Automatic compensation of magnetic field for a rubidium space cold atom clock*

Lin Li(李琳), Jingwei Ji(吉经纬), Wei Ren(任伟), Xin Zhao(赵鑫), Xiangkai Peng(彭向凯), Jingfeng Xiang(项静峰), Desheng Lü(吕德胜)†, and Liang Liu(刘亮)‡

Key Laboratory for Quantum Optics and Center of Cold Atom Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, *China*

(Received 25 February 2016; revised manuscript received 5 April 2016; published online 1 June 2016)

When the cold atom clock operates in microgravity around the near-earth orbit, its performance will be affected by the fluctuation of magnetic field. A strategy is proposed to suppress the fluctuation of magnetic field by additional coils, whose current is changed accordingly to compensate the magnetic fluctuation by the linear and incremental compensation. The flight model of the cold atom clock is tested in a simulated orbital magnetic environment and the magnetic field fluctuation in the Ramsey cavity is reduced from 17 nT to 2 nT, which implied the uncertainty due to the second order Zeeman shift is reduced to be less than 2×10^{-16}. In addition, utilizing the compensation, the magnetic field in the trapping zone can be suppressed from 7.5 μT to less than 0.3 μT to meet the magnetic field requirement of polarization gradients cooling of atoms.

Keywords: laser cooling, space cold atom clock, magnetic field compensation

PACS: 32.30.Bv **DOI:** 10.1088/1674-1056/25/7/073201

1. Introduction

In the past two decades, the accuracy and stability of atomic fountain clock based on laser cooling technology have been improved by several orders of magnitude.[1–4] Due to the gravity on the earth, the interaction time of the fountain clock operated on the ground is limited by the height of the fountain. In the microgravity environment in space; however, the atoms can be cooled and then launched more slowly and the interaction time can be largely increased. The expected fractional frequency stability can be $\sim10^{-13}\tau^{-1/2}$, where τ is the integration time, and the frequency uncertainty could be up to the order of 10^{-16}.[5] For the demonstration of cold atom clock operation in microgravity, we have developed an ^{87}Rb space cold atom clock (SCAC) which will be operated in near-earth orbit.[6] Different from the magnetic environment on the ground, the amplitude and direction of the external magnetic field in space alter periodically which manifests itself mainly in the ultra-low frequency domain (about 90 min in period and about 40 μT in amplitude). Three parts of the SCAC are sensitive to the fluctuation of magnetic field. First, the fluctuation of magnetic field in the Ramsey cavity will inevitably contribute to the frequency shift of the clock transition via the second-order Zeeman effect.[7] To achieve a fractional frequency uncertainty of the order of 10^{-16}, the fluctuation of the magnetic field in the Ramsey interaction zone should be less than 4 nT. Second, the fluctuation of the magnetic field in the magneto-optical trap (MOT) over 1 μT may affect the temperature of the cooled atom sample,[8] which is cooled to several microkelvins by polarization gradients cooling. Third, the magnetic field direction cannot be reversed and the field gradient remains low to avoid frequency mixing between the transitions due to the Majorana transitions.[7] Typically, the rubidium tube of the fountain clock on the ground is surrounded by multilayer magnetic shields to attenuate the magnetic field. The results obtained from the experiments on the shields of the SCAC flight model show that the axial magnetic field attenuation resulted from the three layers of static shields alone is not sufficient to satisfy the mission requirements. One choice to further improve the magnetic shielding factor is to add more magnetic shields. However, because of mass limitation in space application, an active compensation system of magnetic field is requisite to reducing the fluctuation of the magnetic field in MOT and the Ramsey cavity in the near-earth orbit. The PHARAO project of European Space Agency (ESA) established a complicated mathematical model for the magnetic compensation,[7,8] which is based on their magnetic architecture of a cesium clock and the position of the magnetic sensor.

In this work, we present extensive measurements performed on the magnetic shield of the SCAC flight model. By the optimized choice of the sensor position, a simple model is developed to describe the magnetic fluctuation in the shields. Based on the model, an active magnetic field is used to suppress the magnetic hysteresis by the combination of linear and incremental compensation. After the SCAC assembly and

*Project supported by the Ministry of Science and Technology of China (Grant No. 2013YQ09094304), the Youth Innovation Promotion Association, Chinese Academy of Sciences, and the National Natural Science Foundation of China (Grant Nos. 11034008 and 11274324).

†Corresponding author. E-mail: dslv@siom.ac.cn

‡Corresponding author. E-mail: liang.liu@siom.ac.cn

© 2016 Chinese Physical Society and IOP Publishing Ltd

space qualification tests, we have verified the magnetic properties by operating the clock to the hyperfine transition frequency which is linearly proportional to the magnetic field. The fluctuation of the magnetic field in the Ramsey cavity is reduced to 2 nT to meet the mission requirement.

