International Journal of Pure and Applied Mathematics
Volume 116 No. 3 2017, 739-750
ISSN: 1311-8080 (printed version); ISSN: 1314-3395 (on-line version)
url: http://www.ijpam.eu
doi: 10.12732/ijpam.v116i3.20

ijpam.eu

THE EFFECT OF SUPER-HIGH-FREQUENCY HIGH POWER SIGNAL TRANSMISSION ON THE WAVEGUIDE THERMOELASTIC STATE

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Abstract: Waveguides are guide systems and are widely used to transmit high frequency energy in electronic facilities. The represented research is, therefore, relevant. The objective of the paper is studying the cross-disciplinary problem on the effect of power loss of super-high-frequency signals transmitted over waveguides on their thermoelastic state. Studying all physical characteristics of waveguide affected by temperature is taken as a dominant approach. It has been found that assessment of waveguide temperature field is carried out based on developed mathematical models with thermal balance differential equations, which consider various operating conditions. Obtained temperature distribution can be used to calculate stress-strain state of waveguide as a whole, as well as its current conducting coating in order to secure its strength and rigidity.

AMS Subject Classification: 58Z05, 70G70
Key Words: electromagnetic wave, magnetic signal, loss factor, thermal cycling, temperature field

1. Introduction

Waveguides are designed to transmit super high frequency (SHF) electromag-

Received: July 4, 2017
Revised: September 4, 2017
Published: October 26, 2017

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netic signals between aerials and transmitting-receiving units in various equipment, for example, in aerospace devices, radiolocation, military and civil communication, etc. Waveguides are exposed to different external loads in the course of usage: deformation, force impact, thermal effects due to solar radiance, as well as power loss when transmitting high-frequency signals [1].

In order to secure general strength and rigidity of waveguides, corresponding methods for calculating deformation and force external loads were developed and are being used [2, 3, 4]. In addition, today there's a tendency towards an increase in transmitted signal power via waveguides with simultaneous extension of their active life to 15 years and more. This requires updating existing waveguide calculation methods to take into account external factors that were previously considered minor. For example, ground tests of waveguides we had carried out demonstrated that waveguide heat up to 4060 $^{\circ}C$ in the transfer of high frequency signals of increased power, 10 W and more. Since high power signals are regularly transmitted when using waveguides, this heating will contribute to additional thermal cycling, which should be necessarily considered as a part of cyclic heating due to solar radiance and other thermal effects.

A difference in mechanical (elastic modulus, Poisson's ratio etc.) and thermal (expansion coefficient, heat capacity, etc.) properties of waveguide material (aluminum, copper, alloys) and current conducting coating applied on its inner walls (gold, silver, copper, etc.) causes shearing stress in junctions, which change in the course of time under periodic law in line with heating periodicity from signal transmission. As a result of this thermal cycling microcracks may appear in the structure, which taken with shearing stress cyclic effect will lead to conductive coat peeling and waveguide seal failure [5].

The problem is complicated by the fact that opportunities for dissipating excessive heat under conditions of open space are severely limited, especially in the event of non-hermetic space vehicle when all its components and systems are exposed to solar radiance and there's little convective exchange. All this makes it difficult to withdraw heat in an effective way and requires consideration of the impact of transmitting SHF signals over waveguides on their thermoelastic state.

2. Materials and Methods

Availability of a discrete set of vibration modes is possible in waveguides as in distributed parameter systems, each mode of vibrations is distributed at its phase and group speeds. All vibrations have dispersion, i.e. their phase speeds depend on frequency and differ from group speeds. Given that the effect of super-high-frequency high power signal transmission on the waveguide thermoelastic state is a complex process, the following methods were used: systematics, analysis, accuracy, observation, and other empirical and theoretical research methods. Theoretical methods help to synchronize and effectively analyze the stated range of problems. The analysis made it possible to divide the subject on properties, features. Accuracy is necessary when measuring parameters, which are necessary for calculating and studying waveguide thermoelastic state.

