An Optimal Structure Design of Artificial Load Based On Certain Frequency*

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Abstract—An air bearing gravity unloading facility for the antenna pointing mechanism (APM) is presented which is used to simulate micro-gravity environment for testing the APM on the ground. An artificial load for the APM is presented to simulate the inertia, mass and frequency to reflect the performance of the pointing mechanism. The structure design of artificial load is based on the lexicographic method. With the comparison of different load configurations, the load structure is designed reasonably with certain size parameters. This structure design solves the inertia coupling problem of two axes. To fit the given frequency, repeatedly iterative design is done. In this process, the size parameters are modified which affect the frequency until it reaches the given frequency. The load structure is optimized further to ensure the adjustment of the inertia within a certain range and maintain a substantially constant frequency. At last, the design method is summarized and it is suitable for multi-target structure design based on certain frequency.

I. INTRODUCTION

Space environment has the characteristic of micro-gravity, intense radiation, high vacuum, ultra-low temperature, etc. The one which has great influence on the dynamic capability of the spacecraft is the characteristic of micro-gravity. Many countries have designed kinds of micro-gravity simulator to emulate the micro-G environment on the ground. The simulators include air bearing simulator, suspending simulator, neutral buoyancy simulator, micro-gravity tower (drop tube), and so on [1]. The air bearing simulator is used widely due to its technology, simple structure and low cost of construction and maintenance. The countries which have built air bearing simulator include America [2-5], Britain [6], German [7], Japan [8], China [9,10,11], etc. The simulators built by MIT, NASA and University of Southampton emulate the mass and inertia of spacecraft with planar air bearings [2, 5-7]. JERMS of Japan emulate micro-G environment by support the robotic arm with planar air bearing, but the influence of the air bearing on the mass and moment of inertia is neglected [12-15]. The structure of the emulated spacecraft on the simulator is different from the structure in space. What’s more, the air bearings also change the mass, moment of inertia and modal. Thus the test result on the simulator is different from its real capability.

A gravity unloading facility (simulator) is designed to test the performance of the antenna pointing mechanism (APM) of the Tracking and Data Relay Satellite (TDRS) on the ground. The mass, moment of inertia and basic modal frequency are all taken into consideration to reflect the real characteristic of the antenna. The structure of the artificial load is designed specially. So the results got on the facility are more reliable.

II. STRUCTURE OF THE GRAVITY UNLOADING FACILITY

The APM of the TDRS include two orthogonal axes, shown in Fig. 1. The APM is consisted of three parts: the vertical stator (act as the base), the vertical rotor (fixed on the horizontal stator) and the horizontal rotor. As an APM, the vertical stator is mounted on the satellite while the antenna is mounted on the horizontal rotor. The antenna is so large that its weight may destroy the APM on the ground in the gravity field if the antenna is mounted on the APM directly without extra support. A gravity unloading facility is designed to test the performance of the APM on the ground before launch the satellite. An artificial load is designed with extra support for the gravity unloading facility to replace the antenna. One of the most important functions of the facility is to unload the gravity of the artificial load.

Air bearings are applied on the facility to compensate the gravity with the development of air bearing technology, simple structure and its stability. The gravity unloading facility unloads the gravity with planar air bearings and air spindle because of the two orthogonal axes. The structure of the facility is shown in Fig. 2.

![Figure 1. Antenna pointing mechanism](image_url)
The air spindle unloads the gravity of artificial load and horizontal rotor while the horizontal joint rotating. The artificial load consists of horizontal payload, air spindle rotor, frameless motor’s stator, and other connect parts. The planar air bearings unload the gravity of horizontal stator, vertical rotor, air spindle, frameless motor stator, flatbed and artificial load when the vertical joint rotates. This gravity unloading facility is designed with two layers (shown in Fig. 2-a). The bottom layer consists of three planar air bearings placed as a triangle while the upper layer is the air spindle (shown in Fig. 2-b). Three planar air bearings are mounted under the support flatbed while the air spindle is fixed on the top of the flatbed.

Firstly, the air spindle bears the gravity of horizontal rotor and the artificial load. The horizontal rotor and the artificial load are mounted on the rotor of the air spindle firmly. The gap between the rotor and stator is full of high-pressure air to reduce the friction. The horizontal rotor, the artificial load and other testing devices are all fixed together coaxially with the rotor of the spindle and rotate around the horizontal axis. Their gravity is supported by the air film in the air spindle without any direct contact which has extremely low friction while rotating. Thus the horizontal joint of the antenna pointing mechanism got its degree of freedom (DOF) of rotation around horizontal axis without the influence of gravity.

