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# Rigid-flexible-thermal coupling dynamic formulation for satellite and plate multibody system

Jinyang Liu *, Keqi Pan

*Department of Engineering Mechanics, Shanghai Jiao Tong University, Shanghai, 200240, PR China*

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ABSTRACT

Thermoelastic coupling problems of spacecrafts have been investigated for a long time. However, in most of the investigations, the coupling effect of the rigid body motion, the elastic deformation and the temperature were not taken into account since the heat flux was assumed to be independent of the rigid body motion and the elastic deformation. The aim of this investigation is to propose a complete rigid-flexible-thermal coupling dynamic model. The most interesting feature of the study is that such model considers the influence of both the rotational motion and the elastic deformation on the intensity of the heat flux applied on the elastic bodies. Based on virtual work principle and floating frame of reference formulation, the coupled dynamic equations of the first kind and the heat conduction equations are derived. A low earth orbit spacecraft composed of satellite and solar array is simulated to show the rigid-flexible-thermal coupling performance. The thermal load includes not only the solar radiation flux, but also the earth-reflected heat radiation flux, earth-emitted heat radiation flux and the surface radiation. Three dynamic models are compared to show the coupling effect: the uncoupling model, the rigid-thermal coupling model and the complete rigid-thermal coupling model. It is concluded that the complete rigid-flexible-thermal coupling model can show the coupling effect of both the rotational motion and elastic deformation on the temperature gradient, therefore it can reveal the thermally induced fluttering effect. Further investigations indicate that in addition to the solar heat flux, the coupling effect of the other spatial heat fluxes can not be ignored. Finally, it is indicated that with the increase of the damping coefficient, the thermally induced fluttering effect can be significantly reduced.



## 1. Introduction

Thermally induced vibration of the satellite plate has been paid attention in the recent 30 years. It is known that structural deformation may affect the attitude dynamics of low earth orbiting satellites during eclipse transitions. Unstable vibrations of the appendages may be induced due to the interaction of structural deformations and incident heating, which is called thermally induced fluttering effect. Due to the conservation of the total angular momentum of the system, the thermally induced vibration of the flexible appendages may lead to rigid body rotations of the entire satellite, which may violate pointing accuracy. Thornton and Kim [1] developed an analytical approach for determining the thermal–structural response of a flexible rolled-up solar array due to a sudden increase in external heating. Two analyses were presented: an uncoupled thermal–structural analysis that assumes the heating and temperature gradients are not affected by thermally induced motions, and a coupled thermal–structural analysis that includes the effects of structural deformations on heating and temperature gradients. The analytical methods identified key parameters for understanding the static and dynamic response. A stability criterion given in non-dimensional parameters established the conditions for thermal flutter. In the investigation, the rotational motion of the spacecraft was not taken into account. Johnston and Thornton [2] investigated the effects of thermally induced structural disturbances of a flexible appendage on the attitude dynamics of a simple spacecraft. The governing equations, including transient thermal effects, were formulated using a generalized form of Lagrange's equations for hybrid coordinate dynamical systems. An approximate solution based on modal expansion was presented for the case of a step change in solar heating that simulates an orbital eclipse transition. Analytical models were presented for the thermal–structural response of two types of flexible appendages: a thin-walled boom with tip mass and a solar panel. Numerical results demonstrated that the attitude response of the system consists of a slowly developing pointing error and superimposed

* Corresponding author. Tel.: +86 21 34206489.
*E-mail address:* liujy@sjtu.edu.cn (J. Liu).

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oscillations whose magnitude is related to the ratio of the thermal and structural response times of the flexible appendage, and then Johnston and Thornton [3] further investigated thermally induced dynamics of solar panels, including an analysis of satellite attitude dynamics resulting from thermally induced structural motions and a laboratory investigation of the thermal–structural performance of a satellite solar panel. Analytical and experimental results demonstrated thermal bending deformations with acceleration transients that have characteristic thermal snap disturbance histories in response to rapid changes in heating. The studies showed that solar panel thermal snap disturbances are caused by through-the-thickness temperature differences that vary at a nonconstant rate and concluded that finite element analysis correctly predicted the thermal snap phenomenon observed in the solar panel experiments. Oguamanam et al. [4] examined the nonlinear response of a composite laminated panel that is suddenly exposed to a heat flux. The panel is attached onto a rigid hub, the rotational motion of which is either fully or partially restrained. Structural nonlinearity in the form of geometric nonlinearity is considered and is modeled via the Von Karman strain–displacement formula. Liu et al. [5] investigated the transient longitudinal and transverse deformation of a planar flexible beam with large overall motions in a temperature field. Considering the thermal strain, equations of motion of a flexible beam with arbitrary large overall motion were derived based on virtual work principle. The high order terms of the strain tensor were taken into account, such that the geometric nonlinear deformation terms were included in the dynamic equations. Simulation results of a rotating beam were shown to reveal the thermal effect and nonlinear effect on the dynamic performance of the beam. Although the investigations of Oguamanam and Liu considered geometric nonlinear effect in the formulation, the rigid-flexible-thermal coupling effect were not taken into account since the time histories of the temperature and the temperature gradient were assumed to be prescribed.