The method of scientific-methodical literature analysis is that any qualifying paper starts with literature review on the problem under study. In this regard, an analysis of literary sources, which provided a big picture in this regard, was carried out, different concepts and ideas were examined. It's possible to compare information and prove it in one's research in the process of working on the basis of other researches. Mathematical and statistical methods recognize not only technology factor changes but also complex sociopsychological factors of manufacturing process management. Although these effects are of a systematic nature, the mass character of manifestation allows revealing them using statistical methods.

The made analysis of existing literature [6, 7, 8, 9, 10, 11] on the current problem showed that the authors of considered sources indicate very small losses from transmitted signals in waveguides as compared to other types of guide systems and they, therefore, conclude that there's no need for considering heat generation.

The used methods give an insight into our paper and help to study the problem of the effect of super-high-frequency high power signal transmission on the waveguide thermoelastic state.

3. Results and Discussion

3.1. Signal Power Loss

According to exiting methods [6, 7, 8, 9, 10, 11], in the course of EM wave transmission over waveguide the transmitted signal attenuates due to partial energy dissipation over thin-wall structure. There are several causes of signal attenuation: 1) losses in material conductive layer on waveguide inner walls;

2) losses in dielectrics in waveguide body cavity;

3) losses due to radiation because of loose coupling of separate elements of

waveguide-distribution system segment, etc.

As a result, all components of electromagnetic field (EMF) along the waveguide center axis will decrease under exponential law [6, 7, 8, 9, 10, 11], according to which a decrease in energy flow along waveguide can be characterized by the change of power ΔP of signal transferred:

$$\Delta P = P_{in} - P_{out} = P_{in} - P_{in}e^{-2\alpha l} = P_{in}\left(1 - e^{-2\alpha l}\right) \ [W] \qquad (1)$$

where P_{in} – input power duct, W;
P_{out} – output power, W;
α – loss factor, d/m;
l – waveguide length, m.

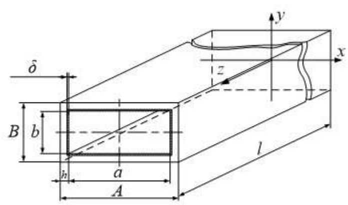

Figure 1: Waveguide straight segment structure

According to the expression (1), power loss of ΔP signal in waveguide can be described with loss (attenuation) factor α, which is used to measure EM energy power dissipation in its dissemination along waveguide taking into account all potential reasons of this phenomenon.

3.2. Loss Factor

The value of loss factor α can be determined experimentally (empirically) or using theoretical dependences obtained by different authors [6, 7, 8, 9, 10, 11] who take into account signal propagation conditions: waveguide type and sizes, walls' and skin layer's material properties, availability/absence of a dielectric, transmitted EM wave characteristics, etc.

For example, in the most common case of transmitting magnetic wave of 10 type over rectangular cross-section waveguide, the theoretical value of loss factor α, according to [6], can be determined under the following dependence:

$$\alpha = 10^{-3} \cdot \sqrt{0,1 \cdot \pi \cdot f \cdot \mu_{\alpha} \cdot \rho} \cdot \frac{1 + \frac{2b}{a}\left(\frac{\lambda}{2a}\right)^2}{bZ \cdot \sqrt{1 - \left(\frac{\lambda}{2a}\right)^2}} \ [dB/m] \qquad (2)$$

where $\pi - 3,1415\ldots$;
f – transmitted signal frequency, hz;
μ_a – environment absolute magnetic permittivity, H/m;
ρ – skin layer material specific resistance, Ohm/m;
a – waveguide body cavity width ($> b$), m;
b – waveguide body cavity height ($> b$), m;
λ – transmitted signal wave length, m;
Z – wave resistance of signal propagation environment, Ohm.

However, authors state [6, 7] that the actual values of loss factor will be higher than calculated ones by 10-30% due to unaccounted losses due to connection looseness, contact resistance, lacquer coating, etc.

3.3. Waveguide Heating Simulation

The process of heating can be divided into two stages: thin skin layer warming up at fast signal and heating-up of the entire structure of waveguide at long term SHF signal transmission. Previous researches showed that current conducting coating warming up takes little time and the first stage can be disregarded. In the course of waveguide wall heating up, heat exchange with the environment starts affecting its temperature field, that's why this process can no longer be considered adiabatic.