Secondly, the gravity of horizontal stator and vertical rotor is compensated by the adjustable spring mechanism-1 fixed on the support flatbed. The gravity center is just within the contact plane pair which is two square plane areas. There is an adjustable structure to modify the force of the spring to improve the accuracy of gravity compensation. The support flatbed is sustained on the granite platform by three planar air bearings (three support forces are shown in Fig. 2-b). Three planar air bearings are placed as a triangle, so that the gravity center of the artificial load, the air spindle, the support flatbed, frameless motor’s stator, horizontal stator, vertical rotor and horizontal rotor is just above the centroid of the triangle. This makes the load of three planar air bearings evenly. The gap between the planar air bearings and the granite is also full of high-pressure air. Thus the flatbed can spin around the vertical axis with air viscous resistance which is extremely small. What’s more, the air spindle stator is also fixed on the support flatbed and rotates around the vertical axis together with the flatbed driven by the vertical joint of APM. So the horizontal joint and the vertical one rotate together as if there is no gravity without any interference.

Thirdly, the gravity of vertical stator is unloaded precisely by a spring which is connected to adjustable mechanism-2. Guide and block pairs are used to set free the vertical translation DOF because there are vertical movements of the planar air bearings and air spindle while the start and end of the simulation. The spring and guide-block pairs mechanisms fixed on the granite platform can protect the antenna pointing mechanism from being damaged by the extra force of air bearings. With only one DOF of vertical translation in extremely small range, vertical stator still acts as a base of vertical rotor, horizontal stator, horizontal rotor and the artificial load.

The gravity unloading facility affords two DOFs of rotation around vertical and horizontal axes with the gravity compensation method described above. Especially, the unloading is working no matter those two axes rotate respectively or simultaneously. Three planar air bearings are placed on the same plane to assure the rotation around vertical axis while unloading vertical rotor, horizontal stator, horizontal rotor, the artificial load, air spindle and all other parts. The air spindle can also unloading horizontal rotor and the artificial load while rotating around horizontal axis. Both axes rotate with extremely low resistance which is air viscous resistance of air films. Thus the antenna pointing mechanism runs in the environment of microgravity just as running in space.

III. TARGETS AND RESTRICTIONS DURING THE DESIGN OF ARTIFICIAL LOAD

The artificial load to replace the antenna is specially designed to test the performance of the APM. The APM runs on the gravity unloading facility which emulates the micro-gravity environment on the ground. The design targets of the artificial payload are as follows:

1. The moment of inertia of both axes must meet the requirements.
2. The frequency of the artificial payload is given within a certain range to make sure that the result of the test is reliable.
3. The moment of inertia is adjustable within a certain range while the frequency meets the requirement.
The following restrictions are taken into consideration during the design of the artificial payload:

1. The artificial load of horizontal axis includes the rotor of the air spindle, the horizontal payload, the rotor of the torque compensation motor (the frameless motor), and so on. The load of the vertical axis includes the artificial load of the horizontal axis, the stator of the air spindle, the stator of frameless motor, the support flatbed, the planar air bearings and other connection parts. The loads of two axes are different, so the coupling of two axes’ load is taken into consideration and the integrated design is done.

2. The frequencies of both axes’ loads are different because of the difference of the loads structure. The frequency of horizontal axis’ load is chosen to meet the requirement because it is the load which mounted on the same position with the real antenna.

3. There is moment of inertia coupling problem between two axes which means that moment of inertia of one axis may change when another axis is rotating, so the artificial payload is designed reasonably to ensure the constant and uncoupling of inertia.

4. APM is tested on the gravity unloading facility with the load. The angle range of APM should be enough to avoid constructive interference between the artificial load and the facility.

5. The air spindle and the planar air bearings should have enough capacity to unload the gravity of payload.

The design restrictions are as following which have taken the mass, moment of inertia and frequency into consideration:

\[
\begin{align*}
J_{\text{min}} & \leq J_{h} \leq J_{\text{max}} \\
J_{\text{min}} & \leq J_{v} \leq J_{\text{max}} \\
freq_{\text{min}} & \leq freq \leq freq_{\text{max}} \\
\text{s.t.} & & \theta_{h} \geq \theta_{v} \\
& & \theta_{h} \geq \theta_{v} \\
& & \sum_{i} m_{i} \leq m_{\text{max h}} \\
& & \sum_{i} m_{i} \leq m_{\text{max v}}
\end{align*}
\]

(1)

Where, \( \sum_{i} m_{i} \) and \( \sum_{i} m_{i} \) are the mass of horizontal and vertical axes respectively while the \( m_{\text{max h}} \) and \( m_{\text{max v}} \) are the limit. \( \theta_{h} \) and \( \theta_{v} \) are the angle ranges of horizontal and vertical axes respectively while the \( \theta_{h} \) and \( \theta_{v} \) are the limit. \( J_{h} \) and \( J_{v} \) are the moment of inertia of horizontal and vertical axes respectively while the \( J_{\text{min}} \) and \( J_{\text{max}} \) are the limit. The moment of inertia is the function of the distribution of the mass: \( J_{h} = \int_{h} \Delta m_{h} r_{h}^{2} \), \( J_{v} = \int_{v} \Delta m_{v} r_{v}^{2} \). \( freq \) is the basic modal frequency of the horizontal artificial load while the \( freq_{\text{min}} \) and \( freq_{\text{max}} \) are the limit.

