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Model of a fairing flat dielectric layer under aerodynamic heating

This model analyses how aerodynamic heating affects the behaviour of a flat dielectric layer in a fairing. The study aims to provide insights into the performance of the system and inform the development of more effective fairing designs that can withstand high temperatures and other environmental factors.

Introduction

Aerodynamic heating of radio-transparent fairings at high aircraft speeds leads to changes in the dielectric constant and losses of the fairing material, affecting the passage of radio waves and causing errors in the radar antenna system. This problem is particularly significant in digital signal processing, where changes in fairing heating temperature affect the system's characteristics over time. To address this, a four-pole model of a flat dielectric layer during aerodynamic heating is proposed. This representation allows for the consideration of temperature distribution effects on electromagnetic field passage through the dielectric layer under various boundary conditions.

1. Statement of the problem

The objective of this study is to investigate the behaviour of the electromagnetic field in a flat dielectric layer under aerodynamic heating. The problem is approached by determining the temperature and permittivity distribution across the layer's thickness. This information is then used to find the wave resistance and subsequently derive the equivalent quadripolar parameters. To achieve this, the resistance matrix or system of Z-parameters was utilized. By solving this problem, a better understanding of the effects of aerodynamic heating on electromagnetic field behaviour can be gained.

2. Literature review

Numerous studies have been conducted on the electromagnetic field in antenna radome walls and the development of special radome materials [1-22]. These materials can be classified into two groups: structural materials and materials interacting with electromagnetic fields during aerodynamic heating, including with lasers. Dielectric materials are important in both groups, serving as mechanical carriers and microwave materials [1-7, 11-12, 18-21]. However, their radio engineering parameters must meet stringent requirements, particularly with regard to stability when subjected to temperature effects. Current methods for measuring the temperature dependencies of dielectric parameters do not provide information on the dynamic dependence during heating. Moreover, current design methods rely on averaging temperature over wall thickness, which can result in large errors when temperature gradients change during aircraft manoeuvres [2,3,12]. Thus, new methods and specialized equipment are needed to accurately measure the parameters of dielectric materials under thermal conditions similar to operational ones.

3. Materials and methods

For the calculation of electrodynamic objects, a flat layer with a constant value of E and H vectors subjected to aerodynamic heating with uneven temperature distribution is used. Quartz ceramic, widely used in fairing creation, is chosen as the layer material, and its absolute permittivity depends on temperature.

$$\varepsilon(x) = \varepsilon_0 exp[1 - \Pi + 2{,}6 \cdot 10^{-5}(T(x) - 290)] \quad (1)$$

where *T(x)* – temperature distribution, K; П – porosity (volume fraction of pores); ε_0- absolute permittivity at zero porosity and at T = 290 K. The numeric coefficient $2{,}6 \cdot 10^{-5}$ does not play a fundamental role and is determined by the type of material used.

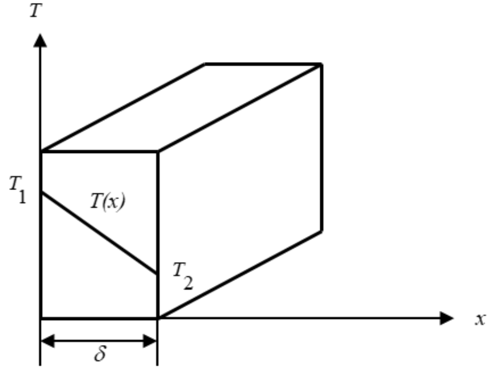

Fig. 1. Temperature distribution over the thickness of the dielectric layer

According to the law of temperature distribution over the layer thickness [13], we have

$$T(x) = (T_2 - T_1)\frac{x}{\delta} + T_1 \quad (2)$$

Substitute (2) в (1):

$$\varepsilon(x) = \varepsilon_0\, exp[1 - \Pi + 2{,}6 \cdot 10^{-5}(T(x) - 290)] =$$

$$\varepsilon_0\, exp[1 - \Pi + 2{,}6 \cdot 10^{-5}(T_1 - 290)] \cdot exp\left[2{,}6 \cdot 10^{-5}\left((T_2 - T_1)\frac{x}{\delta}\right)\right]. \quad (3)$$