3.3.1. Heat-Transfer Equation

A temperature difference between inner and outer walls will result in heat flow through waveguide walls [12]. Heat transmission direction in waveguide when transmitting electromagnetic signal will occur normally $\dot{n}$ towards outer walls (Fig. 2,). Border effects in plate connection joint corners will be neglected.

The adopted approach allows adopting a one-dimension transfer model to calculate waveguide temperature field, and heat generation ΔQ in skin layer when electromagnetic signal is passing over is modeled with source of heat with an intensity $W(t)$.

Then waveguide temperature field can be described with a one-dimension parabolic differential thermal conductivity equation with source of heat as follows [13]:

$$\frac{\partial T(x,t)}{\partial t} = a_2 \frac{\partial^2 T(x,t)}{\partial x^2} + \frac{W(t)}{c_1 \gamma_1}, \tag{3}$$

where a_2 – waveguide wall material temperature conductivity coefficient determined using the formula:

$$a_2 = \frac{\lambda_2}{c_2\gamma_2}\left[\frac{m^2}{s}\right], \tag{4}$$

where: λ_2 – wall material heat-conductivity factor, $\frac{W}{m\cdot}{}^{\circ}C$;
c_2 – wall material specific-heat capacity, $\frac{J}{kg\cdot{}^{\circ}C}$;
γ_2 – wall material specific density, $\frac{kg}{m^3}$.
c_1 – skin layer material specific-heat capacity, $\frac{J}{kg\cdot{}^{\circ}C}$;
γ_1 – skin layer material specific density, $\frac{kg}{m^3}$;
$W(t)$ – heat source intensity in skin layer, $[\frac{W}{m^3}]$:

$$W(t) = \frac{\Delta P(t)}{V} = \frac{\Delta P(t)}{S\cdot\delta} = \frac{\left(1 - e^{-2\alpha l}\right)P(t)}{S\cdot\delta} \tag{5}$$

where S – lateral area of all waveguide walls, m^2.

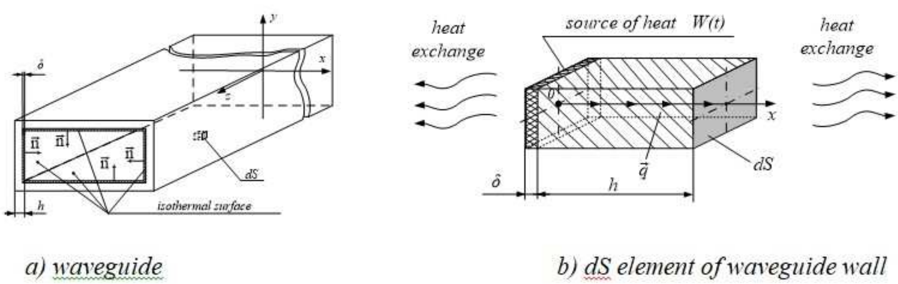

Figure 2: Calculation model of heat transfer over waveguide wall

To get a single-valued solution of differential equation (3) it's necessary to set boundary conditions, which include initial and boundary conditions on waveguide outer and inner walls.

3.3.2. Boundary Conditions

A homogeneous temperature field can be adopted as an initial condition, which will have a form of equation of temperatures in all waveguide points of some set value at the initial instant $t = 0$ for a one-dimensions model:

$$T(x, t = 0) = T_0 = const. \tag{6}$$

Boundary conditions are set at the borders of considered area, in the case under study these are waveguide inner and outer walls (Fig. 3), where convection of heat with environment with a temperature of T_{amb} will take place (boundary conditions of the 3^{rd} genus).

For wall interior surface ($x = 0$), the heat exchange condition will be as follows:

$$\lambda_1 \frac{\partial T_1 (x = 0, t)}{\partial x} + \alpha_1 [T_1 (x = 0, t) - T_{amb1}] = 0, \quad (7)$$

where $T_1(x = 0, t)$ – waveguide inner wall surface temperature;

α_1 – heat transfer coefficient of waveguide inner wall with environment inside waveguide, $\frac{W}{m^2 \cdot {}^\circ C}$;

T_{surr1} – ambient temperature inside waveguide, $^\circ C$.

