COMPUTER-AIDED DESIGN SYSTEMS

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OPTIMIZATION OF ARRANGEMENT HEAT-PRODUCING FUNCTIONAL UNITS AND RADIO ELEMENTS ON THE PRINTED CIRCUIT BOARD

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Abstract—*In this work discusses the methods of automated arrangement of the heat-producing functional units on the printed circuit board. Proposed mathematical models for determination the parameters of thermal fields in micro assemblies. The design aim to reduce the temperature of heat-producing elements, and this can be achieved by appropriately placing the latter, removing them from each other to reduce interference and improve heat transfer. The described complex software module for temperature calculation of the electronic structure elements established on the basis of micro assembly, and performance of its reliability.*

Index Terms—Reliability; radio electronic devices; heat-producing elements; failure; thermal field; heat; failure rate; automation; reliability calculation.

I. STATEMENT OF THE PROBLEM

While designing electronic device cells the arrangement of functional units (FU) and electronic components (EC) on the printed circuit board (PCB) is most often determined by providing electrical and electromagnetic connections. But reliability of all device essentially depends from the thermal regime of EC, vibration and shock resistance. Optimization of the thermal regime of the cell can be achieved by an appropriate placement of the heat-producing elements (HPE), because the temperature of each of them is determined by convective, conductive and radiative connections with elements of construction and each other.

Therefore, the necessary are the methods for determining placement of HPE on printed circuit boards, enabling to provide optimal thermal conditions – to reduce the maximum temperature of FU and EC, and improve the reliability of the entire cell. The same problem arises in the design of micro assemblies with their substrates placed on integrated microcircuits.

II. THE TEMPERATURES OF HPE ON PRINTED CIRCUIT BOARD

They are usually found by solving the heat balance equation, which for one of the HPE looks like this:

$$P = Q_{\text{k}} + Q_{t} + Q_{\text{p}},$$

where P is the power of HPE; Q_{k}, Q_t, Q_{p} is the heat that is given, respectively, by convection, conduction (thermal conductivity), radiation.

A Heat transfer by convection

The value of Q_{k} can be determined if we know the coefficient of convective heat transfer α_{k}, the square of HPE S_{k}, from which heat is given by convection and the temperature difference between T and T_{c} – i.e. the temperatures of the HPE surface and the environment (it is usually air or another gas):

$$Q_{\text{k}} = \alpha_{\text{k}} S_{\text{k}} (T - T_{\text{c}}).$$

Criterion α_{k} of convective heat transfer is calculated by determining the Nusselt criterion Nu for the respective mode of heat transfer [1]:

$$\alpha_{\text{k}} = \text{Nu}\, \lambda / d, \tag{1}$$

wherein λ is the criterion of thermal conductivity of air in the internal volume of radio electronic device (or the cell itself, if it is sealed); d is the so-called the determining size of the HPE.

For natural convection Nu = Nu (GrPr), for forced Nu = Nu (Re), which, in turn, Gr is the Grashof criterion, Pr is the Prandtl number; Re is the Reynolds.

B Heat transfer by conduction

Using the solution obtained in [2] by the method of integral transformation for HPE mounted on the PCB with sizes $a \times b \times \delta$ and the criterion of thermal conductivity of the material λ, the heat allotted to the PCB by conduction (and then it is given by the PCB surface to the environment) calculated as :

$$Q_{\text{t}} = \frac{\lambda\delta}{\theta(x, y)}\left(T - T_{\text{c}}\right),$$

where $\theta(x, y)$ is the function that determines the relative temperature at the point of the PCB with coordinates $\xi = x / a$, $\vartheta = y / b$ depending on the coordinates of HPE on PCB $\xi_0 = x_0 / a$, $\vartheta_0 = y_0 / b$, and HPE contact pads sizes $\Delta\xi = \Delta x / a$, $\Delta\vartheta = \Delta y / b$:

