ($i = X, Y, Z$, the subscripts AC indicate oscillating values) is initially chosen to provide complete compensation for the relevant component of the Earth magnetic field $\boldsymbol{H}_i$. In practice, the initial choice of the fields and the orientation of the coil system are implemented using a priori information about the measured field vector. After that, all the components are being automatically compensated using a system of feedback loops.

When the compensating fields are turned on simultaneously in all three coils, the total field at the sensor vanishes. Switching the field of the i-th coil off ($i = X, Y, Z$) leads to the appearance of the corresponding uncompensated i-th component which can be measured by the sensor. The accuracy of the measurement, in this case, is by a few orders of magnitude higher than the accuracy of compensation for the orthogonal components of the field, because the contribution ΔH of the uncompensated orthogonal component ΔH_i is proportional to 1-cos(α), where α is a small angle ($\alpha \sim \Delta H_i / H_i$).

Taking as an example the measurement of the X-component, let us estimate the requirements to the accuracy of the transverse component compensation. Let us assume that the module of the measured field equals 50000 nT, so the mean value of any field component $|\boldsymbol{H}_i| = |\boldsymbol{H}_0|/\sqrt{3} \approx 28867$ nT, and the error introduced into the measurement of the X-component due to inaccuracy in compensation for the Z-component should not exceed $\Delta H_x = 0.1$ nT. Therefore, the maximum value of the field in the Z-component is $\Delta H_z = H_i \cdot \sin[\arccos(1\text{-}\Delta H_X / H_X)]$; in the presence of two components that are simultaneously not completely compensated, $\Delta H_Y = \Delta Hz = 54$ nT. In other words, the relative error of the transverse component compensation may reach $1.8 \cdot 10^{-3}$. It means that the coil system may be manufactured using any material that provides constancy of geometrical shape of the system (orthogonality of the coils) with no special requirements to the size stability of the coil system.

A cycle of such measurements over $i = X, Y, Z$ will provide full information about all three components of the field. This information, in turn, is used to adjust the values of the compensating fields H_{ACX}, H_{ACY}, H_{ACZ} in the coils X, Y, Z by means of three feedback loops.

The next step consists in changing from discrete measurements of the field to continuous or quasi-continuous measurements: we make the field rotate continuously or quasi-continuously (discretely, with a small step) in such a way that three points on the rotating vector hodograph meet the above conditions $H_{Aci} = 0$ $(i = X, Y, Z)$. The total magnetic field vector, in this case, is always tilted by 35.2° with respect to the axis of optical pumping of the M_x-magnetometer. Thus, one may provide continuity of locking the resonance, and real measurements are made in three points of the rotation circle. It is important that the measurement of the component H_i is performed, as before, at the moment when the corresponding compensating field H_{ACi} is turned off, and only the compensating fields orthogonal to H_i are on. In this way, the absolute measurements of the field components are realized.

3. Discussion

Let us discuss the main drawbacks of this method and possible ways of their elimination:

1. The requirements to orthogonality of the coils are rather severe, namely, the limitation of the error by the value 0.1 nT leads to the requirement on orthogonality of the coil axes on the level of $3 \cdot 10^{-6}$ or 0.6″ which can be hardly achieved. Therefore, the non-orthogonality of the coils in the system should be measured periodically and should be compensated electronically. Then the estimate of 0.6″ will refer to variation of the angles between the coils of the system. The procedure of calibration of the systems characterized by a no ideal orthogonality of the axes is described in (Merayo 2000).

2. The inertness of the magnetic coils and of the sensor will lead to a delay in the measurement of the magnetic field and, as a consequence, to a shift of the points on the circle in which the measurements are made. Negative effect of this delay is rather small, but if the system is required to be fast, the most efficient way to suppress the effect of this delay is to create conditions when the direction of the magnetic field constantly coincides with the principal axis of the system.

3. The constancy of the module of the magnetic field upon its rotation holds only for small angular deviations of the measured magnetic field from the axis of the coil system. For large angular deviations of the field, the rate of variation of the field module upon its rotation increases which may reduce the accuracy of the measurements. Two last drawbacks may be eliminated by continuous compensation for the field variations using (a) slow compensating fields H_{DCi} of the coils – in this case, the method partly loses its absoluteness, or (b) using a mechanical servo-system. This last method does not affect the absoluteness of the measurements, but is much more complicated.

In both cases, the additional slow feedback systems provide constancy of the total magnetic field module in all points of the rotation circle. The closely lying points of the circle become equivalent; this fact strongly mollifies the requirements to the accuracy of choosing the points on the circle and makes it possible to pass from measuring the magnetic field in three points on the circle to measuring on the whole circle detecting vector signal from this measurement.

4. The rotation of the magnetic field at a frequency of ω around the axis of the M_x-sensor is known to cause a shift of the measured field strength by the value $\pm\omega/\gamma$ (where γ is the gyromagnetic ratio) depending on the rotation direction (the so-called gyroscopic effect). However, since the rotation rate is known, this effect can be easily taken into account without the loss of the accuracy of the measurements.

4. Numerical Simulation

We have numerically tested two models: (1) with the measurements in three points of the circle and (2) with synchronous detection of the signal over whole circle as mentioned above. Both models were examined: (A) with no system of compensation for the field variations and (B) with the systems of compensation. It was assumed that the compensation for the field variations and the field modulation are performed using the same coils.

We simulated the systems with a potassium sensor with the resonance line width $\Gamma = 1$ nT, as well as the systems with a cesium censor ($\Gamma = 20$ nT) characterized by the intrinsic short-term sensitivity $\sigma_{0.1\mathrm{s}} = 10$ pT r.m.s. As expected, the use of the sensor with a broad resonance line, at the expense of reduced sensitivity, provided advantages both in the width of the frequency locking range and in the field tracking speed.

Our test showed the best results when using model 2B (signal detection over the whole modulation period and with the field variation compensation) with Cesium censor; it has shown the following values of the parameters:

- absolute accuracy $|\delta H_i| = 0.1$ nT;
- response time $\tau = 0.1$ s;
- short-term (0.1 s) sensitivity in the field components $\sigma_i = 0.015$ nT r.m.s.;
- the range of tracking of the field variations $|\Delta H_{i\mathrm{max}}| > 1000$ nT;
- the maximum allowable variation of the angle between coils $|\Delta\beta| = 0.6''$;
- the maximum allowable drift of the magnetic coil system: $|\Delta k_{i\mathrm{max}}|$=115 ppm.

When using a mechanical servo-system instead of electronic system of compensation for the field variations, the admissible drift of the magnetic coil system may reach ±1350 ppm.

5. Conclusion

The numerical tests of the new method show that, using an optically pumped M_x-magnetometer and a three-component symmetric magnetic coils system, it is possible to simultaneously measure all three components of the Earth magnetic field with an absolute accuracy of ±0.1 nT short-term (0.1 s) and sensitivity of 0.015 nT r.m.s at 0.1 s time.

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