THERMALLY INDUCED VIBRATION OF COMPOSITE FLEXIBLE SOLAR PANELS OF SATELLITE

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Abstract

Thermally induced structural motions are known to affect the attitude dynamics of earth orbiting satellite. During eclipse transitions, the suddenly applied thermal loading is apt to introducing dynamics of flexible solar panels. Solar panel consists of honeycomb sandwich structures with facesheets. To enable future improvements, the FGM facesheets are considered instead of aluminium and laminate facesheets. In this paper, transient analyzes were conducted to predict the thermal distortion of the solar panels. A p-version of the finite element method is developed to solve the transient temperature field and dynamic response of the panel during phase transitions. The effect of the non-homogeneity of the FGM on the temperature distribution and dynamic response is considered. The results show that the solar panels with FGM facesheets are beneficial with regard to thermal distortion during the mission when compared to those with aluminium and laminate facesheets.

1 Introduction

For maximum electricity supply the satellites are equipped with very large solar panels. The dimensions can reach 40m long and 3m wide, but against the thickness is very low so as not to overload the satellite. Indeed, satellite designers have always been faced with weight requirements. Henceforth, these designers have turned to lightweight materials such as composites, and thin structures. The obligation to respect these criteria means that solar panels are very flexible. This flexibility is often the cause of instability and pointing of the satellite [1]. Thermally induced structural motions are known to affect the attitude dynamics of earth orbiting satellite. During eclipse transitions, the suddenly applied thermal loading is apt to introducing dynamics of flexible solar panels. Motions of these structures lead to rigid body rotations of the satellite, these disturbances may violate pointing accuracy. Foster [2] investigated solar array induced disturbances of the Hubble space telescope pointing systems. They found that disturbances were particularly pronounced during orbit day-night transition. Johnston and Thornton [3] evaluated analytically and experimentally the thermally induced structural motion of satellite. Results demonstrate thermal bending deformations with acceleration transients that have characteristics thermal snap disturbance histories in response to rapid changes in heating. The studies show that solar panel thermal snap disturbances are caused by through the thickness temperature difference. Xue et al. [4] analyzes the nonlinear vibration of practical thin walled large scale structures subjected to suddenly applied thermal loading. The transient analyzes were conducted to predict the thermal distortion of the Korea-Purpose Satellite solar array during its orbital motion [5]. The results show that the solar arrays with composite facesheets are beneficial compared to those with aluminum facesheets. The main objective of this study is to develop a new solar panel array model with FGM instead of aluminium and laminate facesheets, to minimize the deformation of the panel during eclipse transitions. A p-version of the finite element method is developed to solve the transient temperature field and dynamic response of the panel during phase transitions. The effect of the non-homogeneity of the FGM on the temperature distribution and dynamic response is considered. Pertinent conclusions are outlined.

2 Temperature distribution analysis

To conduct the thermally induced vibration analysis it is necessary to calculate the temperature distribution on the cross section of the sandwich plate. In space the heat transfer is governed by the radiation exchange. The thermal environment for low earth orbiting spacecraft consists of radiation directly from the sun, albedo, and earth emitted infrared energy. The convection heat transfer inside the panel is negligible. A p-version of the finite element method [6] in conjonction with the thermal layers theory [7] is developed to solve the transient temperature field in the panel during phase transitions. A rectangular Fourier *p*-element (with three degrees of freedoms by node) is developed to set up the bi-dimensional nonlinear heat conduction equations instead of a three-dimensional analysis using the solid element (used in commercial package). The temperature is formulated in terms of linear shape functions used generally in finite element method plus a variable number of trigonometric shapes functions representing the internals degrees of freedoms. The p-version of the FEM has, amongst others, the following advantages over the h-version: simple structures can be modeled using just one element, thus there are no inter-element continuity requirements and the assemblage of the elements is avoided; the p-version of the FEM gives accurate results with fewer degrees of freedom than the h-version, in general monotonic and uniform convergence is guaranteed. Applying Galerkin's method, the finite element equation of heat transfer can be expressed as