2. Experimental setup and compensation method

The magnetic architecture of the SCAC is shown in Fig. 1. The rubidium tube is composed of the MOT, the state selection cavity, the Ramsey cavity and the detection zone. The ^{87}Rb atoms are cooled and trapped in the MOT, and then launched by moving molasses. The cold atom sample interacts with two $\pi/2$ microwave pulses in the a-zone and b-zone of the Ramsey cavity during the flight. Finally, the population of the ground state hyperfine structure is detected by resonance fluorescence. The rubidium tube is surrounded by three cylindrical Mumetal shields: inner shield S1, middle shield S2, and outer shield S3. The thickness, length, and diameter of the S1, S2, and S3 in mm are (1, 450, 150), (1, 720, 200), and (1, 900, 250), respectively. Two ion pumps for vacuum sustaining are installed outside the shields. Only the Ramsey cavity is installed in the inner shield S1, and the C-field coil C1 is wound around the Ramsey cavity to provide the offset C-field about 100 nT. The MOT is between the outer shield S3 and the middle shield S2, and a compensating coil C4 is wound around the MOT. The selection cavity is placed in the middle shield S2, and the coil C3 is wound around the selection cavity for providing the field for state selection and C4 is placed between the preparation cavity and Ramsey cavity to ensure no zero magnetic fields. Two magnetic fluxgates (F1 and F2) are placed inside the magnetic shield. The fluxgate F1 is used for detecting the fluctuation of the magnetic field in the shield induced by the external magnetic field. It is placed in the middle shield beside the detection zone where the fluxgate is spatially separated from the Ramsey cavity and is hardly affected by the C-field coil C1 and other compensating coils. The other fluxgate F2 is besides the state selection cavity, which is used to monitor the magnetic field if the zero crossing occurred after the state selection. The active magnetic field compensation is a feed-forward system which is composed of the magnetic fluxgate F1 and the compensation coils. The magnetic fluxgate F1 is used to detect the fluctuation of the magnetic field inside the magnetic shield, and then the current in C1 for C-field compensation and C4 for the MOT field is controlled for compensation.

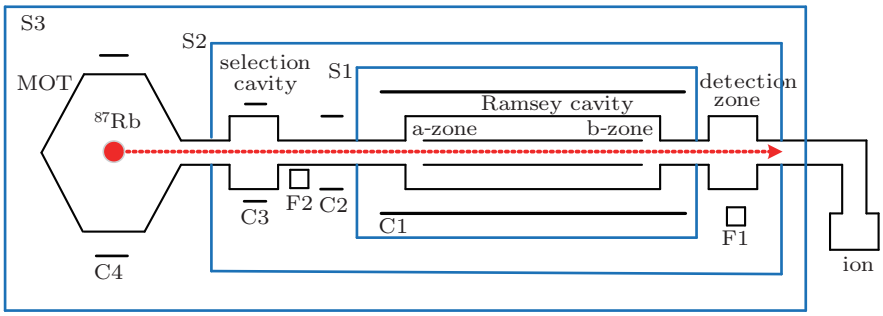


Fig. 1. (color online) The magnetic architecture of the SCAC. MOT: magneto-optical trap; S1: inner shield; S2: middle shield; S3: outer shield; C1: C-field coil wound around the Ramsey cavity; C2: coil wound between the state selection cavity and the Ramsey cavity; C3: coil wound around the state selection cavity; C4: coil wound around the MOT; F1: magnetic fluxgate as a sensor for compensation; F2: magnetic fluxgate; ion: ion pumps used to maintain the vacuum.

Then, the fluctuation of magnetic field is measured by altering the external magnetic field to simulate the near-earth orbit environment (about 90 min in period and 40 μT in amplitude). The fluctuations of magnetic field in the MOT, at the fluxgate, and in the Ramsey cavity are measured by a commercial magnetometer (Mag-01), as shown in Fig. 2(a). The fluctuation of magnetic field is measured about ±3 μT in the MOT, ±0.9 μT at the fluxgate F1, and ±10 nT in the Ramsey cavity. The fluxgate F1 as a sensor for the automatic compensation is placed near the detection zone. Figure 2(b) shows the fluctuations of magnetic field at the a-zone and b-zone in the Ramsey cavity, which represents a good homogeneity in the inner shield.

