Simulation Analysis of Spacecraft Automatic Levelling and Equalizing Hoist Device based on Hanging Point Adjustment

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Abstract. In this paper, the virtual prototype of the Spacecraft Automatic Levelling and Equalizing Hoist Device based on Hanging Point Adjustment is modelled and the Automatic levelling and equalizing process is simulated. Variable structure adaptive control system is verified to be asymptotically stable under the interference of the support vehicle. Finally, through the refinement of the ductility of the sling, which is proved that the ductility of the sling has no effect on the stability, the system is proved to have good robustness.

1. Introduction
Hoist device, as an important actuating unit in spacecraft manufacturing, has been widely used in assembly of spacecraft, such as propellant tank assembling, modules docking, environment test, containing and transportation.¹² However, currently, the deviation of spacecraft COG from its geometric centre or theoretical centre is contributed to differences in assembly degree and operating condition. This would become hidden safety trouble such as inclinations, swing and clash, by special hoisting device of traditional fixed structure which could not self-adapt the eccentric spacecraft.¹⁶

To resolve problems above, spacecraft automatic levelling and equalizing hoist device based on hanging point adjustment has been developed in some academy. The device mainly consists of mechanical part and electric part. Mechanical part consists of hanging beam, XY-workbench, ring and so on. Electric part consists of tilt sensor, tension sensors, electrical cabinet, LED displays, motors, power supply and control software. Compositions of the device are shown in Figure 1.¹³

![Figure 1. structure diagram of the hoisting device](image-url)
At the same time, a saturated variable structure adaptive control system is designed for matching. The system is used as the reference model by the free suspension state, and is used as supporting role for support vehicle by the saturated nonlinear link, and enters the adaptive regulator by the judgment link which judges the state of suspension to system identification for unknown eccentricity. The system block diagram is shown in Figure 2. \[\text{[1-2]}\]

![Figure 2. structure diagram and block model of the hoisting device](image)

The workflow of the device is described as follows: \[\text{[1-2]}\]

1. Spacecraft and the device is connected by slings.
2. Hoisting spacecraft a little height, makes spacecraft generate a small inclination angle, and docking frame of spacecraft is suspended partially from docking frame of support vehicle.
3. Horizontal degree is measured by two-dimensional tilt sensor.
4. Land the spacecraft back on the support vehicle.
5. XY-workbench is moved to the specified location which is calculated by controller through the sensors.
6. Repeat steps above, until the horizontal degree is within the allowable range.

Although the control system is proved to be asymptotically stable by means of Lyapunov function.

The above mathematical models are based on the following two assumptions:

1) When the sling is tilted, the angular displacement is very small, and the rotation angles of the axes are independent of each other, which can be approximated by infinitesimal angular displacement.
2) Overlook the manufacturing errors and ductility of the sling.

In fact, when the sling is tilted in one direction, it will rotate in two other directions, and the angles are not strictly independent. In addition, the sling is not rigid, and it will produce elastic deformation under the action of tension. The four slings cannot be strictly equal in length, causing a new tilt. These errors will cause uncertainty in the swing of spreader.

7) In order to solve the above two problems, using ADAMS to provide geometric simulation and physical simulation environment, and using MATLAB to carry out controller calculation, the two methods of simulation analysis are put forward in this paper. The simulation analysis methods verify the effectiveness of the adjustment of the horizontal regulation controller. The slant ductility model is refined to verify that the cable ductility has no influence on the stability of the controller. To sum up, the system has good robustness.

2. Virtual simulation method

2.1. Create parts in ADAMS
The relationship between the inclination angle of the sling and the amount of adjustment, under the eccentric action of the spacecraft, is studied in the paper. The deformation of the components is not the focus of this paper. Therefore, all the parts of the virtual simulation model are modeled by rigid bodies. In addition, in order to facilitate the analysis of stability, the sling extension is ignored firstly, and the ductility of the next section is considered. As shown in Figure 3.

![Figure 3 Virtual simulation method](image)

Taking some type satellite as an example, the parameters of each part are as follows:

1. The mass of the X workbench \(G_{dx}\) is 50kg, its height is 0.2m high, and the center of mass \(H_{dx}\) is located in the body coordinate system of the spreader \((0,0,-0.1m)\).
2. The mass of the Y workbench \(G_{dy}\) is 50kg, its height is 0.2m high, and the center of mass \(H_{dy}\) is located in the body coordinate system of the spreader \((0,0,-0.3m)\).
3. The lifting beam mass \(G_{dl}\) is 200kg, its height is 0.2m, and the center of mass \(H_{dl}\) is located in the body coordinate system of the spreader \((0,0,-0.5m)\).
4. The shape of the spacecraft is 2.2m×2.2m×3.7m (length * width * height), mass 1500kg, and the original position of the center of mass \(H_{h}\) in the spacecraft body coordinate system \((0,0,-2\ m)\).
5. The height of support vehicle is 1m high, with a circular interface frame on the top surface, and its diameter is 1.2m.
6. The sky car is high 13m.
7. The sling of the hoist device is long 1m, and the distance is 1.2m x 1.2m.

