Design and Analysis of Physical Simulation System for Satellite Rotating Panels

Meng Yin, Yun He, Zhigang Xu, Zhe Liu, Xiaodong Shao

Abstract—Flexible accessories is an important part of modern satellite, the elastic vibration is the main factor influencing the control performance of space vehicle, which make it necessary to test the performance of vibration suppression for the control system on the ground. The difficulty of physical simulation is to simulate the space microgravity environment, the length of solar array is large and frequency is low, which make it extremely difficult to build the space microgravity environment. In view of the above situation, this paper proposes a method of flexible solar simulator based on air flotation, and we design the physical simulation system based on equivalent spindle inertia and flexible frequency. Dynamic model is established for the simulation system to make sure that the system can equivalently simulate the torque characteristics of flexible satellite rotating panels, which reduces the difficulty to simulate ground microgravity environment. The rationality of the scheme is verified by the simulation results, whose results show that, the simulator has torque characteristics consistent with real solar panels, and we can achieve a smooth change of parameters by a simple operation to simulate different parameters and structure of the solar array. This method meets the test requirements and can effectively and efficiently examine the vibration performance of the control algorithm.

Keywords—Physical Simulation System; Flexible satellite rotating panels ; Structure design ; Simulation verification

I. INTRODUCTION

With the increase of the earth observation mission and the diversification of the satellite's functional requirements, the application of flexible satellite becomes more and more extensive[1]. In history, a series of accidents caused by the vibration of the flexible satellite caused the decline in control performance. The elastic vibration caused by flexible appendages is the main reason that affects the pointing accuracy and control performance of the space vehicle[2]. For a rotating flexible solar array of satellite solar array, due to motion, the dynamics become more complex. Therefore, in order to effectively suppress the flexible vibration, improve the reliability of its orbit operation and reduce the risk of losing control, it is needed to verify the performance of the control system.

With the United States and Russia as the representative of the developed countries, a large number of funds invested in the spacecraft simulation. At present, the method for the verification of a rotating flexible mainly is mathematical simulation. Compared with physical simulation, it has the disadvantage of low credibility. In physical simulation, it is not necessary to establish the complicated mathematical model of the controlled object, which can effectively verify the control scheme, and the simulation results are more reliable, but it is also the most difficult to achieve. The difficulty of physical simulation is to simulate the space microgravity environment. Due to low frequency and length of the larger solar panels, the cost and difficulty for the construction of a large range of movement space is great[3].

In view of the above situation, a simulator based on equivalent principal axis inertia and flexible frequency is proposed. The parameters can be simply and smoothly adjusted to simulate solar cell array with different structures and parameters, which can be flexibly rotated. Based on the air flotation method, we established microgravity rotating flexible panel simulation environment. The performance of the control system is verified, and the efficiency and economy of the test are greatly improved.

II. WORKING PRINCIPLE OF PHYSICAL SIMULATION SYSTEM

The satellite flexible physical simulation system is mainly composed of marble air bearing platform, single axis air bearing table, driving unit and flexible simulator, as shown in Figure 1. The marble air bearing platform and the single axis air bearing platform can simulate the micro gravity environment of space.

The driving unit is the core of the whole experimental system, which is composed of a supporting unit, a driving motor, a disturbance torque sensor, a load torque sensor and a circular grating. The driving motor is the power source of the driving unit, and is also the experiment object of the whole physical simulation. The real experiment is carried out by the real driving mechanism of the satellite, the driver is installed on the side wall of the supporting base. The disturbance torque sensor is arranged between the driving mechanism and the supporting frame body, and is used for measuring the reaction torque of the driving mechanism, so as to verify the control algorithm of the driving mechanism. The material of the supporting frame body has high rigidity, the first-order natural frequency is far greater than 0.5Hz. In order to reduce the
output angle of the driving mechanism and the angular velocity phase lag, the other end of the drive mechanism is connected with a high precision reducer, which has the same function as the harmonic reducer of the true driving mechanism. The single axis air bearing table and the reducer are connected by the circular grating and the load torque sensor. Circular grating can overcome the driving mechanism's own end jump and transmission error. Accurate measurement of the driving mechanism can output motion parameters and can form a closed loop control. On the one hand, the load torque sensor can calibrate the inertia tensor of the flexible simulator. On the other hand, the load torque sensor can be used to measure the driving torque acting on the output shaft of the driving mechanism, and this is one of the key test data of this test bench.