$$\begin{aligned}\theta(x,y)=&\frac{\beta}{\mathrm{Bi}}+\frac{4\alpha^2}{b\Delta x}\sum_{n=2}^{\infty}\frac{\cos\left(\mu_n\xi_0\right)\sin\left(\mu_n\Delta\xi/2\right)}{\mu_n\left(\mathrm{Bi}_x+\mu_n^2\right)}\cos\left(\mu_n\xi\right)+\frac{4b^2}{a\Delta y}\sum_{m=2}^{\infty}\frac{\cos\left(\mu_m\vartheta_0\right)\sin\left(\mu_m\Delta\vartheta/2\right)}{\mu_m\left(\mathrm{Bi}_y+\mu_m^2\right)}\cos\left(\mu_m\vartheta\right)\\&+\frac{16ab}{\Delta x\Delta y}\sum_{n=2}^{\infty}\sum_{m=2}^{\infty}\frac{\sin\left(\mu_n\Delta\xi/2\right)\sin\left(\mu_m\Delta\vartheta/2\right)}{\mathrm{Bi}+\mu_n^2/\beta+\beta\mu_m^2}\cdot\cos\left(\mu_n\xi_0\right)\cos\left(\mu_m\vartheta_0\right)\cos\left(\mu_n\xi\right)\cos\left(\mu_m\vartheta\right),\end{aligned}\qquad(2)$$

a Bio criteria, which determining the convective heat transfer to the PCB:

$$\mathrm{Bi}=\frac{\alpha ab}{\lambda\delta};\quad \mathrm{Bi}_x=\frac{\alpha a^2}{\lambda\delta};\quad \mathrm{Bi}_y=\frac{\alpha b^2}{\lambda\delta};$$

$$\mu_n=\pi\left(n-1\right);\quad \mu_m=\pi\left(m-1\right);\quad \beta=\frac{b}{a}.$$

C Heat transfer by radiation

Part of the heat withdrawn from the HPE by radiation [1]:

$$Q_{\mathrm{p}}=c_0\,\varepsilon\,S_{\mathrm{p}}\,(T^4-T_c^4),$$

where c_0 is the emissivity blackbody; ε is the emissivity of the radiating surface; S_{p} is the radiating surface of HPE.

III. TEMPERATURES OF HPE AND TEMPERATURE FIELD OF PCB WITH MANY HPE

The equation of thermal balance for a single HPE can be written as:

$$P=\alpha_{\mathrm{k}}S_{\mathrm{k}}\left(T-T_{\mathrm{c}}\right)+\frac{\lambda\delta}{\theta(x,y)}\left(T-T_{\mathrm{c}}\right)+c_0\varepsilon\,S_{\mathrm{p}}\left(T^4-T_{\mathrm{c}}^4\right).$$

If we assume that the temperature T_{c} is given (e.g. T_{c} = 273 K), and select constituents with the temperature T, the last can be found from the equation:

$$c_0\varepsilon\,S_{\mathrm{p}}T^4+\left(\alpha_{\mathrm{k}}S_{\mathrm{k}}+\frac{\lambda\delta}{\theta(x,y)}\right)T=P+\left(\alpha_{\mathrm{k}}S_{\mathrm{k}}+\frac{\lambda\delta}{\theta(x,y)}\right)T_{\mathrm{c}}+c_0\varepsilon\,S_{\mathrm{p}}T_{\mathrm{c}}^4.$$

In real cells on the PCB sometimes are placed dozens of HPE, so the problem of determining the temperature becomes much more complicated: it is necessary to take into account for each of them the influence of all the others on the temperature of the PCB, as well as mutual radiation heat transfer between them.

Temperature field of the PCB, as well as the temperature of each of the HPE can find a by superposition of individual temperature fields from all FU and elements, if the provisions of the latter on the PCB identified.

Criteria of convective heat transfer α_{k} is calculated using equations (1); if different HPE have different determining sizes d, can be the difference between values of α_{k}.

In the calculations of conductive heat transfer the greatest number of calculations is require determine the expressions with functions θ(x, y), and to obtain the necessary accuracy may need to take into account a significant number of terms of the series in the amounts of expressions (2) – perhaps several dozen in each sum.

Radiative heat exchange between FU – mutual irradiation of each other – may influence the temperature of each of them. The amount of heat Q_{12}, transmitted by the radiation between the physical bodies with radiation surfaces F_1 and F_2 and absolute temperatures T_1 and T_2, respectively, are determined by the Stefan–Boltzmann law [1]:

$$Q_{12}=c_0\varepsilon_n\left(\varphi_{12}F_1\,T_1^4-\varphi_{21}F_2\,T_2^4\right),$$

where φ_{12} and φ_{21} are coefficients of mutual exposure, which can be calculated by the equations:

$$\varphi_{12}=\frac{F_2}{\pi r^2}\cos\psi_1\cos\psi_2\;;\quad \varphi_{21}=\frac{F_1}{\pi r^2}\cos\psi_2\cos\psi_1\;,\qquad(3)$$

where r is the distance between the centers of the pads F_1 and F_2; ψ_1 and ψ_2 are angles between the normal to that surface and the direction to the other; ε_n is the reduced emissivity surfaces:

$$\varepsilon_n=1/(1/\varepsilon_1+1/\varepsilon_2-1).$$

For the curved surface as the platform F_i consider the projection of the surface on a platform that is tangent to the surface where the main normal passes.

