Dynamic Characteristics of Integrated Active and Passive Whole-Spacecraft Vibration Isolation Platform Based on Non-Probabilistic Reliability

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The whole-spacecraft vibration isolation (WSVI) platform can enhance the dynamic environment in the launch loads of rocket launchers during trips into orbit. In this dissertation, non-probabilistic reliability research is conducted for the dynamic characteristics of the integrated active and passive WSVI platform. First, the non-probabilistic reliability theory of the uncertain integrated active and passive vibration isolation system is established. Then, through the first-order equivalent dynamics model for the integrated active and passive WSVI system, the non-probabilistic reliability analysis of the WSVI platform is conducted. Finally, the analyzed accuracy of the non-probabilistic reliability for the WSVI platform is tested by experiments, through which the reliability and security of the integrated active and passive WSVI platform launch are enhanced.

Key Words: WSVI, Integrated Active and Passive Platform, Uncertainty, Non-Probabilistic Reliability, Vibration Test

Nomenclature

- $G$: lower bound of the damping matrix
- $G$: upper bound of the damping matrix
- $g_z(f)$: limit state function for the inherent frequency
- $g_z(T)$: limit state function for the vibration transmissibility
- $M$: lower bound of the mass matrix
- $M$: upper bound of the mass matrix
- $M_z$: lower bound of the limit state function for the inherent frequency
- $M_z$: upper bound of the limit state function for the inherent frequency
- $T_z$: lower bound of the vibration transmissibility
- $T_z$: upper bound of the vibration transmissibility
- $\varphi$: eigenvectors corresponding to lower bound
- $\varphi$: eigenvectors corresponding to upper bound

1. Introduction

Satellites are subject to poor, uncertain dynamics in their environment during launch. The traditional connecting method of rocket launchers and satellites is the payload attach fitting (PAF) system, which is high in stiffness and low in damping. The PAF usually directly transfers large vibration loading onto the satellite. The whole-spacecraft vibration isolation (WSVI) technology adapts the new vibration isolation platform that is substituted and embedded in the PAF system. The technology can enhance the dynamics of the environment of satellite launching without the need to change the structure of the satellite or add redundant mass.

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vibration isolation system. Meanwhile, the non-probabilistic reliability of the dynamic characteristics is analyzed. Then, through experiments, the analysis for non-probabilistic reliability is tested for accuracy to ensure the reliability and security of satellite launching.

2. Non-Probabilistic Reliability Theory of Integrated Active and Passive Vibration Isolation System

With the structural damping degree of freedom \( n \), the dynamic model of the integrated active and passive vibration isolation system is given as follows.

\[
M\ddot{x} + (K + jG)x = Fu + \Gamma Fp
\]  

(1)

\[
M\ddot{x} + (K + jG)x = Fu + \Gamma \begin{bmatrix} q_{p1}K_{p1} & \vdots & q_{pp}K_{pp}\end{bmatrix} x_{pp}^{T}n
\]  

(2)

In Eq. (2), \( K_{pp} \) represents the controlling transmission gain, \( x_{pp} \) represents the acceleration response of the controlled object, and \( q \) represents the controlling component quantity of the same dimensionality.

Abbreviating the Eq. (2) yields

\[
\begin{bmatrix} 0 & q_{p1}K_{p1} & \vdots & q_{pp}K_{pp}\end{bmatrix} x_{pp}^{T}n
\]

The high failure rate for the control elements of the integrated active and passive vibration isolation system harms the vibration isolation system. In Eq. (3), \( q \) can be regarded as uncertainty. The integrated active and passive vibration isolation system design of the uncertain parameters can enhance the vibration isolation reliability.

\[
\begin{bmatrix} M - \Gamma_{n\times n} & \vdots & q_{pp}K_{pp}\end{bmatrix} x_{pp}^{T}n
\]

(3)

The equation can be abbreviated into

\[
M\ddot{x} + (K + jG)x = Fu
\]  

(4)

Considering the uncertainty of the integrated active and passive vibration isolation system, the following are assumed.