$$\left[C_{cp}\right]\left\{\dot{\theta}\right\}+\left[\left[K_{cd}\right]+\left[K_{rd}(\overline{\theta})\right]\right]\left\{\theta\right\}=\{Q\} \tag{1}$$

$$\{\theta\}=\begin{Bmatrix}T_0\\ \alpha_0\\ \beta_0\end{Bmatrix} \tag{2}$$

Where $T_0^{(k)}$ is the temperature of the middle plane of the kth layer, $\alpha_0^{(k)}=T_{0,z}^{(k)}$ and $\beta_0^{(k)}=T_{0,zz}^{(k)}$. the temperature in the kth layer is given by [7]

$$T^{(k)}(x,y,z)=\ T_0^{(k)}(x,y)+z_k\alpha_0^{(k)}(x,y)+\frac{1}{2}{z_k}^2\beta_0^{(k)}(x,y),\qquad -\frac{t_k}{2}\le z_k\le\frac{t_k}{2} \tag{3}$$

Where $[K_{cd}]$ is the conductance, $\left[C_{cp}\right]$ is the capacitance matrix, $[K_{rd}]$ is the radiation matrix and $\{Q\}$ is the heat load vectors related to the thermal environment.

The thermal analysis consists of two dimensional conduction through the thickness of the panel subjected to radiation boundary conditions on the front and back surfaces. The boundary conditions consist of direct solar heat flux, albedo and earth emitted flux.

3 Dynamic response model

Using the results from the previously temperature distribution analysis, coupled thermal-structural analyses are done to calculate the dynamic response of the solar panel. For the dynamic response the sandwich panel is modelled by a rectangular Fourier *p*-element. The flexible panel is idealized as just one finite element and the number of trigonometric terms is varied. For irregular geometries more elements can be used. The nodal d.o.f. of the element at each node are noted v, w, $v_{,x}$, $w_{,x}$. The displacements are expressed as the combination of the in-plane and out-of-plane shape functions. These are formulated in terms of linear and cubic polynomial functions used generally in FEM in addition to a variable number of trigonometric shape functions which represent the internal d.o.f. for the sandwich plate. The system of algebraic equations of motions is given as

$$[\mathrm{M}]\{\ddot{\mathrm{q}}(\mathrm{t})\} + [\mathrm{K}]\{\mathrm{q}(\mathrm{t})\} = \{\mathrm{F}(\mathrm{t})\} \tag{4}$$

Where $[\mathrm{M}]$ is the mass matrix, $[\mathrm{K}]$ is the stiffness matrix, and $\{\mathrm{F}(\mathrm{t})\}$ is the vector of the thermal force.

4 Numerical example

The following example illustrates the thermally induced distortion of a simple satellite with a solar panel made by FGM facesheets. Results for the thermal and dynamic responses of the solar panel with FGM facesheets are presented and compared with those with aluminium and laminate facesheets. The analysis considers the case of a 600 km circular orbit whose orbital plane lies in ecliptic. This case is representative of typical low earth orbital satellite, such as that used by UARS satellite. The parameters used in this study are given in Table 1 and 2. The solar panel is manufactured by a sandwich plate (40m long and 3m wide) having an aluminum honeycomb core and two facesheets. Thermal transient simulations have been performed by using the developed p-version of the FEM in conjunction with the thermal layers theory (TLT). The transverse section of the solar panel is given by figure 1.