### 2.2. Create constraints in ADAMS

After the creation of the rigid body, it is necessary to create constraints to define their movement form and movement range.
2.2.1. *Creates Joints*

For the rigid body which moves around the point, spherical joint is used to define the relation between the motion and the connected rigid body, such as the connection between the crane sling and the crane, the sling and the hoist device, the sling and the spacecraft. In order to accurately reflect the stress characteristics of the connecting point, the friction is set in all the revolving parts, in which the dynamic friction coefficient and the radius of rotation can be adjusted to speed up the stability of the model at the equilibrium point.

For the connection of the crane sling and the universal joint with lifting points, the universal joint is adopted, and the setting method is similar to the spherical joint.

2.2.2. *Fixed joints*

Fixed joints are used to connect between the crane and the earth, the carriage and the earth. Fixed joints are also used to the relative displacement and relatively static connection between the X worktable, the Y worktable and the hanging beam. Because, their the relative displacement and relative rest are in different working conditions, in which the XY worktable does not move when the sling is hoisted, so the position between the three is still relatively stationary. Therefore, for each simulation, fixed constraints can be adopted, and the relative displacement between two adjacent simulations can be achieved by modifying the position parameter method of the rigid body to achieve the purpose of simulation.

2.2.3. *Contact joints*

When the spacecraft hoisted, the contact and interaction force are produced between spacecraft and the support vehicle, before the spacecraft completely leaving the support vehicle. Therefore, the contact joint is used between spacecraft and the support vehicle.

2.3. *Create loads in ADAMS*

Due to simulation of the change of the tilt angle stably after adjustment each time, the crane is no longer working, and the hoist device and the spacecraft are only under their own gravity (the support of the stents is set by the constraints imposed by the above). So, it only needs to apply gravity.

2.4. *Create measure in ADAMS*

According to the workflow of the hoist device, it is necessary to measure the inclination of the hoist device and the pulling force of the sling as the input and feedback for the control system. Therefore, measure is created on the simulation model, also to draw real-time curves of inclining angle and pulling force. For the inclination angle between the hoist device and the spacecraft, a fixed point can be selected on the rigid body to measure the Euler angle between the coordinate system and the geodetic coordinate system. For the sling between the hoist device and the spacecraft, the pulling force can be measured by the restraint imposed between the sling and the spacecraft (or hoist device).

2.5. *Calculation of adjustment in Matlab*

According to the state equations of the control system designed, it is programmed in Matlab environment. Its input is the inclination angle and pulling force from ADAMS simulation, and the initial masses of the hoist device and spacecraft. And its output is the adjusting amount of the hoist device. The system state equations are as shown in Figure 4.

2.6. *Simulation flow*

According to the block diagram and state equation of this adjustment method, the controller, the reference model and the adaptive regulator are all discrete numerical calculations, which can be programmed by MATLAB software to realize the calculation and judgment function. The output of the controlled object should be the result of the physical system movement, so the control amount
calculated by the MATLAB is used as the input of virtual prototype. The simulation software ADAMS is used to simulate the motion of the system in a virtual environment, observe the results of the motion, and use the results as feedback entering the MATLAB software to calculate the control quantity for the next cycle. Iteratively iterated, until results of final inspection and adjustment meet the requirements of use, in order to verify the rationality of controlled object modeling and the effectiveness of control. The specific flow chart is shown in Figure 5. [1]

Where

\[
f(x) = \begin{cases} 
-x_{lm} \leq x \\
\frac{x_{lm}}{x} & \text{if } x > x_{lm} \\
-x_{lm} & \text{if } x < -x_{lm} 
\end{cases}
\]

\[
H_{bg}(k+1) = \begin{cases} 
\frac{x_{3}(k) - x_{3}(k-1)}{x_{3}(k-1) - x_{3}(k)} & \text{if } |x_{3}(k-1)| < x_{lm} \\
\frac{x_{4}(k) - x_{4}(k-1)}{x_{4}(k-1) - x_{4}(k)} & \text{if } |x_{4}(k-1)| < x_{lm} \\
H_{bg}(k), |x_{3}(k)| \geq x_{lm}, \text{ and } |x_{4}(k)| \geq x_{lm} & \text{otherwise}
\end{cases}
\]

