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Mathematical model for temperature estimation forecasting of electrically conductive plate elements under action of pulsed electromagnetic radiation of radio-frequency range

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A mathematical model for determining the temperature of an electrically conductive plate element under the action of pulsed electromagnetic radiation of the radio-frequency range is proposed. This model allows us to take into account the influence of the process of thermoelastic energy dissipation on the forecasting of the value of temperature in addition to the joule heat. This process is determined by thermal expansion and the action of poendromotive forces arising in the element. This approach allows us to predict a decrease in the error of temperature determination. On this basis, the distributions of temperature in an electrically conductive plate element under the action of an amplitude-modulated radio pulse have been investigated numerically. Thermoelastic energy dissipation is taken into account when using the frequencies of the carrying electromagnetic oscillations beyond the resonant frequencies and of the first resonant frequency of the electromagnetic field for this element. An estimate of the influence of the process of taking into account mechanisms of energy dissipation on the total value of temperature in the element at the specified action and used frequencies is obtained. This has allowed us to increase the accuracy of temperature measurements in this element.

Keywords: *electroconductive plate element, electromagnetic radiation, radio frequency range, amplitude modulated radio pulse, carrier and resonant frequencies, the Joule heat, ponderomotive force, dissipation of energy, temperature, measurement error.*

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1. Introduction

Electroconductive plates are widely used as structural elements of many devices, in particular, in aviation and ship systems, in nuclear energy. These devices during operation are affected by many physical factors, in particular, the action of pulsed electromagnetic radiation of the radio frequency range [1]. As a result of such influence, the sources of the heat of Joule and ponderomotive forces emerge in these elements [2]. These factors cause a change in the temperature of the element, which consists of two components – the temperature component T^Q due to the Joule heat and the temperature component T^F caused by the deformation of the element by ponderomotive forces [3, 4]. The last component of the temperature is the result of the process of internal energy dissipation due to the deformation of the element. When measuring the temperature of an element, which is important for ensuring reliable operation and predicting its normal functioning [5, 6] under the influence of pulsed electromagnetic action, it is important to be able to simulate their temperature-force regimes to reduce temperature measurement error.

There are some works on determining the temperature of the plate elements under surface thermal heating [7–9]. However, the estimation of the temperature in the considered elements under the action of pulsed electromagnetic radiation of the radio frequency range, which is important in practical applications in devices of aviation and nuclear technology, has not been sufficiently studied. This work is devoted to taking into account the influence on the temperature estimation of the electrically conductive plate element of the process of thermoelastic energy dissipation under the action of an amplitude-modulated radio pulse.

In the manufacturing and operation, the conductive structural elements of many devices are exposed to external electromagnetic radiation of the radio frequency range. Due to this effect, the Joule heat sources and ponderomotive forces arise in these elements. Such factors cause a change in the temperature, which consists of two components – the component of temperature due to the Joule heat and the component of temperature – due to deformation of the element by the ponderomotive forces. The last component of temperature is the result of the internal energy dissipation process due to the deformation of the element. When measuring the temperature of an element, which is important in terms of ensuring the reliable operation of such elements and predicting their normal functioning under the influence of electromagnetic action, it is important to simulate their temperature-force regime to reduce the error of temperature measurement.

For example, in aviation and ship systems affected by the external electromagnetic radiation, electrically conductive plates are used as plate elements for measuring temperature and mechanical oscillations of elements of their structures; such electrically conductive plate elements operate under the action of non-stationary electromagnetic fields (NEMF). On this basis, there arises a problem of development of a mathematical model that takes into account, in addition to natural surface thermal and force factors affecting the performance and reliability of such plate elements, also additional volumetric thermal and force factors: the Joule heat Q and the ponderomotive forces $\boldsymbol{F}$ [1].

There are some known works on the method of determining the temperature and the study of the temperature-force regime of operation of the plate elements due to surface thermal heating and force load [2, 3]. However, the estimation of the temperature in the considered elements under the action of electromagnetic radiation of the radio frequency range, which is important for the study of the temperature-force regime of operation of such elements under the action of NEMF has not been sufficiently studied.

This work is devoted to taking into account the influence on the estimation of temperature in a conductive plate element under the action of NEMF, which is an urgent task to optimize the designing and calculation of the reliability of plate elements under the action of amplitude-modulated radio pulses used in modern technologies of processing.