Temperature field of the PCB with n HPE can be found from the system of equations:

$$\sum_{i=1}^{n}\left[\begin{aligned}&\alpha_{\mathrm{k}i}S_{\mathrm{k}i}\left(T_i-T_{\mathrm{c}}\right)+\frac{\lambda\delta}{\theta_i(x,y)}\left(T_i-T_{\mathrm{c}}\right)+c_0\varepsilon_iS_{\mathrm{p}i}\left(T_i^4-T_{\mathrm{c}}^4\right)-\sum_{j\neq i}^{n}\frac{\lambda\delta}{\theta_{ij}\left(x,y\right)}\left(T_i-T_j\right)+\\&\qquad+\sum_{j=1}^{n}c_0\varepsilon_{nj}\left(\varphi_{ij}F_iT_i^4-\varphi_{ji}F_jT_j^4\right)-P_i=0\end{aligned}\right]\qquad(4)$$

In these equations the individual components for each HPE define:

$\alpha_{ki} S_{ki} \left(T_i - T_c\right)$ is the heat removed by convection to the environment;

$\frac{\lambda\delta}{\theta_i(x,y)}\left(T_i - T_c\right)$ is the heat removed by conduction into the material of PCB;

$c_0 \varepsilon_i S_{pi} \left(T_i^4 - T_c^4\right)$ is the heat carrier radiation into the environment;

$\sum_{j \neq i}^{n} \frac{\lambda\delta}{\theta_{ij}(x,y)}\left(T_i - T_j\right)$ is the heat being applied to the element by conduction from other HPE through the PCB material;

$\sum_{j=1}^{n} c_0 \varepsilon_{nj} \left(\varphi_{ij} F_i T_i^4 - \varphi_{ji} F_j T_j^4\right)$ is the heat being applied to the element from other HPE due to radiation heat transfer;

P_i is the thermal capacity of HPE.

The solution of system (4) will give the temperature of each FU or element.

This system of equations can be solved numerically using mathematical packages Mathcad, Matlab, or integrated software environment (e.g. C++Builder, Visual Studio).

IV. OPTIMIZATION OF THE THERMAL REGIME OF HPE

Typically, the design aim to reduce the temperature of FU and HPE, and this can be achieved by appropriately placing the latter, removing them from each other to reduce interference and improve heat transfer. In system of equations (4), this effect is taken into account by function $\theta(x, y)$ and the coefficients of φ_{ij} and φ_{ji} are expressions (2) and (3).

Optimization of the thermal regime can be achieved by selecting the coordinates x, y of each of the HPE, which leads to the typical problems of parametric optimization of the objective function (OF) – $F(x_1, x_2, \ldots, x_n)$ with many variables. As such a function can be selected, for example, *TempSum* – sum of the temperatures of all the HPE.

V. METHODS OF OPTIMIZATION OF FUNCTIONS OF SEVERAL VARIABLES

For this purpose necessary the software for constrained optimization, i.e. optimization with constraints. The program should determine the coordinates of the centers of FU and HPE, and the square bases HPE can't "overlap" each other. The best program for constrained optimization suitable for solving this problem – a method of random search with a decrease search interval (RSDSI) and generalized algorithm of variable order (GAVO) [4].

According to the method RSDSI the minimum of objective function are finding by successive iterations (steps), by generating the vectors of parameters x_{ik}, which will vary randomly:

$$x_{ik} = x_{imink} + (x_{imaxk} - x_{imink})\eta_{ik}\,,\ i = 1, 2, \ldots, n,$$

where η_{ik} is the multiplier created by the generator of uniformly distributed numbers; k is the step number.