III. DESIGN OF MOMENT OF INERTIA SIMULATOR

The design performance of the flexible simulator directly determines the true degree of the ground test. The design of the flexible simulator needs to meet the requirements of flexible frequency and moment of inertia in technical specifications. The flexible simulator is mainly composed of a flexible plate, a flexible joint, an adjustable mass block and a planar air bearing frame. The structure is shown in Figure 2 below. The flexible plate is a flexible part of the flexible simulator, which can satisfy the requirement of the frequency of the satellite's true flexible appendages. The flexible plate adopts a hollow structure to reduce drag force, the size and quantity of the flexible joint can be adjusted. The formation of gas bearing plane caused by air bearing can balance the gravity of flexible simulator, which ensures that the flexible sheet does not occur buckling. One end of the flexible simulator is a free end, and the other end is connected with the dynamic torque sensor of the drive unit through the connecting piece of the rotating shaft.

The change of the length and thickness of the flexible joint can realize the change of moment of inertia and the wide range of natural frequency. The rigid part of the flexible simulator is a mass block located on the flexible plate, and the moment of inertia and the flexibility of the flexible simulator can be tuned in a certain range by changing the layout.

Through repeated iterative test, reasonably determine the number and size of the flexible plate, we can achieve achieve the requirements of flexible frequency and moment of inertia. The adjustment principle of the frequency and principal axis inertia of the flexible simulator is: by adjusting the distance LX and the distance LY to adjust the flexible frequency, to change the principal moment of inertia by adjusting the number and distance LY, first we achieve a rough adjustment of the single variable and then we coordinate the two iterations to achieve fine tuning. When LY is small, the influence of mass on the flexible frequency is obvious. When LY is large, the influence of mass on the moment of inertia is more obvious. So the adjustment of the flexible frequency and principal axis inertia is relatively independent. Because of the accuracy of the distance adjustment is high, the precision of the frequency and the moment of inertia can reach a high precision. The definition of frequency and inertia adjustment variable of flexible simulator is shown in Figure 3.
IV. MATHEMATICAL MODELLING OF EQUIVALENT MOMENT OF INERTIA AND LOAD TORQUES

A. ESTABLISHMENT OF DYNAMIC MODEL OF FLEXIBLE SATELLITE

As shown in Figure 4 is the satellite model with rotating flexible solar arrays. In the process of change in the attitude of solar array, flexible accessories do small vibration deformation. So we can use the method of lumped mass and modal analysis to describe the motion of flexible appendages. Set \( \omega_0 = \omega_x \omega_y \omega_z \) is the satellite three axis attitude angular velocity, \( \Omega \) is speed for panel arrays, \( \eta = [\eta_1 \eta_2 \cdots \eta_n]^T \) is \( n \) order flexible modal coordinates.

The Lagrange equation is applied to the satellite attitude control system:

\[
\frac{d}{dt}(\sigma_s) + \omega_s = M
\]

\[
d \frac{\partial B}{\partial j} - \frac{\partial L}{\partial \dot{j}_i} = Q_i, \quad i = 1, \ldots, m
\]

Among them, \( \sigma_s \) is skew symmetric matrix.

\[
\sigma_s = \begin{pmatrix} 0 & -\omega_3 & \omega_2 \\
\omega_3 & 0 & -\omega_1 \\
-\omega_2 & \omega_1 & 0 \end{pmatrix}
\]

The \( M \) is control torque applied on the solar arrays, \( \eta_i \) and \( Q_i \) are the nth modal coordinates and the corresponding generalized force of the elastic vibration of the flexible appendages. \( L \) is the Lagrange function, which is the difference of the kinetic energy \( T \) and potential energy \( V \) of the satellite.

\[
L = T - V
\]

The kinetic energy \( T \) of the satellite is composed of two parts, namely, the kinetic energy \( T_b \) of the stars and the kinetic energy \( T_s \) of the object.

\[
T = T_b + T_s
\]

Among them, the expressions of \( T_b \) and \( T_s \) are respectively:

\[
T_b = \frac{1}{2} \omega^T J_b \omega,
\]

\[
T_s = \frac{1}{2} \sum_{k=1}^{n} m_k v_k^T v_k
\]

\( J_b \) is the inertia matrix of stars, \( m_k \) and \( v_k \) are the quality and velocity vectors of the attachment node \( k \), respectively. Note \( S \) is the rotation transformation matrix of the celestial coordinate system \( x_b y_b z_b \) to the accessory coordinate system \( x_s y_s z_s \), so:

\[
v_k = -(\bar{S}_{x_b} + \bar{r}_k) + \Phi_k \tilde{\eta}(t)
\]

Using formula (5) and (8), set:

\[
C = \tilde{r}_p^T (\sum_k m_k \Phi_k) + \tilde{S} (\sum_k m_k \tilde{\Phi}_k)
\]

