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THE EFFECT OF THE MAGNETIC FIELD ON THE SHIELDING EFFICIENCY IN A RUBIDIUM ATOMIC CLOCK

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Abstract. The paper presents the experimental study results of the dependence of the longitudinal shielding coefficient of a magnetic shield (in the direction of the shield axis) on the strengths and mutual orientation of the operational internal and additional external magnetic fields of a small-sized rubidium atomic clock (RAC). In this case, an additional field magnetizes the RAC's magnetic shield from the outside and penetrates inside it. The significant influence of these fields in their interrelation on the shielding properties of the magnetic shield of the RAC has been found. The obtained results allowed us to determine the longitudinal RAC-shielding coefficient at the effective values of the operational and additional magnetic fields and, as a consequence, to compensate for the effect of geomagnetic field variations on the frequency of the onboard RAC.

Keywords: rubidium atomic clock, magnetic field, magnetic screen, longitudinal shielding coefficient

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ВЛИЯНИЕ МАГНИТНОГО ПОЛЯ НА ЭФФЕКТИВНОСТЬ МАГНИТНОГО ЭКРАНИРОВАНИЯ В РУБИДИЕВЫХ АТОМНЫХ ЧАСАХ

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Аннотация. В работе представлены результаты экспериментальных исследований зависимости продольного коэффициента экранирования магнитного экрана (в направлении оси экрана) малогабаритных рубидиевых атомных часов (РАЧ) от напряженностей и взаимной ориентации их внутреннего рабочего и дополнительного внешнего магнитных полей. При этом дополнительное поле намагничивает извне магнитный экран РАЧ и проникает внутрь него. Установлено существенное влияние этих полей в их взаимосвязи на экранирующие свойства магнитного экрана РАЧ. Полученные результаты позволяют определять продольный коэффициент экранирования РАЧ при действующих значениях рабочего и дополнительного магнитных полей и, как следствие, компенсировать влияние вариаций геомагнитного поля на частоту бортовых РАЧ.

Ключевые слова: рубидиевые атомные часы, магнитное поле, магнитный экран, продольный коэффициент экранирования

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Introduction

Low-Earth satellite systems are crucial for navigation applications. The accuracy of such systems largely depends on the characteristics of onboard atomic clocks [1–3], which can be used for mini and nanosatellites using small-sized rubidium atomic clocks (RAC) [4]. The magnetic shield of the latter weakens the influence of variations in the external magnetic (geomagnetic) field on RAC frequency. However, due to unavoidable defects (for example, seams and communication ports), such shields do not allow to completely exclude the influence of field variations on the stability of RAC frequency [5]. These irregularities in the shield design lead to a sharp difference in the transverse and longitudinal (along the shield axis) shielding coefficients [6]. Such a difference in the shielding factors leads to a change in the magnitude and direction of the magnetic field penetrating the magnetic shield for RAC located, for example, on-board a satellite [7] moving in low-Earth orbit and leading to orientation dependence of the frequency of onboard RAC. Multilayer magnetic shields providing sufficiently high stability of RAC frequency are commonly used to weaken this dependence. For example, a five-layer magnetic shield was used in the onboard laser-pumped cesium-beam atomic clock described in [8] to obtain long-term relative frequency instability at the level of $3.5\cdot10^{-15}$ with short-term relative instability of 10^{-13}. The experimental value of the shielding factor was $3\cdot10^{5}$ in a magnetic field equal to ±24 A/m.

A drawback of multilayer magnetic shields in onboard RAC (especially small-sized ones) is an increase in their total dimensions and weight. This is why there is a search for new design solutions ensuring the required stability of RAC frequency. It was shown in our earlier paper [9] that magnetization of a two-layer magnetic shield by an additional constant external field significantly increases its shielding factor, which reduces the influence of variations in the external magnetic field on the stability of RAC frequency. In particular, an eightfold increase in the shielding factor was observed for the additional constant magnetizing field of about 12.8 A/m, directed perpendicular to the RAC axis (the direction of the largest shielding factor of the RAC magnetic shield), with an amplitude of an external rotating magnetic field of about 2.5 A/m, simulating the geomagnetic field in the orbit of a navigation satellite.

Further experiments found that at the given values of the additional magnetizing and rotating magnetic fields, the shielding factor of the RAC magnetic shield depends both on the magnitude and on the orientation of the operating magnetic field $\mathbf{H}_{op}$ (internal RAC field) generated in the vicinity of the gas cell by the magnetic system of the RAC.

In this paper, we analyze the details of this dependence based on the measurement results for shifts in RAC frequency at orthogonal and coaxial orientations of the additional constant external magnetic field $\mathbf{H}_0$ relative to the operating magnetic field $\mathbf{H}_{op}$.