2. Mathematical statement of the problem

An electroconductive plate element is considered in the form of a plate of the constant thickness $2h$ referred to a Cartesian coordinate system (x, y, z) whose plane xOy coincides with the middle surface of the plate. The plate material is homogeneous, isotropic, non-ferromagnetic, and its physical and mechanical characteristics are constant over the considered temperature range of the element. The plate is affected by the NEMF given by the values of the tangent component H_y of the magnetic field strength vector $\boldsymbol{H} = \{0; H_y; 0\}$ on its surfaces $z = \pm h$, which are in the conditions of convective heat exchange with the environment and are free from the force surface loading.

The components $H_y(z, t)$ of the vector $\boldsymbol{H}$ and the temperature $T(z, t)$ are selected as the determining functions for describing the temperature-force regime of the given plate. Such functions correspond to the functions of the thickness variable z and time t.

The process of the thermo-force regime of the plate under the action of NEMF consists of two stages. In the first stage, the NEMF is determined from the Maxwell relation. It is described by the vector $\boldsymbol{H}$, and caused by it the volumetrically distributed non-stationary Joule heat sources Q and ponderomotive forces $\boldsymbol{F}$ taking into account the given initial and boundary conditions. In the second stage from the system of equations of connected dynamical problem of thermoelasticity for a plate with plane-parallel boundaries [8], the nonstationary temperature field T and normal (with respect to the plate surface) component σ_{zz} of the tensor of dynamic stresses are defined. From the obtained Joule heat Q and ponderomotive force $\boldsymbol{F} = \{0; 0; F_z(z, t)\}$ we define components of the temperature T^Q and T^F caused by these physical factors, and summary temperature $T = T^Q + T^F$. Let consider each of the steps in sequence.

2.1. Definition of NEMF

The non-zero component $H_y(z,t)$ of the vector $\boldsymbol{H}$ in the plate is determined from the equation

$$\frac{\partial^2 H_y}{\partial z^2} - \sigma\mu\frac{\partial H_y}{\partial t} = 0, \tag{1}$$

under boundary conditions on the surfaces $z = \pm h$ of the plate

$$H_y(-h,t) = H_y^-(t), \quad H_y(h,t) = H_y^+(t),$$

and zero initial condition

$$H_y(z,0) = 0,$$

where $H_y^-(t)$, $H_y^+(t)$ are the given time functions that describe the specific nature of the change in time of the NEMF; σ, μ are coefficients of electric conductivity and magnetic permeability of the plate material.

From the equation (1) under specified boundary and initial conditions, the function $H_y(z,t)$ determines the specific densities of the Joule heat $Q(z,t)$ and ponderomotive forces $\boldsymbol{F} = \{0;0;F_z(z,t)\}$ in the form of ratios

$$Q = \frac{1}{\sigma}\left(\frac{\partial H_y}{\partial z}\right)^2, \tag{2}$$

$$F_z = -\mu\left(\frac{\partial H_y}{\partial z}\right)H_y. \tag{3}$$

2.2. Determination of temperature components

According to the chosen physical and mathematical model for determining temperature components T^Q and T^F the system of equations of connected dynamical problem of thermoelasticity for a plate needs to be solved,

$$\begin{aligned} &\frac{\partial^2 T}{\partial z^2} - \frac{1+\varepsilon_*}{\varkappa}\frac{\partial T}{\partial t} - \varepsilon_*\frac{1+2\nu}{\varkappa\alpha E}\frac{\partial \sigma_{zz}}{\partial t} = -\frac{1}{\lambda}Q,\\ &\frac{\partial^2 \sigma_{zz}}{\partial z^2} - \frac{1}{c_1^2}\frac{\partial^2 \sigma_{zz}}{\partial t^2} = \alpha\rho\frac{1+\nu}{1-\nu}\frac{\partial^2 T}{\partial t^2} - \frac{\partial F_z}{\partial z}. \end{aligned} \tag{4}$$

Here $\varkappa$, λ are temperature- and heat conductivity coefficients; α, ν are linear thermal expansion and Poisson coefficients, E, ρ are Young module and plate material density; $c_1 = [(1-\nu)E/(\rho(1+\nu)(1-2\nu))]^{1/2}$ is an elastic wave of expansion velocity; $\varepsilon_* = \frac{\varkappa\alpha^2 E T_0(1+\nu)}{\lambda(1-\nu)(1-2\nu)}$ is the temperature and deformation fields connectivity parameter [9, 10].