The kinetic energy of the whole satellite is:

\[
T = \frac{1}{2} \omega^T J \omega + \frac{1}{2} \tilde{\eta}^T \tilde{C} \tilde{\eta} + \frac{1}{2} \omega^T \tilde{C} \tilde{\eta} + \frac{1}{2} \tilde{\eta}^T \omega
\]

Among them, \( J \) is the moment of inertia of the whole satellite, \( J = J_b + J_s \), the \( J_s \) is the attachment moment of inertia, whose expression is:

\[
J_s = C_{s_h} \tilde{I}_s C_{s_h}^T + m_h \tilde{b} \tilde{b}^T + \tilde{b} \tilde{C} \tilde{c} \tilde{C}^T \tilde{b} + C_{s_h} \tilde{C} \tilde{C}^T \tilde{b}^T
\]

In the formula, \( m_{s_h} \) is the quality of panel arrays, \( I_s \) is the moment of inertia matrix array, \( \tilde{b} \) is the position vector of the hinge point in the satellite body coordinate system, \( c_s \) is a first-order mass matrix array, \( \tilde{b} \) and \( \tilde{c} \) are symmetric matrices of \( b \) and \( c_s \), respectively, \( C_{s_h} \) is a vector from panels attached coordinate coordinates to the body coordinate conversion matrix.
oda damping is introduced in the
the mathematical model of the
g coefficient matrix of satellite
Hs, s

Hs and Hbs are flexible coupling coefficient matrix, Hs
is the coupling matrix of its rotating solar array,
Hbs is the vibration coupling coefficient matrix of satellite
time movement.

Among them, Pbs is the vibration coupling coefficient
matrix of its translation. Obviously, the Hs and Pbs is a
constant matrix, while the Hbs and Jbs are periodic
time-varying matrix, which depends on the position of the
corner panels.

The potential energy of the satellite is the deformation
potential energy of the flexible appendages.

\[ V = \frac{1}{2} \dot{\eta}^T \Omega \dot{\eta} \]  

(16)

We put the above expression into the Lagrange equation and
ignore higher order, modal damping is introduced in the
appendix equation. We can get controllable rotating flexible
solar array dynamic model of the satellite.

\[
\begin{cases}
J \ddot{\omega} + J_{bs} \dot{\Omega} + H_{bs} \dot{\eta} = \tau \\
\ell^T J_{bs} \dot{\omega} + \ell^T J_{bs} \dot{\Omega} + \ell^T H_{bs} \dot{\eta} = \tau \\
H_{bs} \ddot{\omega} + H_{bs} \dot{\Omega} + \dot{\eta} + D \dot{\eta} + K \dot{\eta} = 0
\end{cases}
\]  

(17)

B. THE ESTABLISHMENT OF A DYNAMIC MODEL OF A FLEXIBLE SIMULATOR

As shown in Figure 5, A is the flexible simulator, B is
the floating platform, O is the vertical rotation center of the
air bearing table; O' is the fixed point of flexible simulator in
the air bearing table; s is point-to-point distance; \( \theta \) is the
rotation angle of the air bearing table; u is flexible
def ormation simulator.

Moment of inertia is \( J_{bs} \), the mathematical model of the
flexible simulator is obtained by the lumped mass method
with finite element method. Each mode is \( \Phi_i \), \( i = 1, 2, \cdots, n \), \( \Phi_i \)

nodes are taken on the flexible simulator, and the joint quality
is \( m_j \), the deformation is \( u_j \). The distance to the fixed pivot
\( O' \) is \( y_j \), modal coordinates is \( z_j \).

![Flexible simulator model](image)

**Fig. 5 Flexible simulator model**

Order:

\[ \Phi = [\Phi_1, \Phi_2, \cdots, \Phi_n] \]

(18)

As the mode of vibration is orthogonal, so \( \Phi^T M \Phi = I \), And
the stiffness matrix \( K \) and damping matrix \( c \) are diagonal.