\[
\begin{align*}
M_{ij} & \leq M_{ij} \leq M_{ij} \quad \text{or} \quad m_{ij} \leq m_{ij} \leq m_{ij}, \quad i, j = 1, 2, \ldots, n \\
K_{ij} & \leq K_{ij} \leq K_{ij} \quad \text{or} \quad k_{ij} \leq k_{ij} \leq k_{ij}, \quad i, j = 1, 2, \ldots, n \\
G_{ij} & \leq G_{ij} \leq G_{ij} \quad \text{or} \quad g_{ij} \leq g_{ij} \leq g_{ij}, \quad i, j = 1, 2, \ldots, n
\end{align*}
\]  

(5)

In Eq. (1), \( M \) represents the mass matrix of the structural damping system, \( K \) represents the stiffness matrix, \( G \) represents the damping matrix, \( F_u \) represents the external force vector on the bottom of the vibration isolation system, \( \Gamma \) represents the controlling force position matrix (\( n \times n \) dimension) of the controlling components, and \( F_p \) represents the \( n \times 1 \) dimension controlling force matrix offered by active controlling components. In \( F_p \), under \( p \) different dimensions, \( p \) nonzero elements correspond to \( p \) controlling components that are brought to bear on the controlling force; \( x \) represents the corresponding boundary coordinate.

If adopting the acceleration negative feedback control, Eq. (1) is transformed into the following.

\[
(\omega_n^2)^l = \begin{bmatrix} q_1^T K_{p1} & q_2^T K_{p2} & \vdots & q_{pp}^T K_{pp} \end{bmatrix} \begin{bmatrix} m_1 & m_2 & \ldots & m_{pp} \end{bmatrix} \]

(8)

The expression of the vibration transmissibility interval from the vibration isolation platform to the satellite is

\[
T_z = \begin{bmatrix} \bar{L}_z; \bar{T}_z \end{bmatrix}
\]

(9)

According to the Ref. 11)–13), the non-probabilistic reliability model of the integrated active and passive vibration isolation system is established. The inherent frequency of the vibration isolation system \( f \) and the vibration isolation property \( T \) are defined as basic interval variables, whose expressions are as follows.

\[
M_{ij} = g_{ij}(f) = 1 - (f_{0i} - f) \quad (10)
\]

\[
M_{ij} = g_{ij}(T) = 1 - (T - T_{0i}) \quad (11)
\]

Supposing the inherent frequency and the vibration transmissibility are \( f_{0i} \) and \( T_{0i} \), respectively, before the integrated active and passive vibration isolation system loses efficacy, and when the integrated active and passive vibration isolation system loses efficacy, the inherent frequency and vibration transmissibility are, respectively, \( f \) and \( T \), where \( f \) and \( T \) are interval variables. The upper and lower bounds of the interval for \( f_{0i} \geq f, T \geq T_{0i} \) depends on the interval boundary of the uncertain dynamical parameters of the integrated active and passive vibration isolation system.

Here \( \delta_{ij} = [\delta_{ij1}, \delta_{ij2}, \ldots, \delta_{ijp}] \) are the variable vectors of the standardized interval corresponding to the interval vari-
able vectors \( f = \{f_1, f_2, \cdots, f_n\} \).

In addition, \( \delta_f = \{\delta_{f1}, \delta_{f2}, \cdots, \delta_{fn}\} \) are the variable vectors of the standardized interval corresponding to the interval variable vectors \( T = \{T_1, T_2, \cdots, T_n\} \).

The non-probabilistic reliability index of the inherent frequency may be defined as

\[
\eta_f = \min \{\| \delta_f \|_\infty \} \tag{12}\]

The non-probabilistic reliability index of the vibration transmissibility may be defined as

\[
\eta_T = \min \{\| \delta_T \|_\infty \} \tag{13}\]

Meeting the condition

\[
M_{z1} = g_{z1}(f) = G(\delta_f) = 0 \tag{14}
\]

\[
M_{z2} = g_{z2}(T) = G(\delta_T) = 0 \tag{15}\]

Equations (12)–(15) show that in the patulous space of the standardized interval variables, \( \eta_f, \eta_T \) represent the shortest distance from the origin of coordinate to the invalidated surface. Hence, higher \( \eta_f, \eta_T \) values indicate better robustness of the vibration isolation to uncertain parameters, subsequently implying a high degree of security.