The component T^Q of the temperature we determine from the first equation of the system (4) letting $\varepsilon_* = 0$ under the condition of termal isolation

$$\frac{\partial T(\pm h,t)}{\partial z} = 0$$

of the surfaces $z = \pm h$ and under the zero initial condition

$$T(z,0) = 0.$$

The second equation of the system (4) we solve under boundary conditions $\sigma_{zz}(\pm h,t) = 0$ (surfaces $z = \pm h$ free from force loading) and initial condition $\sigma_{zz}(z,0) = 0$, $\frac{\partial\sigma_{zz}(z,0)}{\partial t} = \frac{\alpha E}{1-\nu}\frac{\partial T(z,0)}{\partial t}$ enforced on component $\sigma_{zz}(z,t) = 0$ of the stress tensor.

It is known [10, 11] that under pulsed electromagnetic action deformation process in electroconductive bodies caused by ponderomotive force, is adiabatic. Taking into consideration this physical law, we determine the temperature component T^F by obtained component σ_{zz}^F of the stresses tensor component σ_{zz}. Component σ_{zz}^F of the stresses tensor we define from the second equation of the system (4), letting $T = 0$. As a result we obtain following formula [3, 4, 12]:

$$T^F = -\frac{\alpha T_0}{\lambda(1-\nu)} \frac{\varkappa(1+2\nu)\sigma_{zz}^F}{[1+3\varepsilon_*(1-\nu)/(1+\nu)]}. \tag{5}$$

The temperature distribution $T(z,t)$ in the plate is determined from (2) and (3) by the specific Joule heat $Q(z,t)$ density in particular, under the boundary conditions of thermal insulation on the inner and outer surfaces of the plate where $\varkappa$ and λ are the coefficients of temperature and thermal conductivity of the plate material. Note that in the case of convective heat transfer, the recorded boundary conditions of the thermal insulation of the plate surfaces are replaced by the corresponding convective heat transfer conditions.

3. Determination of solutions of the formulated initial boundary value problems

To solve the formulated initial boundary value problems, we approximate the distributions of the determining functions $H_y(z,t)$, $T(z,t)$, $\sigma_{zz}(z,t)$ by the plate thickness variable z, by cubic polynomials

$$H_y(z,t) = \sum_{i=0}^{3} a_i(t)\, z^i, \tag{6}$$

$$T(z,t) = \sum_{i=0}^{3} b_i(t)\, z^i, \tag{7}$$

$$\sigma_{zz}(z,t) = \sum_{i=0}^{3} c_i(t)\, z^i. \tag{8}$$

The coefficients $a_i(t)$, $b_i(t)$, $c_i(t)$ of the approximation polynomials (6)–(8) are determined by the integral characteristics $H_{ys}(t)$, $T_s(t)$, $\sigma_{zzs}(t)$ of the key functions $H_y(z,t)$, $T(z,t)$, $\sigma_{zz}(z,t)$

$$H_{ys}(t) = \int_{-h}^{h} H_y(z,t)\, z^{s-1}\, dz, \quad s = 1,2, \tag{9}$$

$$T_s(t) = \int_{-h}^{h} T(z,t)\, z^{s-1}\, dz, \quad s = 1,2, \tag{10}$$

$$\sigma_{zzs}(t) = \int_{-h}^{h} \sigma_{zz}(z,t)\, z^{s-1}\, dz, \quad s = 1,2, \tag{11}$$

and given boundary conditions on the surfaces $z = \pm h$ of the plate. To find the integral characteristics $H_{ys}(z,t)$, $T_s(z,t)$ and $\sigma_{zzs}(z,t)$ the initial equations (1), (4) are integrated according to (9)–(11) taking into account the expressions (6)-8).

As a result, the initial boundary value problems for the definition of the key functions $H_y(z,t)$ and $T(z,t)$ are reduced to the corresponding Cauchy problems for the integral characteristics of these functions, which are described by the systems of equations

$$\begin{cases} \dfrac{dH_{y1}(t)}{dt} - d_1 H_{y1}(t) - d_2 H_{y2}(t) = d_3 H_y^-(t) + d_4 H_y^+(t), \\ \dfrac{dH_{y2}(t)}{dt} - d_5 H_{y1}(t) - d_6 H_{y2}(t) = d_7 H_y^-(t) + d_8 H_y^+(t), \end{cases} \tag{12}$$

$$\begin{cases} \dfrac{dT_1}{dt} + d_1^T T_1 + d_2^T T_2 = W_1(t), \\ \dfrac{dT_2}{dt} + d_3^T T_1 + d_4^T T_2 = W_2(t), \end{cases} \tag{13}$$

