Passive impact/vibration control and isolation performance optimization for space noncooperative target capture

Chong Sun\(^1,2\) and Xiaolei Hou\(^3\)

Abstract

On-orbit capture is an important technique for the space debris removal, refueling, or malfunction satellite repairing. While due to the uncertainty of the motion parameters of the space noncooperative target, the impact between the capture device and the noncooperative target during the capturing process is inevitable, which may bring strong vibration perturbation to the base satellite, and potentially alter the position and the attitude of the servicing spacecraft, or even cause failure of on-orbit tasks. This article presents a new and alternative method for passive suppression of spacecraft impact and perturbation during noncooperative spacecraft capture. The passive device based on bioinspired X-shape is installed between the satellite and the capture device. In the capture process, nonlinear damping of the passive isolation structure can significantly reduce impact/vibration perturbation. For performance analysis, dynamic equations of the isolation system are established. Based on which, the relationship between structure parameters and isolation performance is systematically analyzed. Experiments are conducted for verification of the effectiveness of the proposed method. Moreover, an optimal process using the non-dominated sorting genetic algorithm II optimization method is developed to minimize impact/vibration perturbation effect, and optimal solutions can provide useful reference for the passive isolation system design.

Keywords

Bioinspired X-shape, noncooperative spacecraft capture, impact perturbation control, passive suppression, nonlinear damping

Date received: 23 July 2019; accepted: 24 October 2019

Introduction

On-orbit servicing using space robots has been proposed for many applications including inspection, assembly, and retrieval of malfunctioning satellites or orbital debris in recent years, and it will become routine work in future space operation. For the on-orbit servicing missions for the noncooperative space target parameters or dynamics parameters can not be obtained, like the space debris removal mission, because the parameters of the motion of the them, the mass, the rotation angular speed are hardly to obtain.\(^1,2\) A capturing operation consists of three specific phases: the pre-capture phase, the capture phase, and the post-capture phase. For noncooperative targets especially tumbling

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ones, it is difficult to obtain accurate motion/dynamics states. In addition, there are errors and time delay in control system of on-orbit servicing. Thus, in capture phase, the impact between the space capture device and the noncooperative target is inevitable, which can result in undesired structure vibration of flexible links or drifting movement for the satellite platform, or even cause damage to the onboard instruments of the servicing spacecraft. Thus, the impact/vibration perturbation control is essential in the capture process.

For the impact/vibration perturbation problem in capturing operations missions, there are several different types, including the active control, the passive isolation, and the semi-active control. Active system is very attractive and powerful, as it can use sensors and external actuators to provide feedback signals and control force. There are many works that have been published on this subject. Shibli et al. studied a unified control-oriented modeling of a free-flying space robot to deal with kinematics, constraints, and dynamics of a free-flying space robot interacting with a target satellite. In the study by Carrella et al., a composite controller combining disturbance observer-based control with proportional differential control (PD) control for the flexible spacecraft attitude stability has been investigated. In the studies by Geng et al., the biases in the model that cause degradation of tracking performance are studied, and a Markovian jump ionospheric bias model is presented to transform the model uncertainties to the parameter randomness. Then an optimal linear joint estimator is developed to minimize the mean-squared error sense. Although these active control approaches can perform well in particular vibration control problems, the associated problems are also obvious, such as instability due to spillover effect, and high-power demands strictly limit space applications. In the studies by Robertson et al. and Liu et al., a semi-active vibration suppression system was developed to avoid disadvantages of active systems. The semi-active vibration suppression system does not require any external energy to suppress vibrations but does require external controllers, sensors, and other devices, which consume a substantial amount of electrical energy. Passive isolation systems for impact/vibration perturbation control isolation have been widely applied for space applications, as dynamic energy can be dissipated by structural damping and the friction of passive system. Advantages of passive systems lie on high reliability, simple construction, easy maintenance, and independence of external power. In the study by Casciati et al., the performance of spring-mass-damper (SMD) for repetitive impact is studied, and it showed that the increase of linear damping in SMD system can result in smaller resonant amplitude, while the smaller resonate amplitude may cause worse isolation performance beyond resonant range. In the studies by Onoda et al. and Makihara et al., quasi-zero-stiffness isolation, which can realize negative, zero stiffness was studied, but complex nonlinear behavior may be instable in practice.

In recent years, due to low cost and high reliability, passive impact/vibration isolation methods based on bioinspired X-shaped structure were proposed and studied. In the X-shaped structure, nonlinear damping and stiffness induced by geometric relationship of rod, rotation joints, and spring were exploited to isolate vibration perturbation. It demonstrated that the X-shaped structure can perform good vibration due to the nonlinear damping and stiffness which can be designed through changing structure parameters. In the studies by Dai et al., the X-shaped structure is applied in the post-capture vibration suppression, and numerical simulations are provided to demonstrate validation of the proposed isolation structure.

