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ANISOTROPIC MODEL OF THE SYSTEM FOR MONITORING AND CONTROLLING THE THERMAL PARAMETERS OF BOARD RADIO MODULES

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Abstract. *Background.* In accordance with the modern doctrine of the development of the latest rocket and space technology, the control and management of systems of onboard radio-electronic equipment is extremely important. Increasing requirements for reliability and increasing the density of deployment of radio-electronic means for various purposes, especially on-board equipment, significantly limits the possibility of heat removal using ventilation and convection in multi-level radio-electronic modules. At the same time, the conductive method of heat removal involves the use of thermal maintenance systems, special heat-exchange materials for sealing elements of radio-electronic devices. In many cases, an unbalanced temperature regime leads to an increase in the error of the sensors, which leads to a violation of the stability of the entire complex of rocket and space technology. The aim of the study is to analyze and develop mathematical models of heat transfer processes in radio-electronic modules that have analytical solutions. *Materials and methods.* A mathematical model for the analysis and provision of the thermal regime in radio-electronic modules in the form of a quasi-homogeneous anisotropic parallelepiped with stationary volumetric or flat heat sources placed in a conditional environment with a stable temperature is proposed. *Results and conclusions.* This approach makes it possible to implement the following procedures: complex spatial arrangement replacement of heat sources with simpler ones; multicomponent subsystems with a heterogeneous structure are replaced by quasi-homogeneous regions with effective values of heat transfer properties; spatial arrangement of quantities describing heat transfer processes at the edges of areas replaced their average values. The proposed approach makes it possible to significantly simplify the calculated value of the temperature and these models can be widely used to calculate, measure and analyze thermal regimes in radio-electronic modules with a high density of radio-electronic equipment and are a convenient tool for thermophysical design and ensuring stable operation of on-board radio equipment of rocket-space and special equipment.

Keywords: anisotropic model, board radio modules, thermal management

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АНИЗОТРОПНАЯ МОДЕЛЬ СИСТЕМЫ КОНТРОЛЯ И УПРАВЛЕНИЯ ТЕПЛОВЫМИ ПАРАМЕТРАМИ БОРТОВЫХ РАДИОЭЛЕКТРОННЫХ МОДУЛЕЙ

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Аннотация. *Актуальность и цели.* В соответствии с современной доктриной развития новейшей ракетно-космической техники чрезвычайно важен контроль и управление системами бортовой радиоэлектронной аппаратуры Повышение требований к надежности и увеличение плотности размещения радиоэлектронных средств различного назначения, особенно бортового оборудования, существенно ограничивают возможность отвода тепла с помощью вентиляции и конвекции в многоуровневых радиоэлектронных модулях. В то же время кондуктивный метод отвода тепла предполагает применение систем поддержания теплового режима, специальных теплообменных материалов для герметизации элементов радиоэлектронных устройств. Во многих случаях несбалансированный температурный режим приводит к увеличению погрешности работы датчиков, что приводит к нарушению стабильности работы всего комплекса ракетно-космической техники. Целью исследования является анализ и разработка математических моделей процессов теплообмена в радиоэлектронных модулях, имеющих аналитические решения. *Материалы и методы.* Предложена математическая модель анализа и обеспечения теплового режима в радиоэлектронных модулях в виде квазиоднородного анизотропного параллелепипеда со стационарными объемными или плоскими источниками тепла, размещенными в окружающей условной среде со стабильной температурой. *Результаты и выводы.* Такой подход дает возможность реализовать следующие процедуры: сложное пространственное распределение источников тепла заменяются на более простые; многокомпонентные подсистемы с неоднородной структурой заменяются на квазиоднородные области с эффективными значениями теплообменных свойств; пространственное распределение величин, описывающих процессы теплообмена на краях областей, заменяются на их средние значения. Предлагаемый подход позволяет существенно упростить расчетное значение полей температуры и эти модели могут широко применяться для расчета, измерения и анализа тепловых режимов в радиоэлектронных модулях с высокой плотностью компоновки радиоэлектронной аппаратуры и является удобным инструментом для теплофизического конструирования и обеспечения стабильной работы бортовой радиоаппаратуры ракетно-космической и специальной техники.