This additional field $\mathbf{H}_0$ penetrates from the outside into the shield and is oriented along the longitudinal axis of this shield A small value of the longitudinal (compared with the transverse) shielding factor S characterizes the degree of penetration of the field $\mathbf{H}_0$ inside the screen and, consequently, the sensitivity of RAC frequency to variations in the external magnetic field. Thus, measuring the RAC frequency shifts allows to extract information about the values of the longitudinal shielding factor S.

The goal of this study was to find methods for compensating for the influence of an external magnetic field on the frequency of a rubidium atomic clock. The primary objective was to understand the behavior of the key quantity that is the longitudinal shielding factor of the magnetic shield, whose values can be optimized and used for compensation.

The problem was solved by studying the influence of the operating ($\mathbf{H}_{op}$) and additional ($\mathbf{H}_0$) magnetic fields, as well as the influence of their mutual orientation on the value of S.

Procedure for measuring the longitudinal shielding coefficient of magnetic shield

The longitudinal shielding factor of a two-layer magnetic shield in a commercial small-sized RAC was evaluated using the experimental setup described in our study [10]. The setup contained a magnetic system of three pairs of Helmholtz coils, with small-sized RAC at the center, connected to a circuit for measuring variations in their frequency. The Helmholtz coils were used to completely compensate for the geomagnetic field in area where the RAC was placed (with an accuracy of tens of nT) and generate an additional constant magnetic field $\mathbf{H}_0$ of varying strengths. The vector $\mathbf{H}_0$ was oriented coaxial (orientation ↑↑) or orthogonal (orientation ↑↓) to the operating magnetic field $\mathbf{H}_{op}$. The shield was made of 79NM permalloy, a ferromagnetic Ni alloy. The longitudinal shielding factor S for both orientations (↑↑ and ↑↓) of the operating and additional magnetic fields was determined by measuring the RAC frequency shift relative to the frequency reference at two fixed values of the current in the coil generating the operating magnetic field $\mathbf{H}_{op}$.

The magnitude of the quantity $|\mathbf{H}_{op}|$ was found by a well-known expression for the frequency of the lasing transition of RAC (see monograph [5]) with the addition of the component ΔH_{in}:

$$\nu = \nu_0 + \beta\cdot(H_{op} \pm \Delta H_{in})^2, \tag{1}$$

where ν_0 is the atomic transition frequency for ^{87}Rb atoms (ν_0 = 6.835 MHz); β is the proportionality constant (β = 90.5 MHz·m^2/A^2); ΔH_{in} is the component of the additional external field $\mathbf{H}_0$ penetrating inside the magnetic shield and oriented coaxially with the operating magnetic field $\mathbf{H}_{op}$. The value of the latter in RAC is typically on the order of 10 A/m [5].

In our experiments, the longitudinal shielding factor was measured at two values of H_{op}: 11.68 and 12.16 A/m.

The values of the field increments $\pm\Delta H_{in}$ (acting inside the shield and induced by field increments $\pm\Delta H_0$), necessary for subsequent calculations of the longitudinal shielding factor of the RAC screen, were determined by measuring the frequency difference between the RAC and the frequency reference by Eq. (1).

In contrast to the technique described in [9], this study did not use an external rotating magnetic field; it was unnecessary, since we considered the influence of the increments of the additional field $\Delta\mathbf{H}_0$, simulating the geomagnetic field of the Earth, on RAC.

Measurements of longitudinal shielding factor

Fig. 1 shows example waveforms of the relative frequency shift of RAC in the range of magnetic field increments ΔH_0 from 5 to 30 A/m. Table 1 shows the corresponding values of the relative frequency shift of RAC.

Small-sized RAC of the same type as the one considered in the study was used as reference frequency for measuring the RAC frequency shift. This small-sized clock was located outside the magnetic system generating increments ΔH_0.

The following expression was used to determine the longitudinal shielding coefficient S:

$$S = \Delta H_0/\Delta H_{in}. \tag{2}$$

Based on the data in Table 1, using Eq. (2) (taking into account expression (1)), we calculated the values of the longitudinal shielding factor S for various combinations of the mutual orientation of the vectors $\mathbf{H}_{op}$ and $\mathbf{H}_0$. The results of these calculations are given in Table 1.

