Temperature stabilization of the angular velocity measuring device

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Abstract. The article examines the possibility of using an active two-circuit thermal control system to reduce the influence of temperature disturbances on the components of the angular velocity measuring device. Special attention is devoted to the problem of temperature stabilization in fiber-optic gyroscopes mounted in the measuring device. The study of the inhomogeneous nonstationary temperature field of the angular velocity measuring device with a two-circuit reversible thermal control system on Peltier thermal batteries is carried out. Thermal and mathematical models of the considered dynamical system are constructed. Specialized software for numerical simulation has been developed, which allows calculating and visualizing real-time inhomogeneous, three-dimensional, non-stationary temperature fields of the device under conditions of complex non-stationary thermal effects of internal and external sources. It is shown that the use of a two-circuit reversible thermal control system can help to significantly reduce the influence of external non-stationary temperature disturbances on the temperature stability of fiber-optic gyroscopes in various operating conditions, such as vacuum and weightlessness. The energy consumption and the increase in the weight and size characteristics of the device are estimated.

1. Introduction

In this article, the problem of ensuring temperature stabilization of the angular velocity measuring device (BIUS) on fiber-optic gyroscopes (FOG) with a two-circuit reversible thermal control system is solving. Fiber-optics gyroscopes are the most sensitive for temperature gradients of the BIUS components.

Among gyroscopic devices of the various operating principles, the FOG stands out with relatively low cost, reliability, low power consumption, absence of mechanical parts, and many other advantages. At the same time, such a sensor has some disadvantages, for example, sensitivity to various external influences – mechanical, electromagnetic, temperature and others, which cause inaccuracies of the measured angular velocity.

The modern high-precious FOG has strict requirements for temperature [1-8] because temperature disturbances are one of the significant factors, which is affecting the FOG precision. Most of the FOG errors are associated with the fiber coil – sensitive element of the device [2,5,6,7,13]. Over the past decades, the efforts of Russian and other countries’ scientists have achieved significant results in improving the precision and stability of FOG [9-17]. Many engineering solutions have been found and applied to ensure the maximum possible protection of the FOG from external disturbing influences and to increase its accuracy. There are various methods for minimization of the temperature errors in FOG,
used in navigation systems, such as special methods of winding a fiber on a coil (for example, quadru-pole winding), algorithmic compensation of the thermal drift, etc. [2,4,8,16,17]. The most accurate instruments have an accuracy of 0.01 deg/hour and better.

However, it’s not enough to use only passive methods to achieve inertial accuracies for FOG <0.01 deg/hour. Thermoelastic deformations in micrometers and percentage of micrometers have a significant impact on the performance of high-precision devices. Also, the temperature instability of the radiation source impact on the scale factor (SF) of the FOG. For example, to achieve an accuracy of the FOG <0.01 deg/hour, the relative error of SF [1,7,9,10,11,13], should be less than 0.01%. In contemporary advanced navigation-class navigation systems, an erbium superluminescent optical radiation source can be used, but studies shown [12, 17, 18] that the temperature instability of the radiation source at high rotational speeds has a significant effect on the scale coefficient.

Thus, the problem of minimizing errors caused by temperature perturbations remains relevant.

The purpose of this work is to study the possibility of using an active two-circuit thermal control system (TCS) based on the use of Peltier thermoelements to minimize the influence of external and internal temperature disturbances on the FOG sensor element and the laser radiation source. The object of the study is the angular velocity measuring device (BIUS-M-1) with fiber-optic gyroscopes, designed to use as part of the strapdown navigation system of the spacecraft, which is being developed at the Antares Research and Production Enterprise in Saratov.

To evaluate the efficiency of the TCS, it is necessary to study the non-stationary, inhomogeneous, three-dimensional temperature field of the BIUS-M-1, which contains three fiber-optic gyroscopes, three electronic boards with heat sources of a given power, the internal circuit of the TCS of one FOG, and the external circuit of the TCS of the entire measuring device.

2. Model description
The measuring device is based on three orthogonally arranged FOGs and a service electronics unit. BIUS-M-1 has a modular structure and contains elements (gyroscopes, electronic boards, etc.) with heat sources of a given power. The unit provides for thermal shunting of the heat-generating elements of individual boards to the base through the heat sink racks, shunts, and radiator plates. The guaranteed temperature range of the mounted plane (thermoplastics) of the device during testing and operation mode is in (-10 ÷ 40) °C.

Figure 1. BIUS thermal model. The arrows indicate the thermal connections.
For temperature stabilization, we assumed that the Peltier thermal battery is placed on the device case, which formed the external contour of TCS, and on every FOG included in BIUS (the second and internal contours of TCS).

To construct a thermal model following the general method of thermal modeling [2, 20], the BIUS has to be decompose into separate structural elements. Figure 1 shows the thermal model of the BIUS with an indication of the thermal connections between the structural elements and the external environment.

Each element, if it consists of smaller non-uniform parts and contains heat sources, has also to be divided into smaller elements to obtain a more accurate view of the temperature field. In our case, each of the boards of the service electronics unit containing heat sources is decomposed into 25 elements to obtain a detailed picture of the temperature field.

