Two Degree-of-Freedom Dynamic Theoretical Model on Tile Thermal Protection System

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Abstract: In order to study the dynamic behaviors of the thermal protection system (TPS) and dynamic strength of the strain-isolation-pad (SIP), a two degree-of-freedom dynamic theoretical model is presented under the acoustic excitation and base excitation. The tile and SIP are both considered as the elastic body and simplified as a mass point, a linear spring and a damping element. The theoretical solutions are derived, and the reasonability of theoretical model is verified by comparing the theoretical results with the numerical results. Finally, the influences on the dynamic responses of TPS by the structural damping coefficient of TPS, elasticity modulus and thickness of SIP are analyzed. The results show that the material with higher damping, and SIP with thicker size and lower elastic modulus should be considered to reduce the dynamic responses and intensify the security of TPS. The researches provide a theoretical reference for studying the dynamic behaviors of TPS and the dynamic strength of SIP. Besides, the dynamic theoretical model can be used as a quick analysis tool for analyzing the dynamic responses of TPS during the initial design phase.

Key words: thermal protection system; dynamic theoretical model; acoustic excitation; base excitation

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0 Introduction

The space plane orbiter is subject to aerodynamic heating during the lift-off and re-entry phases[1-4]. A thermal protection system (TPS) is necessary to ensure the internal structure of the orbiter within the sustainable temperature range[5-7]. The ceramic tile is the most widely used heat insulation structure, attached on the surface of structure through a strain-isolation-pad (SIP). 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 structure as well[8]. The above two excitations are the dynamic mechanical loads, the dynamic responses including the acceleration of TPS and the dynamic stress of SIP will be generated. Once the value of dynamic stress of SIP exceeds the strength value, the failure will happen on SIP, and it will result in the separation between the tile and structure of the orbiter. The disastrous accident will happen to the space plane orbiter because of losing the thermal protection function. Therefore, the dynamic analysis for tile and SIP is necessary when designing TPS.

The studies on dynamic behaviors of TPS are very few, and they were mainly analyzed by experimental method. Miserentino et al.[9] studied the dynamic responses of the tile/SIP system under the si-

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nusoidal 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 effects of the sinusoidal motions of the skin on the dynamic responses of the tile/SIP system.

The dynamic behaviors of TPS can be studied by the above experimental method, but it is limited by experimental environment and expenses. In order to study the dynamic behaviors of TPS and analyze the dynamic strength of SIP, the tile and SIP are both considered as the elastic body and simplified as a mass point, a linear spring and a damping element. A two degree-of-freedom dynamic theoretical model for random dynamic behaviors of TPS is presented under the acoustic excitation and base excitation. The theoretical solutions are derived and compared with the numerical solutions. Finally, the parametric studies for the dynamic behaviors of TPS are conducted.

1 Vibration Environment

TPS is under the multi-task environments, including aerodynamic heating, aerodynamic force and base excitation from the structure of orbiter. This paper focuses on the dynamic behaviors of TPS, and the dynamic loads are the acoustic pressure and base excitation[8] (Fig.1) which mainly occur during the lift-off and re-entry phases. The base excitation is generally the acceleration of structure, which comes from the vibration of the engine and acts on the bottom of TPS. However, the acoustic

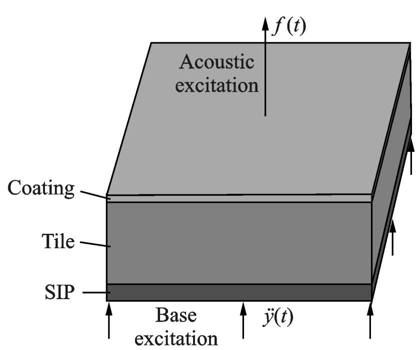

Fig. 1 Tile dynamic load sources

excitation mainly comes from the pulsation of the turbulent boundary layer and acts on the outer surface of TPS.

The acoustic excitation and base excitation are random[8], 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 with the constant value during the frequency range. But the PSD function of the acceleration base excitation is usually ladder spectrum, and the typical PSD function of it is shown in Fig.2. The PSD functions are generally obtained by the experiment and signal processing method. Firstly, the time-domain signal is measured by experiment, and then it is converted into frequency-domain excitation by the fast Fourier transform. Finally, the PSD function is obtained by signal processing method[11].