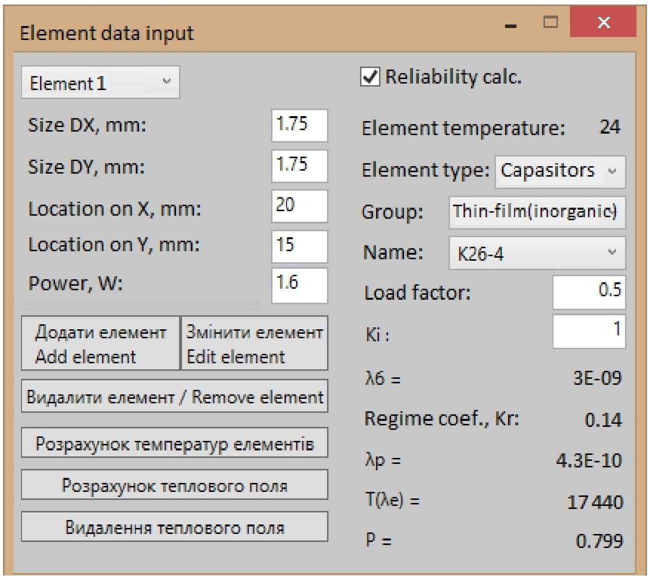
The initial values of parameters x_{imin}, x_{imax} are determined by the boundaries of zones of existence of the function $F(x_1, x_2, \ldots, x_n)$. Optimization is carried out by changing the parameters x_i and test the values of objective function $F(x_1, x_2, \ldots, x_n)$ at each step. The step considered successful if the latter is reduced in comparison with the previous, and the values x_i are taken as the boundary for the next step.

For secure retention of objective function within the specified boundaries, the number of generated sets x_{ik} (and corresponding values of OF) should be large enough: 30–80. The algorithm ensures finding the global minimum for the function $F(x_1, x_2, \ldots, x_n)$. If during the optimization the process is diverges, can be applied a more sophisticated method GAVO or combined methods [4].

VI. THE PROGRAM FOR AUTOMATIC PLACEMENT OF HPE

The program *OptPlat2015* (for placement FU and radio elements on PCB), which might be a module of computer aided design (CAD) cell or block, consists of several software modules. The algorithm of a program provides a solution to the system of equations (4). Software environment – C++ Builder 6, Visual Studio.

Input of initial data is illustrated in Fig. 1.



Element 1

Size DX, mm: 1.75

Size DY, mm: 1.75

Location on X, mm: 20

Location on Y, mm: 15

Power, W: 1.6

☑ Reliability calc.

Element temperature: 24

Element type: Capasitors

Group: Thin-film(inorganic)

Name: K26-4

Load factor: 0.5

Ki : 1

λб = 3E-09

Regime coef., Kr: 0.14

λр = 4.3E-10

T(λе) = 17 440

P = 0.799

Fig. 1. Input of initial data

VII. THE PROGRAM FOR AUTOMATIC PLACEMENT OF HPE

The failure rate λ for the electro radio elements (ERE) linked with their temperature T by the functions of the form $\lambda = \lambda_0 K_T$, where λ_0 is the value of λ at normal temperature, K_T is the temperature coefficient [3]. Values of λ_0 for various ERE (resistors, capacitors, semiconductor devices, transformers) are given in [3], there is possible to find analytical dependences $K_T = K(T)$; the same database with indicators of reliability for most types of the ERE (resistors, capacitors, semiconductor devices, transformers) is contained in the program *OptPlat2015*. Therefore, when the ERE from this list introduced, in to calculated modules automatically are introduced the reliability indicators of the corresponding element.

Formation of objective function $F(x_1, x_2, \ldots, x_n)$, which seek to achieve a minimum with parametric optimization in this program is the sum of the individual HPE temperatures:

$$F(x_1, x_2, \ldots, x_n) = \Sigma_n T_i\,.$$

Its value is calculated at each step of the optimization if the settings x_i are changed, i.e. coordinates of the centers HPE x_i, y_i when they are defined (at each step of the optimization process) temperatures of HPE are found from the system of equations (4). It is a system of nonlinear equations $\Sigma_n f(x_1, x_2, \ldots, x_n) = 0$ with n unknowns. To solve such systems there are different methods [5], for example, the method of simple iteration: the system is converted to the form: $\Sigma_n\,[x_i = \varphi\,(x_1, x_2, \ldots, x_n)]$, find out her approximate values of the parameters x_i and again substituted into the right side of the equation; the process is repeated until then, until the difference between the found value and the previous x_i will not be a valid low.