$$\begin{cases} \dfrac{d\sigma_{zz1}}{dt} + d_1^\sigma \sigma_{zz1} + d_2^\sigma \sigma_{zz2} = W_1^*(t), \\ \dfrac{d\sigma_{zz2}}{dt} + d_3^\sigma \sigma_{zz1} + d_4^\sigma \sigma_{zz2} = W_2^*(t), \end{cases} \tag{14}$$

and are solved under the initial conditions according to (7), (8). The coefficients $d_{1\div 8}$, $d_{1\div 4}^T$, $d_{1\div 4}^\sigma$ are determined by the geometric parameters of the plate and the physical and mechanical characteristics of its material, $W_S(t)$, $(s = 1,2)$, $W_S^*(t)$, $(s = 1,2)$ is the right hand part of the heat conductivity equation (4), integrated according to (10) and (11).

Applying the Laplace integral transformation of time t, the solutions of the Cauchy problem (12), (13) are written as a convolution of functions describing given boundary conditions and homogeneous solutions. As a result we obtain the expressions

$$H_y(z,t) = \sum_{i=0}^{3} \left\{ \sum_{s=1}^{2} a_{is} \sum_{k=1}^{2} \int_0^t \left[A_{s1}(k) H_y^-(\tau) + A_{s2}(k) H_y^+(\tau) \right] e^{p_k(t-\tau)} d\tau + a_{i3} H_y^-(t) + a_{i4} H_y^+(t) \right\} z^i \tag{15}$$

for components $H_y\,(z,t)$ and

$$T(z,t) = \sum_{k=0}^{3} \sum_{s=1}^{2} \left(b_{ks} \sum_{m=1}^{2} \int_0^t \left[B_{s1}(m) W_1(\tau) + B_{s2}(m) W_2(\tau) \right] e^{p_m(t-\tau)} d\tau \right) z^k \tag{16}$$

for the temperature $T(z,t)$, and the expression for the component $\sigma_{zz}(z,t)$

$$\sigma_{zz}(z,t) = \sum_{n=0}^{3} \sum_{\alpha=1}^{2} \left(c_{n\alpha} \sum_{\gamma=1}^{2} \int_0^t \left[C_{\alpha 1}(\gamma) W_1^*(\tau) + C_{\alpha 2}(\gamma) W_2^*(\tau) \right] e^{p_\gamma(t-\tau)} d\tau \right) z^n, \tag{17}$$

where $A_{s1}(k)$, $A_{s2}(k)$ $(s = 1,2)$ are expressions that depend on the roots p_k $(k = 1,2)$ of the characteristic equation of system (12); $B_{s1}(m)$, $B_{s2}(m)$ $(s = 1,2)$ are expressions that correspond to the non-homogeneous solutions of system (13) and depend on the roots p_m $(m = 1,2)$ of its characteristic equation, $C_{\alpha 1}(\gamma)$, $C_{\alpha 2}(\gamma)$ $(\alpha = 1,2)$ are expressions that depend on the roots of the characteristic equation p_α $(\alpha = 1,2)$ of system (14).

Based on the developed general relations (15) and (6), (16) and (7), (17) and (8) for homogeneous non-stationary electromagnetic action, the results of numerical analysis of the temperature-force regime of the plate electrically conductive plate element under the action of amplitude-modulated radio pulse (AMRP) are obtained.

4. Investigation of the temperature-force regime under the action of AMRP

The AMRP action is mathematically described by the function $H_y^\pm(t)$ in the form [4, 13–15]

$$H_y^\pm(t) = k_0 H_0 \left(e^{-\beta_1 t} - e^{-\beta_2 t} \right) \cos \omega t, \tag{18}$$

where k_0 is the normalization factor; β_1 and β_2 are parameters characterizing respectively the times of the increase t_{iner} and decrease t_{dekr} fronts of the modulated pulse which duration is t_i; H_0 is the maximum value of magnetic field strength in AMRP; ω is the frequency of carrier electromagnetic oscillations.

Substituting the expression (16) into expressions (14), (6) and (15), (7), we obtain the expressions for the non-stationary volumetric ponderomotive force and temperature in the plate element under the action of AMRP. The Joule heat Q, the component F_z of the ponderomotive force $\boldsymbol{F}$ and the temperature T in this plate element with thickness $2h = 2\,\text{mm}$ made of X18H9T stainless steel are analyzed. The characteristics β_1 and β_2 are consistent with the duration of the modulated pulse $t_i = 100\,\mu\text{s}$ and the circular frequency $\omega = 628000\,1/\text{s}$.