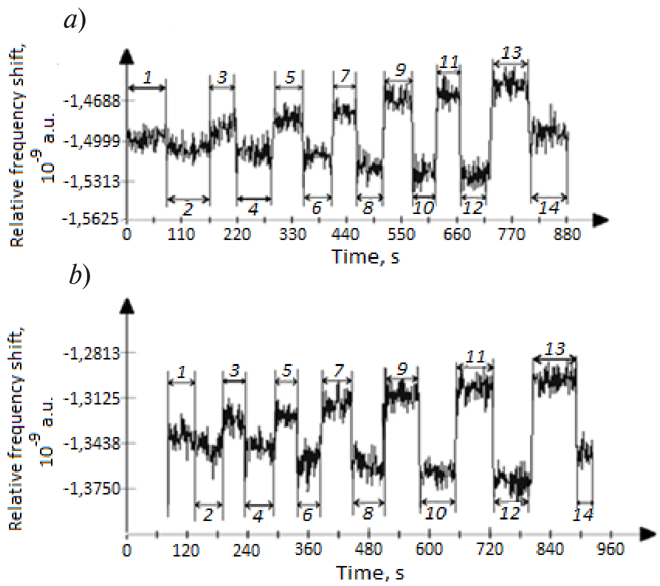

Fig. 1. Waveforms of relative frequency shift of RAC induced by increments $\Delta\mathbf{H}_0$ of additional constant external magnetic field $\mathbf{H}_0$ of different orientation at two magnitudes of operating magnetic field H_{op}, A/m: 11.68 (*a*) and 12.16 (*b*)
Numbers above the segments correspond to the periods (see Table 1)

Table 1

Relative frequency shifts of rubidium atomic clock at different increments of external magnetic field and two magnitudes of operating magnetic field H_{op}

Period	External magnetic field increment ΔH_0, A/m	Relative frequency shift, 10^{-9} rel. units	
		H_{op}=11.68 A/m	H_{op} = 12.16 A/m
1	0	–1.4990	–1.3396
2	+5	–1.5047	–1.3449
3	–5	–1.4881	–1.3201
4	+10	–1.5083	–1.3463
5	–10	–1.4831	–1.3251
6	+15	–1.5113	–1.3539
7	–15	–1.4771	–1.3184
8	+20	–1.5196	–1.3576
9	–20	–1.4655	–1.3112
10	+25	–1.5259	–1.3645
11	–25	–1.4635	–1.3062
12	+30	–1.5262	–1.3707
13	–30	–1.4552	–1.3009
14	0	–1.4917	–1.3521

Table 2

Summary table of longitudinal shielding factors for two magnitudes of operating magnetic field $\mathbf{H}_{op}$ and its orientation relative to external field $\mathbf{H}_0$

ΔH_0, A/m	Longitudinal shielding factor S			
	H_{op} =11.68 A/m		H_{op} = 12.16 A/m	
	↑↑	↑↓	↑↑	↑↓
5	128	329	89	294
10	181	366	219	294
15	200	398	225	323
20	178	310	250	351
25	665	293	240	320
30	205	352	250	305
40	294	265	305	234
60	288	290	307	209
80	313	290	260	173

Notations: $\Delta \boldsymbol{H}_0$ is the increment of the external magnetic field; ↑↑ and ↑↓ are the mutual orientations of the magnetic fields $\mathbf{H}_0$ and $\boldsymbol{H}_{op}$.

It follows from the data in Table 2 that the greatest discrepancy in the values of the shielding factor S for the orientations of the additional external ($\mathbf{H}_0$) and operating ($\mathbf{H}_{op}$) magnetic fields (denoted as ↑↑ and ↑↓) is observed in the range ΔH_0 = 5 A/m, i.e., where the magnetic permeability of the material of the magnetic shield (permalloy) undergoes the most drastic change in the function of the constant external magnetic field [11] whose order of magnitude is comparable to the geomagnetic field intensity in the orbit of navigation satellites. The dynamics of the variations in the shielding factor as a function of the magnitudes of the vectors $\mathbf{H}_{op}$ and $\mathbf{H}_0$ and the directions of their mutual orientation makes it possible to determine the value of the shielding factor for various combinations of both the values and the directions of these fields. Data for the shielding factor allows to determine the parameters of the magnetizing field directed orthogonally to the axis of the magnetic shield for the purpose of increasing its shielding factor [9] as well as compensating for the influence of variations in the external magnetic field on the frequency response.

Conclusion

Analysis of the results obtained in the study allows to draw the following conclusions.

1. The longitudinal shielding factor of the RAC magnetic shield significantly depends on both the operating magnetic field and additional magnetizing field as well as on their mutual orientation.
2. The maximum difference between the shielding factors for two opposite orientations of the additional magnetizing field $\mathbf{H}_0$ and operating field $\mathbf{H}_{op}$ is observed for the field increment $\Delta H_0 \approx 5$ A/m, which approximately corresponds to the geomagnetic field in the orbit of navigation satellites.
3. The obtained dependence of the shielding factor is of fundamental importance for adjuscting the RAC frequency based on the data on variation in the magnitude and direction of the external magnetic field during the satellite's orbital motion.

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