Based on the feasibility investigation of previous results, in this paper, a passive impact/vibration suppression system is proposed and established for capturing noncooperative space targets, and experiments of the impact/vibration isolation systems are provided to validate performance. Based on the relationship between structure parameters and isolation performance, an optimization process is provided to optimize structure parameter and improve impact/vibration isolation performance. The main contributions of this article include the following: (1) A passive impact/vibration suppression system is developed and its dynamic equations of passive isolation structures are systematically investigated for space noncooperative target capture. (2) Prototype of the passive isolation system is developed, and experiments of position/attitude perturbation isolation are conducted for validation. It is shown that experiments results are consistent with that obtained with the numerical approach. (3) Based on analysis of relationship between structure parameters and the suppression performance, an optimization process is proposed to improve vibration isolation performance of the system. The optimization results can provide useful reference for the design of the passive isolation system.

The rest of the article is organized as follows: In the second section, the geometric relationship of passive isolation structures is given, and dynamic equations of the two-degree passive isolation system are developed. Based on these, the relationship between structure parameters and passive suppression effect is analyzed. In the third section, ground experiments of passive isolation are developed to verify the proposed isolation structure systems. Then in the fourth section, an impact/vibration perturbation isolation optimization process is proposed, and structure parameters are optimized to minimize perturbation displacement, velocity, and maximal acceleration. Finally, conclusions are given in the fifth section.

Modeling of the passive impact/vibration isolation system

Problem statement

As motion parameters of the space noncooperative target cannot be obtained accurately in capture, the perturbation
between the manipulator and the space target is inevitable. The large impact or vibration perturbation caused by the spacecraft capture can seriously affect the stability and security of the satellite base, which may result in failure of on-orbit task. For space noncooperative target capture, assuming $H_v$ is the angular velocity inertia matrix of the base, $H_m$ is the manipulator inertia matrix, and $H_{v φ}$ and $H_{ω φ}$ are the linear and angular coupling inertia matrix, the force impulse between the target and the robotic hand can be expressed as equation (1), which is related to relative velocity $v_r$, collision direction $N$, and restitute coefficient $e$ between kinematic and dynamic parameters

$$F_c = -(1 + e)\frac{v_r}{N^T(D_m + D_t)N}$$

(1)

In case that the noncooperative target has flexible appendages like solar sailing panel, the impact perturbation in capture can result in vibration perturbation. In this article, based on the study of bioinspired passive isolation structure in Wu et al., a passive isolation structure is developed. The space noncooperative target capture using the passive impact/isolation is shown in Figure 1. The passive isolation system is installed between the capture mechanism and the satellite base. In the noncooperative target capture, the impact/vibration perturbation is transferred from the capture mechanism to the passive isolation structure, and then affect the state of satellite base.

Modeling of the passive impact/vibration isolation system

The schematic diagram of the two-degree perturbation isolation structure is shown in Figure 2, and $F(t)$ is the perturbation force, $m_1$ is the mass of the target spacecraft, and $m_2$ is the mass of the base. Same as six-degree-of-freedom passive Stewart platform in the study of Bian and Jing, there are $n$ layers of X-shaped structure in perturbation suppression system, and $y_1$ and $y_2$ represent displacements of $m_1$ and $m_2$.

The constrained coordinates $x, \theta_1$ are employed in dynamical modeling as shown in Figure 2, where $x$ is the vertical displacement of connecting joint A and $\theta_1$ is the angle of rotation of rod A. $h = (y_2 - y_1)/2n$ is the horizontal displacement of point A, which is used in constructing geometric relations, $l$ is the length of rod, and $\theta_0$ is the initial assembly angle. In the proposed isolation structure, two springs in the vertical and horizontal directions are installed to increase the structure’s stiffness for the space application.

From Figure 3, geometrical relation of variables $l, x, h, \theta_0, \theta_1$ can be obtained as

$$\begin{align*}
h &= (y_1 - y_2)/n \\
l \sin \theta_0 - h &= l \sin (\theta_0 - \theta_1) \\
l \cos \theta_0 + x &= l \cos (\theta_0 - \theta_1)
\end{align*}$$

(2)

Then it has

$$\begin{align*}
x &= \sqrt{l^2 - (l \sin \theta_0 - (y_1 - y_2)/n)^2} - l \cos \theta_0 \\
h &= (y_1 - y_2)/n
\end{align*}$$

(3)

