Studying the atomic gyroscope magnetic shield residual magnetization by comparing parametric resonance signals

V.V. Chalkov¹, A.N. Shevchenko²

¹Student, ITMO University, Concern CSRI Elektropribor, JSC, Saint Petersburg, Russia
²Head Researcher, Deputy Head of Laboratory, Concern CSRI Elektropribor, JSC, Saint Petersburg, Russia

E-mail: rztbro@gmail.com

Abstract. The paper presents an algorithm for measuring the residual magnetic field in the magnetic shield of a quantum rotation sensor, which is based on the analysis of cesium parametric resonance signal. The effect of the residual magnetic field in the magnetic shield of the passive shielding system of an atomic gyroscope on its performance is investigated. The form of cesium parametric resonance is analysed. The results of experimental verification of the algorithm are presented to confirm its effectiveness.

Introduction

Today, the question of development and application of new types of gyroscopes is relevant more than ever. This work addresses the problems associated with the development of atomic gyroscope. Like in any precision gyroscope, it is essential for stable operation that the value of magnetic field induction within its sensitive element (SE) does not depend on the external magnetic field [1]. A typical solution for reducing the influence of external magnetic fields is a passive shielding system and an active system for magnetic fields compensation, based on magnetic coils which create a compensatory magnetic field. One of the important problems while creating effective shielding is the presence of residual magnetization of the magnetic shield. Large value of the residual magnetic field induction can lead to inhomogeneity of the magnetic field within the SE. Such heterogeneity negatively affects the degree of polarization of the working medium. Lower degree of polarization reduces the possibility for a macro precession spin to be created within the atomic gyroscope SE, which can result in inoperability of the atomic gyroscope. Based on the above factors, it is necessary to regularly monitor the value of the residual magnetization and check that the maximum permissible value of 50 nTl is not exceeded. If this value is exceeded, the magnetic shield needs to be demagnetized to remove the excessive residual magnetization. If the value of the residual magnetic field induction does not exceed the permissible value, it is possible to take the residual magnetization into account.

The required accuracy of the residual magnetization measurement in atomic gyroscope shields is at the level of several nTl. The measurements should be taken with a measuring device with a miniature...
probe, since it is required to measure the magnetization of both the entire atomic gyroscope structure and its individual elements. Due to the above factors, the residual magnetization cannot be measured with the existing magnetometers. This work is an attempt to develop a method for indirectly measuring the residual magnetization of a shield using the signals generated by the atomic gyroscope, in particular, the parametric resonance signal of an alkali metal vapor contained in the gas mixture of the SE cell. In this case, the alkali metal is cesium.

**Studying the atomic gyroscope magnetic shield residual magnetization**

The subject of the research is an atomic gyroscope being developed for navigation tasks. The principle of operation of such a sensor consists in detecting the angular rate of rotating ensemble of a noble gas atoms, with the result further used for calculating the angular rate of the device rotation (Fig. 1), based on the known values of the gyromagnetic ratio, the magnitude of which shows the ratio of the magnetic moment of an elementary particle to its angular momentum, magnetic field induction, and the observed Larmor precession frequency for the species used [2]:

$$\Omega = B \cdot \gamma - \omega,$$

where $\Omega$ is the rotation speed of the base; $B$ is the magnetic field induction; $\gamma$ is gyromagnetic ratio; and $\omega$ is the observed Larmor precession frequency.

In order to detect the rotation speed of the base, it is necessary to pump the noble gas. Pumping is achieved due to spin transfer from an alkali metal to a noble gas via spin exchange. The alkali metal vapor receives the spin using a pump laser. After that, the detection laser will be able to detect the rotation speed of the base.

To study the residual magnetization of the shield, the sensor was used in the mode of cesium magnetometer [3–6] with a modified detuning circuit. In the classical version of this magnetometer, the signal frequency is detuned by alternating magnetic field frequency offset from the resonance. In the proposed method, detuning is performed by changing the value of the constant magnetic field induction. Based on the study of the coil’s and shield’s magnetic field effect on the cesium atoms, as well as changes in the direction of the constant magnetic field created by the coil, caused by the multidirectional currents supplied to the coil, it becomes possible to determine the residual magnetic field in the shield using the following set of equations:

$$\begin{align*}
B_{\text{res}} &= K_{\text{coil}} \cdot I_z + B_{\text{rad}}, \\
B_{\text{res}} &= K_{\text{coil}} \cdot I_z - B_{\text{rad}}.
\end{align*}$$

(2)

where $B_{\text{res}}$ is a theoretical value of the constant magnetic field strength at cesium resonance; $K_{\text{coil}}$, $B_{\text{rad}}$ are the sought coil coefficient and the value of the residual magnetic field of the shield, respectively; and $I_z$ are the values of currents supplied to the coil, at which cesium resonance is observed (resonance centers).

Unknown current values $I_z$ can be calculated by approximating the cesium resonance signal $U_{\text{mes}}$ coming from the measuring channel of the atomic gyroscope photodetector (Fig. 2).