Let \( \omega_i \) is each modal frequency, \( \xi_i \) is each modal damping
coefficient, Then:

\[ \Phi^T K \Phi = diag(\omega_1^2, \cdots, \omega_n^2) \]  

(19)

\[ \Phi^T C \Phi = diag(2\xi_1\omega_1, \cdots, 2\xi_n\omega_n) \]  

(20)

Potential energy:

\[ V = \frac{1}{2} z^T diag(\omega_1^2, \cdots, \omega_n^2) z \]  

(21)

Dissipation due to the damping can be:

\[ D = \frac{1}{2} z^T diag(2\xi_1\omega_1, \cdots, 2\xi_n\omega_n) z \]  

(22)

The kinetic energy of the whole system is:

\[ T = \frac{1}{2} J \ddot{\theta}^2 + B^T \dot{\theta} \dot{z} + \frac{1}{2} z^T \ddot{\theta} \]  

(23)

Among them:

\[ B = \sum_{j=1}^{n} m_j (s + y_j)(\Phi_i^T)_j \]  

(24)

Application of Lagrange equation:

\[
\frac{d}{dt} \left( \frac{\partial T}{\partial \dot{z}} \right) + \frac{\partial D}{\partial \dot{z}} - \frac{\partial T}{\partial z} + \frac{\partial V}{\partial z} = Q
\]  

(25)

Disturbance torque \( M_d \) and control torque \( M_c \) is applied
to the center of rigid body floating platform, so the flexible
plate is not affected by external force. The resulting kinetic
model:

Rigid body:

\[ J \ddot{\theta} + B^T \dot{\theta} \dot{z} = M_d + M_c \]  

(26)

Among them:

\[ B = [B_1, B_2, \cdots, B_n]^T \]

Flexible structure:
\[ \ddot{B} \dot{\theta} + \dot{z} + \text{diag}(2\tilde{\xi}_1\omega_1, \cdots, 2\tilde{\xi}_m\omega_m)\dot{z} + \text{diag}(\omega_1^2, \cdots, \omega_m^2)z = 0 \]  

(27)

V. SIMULATION VERIFICATION

Based on the establishment of dynamic model, we choose the flexible frequency is 0.1 Hz and $I_{xy}$ is 5 kg·m$^2$. When reaching the maximum and minimum angular velocity, we use simulation software to solve the driving torque and angular acceleration, the performance of the flexible simulator is verified by comparing the data obtained.

A. SATELLITE SIMULATION ANALYSIS

Satellite is a very complex system, it is impossible to reproduce every detail by solid modeling, so it is necessary to simplify the structure without prejudice to the authenticity of the study. The final goal of the design is to realize the attitude control of the flexible satellite, therefore, the satellite can be simplified as the satellite body and the flexible appendages of the two parts. The satellite body is simplified as a cubic shell, flexible accessories is simplified as two solar panels. During the motion of the satellite, the satellite is only weakly deformed, and the effect of deformation on the whole motion is very small, so they can be regarded as a rigid body. Solar panels for flexible have elastic deformation during the movement of large, coupled vibration and motion panel should not be ignored, so the finite element method is used for the modal analysis, so as to obtain the finite element model. According to the space position of each part of the satellite, the virtual prototype model of the whole satellite can be obtained by applying the constraints, loads and initial conditions.

ADAMS simulation model with flexible rotating panels, as shown in Figure 7.

Through simulation we can get, when the angular velocity reaches $0.05\,^\circ/s$, the driving torque to the X direction and the Z direction is zero, the most value of the driving torque for Y direction is 0.13 N·m , the acceleration of X direction and the Z direction are zero, the maximum value of drive angle for Y direction is 0.075$^\circ$/s$^2$. The driving torque curve is shown in Figure 8.

B. SIMULATION AND ANALYSIS OF FLEXIBLE SIMULATOR

The dynamic analysis of the designed flexible simulator is carried out. We set up the flexible adjustment of variables to make the simulator and solar panels with similar frequency and inertia spindle. The simulation model of the flexible simulator in ADAMS is shown in the following Figure 10.

Through simulation we can get, when the angular velocity reaches $0.05\,^\circ/s$, the driving torque to the X direction and the

---

**Fig. 7 ADAMS simulation model of the satellite**

| Serial number | Angular velocity | Torque       | Angular acceleration |
|---------------|------------------|--------------|----------------------|
| 1             | $0.05\,^\circ/s$ | 0.13 N·m     | 0.075$^\circ$/s$^2$  |
| 2             | $0.5\,^\circ/s$  | 0.43 N·m     | 0.25$^\circ$/s$^2$   |

**Fig. 8 Drive torque curve of Y direction.**
Z direction is zero, the most value of the driving torque for Y direction is $0.187 \text{N} \cdot \text{m}$, The acceleration of X direction and the Z direction are zero, The maximum value of drive angle for Y direction is $0.75 \degree / s^2$. The driving torque curve is shown in Figure 9.