The solving expression of the non-probabilistic reliability index for the inherent frequency in the integrated active and passive system is

\[
\eta_f = \left( M_{z1}^l + M_{z1}^u \right) / \left( M_{z1}^u - M_{z1}^l \right) \tag{16}\]

where

\[
M_{z1}^l = \min_{\delta_f \in D} G(\delta_{f1}, \delta_{f2}, \cdots, \delta_{fn}) = 0; \]

\[
M_{z1}^u = \max_{\delta_f \in D} G(\delta_{f1}, \delta_{f2}, \cdots, \delta_{fn}) = 0. \]

The solving expression of the non-probabilistic reliability index for vibration transmissibility in the integrated active and passive system is

\[
\eta_T = \left( M_{z2}^l + M_{z2}^u \right) / \left( M_{z2}^u - M_{z2}^l \right) \tag{17}\]

where

\[
M_{z2}^l = \min_{\delta_T \in D} G(\delta_{T1}, \delta_{T2}, \cdots, \delta_{Tn}) = 0; \]

\[
M_{z2}^u = \max_{\delta_T \in D} G(\delta_{T1}, \delta_{T2}, \cdots, \delta_{Tn}) = 0. \]

Thus, the non-probabilistic reliability index of the integrated active and passive vibration isolation structural system is

\[
\eta_S = \min \{\eta_f, \eta_T\} \tag{18}\]

3. Non-Probabilistic Reliability Analysis of the Integrated Active and Passive WSVI Platform

The integrated active and passive WSVI platform that is studied in this dissertation is a new kind with a novel operating principle. The actuator element parallels the integrated active and passive platform, and is constructed on the basis of the passive vibration isolation platform. The operating principle of the vibration platform is shown in Fig. 1.

![Fig. 1. Passive and active vibration isolation integrated platform.](image)

### Table 1. Parameters of piezoelectric stack actuators.

| Parameter | Parameter value |
|-----------|-----------------|
| Nominal cross-section of piezoelectric ceramics | 7 × 7 mm |
| Nominal thickness of piezoelectric ceramics | 0.12 mm |
| Layer number of piezoelectric stack | 300 |
| Piezoelectric constant | 750 pC/N |
| Young’s modulus | 3.6 × 10¹¹ N/m² |

High reliability is required in practical launching. If adopting the vibrating active control, it needs state information on obtained tested structure and must adopt the simple control algorithm for vibration control. In practice, acquiring the acceleration signal is easy. Thus, the present work has adopted loading acceleration feedback for vibration active control, whose actuator element selects piezoelectric stacks as the actuating mechanism. Its parameters are shown in Table 1.

3.1. Integrated active and passive first order equivalent dynamic model

The first crosswise vibration of the WSVI system is its difficult point. Its movement is not an easy crosswise movement. Instead, it consists of crosswise translation and crosswise movement simultaneously, whose first-order simplified dynamic equation is

\[
\begin{bmatrix}
  m_{1y} & J_{30} & m_{2y} \\
  J_{30} & m_{2y} \\
  J_{20} & m_{2y}
\end{bmatrix}
\begin{bmatrix}
  \ddot{y}_1 \\
  \ddot{\theta}_1 \\
  \ddot{y}_2 \\
  \ddot{\theta}_2
\end{bmatrix}
+ \begin{bmatrix}
  k_1 & 0 & -k_1 & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 \\
  -k_1 & 0 & k_a + k_b + k_2 + k_3 + k_1 + jn_k_c & 0 & 0 \\
  0 & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
  y_1 \\
  \theta_1 \\
  y_2 \\
  \theta_2
\end{bmatrix}
= \begin{bmatrix}
  m_{2y} \left( f_a \dot{y} + f_b \dot{\theta} \right) \\
  \left( k_a + k_b + k_2 + k_3 + jn_k_c \right) y_a \\
  0
\end{bmatrix} \tag{19}
\]

In Eq. (19), \( m_{1y} \) represents the modal effective mass of the satellite crosswise first-stage movement; \( k_1 \) represents the corresponding crosswise stiffness; \( m_{2y} \) represents the
surplus modal effective mass of the satellite crosswise first-stage movement; \( k_2 \) represents the crosswise stiffness of the vibration isolator; \( k_{21} \) represents the stiffness of the viscoelasticity damper; \( \eta \) represents the damping dissipation factor of the viscoelasticity damper; \( J_{10} \) is equivalent to the modal effective mass of the satellite crosswise first-stage turn; \( f_a \) and \( f_b \) represent the operating forces that the piezoelectric pile provides; \( l \) represents the next radius of the conical shell; \( J_{20} \) is equivalent to the modal surplus effective mass of the satellite crosswise first-stage movement; \( k_a \) and \( k_b \) represent the crosswise effective stiffness of the piezoelectric pile; \( k_a = k_b \); \( y_1, \theta_1, y_2 \) and \( \theta_2 \) are corresponding boundary coordinates; and \( y_u \) represents the coordinate of the vibration isolation platform bottom.

