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Investigation on dynamic behaviors of thermal protection system using a two degree-of-freedom nonlinear theoretical method

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ABSTRACT

In order to study the nonlinear dynamic behaviors of Thermal Protection System (TPS) and the nonlinear dynamic strength of the strain-isolation-pad (SIP), a two degree-of-freedom nonlinear dynamic theoretical model was presented under the acoustic excitation and base excitation. The tile is simplified as a mass point, a linear spring and a damping element, and the SIP is simplified as a mass point, a nonlinear spring and a damping element. On this basis, the solving process of the nonlinear theoretical model and the iterative process of the equivalent linear stiffness coefficient of SIP were derived by the statistical linearization method. The dynamic responses analyzed by the nonlinear theoretical model and linear theoretical model are compared. The nonlinear stiffness of SIP shows obvious influence on behaviors of TPS and dynamic stress of SIP, and the equivalent linear stiffness of SIP is related to the types of excitations. Finally, the influences on above dynamic responses by the nonlinear stiffness level of SIP were studied. The equivalent linear stiffness coefficient of SIP, acceleration of TPS and dynamic stress of SIP decrease with the increase of the nonlinear level for the stiffness of SIP.

1. Introduction

The spaceplane orbiter is subject to aerodynamic heating during the lift-off and re-entry phases [1–4]. Thermal protection system (TPS) is necessary in order to ensure the internal structure of the orbiter within the sustainable temperature range [5–8]. The ceramic tile is the most widely used heat insulation structure, which is attached to the surface of structure through the strain-isolation-pad (SIP) (Fig. 1). In addition to withstand aerodynamic heating during the lift-off and re-entry phases, TPS is subject to the acoustic excitation on the outer surface of tile and the base excitation of structure as well [9]. The above two excitations are dynamic mechanical loads, the dynamic responses including the acceleration responses of TPS and dynamic stresses of SIP will be generated. Once the value of dynamic stress of SIP exceeds the strength value of SIP, the failure will be occurred on the SIP, and it will result in separation between tile and structure of the orbiter. The disastrous accident will happen on the spaceplane orbiter because of losing the thermal protection function. Therefore, when designing TPS, the dynamic responses for the tile and SIP must be analyzed under the acoustic excitation and base excitation.

The studies on dynamic behaviors of TPS are very few, and they were mainly conducted by experiments. Miserentino et al. [10] studied the dynamic responses of the tile/SIP system 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. Cooper et al. [11] studied the effects of simulated static loads and random dynamic loads on the dynamic behaviors and integrity of TPS to ensure the integrity of TPS before the first flight. Considering the nonlinear stiffening hysteresis and viscous behavior of SIP, Housner et al. [12] studied the effects of the sinusoidal motions of the skin on the dynamic responses of the tile/SIP system. Edighoffer [13] studied the nonlinear dynamic behaviors of the spaceplane tile/pad thermal protection system for imposed sinusoidal and random motions of the shuttle skin and/applied tile pressure. Except for the experimental methods, some studies were conducted for the dynamic behaviors of TPS through theoretical methods. George and Doyle [14] proposed a single degree-of-freedom theoretical model for dynamic responses of TPS under the acoustic excitation and acceleration base excitation. They treated the tile as a rigid body and considered it as a mass point, but the SIP was considered as a spring with linear stiffness and a damping element. Besides, the power spectral density (PSD) functions of the acoustic excitation and acceleration base excitation were both assumed as the band-limited white noises. Finally, the random responses for TPS were predicted through the theoretical

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Nomenclature

c_1, c_2	viscous damping coefficients of tile and SIP, N·s/m
$[C]$	damping matrix of linear theoretical model
$[C_e]$	equivalent damping matrix nonlinear theoretical model
E_1	elasticity modulus of tile, MPa
f_1	linear load-displacement function of tile
f_2	nonlinear load-displacement function of SIP
f_g, f_c	structural and viscous damping force, N
F	external load vector
$\{G\}$	vector of elastic force for system
k_1	linear stiffness coefficient of tile, N/m
k_{e2}	equivalent linear stiffness coefficient of SIP, N/m
$[K]$	stiffness matrix of theoretical model
$[K_e]$	equivalent stiffness matrix nonlinear theoretical model
m_1, m_2	mass of tile and SIP, Kg
$[M]$	mass matrix of theoretical model
$[M_e]$	equivalent mass matrix of nonlinear theoretical model
S	TPS surface area, m^2
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
t_1, t_2	thickness of tile and SIP, mm
x_1, x_2	displacement of tile and SIP, m
ψ_σ^a	root mean square stress of SIP due to acoustic pressure, MPa
ψ_σ^b	root mean square stress of SIP due to base acceleration, MPa
ψ_f	root mean square acoustic pressure, N
$\psi_{\ddot{x}_1}$	root mean square acceleration of tile and tile, m/s^2
$\psi_{\ddot{x}_2}$	root mean square acceleration of SIP, m/s^2
$\psi_{\ddot{y}}$	root mean square base acceleration, m/s^2
ω	angular frequency, rad/s
ω_n	natural frequency of theoretical model, rad/s

Subscripts

c	viscous damping coefficient
e	equivalent
f	acoustic excitation
g	structural damping coefficient
$\ddot{y}$	base excitation

solutions.