Let us introduce the following notation:

$$A = 2{,}6 \cdot 10^{-5} \quad (4)$$

$$A_1 = 1 - \Pi + 2{,}6 \cdot 10^{-5}(T_1 - 290) = 1 - \Pi + A(T_1 - 290) \quad (5)$$

As a result, the permittivity can be written as:

$$\varepsilon(x) = \varepsilon_0 exp(A_1) \cdot exp\left[A\left((T_2 - T_1)\frac{x}{\delta}\right)\right]. \quad (6)$$

Non-magnetic materials with an absolute magnetic permeability μ equal to the absolute magnetic permeability of a vacuum are usually used as dielectric coatings for aircraft antennas. In this case, the wave resistance of the layer at the normal incidence of a plane transverse wave, taking into account (6), is determined by the expression.

$$W(x) = \sqrt{\frac{\mu}{\varepsilon(x)}} = \sqrt{\frac{\mu}{\varepsilon_0 exp(A_1) \cdot exp\left[A\left((T_2 - T_1)\frac{x}{\delta}\right)\right]}} = \sqrt{B}\, exp\left[A\left((T_1 - T_2)\frac{x}{2\delta}\right)\right]. \quad (7)$$

This, expression (7) is used to determine the elements of the resistance matrix of a four-terminal network formed by a dielectric layer during aerodynamic heating.

4. Experiments

Based on the results obtained, the influence of aerodynamic heating of the radome of a two-element antenna array, Fig. 4, on determining the angle of wave arrival was studied.

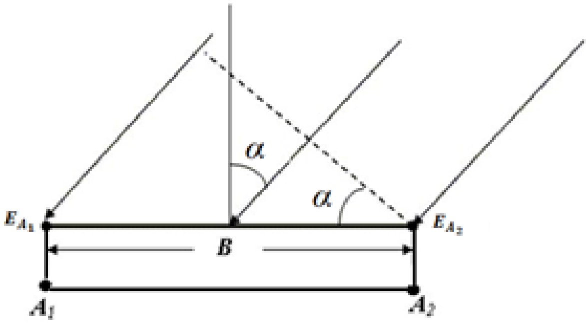

Fig. 2. Two-element antenna array under the dielectric layer

The absolute error in determining the direction of arrival of the wave that occurs when the aerodynamic heating of the fairing is not considered is determined by the expression.

$$\Delta\varphi = \varphi_0 - \alpha = \arcsin\frac{(\Delta\Phi + \beta_1 - \beta_2)\lambda}{2\pi B} - \arcsin\frac{\Delta\Phi\,\lambda}{2\pi B}, \quad \Delta\Phi = \frac{2\pi B}{\lambda}\sin\alpha, \tag{8}$$

where β_1, β_2 - arguments of the dielectric transmission coefficient over the element A_1, A_2 respectively; φ_0 - the angle of arrival of the wave, calculated taking into account the heating of the fairing, α - the angle of arrival of the wave, calculated without taking into account the heating of the fairing.

P9606 (USA) pyroceramic with a relative permittivity at porosity was used as the fairing material. П=0%, equal $\varepsilon_r = 5{,}8$, oscillation frequency f=10 GHz.

Conclusions

The study developed a model of a flat dielectric layer of a fairing, considering the gradient distribution of heat over the layer thickness. The model is represented as a four-terminal network and is an inhomogeneous transmission line with an exponential change in wave resistance. The obtained results increase the accuracy of radome calculations during aerodynamic heating, which is useful in designing antenna-radome systems for moving objects with the required radiation pattern. The study's findings can be used in the development of space communication and navigation systems with increased accuracy. Future research should focus on developing analog and digital radome-antenna systems with increased angular accuracy under aerodynamic heating conditions.

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