The second boundary condition determines the heat exchange condition of waveguide outer walls ($x = h$) with environment and has the following form:

$$\lambda_2 \frac{\partial T_2 (x = h, t)}{\partial x} + \alpha_2 [T_2 (x = h, t) - T_{amb}] = 0, \quad (8)$$

where: $T_2(x = h, t)$ – waveguide walls outer surface temperature;

α_2 – heat transfer coefficient of wall outer surfaces with environment outside waveguide, $\frac{W}{m^2 \cdot {}^\circ C}$;

T_{amb2} – ambient temperature outside waveguide, $^\circ C$.

Convection is taken to be boundary conditions (5,6) as main method of heat exchange with the environment, which corresponds to the waveguide functioning in gas (air), on earth.

Conditions of waveguide usage as a part of space communication unit with an open platform on a planned orbit suggest that they'll function in a vacuum where there's little convection and radiant heat transfer exchange will be the dominant way of transferring and dissipating heat energy of waveguide structure.

In this case instead of convection conditions (6) on waveguide outer walls the condition of radiant heat transfer exchange should be set, which according to Stefan-Boltzman law has the form of set heat flow:

$$\lambda_2 \frac{\partial T_2 (x = h, t)}{\partial x} - \sigma_2 \left[T_{amb2}^4 - T_2^4 (x = h, t)\right] = 0 \quad (9)$$

where σ_2 – reduced radiation coefficient for waveguide outer walls, $\frac{W}{m^2 \cdot {}^\circ C}$.

An analysis of heat transfer in waveguide shows that its inner walls are a closed surface of orthogonal plates between which mutual heating will take place due to radiant heat transfer exchange of a non-linear nature. The condition of the absence of heat exchange with the environment can be, therefore, taken with accuracy sufficient for practical calculations of waveguide inner walls. It will be as follows:

$$\frac{\partial T_1\left(x=0,t\right)}{\partial x}=0 \tag{10}$$

Obtained differential equation (3) with boundary conditions (4-7) allows determining temperature fields of waveguide straight section for any its sizes, SHF signal material and features occurring in practice, for which loss factor α is known.

Methods of solution of differential equation (3) with set initial (4) and boundary conditions (57) are well studied to date [12]. It can be solved by both analytical (method of variable separation, method of sources, etc.) and numerical (difference method, finite elements method, etc.) methods.

The heat calculation of waveguides with a curvelinear axial axis is difficult mainly due to complexity in terms of choosing loss factor α values, since its values aren't given in known literature [6, 7, 8, 9, 10, 11] for this case. However, papers have been recently published studying dissemination of electromagnetic fields in curvelinear waveguides by numeric methods [14].

According to the developed model and obtained resulting equations, calculation of temperature field for waveguide straight sections with different dimension-type of cross-section and wall thickness have been carried out. The solution was carried out by the analytical method of variables separation and numerical method of finite differences under a clear scheme using software developed to this end [15, 16].

4. Waveguide Stress Strain State

The change of the waveguide temperature as a whole towards the remaining elements of aerial feed system structure results in temperature stresses, value and distribution of which depend heavily on the geometry of structure and its attachment method. To consider these features a methodology [17] and a software program for calculating stress strain state of waveguide straight sections [18] were developed. The program uses temperature filed data precalculated using the software [15, 16].

It's suggested to evaluate stress state in waveguide current conducting coating using specified Stoney formula [19], which uses differences in the coefficients of heat expansion and temperature of layers. As a result of normal stress distribution diagram over waveguide wall thickness typical distribution occurs, which is also called "z-system" (Fig. 3).

