Gravity Balance Technique of the Docking Ring in the Spacecraft Docking Testbed

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Abstract—To simulate the zero-gravity activities of the docking ring in a spacecraft docking testbed, a gravity balance device with high respond speed and high precision was designed. Mechanism scheme and working principle of the gravity balance device are introduced. The characteristics of the follower mechanism, which may interfere with the gravity balance system, are analyzed in detail. The accuracy of the gravity balance system is experimented. Analysis and experiment results show that the gravity balance device meets the requirements on friction resistance and inertia resistance. The precision of the gravity balance reaches 1.1%.

Index Terms— gravity balance technique, spacecraft docking, manned spaceflight

I. INTRODUCTION

The successful operation of the Chang’E 1 Lunar Orbiting Spacecraft indicates that China has made a breakthrough on the technique of satellite and the spatial exploration of China comes into a new stage. In 2008, China will send Shenzhou-7 manned spaceship, and the astronauts will have a spacewalk outside the cabin. As stated in the spaceflight development stratagem, China will start sky laboratory program in the next stage. In that stage, the most important task is spatial rendezvous and docking. The technique of the spatial rendezvous and docking is the foundation for building the space station and carrying out complicated tasks in the space [1], [2] and [3].

Spacecraft docking is carried out by the two docking mechanisms installed respectively on two different spaceflight devices. In order to verify the related parameters and to evaluate the performance of the docking mechanism, a test bed on the group is necessary to simulate real space environment and different experiments on dynamics [4], [5], [6] and [7]. Further, to eliminate the gravity effect, a gravity balance device should be added on the docking ring to simulate its weightless state. The balance device must offer an accurate balance force. The difficulty of developing the gravity balance device is how to guarantee the balance precision under the influence of the follower motion. This paper presents a novel mechanism to solve the problem and the analysis and experiment results show that the accuracy of the mechanism meets the requirement.

II. MECHANISM PRINCIPLE

A. The Structure of the Mechanism

The paper mainly study the gravity balance device of the docking ring which is a main structure of the spacecraft docking testbed, the structure is shown in figure 1. It plays an important role in the system and its capability directly affects the precision of the whole system. In the docking process, the active docking ring which has three guiding pieces is expanded out by a parallel mechanism of six degree-of-freedom (hereafter abbreviated as DOF) before the approaching. Then the active and the passive docking mechanisms approach and dock together through the motion of the passive docking mechanism that is generated by the passive six freedom parallel mechanism. At the same time, the interacting force of the docking mechanisms is measured by six freedom force sensors installed in the system. In the entire process, the docking ring may have a displacement of six DOFs and its weightless state must be simulated faithfully. In view of the different phases in the test process, the device needs three different suspending positions for the wire rope to balance the gravity in the docking process. In the phase of capture, emendation and forced emendation, the suspending position is at the docking ring; In the phase when the active and the passive docking mechanisms are pulling together and then rigidly connected, and their docking attitudes are hold, the suspending position of wire rope is at the frame of passive docking mechanism. In the separating phase, the suspending position is at the frame of active mechanism. Finally when the docking ring is pushed out, the suspending position goes back to the docking ring again. The suspending positions are illustrated in Fig. 1.

To simulate the motion of the active docking ring in a real space faithfully, the gravity balance device must meet the follow requirements:

1) The balance device should have six DOFs and can produce a passive motion with high respond speed.

2) Providing 500N balance force and the error of the balance force should be less than 6%.

3) The mass and inertia of the balance device should be as small as possible.
B. Mechanism Principle

The gravity balance device consists of a 2-DOF follower mechanism, a spring balancer, a 6-DOF tensile force sensor, a stand bar and two dragging sets. The device is shown in Fig. 2.

The 2-DOF follower mechanism is a 2-ş planar linkage. The dragging sets are connected to two wire ropes which are attached to the ends of the stand bar through spherical joints. The stand bar, the wire rope and the docking ring form a parallelogram mechanism. When the docking ring rolls about the X-axis, the stand bar rotates about point O1 and the whole gravity balance device has no opposing effect on the rotation of the active docking ring about its center. Obviously the docking ring can pitch about the Z-axis freely via the two spherical joints of the gravity balance device. When the docking ring rotates about and displaces along the Y-axis, the spring balancer and the spherical joint on the stand bar ensure the free run of the motion. The translational DOFs of the active docking ring on the XOZ plane are provided by the passive motion of the 2-DOF follower mechanism. It can be summarized that the device must provide the gravity balance force and ensure the six-DOF movement of the active docking ring. Meanwhile, the tensile force sensor feeds back the balance force in real time.

As a reduction of the mass of the 2-ş mechanism will generally lead to a reduction of the friction force in the bearings installed in the joints and a better performance of the follower mechanism, the key of the mechanical design for the device is to decrease the mass and the inertia of the follower mechanism but still ensure its rigidity at the same time. The structure of gravity balance device is shown as Fig. 3.