\[
f_a = \frac{A_P Y_{33} d_{33}}{t} V - \frac{A_P Y_{33}}{nt} \Delta l
\]  
(20)

Adopting the loading acceleration feedback yields

\[
\begin{bmatrix}
    m_{1y} \\
    m_{2y}
\end{bmatrix}
= \begin{bmatrix}
    k_1 & 0 & -k_1 & 0 \\
    0 & 0 & 0 & 0 \\
    -k_1 & k_a + k_b + k_2 + k_z + k_1 + j\eta k_z & 0 & 0 \\
    0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
    y_1 \\
    \theta_1 \\
    y_2 \\
    \theta_2
\end{bmatrix}
+ \begin{bmatrix}
    \frac{2lA_P Y_{33} d_{33} K_P Z_P l_s}{t} - \frac{0.12 \times 10^{-6} \times 2lA_P Y_{33} K_P Z_P l_s}{nt} \\
    \frac{(k_a + k_b + k_2 + k_z + j\eta k_z) y_u}{0}
\end{bmatrix}
\begin{bmatrix}
    \ddot{y}_1 \\
    \ddot{\theta}_1 \\
    \ddot{y}_2 \\
    \ddot{\theta}_2
\end{bmatrix}
\]

(22)

Transforming the Eq. (22) gives

\[
\begin{bmatrix}
    m_{1y} \\
    m_{2y}
\end{bmatrix}
= \begin{bmatrix}
    k_1 & -k_1 \\
    -k_1 & k_a + k_b + k_2 + k_z + k_1 + j\eta k_z
\end{bmatrix}
\begin{bmatrix}
    y_1 \\
    y_2
\end{bmatrix}
+ \begin{bmatrix}
    0 \\
    (k_a + k_b + k_2 + k_z + j\eta k_z) y_u
\end{bmatrix}
\]

(23)

\[
\begin{bmatrix}
    m_{1y} \\
    m_{2y}
\end{bmatrix}
= \begin{bmatrix}
    \frac{2lA_P Y_{33} d_{33} K_P Z_P l_s}{t} - \frac{0.12 \times 10^{-6} \times 2lA_P Y_{33} K_P Z_P l_s}{nt} \\
    0
\end{bmatrix}
\begin{bmatrix}
    \ddot{y}_1 \\
    \ddot{\theta}_1 \\
    \ddot{y}_2 \\
    \ddot{\theta}_2
\end{bmatrix}
\]

(24)

Transforming Eq. (24) by the dimensionless change generates

In Eq. (21), \( t \) is the thickness of the piezoelectric patches, \( A_P \) is the transversal area of the piezoelectric patches, \( Y_{33} \) is Young’s modulus of the piezoelectric patches, \( d_{33} \) is the strain coefficient of the piezoelectric patches, \( h \) is the height from the satellite to the vibration isolation bottom, \( K_P \) is the loading feedback magnification coefficient, \( K_P = 150K_u \), \( K_u \) is the negative feedback gain coefficient, \( n \) is the layer number of the piezoelectric pile, \( Z_P \) is the conversion coefficient of the change from acceleration signal to voltage signal, and \( l_s \) is the upper radius of the conical shell. According to the displacement test result of the piezoelectric pile, the relationship between the voltage signal and piezoelectric pile displacement is \( h_{\text{biasing}} = 0.12 \times V \) (\( \mu \)m).

Substituting Eq. (21) into Eq. (19) yields...
\[ T_1 = \frac{Y_1}{Y_u} = \frac{\rho (\gamma^2 + \gamma_y^2 + j\eta \gamma_y^2)}{\rho (1 - \Omega^2)(\rho^2 + \gamma^2 + \gamma_y^2 + j\eta \gamma_y^2 - \Omega^2)} = \rho^3 \]  

(25)