The Lagrange’s equations are used to formulate nonlinear dynamics system. The kinetic energy of impact suppression system is

$$T = \frac{1}{2} m_1 \dot{y}_1^2 + \frac{1}{2} m_2 \dot{y}_2^2$$

(4)

And the potential energy of the whole system can be written as

$$V = \frac{1}{2} k_1 (x_0 + 2x)^2 + \frac{1}{2} k_2 \left(\frac{y_1 - y_2}{n}\right)^2 + \frac{1}{2} k_b (x_b + y_2)^2$$

(5)

Then the whole energy is

$$L = T - V = \frac{1}{2} m_1 \dot{y}_1^2 + \frac{1}{2} m_2 \dot{y}_2^2 - \frac{1}{2} k_1 (x_0 + 2x)^2 - \frac{1}{2} k_2 \left(\frac{y_1 - y_2}{n}\right)^2 - \frac{1}{2} k_b (x_b + y_2)^2$$

(6)

where $x_0$ and $x_b$ are elongation of spring $k_1$ and compression of spring $k_2$ in initial state, respectively. It is assumed...
\[
\delta W = -2n_c \dot{\theta}_1 \delta \dot{\theta}_1 + C_d (y_2 - y_1)(\delta y_1 - \delta y_2) + F(t) \delta y_1
\]

\[
= Q_1 \delta y_1 + Q_2 \delta y_2
\]

\[
= \left[ -2n_c \dot{\theta}_1 \frac{\partial \dot{\theta}_1}{\partial y_1} + C_d (y_2 - y_1) + F(t) \right] \delta y_1
\]

\[
+ \left[ -2n_c \dot{\theta}_1 \frac{\partial \dot{\theta}_1}{\partial y_1} + C_d (\dot{y}_1 - \dot{y}_2) \right] \delta y_2
\]

The equations of motion of present system under external forces can be established by Lagrange’s equations

\[
\frac{d}{dt} \left( \frac{\partial L}{\partial \dot{y}_1} \right) - \left( \frac{\partial L}{\partial y_1} \right) = Q_i
\]

Then dynamic equation can be obtained as

\[
\begin{aligned}
\dot{y}_1 &= \frac{\frac{m_1 \dot{y}_1 + 2k_1(x_0 + 2x)}{n} - k_2\left(y_0 - \frac{\frac{y_1 - y_2}{2n}}{n}\right)^2 - \frac{m_2 \dot{y}_2 + 2k_1(x_0 + 2x)}{n} + k_1(x_0 + 2x)}{n} + \frac{k_2\left(y_0 - \frac{\frac{y_1 - y_2}{2n}}{n}\right)^2}{n} - n_c \dot{\theta}_2 \frac{1}{n} \left( \frac{\frac{y_1 - y_2}{2n}}{n} \right)^2}{= 0}
\end{aligned}
\]

Then it has

\[
\begin{aligned}
\dot{y}_1 &= \frac{\frac{2k_1 l \cos \theta_0 \left( l \sin \theta_0 - \frac{\frac{y_1 - y_2}{2n}}{n}\right)}{n} - k_2\left(y_0 - \frac{\frac{y_1 - y_2}{2n}}{n}\right)^2}{\left( \frac{\frac{y_1 - y_2}{2n}}{n} \right)^2} + \frac{\frac{n_c}{n^2} \left( \frac{\frac{y_1 - y_2}{2n}}{n} \right)^2 + C_d}{\left( \frac{\frac{y_1 - y_2}{2n}}{n} \right)^2} \left( \frac{\frac{y_1 - y_2}{2n}}{n} \right)^2}{= 0}
\end{aligned}
\]

\[
\begin{aligned}
\dot{y}_2 &= \frac{\frac{2k_1 l \cos \theta_0 \left( l \sin \theta_0 - \frac{\frac{y_1 - y_2}{2n}}{n}\right)}{n} - k_2\left(y_0 - \frac{\frac{y_1 - y_2}{2n}}{n}\right)^2}{\left( \frac{\frac{y_1 - y_2}{2n}}{n} \right)^2} + \frac{\frac{n_c}{n^2} \left( \frac{\frac{y_1 - y_2}{2n}}{n} \right)^2 + C_d}{\left( \frac{\frac{y_1 - y_2}{2n}}{n} \right)^2} \left( \frac{\frac{y_1 - y_2}{2n}}{n} \right)^2}{= 0}
\end{aligned}
\]
Using Taylor expansion series, this equation can be transformed as