Above scholars studied the dynamic responses of TPS by the experimental and theoretical models, and achieved some significant research results. However, experimental method is limited by experimental environments and expenses. Besides the theoretical model is only a linear system. Actually, the stiffness of SIP is usually nonlinear [12,13], the linear theoretical model can't analyze the dynamic behaviors of TPS and the dynamic strength of the SIP accurately.

In order to study the influences on the dynamic behaviors of TPS and the dynamic strength of the SIP by the nonlinear stiffness of SIP, the tile is simplified as a mass point, a linear spring and a damping element, and the SIP is simplified as a mass point, a nonlinear spring and a damping element, and a two degree-of-freedom nonlinear theoretical model for random dynamic responses of tile and SIP was presented under the acoustic excitation and base excitation. The solving process of the nonlinear theoretical model and the iterative process of the equivalent linear stiffness coefficient of SIP were derived by the statistical linearization method [15]. Finally, the influences on the dynamic responses of TPS and the dynamic strength of the SIP by the nonlinear stiffness level of SIP were studied.

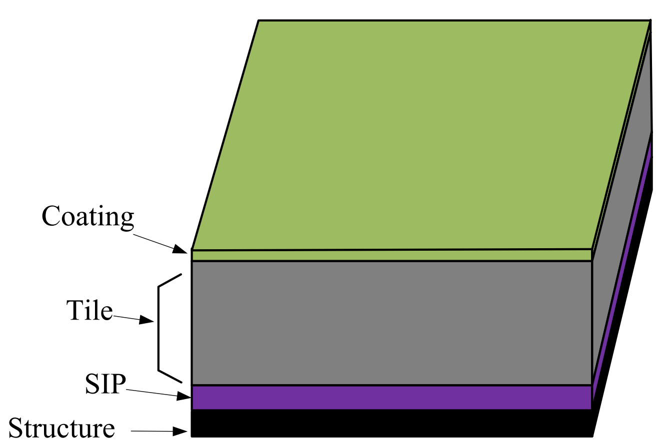

Fig. 1. An element of standard TPS assembly.

2. Vibration environment

TPS is under the multi-task environments, including aerodynamic heating, aerodynamic force and base excitation from the structure of orbiter. The studies in this paper are about dynamic behaviors of TPS, and the dynamic loads are the acoustic pressure and base excitation [6,14] (Fig. 2). As the acoustic excitation and base excitation act randomly, the PSD function of the acoustic excitation is usually the band-limited white noise with the constant value during its frequency range. But the PSD function of the acceleration base excitation is usually ladder spectrum [14], and the typical PSD function of it is shown as Fig. 3. The PSD functions are generally obtained by the experiments and signal processing methods [16].

3. Nonlinear theoretical model

3.1. Assumptions

The tile and SIP are both considered as the elastic bodies in this paper. The stiffness of SIP is usually nonlinear actually, and the load-displacement curve can be expressed by the cubic function approximately [10,11]. Since the coating is very thin, and its effect on the dynamic behaviors of TPS is very small, the dynamic model in this paper does not consider it. The investigations in this paper are aimed to analyze only the launch environment, thus only the vibration and acoustic environment loads are applied. The following assumptions are

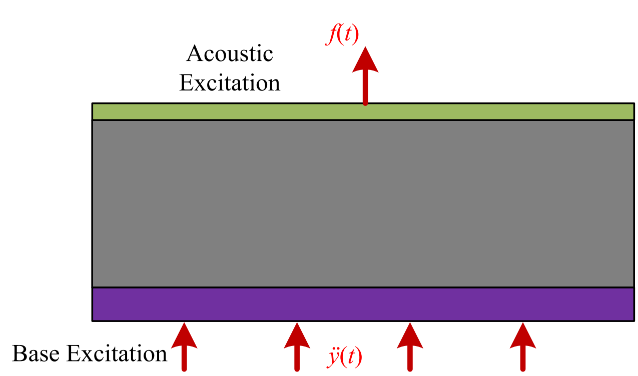

Fig. 2. The dynamic load sources.