![Fig. 9 Drive torque curve of Y direction.](image)

Through simulation we can get, when the angular velocity reaches $0.5 \degree / s$, the driving torque to the X direction and the Z direction are zero, the maximum value of the driving torque for Y direction is $0.54 \text{N} \cdot \text{m}$, the acceleration of X direction and the Z direction are zero, the maximum value of drive angle for Y direction is $0.25 \degree / s^2$. The torque and angular acceleration of Y direction is larger, the driving torque and angular acceleration of X and Z direction is zero, so when we carry out the ground simulation test, we only need to consider the direction of rotation of the spindle inertia. The simulation data are shown in the following table 2.

| Serial number | Angular velocity | Torque | Angular acceleration |
|---------------|------------------|--------|----------------------|
| 1             | 0.05\degree / s  | 0.187 \text{N} \cdot \text{m} | 0.075\degree / s^2 |
| 2             | 0.5\degree / s   | 0.54 \text{N} \cdot \text{m} | 0.25\degree / s^2 |

### VI. CONCLUSION

This paper presents satellite rotating flexible solar simulator based on an equivalent spindle inertia and flexible frequency, which has an equivalent simulation on the vibration characteristics of a rotating flexible satellite array and reduces the difficulty to test flexible satellite rotation array in ground microgravity environment. This method can effectively and efficiently test the vibration performance of the control algorithm. Simulation results show that, The simulator can change the parameters smoothly by simple operation to simulate different panels that have different parameters and structure. The simulator has vibration characteristics consistent with real solar panels, which meet the test requirements. The next step will be to build a physical system for further verification. This method has a certain reference value for other ground test of solar panels, which can effectively reduce the difficulty and cost of ground performance testing.

### REFERENCES

[1] Wang Yousong. Research on Satellite Attitude Control and Implementation Method of the Group Simulation[D]. Harbin: Harbin Institute of Technology, 2014

[2] Lu Dongrui, Liu Yi. Adaptive Control of the Spacecraft with a Rotating Flexible Solar Array[J]. Aerospace Control. 2014, 32(1): 49-54

[3] Li Zhiqiang, BAI Xinxin, WANG Junyi, HE Yun. Load Carrying Capacity Test of the Space Station Redocking Manipulator Based on the Equivalent Inertia Simulation Method[J]. Robot. 2015. 37(2) : 231-236

[4] Yang Hui, Hong Jiachen, Yu Zhengyue. Experiment Investigation on a Hub-Beam system[J]. Chin J Spac Sci. 2002. 22(4): 372-379

[5] Xu Wenfu, Liang Bin, Li Cheng, Liu Yu, Qiang Wenyi. The research summary of space robot microgravity simulation experiment[J]. Robot. 2009. 31(1) : 88-96

[6] Wang Yajun, Xu Zhigang, He Yun, He Xibin. Design of unfolded mechanical properties testing system for multidimensional Deployment Mechanism of Antenna [J]. Chin J Spac Sci. 2016. 36(2): 227-236

[7] Payam Zarafshan, S.Ali.A.Moosavian. Manipulation Control of Space Robot with Flexible Solar Panel[J]. 2010 IEEE/ASME Intelligent Mechatronics Montréal, Canada, July 6-9, 2010: 1099-1104

[8] Bao Hanbin. Control Method of Flexible Satellite Attitude Maneuvering[D]. Harbin: Harbin Institute of Technology. 2012 [9] Bai Shengjian. Research on Modeling and Control of Flexible Spacecraft[D]. Changsha: National University of Defense Technology. 2005

[9] Liu Yingying, Zhou Jun, Sun Jian. Experiment Research for Satellites' Multi-axis Pointing Attitude Control [J]. J Astrona. 2006. 27(4): 271-273

[10] Xu Z G, Xin L M, Zhao M Y. Gravity balance technique of active docking ring for space docking test table [J]. Chinese Journal of Scientific Instrument, 2009, 30(6): 1140-1144

[11] Chang P M, Jayasuriya S. An Evaluation of several controller synthesis methodologies using a rotating flexible beam as a test bed. ASME J. Dyn. Sys. Meas. Cont. 1995

[12] Jiang J N, Yang L F, Huang J K, Macauley R. Rapid rotational/translational maneuvering experiments of a flexible steel beam. In: Proc. 1989 Amer. Cont. Conf. IEEE. 1989

[13] Hastings G G, Book W J.A linear dynamic model for flexible robotic manipulators. IEEE Control Systems Magazine. 1987

[14] Jiang J N, Horta L G, Robertshaw H.A slewing control experiment for flexible structures. Journal of Guidance Control and Dynamics. 1986

[15] Low K H, Lau M W S. Experimental investigation of the boundary condition of slewing beams using a high-speed camera system. Mechanism and Machine Theory. 1995