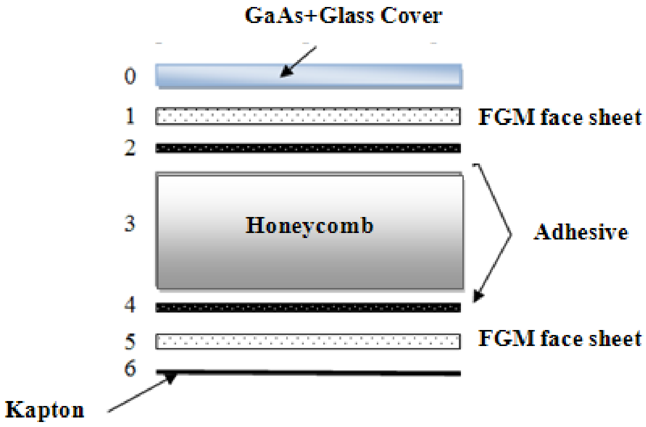

Figure 1. Transverse section of the solar panel

In this part of the study, we propose to replace the Al. 6061 with a composite material. Two proposals have been made: a graphite-epoxy laminate (T300-934) and an FGM: Aluminum (2024) and Silicon Carbide (SiC). The following Table 2 gives the properties of both composites. The laminates used consist of a superposition of four layers, two stacks are considered: [0/90]S and [45/-45]S. In the case of FGM (Al / SiC), the properties of skin vary between the properties of aluminum at the interface (z =-h / 2) and the properties of silicon carbide at the interface (z = h / 2). The three values of n (0.35,1 and 5) in this study are chosen so as to emphasize the homogeneity properties of FGM. In order to achieve the same lightness as a laminate, the thickness of FGM is halved.

Layer	**0**	**1**	**2**	**3**	**4**	**5**	**6**
Material		**Alum. 6061**	**Epoxy**	**Alum. 5056**	**Epoxy**	**Alum. 6061**	**kapton Z93**
Density (kg/m3)		2700	1150	30	1150	2700	
Capacitance (J /kg K)		896	750	920	750	896	
Thermal Conductivity (Wm/K)		167	0.4	1.2	0.4	167	
Thickness (mm)		0.254	0.127	25.4	0.127	0.254	
Emittance ε	0.81						0.86
Solar absorption α	0.79						
Young's Mod. E (GPa)		68.9	6	0.31	6	68.9	
Poisson Coefficient ν		0.33	0.3	0.3	0.3	0.33	
Shear Mod. G (GPa)		26.0	2.31	0.11	2.31	26.0	
Coef. Therm expansion (10^{-6}m/mK)		23.6	54	23.76	54	23.6	

Table 1: Mechanical and thermo-mechanical properties of the solar panel with aluminum facesheets.

Material	**Density (kg/m^3)**	**Capacitance (J /kg K)**	**Thermal Conductivity (Wm/K)**	**E11/E22/G12/v12 (GPa)**	**α_1/α_2 (10^{-6}m/mK)**
T300/934	1460	1300	5.73	141.6/10.7/3.88/0.268	0.006/30.04
SiC	3210	750	132	430/430/188/0.14	3.4/3.4

Table 2: Mechanical and thermo-mechanical properties of composite facesheets.

By applying the solar flux as a boundary condition on the faces of the panel, we can determine the temperature distribution in the sandwich. Figure2 shows the variation of the temperature of the two faces of the sandwich for the various materials used. Note that the variation is almost identical to the aluminum skins and in FGM, this is because the thermal conductivity of SiC is similar to that of Al 6061. We see that the temperature variation in the T300/934 is different compared to the other two materials because of its low conductivity. However, the variation of the temperature gradient in the different models studied has shown little difference at the beginning of the phase transition. After the gradient stabilizes at a value of 11.5 ° C. This is explained by the fact that heat exchange in the solar panel is heavily influenced by heat transfer in the core, see Figure 3.

Once the temperature gradient determined, it is possible to calculate subsequently the mechanical response of the solar panel. Figure 4 shows the variation of the transverse displacement of a tip point of the panel according to the orbital time phase. We can see the advantage of using composite materials instead of aluminum, as long as the results show a clear decrease of the displacement, which is equal to -0.46 m in the case of aluminum. The results obtained demonstrate the choice of fiber orientation. The use of [0/90]S has reduced the displacement to 0.12m. By stacking against the [45/-45]S gives a value of-0.29m. The same for skins in FGM, the results show that the choice of the homogeneity coefficient n is crucial. For n equal to 5 is reduced to the displacement-0.13m. This decrease is mainly due to two factors: elastic modulus and coefficient of thermal expansion.