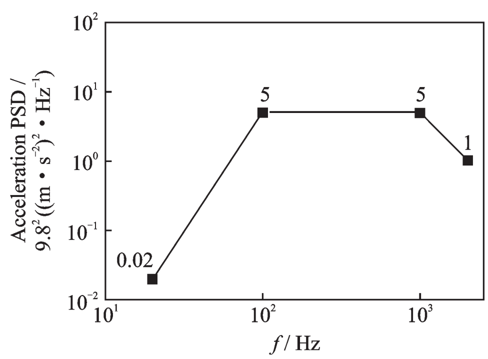

Fig. 2 Typical acceleration base PSD function

2 Dynamic Theoretical Model

The elasticity modulus of the tile is usually between 10 MPa and 50 MPa, and that of SIP is usually between 1 MPa and 10 MPa. Compared with SIP, the tile cannot be treated as a rigid body, so the tile is considered as the elastic body in this paper. As the width of TPS is small and usually between 50 mm and 200 mm, the acoustic excitation and base excitation are approximately uniformly distributed. Since the effect of the coating on the dynamic behaviors of TPS is very small, this paper does not consider its influence. According to the above discussions, the assumptions made in the dynamic theoretical model are given by:

(1) The dynamic system obeys the stationary

random vibration, and all the excitations obey the Gauss stochastic process.

(2) The tile is simplified as a mass point, a linear spring and a damping element to describe the inertial force, elastic force and damping force of tile.

(3) The SIP is simplified as a mass point, a linear spring and a damping element to describe the inertial force, elastic force and damping force of SIP.

(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 excitation and base excitation (Fig. 3). 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.

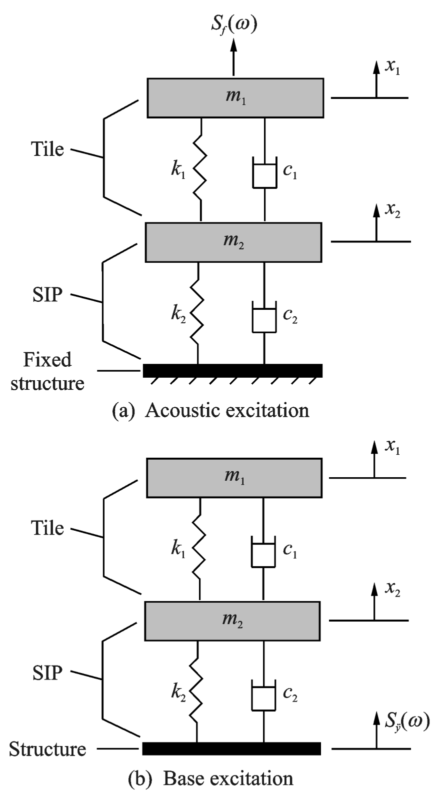

Fig. 3 Dynamic theoretical models

3 Acoustic Excitation

The two degree-of-freedom dynamic theoretical model under the acoustic excitation is shown in Fig. 3(a), and the motion equation of the dynamic system is given by

$$\boldsymbol{M}\ddot{\boldsymbol{x}}(t)+\boldsymbol{K}\boldsymbol{x}(t)+\boldsymbol{C}\dot{\boldsymbol{x}}(t)=\boldsymbol{F}_f(t) \tag{1}$$

where $\boldsymbol{M}$ is the mass matrix, $\boldsymbol{K}$ the stiffness matrix, $\boldsymbol{C}$ the damping matrix, $\boldsymbol{F}_f$ the external acoustic load vector and $\boldsymbol{x}$ the displacement vector.

$$\begin{aligned}
&\boldsymbol{M}=\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}\\
&\boldsymbol{K}=\begin{bmatrix} k_1 & -k_1 \\ -k_1 & k_1+k_2 \end{bmatrix}\\
&\boldsymbol{C}=\begin{bmatrix} c_1 & -c_1 \\ -c_1 & c_1+c_2 \end{bmatrix}\\
&\boldsymbol{F}_f(t)=\{ f(t) \quad 0 \}^{\mathrm{T}}\\
&\boldsymbol{x}=\{ x_1 \quad x_2 \}^{\mathrm{T}}
\end{aligned} \tag{2}$$