According to the Preisach model, the magnetic hysteresis loop induced by an unsaturated periodical field can be described as the minor loop.[10,11] The magnetic hysteresis inside the magnetic shields is mainly induced by the outer shield S3.[12] We have measured the magnetic field in the MOT, at the fluxgate F1 and in the Ramsey cavity as a function of the external magnetic field, respectively, which manifest the similar shapes, as shown in Fig. 2(a). It can be assumed that the fluctuation of magnetic field at a given position inside only the outer shield S3 has a linear dependence vs. the magnetic field at the fluxgate. Furthermore, the middle shield S2 and inner shield S1 can lead to a linear attenuation and a residual magnetic hysteresis. Therefore, the fluctuation of magnetic field C at a given position can be expressed as

$$C = (aC_{\mathrm{F}} + b) + \Delta C'_{\mathrm{C}}, \tag{1}$$

where C_F is the magnetic field at the fluxgate F1. The first term $(aC_F + b)$ indicates the linear term, and the second term $\Delta C'_C$ denotes the residual field which is induced by the shield S1 or S2. The coefficients a and b are determined by a linear fitting of C versus C_F. We also compared the measured magnetic hysteresis of the a zone and b zone of the Ramsey cavity as shown in Fig. 2(b), and find they are almost the same. One can conclude here, the residual magnetic hysteresis induced by the inner shield is spatially independent. The residual field $\Delta C'_C$ can be calculated from subtracting the linear term from C and further suppressed by the incremental compensation. The incremental compensation coefficients α can be derived by linear fitting the residual field with the incremental change of the fluxgate's magnetic field,

$$\Delta C'_C = \alpha \Delta C_F, \tag{2}$$

where $\Delta C_F = C_{Fn} - C_{F(n-1)}$.

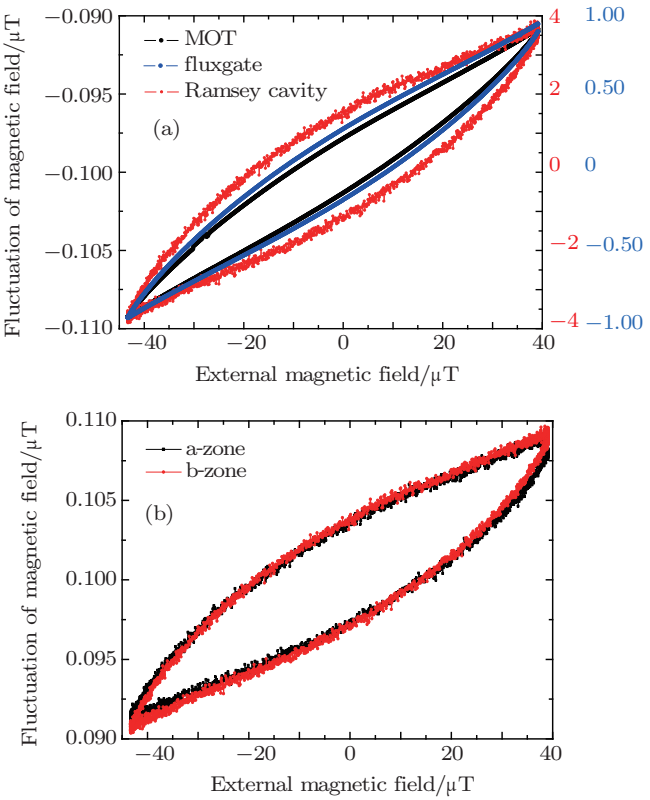


Fig. 2. (color online) (a) Fluctuation of magnetic field inside the magnetic shields versus external magnetic field altering from −40 μT to 40 μT in amplitude. Black: center of the MOT; blue: at the fluxgate F1; red: center of the Ramsey cavity. (b) The fluctuation of magnetic field in the Ramsey cavity versus external field. Black: magnetic field at a-zone; red: magnetic field at b-zone.

For example, the linear term of the fluctuation of the C-field C_C in the Ramsey cavity is calculated from Eq. (1) (see the blue curve in Fig. 3(a)). By the linear compensation, the residual $\Delta C'_C$ is obtained (see the red curve in Fig. 3(a)). After linear compensation, the residual magnetic field has been suppressed from 20 nT to 2 nT. Following the strategy of the incremental compensation represented by Eq. (2), we observed that the residual magnetic hysteresis $\Delta C'_C$ has been further suppressed, as shown in Fig. 3(b). Finally the residual field is reduced by half to about 1 nT. Therefore, the linear compensation is utilized to suppress the magnetic fluctuation linearly dependent to C_F, and the incremental compensation is used to further suppress the residual field. The magnetic hysteresis of the magnetic field can be subdued by the combination of linear compensation and incremental compensation.