3. Mathematical model and the temperature regulation low

The mathematical model of the non-stationary inhomogeneous temperature field for the considering problem is presented in the form of a finite difference algorithm and have the following view [2, 20]:

$$T_i(t + \Delta t) = \left[1 - \frac{\Delta t}{ct_i} \left( \sum_{j=1}^{N} q_{ij} + q_{e} \right) \right] T_i(t) + \frac{\Delta t}{ct_i} \left( \sum_{j=1}^{N} q_{ij} T_j + q_{en} + Q_i \right),$$

where: $T_i(t)$, $T_i(t + \Delta t)$, $c_i$ ($i = 1, \ldots, M$) – temperatures of the $i$-th element in the current and subsequent moment and his thermal capacity; $q_{ij}$ - thermal conductivity between elements $i, j$ ($j = 1, \ldots, N$); $q_{e}$ - thermal conductivity between $i$-th element and the environment; $T_{en}$ - environment temperature; $Q_i$ - heat source power; $M$ – the number of elements; $N$ - the number of elements that have thermal contact with $i$-th element; $\Delta t$ - calculation step.

Thermal conductivity coefficients included in the expression (1), are determined by known formulas [2, 20] for any type of heat exchange.

The main supposed difference of the device design from the base one is the presence of TCS actuators, namely, three Peltier thermoelements for each FOG with radiators.

The equations describing the thermoelectric characteristics of Peltier batteries have the form:

$$Q_i = -\varepsilon_i J(T_{in} + 273) + \frac{J^2 R}{2} \text{ nm}, \quad Q_e = \varepsilon_i J(T_{en} + 273) + \frac{J^2 R}{2} \text{ nm},$$

where $Q_i$ - the power of the heat dissipation (cooling facilities) on the working junction; $Q_e$ - the power of the heat dissipation (cooling facilities) on the external junction; $\varepsilon_i$ – coefficient of thermoelectromotive force in thermoelements; $J$ – current flowing through the thermocouple; $R$ – electrical resistance; $n, m$ - the number of thermoelements in one Peltier module and the number of modules.

The most widely used systems in aerospace instrument engineering are proportional and positional temperature control systems, which provide sufficient accuracy of temperature control and at the same time are relatively simple, cheap, and reliable in operation. The expression describing such a Peltier thermoelectric current control law has the form:

$$J = \begin{cases} J_{max}, & \text{for } T_a - T_z \geq T_L; \\ k(T_a - T_z - T_N), & \text{for } T_N \leq T_a - T_z \leq T_L; \\ 0, & \text{for } -T_N \leq T_a - T_z \leq T_N; \\ k(T_a - T_z + T_N), & \text{for } -T_L \leq T_a - T_z \leq -T_N; \\ -J_{max}, & \text{for } T_a - T_z \leq -T_L; \end{cases}$$

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where \( J_{\text{max}} \) – maximum current value; \( T_L, T_N \) – linearity and insensitivity zones; \( k = \tan \alpha = J_{\text{max}} / (T_L - T_N) \) – slope of characteristics of the temperature control law; \( T_Z \) – preset temperature of thermal stabilization; \( T_d \) – the temperature of the temperature sensors installed in the necessary places of the BIUS and FOG.

The graph describing the control law (3) is shown in figure 2.

![Figure 2. The law of temperature control in the Peltier module.](image)

The theory and practice of the use of TCS on Peltier thermoelements [17-19] show that while choosing the optimal parameters of the TCS in terms of energy consumption and the efficiency of maintaining a given thermal regime, the following rules should be followed:

- initial temperature \( T_0 \) should be selected as close as possible to the preset temperature of thermal stabilization \( T_Z \). The stabilization temperature for BIUS is assumed to be equal to \( T_Z = +30^\circ\text{C} \) from the maximum range \( T_c = (-10\pm+40)^\circ\text{C} \)
- preferred locations of the thermal sensors are on the BIUS case and the FOG cases.
- some kinds of thermal insulation of the device and FOGs are necessary for the effective operation of the TSC.

4. **Computer simulation**

All constructed mathematical models were implemented in specialized software for the numerical simulation. The specialized software is developed on the C++ programming language and allows visualizing non-stationary inhomogeneous three-dimensional temperature fields of the device under consideration in dynamics.

With the help of the developed software, a series of computer experiments was carried out to simulate thermal processes in the BIUS in the main thermal modes defined in previous works [3], simulating the Earth conditions and the conditions of outer space (vacuum and weightlessness). At the same time, a comparative analysis of temperatures was carried out when the TCS was turned on and off.

Below are color topograms of the temperature field of the BIUS-TCS dynamic system (figure 3), and graphs of the current temperatures of the parameters of the TCS (figure 4), obtained as a result of computer modeling in terrestrial conditions (1 - thermal mode) [3].
Figure 3. Temperature fields of the BIUS-TCS dynamic system and temperature topograms on electronics boards in steady-state mode at $T_{с} = T_T = +40^\circ C$: a) when the TCS is turned off; b) when the TCS is turned on.