Conclusion

We presented a detailed analysis of the thermo-elastic panel by changing each time the material of the two skins: aluminum, laminated and FGM, to see their influence on the thermal and mechanical behavior of the panel. The results of thermal analysis show that the gradient reaches its maximum value at the end phase of sunshine and its minimum value at the end of the eclipse phase, with an abrupt change during the transition phases. We noticed that the temperature distribution is almost independent of the choice of the material of the two skins. This is explained by the fact that heat exchange in the solar panel is heavily influenced by heat transfer in the core. The mechanical behavior of the material depends on the choice of two skins. We can see the advantage of using FGM instead of aluminum, as long as the results show a clear decrease of the displacement during the eclipse transitions.

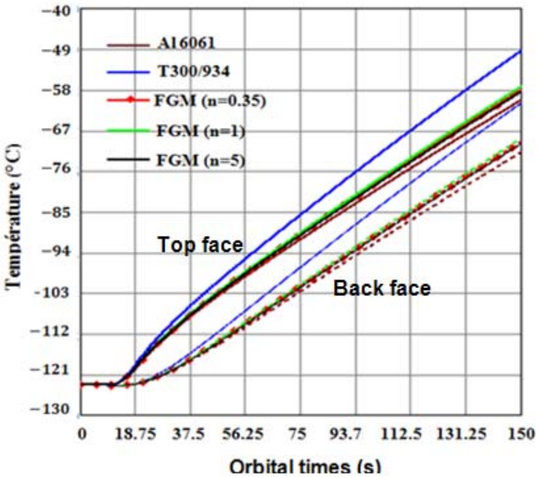

Figure 2. Temperature distribution in the top and back face of the solar panel during phase transition

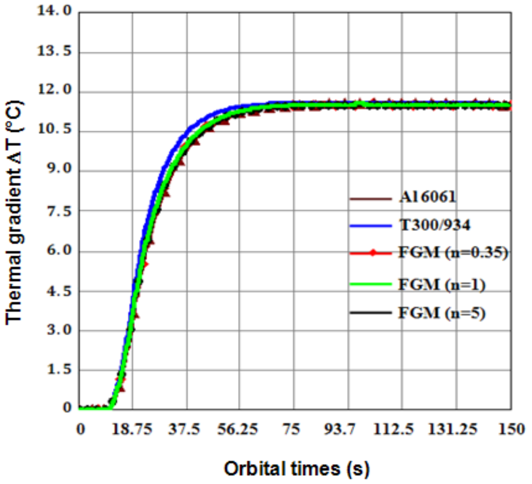

Figure 3. Thermal gradient distribution in cross section of the solar panel during phase transition

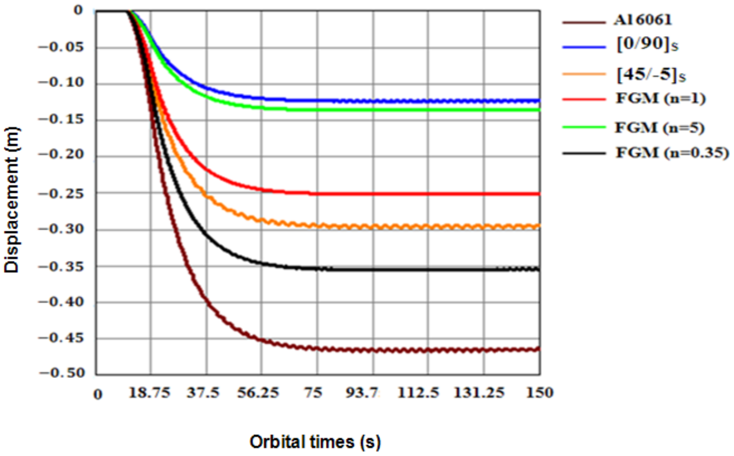

Figure 4. Tip displacement of the solar panel during phase transition

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