\[
\begin{align*}
    &\left\{m_1\ddot{y}_1 + (\lambda_0 + \lambda_1(y_1 - y_2) + \lambda_2(y_1 - y_2)^2 + \lambda_3(y_1 - y_2)^3)(y_1 - \dot{y}_2) + \eta_1(y_1 - y_2) + \eta_2(y_1 - y_2)^2 + \eta_3(y_1 - y_2)^3 + \eta_4(y_1 - y_2)^4\right\} = F(t) \\
    &m_2\ddot{y}_2 + (\lambda_0 + \lambda_1(y_1 - y_2) + \lambda_2(y_1 - y_2)^2 + \lambda_3(y_1 - y_2)^3)(y_1 - y_2) - \eta_1(y_1 - y_2)^2 - \eta_3(y_1 - y_2)^3 - \eta_4(y_1 - y_2)^4 = 0
\end{align*}
\]

where

\[
\begin{align*}
    \lambda_0 &= \frac{n_c}{2n^3}\sec^2\theta_0 + C_d \\
    \lambda_1 &= -\frac{n_c}{2n^3}\tan\theta_0\sec^3\theta_0 \\
    \lambda_2 &= \frac{n_c}{8n^4}\left(\sec^4\theta_0 + 3\tan^2\theta_0\sec^4\theta_0\right) \\
    \lambda_3 &= \frac{n_c}{4n^4}\left(\tan\theta_0\sec^7\theta_0 + \tan^3\theta_0\sec^5\theta_0\right) \\
    \eta_1 &= k_1\frac{1}{n^2}(\sec^2\theta - 1) + \frac{k_2}{n^2}(y_2 - y_1) \\
    \eta_2 &= -\frac{3k_1}{4n^3}\sec^3\theta_0\tan\theta_0 \\
    \eta_3 &= \frac{k_1}{8n^4}\sec^6\theta_0(2\cos2\theta_0 - 3) \\
    \eta_4 &= -\frac{k_1}{32n^4}\sec^8\theta_0(9\sin\theta_0 - \sin3\theta_0)
\end{align*}
\]

### Impact/vibration suppression

In this section, taken example of the passive isolation, the relationship between isolation system parameters and the isolation performance is studied and analyzed in case of the impact perturbation and the vibration perturbation.

### Impact perturbation

In case of the impact isolation for the noncooperative spacecraft, the external force \(F(t)\) in equation (10) is zero, and the impact effect for impulse acting on system can be converted as the velocity of front mass in system. The aim of the whole system is to minimize perturbation effect, including the maximum acceleration, the maximum velocity, and the displacement of back mass. In case of the vibration isolation, displacement transmissibility is denoted as \(T_d = \frac{\Delta y}{\Delta x}\), which means the ratio between the vibration amplitude of the front mass and that of the back mass. The aim of this study is to minimize the displacement transmissibility, velocity, and maximum acceleration. In numerical simulation, the initial state of X-shaped structure is chosen as springs are undeformed, and parameters of system are set as \(m_1 = 10, m_2 = 50, k_1 = 1200, k_2 = 800, \theta = 45\text{deg}, l = 0.25, C_d = 0.1, c = 0.2, n = 2.\) In this case, Runge-Kutta (RK4) method is employed to numerically integrate governing equations. As impulsive force acted on structure, effect of impulsive acting on front mass can be converted into system’s initial states. Then the displacement, the velocity, and the maximum acceleration of the back mass are calculated. The relationship between parameters of the structure and the impact isolation effect (position, velocity, and acceleration of the back mass) is analyzed. In this simulation case, the stiffness is set as \(k_1 = 800 \text{N/m}, 1000 \text{N/m}, 1200 \text{N/m}.\) The effect of stiffness parameter \(k_1\) to impact isolation effect is shown in Figure 4. It shows that the position displacement is in the range of \([-0.04, 0.04]\), the velocity is in the range of \([0, 0.1]\), and the acceleration is in the range of \([-0.3, 0.3]\). It demonstrates that the magnitude of displacement decreases slightly with the increase in parameter \(k_1\), and decay time also decreases. Figure 5 shows the influence of stiffness parameter \(k_2\) to impact isolation effect. The stiffness parameter is set as \(k_2 = 800 \text{N/m}, 600 \text{N/m}, 400 \text{N/m}.\) It shows that the magnitude of the displacement, the velocity, and the acceleration decrease slightly with the increase in parameter \(k_1\), and the decay time also reduced. Thus, it demonstrates that the increase in stiffness parameters can be slightly beneficial for the impact isolation performance.