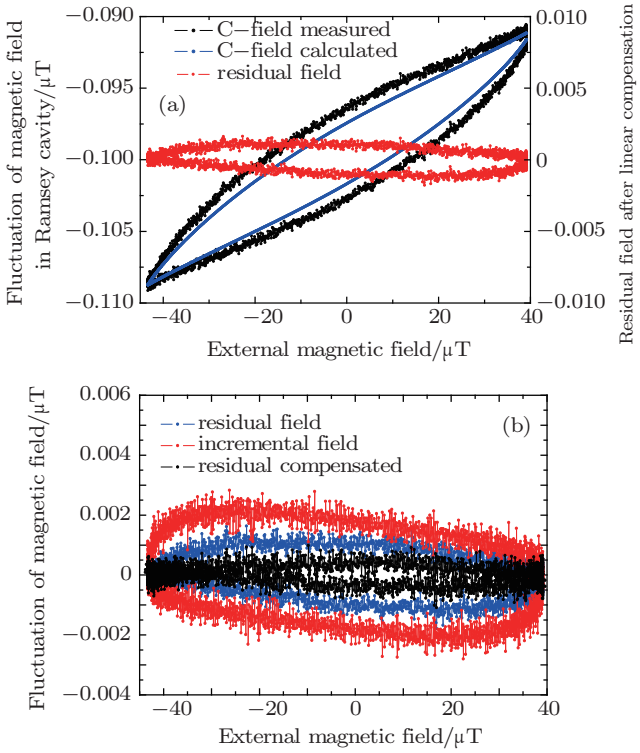


Fig. 3. (color online) (a) The fluctuation of magnetic field in the Ramsey cavity suppressed by linear compensation. Black: measured C-field; blue: C-field calculation from the magnetic field at fluxgate; red: the residual magnetic field. (b) The incremental compensation of the fluctuation of magnetic field in the Ramsey cavity. Blue: the residual magnetic field compensated after the linear compensation; black: the magnetic field compensated after the incremental compensation; red: the incremental field $C_{Fn} - C_{F(n-1)}$.

3. Results and discussion

To verify the compensation strategy mentioned above, we have built a device to simulate the variation of the magnetic field in near-earth orbit. The SCAC is placed inside four coils which are arranged in parallel with each other. By altering the amplitude and the direction of the current in the coils, we can generate the external magnetic field along the axial direction that is regularly changed as the realistic situation in the near-earth orbit, i.e., each cycle of 90 min with the amplitude of 40 μT.

Firstly, the compensation result in the MOT with above linear compensation is shown in Fig. 4. The fluctuation of the magnetic field in the MOT is measured by a commercial magnetometer. After the compensation, the residual magnetic field in the MOT is less than 1 μT and its fluctuation is less than

0.3 μT when the external field varied as in the near-earth orbit. The suppression factor of the compensation is about 25, which is obtained from the peak to peak ratio of the unsuppressed magnetic field about 7.5 μT and the suppressed magnetic field about 0.3 μT.

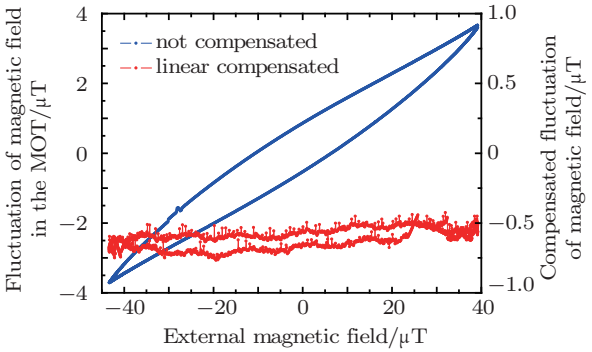


Fig. 4. (color online) The fluctuation of the magnetic field in MOT versus the external magnetic field altering from −40 μT to 40 μT. Blue: the magnetic field in the center of the MOT before compensation; red: the magnetic field in the center of the MOT after linear compensation.

Simultaneously, the C-field in the Ramsey cavity is also compensated and the result is shown in Fig. 5. The magnetic field in the cavity is also directly measured by a commercial magnetometer. A bias current of 1.2 mA is fed to the C-field coil to provide a bias C-field about 100 nT to lift quantum state degeneracy. With the linear fitting of the C-field versus the fluxgate data, we obtain $a = 0.0096$ and $b = 0.1003$; with the fitting residual field from the incremental field of fluxgate' field $C_{Fn} - C_{F(n-1)}$, we can get $\alpha = 0.36$. Then, by the combination of linear and incremental compensation, the peak to peak C-field fluctuation C_C is reduced from about 20 nT to 3 nT with the external field varying as in the near-earth orbit. Consequently, the suppression factor is about 6.

