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Optimisation and thermal control of a multi-layered structure for space electronic devices and thermal shielding of re-entry vehicles ☆

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ABSTRACT

All electronic devices, due to Joule effect, present heat dissipation, when they are electrically fed. The heat overstocking produces efficiency and performances reduction. On account of this the thermal control is mandatory. On small electronic equipments, the difficulty or impossibility of using a cooling fluid for the free or forced convection heat dissipation imposes the presence of cooling systems based on another kind of functioning principle such as the conduction. In this paper the thermal control, via pyroelectric materials, is presented. Furthermore, an optimisation of geometric, thermal and mechanical parameters, influencing the thermal dissipation, is studied and presented. Pyroelectric materials are able to convert heat into electrical charge spontaneously and, due to this capability, such materials could represent a suitable choice to increase the heat dissipation. The obtained electric charge or voltage could be used to charge a battery or to feed other equipments. In particular, a sequence of different materials such as Kovar®, molybdenum or copper–tungsten, used in a multi-layer pyroelectric wafer, together with their thicknesses, are design features to be optimised in order to have the optimal thermal dissipation. The optimisation process is performed by a hybrid approach where a genetic algorithm (GA) is used coupled with a local search procedure, in order to provide an appropriate balance between exploration and exploitation of the search space, which helps in the search for the optimal or quasi-optimal solution. Since the design variables used in the optimisation procedure are defined in different domains, discrete (e.g. the number of layers in the pyroelectric wafer) and continuous (e.g. the layers thickness) domains, the genetic representation for the solution should take it into account. The chromosome used in the genetic algorithm will mix both integer and real values, what will also be reflected in the genetic operators used in the optimisation process. Finally, numerical analyses and results complete the work.

1. Introduction

In the last decades the space design research has been involved in the optimisation of missions, of costs, of primary and secondary structures and of all other equipments onboard the spacecraft. The thermal design is one of the most important and expensive issues of a spacecraft design. In fact the designer must provide a thermal protection system (TPS) in order to control effects of external thermal sources (i.e. the Sun heat flux) and efficient internal thermal devices to drain the heat fluxes generated by the electronic equipments.

Actually most of the internal thermal control is provided by thermal pipes or by exploiting the thermal characteristics of equipments constituting materials such as the thermal conductivity in order to increase the heat dissipation and to reduce the heat overstocking.

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In order to perform costs reduction and to enhance the efficiency and the performances, an optimisation procedure could be introduced in the design process.

In this paper different optimisation techniques, in order to control the temperature distribution inside multi-layered walls, are presented and many numerical simulations are performed.

2. Unsteady thermal problem

Before addressing the problem of the structural thermal control on a multi-layer structure and introducing the optimisation technique for the choice of the materials and their mechanical and geometrical properties, let us introduce a brief insight on the one-dimensional unsteady thermal problem of a multi-layered structure. In the following formulation the mechanical and thermal characteristics will be considered constant through thickness of the generic layer. Fig. 1 shows the considered multi-layered wall configuration.

The multi-layer configuration in order to represent typical space thermal problems has been chosen because it is suitable to represent microelectronics packages, made up of electric circuits, support boards and relevant housing, or to represent a classic thermal shield configuration. In fact a large number of TPS' are based on the superposition of different material layers, typically ceramics, in order "to brake" the thermal flux that flows through the thickness. The generic thermal problem is ruled by the classic Fourier Law that reads as follows [1]:

$$k\nabla^2 T - \rho c \frac{\partial T}{\partial t} - q_v = \mathcal{A}T + \text{B.C.} + \text{I.C.}, \tag{1}$$

where k, ρ and c are the thermal conductivity, the density and the heat capacity of the material, respectively, q_v is an internal heat source/sink, T is the temperature, t is the time variable and $\mathcal{A}$ is a non-linear operator in order to take the boundary and initial conditions into account. The problem definition is completed by the boundary (B.C.) and initial conditions (I.C.).