Initial temperatures of HPE can be found from the condition that all of the heat from the HPE is given only by convection and conduction:

$$T_i = \frac{P_i}{\alpha S_{ki} + \dfrac{\lambda\delta}{\theta_i(xy)}} - T_c.$$

When debugging the program revealed that the method of simple iteration leads to a divergence of the iterative process. Therefore, to determine the temperature T_i at each step, we used the method of Newton – formed system of linear equations with the matrix of partial derivatives $\partial f_j(x_i)/\partial x_i$, the vectors of residuals Δx_i and them functions $f_j(x_i)$:

$$\begin{bmatrix} \dfrac{\partial f_1}{\partial x_1} \cdots \dfrac{\partial f_1}{\partial x_n} \\ \cdots \\ \dfrac{\partial f_n}{\partial x_1} \cdots \dfrac{\partial f_n}{\partial x_n} \end{bmatrix} \begin{bmatrix} \Delta x_1 \\ \cdots \\ \Delta x_n \end{bmatrix} = \begin{bmatrix} -f_1 \\ \cdots \\ -f_n \end{bmatrix}. \tag{5}$$

In the system (5) the functions $f_j(x_i)$ formed from the respective equations (4):

$$f_i = \frac{1}{\alpha S_{ki} + \dfrac{\lambda\delta}{\theta_i(x,y)}} \left[P_i - c_0 \varepsilon_i S_{pi} \left(T_i^4 - T_c^4\right) + \sum_{j \neq i}^{n} \frac{\lambda\delta}{\theta_{ij}(x,y)} \left(T - T_c\right) + c_0 F_{ij} \left(T_j^4 - T_i^4\right) + T_c \right] - T_i.$$

Solution of the system of linear equations (5), i.e. definitions of Δx_i, conducted by Gauss method. When achieved $\Delta x_i \leq 10^{-3}$, it was considered that the temperatures T_i is determined. After that was calculated the value of the objective function.

The module of parametric optimization method corresponds to the algorithm RSDSI. At each optimization step generates a 84 sets of parameters x_i (the number of x_i twice the number of HPE: for each of the latter has two coordinates – x and y) and calculated the 84 values of OF; and from them is selected one with the minimum value. In the process of calculating the coordinates is performed conditional restrictions – eliminates the possibility of overlapping HPE pads each other. If after any step change in OF becomes smaller then 10^{-3}, the optimization ends.

The program calculates the OF – *TempSum* and resource τ for the initial arbitrary location of the HPE and the values of the same quantities after optimization, as well as increased resource $\Delta\,\tau$, obtained by optimization.

Visualization module displays on the monitor structural diagram of the PCB with the placement of FU and ERE. The sizes of PCB and venues contact of HPE, placement of the last portrayed in the scale, and can be compared the optimum layout FU and ERE with initial.

The initial values of the coordinates and temperatures of HPE and obtained after optimization values of these parameters the program writes in to results file. In addition, fixed values of objective function – initial and obtained as a result, as well as background information – number of iterations and calculations.

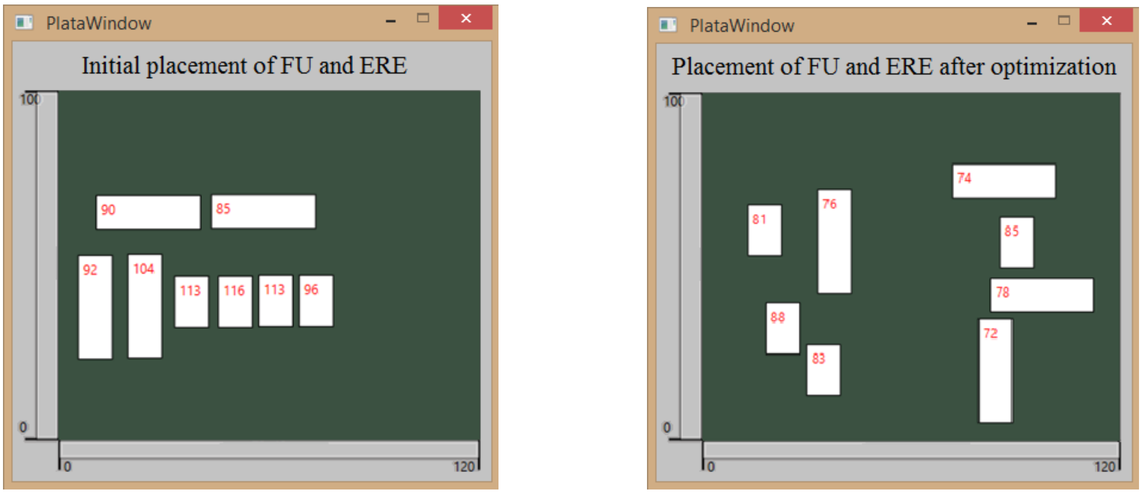
VIII. THE SIMULATION RESULTS OF THE OPTIMIZATION PROCESS

Modeling the optimization process and the obtained results conducted on several variants of the PCB cells and at different positions FU and HPE.