In Eq. (25),

\[ \gamma = \omega_2/\omega_1, \quad \gamma_y = \omega_y/\omega_1, \quad \Omega = \omega/\omega_1, \quad \omega_1 = \sqrt{\frac{k_1}{m_{1y}}} \]

\[ \omega_2 = \sqrt{\frac{k_u + k_b + k_2}{m_{2y}}} \]

\[ \rho = \frac{m_{1y}}{m_{2y}}, \quad \omega_y = \sqrt{\frac{k_c}{m_{2y}}} \]

According to Eq. (24), the following can be obtained.

\[ Z_1 \theta_1 = Z_2 y_1 \]  

(26)

In Eq. (26),

\[ Z_1 = \sqrt{\left[ \frac{1}{J_{10}^2} - \frac{2I\rho Y_{33}d_{35}KbZ_P}{nt} - 0.12 \times 10^{-6} \times \frac{2I\rho Y_{33}KbZ_P}{nt} \right]^2} \]

\[ Z_2 = -\left( \frac{2I\rho Y_{33}d_{35}KbZ_P}{nt} - 0.12 \times 10^{-6} \times \frac{2I\rho Y_{33}KbZ_P}{nt} \right)^2 I \]

Substituting Eq. (26) into Eq. (23) and transforming it gives

\[ \begin{bmatrix} m_{1y}(Z_1/Z_2) & 0 \\ 0 & m_{2y} \end{bmatrix} \begin{bmatrix} \theta_1 \\ y_2 \end{bmatrix} + \begin{bmatrix} (Z_1/Z_2)k_1 & -k_1 \\ -(Z_1/Z_2)k_1 & k_u + k_b + k_2 + k_c + j\eta k_c \end{bmatrix} \begin{bmatrix} \theta_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} 0 \\ (k_u + k_b + k_2 + k_c + j\eta k_c) y_u \end{bmatrix} \]

(27)

In the same argument, transform Eq. (27) dimensionlessly, getting

\[ \begin{bmatrix} \rho \left( \frac{(Z_1/Z_2)}{\sqrt{Z_1/Z_2}} \right) & -\delta \rho_1 \omega_1 \omega_2 \\ \delta \rho_1 \omega_1 \omega_2 & \rho \left( \frac{(Z_1/Z_2)}{\sqrt{Z_1/Z_2}} \right) \end{bmatrix} \begin{bmatrix} \theta_1(s) \\ Y_u \end{bmatrix} = \begin{bmatrix} 0 \\ \rho \left( \frac{(Z_1/Z_2)}{\sqrt{Z_1/Z_2}} \right) \end{bmatrix} \]

(28)

Thus, according to Eq. (28),

\[ T_\theta = \frac{\theta_1(s)}{Y_u} = \frac{I_s \rho \omega_1^2 (\omega_2^2 + \omega_y^2 + j\eta \omega_y^2)}{(Z_1/Z_2) \rho \left( \omega_1^2 - \omega_2^2 \right) \left( \rho^2 \omega_2^2 + \omega_2^2 + \omega_y^2 + j\eta \omega_y^2 - \omega_1^2 \right) - \rho^4 \omega_1^4} \]  

(29)

Simplifying the equation further yields

\[ T_\theta = \frac{\theta_1(s)}{Y_u} = \frac{I_s \rho (\gamma^2 + \gamma_y^2 + j\eta \gamma_y^2)}{(Z_1/Z_2) \rho \left( 1 - \Omega^2 \right) \left( \rho^2 + \gamma^2 + \gamma_y^2 + j\eta \gamma_y^2 - \Omega^2 \right) - \rho^4} \]  

(30)

Thus, the crosswise vibration transmissibility obtained from the vibration isolator bottom to the satellite is

\[ T = \sqrt{T_1^2 + T_\theta^2} \]  

(31)

In estimating the accuracy of the equivalent model, the simulation test of the dynamic model accuracy is conducted using Eq. (31). The simulation results of the passive vibration isolation platform are given in Fig. 2. According to the maximum value of the vibration isolation system, the satellite top adopts the passive control, and the maximum voltage that the piezoelectric pile can withstand is 150 V. The maximum yield value of the controlling system that can be obtained is \( K_u = 7.5 \text{ V/(m·s}^2) \). Thus, choosing two inflated piezoelectric piles gives the yield value of \( K_u = 3 \text{ V/(m·s}^2) \). The operating condition that parallels the damper is conducted, comparing simulation and test runs. The simulation result is shown in Fig. 3.

Figure 3 shows that the equivalent simplified dynamic
3.2. Non-probabilistic analysis of the integrated active and passive platform vibration isolation system.