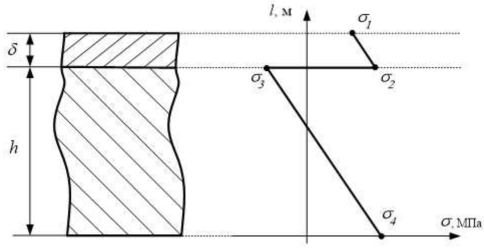

Figure 3: Stress distribution over waveguide wall thickness

Stress values in diagram representative points (Fig.3) after updating Stoney formula [20] are defined by the following formulas:

$$\sigma_1 = \frac{E \cdot \Delta\alpha \cdot \Delta t \cdot h}{h+\delta} - \frac{E \cdot (h+\delta)}{2\rho}[Pa] \quad (11)$$

$$\sigma_2 = \frac{E \cdot \Delta\alpha \cdot \Delta t \cdot h}{h+\delta} - \frac{E \cdot (h-\delta)}{2\rho}[Pa] \quad (12)$$

$$\sigma_3 = -\frac{E \cdot \Delta\alpha \cdot \Delta t \cdot \delta}{h+\delta} - \frac{E \cdot (h-\delta)}{2\rho}[Pa] \quad (13)$$

$$\sigma_4 = -\frac{E \cdot \Delta\alpha \cdot \Delta t \cdot \delta}{h+\delta} + \frac{E \cdot (h+\delta)}{2\rho}[Pa] \quad (14)$$

where – average Young modulus of material and coating assuming its close values;

$\Delta\alpha$ – difference in the coefficients of heat expansion of current conducting coating and waveguide wall;

Δt – temperature difference, $^\circ C$;

ρ – wall curve radius caused by curve due to difference in the coefficients of heat expansion of current conducting coating and waveguide wall can be determined as follows [21]:

$$\rho = \frac{1}{\Delta\alpha \cdot \Delta t}\left[\frac{h+\delta}{2} + \frac{1}{6\cdot(h+\delta)}\left(\frac{E_1\delta^3}{1-\mu_1} + \frac{E_2 h^3}{1-\mu_2}\right) \times \right. \\ \left. \times \left(\frac{1-\mu_1}{E_1}\delta + \frac{1-\mu_2}{E_2}h\right)\right][m], \quad (15)$$

where E_1, μ_1 and E_2, μ_2 – Young modulus and Poisson's ratio of current conducting coating and waveguide wall, correspondingly.

When substituting data for waveguide with a dimension-type 15×35, normal stress distribution diagram over waveguide wall thickness will take the form shown in Fig. 4. Here line 1 corresponds to temperature difference $20°C$, line 2 – $\Delta t = 75°C$, line 3 – $\Delta t = 100°C$. Waveguide material – aluminum, coating – silver.

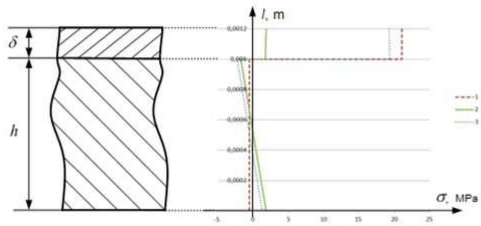

Figure 4: Stress state of current conducting coating

For all calculation cases a significant stress jump in the connection area of current conducting coating and mount is typical, which results in shearing stresses in this place. The intermittent action of shearing stresses in periodic intervals may lead to fatigue break-down of coating and mount connection. To avoid it a corresponding choice of methods and technology parameters of coating application is necessary. For example, a mode of coating application when residual compression stresses with proper values will be active in the coating after manufacturing may be chosen to reduce the maximum value of pulling stresses at the coating and mount connection (lines 2 and 3 in Fig.4).

Conclusion

The paper represents an estimation method of the effect of super-high-frequency signal power loss when transmitted over waveguides on their thermoelastic state.

The mathematical models of the process of waveguide heating were developed and solving differential equation of the task with initial and boundary conditions corresponding to waveguide operation conditions on earth and in open space were obtained. Taking into account developed methods and obtained dependences we developed a computer program for calculating temperature fields and considering their effect on waveguide stress strain state as a whole.

Dependencies, which determine distribution of stresses over waveguide wall thickness, were obtained taking into account current conducting coating. The obtained distribution of temperatures and stresses can be used to calculate the stress strain behavior state of waveguide as a whole, as well as its current conducting coating in order to secure strength and rigidity conditions.

Based on findings we consider a possibility of developing methods to calculate fatigue resistance of waveguide skin layer material.

Acknowledgment

The reported study was funded by Russian Foundation for Basic Research, Government of Krasnoyarsk Territory, Krasnoyarsk Region Science and Technology Support Fund to the research project #16-48-242110

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