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# ANALYSIS OF THE HEAT EXCHANGE PROCESSES OF THE REMOTE MEASUREMENT DEVICE OF MECHANICAL VALUES

*Об'єктом дослідження є модель теплового стану приладу дистанційного вимірювання, що визначається умовами експлуатації і викликана необхідністю підтвердити функціонування приладу в навколишніх умовах згідно вимогам технічного завдання. В ході дослідження використовувалася фізична постановка задачі визначення теплового стану приладу дистанційного вимірювання при різних умовах експлуатації і їх математичний опис. Вибір стратегії ґрунтується на рішенні технологічних завдань, що забезпечують оптимальний процес контролю. Розроблена теплова і математична модель теплового режиму приладу для розрахунку багатомірних полів температур елементів приладу. Отримано модель теплового режиму приладу дистанційного вимірювання. Запропонований метод дозволяє визначити температурні режими вузлів в режимі підготовки й основної роботи при різних температурах навколишнього середовища. Зокрема, визначити виділяючу потужність на стані проектування та зміни на протязі часу. В моделі враховані геометричні параметри основних елементів конструкції приладу. В той же час, для дотримання теплового балансу й адекватності моделі до основних елементів приладу в математичній моделі введені додаткові характеристики цих компонентів. Так, враховується радіаційний теплообмін між зовнішніми поверхнями приладу і оточуючими його конструкціями відсіку. Враховується закономірність зміни температури навколишнього середовища в залежності від режиму експлуатації приладу. Розглядається нестаціонарний тепловий стан приладу дистанційного вимірювання з урахуванням радіаційно-конвективного теплообміну зовнішніх поверхонь приладу з навколишнім середовищем. Згідно проведеним дослідженням, при двох варіантах температурних умов експлуатації приладу дистанційного вимірювання було визначено теплофізичні характеристики матеріалів, які використовуються в моделі. Модель реалізована в програмному коді STAR-CCM на основі методу контрольних об'ємів. Дана методика спрощує розробку чисельної тривимірної моделі з контрольних об'ємів приладу дистанційного вимірювання для комп'ютерного аналізу. Дані дослідження є невід'ємною складовою в проектуванні, розробці та використанні приладу дистанційного вимірювання на базі гіродатчиків в різних температурних умовах.*

**Ключові слова:** *стратегія вимірювання, модель теплового стану, дистанційне вимірювання, закономірність температури часу, готовність гіродатчика.*

## 1. Introduction

Significant results in the field of the most optimal arrangement of elements at the design stage, methodological studies and various computational and experimental approaches for building a model were made by scientists [1, 2]. Each design model of the thermal state of the device has its own characteristics and requires further measures to improve it. In [3], a variety of design models were proposed that made it possible to determine the thermal state of individual elements. Calculations of the heating of the main parts of the stator and the rotor were carried out in various machine load modes. The features of the use of dimensional analysis to calculate tolerances with regard to the operational error [4, 5] were also considered, which reflected the importance of using dimensional analysis for a given accuracy and ensuring the necessary performance. Despite the fact that a lot of research has been done in the last decade [6–8], there are still issues of improving and analyzing the heat exchange processes of devices for remote measurement of mechanical quantities. And also repeatedly considered the problem of obtaining reliable data in the design of the device [9, 10] and the study of temperature regimes in various conditions of use [11], confirms the relevance of this direction. So, *the object of research* is the model of the thermal state of the remote measurement device, determined by the operating conditions and caused by the need to confirm the operation of the device in the environment according to the requirements of the technical specification (TS). *The aim of the research* is determination both local temperature values and average temperature values for individual structural elements. This allows to optimally assemble the structural elements at the design stage.

## 2. Methods of research

The design of the remote measurement device (RMD) contains the following main elements: the device case, three accelerometers, two gyro sensors, external covers, electronic devices under the lower case.

The model takes into account the geometric parameters of the main structural elements of the device. In order to optimize the computational grid during its creation, as well as to reduce the number of control volumes of the thermal model, the following assumptions were made when modeling the elements of the device:

a) in the device case there are no openings;

b) in the thermal model of the device does not take into account the geometry of the wires, fasteners, boards. At the same time, in order to maintain the heat balance and the adequacy of the model, additional characteristics (power dissipation, density and average heat capacity) of these components – wires, fasteners, boards were introduced in the mathematical model.

The following assumptions are made in the mathematical model:

1. Heat dissipation in the accelerometer and gyro sensor is set uniformly throughout the volume.
2. Radiation and convective heat transfer in the upper and lower lids of the device at this stage will be ignored. The main type of heat exchange inside the device is conductive heat transfer.
3. The radiation temperature of the surrounding RMDs and the ambient temperature are plotted as a function of time.
4. Heat release in the boards is simulated by heat generation in the device case.
5. Heat exchange due to thermal conductivity of the shock absorbers neglected.

To account for the main features of heat transfer in the operating conditions of the device, the following requirements were introduced for the mathematical and computer models:

1. The non-stationary three-dimensional temperature field of the RMD with free-convective heat transfer from the external surfaces of the device is considered.
2. Radiation heat exchange between the external surfaces of the device and the structures of coordinates-measuring machine surrounding it is taken into account.
3. The regularity of changes in ambient temperature depending on the mode of operation of the coordinates-measuring machine (CMM) is taken into account.