Suppose the acoustic excitation $\tilde{f}(t)=\sqrt{S_f(\omega)}\,\mathrm{e}^{\mathrm{i}\omega t}$, and then the displacement, velocity and acceleration can be given by

$$\begin{aligned}
&\tilde{x}_1(t)=H_1(\omega)\tilde{f}(t),\quad \tilde{x}_2(t)=H_2(\omega)\tilde{f}(t)\\
&\tilde{\dot{x}}_1(t)=H_1(\omega)\tilde{\dot{f}}(t),\quad \tilde{\dot{x}}_2(t)=H_2(\omega)\tilde{\dot{f}}(t)\\
&\tilde{\ddot{x}}_1(t)=H_1(\omega)\tilde{\ddot{f}}(t),\quad \tilde{\ddot{x}}_2(t)=H_2(\omega)\tilde{\ddot{f}}(t)
\end{aligned} \tag{3}$$

where H_i is the frequency response function between the displacement x_i and the acoustic pressure f.

Substituting Eq.(3) into Eq.(1) yields

$$\boldsymbol{A}\begin{Bmatrix} H_1 \\ H_2 \end{Bmatrix}=\begin{Bmatrix} 1 \\ 0 \end{Bmatrix} \tag{4}$$

$$\boldsymbol{A}=\begin{bmatrix} -\omega^2 m_1+k_1+\mathrm{i}\omega c_1 & -k_1-\mathrm{i}\omega c_1 \\ -k_1-\mathrm{i}\omega c_1 & -\omega^2 m_2+k_1+k_2+\mathrm{i}\omega(c_1+c_2) \end{bmatrix} \tag{5}$$

So the frequency response function H_i can be derived as

$$H_1(\omega)=\frac{\mathrm{i}\omega(c_1+c_2)+k_1+k_2-\omega^2 m_2}{(-m_1\omega^2+\mathrm{i}\omega c_1+k_1)[-m_2\omega^2+\mathrm{i}\omega(c_1+c_2)+(k_1+k_2)]-(\mathrm{i}\omega c_1+k_1)^2}$$
$$H_2(\omega)=\frac{\mathrm{i}\omega c_1+k_1}{(-m_1\omega^2+\mathrm{i}\omega c_1+k_1)[-m_2\omega^2+\mathrm{i}\omega(c_1+c_2)+(k_1+k_2)]-(\mathrm{i}\omega c_1+k_1)^2} \tag{6}$$

Based on the pseudo excitation method (PEM) [12], the PSD functions of responses can be calculated by

$$\begin{aligned} S_{x_1}(\omega)&=\tilde{x}_1\cdot\bar{\tilde{x}}_1,\ S_{x_2}(\omega)=\tilde{x}_2\cdot\bar{\tilde{x}}_2\\ S_{\dot{x}_1}(\omega)&=\tilde{\dot{x}}_1\cdot\bar{\tilde{\dot{x}}}_1,\ S_{\dot{x}_2}(\omega)=\tilde{\dot{x}}_2\cdot\bar{\tilde{\dot{x}}}_2\\ S_{\ddot{x}_1}(\omega)&=\tilde{\ddot{x}}_1\cdot\bar{\tilde{\ddot{x}}}_1,\ S_{\ddot{x}_2}(\omega)=\tilde{\ddot{x}}_2\cdot\bar{\tilde{\ddot{x}}}_2 \end{aligned} \tag{7}$$

where $\bar{\tilde{\ddot{x}}}_i$, $\bar{\tilde{\dot{x}}}_i$ and $\bar{\tilde{x}}_i$ are the conjugate complex of $\tilde{\ddot{x}}_i$, $\tilde{\dot{x}}_i$ and $\tilde{x}_i$ respectively.

By substituting Eqs.(3, 6) into Eq.(7), the PSD functions of the responses are given by

$$\begin{aligned} S_{x_1}(\omega)&=|H_1|^2 S_f,\ S_{x_2}(\omega)=|H_2|^2 S_f\\ S_{\dot{x}_1}(\omega)&=\omega^2|H_1|^2 S_f,\ S_{\dot{x}_2}(\omega)=\omega^2|H_2|^2 S_f\\ S_{\ddot{x}_1}(\omega)&=\omega^4|H_1|^2 S_f,\ S_{\ddot{x}_2}(\omega)=\omega^4|H_2|^2 S_f \end{aligned} \tag{8}$$

where $S_{\ddot{x}_i}(\omega)$, $S_{\dot{x}_i}(\omega)$ and $S_{x_i}(\omega)$ are the PSD functions of acceleration, velocity and displacement respectively.