The influence of the rod length for the impact isolation performance is shown in Figure 6, the rod length is set as \(l = 0.15 \text{m}, 0.2 \text{m}, 0.25 \text{m}.\) It shows that in case of \(l = 0.15 \text{m}, 0.2 \text{m}, 0.25 \text{m},\) the maximum displacement is \(\Delta y = 0.031 \text{m}, 0.0275 \text{m}, 0.0212 \text{m},\) and the decay time is \(t_s = 3.17 \text{s}, 5.57 \text{s}, 8.79 \text{s};\) the maximum velocity is \(v_{\text{max}} = 0.08 \text{m/s}, 0.09 \text{m/s}, 0.09378 \text{m/s},\) and the decay time is \(t_s = 2.96 \text{s}, 5.37 \text{s}, 8.59 \text{s};\) the maximum acceleration is \(a_{\text{max}} = 0.307 \text{m/s}^2, 0.329 \text{m/s}^2, 0.34 \text{m/s}^2,\) and the decay time is \(t_s = 3.47 \text{s}, 5.93 \text{s}, 8.8 \text{s},\) respectively. From the simulation results, it can find that with the increase in rod length, the displacement, velocity, and acceleration increase significantly, and the decay time also reduces. Thus, it can obtain conclusion that the decrease in rod length can be beneficial for the impact isolation effect.
The effects of rotation friction are shown in Figure 7. The rotation friction coefficients are set as $c = 0.1, 0.2, 0.3$. The simulation results show the maximum displacement of the back mass is $D_y = 0.0386 \text{ m}$, $0.0373 \text{ m}$, $0.0362 \text{ m}$, and the decay time is $t_s = 1.72 \text{ s}$, $8.79 \text{ s}$, $5.96 \text{ s}$; the maximum velocity is $v_{\text{max}} = 0.096 \text{ m/s}$, $0.0937 \text{ m/s}$, $0.0911 \text{ m/s}$, and the corresponding decay time is $t_s = 17.09 \text{ s}$, $8.59 \text{ s}$, $5.75 \text{ s}$; the maximum acceleration is $a_{\text{max}} = 0.37 \text{ m/s}^2$, $0.34 \text{ m/s}^2$, $0.33 \text{ m/s}^2$, and the decay time is $t_s = 17.29 \text{ s}$, $8.8 \text{ s}$, $5.96 \text{ s}$. The simulation results demonstrate that with the increase in rotation friction, the displacement, the velocity, and the acceleration can significantly reduce, which is beneficial to the impact isolation performance.

The curves of the displacement, the velocity, and the acceleration for different value of layer number can be found in Figure 8. The layer number is set as $n = 1, 2, 3$, and the maximum displacement is $D_y = 0.0185 \text{ m}$, $0.0373 \text{ m}$, $0.0562 \text{ m}$, its decay time is $t_s = 3.81 \text{ s}$, $8.79 \text{ s}$, $13.7 \text{ s}$; the maximum velocity is $v_{\text{max}} = 0.09 \text{ m/s}$, $0.0937 \text{ m/s}$, $0.0938 \text{ m/s}$, its decay time is $t_s = 3.88 \text{ s}$, $8.59 \text{ s}$, $13.47 \text{ s}$; the maximum acceleration is $a_{\text{max}} = 0.68 \text{ m/s}^2$, $0.34 \text{ m/s}^2$, $0.22 \text{ m/s}^2$, and its decay time is $t_s = 3.99 \text{ s}$, $8.8 \text{ s}$, $13.7 \text{ s}$. It can be find that with the increase of the layer number, the displacement increases significantly, but the velocity does not be notably influenced by layer number. With the increase in layer number, the acceleration can be significantly reduced.

The influence of the assembly angle for impact isolation performance is provided in Figure 9. The assembly angle is set as $\theta = \pi/6, \pi/4, \pi/3$, the maximum displacement
is $\Delta y = 0.0481$ m, $0.0373$ m, $0.0250$ m, the decay time is $t_d = 12.9$ s, $8.79$ s, $4.31$ s; the maximum velocity is $v_{\text{max}} = 0.0944$ m/s, $0.093$ m/s, $0.092$ m/s, its decay time is $t_v = 12.6$ s, $8.59$ s, $4.42$ s; the maximum acceleration is $a_{\text{max}} = 0.272$ m/s$^2$, $0.343$ m/s$^2$, $0.487$ m/s$^2$, and its decay time is $t_a = 13.4$ s, $8.8$ s, $4.56$ s. It shows that with the increase in assembly angle, the displacement decreases steadily, and the velocity decreases slightly; the acceleration can be significantly increased. The decay time of the whole system is decreased rapidly with the increase in assembly angle.