III. THE CONTROL OF THE INTERFERENCE FORCE

There will be interference force when the docking ring moves laterally. In order to control the magnitude of the interference force within an acceptable range, we should choose a proper height of the suspending wire rope which takes on the gravity balance force. Suppose the interference force must be less than 3 kg, then the height of the suspending wire rope L can be computed as follows:

\[ F_x = T \cdot \sin \theta \]
\[ F_y = T \cdot \cos \theta \]
\[
F_x / F_y = \sin \theta / \cos \theta \\
F_x = F_y \cdot \tan \theta = G \cdot \tan \theta \\
\tan \theta = a_1 / l \\
F_x = G \cdot (a_1 / l) \\
F'_x = G \cdot (a_2 / l) \\
\sum F_x = \sqrt{F_{x1}^2 + F_{x2}^2} = \sqrt{a_1^2 + a_2^2} \cdot G / l \\
\sqrt{a_1^2 + a_2^2} \cdot G / l \leq 3
\]

Substitute the design parameters into the above equation, this gives
\[
l \geq a_1^2 + a_2^2 = \sqrt{100^2 + 120^2} \cdot 50 / 3 = 2603.4 \text{mm}
\]
Thus we may choose \( l = 2800 \text{mm} \).

The analysis for the characteristic of the follower set

The gravity balance device must take on the gravity balance force and also need to meet the precision requirement for the passive translation of the active docking ring. Since the motion direction of the active docking ring is uncertain, it is very crucial to ensure a high respond speed of the passive movement of the gravity balance device. Here the dynamic characteristics of the follower mechanism will be analyzed first.

The balance device model is shown in Fig. 5. The \( \phi \) is the angle of inclination of line BC with respect to level and the \( \psi \) is the angle of line AB with respect to level; the \( \theta \) is the swing angle of \( m_3 \); The wire rope is inelastic and fixed. Because the coefficient of friction is very small, it can be considered that the lateral motion of \( m_3 \) is almost coincident with the point A. Therefore in the simplified model the device has two DOFs, and \( \phi \) and \( \psi \) are taken as general coordinates.

We have following basic equations:
\[
\omega_{BC} = \dot{\phi} \; , \; \omega_{AB} = \dot{\psi} \; , \; \vec{v}_a = \vec{v}_e + \vec{v}_r
\]
The Center velocity of the bar AB is:
\[
\nu_e^2 = (l_{BC} \omega_{BC})^2 + (l_{ab} \cdot \frac{1}{2} \omega_{BA})^2 + 2 \omega_{BC}l_{BC} \cdot \omega_{BA} \cdot \frac{1}{2} \sin(\phi + \psi)
\]
\[
= \phi^2 l_{BC}^2 + \frac{1}{4} \psi^2 l_{BA}^2 + \phi \psi l_{BC} l_{AB} \sin(\phi + \psi)
\]

The velocity of \( m_3 \) is:
\[
\nu_{m}^{2} = (\omega_{BC}l_{BC})^{2} + (\omega_{AB}l_{AB})^{2} + 2\omega_{BC}l_{BC}\omega_{AB}l_{AB}\cos(\phi + \psi)
\]

\[
= \phi^{2}l_{BC}^{2} + \psi^{2}l_{BC}^{2} + 2\phi\psi l_{BC}l_{AB}\cos(\phi + \psi)
\] (2)

The kinetic energy of the system is:

\[
T = T_{BC} + T_{AB} + T_{m}
\]

\[
= \frac{1}{2} I_{c}\omega_{BC}^{2} + \frac{1}{2} m_{AB}v_{C}^{2} + \frac{1}{2} I_{BA}\omega_{BA}^{2} + \frac{1}{2} m_{3}v_{m}^{2}
\]

\[
= \frac{1}{2} \left( \frac{1}{3} m_{l}^{2}l_{BC}^{2}\omega_{BC}^{2} + \frac{1}{2} m_{2}\theta^{2} + \frac{1}{2} \frac{(1}{3} m_{2}l_{AB}^{2}\omega_{BA}^{2} + \frac{1}{2} m_{3}\dot{\theta}_{m}^{2}
\]

(3)

Using Eqs. (1), (2) and (3), we get

\[
T = \phi^{2} \left( \frac{1}{6} m_{l}l_{BC}^{2} + \frac{1}{2} m_{2}l_{BC}^{2} + \frac{1}{2} m_{3}l_{BC}^{2} \right) + \psi^{2} \left( \frac{1}{8} m_{2}l_{AB}^{2} + \frac{1}{2} m_{3}l_{AB}^{2} \right) + \phi\psi \cos(\phi + \psi) l_{AB}l_{BC} \left( \frac{1}{2} m_{2} + m_{3} \right)
\]

where the reference plane is the horizontal plane, then the general coordinate of F is:

\[
Q_{\phi} = \frac{\sum \delta \omega}{\delta \phi} = Fl_{BC} \cos \phi,
\]

\[
Q_{\psi} = \frac{\sum \delta \omega}{\delta \psi} = Fl_{AB} \cos \psi
\]

The derivative of kinetic energy for \(\phi\) and \(\psi\) are

\[
\frac{\partial T}{\partial \phi}, \quad \frac{d}{dT} \left( \frac{\partial T}{\partial \phi} \right)
\]