By integrating the above PSD functions in the frequency domain, the corresponding mean square values are calculated by

$$\begin{aligned} \psi_{x_1}^2&=\int_{\omega_1}^{\omega_2}S_{x_1}(\omega)\mathrm{d}\omega,\ \psi_{x_2}^2=\int_{\omega_1}^{\omega_2}S_{x_2}(\omega)\mathrm{d}\omega\\ \psi_{\dot{x}_1}^2&=\int_{\omega_1}^{\omega_2}S_{\dot{x}_1}(\omega)\mathrm{d}\omega,\ \psi_{\dot{x}_2}^2=\int_{\omega_1}^{\omega_2}S_{\dot{x}_2}(\omega)\mathrm{d}\omega\\ \psi_{\ddot{x}_1}^2&=\int_{\omega_1}^{\omega_2}S_{\ddot{x}_1}(\omega)\mathrm{d}\omega,\ \psi_{\ddot{x}_2}^2=\int_{\omega_1}^{\omega_2}S_{\ddot{x}_2}(\omega)\mathrm{d}\omega \end{aligned} \tag{9}$$

where $\psi_{\ddot{x}_i}$, $\psi_{\dot{x}_i}$ and ψ_{x_i} are root-mean-square (RMS) values of the acceleration, velocity and displacement, respectively.

According to the elastic force and damping force of SIP, the RMS values of the total force ψ_F and stress ψ_σ for SIP are calculated by

$$\psi_F=k_2\psi_{x_2}+c_2\psi_{\dot{x}_2} \tag{10}$$

$$\psi_\sigma=\frac{\psi_F}{A} \tag{11}$$

4 Base Excitation

The two degree-of-freedom dynamic theoretical model under the base excitation is shown in Fig. 3(b), and the motion equation of the dynamic system is given by

$$\boldsymbol{M}\ddot{\boldsymbol{x}}(t)+\boldsymbol{K}\boldsymbol{x}(t)+\boldsymbol{C}\dot{\boldsymbol{x}}(t)=\boldsymbol{F}_y(t) \tag{12}$$

where $\boldsymbol{F}_y$ is the external base load vector.

$$\boldsymbol{F}_y=\{0\quad k_2 y(t)+c_2\dot{y}(t)\}^{\mathrm{T}} \tag{13}$$

Suppose the base excitation $\tilde{y}=\sqrt{S_y(\omega)}\,\mathrm{e}^{\mathrm{i}\omega t}$, and then the displacement, velocity and acceleration can be given by

$$\begin{aligned} \tilde{x}_1(t)&=H_1(\omega)\tilde{y}(t),\ \tilde{x}_2(t)=H_2(\omega)\tilde{y}(t)\\ \tilde{\dot{x}}_1(t)&=H_1(\omega)\tilde{\dot{y}}(t),\ \tilde{\dot{x}}_2(t)=H_2(\omega)\tilde{\dot{y}}(t)\\ \tilde{\ddot{x}}_1(t)&=H_1(\omega)\tilde{\ddot{y}}(t),\ \tilde{\ddot{x}}_2(t)=H_2(\omega)\tilde{\ddot{y}}(t) \end{aligned} \tag{14}$$

where H_i is the frequency response function between the displacement x_i and the base excitation y. Besides H_i is also the frequency response function between the acceleration $\ddot{x}_i$ and excitation $\ddot{y}$.

Substituting Eq.(14) into Eq.(12) yields

$$\boldsymbol{A}'\begin{Bmatrix}H_1\\H_2\end{Bmatrix}=\begin{Bmatrix}0\\k_2+\mathrm{i}\omega c_2\end{Bmatrix} \tag{15}$$

$$\boldsymbol{A}'=\begin{bmatrix}-\omega^2 m_1+k_1+\mathrm{i}\omega c_1 & -k_1-\mathrm{i}\omega c_1\\ -k_1-\mathrm{i}\omega c_1 & -\omega^2 m_2+k_1+k_2+\mathrm{i}\omega(c_1+c_2)\end{bmatrix} \tag{16}$$