**Vibration isolation**

The vibration isolation structure is set as $m_1 = 2$, $m_2 = 100$, $k_1 = 1000$, $k_2 = 800$, $\theta_0 = \pi/6$, $n = 2$, $l = 0.2$, $c_d = 0.1$, $c = 0.2$. The influence of stiffness for maximum amplitude and displacement transmissibility are shown in Figures 10 and 11. The range of frequency is set as $\omega \in [0, 20]$; and stiffness is set as $k_1 = 1000$N/m, $2000$N/m, $3000$N/m; $k_2 = 400$N/m, $600$N/m, $800$N/m. The amplitude versus excitation frequency is shown in Figures 12(a) and 13(a). The effect of stiffness for displacement transmissibility is shown in Figures 12(b) and 13(b). For $k_1$, the maximum amplitude is $0.0323$, $0.0278$, $0.0257$, respectively, and the corresponding frequency is $\omega = 7.7$, $8.9$, $9.7$, respectively. The maximum displacement transmissibility is $55.54$, $59.73$, $72.51$, respectively. For $k_2$, the maximum amplitude is $0.041$, $0.035$, $0.032$, respectively, and the corresponding frequency is $\omega = 6.4$, $7.2$, $7.9$, respectively. The maximum amplitude is $0.038$, $0.033$, $0.03$, respectively. The simulation results demonstrate that the increase in stiffness can decrease the maximum displacement, but does not notably influence the displacement transmissibility.

The influence of rotation friction coefficients for the maximum amplitude and the displacement transmissibility are shown in Figure 12. The rotation friction coefficients are set as $c = 0.1$, $0.2$, $0.3$, respectively, and the amplitude versus excitation frequency is shown in Figure 14(a). It is found that in the range of $\omega \in [0, 20]$, the maximum

![Figure 6](image6.png)

Figure 6. The effect of rod length (a) position displacement, (b) the velocity, (c) the acceleration.

![Figure 7](image7.png)

Figure 7. The effect of rotation friction coefficients (a) position displacement, (b) the velocity, (c) the acceleration.
amplitude is $0.063, 0.031, 0.021$, respectively, and the maximum displacement transmissibility is $63.18, 69.18, 75.28$, respectively. It is found that with the increase in rotation friction coefficients, the maximum displacement decreases significantly, and the displacement transmissibility increases significantly.

The effect of the rod length for the maximum amplitude and the displacement transmissibility is shown in Figure 13. The rod length is set as $l = 0.15, 0.2, 0.25$, respectively. The maximum displacement is $0.012, 0.021, 0.033$, respectively, and the displacement transmissibility is $53.19, 63.18, 70.17$, respectively. The simulation results show that the maximum amplitude decreases significantly with the increase in rod length, while the displacement transmissibility increases notably. It demonstrates that the increase in rod length can be beneficial for the vibration isolation.

The influence of layer number for maximum amplitude and displacement transmissibility are shown in Figure 14. The layer number is set as $n = 1, 2, 3$, and the amplitude versus excitation frequency is shown in Figure 14(a). It is found that in the range of frequency $\omega \in [0, 20]$, the maximum amplitude is $0.0067, 0.031, 0.077$, respectively. With the increase in layer number, the maximum displacement decreases significantly. The effect of layer number for displacement transmissibility is shown in Figure 14(b). It is found that the maximum displacement transmissibility is $60.10, 69.07, 72.36$. The simulation results demonstrate...
that the increase in layer number can notably improve the displacement transmissibility.

The curves of effect of assembly angle for maximum amplitude and displacement transmissibility are shown in Figure 15. The assembly angle in three cases is set as \( \theta_0 = \pi/6, \pi/4, \pi/3 \) respectively, and the curve of the amplitude versus excitation frequency is shown in Figure 15 (a), where it can be found that in the range of
frequency \( \omega \in [0, 20] \), the maximum amplitude is 0.0310, 0.0160, 0.0554, and the corresponding frequency is 7.5, 9.8, 14.3. With the increase in assembly angle, the maximum displacement decreases notably. The effect of assembly angle for the displacement transmissibility is shown in Figure 15(b), where it can be found that the maximum displacement transmissibility is 70.20, 68.50, 62.36. The simulation results demonstrate that the assembly can significantly influence the displacement transmissibility.
In sum, from the simulation results, it is found that, for both of the impact case and the vibration case, the isolation performance is significantly influenced by the structure parameters, like the stiffness parameter, the layer number, the rod length, and the rod friction of the system. The simulation results demonstrate that the relationship between these structure parameters and the isolation performance is highly nonlinear. From equation (9), it can be found that, in case of impact $F(t) = 0$, the initial impact impulse in capture process is transformed as the initial velocity of the mass; for case of vibration $F(t) \neq 0$, then through RK4 algorithm, the solution can be obtained. The simulation results show that the external periodic perturbation can result in periodic disturbance, and the displacement transmissibility is determined by these structure parameters, namely the damping of the isolation system. The main reason is that these structure parameters effect the damping of the isolation system. For case of the large damping, the displacement is small while the acceleration is large; for case of small damping, the displacement is large but the impact acceleration is small. Through adjusting the structure parameters, the damping of the system is changed, and results in different isolation performance. Thus, the isolation performance can be optimized through the parameter selection for the space noncooperative target capture.