Below are the results of optimizing the topology of the board with sizes 120×100×1.5 mm, of the ceramics with λ = 15 W/m.K, which has the FU and HPE with a total capacity $P_\Sigma = 9.5$ W. The criterion of heat transfer from the surface of the board and HPE (α = 12 W/m^{2}K) correspond to the convective heat transfer in the forced convection, although the program can be modified so that these criteria were calculated according to the formulas (1) is the algorithm of the program remains unchanged. The interval of time for which determines the probability of failure-free operation adopted 10^5 hours.

Duration of the iteration process is dependent on the power of a PC (personal computer) and the number of HPE; to set of the initial parameters listed above – 8 HPE – a PC with a clock speed of 3.3 GHz to compete the optimization spent 6 iterations and 493 compute of objective function, and it spent 35 s.

Figure 3 shows the positions of FU – before and after optimization.



(a) (b)

Fig. 3. Placement of FU on the PCB: (a) is the initial; (b) is the after optimization

Indicator *TempSum* before optimization was 809 °C, after it – 647 °C, i.e. the temperature dropped on 20%; the probability of no-failure operation increased by 25.3%.

IX. CONCLUSIONS

Operation of the program *OptPlat2015* showed that with its help it is possible to optimize the temperature field of the PCB by the right placement of HPE on it – to reduce the temperature of most of the FU and ERE installed on board of a cell or on a substrate of micro assembly. Temperatures of the most loaded thermally HPE reduced by reducing their mutual thermal influence. This reduction for a particular HPE will be even more prominent, the more its thermal capacity. If found that the temperature of some of them is unacceptably high, it will be an indication for the designer: the need to apply additional cooling of the element, for example, by a radiator. Influence of the radiator is taken into account an increase in heat-transfer surface area of the corresponding source.

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А. В. Нікітчук, Б. М. Уваров. Оптимізація розміщення тепловиділяючих функціональних вузлів та електрорадіоелементів на друкованій платі

Розглянуто методи та програму автоматизованого розміщення тепловиділяючих функціональних вузлів та електрорадіоелементів на друкованій платі радіоелектронного апарату, які забезпечують оптимальність теплового режиму та підвищення надійності. Температури найбільш навантажених у тепловому відношенні тепловиділяючих елементів знижуються завдяки зменшенню їх взаємного теплового впливу. Зазвичай при проектуванні прагнуть зменшувати температури функціональних вузлів та електрорадіоелементів, а цього можна досягти відповідним розміщенням останніх, віддаляючи їх один від одного, щоб зменшити взаємний вплив і поліпшити умови тепловіддачі.

Ключові слова: тепловиділяючі елементи; радіоелектронні пристрої; відмова; теплове поле; тепловиділення; інтенсивність відмов; автоматизація; розрахунок надійності.

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Никитчук А. В., Уваров Б. М. Оптимизация размещения тепловыделяющих функциональных узлов и электрорадиоелементов на печатной плате

Рассматриваются методы и программа автоматизированного размещения тепловыделяющих функциональных узлов и электрорадиоэлементов на печатной плате радиоэлектронного аппарата, обеспечивающие оптимальность теплового режима и повышение надежности. Температуры наиболее нагруженных в тепловом отношении тепловыделяющих элементов снижаются благодаря уменьшению их взаимного теплового влияния. Обычно при проектировании стремятся уменьшать температуры функциональных узлов и электрорадиоэлементов, а этого можно достигнуть соответствующим размещением последних, удаляя их друг от друга, чтобы уменьшить взаимное влияние и улучшить условия теплоотдачи.

Ключевые слова: тепловыделяющие элементы; радиоэлектронные устройства; отказ; тепловое поле; тепловыделение; интенсивность отказов; автоматизация; расчет надежности.

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