So the frequency response function H_i can be derived as

$$H_1(\omega)=\frac{(-\mathrm{i}\omega c_1-k_1)(\mathrm{i}\omega c_2+k_2)}{(\mathrm{i}\omega c_1+k_1)^2-(-m_1\omega^2+\mathrm{i}\omega c_1+k_1)[-m_2\omega^2+\mathrm{i}\omega(c_1+c_2)+(k_1+k_2)]}$$
$$H_2(\omega)=\frac{-(-m_1\omega^2+\mathrm{i}\omega c_1+k_1)(\mathrm{i}\omega c_2+k_2)}{(\mathrm{i}\omega c_1+k_1)^2-(-m_1\omega^2+\mathrm{i}\omega c_1+k_1)[-m_2\omega^2+\mathrm{i}\omega(c_1+c_2)+(k_1+k_2)]} \tag{17}$$

Based on the PEM, the PSD functions of responses can be calculated by

$$\begin{aligned} S_{x_1}(\omega)&=\tilde{x}_1\cdot\bar{\tilde{x}}_1,\ S_{x_2}(\omega)=\tilde{x}_2\cdot\bar{\tilde{x}}_2\\ S_{\dot{x}_1}(\omega)&=\tilde{\dot{x}}_1\cdot\bar{\tilde{\dot{x}}}_1,\ S_{\dot{x}_2}(\omega)=\tilde{\dot{x}}_2\cdot\bar{\tilde{\dot{x}}}_2\\ S_{\ddot{x}_1}(\omega)&=\tilde{\ddot{x}}_1\cdot\bar{\tilde{\ddot{x}}}_1,\ S_{\ddot{x}_2}(\omega)=\tilde{\ddot{x}}_2\cdot\bar{\tilde{\ddot{x}}}_2 \end{aligned} \tag{18}$$

By substituting Eqs.(14,17) into Eq.(18), the PSD functions of the responses are given by

$$\begin{aligned} S_{\ddot{x}_1}(\omega)&=|H_1|^2 S_{\ddot{y}},\ S_{\ddot{x}_2}(\omega)=|H_2|^2 S_{\ddot{y}}\\ S_{\dot{x}_1}(\omega)&=|H_1|^2 S_{\ddot{y}}/\omega^2,\ S_{\dot{x}_2}(\omega)=|H_2|^2 S_{\ddot{y}}/\omega^2\\ S_{x_1}(\omega)&=|H_1|^2 S_{\ddot{y}}/\omega^4,\ S_{x_2}(\omega)=|H_2|^2 S_{\ddot{y}}/\omega^4 \end{aligned} \tag{19}$$

By integrating the above PSD functions in the frequency domain, the corresponding RMS values are calculated. And according to the Newton's Second Law, the RMS values of the total force ψ_F and stress ψ_σ for SIP are calculated by

$$\psi_F = m_1 \psi_{\ddot{x}_1} + m_2 \psi_{\ddot{x}_2} \tag{20}$$

$$\psi_\sigma = \frac{\psi_F}{A} \tag{21}$$

5 Numerical Verification

An example is presented in this paper to verify the dynamic theoretical model by the comparisons between the theoretical and numerical solutions. In the example, the length and width of TPS are both 150 mm, besides, the thickness t, elasticity modulus E, Poisson's ratio ν, density ρ and structural damping coefficient g of the tile and SIP are listed in Table 1. The corresponding mechanical parameters for theoretical model are listed in Table 2. The PSD function of the acoustic excitation on the outer surface of tile is band-limited white noise with the constant value 1 000 N^2/Hz in the frequency ranges from 20 Hz to 2 000 Hz. However, the PSD function of the acceleration base excitation is the ladder spectrum shown in Fig.2. Finally, structural damping coefficient g can be translated into the viscous damping coefficient c_n through the natural frequency ω_n

$$c_n = g m_n \omega_n \tag{22}$$

The finite element numerical model is established as shown in Fig.4, and the numerical results are analyzed by the software MSC / NASTRAN. The range of numerical results and the values of theoretical results are listed in Table 3. According to the results, the acceleration response of tile is greater than that of SIP under the both acoustic and base excitations, and all the theoretical results almost fall within the range of numerical results. Besides, theoretical results are close to the maximum values of numerical results. So the reasonability of the dynamic theoretical model is verified, and the dynamic theoretical model can be used to estimate the acceleration responses of tile/SIP and the stress response of SIP.