From the analysis above, the equivalent dynamic model can reveal the first-order vibration characters of the WSVI platform. Contrasting Figs. 2 and 3 shows that the simulation result of the integrated active and passive vibration isolation platform has a better vibration isolation effect compared with the passive platform, whose first-order vibration transmissibility is lower by 17%.

3.2. Non-probabilistic analysis of the integrated active and passive platform dynamic characteristics

In aerospace engineering, integrated active and passive controlling systems usually adopt simple controlling arithmetic and reserve a set of controlling systems. Compared with the controlling system, active controlling elements lose efficacy more easily. Their security and reliability may restrict the application of the integrated active and passive vibration isolation platform in aerospace engineering. Thus, focusing mainly on the ineffectiveness of the active controlling elements below, the current work focuses on non-probabilistic reliability analysis of the integrated active and passive WSVI platform dynamic characteristics to improve the security and reliability of the platform.

When the vibration isolator loses efficacy because of existing $q$ actuators in invalid controlling elements, the transmissibility is lower by 17%.

Fig. 2. Simulation and test results.

Fig. 3. Simulation result of passive control.

Table 2. Simulation correction of non-probabilistic reliability index of integrated passive and active vibration isolation system.

| $K_a$ | $f$ | $T$ | $\eta_{12}$ | $\eta_{21}$ | $\eta_{13}$ |
|-------|-----|-----|-------------|-------------|-------------|
| 1     | [42.01, 43] | [7.0069, 19.6706] | 1.0202 | -0.8421 | -0.8421 |
| 3     | [42.01, 43] | [6.5492, 7.158] | 1.0202 | 2.2852 | 1.0202 |
| 5     | [42.01, 43] | [6.5198, 7.0204] | 1.0202 | 2.9952 | 1.0202 |
| 7     | [42.01, 43] | [6.5118, 6.9853] | 1.0202 | 3.2239 | 1.0202 |

Operating force range of the actuators can be expressed as

$$f_z = [(2 - q)f_a, 2f_a] \quad (q = 1, 2) \quad (32)$$

Equation (19) can be transformed into

$$\begin{bmatrix}
    m_{1y} & J_{10} \\
    m_{2y} & J_{20}
\end{bmatrix}
\begin{bmatrix}
    \dot{y}_1 \\
    \dot{y}_2
\end{bmatrix}
+ \begin{bmatrix}
    k_1 & 0 & -k_1 & 0 \\
    0 & 0 & 0 & 0 \\
    -k_1 & 0 & k_a + k_b + k_2 + k_z + k_1 + j\eta k_z & 0 \\
    0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
    y_1 \\
    \theta_1 \\
    y_2 \\
    \theta_2
\end{bmatrix} = \begin{bmatrix}
    0 \\
    [(2 - q)f_a l, 2f_a l] \\
    (k_a + k_b + k_2 + k_z + j\eta k_z)y_a \\
    0
\end{bmatrix} \quad (33)$$

Through Eq. (33), when a single actuator loses efficacy, the inherent frequency variant range and vibration transmissibility variant range can be obtained. According to Eqs. (10), (11), (16) and (17), the non-probabilistic reliability analysis of the integrated active and passive WSVI platform could be conducted, and the simulation results obtained are given in Table 2.

According to the simulation results in Table 2, before and after invalidation, the vibration transmissibility of the vibration isolation system reduces with the increase of the transmissibility gain of the controlling system. When the transmissibility gain of the vibration isolation system is $K_a = 3$–7 V/(m·s$^{-2}$), the vibration isolation system has better vibration isolation effects, meeting the reliability demands and resisting the uncertainty of the external environment. If the transmissibility gain of the integrated active and passive vibration isolation system is $K_a = 1$ V/(m·s$^{-2}$), and when lost efficacy is worse than the passive vibration controlling efficacy, the vibration isolation affects the integrated active and passive vibration isolation system. The reliability index of the integrated active and passive structure system is at the minimum and does not meet the demands.

4. Non-Probabilistic Reliability Test of the Integrated Active and Passive Vibration Isolation Platform

The theoretical non-probabilistic reliability test of the in-
Integrated active and passive WSVI platform is conducted in order to test the accuracy of the non-probabilistic reliability analysis on the integrated active and passive WSVI vibration isolation platform. The experiment is conducted in the vibration platform (DC-2000), which is adopted by the dSPACE control system (dSPACE1104). And the control system is the RC-2000. The acceleration sensor is the piezoelectric type. The experiment is as shown in Fig. 4.