\[
H_{kg}(k+1) = \frac{H_{bg}(k), |x_{3}(k)| \geq x_{lm}, \text{ and } |x_{4}(k)| \geq x_{lm}}{H_{bg}(k), |x_{3}(k)| \geq x_{lm}, \text{ and } |x_{4}(k)| \geq x_{lm}}
\]

\[
K(k) = \frac{\frac{x_{3}(k) - x_{3}(k-1)}{x_{3}(k-1) - x_{3}(k)} \cdot H_{bg}(k)}{x_{3}(k) - x_{3}(k-1)}
\]

and use the results as feedback entering the MATLAB software to calculate the control quantity for the next cycle. Iteratively iterated, until results of final inspection and adjustment meet the requirements of use, in order to verify the rationality of controlled object modeling and the effectiveness of control. The specific flow chart is shown in Figure 5. [1]

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**Figure 4** System state equations [1]

**Figure 5** Simulation flow chart [1]
3. Simulation result

3.1. Simulation results of variable structure non adaptive control with support vehicle

Table 1 Simulation results of variable structure non adaptive control with support vehicle

| No. | $x_1$ (mm) | $x_2$ (mm) | $r_x$ (mm) | $r_y$ (mm) | $x_3$ (°) ($\theta_1$) | $x_4$ (°) ($\theta_2$) | $r(N)$ | $\varphi_1(°)$ | $\varphi_2(°)$ | $\varphi(°)$ | Levelness (mm/m) |
|-----|------------|------------|------------|------------|-----------------------|-----------------------|--------|---------------|---------------|--------------|-----------------|
| 0   | 0          | 0          | 0          | 0          | -0.4061               | 0.3232                | 14012  | 0.3232        | 0.5190        | 9.059        |
| 1   | 12.9       | 16.7       | 12.9       | 16.7       | -0.4348               | 0.2498                | 14710  | 0.2498        | 0.5014        | 8.752        |
| 2   | 10.0       | 17.9       | 22.9       | 34.6       | -0.005106             | 0.02169               | 14711  | 0.02169       | 0.02228       | 0.3889       |
| 3   | 0.9        | 0.2        | 23.8       | 34.8       | -0.003629             | 0.0146                | 14710  | 0.0146        | 0.01504       | 0.2626       |
| 4   | 0.6        | 2.4        | 24.4       | 35.0       | -0.002157             | 0.00979               | 14711  | 0.00979       | 0.01021       | 0.1782       |
| 5   | 0.4        | 0.1        | 24.8       | 35.1       | -0.001421             | 0.006926              | 14710  | 0.006926      | 0.007070      | 0.1234       |

3.2. Simulation results of saturated variable structure adaptive control with support vehicle

Table 2 Simulation results of variable structure adaptive control with support vehicle

| No. | $x_1$ (mm) | $x_2$ (mm) | $r_x$ (mm) | $r_y$ (mm) | $x_3$ (°) ($\theta_1$) | $x_4$ (°) ($\theta_2$) | $r(N)$ | $\varphi_1(°)$ | $\varphi_2(°)$ | $\varphi(°)$ | Levelness (mm/m) |
|-----|------------|------------|------------|------------|-----------------------|-----------------------|--------|---------------|---------------|--------------|-----------------|
| 0   | 0          | 0          | 0          | 0          | -0.4061               | 0.3232                | 14012  | 0.3232        | 0.5190        | 9.059        |
| 1   | 12.9       | 16.7       | 12.9       | 16.7       | -0.4348               | 0.2498                | 14710  | 0.2498        | 0.5014        | 8.752        |
| 2   | 10.0       | 17.9       | 22.9       | 34.6       | -0.005106             | 0.02169               | 14711  | 0.02169       | 0.02228       | 0.3889       |
| 3   | 0.9        | 0.2        | 23.8       | 34.8       | -0.003629             | 0.0146                | 14710  | 0.0146        | 0.01504       | 0.2626       |
| 4   | 1.8        | 0.5        | 25.6       | 35.3       | 0.000049              | 0.00086               | 14710  | 0.000049      | 0.000866      | 0.01503      |
| 5   | 0.1        | 0          | 25.7       | 35.3       | 0.000049              | 0.000104              | 14711  | 0.000104      | 0.0001147     | 0.02002      |

3.3. Result analysis

Compare the output results of Table 1 and Table 2, as shown in Figure 6 and Figure 7.

![Figure 6](a) Variation curve of spacecraft inclination angle $\varphi$, and local large map

![Figure 7](a) Horizontal variation curve of spacecraft interface, and local large map
1. The initial state and the 1st adjustment in Figure 6 (a) and Figure 7 (a), can be seen that the tilt angle on the hoist device is nearly the same, near the maximum angle of inclination; and the inclination and horizontal degree between the spacecraft and the support vehicle are almost the same. It is verified that the saturation nonlinearity of the support vehicle to the spacecraft, and the incremental adjustment strategy effectively avoids the problem of invariable input and output.