Table 1 Material properties of TPS

Part	t/mm	E/MPa	ν	ρ/(kg·m^{-3})	g/%
Tile	54.8	60.0	0.25	420	4
SIP	5.20	1.46	0.40	521	4

Table 2 Mechanical parameters of theoretical model

Part	m/kg	k/(kN·mm^{-1})	c/(N·s/m)
Tile	0.517 9	24.6	62.21
SIP	0.060 9	6.32	56.98

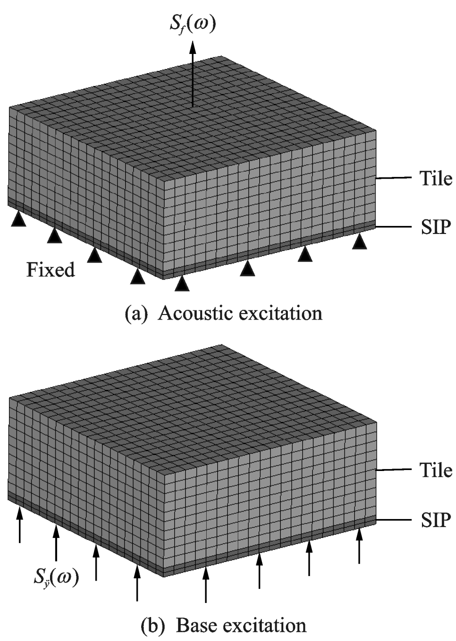

Fig. 4 3D finite element models of TPS

Table 3 Comparisons between theoretical and numerical results

Excitation	Method	SIP		Tile
		$\psi_{\ddot{x}_2}$/(km·s^{-2})	ψ_σ/MPa	$\psi_{\ddot{x}_1}$/(km·s^{-2})
Base	FEM	(0.81, 3.18)	(0.054, 0.094)	(2.71, 4.11)
	Theoretical	3.22	0.10	3.97
Acoustic	FEM	(0, 9.61)	(0.18, 0.26)	(8.84, 11.20)
	Theoretical	8.48	0.26	10.37

6 Discussion

The influences on the random dynamic responses of TPS by the structural damping coefficient g, the thickness of SIP t_2 and the elasticity modulus of SIP E_2 are studied in this paper (Figs. 5—7). The results show that the higher structural damping coefficient of TPS and the thicker SIP can reduce the responses of the dynamic system effectively. So the material with higher damping and SIP with thicker size should be considered when designing TPS.

According to Eq. (22), the higher elasticity modulus of SIP can result in a higher viscous damping. The higher damping coefficient will reduce the vibration of TPS. However, the higher elasticity modulus of SIP will intensify the vibration. When the elasticity modulus of SIP is lower than a critical value, the effect of the higher elasticity modulus of SIP is greater than that of the higher viscous damping. When the elasticity modulus of SIP is higher than the critical value, the effect of the higher elasticity modulus of SIP is smaller than that of the higher viscous damping. So as the elasticity modulus of SIP increases, all the responses increase firstly and then decrease. Above analysis is conducted in the case of changing elasticity modulus of SIP only, but the damping of actual material usually decreases with the increasing stiffness. So SIP with lower elastic modulus should be considered to reduce the vibration of TPS.