So, the non-stationary thermal state of the RMD is considered, taking into account the radiation-convective heat exchange of the external surfaces of the device with the environment, the temperature of which varies according to a predetermined law:

$$cp\frac{\partial T}{\partial \tau}=\frac{\partial}{\partial x}\left[\lambda_x\frac{\partial T}{\partial x}\right]+\frac{\partial}{\partial y}\left[\lambda_y\frac{\partial T}{\partial y}\right]+\frac{\partial}{\partial z}\left[\lambda_z\frac{\partial T}{\partial z}\right]+q_v,$$

$$0<x<x_{\max};\ 0<y<y_{\max};\ 0<z<z_{\max};$$

$$0<\tau<\tau_{\max};$$

$$c=c(x,y,z);\ p=p(x,y,z);\ \lambda=\lambda(x,y,z), \qquad (1)$$

where $c$ – heat capacity; $p$ – density; $T$ – temperature; $\tau$ – time; $q_v$ – volumetric heat release; $\lambda$ – material thermal conductivity ($\lambda_x$, $\lambda_y$, $\lambda_z$ – thermal conductivity in the corresponding space coordinate); $x$, $y$, $z$ – spatial coordinates ($x_{\max}$, $y_{\max}$, $z_{\max}$ – their maximum value is equal to the maximum dimensions of the RMD device).

Initial condition:

$$T(x,y,z,0)=t_0,$$

where $t_0$ – the initial temperature.

The boundary condition on the outer surface of the device:

$$-\lambda\frac{\partial T}{\partial n}=a\left(T_f-T\right)+\varepsilon\sigma\left[T_f^4-T^4\right], \qquad (2)$$

$$T_f=f(\tau), \qquad (3)$$

where $a$ – convective heat transfer coefficient; $T_f$ – ambient temperature (air); $\varepsilon$ – blackness degree; $\sigma$ – Stefan-Boltzmann constant.

Equation (1) describes the temperature regime of the RMD elements, the physical properties of which are taken into account by the coefficients $c$, $p$, $\lambda$. Equation (3) is the change in the ambient (gas) temperature according to the graph shown in Fig. 1.

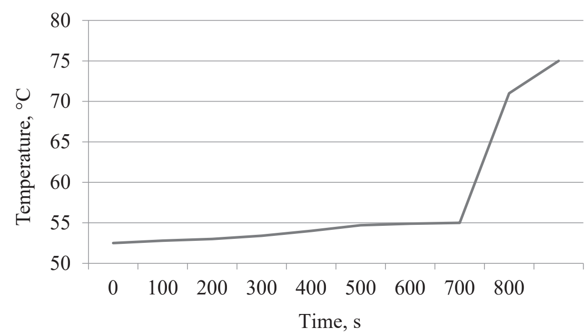


**Fig. 1.** The change in ambient gas temperature during the preparation of a remote measurement device in the coordinate measuring machine

Table 1 shows the thermophysical characteristics and the initial data on heat release in the main elements of the device.

**Table 1**

Thermophysical characteristics of materials used in the remote measurement device model

| Component name | Material | Thermal characteristics | | |
|---|---|---|---|---|
| | | λ, W/m·K | c, J/(kg·K) | ε |
| Case | Aluminum alloy Д16 | 120 | 890 | 0.84 |
| Accelerometer | Stainless steel | 16 | 560 | – |
| Gyro sensor | Stainless steel | 16 | 560 | – |
| Upper cover | Aluminum alloy АМц | 150 | 896 | 0.84 |
| Bottom cover | Aluminum alloy АМц | 150 | 896 | 0.84 |

Two options for temperature conditions of RMD operation are considered

*Option 1.* The initial temperature $t_{in}=-40$ °C; ambient $t_{amb..av}=-40$ °C; the total amount of summed heat $Q_\Sigma=20$ W; time of the RMD preparation mode $\tau=500$ s.

*Option 2.* The initial temperature $t_{in}=50$ °C; ambient temperature $t_{amb..av}=f(\tau)$ °C; the total amount of heat applied $Q_\Sigma=60$ W in operation; time of preparation mode and main work $\tau=800$ s.

Physical formulation of the problem describing internal heat sources and limiting heat transfer requirements on the RMD external surfaces.

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The model is implemented in the STAR-CCM program code based on the control volume method. The control volume method for the derivation of finite difference equations is similar to the integral method, but more physical in essence. The STAR-CCM program code belongs to the family of programs that implement the CFD (ComputationalFluidDynamic) approach. CFD is based on modern computer technologies, the latest mathematical models of transfer processes, as well as efficient and highly accurate numerical algorithms. CFD models make it possible to predict the temperature, pressure, and gas velocity fields at each point in space and time, as well as the temperature fields at any point in solids that are analyzed.

For RMD computer analysis, a numerical three-dimensional model of control volumes was developed. The grid was built taking into account the geometry of the device. Step after time when solving non-stationary tasks was chosen in the range of 0.5–10 s, the number of iterations at each step was 4–7.