**Experiments on impact perturbation**

In this section, to verify the efficiency of the proposed method for both the impact isolation and the vibration isolation, experiments of the position isolation performance are provided using the two-degree passive isolation system.

To validate the performance of the proposed impact/vibration isolation system, a scaled physical model was built, in Aerospace Flight and Dynamical Laboratory at Northwestern Polytechnic University, as shown in Figure 16. The schematic of the isolation system shows that the isolation structure is installed between the front and the behind platforms to isolate impact/vibration that transforms from the front platform to the back platform. The front platform represents capture mechanism of the satellite, and the behind platform represents the satellite base.

In experiment equipment, the front mass, the back mass, and the isolation system can slide on smooth parallel bars. As the friction is very small and can be ignored, the whole system can be utilized as simplification of the two-degree of spacecraft impact/vibration isolation modeling. In this experiment simulation section, structure parameters are chosen as $\theta_0 = \pi/4$, $l = 0.25$m, $n = 3$, $c = 0.2$, $C_d = 0.05$; and $m_1 = 0.65$kg, $m_2 = 1.6$kg, $k_1 = 100$N/m, $k_2 = 80$N/m. These parameters values given above are fixed as reference values. In case of the impact isolation experiment, the printed circuit board (PCB) accelerometer is attached on the front mass and back mass. The hammer is utilized to generate impact to the front mass, and the impact signal is transferred from the hammer to data acquisition through a fiber-optic cable, as shown in Figure 17. In experiment, the impact effect is transferred from the front mass to the back mass, and the acceleration of two masses is recorded using the data acquisition. The computer is linked with the data acquisition, and the software is applied to analyze the data of the impact isolation experiment.

The numerical and experiment simulation results are shown in Figures 18 to 20. From Figure 18, it is shown that the system keeps stable after 0.84 s. The maximum relative displacement is about 0.015 m, and the final relative displacement is zero using the numerical simulation result; while experiment simulation results show that the displacement did not change after 1.32 s, the maximum relative displacement reaches to 0.040 m, and the average final relative displacement is 0.004 m. For velocity, the maximum velocity using the numerical approach is about...
Performance optimization

Optimization problem statement

For the space noncooperative target capture mission, the displacement, the velocity, and the acceleration of the servicing spacecraft can be regarded as indexes of impact/vibration isolation performance. From the second and third sections, it can be found that the geometric parameters, stiffness, friction coefficients, and the layer number of the isolation structure can significantly influence the isolation performance. In this section, an optimization program is developed to minimize the impact/vibration perturbation. Considering the indexes of the isolation performance as the optimal targets, then the isolation performance optimization problem can be converted as a multi-objective optimization problem (MOP). A MOP can be stated as follows

\[
\text{Minimize } F(x) = (f_1(x), \ldots, f_m(x))
\]

Subject to \( x \in \Omega \)

where \( \Omega \) is the variable space, \( \mathbb{R}^m \) is the objective space, and \( F : \Omega \rightarrow \mathbb{R}^m \) consists \( m \) real-valued objective functions. Let \( u = (u_1, \ldots, u_m), v = (v_1, \ldots, v_m) \in \mathbb{R}^m \) be two vectors, \( u \) is said to dominate \( v \) if \( u_i \leq v_i \) for all \( i = 1, \ldots, m \), and \( u \neq v \). A point \( x^* \in \Omega \) is called Pareto optimal if there is no \( x \in \Omega \) such that \( F(x) \) dominates \( F(x^*) \). The set of all the Pareto optimal points is called the Pareto set.

Optimization process and results analysis

As stated in the “Optimization problem statement” section, three indexes including position displacement, velocity, and acceleration of capture satellite are set as objects of optimization targets. The isolation system parameters, like stiffness, rod length, initial assembly angle, friction coefficients, are set as optimal variables. In this section, non-dominated sorting genetic algorithm (NSGA) is applied for the impact/vibration isolation performance problem. The detailed algorithm flow is provided as follows:

Step 1: Select an initial population randomly from the set: \( x_1, x_2, x_3, x_4 \) by uniformly randomly sampling form \( \Omega = \{k_1, k_1'; k_2, k_2'; n_1, n_1'; l_1, l_1'; \theta_1, \theta_1'\} \).