Ключевые слова: анизотропная модель, бортовые радиомодули, терморегулирование

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Introduction

Radio equipment of different purpose refers to complex engineering systems and typically constitute a modular hierarchical structure. High density of arrangement of radio-electronic equipment limits significantly the possibility of heat removal by means of ventilation and convection in multi-level structural modules. The engineering solutions that do not pay due attention to the efficiency of heat removal, decrease the efficiency and accuracy of the equipment operation and can significantly lower its service life. In this situation, the conductive method of heat removal, that suggests the use of the systems of thermal management, special heat-exchange materials for sealing elements of radio-electronic equipment. Optimum solutions for heat removal can be achieved by various means – analytical calculations, laboratory physical modelling; mathematical modelling, including with the use of analytical solutions and computer simulation.

General overview of research problem

Hierarchical geometrical model of radio system with high density of structural modules arrangements can be represented, according to [1–4] as a certain total of parallelepipeds and plates in an enclosed space with different types of attachment to each other and different orientation. The outer surface of this total of bodies is the border with the external environment (external surface) [4–6].

Let us assume that in a system under analysis randomly distributed in space heat sources are in action and have content intensity over time period. The input ventilation and corresponding heat outlets are absent. As a lot of elements in this enclosed space are close in their structure, the heat exchange can be described on the basis of the model with distributed parameters. Characteristics for heat propagation within the system are the coefficient values of effective heat exchange. The coefficient values will depend on physical properties of the system, material of the bearing structure; geometrical forms; conditions accompanying the mutual heat exchange between structural modules. The coefficients are calculated using the pattern for long-range order systems, i.e. for one elementary unit [3–6]. A structural module and adjacent space – air, parts of mounting and bearing structure – are considered as an elementary unit.

This approach to modelling can be also applied to objects with some deviations from long-range order, local geometrical and heat-transfer properties. System thermal conditions will be influenced by environment and other objects of the systems which emit heat: supports, sections, blocks etc. [1–3, 6]. It can be assumed that the object under study is placed in a certain ‘conventional’ environment, at a calculated temperature t_{conv}, taking into consideration all temperature influences. Heat exchange with the external environment proceeds according to Newton’s law [4, 5], with each surface of the external area characterized by corresponding heat exchange coefficients α.

This model is then applied gradually according to the descending order of modelling heat exchange in structural modules of RS. In the model of the analyzed structure the low-level structural modules with power evenly distributed in space are counted as heat sources.

Heat sources in different structural modules have different forms, according to these features the models can be differentiated and classified [1–3, 6]. For example, separate models in heated areas of support without ventilation are classified according to the following forms of heat sources: rectangle, parallelepiped with parameters equal the model size; parallelepiped with parameters differing from the model size.

In the research, conducted by the authors, in line with [6–8] the complex of new models was developed on the basis of this approach. These include support areas experiencing heat, sections, modules with high density of element arrangement; micro-modules with compound cover; PCBs with flat surface elements.

Support areas experiencing heat, sections, devices are shown as the total of structural modules of low levels (sections, blocks) that have high density of arrangement of bearing structure and air gaps between them. The conventional environment for heated areas is considered to include parts of the structure (external coating of supports and devices), adjacent air, whose external surfaces experience heat transfer and whose temperature values were calculated at preceding modelling stages. The conventional environment for PCBs and microassemblies is considered to include surface of the screen, cover (if present) and surfaces of the neighboring (including the bearing microassemblies) of PCBs, cover walls, air inside blocks, sections, devices where they are positioned.

To conduct the analysis of thermal conditions, RS support in particular, thermal model for structural modules [6,8,9], that has the form of homogeneous anisotropic parallelepiped, consisting of 3D heat sources – blocks. It has to be noted, that the resultant model with accepted limitations and allowances, including those imposed by the chosen methods of solution, does not have a wide sphere of application. As the object has to be given in the form close to the plate, the depth of all heat sources must be the same and equal the total depth. It is also impossible to set different conditions characterizing heat exchange at external surfaces.

Considering the above mentioned drawbacks, it is worthwhile to develop an improved model, free of the limitations mentioned earlier.

The development of the mathematical model

As the studied models of objects are different from each other not only in forms of heat sources, the general model of structural modules with high density of arrangement can be presented in the form of quasi-homogeneous anisotropic parallelepiped with different-size stationary 3D (parallelepipeds) or flat (rectangles) heat sources that are located in the conventional environment with stable temperature.