## 3. Research results and discussion

As discussed earlier, two options were considered for the temperature conditions of the device.

*Option 1* – RMD preparation mode (τ=500 s), Fig. 2, 3.

*Option 2* – preparation mode and main operation mode (τ=800 s), Fig. 4, 5.

Temperature graphs in Fig. 1–5 of temperature changes over time of the elements of the VAT device for the accepted characteristic modes of operation allow to draw the following conclusions:

1. When preparing with an ambient gas temperature of –40 °C, the temperature of the device of the gyro reaches 50±2 °C after about 8 minutes.

2. In the main operation mode, the temperature of the device and the structural elements increases by 25 °C (the cover of the case), and the gyro sensor increases by 42 °C relative to their temperature at the end of preparation.

3. In the preparation mode and the main operation at the ambient gas temperature according to Fig. 1 temperature on the supporting structures of the electronics unit does not exceed 70±5 °C.

4. In the mode of preparation and main operation, the maximum emitting power of RMD in a CMM does not exceed 12±2 W.

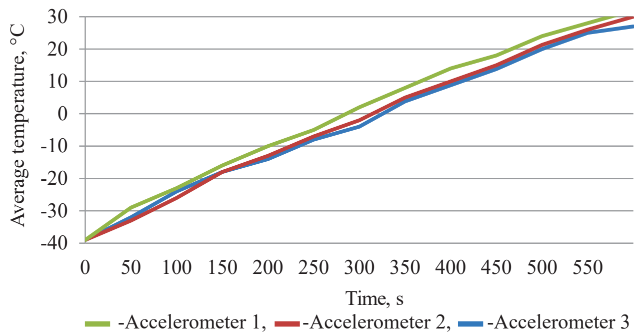


**Fig. 2.** Changes in the average temperature over the accelerometer volume in time (option 1)

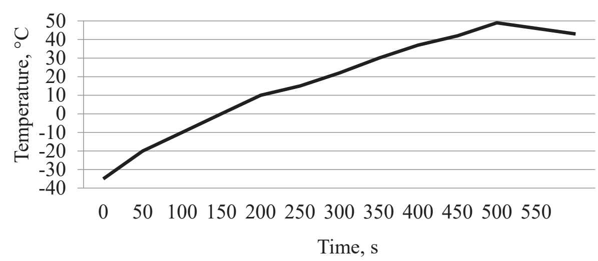


**Fig. 3.** Changes in the average temperature over the volume of the gyro sensor in time (option 1)

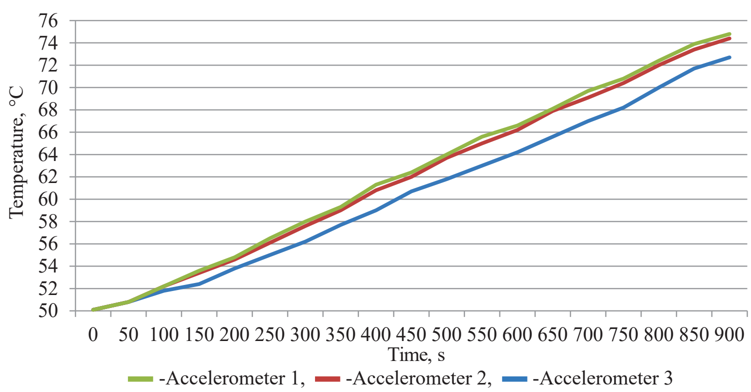


**Fig. 4.** Changes in the average temperature over the accelerometer volume in time (option 2)

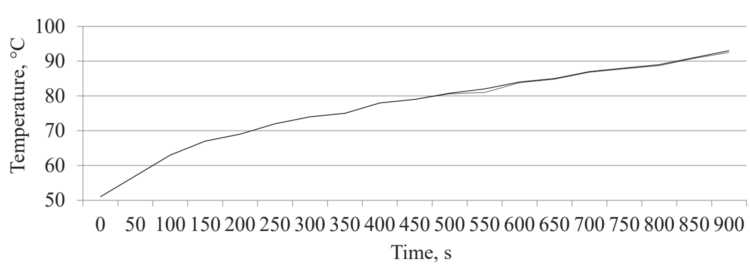


**Fig. 5.** Changes in the average temperature over the gyro sensor volume in time (option 2)

## 4. Conclusions

During the study, a model of thermal state was obtained, determined by the operating conditions and caused by the need to confirm the operation of the device in the surrounding conditions, and which can be used for the optimal combination of the structural elements of the remote measurement device. The RMD structure includes the following elements: the device case, three accelerometers, two gyro sensors, external covers, electronic devices under the lower case. The simulation took into account the geometric parameters of the main structural elements of the device, optimized the computational grid during its creation, as well as reducing the number of control volumes of the thermal model. A thermal and mathematical model of the RMD thermal mode has been developed that allows calculations of the multidimensional temperature fields of the device elements for various conditions of its operation. The results obtained in this work allow to optimally assemble an device during design and investigate temperature conditions under various conditions of use.

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