2. From the second, third, fourth adjustment, it can be seen that the inclination of the interface of the spacecraft is rapidly reduced first, and then slowly near the zero line. The trend of the graphic change is similar to that of Figure 6 and Figure 7, indicating that the tilt angle of the spacecraft is out of the limit area and enters a completely suspended area without the support of the support vehicle. It converges to zero at last, so the hybrid control structure converges to stability.

3. In Figure 6(b) and Figure 7(b), the output results locally amplified are shown that the adaptive control can still improve the convergence speed and improve the control precision when the spacecraft inclining angle is out of the limit area and entering the completely suspended area without the support of the support vehicle.

4. According to Figure 7(b), it is known that after two times adjustments, the level of the interface of the spacecraft has reached 0.4mm/m, meeting the technical index of 5mm/m; and only need to adjust two times to meet the requirements of use. The results of adaptive control can meet the requirement of higher accuracy.

4. Refinement and simulation of the model

4.1. Refinement of the model

After preliminarily simulating the basic movement of the model, a more complex element can be added to the model: the rigid sling originally in the model is modified to a flexible sling, which makes the model more approximate to the real system, and studies the effect of the ductility of the sling to the horizontal adjustment precision, and verifies the correctness of the assumption that the ductility can be ignored. The concrete refinement method is to replace the rigid part and the corresponding ball pair with an equal length spring, whose spring stiffness coefficient is set by Doleco lifting & lashing Ltd.: K=10000N/mm.

4.2. Simulation results of refined model

Table 3 Simulation results of refinement of the model of variable structure adaptive control with support vehicle

| No. | x1 (mm) | x2 (mm) | r1 (mm) | r2 (mm) | θ1 (°) | θ2 (°) | r (N) | φ1 (°) | φ2 (°) | φ (°) | levelness (mm/m) |
|-----|---------|---------|---------|---------|--------|--------|------|-------|-------|-------|------------------|
| 0   | 0       | 0       | 0       | 0       | -0.3797| 0.3000 | 13983| -0.3800| 0.3002| 0.4843| 8.452            |
| 1   | 12.0    | 15.6    | 12.0    | 15.6    | -0.4075| 0.2606 | 14599| -0.4088| 0.2617| 0.4854| 8.472            |
| 2   | 10.4    | 16.8    | 22.4    | 32.4    | -0.03776| 0.02534| 14710| -0.04002| 0.02705| 0.04830| 8.431            |
| 3   | 1.1     | 1.7     | 23.5    | 34.1    | -0.01544| 0.01655| 14710| -0.01775| 0.01827| 0.02547| 0.4446          |
| 4   | 1.3     | 1.2     | 24.8    | 35.3    | 0.000558| 0.00653| 14710| -0.001780| 0.008269| 0.008458| 0.1476          |
| 5   | 0.4     | 0       | 25.2    | 35.3    | 0.000558| 0.003591| 14710| -0.001779| 0.005246| 0.005339| 0.09668         |

4.3. Result analysis for refined model

Compare the output results of Table 2 and Table 3, as shown in Figure 8 and Figure 9.

As shown in Figure 6, Figure 7, Figure 8, and Figure 9, the simulation output of the flexible sling model is the same as the simulation output of the rigid sling model. Their general trend is the same which converges to the zero line. It shows that the ductility of the flexible sling has no obvious influence on the level regulation, and does not affect the stability of the control method. The variable structure adaptive control method is as effective as the flexible sling model.
From Figure 6, Figure 7, Figure 8, and Figure 9, it is known that the simulation output of the flexible sling model and the simulation output of the rigid sling model have certain deviations, but the deviation is gradually reduced. It shows that the ductility of the flexible sling affects the precision of horizontal adjustment to a certain extent. The deviation of the first and second adjustment levels is about 0.5mm/m, and the deviation gradually diminishing. But the effect is little: the result of the second adjustment is only 1mm/m, which has met the technical index of 5mm/m, so does not affect the use requirements.

5. Conclusions

In summary, the conclusions is shown as follows:

1) The mechanism and the control system of the hoist device can adjust the eccentric of the spacecraft to meet the requirements of the horizontal adjustment by simulation and verification.

2) The saturated variable structure nonlinear control system has good stability and effectively solves the limitation of the support vehicle to the spacecraft. The adaptive control system of system identification has good stability, and can accelerate convergence and improve control precision of the system.

3) The ductility of the sling does not affect the stability of the control system. It has a certain degree of influence on the control accuracy, but it does not affect the use of it.

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