There is not a structure to define the parameters used in the optimization at the beginning, so the lexicographic method is used to design the structure of the artificial load. Solve the objective function by turns, and the latter function should be within the optimal solutions of the front one.

IV. DESIGN OF ARTIFICIAL PAYLOAD STRUCTURE

Firstly, the configuration of the artificial payload is designed with the restriction of the angle range according to the lexicographic method. Then the parameters of the designed structure are optimized to meet the requirement of the moment of inertia and the frequency.

A. The configuration of the artificial payload

The planar air bearings (Fig. 3-a) and air spindle (Fig. 3-b) are used to unload the gravity. The load on the air spindle is balanced to avoid the abrasion damage of the overturning moment. The payload is designed to be the configuration of U type fork, so the gravity center is in the center of the air spindle.
Counter weights are used to adjust the moment of inertia in redesigned structure (a) and (b). The inertia of both axes must be constant in the process of testing while both axes are rotating. The moment of inertia coupling problem is found in redesigned structure (a). The moment of inertia of the vertical axis is changing while the inertia of horizontal axis is constant when the horizontal joint is rotating. This problem is solved in the redesigned structure (b) in which the moment of inertia of vertical axis is also constant (shown in Fig. 7).

\[ J_{\text{m}} = 2mr^2 \]  
\[ J_{\text{mc}} = 2m \left( \sqrt{r \cos \beta} + l^2 \right) \]  
\[ = 2ml^2 + 2mr^2 \cos^2 \beta \]  

Where, \( m \) is the weight of each counterweight, \( r \) is the distance between the counterweight and the horizontal axis, \( l \) is the distance between the center of the air spindle and the vertical axis. \( \beta \) is the angle that the horizontal axis rotates relatively to its initial position.

Fig. 7-b shows the model of equilateral triangular structure. The moments of inertia around both axes are constant.

\[ J_{\text{ab}} = 3mr^2 \]  
\[ J_{\text{a}} = m \left( \sqrt{r \sin \beta} + l^2 \right)^2 \]  
\[ + m \left( \sqrt{r \cos (30^\circ + \beta)} + l^2 \right)^2 \]  
\[ + m \left( \sqrt{r \cos (30^\circ - \beta)} + l^2 \right)^2 \]  
\[ = 3ml^2 + \frac{3}{2}mr^2 \]  

The conclusion is that the moment of inertia of the vertical axis is changed with the rotation of horizontal axis in the dumbbell-shaped structure while the inertia in the equilateral triangular structure is constant. The inertia coupling problem is solved in the equilateral triangular structure, so the configuration of the artificial payload is chosen for the facility.

B. Parameters of the artificial payload

The selected structure must be optimized to meet the moment of inertia requirements of both axes at the same time. The parameters include the length \( r \) of the U type fork, the mass \( m \) of each counterweight and the distance \( l \) between the load and the vertical axis.

\[
\begin{align*}
J_H &= 3mr^2 + \Delta J_H \\
J_V &= 3ml^2 + \frac{3}{2}mr^2 + \Delta J_V \\
m_H &= m + \Delta m_H \\
m_V &= m + \Delta m_V
\end{align*}
\]  

Where \( m_H, J_H, m_V \) and \( J_V \) are the mass and moments of inertia around horizontal and vertical axis respectively. \( \Delta m_H, \Delta J_H, \Delta m_V, \Delta J_V \) are the mass and moment of inertia of auxiliary parts around horizontal and vertical axis respectively. \( r \) and \( l \) are the parameters to describe the structure of the gravity unloading facility, so they are not adjustable to meet the range of the moment of inertia. The mass of counterweights \( m \) is chosen to adjust the moment of inertia. The moment of inertia is adjusted by selecting different counterweights designed in advance. The structure designed is shown in Fig. 6.

Thus, the artificial payload shown in Fig. 6 meets the requirement of angle range, moment of inertia and mass. The influence of the frequency is analyzed in the following.

C. The frequency of the horizontal artificial load

Impact damping is usually neglected when calculating the natural frequencies and modes of vibration [16, 17].
Differential equation of free vibration of n DOF (degree of freedom) structure is shown in the following:

$$[M][\ddot{X}]+[K][X]=\{0\}$$  \hspace{1cm} (7)

Where, $[M]$ and $[K]$ are the mass matrix and stiffness matrix of the structure respectively. $\{\ddot{X}\}$ and $\{X\}$ are the acceleration and position of nodes in the reference coordinate system.