We will be looking for the solution of the problem on stationary temperature field of quasi-homogeneous parallelepiped. Let us analyze the linear problem in which heat exchange parameters of internal and external heat transfer of the model $(\lambda_x, \lambda_y, \lambda_z, \alpha)$ are considered unaffected by temperature. Using the principle of superpositioning of temperature fields we obtain a mathematical expression that looks as follows:

$$t_j = t_{conv} + \sum_{i=1}^{N} \vartheta_{ij}$$

where t_j is the temperature in j point (area) of the parallelepiped; ϑ_{ij} is the heat over the environment temperature obtained in j-th point as a result of i-th heat source; N is the number of heat sources.

Thus, the main problem can practically be reduced to the determining the temperature field in a parallelepiped, induced as a result of the activities of each source. Stationary temperature field in this case is described by differential equation of the heat exchange (index i is later dropped):

$$\lambda_x \frac{\partial^2 \vartheta}{\partial x^2} + \lambda_y \frac{\partial^2 \vartheta}{\partial y^2} + \lambda_z \frac{\partial^2 \vartheta}{\partial z^2} + W \cdot 1\{S\} = 0 \tag{1}$$

with the following boundary conditions:

$$\left[\frac{\partial \vartheta}{\partial n} - \frac{\alpha_{0n}}{\lambda_n} \vartheta\right]_{n=0} = 0,$$

$$\left[\frac{\partial \vartheta}{\partial n} - \frac{\alpha_{1n}}{\lambda_n} \vartheta\right]_{n=L_n} = 0, \tag{2}$$

$$n = x, y, z$$

where ϑ is the overheating realitvely the environment temperature, induced in point (x, y, z) of the model by i-th heat source; $\lambda_x, \lambda_y, \lambda_z$ are coefficients of heat-exchange efficiency of the model; $W = \dfrac{P}{8\Delta a \Delta b \Delta c}$ is the volume specific power of the source;

$$1\{S\} = \begin{cases} 1 - \text{in S area under the influence of the source,} \\ 0 - \textit{outside}\ \text{S area,} \end{cases}$$

α_{0n}, α_{1n} – heat transfer coefficient on the faces of the parallelepiped when $n = 0$ and $n = L_n$ correspondingly.

Using the approximate analytical method [5, 8–12, 15–18] we get solutions for the equations (1) and (2).

The choice of the solution method was based on the following criteria:

- precision that is necessary for engineering calculations;
- small amount of work required to learn it and the process of solving the problem;
- the solution of the problem must result in the form which is suitable for further analysis of temperature field, so that to ensure possibility to analyze any overheating, induced by each separate source;
- the form of the problem solution must be suitable for further development of algorithms and computer programs;
- the resultant mathematical expression must be easily subjected to coordinate integration, so as to obtain data of surface-average and volume-average temperatures, which may be used as input data in the form, for example, of limiting conditions, at further stages of modelling.

The final expression for the model temperature field with one heat source will look as follows:

$$\vartheta(x, y, z) = P \cdot F(x, y, z)$$

where $F(x, y, z) = f_0, f_x, f_y, f_z,$ is the heat coefficient,

$$f_0 = \frac{L_z p_x p_y p_z}{8\lambda_z L_x L_y} \begin{bmatrix} H_x H_y p_z \left(B_{i0z} A_{z1} + B_{i1z} A_{z2}\right) + \\ + H_x H_z p_y E_y \left(B_{i0y} A_{y1} + B_{i1y} A_{y2}\right) + \\ + H_y H_z p_x E_x \left(B_{i0x} A_{x1} + B_{i1x} A_{x2}\right) \end{bmatrix}^{-1}; \tag{3}$$

$$f_n = \begin{cases} A_{n1}\left(e^{p_n \bar{n}}\left(1 + B_{i0n}/p_n\right) + e^{-p_n \bar{n}}\left(1 - B_{i0n}/p_n\right)\right) \\ \text{при } \bar{n} \in [0, \bar{\alpha} - \Delta\bar{\alpha}]; \\ \left(1 + B_{i0n}/p_n\right)\left(1 - B_{i1n}/p_n\right) e^{p_n(\bar{n} - 1 + \bar{\alpha})} + \\ + \left(1 + B_{i1n}/p_n\right)\left(1 - B_{i0n}/p_n\right) e^{-p_n(\bar{n} - 1 + \bar{\alpha})} + \varphi_n \\ \text{при } \bar{n} \in [\bar{\alpha} - \Delta\bar{\alpha}, \bar{\alpha} + \Delta\bar{\alpha}]; \\ A_{n2}\left(e^{p_n(1 - \bar{n})}\left(1 + B_{i0n}/p_n\right) + e^{-p_n(1 - \bar{n})}\left(1 - B_{i1n}/p_n\right)\right) \\ \text{при } \bar{n} \in [\bar{\alpha} + \Delta\bar{\alpha}]. \end{cases} \tag{4}$$

