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Finite Element Algorithm for Dynamic Thermoelasticity Coupling Problems and Application to Transient Response of Structure with Strong Aerothermodynamic Environment

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Abstract. As an exploratory study for structural deformation and thermodynamic response induced by spacecraft reentry aerodynamic force and thermal environment, a finite element algorithm is presented on the basis of the classic Fourier heat conductive law to simulate the dynamic thermoelasticity coupling performance of the material. The Newmark method and Crank-Nicolson scheme are utilized to discretize the dynamic thermoelasticity equation and heat conductive equation in the time domain, respectively, and the unconditionally stable implicit algorithm is constructed. Four types of finite-element computing schemes are devised and discussed to solve the thermodynamic coupling equation, all of which are implemented and compared in the computational examples including the one-dimensional transient heat conduction in considering and not considering the vibration, the transient heat flow for the infinite cylinder, and the dynamic coupling thermoelasticity around re-entry flat plate from hypersonic aerothermodynamic environment. The computational results show that the transient responses of temperature and displacement field generate lag phenomenon in case of considering the deformation effect on temperature field. Propagation, rebounding, attenuation and stabilized phenomena of elastic wave are also observed by the finite-element calculation of thermodynamic coupling problem considering vibration and damping, and the oscillation of the temperature field is simultaneously induced. As a result, the computational method and its application research platform have been founded to solve the transient thermodynamic coupling response problem of the structure in strong aerodynamic heating and force environment. By comparing various coupling calculations, it is demonstrated that the present algorithm could give a correct and reliable description of transient thermodynamic responses of

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structure, the rationality of the sequentially coupling method in engineering calculation is discussed, and the bending deformation mechanism produced by the thermodynamic coupling response from windward and leeward sides of flying body is revealed, which lays the foundation in developing the numerical method to solve material internal temperature distribution, structural deformation, and thermal damage induced by spacecraft dynamic thermoelasticity coupling response under uncontrolled reentry aerothermodynamic condition.

AMS subject classifications: 65Y10, 65Z05, 74S05, 76K99, 80A10

Key words: Dynamic thermoelasticity, finite element algorithm, Newmark method, Crank-Nicolson scheme, fluid-structure interaction, structural deformation.

1 Introduction

Large-scale spacecraft in orbit will face the problems of de-orbiting in fall around the end of life, and disintegrate because they suffer tremendous aerodynamic/thermal environment and overloads [1–5] during reentering back to the earth. The high-temperature thermo-chemical non-equilibrium gas flows produced by spacecraft re-entering dense atmospheric surrounding will create cumulative effect of ablative pyrolysis, and metal truss softening and melting. Under this circumstance, hypersonic aerothermodynamic problems need to be solved and meanwhile various fluid-structure interaction approaches are studied [6–8]. The high-temperature induced problems also require the analysis of the materials' phase transition and nonlinear behavior of structural response [9–15]. As a preliminary research for above issues, there will be practical significance [16, 17] to develop the dynamic thermal coupling finite-element algorithm [18] in analyzing and investigating integrated thermo-mechanical response of material structure under strong aerothermodynamic surrounding. A nonlinear finite-element method needs to be developed to study the softening/deforming and melting/failing behavior during spacecraft' reentry of uncontrolled state, and finally a fluid-thermal-solid integrated coupling numerical algorithm needs to be constructed, which has been being a challenge problem to be solved.

In engineering problems, the determination of thermal stresses is usually carried out in two steps. First, the temperature distribution is obtained from the Fourier's heat-conduction equation, the stresses are then calculated by the equations of elastostatics, including the temperature terms in the stress-strain relations. This procedure omits two important effects – the effect on the distribution of temperature as a result of the straining of the body, and the dynamic effects resulting from the inertia forces. When the material is subjected to the strong aerodynamic force and rapid aerodynamic heating, its deformation will significantly affect the temperature distribution in the interior of the material. The thermal-induced vibration should also not be neglected, and in some extreme condition, thermal shock interaction for instance, the heat propagation is to be viewed as a