For a generic multi-layered wall and in the case of one-dimensional unsteady thermal problem Eq. (1) becomes simpler

$$k^{(i)} \frac{\partial^2 T^{(i)}(z,t)}{\partial z^2} - \rho^{(i)} c^{(i)} \frac{\partial T^{(i)}}{\partial t} - q_v^{(i)} = 0, \tag{2}$$

where apex $i = 1, \ldots, N$ indicates the generic i-th layer of the wall. In order to solve the problem the boundary and the initial conditions must be considered

$$\text{B.C.} \rightarrow \begin{cases} q(0,t) = -k^{(1)} \dfrac{dT^{(1)}(0,t)}{dz} = q_u, \\ T^{(N)}(h^{(N)},t) = T_l, \end{cases}$$
$$\text{I.C.} \rightarrow T(z,0) = T_0, \tag{3}$$

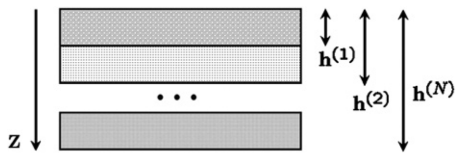

Fig. 1. Multi-layered wall configuration.

where $h^{(N)}$ is the end abscissa of the N−th layer, q_u is the heat flux on the external upper surface, T_l is the lower external surface temperature of the wall and T_0 is the internal temperature distribution through the wall thickness at the initial time $t=0$. These conditions are not sufficient to solve the problem. It is necessary to add the temperature and flux continuity conditions, defined at the layers interfaces with $i = 1, \ldots, N-1$:

$$T^{(i)}\big|_{z=h^{(i)}} = T^{(i+1)}\big|_{z=h^{(i)}},$$
$$-k^{(i)} \frac{dT^{(i)}}{dz}\bigg|_{z=h^{(i)}} = -k^{(i+1)} \frac{dT^{(i+1)}}{dz}\bigg|_{=h^{(i)}}. \tag{4}$$

The temperature distribution, through the thickness of each layer, can be expressed as the sum of a steady state distribution $\Phi(z)$ and an unsteady distribution $\Psi(z,t)$. By combining them we have:

$$T^{(i)} = \Phi^{(i)}(z) + \Psi^{(i)}(z,t). \tag{5}$$

The stationary solution $\Phi(z)$ for the generic i-th layer is given by [2]

$$\Phi^{(i)}(z) = \frac{1}{2} \frac{q_v^{(i)}}{k^{(i)}} z^2 + H^{(i)} z + G^{(i)}, \tag{6}$$

where H and G are the coefficients obtained by the solution of the stationary problem by imposing boundary and continuity conditions. The unsteady solution we have reads as follows:

$$\Psi^{(i)}(z,t) = \sum_{k=1}^{\infty} \varphi_k(T_0) [A_k^{(i)} \cos(z_k \omega_k) + B_k^{(i)} \sin(z_k \omega_k)] e^{\alpha^{(i)} \omega_k^2 t}. \tag{7}$$

The coefficients $\varphi_k(T_0)$ are determined by imposing the initial condition

$$\varphi_k(T_0) = \frac{\sum_i \int_{h^{(i)}} k^{(i)} T_0 \chi^{(i)}(z,\omega_k)\, dh}{\sum_i \int_{h^{(i)}} k^{(i)} \chi^{(i)}(z,\omega_k) \chi^{(i)}(z,\omega_k)\, dh} + \\ - \frac{\sum_i \int_{h^{(i)}} k^{(i)} \Phi^{(i)} \chi^{(i)}(z,\omega_k)\, dh}{\sum_i \int_{h^{(i)}} k^{(i)} \chi^{(i)}(z,\omega_k) \chi^{(i)}(z,\omega_k)\, dh}, \tag{8}$$

where $\chi^{(i)}(z,\omega_k)$ are the thermal eigenvectors of the thermal problem and ω_k are the associated eigenvalues. The algebra and the solving procedure is widely reported in [3,4].

3. Thermal control

As mentioned above the structural thermal control is a primary problem for space systems. In this paragraph two different examples, the former one applied to control the temperature inside an electronic device used for transmission operations and the latter one applied to a Re-entry Thermal Protection Subsystem, will be analysed.

3.1. RF electronic devices and pyroelectric materials

Concepts and numerical techniques presented so far to analyse the temperature distribution inside a multi-layered structure will be applied.

In particular, we will deal with a Radio Frequency (RF) module, see Fig. 2 used to transmit and receive operations.