In expressions (3) and (4) the following designations are used: $n = x, y, z;\ \bar{n} = \dfrac{n}{L_n};$ $\bar{\alpha} = \overline{a}, \overline{b}, \overline{c};$ $\overline{\alpha} = \overline{\Delta a, \Delta b, \Delta c}$ is accordingly when $n = x, y, z$:

$$\bar{a} = \frac{a}{L_x},\ \bar{b} = \frac{b}{L_y},\ \bar{c} = \frac{c}{L_z};\ \Delta\bar{a} = \frac{\Delta a}{L_x},\ \Delta\bar{b} = \frac{\Delta b}{L_y},\ \Delta\bar{c} = \frac{\Delta c}{L_z}. \tag{5}$$

Biot number [4]:

$$B_{i0n} = \alpha_{0n} L_n / \lambda_n, B_{i1n} = \alpha_{1n} L_n / \lambda_n, E_n = \lambda_n L_z^2 / \lambda_z L_n^2,$$

$$A_{n1} = \left(B_{i1n}/p_n + 1\right) e^{p_n(1 - \bar{\alpha})} - \left(B_{i1n}/p_n - 1\right) e^{-p_n(1 - \bar{\alpha})},$$

$$A_{n2} = \left(B_{i0n} / p_n + 1\right) e^{p_n \bar{\alpha}} - \left(B_{i1n} / p_n - 1\right) e^{-p_n \bar{\alpha}},$$

$$\begin{aligned} H_n = {} & \left(B_{i0n} / p_n + 1\right) e^{-p_n} \left[\left(B_{i0n} / p_n + 1\right) h_n - B_{i0n} / p_n e^{-p_n \bar{\alpha}}\right] + \\ & + e^{-p_n} \left(B_{i1n} / p_n - 1\right) \left[B_{i0n} / p_n e^{p_n \bar{\alpha}} - \left(B_{i0n} / p_n - 1\right) h_n\right] - B_{i1n} / p_n A_{n2}, \end{aligned}$$

$$\varphi_n = \frac{\begin{bmatrix} e^{p_n} \left(B_{i0n} / p_n + 1\right)\left(B_{i1n} / p_n + 1\right)\left(1 - ch\, p_n \left(\bar{n} - \bar{\alpha}\right) e^{-p_n \Delta \bar{\alpha}}\right) - \\ - e^{p_n} \left(B_{i0n} / p_n - 1\right)\left(B_{i1n} / p_n - 1\right)\left(1 - ch\, p_n \left(\bar{n} - \bar{\alpha}\right) e^{p_n \Delta \bar{\alpha}}\right) \end{bmatrix}}{sh\, p_n \Delta \bar{\alpha}},$$

$$h_n = \begin{cases} 1 \;\; in\, \bar{\alpha} = 0, \\ p_n \Delta \bar{\alpha} / sh\, p_n \Delta \bar{\alpha} \;\; in\, \bar{\alpha} \neq 0, \end{cases}$$

p_x, p_y, p_z – parameters are roots of transcedental equations.

Conclusion

It should be noted that in case the model was used at the ‘support’ hierarchical level [9, 10–14], then for such multi-component system the coefficients of heat exchange are ‘summed’ and the information is accumulated on heat-exchange and structural properties of lower-level structural modules [15–18], that are still under development by engineers. This means that values of these coefficients can be obtained from CAD databases as statistical average for base bearing structures. They can be preliminary calculated using data for parameters of the standard design of modules (sections, blocks) [1–3, 17–19]. The developed models are used in the engineering process for specific RS, that make use of advanced electronics articles and bearing structures. Apart from that, with their help it is possible to predict thermal processes in RS and their structural modules at early stages of design.

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