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Uncertainty dynamic theoretical analysis on ceramic thermal protection system using perturbation method

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ABSTRACT

A two degree-of-freedom uncertainty dynamic theoretical model under the acoustic and base excitations was presented to analyze the uncertainty dynamic behaviors of thermal protection system (TPS) and the uncertainty dynamic strength of strain-isolation-pad (SIP). The tile and SIP are both simplified as the combination of a mass point, a linear spring and a damping element, and all the dynamic parameters obey the normal distribution. The probability distributions of responses were derived from adopting the perturbation method. The difference method is used to analyze the sensitivity of the mean responses to random parameters, and the reasonable sensitivity values are obtained under a difference step which is equal to the standard deviation of the random parameter. The probability distributions calculated by the uncertainty theoretical model match well with the Monte Carlo numerical results, so the accuracy of the uncertainty dynamic theoretical model is verified. The researches in this paper provide a theoretical foundation for studying the uncertainty dynamic behaviors of TPS, analyzing uncertainty dynamic strength of SIP and intensifying the integrity and security of TPS.

1. Introduction

The space shuttle orbiter is subject to the aerodynamic heating during the lift-off and re-entry phases [1–3]. A thermal protection system (TPS) is necessary to ensure the internal structure of the orbiter within the sustainable temperature range [4–6]. The ceramic tile is the most widely used heat insulation structure, and is attached on the surface of structure through a strain-isolation-pad (SIP) (Fig. 1). In addition to resisting the aerodynamic heating, TPS is subject to the acoustic excitation on the outer surface of tile and the base excitation of the structure as well [7]. The above two excitations are both the dynamic mechanical loads, the dynamic responses including the acceleration responses of TPS and the dynamic stresses of SIP will be generated. Once the value of dynamic stress of SIP exceeds the strength value, the disastrous accident will happen to the space plane orbiter because of losing thermal protection function. Therefore, the dynamic analysis for tile and SIP is necessary when designing TPS.

Only a few studies on dynamic behaviors of TPS can be found at present, which are mainly conducted by experiments. Cooper et al. [8] studied the influences of simulated static loads and random dynamic loads on the dynamic behaviors of ceramic TPS to ensure the integrity of TPS before the first flight. Miserentino et al. [9] studied the dynamic responses of ceramic TPS under the sinusoidal excitation by experiments. A dynamic instability is described which has large in-plane motion at a frequency one-half that of the nominal driving frequency. Considering the nonlinear stiffening hysteresis and viscous behavior of SIP, Housner et al. [10] studied the influences of the sinusoidal motions of the skin on the dynamic responses of the tile/SIP system. Edighoffer [11] studied the nonlinear dynamic behaviors of the space shuttle TPS for imposed sinusoidal and random motions of the shuttle skin and/applied tile pressure. In addition to the experimental methods, some studies were conducted on the dynamic behaviors of tile/SIP system by theoretical methods. George and Doyle [12] proposed a single degree-of-freedom theoretical model for dynamic responses of TPS under the acoustic and acceleration base excitations. The tile was considered as a rigid body and simplified as a mass point, and the SIP was simplified as a linear spring and a damping element. Finally, the random responses of tile and SIP were predicted through the theoretical model.

The above-mentioned scholars studied the dynamic behaviors of TPS by experimental and theoretical methods, and achieved some significant research results. However the mass, stiffness and damping of the tile and SIP usually show obvious uncertainties. The above certainty studies don't consider the uncertainties of dynamic system parameters, so it is necessary to study the uncertainty dynamic behaviors of TPS.

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Nomenclature

A	TPS surface area, m^2
c_1, c_2	viscous damping coefficients of tile and SIP, N·s/m
$\boldsymbol{C}$	viscous damping coefficient matrix
E	elastic modulus, MPa
f	acoustic pressure, Pa
$\boldsymbol{F}$	external load vector
$\boldsymbol{F}_f$	external load vector of acoustic excitation
$\boldsymbol{F}_y$	external load vector of base excitation
g	structural damping coefficient
G	gravitational acceleration, m/s^2
H	frequency response function
k_1, k_2	stiffness coefficients of tile and SIP, N/m
$\boldsymbol{K}$	stiffness matrix
m_1, m_2	mass of tile and SIP, Kg
$\boldsymbol{M}$	mass matrix
N	maximum simulation times of Monte Carlo method
r	Poisson's ratio
S_f	acoustic pressure PSD, N^2/Hz
$S_{\ddot{x}_1}$	tile acceleration PSD, (m/s^2)^2/Hz
$S_{\ddot{x}_2}$	SIP acceleration PSD, (m/s^2)^2/Hz
$S_{\ddot{y}}$	base acceleration PSD, (m/s^2)^2/Hz
u_k	element of RMS response vector
$\boldsymbol{u}$	RMS response vector
x_1, x_2	displacements of tile and SIP, m
y, $\ddot{y}$	displacement and acceleration of base excitation
η_k	element of random parameter vector
$\boldsymbol{\eta}$	random parameter vector
λ	constant coefficient
v	covariance
ρ	density
ρ_{kq}	correlation coefficient between random parameters
σ	standard deviation
φ_s	root mean square stress of SIP, MPa
$\varphi_{\ddot{x}_1}$	root mean square acceleration of tile, m/s^2
$\varphi_{\ddot{x}_2}$	root mean square acceleration of SIP, m/s^2
$\varphi_{\ddot{y}}$	root mean square base acceleration, m/s^2
ω	angular frequency, rad/s
Δu_k	increment of RMS response
$\Delta \eta_k$	increment of random parameter