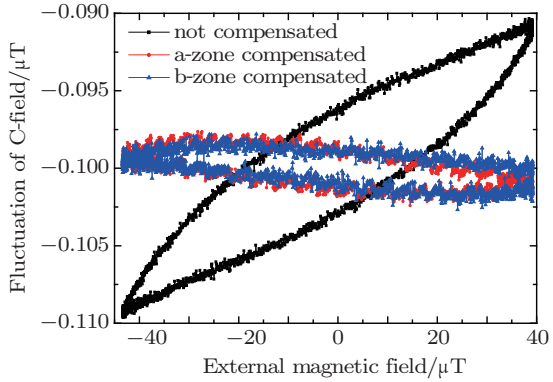


Fig. 5. (color online) The fluctuation of the C-field versus external magnetic field altering from −40 μT to 40 μT. Black: the magnetic field in the Ramsey cavity before compensation; red: the magnetic field in the a-zone Ramsey cavity after compensation; blue: the magnetic field in the b-zone Ramsey cavity after compensation.

Finally, we test the fluctuation of C-field in the Ramsey cavity using the transition between $F = 1$, $m_F = 1$ and $F = 2$, $m_F = 1$ of the ^{87}Rb, which has a linear dependence on the C-field. The Zeeman frequency shift is about 240 Hz and the corresponding C-field fluctuation is about 17 nT with the external field varying as in the near-earth orbit. While it is suppressed to about 30 Hz and the C-field fluctuation is suppressed to 2 nT with the above compensation method, which coincides with the results measured above. Thus, the second-order Zeeman frequency shift of the clock transition due to the C-field fluctuation can be controlled to only 0.92 μHz and the fractional frequency uncertainty can reach about 1.3×10^{-16}.

4. Conclusion and perspectives

In this work, we have measured the fluctuation of magnetic field inside the magnetic shields of the SCAC. To meet the mission requirement, we have developed a compensation method for reducing the magnetic field fluctuation in the near-earth orbit in space. The magnetic hysteresis is suppressed by the active compensation. The magnetic field fluctuation in the MOT is suppressed to 0.3 μT with a suppression factor about 25, while the fluctuation of the C-field is reduced to 2 nT with an external field varying as in the near-earth orbit. With the compensation, the frequency uncertainty due to second-order Zeeman shift should be improved by an order of magnitude from 10^{-15} to 10^{-16} during the operation around the near-earth orbit in space. More and more atomic sensors, like the atomic interferometer and atomic gyroscope, etc, would be operated in space. In future, the compensation method can also be used in the equipment as they are all sensitive to the magnetic field.

Acknowledgment

The authors would like to thank the Shanghai Maritime University for their support of fluxgates.

References

[1] Guéna J, Abgrall M, Rovera D, Laurent PH, Chupin B, Lours M, Santarelli G, Rosenbusch P, Tobar M E, Li R X, Gibble K, Clairon A and Bize S 2012 *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **59** 391
[2] Ovchinnikov Y and Marra G 2011 *Metrologia* **48** 87
[3] Levi F, Calonico D, Calosso C E, Godone A, Micalizio S and Costanzo G A 2014 *Metrologia* **51** 270
[4] Gerginov V, Nemitz N, Weyers S, Schroder R, Griebsch D and Wynands R 2010 *Metrologia* **47** 65
[5] Laurent P H, Abgrall M, Jentsch C H, Lemonde P, Santarelli G, Clairon A, Maksimovic I, Bize S, Salomon C H, Blonde D, Vega J F, Grosjean O, Picard F, Saccoccio M, Chaubet M, Ladiette N, Guillet L, Zenone I, Delaroche C H and Sirmain C H 2006 *Appl. Phys. B* **84** 683
[6] Lü D S, Liu L and Wang Y Z 2011 *Manned Spaceflight* **1** 47
[7] Vanier J and Audoin C 1989 *The Quantum Physics of Atomic Frequency Standards* (Adam Higger)
[8] Salomon C, Dalibard J, Phillips W D, Clairon A and Guellati S 1990 *Europhys. Lett.* **12** 683
[9] Morić I, Graeve C D, Grosjean O and Laurent P H 2014 *Rev. Sci. Instrum.* **85** 075117
[10] Torre E D 1999 *Magnetic Hysteresis* (IEEE Press)
[11] Sumner T J, Pendlebury J M and Kof S 1987 *J. Phys. D: Appl. Phys.* **20** 1095
[12] Moric I, Laurent P H, Chatard P, Graeve C D, Thomin S, Christophe V and Grosjean O 2014 *Acta Astronautica* **102** 287