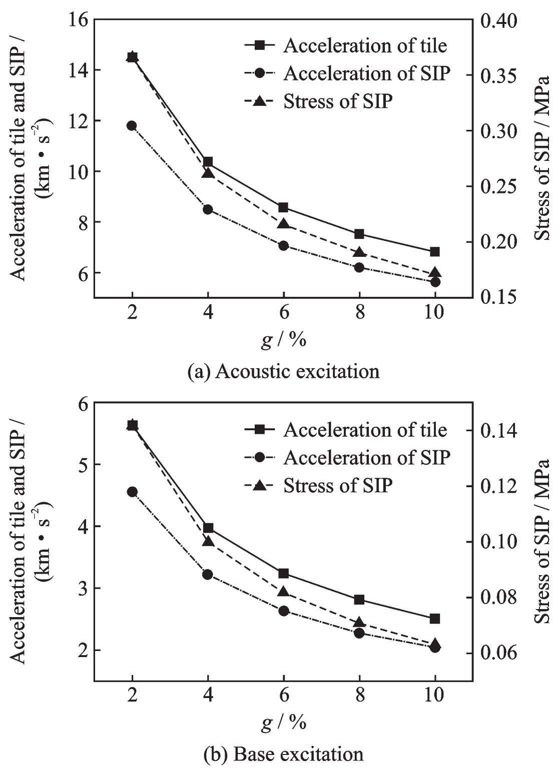

Fig. 5 Dynamic responses vs. structural damping coefficient

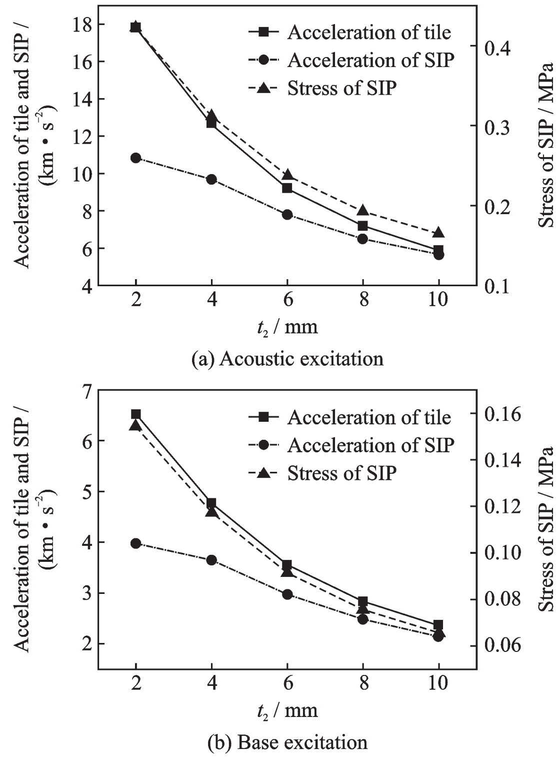

Fig. 6 Dynamic responses vs. thickness of SIP

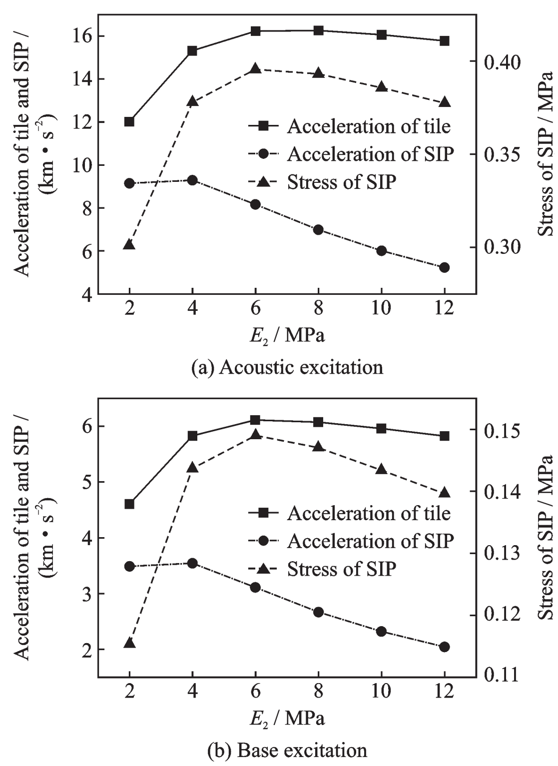

Fig. 7 Dynamic responses vs. elasticity modulus of SIP

7 Conclusions

(1) A two degree-of-freedom dynamic theoretical model is presented to study the dynamic behaviors of TPS and dynamic strength of SIP under the acoustic excitation and base excitation. The tile and SIP are both considered as elastic body and simplified as a mass point, a linear spring and a damping element. And the reasonability of the theoretical model is verified by the comparisons between the theoretical and numerical solutions.

(2) The material with higher damping, and SIP with thicker size and lower elastic modulus should be used to reduce the dynamic responses and intensify the integrity and security of TPS.

The paper provides a reference foundation for studying the dynamic behaviors of TPS and the dynamic strength of SIP. Besides, the dynamic theoretical model can be used as a quick analysis tool for the dynamic responses of TPS during the initial design phase.

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Author contributions Mr. **HUANG Jie** established the models. Prof. **YAO Weixing** checked the models. Mr. KONG Bin, Mr. **YANG Jiayong**, Mr. **WANG Man** and Mr. **ZHANG Qingmao** calculated the results. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

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