Step 2: Calculate if these variables can satisfy boundary constraints.
Step 3: Initialize $z^1 = (z_1, z_2, ..., z_m)$, $m_1 < N$ by setting $z^1 = \min_{i \leq N} f_j(\Delta y, v, a)$, where $\Delta y$ is maximum position displacement, $v$ is maximum velocity, and $a$ is maximum acceleration of capture satellite. Record $z^i (i = 1)$ as a non-dominated sorting. Then remove this non-dominated sorting, and sort the left population until all population are ranged.

Step 4: Set $P_i = \{z^1, z^2, ..., z^{i+1}\}$ as a new population. If the number of the population is $N$, then go to step 2, else calculate the crowding degree of the new population, and add the largest crowding degree into new population, until the number reaches $N$. The crowding degree is defined as $c_m = \sum_{j=1}^{m} \left| f_j^i - f_j^{i-1} \right|$. If $i \leq N$, repeat step 4.

Step 5: Generate subpopulation using GA cross-variation algorithm.

Step 6: Form population and subpopulation as a new population, and return to step 2. If the evolution number satisfies the stopping criterion, record the best range.

Here an impact/vibration perturbation isolation structure system optimization problem is provided. As stated in the “Optimization problem statement” section, in space target capture, the relative velocity $v_r$ is set as $[-0.2, 0.2]m/s$, the collision direction $N$ is in the range of $\theta_n \in [-\pi/2, \pi/2]$, and the restitute coefficient $e$ is in the range of $[0, 1]$, thus through equation (10), the maximum impact perturbation and the maximum moment perturbation can be obtained. For the space application, the mass constraint, the geometric length constraints are set as

$$
\begin{cases}
0 < 2n/\sin \theta < 5 \\
0 < m_1 < 10
\end{cases}
$$

The optimal result of the impact isolation and vibration isolation are shown in Figures 24 and 25. Each point in the figure is an optimal result, and all of these points formed optimal Pareto set. The results show that the acceleration range is $[0.2m/s^2, 0.5m/s^2]$, the displacement range is $[0.293m, 0.2945m]$, and the velocity range is $[0.02m/s, 0.04m/s]$. For vibration isolation, the optimal acceleration is in the range of $[0.008m/s^2, 0.013m/s^2]$, the displacement transmissibility is in the range of $[1.2, 7]$, and
the velocity is in the range of $[0.02\text{m/s}, 0.04\text{m/s}]$. From simulation results, it can be found that, given the range of the impact/vibration perturbation and constraints of the structure parameters, the optimal impact/vibration isolation performance and the corresponding structure parameters can be obtained.

In the on-orbit servicing application, the impact between the capture satellite and the target is inevitable and it is difficult to obtain the magnitude of impulse and disturbance force accurately. However, as the relative velocity between the servicing satellite and the target satellite can be estimated, the range of the impact/vibration magnitude can also be estimated. Thus, the proposed optimization approach can be utilized to optimize the structure parameters to minimize the impact/vibration perturbation performance, in order to guarantee the safety of the on-orbit servicing. It is useful in the structure design of the impact/vibration isolation system. Taking example of the malfunction satellite capture, given the range of the structure parameters of the isolation system, the optimal isolation performance, namely the displacement, the minimal impact acceleration of the servicing satellite can be obtained using the proposed method. These impact/vibration isolation performance results can be utilized to calculate the maximum control error of the servicing satellite in the process of the control system design.

**Conclusions**

In this article, a passive anti-vibration/impact method for impact/vibration perturbation isolation of space noncooperative target capture is presented systematically with both theoretical analysis and experimental validation on ground. The following conclusions can be drawn:

- Novel prototypes of a passive isolation structure system are developed, and the corresponding dynamics equations are established and analyzed systematically for capturing noncooperative space targets.
- For position perturbation, the maximum error between numerical simulation results and experiment results for the impact isolation is less than 25.5% (position displacement), and for vibration case, the error between the numerical simulation and the experiment result is less than 24.3% (displacement transmission). Considering there are a few parameters, like friction coefficients, which cannot be obtained accurately in experiments and also due to noise effect, the overall results demonstrate a reasonable match between theoretical and experimental results.
- For space noncooperative targets capture, the parameters of the X-shaped structures can significantly affect isolation performance. An optimization process is developed to optimize impact/vibration perturbation isolation performance. It is shown that the optimization process based on NSGA-II algorithm can optimize structure parameters to minimize perturbation.

**Acknowledgment**

The authors would like to thank the colleagues from Northwestern Polytechnic University and the Hong Kong Polytechnic University for their valuable assistance in the laboratory experiments.

**Declaration of conflicting interests**

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

**Funding**

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the National Natural Science Foundation of China (grant no. 11802238) and science award project of Xi’an city (grant no. 201616HK1020QYC1).

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