The experimental data $I_z$ from the photodetector measuring channel were approximated using a dispersion curve [7] with additional terms:

$$y_i = \frac{a \cdot (I_{zz} - I_{zz}) + b}{(I_{zz} - I_{zz})^2 + \lambda^2} + y_0, \quad i = 1, n,$$

(3)

where $I_{zz}$ are the sought current values corresponding to the center of cesium resonance line; $y$ is approximation of cesium resonance signal; $a$ is the unknown value of the amplitude of cesium resonance signal; $I_z$ is the current supplied to the coil; $\lambda$ is the unknown half-width of cesium resonance signal line; $y_0$ is the unknown constant component of the cesium resonance signal; and $b$ is the term used for compensating for the magnetic field unbalance.
The approximation parameters were selected using the generalized reduced gradient method [8] from the criterion minimization condition:

$$
\varepsilon = \sum_{i=1}^{n} (U_{\text{mes},i} - y_i)^2,
$$

(4)

where $U_{\text{mes}}$ is the photodetector signal value obtained during the experiment.

It is important to note that approximation using a dispersion curve is not always optimal in terms of reducing the criterion (4). If the coils of the magnetic field active suppression system do not properly compensate for the external magnetic field, then the graph of the current collector signal (Fig. 2) will have a different shape due to the influence of the term $b$ in (3). To take this factor into account, it is necessary to evaluate the term $b$ and introduce it in the equation of the dispersion curve.

The performed approximation allowed us to calculate the values $I_{\pm z}$, using which, taking into account the expression (2), the values $K_{\text{coil}}$ (5) and $B_{\text{rad}}$ (6) were calculated:

$$
K_{\text{coil}} = \frac{2B_{\text{res}}}{I_{+z} + I_{-z}},
$$

(5)

$$
B_{\text{rad}} = \frac{1}{2} \cdot (K_{\text{coil}} \cdot I_{+z} - K_{\text{coil}} \cdot I_{-z}).
$$

(6)

The data resulting from a series of measurements of residual magnetization are summarized in table 1. If the residual magnetization did not exceed the permissible value of 50 nTl, demagnetization was not carried out. After each experiment in which the value of the residual magnetic field exceeded the permissible value, the operation of demagnetization was carried out with subsequent assembly and measurement of the residual magnetization.

**Table 1**

| Pos. no. | $I_{+z}$ mA | WidCs + | $I_{-z}$ mA | WidCs - | $K_{\text{coil}}$ nTl/mA | $B_{\text{rad}}$, nTl | Demagnetization done |
|----------|--------------|---------|--------------|---------|--------------------------|----------------------|---------------------|
| 1        | 2.783        | 0.110   | -2.794       | 0.105   | 3.587                    | -19.47               | No                  |
| 2        | 2.806        | 0.102   | -2.798       | 0.103   | 3.576                    | 29.91                | No                  |
| 3        | 2.769        | 0.099   | -2.846       | 0.107   | 3.563                    | -136.45              | Yes                 |
| 4        | 2.800        | 0.109   | -2.795       | 0.092   | 3.577                    | 8.76                 | No                  |
| 5        | 2.818        | 0.035   | -2.833       | 0.037   | 3.540                    | -25.26               | No                  |

Fig. 2. Graph of the photodetector current signal and its approximation
It follows from the table 1 that demagnetization is not always necessary. In most experiments, the magnitude of residual magnetization makes it possible to compensate for it by changing the current supplied to the arms of the coils forming the field of the sensitivity axis.

### Conclusions

In the course of work, the presented results have been obtained, confirming the possibility of measuring the residual magnetic field strength in the magnetic shield of a quantum rotation sensor, using cesium parametric resonance signals. The corresponding algorithm has been described. The effect of the residual magnetic field in the magnetic shield of the passive shielding system of an atomic gyroscope on its performance has been described. By taking the measurements, it is possible to quickly estimate the degree of the magnetic shield magnetization and to take a decision whether demagnetization process is required. The possibility of making such a decision positively affects the speed and quality of further experiments.

### REFERENCES

1. Kislitsyna, E.A. and Shevchenko, A.N., Magnetic field gradient requirements determination to identify a nuclear magnetic resonance gyroscope metrological characteristics, *Almanac of the ITMO University Young Scientists Scientific Papers*, St. Petersburg, 2018, pp. 176–179.

2. Vershovskii, A.K., Litmanovich, Yu.A., Pazgalev, A.S. and Peshekhonov, V.G., Nuclear magnetic resonance gyro: ultimate parameters, *Gyroscopy and Navigation*, 2018, vol. 9, no. 3, pp. 162–176.

3. Aleksandrov, E.B. and Vershovskii, A.K., Modern radio-optical methods in quantum magnetometry, *Physics–Uspekhi*, 2009, vol. 52, no. 6, pp. 573–601.

4. Ding, M., Development and prospects of quantum sensing technology, *Proc. 20th Conference of Young Scientists "Navigation and Motion Control"*, Concern CSRI Elektropribor, St. Petersburg, 2018, pp. 21–22.

5. Riehle, F., Frequency Standards: Basic and Applications [Russian translation], Moscow: Fizmatlit, 2009.

6. Loesche, A., Nuclear Induction [Russian translation], Moscow: Inostrannaya literatura, 1963.

7. Farrar, T.C. and Becker, E.D., Pulse and Fourier Transform NMR: Introduction to Theory and Methods, New York: Academic Press, 1971.

8. Baryshev, A.V. and Fedotova, E.F., Finding optimal solutions for linear programming decision problems using Microsoft Excel Solver Add-in, *Naukovedenie Internet Journal*, 2015, vol. 7, no. 3(28), p. 88.