Figures 1–3 show the changes in time of the Joule heat Q, the ponderomotive force F_z and temperature T^Q (T^Q is temperature which is caused by the Joule heat Q). Lines 1, 2, 3 in the figures correspond to the values of the thickness coordinate $z = h; 0.5h; 0$. It should be noted that the maximum values of the considered value are reached on the surface of the plate, and the minimum – on its middle surface.

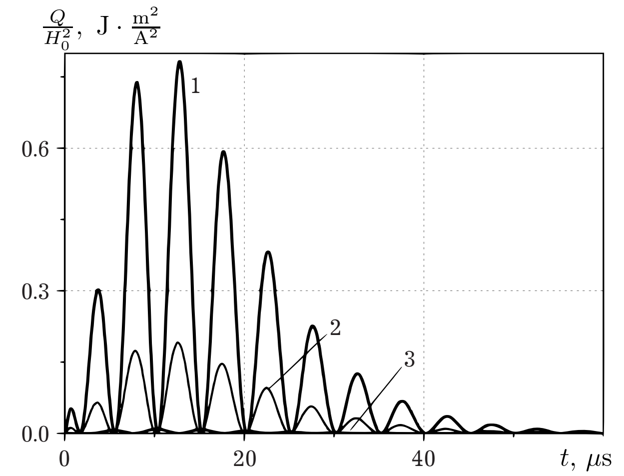

Fig. 1. The change in time of the Joule heat dissipation in the plate element.

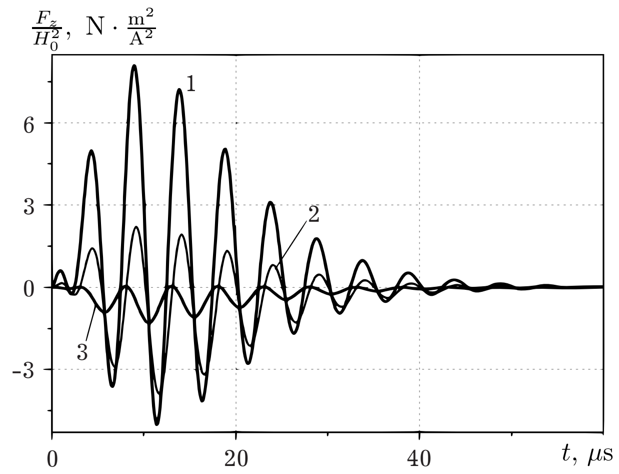

Fig. 2. The change in time of the ponderomotive force in the plate element.

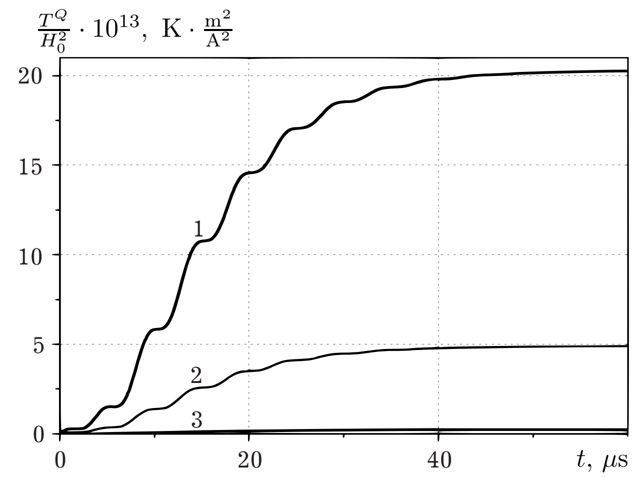

Fig. 3. The change in time of the temperature T^Q in the plate element.

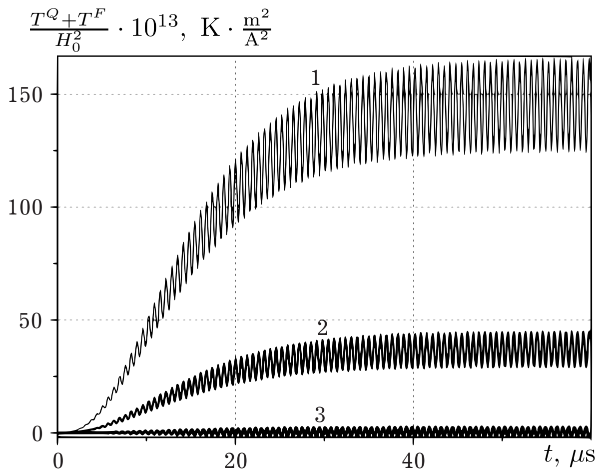

Fig. 4. The change in time of the total temperature in the plate element at $\omega = \omega_{r1}$.