In order to study the uncertainty dynamic behaviors of TPS and the uncertainty dynamic strength of SIP, a two degree-of-freedom uncertainty dynamic theoretical model was presented under the acoustic and base excitations. The tile and SIP are both considered as elastic bodies and are both simplified as the combination of a mass point, a linear spring and a damping element. The probability distributions of the responses were derived and the theoretical results were compared with the Monte Carlo numerical results.

2. Vibration environment

TPS is under the multi-task environment, where aerodynamic heating, aerodynamic force and base motion from the structure of the orbiter exist. This paper focuses on the dynamic behaviors of TPS, and the dynamic loads are the acoustic pressure and base motion [7,12] (Fig. 2). The base excitation is generally the acceleration of structure, which comes from the vibration of the engine and acts on the bottom of TPS. And the acoustic excitation mainly comes from the pulsation of the turbulent boundary layer and acts on the outer surface of TPS.

The acoustic and base excitations are random, so the random vibration method should be used in the dynamic analysis of TPS. The power spectral density (PSD) function of the acoustic excitation is usually the band-limited white noise, and the PSD function of the acceleration base excitation is usually ladder spectrum (Fig. 3). The PSD functions are generally obtained by the experiment and signal processing method [13].

3. Dynamic theoretical model

The elastic modulus of the tile is usually between 10 MPa and 50 MPa, and that of the SIP is usually between 1 MPa and 10 MPa. Compared with SIP, the tile can't be treated as a rigid body, so the tile is considered as the elastic body in this paper. Besides, the width of TPS is small and usually between 50 mm and 200 mm, the acoustic and base excitations are approximately uniformly distributed. Therefore the following assumptions in the dynamic theoretical model are made.

1) The dynamic system obeys the stationary random vibration, and all the excitations obey the Gauss stochastic process;
2) The tile is simplified as the combination of a mass point, a linear spring and a damping element to describe the inertial force, elastic force and damping force of tile respectively;
3) The SIP is simplified as the combination of a mass point, a linear spring and a damping element to describe the inertial force, elastic force and damping force of SIP respectively;
4) The acoustic excitation and base excitation are uniformly distributed on the outer surface of tile and bottom of SIP respectively.

According to the above assumptions, a two degree-of-freedom dynamic theoretical model for the random vibration of TPS is presented under the acoustic and base excitations (Fig. 4). In the theoretical model, $S_f(\omega)$ and $S_{\ddot{y}}(\omega)$ are the PSD functions of acoustic excitation and acceleration base excitation respectively; m_1 and m_2 are the masses of the tile and SIP respectively; k_1 and k_2 are the linear stiffness coefficients of the tile and SIP respectively; c_1 and c_2 are the viscous damping coefficients of the tile and SIP respectively; x_1 and x_2 are the displacements of the tile and SIP respectively. The acoustic excitation acts on the outer surface of the tile, and the base excitation acts on the bottom of SIP.

The motion equation of the dynamic system under the acoustic and

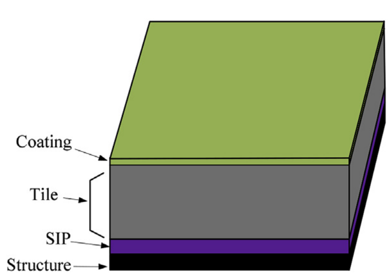

Fig. 1. An element of standard TPS assembly.

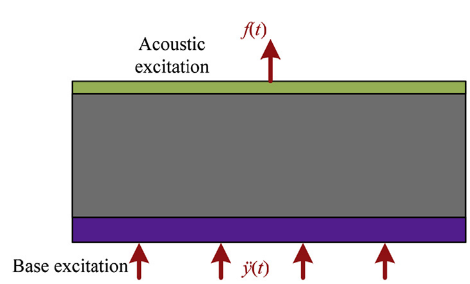

Fig. 2. Tile dynamic load sources.