Substituting the above equations into Lagrange equation, we have:

\[
\begin{align*}
\dot{\phi}\left( \frac{1}{6} m_{l}l_{BC}^{2} + \frac{1}{2} m_{2}l_{BC}^{2} + \frac{1}{2} m_{3}l_{BC}^{2} \right) - \psi^{2} \left( \frac{31}{8} m_{2}l_{AB}^{2} + \frac{1}{2} m_{3}l_{AB}^{2} \right) + \phi^{2} \cos(\phi + \psi) l_{AB}l_{BC} \\
\left( \frac{1}{6} m_{l}l_{BC}^{2} + \frac{1}{2} m_{2}l_{BC}^{2} + \frac{1}{2} m_{3}l_{AB}^{2} \right) = 2 Fl_{BC} \cos \phi \\
\left( \frac{1}{2} m_{2}l_{BC}^{2} + \frac{1}{2} m_{2}l_{AB}^{2} + m_{3}l_{BC}^{2} \right) \psi - \sin(\phi + \psi) \left( \frac{1}{2} m_{2}l_{AB}^{2} + \frac{1}{2} m_{3}l_{BC}^{2} \right) \dot{\psi} + l_{AB}l_{BC} \\
\left( m_{2} + \frac{1}{3} m_{l} \right) \phi \dot{\psi} = Fl_{AB} \cos \psi
\end{align*}
\] (4)

Substituting for given conditions into Eq. (4) yields:
\[ F' = F_{BC} + F_{AB} = \frac{1}{2} m_3 \cos^2 \phi \cos(\psi + \phi) - \frac{1}{2} (m_1 + m_2) \sin^2 \psi \cos(\phi + \psi) + \sin(\phi + \psi) \cdot \left( \frac{1}{2} m_1 + \frac{1}{2} m_2 + \frac{3}{8} m_3 \right) \]

(5)

Since \( m_1, m_2 < m_3 \), we have \( F' \ll F \), we can deduce that the interference from the follower mechanism is very small and the follower set has a high respond speed, and the dynamic performance is good.

\[ a = \frac{\Delta F}{m \cdot g} = \frac{5.6}{53 \times 9.8} = 1.1\% \]

where \( m \) is the mass of the docking ring. The experiment demonstrates that the spring balancer can meet the requirements of the test and its balance precision reaches 1.1%. When the stretched length of the wire rope is from 300mm to 900mm, the spring balancer performs the best.

### TABLE I

<table>
<thead>
<tr>
<th>Displacement of Wire Rope (mm)</th>
<th>Up Tensile Force (N)</th>
<th>Down Tensile Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>9.8</td>
<td>7.8</td>
</tr>
<tr>
<td>150</td>
<td>6.9</td>
<td>4.9</td>
</tr>
<tr>
<td>300</td>
<td>3.9</td>
<td>5.9</td>
</tr>
<tr>
<td>450</td>
<td>0.98</td>
<td>0</td>
</tr>
<tr>
<td>600</td>
<td>0.98</td>
<td>2.0</td>
</tr>
<tr>
<td>750</td>
<td>3.9</td>
<td>2.0</td>
</tr>
<tr>
<td>900</td>
<td>5.6</td>
<td>3.9</td>
</tr>
<tr>
<td>1050</td>
<td>6.9</td>
<td>4.6</td>
</tr>
<tr>
<td>1200</td>
<td>7.8</td>
<td>5.9</td>
</tr>
<tr>
<td>Average</td>
<td>8.8</td>
<td>8.8</td>
</tr>
</tbody>
</table>

V. EXPERIMENT

The spring balancer is the important part of the gravity balance device; it takes on the gravity balance force of active docking ring and provides the tensile force for the follower mechanism. The precision of spring balancer play an important role on the accuracy of whole system.

So the precision of spring balancer is tested. The mass of spring balancer is 12kg; its bearing capacity is 50kg–60kg. In the test process, the spring balancer takes on the weight of the docking ring that is 53kg. After the spring is in a balanced state, exert certain tensile force to let the wire rope extend and reach certain stretched length and then measure the magnitude of the force. For example, when the stretched length is 30mm, the upward tensile force is 9.8 N and downward tensile force is 7.8 N; when the stretched length is 150mm, the upward tensile force is 6.9 N and downward tensile force is 4.9 N. The detail result is listed in Table 1.

From the Table 1, we can see that with the different stretched lengths of the wire rope, the mean square values of the upward tensile force and the downward tensile force are 5.6 N and 4.6 N respectively. Thus we may take the tensile force \( \Delta F \) as 5.6 N.

Define \( a \) as the precision of the balance device, it can be computed as

VI. CONCLUSION

This paper presents the gravity balance techniques used in a spacecraft docking testbed. The result of the experiment indicates that the gravity balance device can balance the gravity of the active docking ring. The follower mechanism bears characteristics of high precision, small mass and little friction. Thus the follow motion of the device has also an excellent respond speed and the balance precision of the gravity balance device can reach about 1%. The gravity balance techniques can improve the docking experiments of the test bed, and can benefit other applications in the field of spaceflight.

REFERENCES