Figure 4 shows the change in time of the total temperature $T = T^Q + T^F$ (T^F is the temperature of the plate element due to its deformation by the ponderomotive force $\boldsymbol{F}$) for the frequency of the carrier electromagnetic oscillations $\omega = \omega_{r1} = 4.678 \cdot 10^6\,1/\text{s}$. Here ω_{r1} is the first resonant frequency of the carrier electromagnetic oscillations for a given plate element. Lines 1—3 in Fig. 4 correspond to the values of such lines in Fig. 3.

Note that at the carrier frequency ω_{r1}, the maximum values of the total temperature increase approximately $8-10$ times compared to the temperature values for the frequency $\omega = 628000\,1/\text{s}$ (this frequency is outside the resonant frequency range ω_{r1}). Note that the contribution of the temperature component T^F to the total temperature at frequency $\omega = 628000\,1/\text{s}$ relative to the component T^Q can be neglected. Accordingly, for the frequency $\omega = \omega_{r1}$ the contribution of the temperature component T^F is $20-25\%$ compared to the contribution of the component T^Q.

The change in the total temperature $T^Q + T^F$ at the frequency $\omega = \omega_{r1}$ has oscillating character in accordance with the nature of change in time of the ponderomotive force, and its maximum values are an order of magnitude higher than the same values of the total temperature at the frequency $\omega = 628000\,1/\text{s}$.

5. Conclusions

The proposed method allows us to determine the temperature and volumetric ponderomotive forces in the considered electrically conductive plate element under the action of a homogeneous external NEMF.

On the basis of this technique, the initial-boundary value problems for the determining functions (the tangent component of the magnetic field intensity vector and the temperature) are reduced to the Cauchy problems for the integral characteristics of these functions. The Cauchy problem solutions were written using the Laplace integral transform in the form of functions convolutions. Such functions describe the given boundary conditions and homogeneous solutions of the problems of electrodynamics and heat conductivity under the homogeneous non-stationary electromagnetic action.

Based on the obtained solutions, a numerical analysis of the change in the time of the Joule heat, the ponderomotive force, and total temperature under the action of the AMRP on the considered plate element was performed. The regularities of the change in time of these physical quantities at the frequency of the carrier signal AMRP, which is outside the range of resonant frequencies of the electromagnetic field, as well as at the first resonant frequency, are investigated.

The proposed approaches and the qualitative and quantitative regularities of temperature change can be a theoretical basis for improving the accuracy of measurement and reliability of the plate elements under the action of AMRP, which are used in navigation systems and nuclear power stations.

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Математична модель прогнозування оцінки температури електропровідних пластинчастих елементів за дії імпульсного електромагнітного випромінювання радіочастотного діапазону

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Запропоновано математичну модель визначення температури електропровідного пластинчастого елемента за дії імпульсного електромагнітного випромінювання радіочастотного діапазону. Дана модель дозволяє враховувати вплив на прогнозування значення температури крім тепла джоуля ще й процесу термопружного розсіювання енергії. Цей процес зумовлений тепловим розширенням і дією пондеромоторних сил, що виникають в елементі. Такий підхід дозволяє прогнозувати зменшення похибки визначення температури. На цій основі чисельно досліджено розподіли температури в електропровідному пластинчастому елементі за дії амплітудно-модульованого радіоімпульсу. Враховано термопружне розсіювання енергії за використання частот несучих електромагнітних коливань поза околом резонансних частот і рівних першій резонансній частоті електромагнітного поля для даного елемента. Отримано оцінку впливу процесу врахованих механізмів дисипації енергії на сумарне значення температури в елементі за вказаної дії і використовуваних частот. Це дозволяє підвищити точність вимірювання температури в даному елементі.

Ключові слова: *електропровідний пластинчастий елемент, електромагнітне випромінювання, радіочастотний діапазон, амплітудно модульований радіоімпульс, несучі та резонансні частоти, тепло Джоуля, пондеромоторна сила, дисипація енергії, температура, похибка вимірювання.*