The following equation is given after series of derivation:

$$\det(-\omega^2[M]+[K])=0$$  \hspace{1cm} (8)

A set of $\{\omega_1, \omega_2, \ldots, \omega_n\}$ is the solution of the equation above. This set is the natural frequencies of the structure, and the mode of vibration can be calculated for each frequency. The natural frequencies are the function of mass matrix and stiffness matrix of the structure, so the requirement of frequency is met by adjusting the mass and stiffness repeatedly. The frequency of structure is lower with larger mass or lower stiffness, vice versa.

The stiffness is chosen to be adjusted to meet the requirement of frequency because the mass and inertia must meet their own requirements. The frequency of original structure is relatively larger after calculation (there is a bearing constraint on the rotor of air spindle when calculating the frequency), so the structure is modified to reduce the stiffness repeatedly. The result is shown in Fig. 6.

### D. Structure optimization

The structure shown in Fig. 6 meets the requirements of moment of inertia, mass and frequency, but there are still shortcomings.

1. It is not convenient to adjust the moment of inertia. The whole counterweight is changed when adjusting the inertia. The mass is relatively large, so it is not easy to adjust the inertia.
2. There is stress concentration on the U type forks. The stiffness of the forks is reduced significantly to meet the frequency requirement, resulting in greater local stress.
3. The deformation of the forks is also increased due to the stiffness reduction.

The structure is optimized to overcome the shortcomings above. Each counterweight is divided into three parts, so only three small counterweights are changed to adjust the moment of inertia. The U type forks are also optimized to reduce the deformation and stress concentration with the application of wires between every two sets of counterweights. The optimized structure is shown in Fig. 8. The maximum deformation is reduced greatly from 268mm to 29mm (shown in Fig. 9), thus the size of the whole facility is reduced.

The moment of inertia is adjustable in certain range by changing different counterweights while the frequency is within a certain range (shown in Fig. 10). Two increasing curves are the moment of inertia of horizontal and vertical axes which increase with the thickness of the changeable counterweights. The decreasing curve shows the frequency.

### V. METHOD OF STRUCTURE DESIGN BASED ON CERTAIN FREQUENCY

The following describes the design process of the multi-target artificial load based on certain frequency. There are usually multi-target to design the artificial payload such as the mass, moment of inertia, frequency, size, stiffness, strength, and so on. The target of the artificial payload on the gravity unloading facility includes mass, moment of inertia and frequency. The size and stiffness are also taken into consideration in the optimization. The designing process is shown in Fig. 11.

1. Select the reasonable configuration according to the design targets and restrictions. The DOF of the structure and connection are also designed.

Figure 8. Optimized structure

Figure 9. The deformation

Figure 10. The change of the moment of inertia and frequency
(2) The main parameters are calculated such as the length, weigh and mass based on the structure configuration and restriction.

(3) Calculate the frequencies and vibration modes of the structure. The structure is optimized if the frequencies meet the requirement. Otherwise, the size of the structure is adjusted to verify the matrix of mass and stiffness until the frequencies meet the requirement. The mass is increased and the sectional dimension is reduced if the frequencies are larger than required, vice versa.

(4) Repeat step (3) until the frequency meets the requirement. Further optimization is done for the stress concentration, deformation and the size of the whole structure. Then the frequency is verified and the structure is the final artificial load needed.

There is not a formulation to calculate the frequency of a complex structure, so finite element method is applied to calculate the frequency on the computer. The mass and stiffness are adjusted repeatedly to meet the frequency requirement for an artificial load design based on certain frequency.

VI. CONCLUSION

Firstly, the gravity unloading facility is analyzed to demonstrate the method of gravity unloading for the antenna pointing mechanism.

Then the design of the artificial load to replace the antenna is shown in detail. The requirement of mass, moment of inertia and frequency are listed. The parameters can’t be calculated directly because there is not a formulation for calculating frequency of complex structure. The lexicographic method is used to design the artificial load. The requirement of mass and inertia are met firstly. Then the parameters affecting the frequency are modified to meet the frequency requirement. The moment of inertia coupling problem is solved by applying the equilateral triangular structure. The moment of inertia of final structure is adjustable and the change of frequency is very slight.

At last, the design method is summarized. The design process of multi-target artificial payload based on certain frequency is described in detail. This method may be used for similar structure design.

ACKNOWLEDGMENT

This study was co-supported by the State Key Laboratory of Robotics, Shenyang Institute of Automation Chinese Academy of Sciences and Beijing Institute of Control Engineering.

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