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Probabilistic transient thermal analysis of an atmospheric reentry vehicle structure

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Abstract

Thermal analysis plays an important role in the structural design of atmospheric reentry vehicles, which are subjected to severe aerodynamic heating. It is sometimes difficult to assess the design safety margin because of uncertainties in the predicted heat flux and the material properties used in the thermal analyses. However, probabilistic techniques allow the effects of uncertainties to be analyzed, and the present study demonstrates the probabilistic thermal analysis of the PARTT reentry vehicle using the Monte Carlo technique to investigate the probabilistic temperature responses. The temperature responses were found to depend significantly on time and location, and reliability was predicted at all locations. The peak temperature of the vehicle's main structure was found to be strongly correlated with heat shield temperature, and analysis of the contributions of random parameters showed that heat flux and heat shield emissivity significantly affect the peak temperature. These results indicate that the thermal design of the heat shield shell is very important for the whole structure. It is expected that such information will provide good insight for the design of a reentry vehicle's structure.

Keywords: Probabilistic analysis; Transient thermal analysis; Correlation coefficient; Index of reliability; Monte Carlo method; Atmospheric reentry vehicle

1. Introduction

Thermal analysis plays an important role in the structural design of atmospheric reentry vehicles, which are subjected to severe aerodynamic heating. However, the thermal analysis is subject to a number of uncertainties. For thermal protection systems (TPS), it is sometimes difficult to deterministically obtain the thermal properties of materials that strongly depend on temperature and/or pressure. There can also be high uncertainty in the prediction of aerodynamic heat flux, due to factors such as scatter in the reentry trajectory and highly complex phenomena that are difficult to analyze. In some cases, especially in complex systems, the effect of uncertainties can be significant [14]. Understanding the effects of these uncertainties through the assessment of thermal reliability and safety margin is essential for the design of high temperature components.

It is becoming evident that deterministic analysis is not sufficient for the structural design of complex aerospace components for severe thermal/mechanical environments. A probabilistic approach has been shown to be useful for evaluating the effects of uncertainties and for assessing thermal reliability. As a part of the preparation for the first launch of the Space Shuttle orbiter, uncertainty bands were investigated around expected or nominal TPS thermal responses during reentry, and individual flow field and TPS parameters that make major contributions to these uncertainty bands were identified [5,11]. Recently, Dec et al. discussed the design margins on sizing the TPS of a Mars Sample Return Earth Entry Vehicle using the Monte Carlo method [2]. Nakamura applied the stochastic finite element method to the transient thermal analysis of a simplified TPS model [10].

The probabilistic approach is now being increasingly applied, often in conjunction with complex multidisciplinary analysis. Probabilistic thermal-structural analyses have been conducted to assess static, dynamic, and fatigue damage of the Space Shuttle Main Engine turbine blades [1,12], and it was expressed that sensitivities to uncertainties are useful aids in

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Nomenclature

c	specific heat .... J/kg/K	TPS	thermal protection system
COV	coefficient of variation	r, z	cylindrical coordinates (axisymmetric)
IOR, β	index of reliability	ε	emissivity
Q	heat flux at surface of the body in the direction of the interior .... W/m^2	λ	solid conductivity .... W/m/K
		μ	mean value
Q_0	heat flux at stagnation point .... W/m^2	μ_L	mean value of load
Q_{emis}	radiative heat flux .... W/m^2	μ_S	mean value of strength
Q_n	nominal heat flux .... W/m^2	ρ	density .... kg/m^3
R	reliability	σ	standard deviation
T	absolute temperature .... K	σ_L	standard deviation of load
t	time, sec.	σ_{SB}	Stefan–Boltzmann constant .... 5.6696×10^{-8} $W/m^2 K^4$
T_a	design limit temperature .... K		

design, inspection, and maintenance procedures and in determining safety requirements. Gorla et al. computed cumulative distribution functions and sensitivity factors for the stress responses of a combustor line due to aerodynamic, mechanical and thermal random variables [6]. The significant point of their work is the probabilistic evaluation of the CFD methodology, where three-dimensional unsteady compressible Navier–Stokes equations coupled with the $k-\omega$ SST turbulence model were employed. A stochastic approach is inevitable for the thermomechanical analysis of composite materials/structures, and Kamiński et al. presented the stochastic finite element analysis of transient heat transfer in a three-component layered composite with randomly defined thermal properties [7].

The objective of the present study is to investigate the probabilistic thermal responses of the PARTT reentry module structure. PARTT is a Piggyback Atmospheric Reentry Technology Testbed, and is described in the following section. In this investigation, aerodynamic heat flux, heat shield emissivity, and insulator thermal conductivity are selected as random parameters. Because of the strong time dependency of aerodynamic heat flux during reentry flight, the transient behaviors of the probabilistic temperature response are focused on. Finally, thermal reliability is assessed based on the simulation results.

2. Piggyback Atmospheric Reentry Technology Testbed (PARTT)

In developing any kind of atmospheric reentry vehicle, flight experiments are highly important not only to confirm ground test data but also to understand reentry phenomena such as the catalytic effect and aero-thermodynamics. However, budget restrictions often limit the opportunity for flight experiments, and the resulting lack of scientific knowledge of reentry flight can lead to overly conservative design.

In view of this, the Institute of Aerospace Technology (IAT) of the Japan Aerospace Exploration Agency (JAXA) has been conducting a conceptual study on a reentry testbed "PARTT" (Piggyback Atmospheric Reentry Technology Testbed) that will have sufficiently low cost to enable many flights. This section briefly overviews the PARTT system, while details have been given by Fujii et al. [3,4].

The PARTT vehicle is intended to be launched "piggyback" with a main payload, using surplus payload delivery capacity of the launch vehicle. To allow this, it should be as small as possible. Referring to the standard piggyback payload of the Japanese H-IIA launch vehicle, the weight and the diameter of the PARTT reentry module are tentatively assumed as 40 kg and 0.7 m, respectively.

The PARTT system consists of an orbiter module and a reentry module. The system is injected into a 250 km-altitude circular orbit (the parking orbit of an H-IIA GTO mission). After separation from the orbiter module, the reentry module reenters the earth's atmosphere and deploys parachutes at 10 km altitude for ground recovery. The altitude of the reentry interface is 120 km, at which the flight path angle is determined to be −2 degrees. The aerodynamic and aero-thermal analyses consider the effect of the atmosphere below this altitude.

3. Analysis procedure

3.1. Reentry module structure and computational model

Thermal analysis is conducted only on the reentry module structure, shown in Fig. 1. The reentry module consists of a main body that houses electronic equipment, the parachute system etc., and a heat shield shell that protects the body from aerodynamic heating. The shell is connected to the main body by a support structure. The materials and dimensions of the structure are shown in Table 1.

One of the main objectives of PARTT is to investigate physical phenomena during reentry flight such as real gas effect and catalysis. An ablative TPS is not adopted in order to avoid contaminating the flow with ablation products that can affect aerodynamic and aero-thermal phenomena. Carbon/carbon (C/C) composite is therefore selected for the heat shield material.

The ANSYS Finite Element program was used in the present study. The finite element model is shown in Fig. 1, where axisymmetric elements with four nodes (PLANE55 of ANSYS