Based on the real-time control of dSPACE, the loading acceleration feedback control algorithm is programmed using the software Simulink, as shown in Fig. 5.

First, the vibration transmissibility testing curve of the passive vibration isolation platform is established. The specific experiment results are as shown in Fig. 6.

In conducting the non-probabilistic reliability study of the integrated active and passive vibration isolation system, four working conditions are set in the experiment for the actuator losing efficacy:

1. The transmission gain that the integrated active and passive WSVI system receives is $K_a = 1 \text{ V/(m-s}^2\text{)}$.
2. The transmission gain that the integrated active and passive WSVI system receives is $K_a = 3 \text{ V/(m-s}^2\text{)}$.
3. The transmission gain that the integrated active and passive WSVI system receives is $K_a = 5 \text{ V/(m-s}^2\text{)}$.
4. The transmission gain that the integrated active and passive WSVI system receives is $K_a = 7 \text{ V/(m-s}^2\text{)}$.

The experimental results are shown in Fig. 7. Figure 7 provides the figures in Table 3.

Table 3 shows that whether it is gaining or not, the active actuator of the integrated active and passive vibration WSVI system loses efficacy. The vibration transmissibility of vibration isolation reduces with the increase in transmission gain of the controlling system. When the transmission gain of the vibration system is $K_a = 1 \text{ V/(m-s}^2\text{)}$, the vibration isolation effects of the integrated active and passive vibration isolation system are worse than that of the passive vibration controlling system after the integrated active and passive vibration isolation system loses efficacy. When the transmission gain of the vibration system is $K_a = 3 \text{ V/(m-s}^2\text{)}$, vibration isolation effects are lower by 13%, compared with the passive vibration isolation platform. Thus, the accuracy of the theoretical analysis which is based on the result of Table 2 calculated by the Eq. (33) is verified.

According to Table 3, the non-probabilistic reliability index of the integrated active and passive WSVI system can be calculated, as shown in Table 4.

Table 4 shows that the non-probabilistic reliability index $\eta_T$ of the vibration transmissibility meets the reliability demands, which fall in the range of the transmission gain of $K_a = 3-7 \text{ V/(m-s}^2\text{)}$. Moreover, $\eta_T$ can resist the uncertainty of the external environment. The non-probabilistic
reliability index \( \eta_f = 1.0408 \) of the first-order inherent frequency in the integrated active and passive vibration isolation system meets the reliability demands. The non-probabilistic reliability index \( \eta_f \) of the vibration isolation system meets the reliability demands in the range of the transmission gain of \( K_a = 3 \rightarrow 7 \text{ V/(m}\cdot\text{s}^2) \). When the transmission gain is \( K_a = 1 \text{ V/(m}\cdot\text{s}^2) \), vibration isolation may be reliable or invalid, which does not meet the demand. The analysis above indicates a high tendency for the accuracy of the theoretical analysis. The transmission gain of the integrated active and passive WSVI system meets the satellite launch demands and has a stable system in the range of \( K_a = 3 \rightarrow 7 \text{ V/(m}\cdot\text{s}^2) \).

5. Conclusion

The integrated active and passive WSVI technology was able to enhance the low-frequency dynamic environment in the process of satellite launching. In this study, non-probabilistic reliable methods were adopted to establish the non-probabilistic reliability model of the integrated active and passive uncertain vibration isolation system, and then the first-order equivalent dynamic model of the integrated active and passive vibration isolation system was established. In testing the efficacy of the model, the equivalent model was found capable of accurately addressing the first-order dynamic character of the WSVI. The proposed model was used to conduct the non-probabilistic reliability simulation of the new type of integrated active and passive WSVI platform. The simulation results revealed that the vibration isolation platform could resist the uncertainty in the certain transmission gain range and demonstrated excel-
lent vibration isolation. Further, the vibration isolation platform completed the design of the controlling system. The non-probabilistic reliability tests of the integrated active and passive WSVI platform were conducted theoretically. The experimental results of the test of accuracy of the non-probabilistic reliability simulation analysis tendency showed that the accuracy of the theoretical analysis is sufficient. The reliability and security of the integrated active and passive WSVI platform launch were likewise enhanced.

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