Figure 4. Current temperatures in the BIUS-TCS dynamic system at $T_c = T_T = +40^\circ C$ in first thermal mode: a) when the TCS is turned off; b) when the TCS is turned on;
An analysis of the results shows the following. The nature of thermal processes when the TCS supply system is switched off and running is significantly different.

The behavior of the BIUS-TCS dynamic system changes significantly when the TCS is enabled. By $T_c = +40^\circ C$, the maximum temperature of the hottest BIUS element (on the power supply board) has decreased by 11 °C and do not exceed 38°C (then the TCS turned off it was 49°C). The temperature of the remaining elements takes the value, close to $T_Z$ accurate to tenths of a degree (0.3°C), and for gyroscopes and the body equal to $T_Z$ accurate to hundredths of a degree (0.02°C).

The next stage is the analysis of the BIUS temperatures in the second thermal mode, which simulates the conditions of outer space (vacuum and weightlessness).

The graphs of the BIUS temperatures obtained from the results of calculations in the second thermal regime are shown in figure 5.

Comparing the results of simulations of the 1st and 2nd thermal heating modes of the BIUS-M-1 with the operating TCS, we see that the maximum superheat over the thermal board in zero gravity and under vacuum outside and inside the unit have naturally increased and reached the values of $\Delta T_{\text{max}} = 8.5^\circ C$ on boards, which is in 2 times more than overheating in terrestrial conditions. However, this is still more than 2 times less than in the basic design without the TCS under the same conditions ($\Delta T_{\text{max}} = 20^\circ C$). In the other elements of the BIUS, the temperature is close to the set one $T_Z$.

The simulation of the non-stationary inner temperature disturbance based on the given cyclogram simulating the tests of a measuring unit in a thermal chamber is particularly indicative from the point of view of the effectiveness of the use of the TCS.

Figure 6 shows the graphs of the current temperatures at all calculated points of the device, obtained as a result of computer modeling.

**Figure 5.** Current temperatures in the BIUS-TCS elements at the temperature of the medium and the thermal board +40°C in zero gravity and vacuum a) when the TCS is turned off; b) when the TCS is turned on.

**Figure 6.** Current temperatures in the BIUS-TCS dynamic system at a temperature perturbation according to a given cyclogram: a) when the TCS is turned off; b) when the TCS is turned on.
From the presented graphs, the effect of the working TCS is obvious. Due to thermal stabilization, the temperature situation is significantly improved by the maximum overheating of the elements with internal heat sources over the environment (with the TCS running, the maximum temperature difference over the medium temperature decreased by 9°C). The total power consumption of the TCS, takes the value <2.5 W under normal conditions.

When the temperature of the medium and the housing changes from the "shelf" to the "shelf" according to the linear law (-10 ÷ +40) °C the temperatures of the main elements of the BIUS vary slightly around the set temperature $T_z$ (figure 6b), and the temperatures of the gyroscopes are equal to the set temperature with an accuracy of 0.2°C.

Peak power consumption of the external circuit TCS (at maximum differences between $T_z$ and $T_2$), in the thermal stabilization mode < 12 W under normal and extreme conditions.

5. Conclusion

The article examines the possibility of using an active two-circuit thermal control system to reduce the influence of temperature disturbances on the components of the angular velocity measuring device on the example of the BIUS-M-1 developed at the Antaeres Research and Production Enterprise in Saratov.

Mathematical models of thermal processes occurring in the BIUS-M-1 dynamic system with fiber-optic gyroscopes and a two-circuit reversible TCS are constructed and implemented in specialized software. The specialized software allows calculating and visualizing inhomogeneous, three-dimensional, non-stationary temperature fields of the system under consideration under conditions of complex non-stationary thermal effects of internal and external character.

Computational experiments were carried out using the developed software and a detailed thermal analysis of the operation of the BIUS-M-1 device under thermal conditions was performed. Qualitative and quantitative estimates of the parameters of thermal processes are obtained.

It is shown that in the case of the use of TCS, we can expect a decrease in the maximum overheating over the temperature of the medium to -1°C. At the same time, the calculations show that the accuracy of temperature stabilization of the external circuit is not worse than 0.32°C, and in FOG area (inner circuit) is not worse than 0.02°C. The peak power and current consumption of both TCS circuits are 3 W and 0.9 A, respectively, and in steady-state mode, the total power consumption does not exceed 3 W, and the current is 0.2 A. According to calculations, the influence of external temperature changes on the temperature of the BIUS and its components can be weakened by about 250 times.

The "price" for such an improvement in the temperature situation in the BIUS with the TCS is the power consumption of the thermal control system up to 13 W in steady-state mode at normal gravity and normal pressure of the medium and the accepted degree of thermal insulation of 0.25; an increase in weight and dimensions due to the executive elements of the TSC and the use of thermal insulation by about 5-10% compared to the basic version of the BIUS without the thermal control system.

Thus, it can be expected that the use of the connected two circuits of the TCS will significantly reduce the influence of external and internal thermal influences on the gyroscopes and other elements of the BIUS. However, due to the contemporary strict requirements for energy consumption and the overall mass characteristics of space-based devices, in the case of the implementation of the design solution for the implementation of the considered TCS in the BIUS, there may be restrictions on its application due to the above reasons.

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