Due to smoothly and continuously varying material properties from one surface to the other, functionally graded material (FGM) is superior to the conventional composite materials in mechanical behavior, therefore functionally graded materials will be widely used in aerospace technology in future. Shen et al. [6] investigated the large amplitude vibration behavior of a shear deformable FGM cylindrical panel resting on elastic foundations in thermal environments. Two kinds of micromechanics models, namely, Voigt model and Mori–Tanaka model, were considered. The motion equations were based on a higher order shear deformation shell theory that includes shell panel-foundation interaction. The thermal effects were also included and the material properties of FGMs were assumed to be temperature-dependent. The equations of motion were solved by a two step perturbation technique to determine the nonlinear frequencies of the FGM cylindrical panel. Tounsi et al. [7] proposed a refined trigonometric shear deformation theory (RTSDT) taking into account transverse shear deformation effects for the thermoelastic bending analysis of functionally graded sandwich plates. Based on the refined trigonometric shear deformation theory, Bouderba et al. [8] investigated the thermomechanical bending response of functionally graded plates resting on Winkler–Pasternak elastic foundations, and then Zidi et al. [9] investigated the bending response of functionally graded material (FGM) plate resting on elastic foundation and subjected to hygro-thermo-mechanical loading. The elastic coefficients, thermal coefficient and moisture expansion coefficient of the plate are assumed to be graded in the thickness direction. The study is relevant to the simulation of rocket launch pad structures subjected to intense thermal loading. Khalfi et al. [10] developed a refined and simple shear deformation theory for thermal buckling of solar functionally graded plate (SFGP) resting on two-parameter Pasternak's foundations. The nonlinear strain–displacement relations are also taken into consideration. The effects of the foundation parameters, plate dimensions, and power law index are presented comprehensively for the thermal buckling of solar functionally graded plates. In these investigations, thermoelastic analysis of functionally graded materials is carried out. Since the functionally graded materials are being widely used in aerospace technology, rigid-flexible-thermal coupling dynamic analysis of functionally graded materials will be an important research topic in the future.

To investigate the structural–thermal coupling effect, Daneshjo et al. [11] proposed a new mixed finite element formulation to analyze transient coupled thermoelastic problems. Coupled model of dynamic thermoelasticity is selected for a laminated composite and a homogeneous isotropic plate. Heckmann et al. [12] presented a new methodology to simulate the behavior of flexible bodies influenced by multiple physical field quantities in addition to the classical mechanical terms. The theoretical framework was based on the extended Hamilton Principle and an adapted modal multifield approach. The method was applied to simulate a structure with distributed piezo-ceramic devices inducing an additional electrostatic field. Two thermoelastic problems, which considered the influence of spatial temperature distribution, also demonstrated the benefits of the presented approach. However, the influence of the rotational motion and deformation on the heat flux was not taken into account. Shen and Tian [13] conducted a coupled thermal–structural analysis based on the Euler–Bernoulli beam model within a framework of Absolute Nodal Coordinate Formulation. The coupled transient heat conduction equation and structural dynamics equation were established and solved interactively by the generalized-$\alpha$ scheme. With the coupled thermal–structural analysis, the thermal flutter can be well predicted for a cantilever beam moving from eclipse with large incident angles of solar radiation, and the proposed model was also able to characterize the coupled thermal–structural dynamics when a flexible beam is subjected to a large rotation. In these investigations, only the solar radiation heat flux was taken into account, which is suitable for high-earth orbit spacecraft.

Recently, Kim et al. [14] investigated the in-orbit characteristics of a fixed-type solar array in a low-earth orbit satellite and the usefulness of the analytical solution to predict the worst hot temperature of the solar array through both analytical and numerical methods. Kayhani et al. [15] presented a steady analytical solution for heat conduction in a cylindrical multilayer composite laminate in which the fiber direction may vary between layers. The analytical solution was obtained for general linear boundary conditions that are suitable for various conditions including combinations of conduction, convection, and radiation both inside and outside the cylinder. Recently Li and Yan [16] developed a thermal analysis model of composite solar array with complex structure to characterize the thermal response of the whole solar array system subjected to space heat flux. Simulation results revealed the evolution process of the transient temperature field of the whole solar array system, and then Li and Yan [17] presented a numerical method to characterize the thermal response of a composite solar array subjected to space heat flux. Thermally induced vibration was investigated based on this method. The thermally induced vibrations of a solar array using two commonly used materials were also compared. Thermally induced vibrations in different thermal environments, incident angles of solar radiation, and material properties of honeycomb panel were discussed to reveal the causes of thermally induced vibration. However, these investigations have not been extended to investigate the rigid-flexible-thermal coupling dynamics of flexible multibody system in complicated thermal environment yet.

It is indicated that the previous thermal–structural analysis theories of solar array have not considered the influence of both the rotational motion and the elastic deformation on the intensity