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Design and Development of Automatic Leveling and Equalizing Hoist Device for Spacecraft

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***Abstract*—**To solve the quick and accurate level-adjusting problem in the process of spacecraft precise mating, automatic leveling and equalizing hoist device for spacecraft is developed. Based on lifting point adjustment by utilizing XY-workbench, the leveling and equalizing controller by a self-adaptive control algorithm is proposed. By simulation analysis and lifting test using engineering prototype, validity and reliability of the hoist device is verified, which can meet the precision mating requirements of practical applications for spacecraft.

***Keywords*—**automatic leveling and equalizing, hoist device, lifting point adjustment, self-adaptive control

I. Introduction

HOIST device, as one of the important Mechanical Ground Supporting Equipment (MGSE), has been widely used in the assembly and integration of spacecraft, such as mating between payload module and satellite platform, assembling for heavy camera and antenna, lifting whole satellite, containing and transportation for spacecrafts.

Because of the influence on the assembly schedule, differences of the hoisting status, spacecraft centers of gravity (COG) usually deviate from their geometric centers or theoretical centers [1]. This would cause inclination, swing and lateral forces (such as point-to-point contact) in the entire course, which usually leads to payloads' distortion, damage, or even complete destruction, and/or hurt workers and nearby objects. To achieve the leveling control, traditional adjustment devices using 4-rope length adjustment or counterweigh adjustment are universally adopted in practical applications [2]-[8]. Disadvantages of these methods are obvious, on the one hand, great labor intensity, low efficiency, and low precision, on the other hand, hidden safety risks such as inclination, swing or resting against guide pins [9].

To solve these problems effectively, an automatic leveling and equalizing hoist device which adopts tilt angles and tensions as input, and lifting point adjustment as output, is designed and developed [10]. According to simulation analysis by ADMAS and hosting tests [11], it can meet the requirements of quick and accurate level-adjusting for spacecrafts.

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II. Structure of the Hoist Device

In this section we present an engineering prototype of the Automatic Leveling and Equalizing Hoist Device. This hoist device mainly consists of mechanical subsystem and electrical control subsystem. Mechanical subsystem mainly includes hoisting beam, XY-workbench, and hoisting ring unit. Electrical control subsystem includes tilt sensor, tension sensor, electrical cabinet, light-emitting diode (LED) display, stepper motor (including motor driver), and power supply. The XY-workbench is mounted on the center of the hoisting beam, and the hoisting ring unit is installed on the XY-workbench. Moving the XY-workbench can change the lifting point. LED displays are mounted the cover of XY-workbench and the hoisting beam. The tilt-measuring circuitry and tension-measuring circuitry turn on different LED to indicate the measurement values. One end of the hoisting beam is constructed to fix tilt sensor and electrical cabinet, whereas power supply is placed at the other end. Under the hoisting beam, four slings with 4 tension sensors are linked. The structure of the hoist device is shown in Fig. 1, and the appearance of the engineering prototype is shown in Fig. 2.

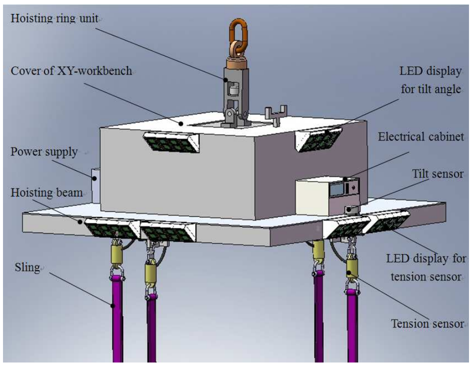

Fig. 1 Structure of the hoist device

Fig. 2 Physical appearance of the hoist device

III. Theoretical Model

A. Simplification of Boundary Condition

To realize leveling and equalizing in the entire hoisting course, it is very important to accurately obtain the mass properties of spacecraft. With the influence on the assembly schedule, furthermore the supporting force and contact point are changed with the changes of hoisting process, so the mass and center of gravity of spacecraft cannot be measured directly. We can obtain mass properties of spacecraft only using indirectly measurement, such as tension and tilt angle.

In the course of spacecraft assembly and integration, the tilt angles in X and Y direction can be approximately considered as independent. So we can independently analyze the hoisting process with the reference coordinate system $\sum$ OXYZ. And we assume that the system involved the spacecraft and hoist device satisfies the reasonable conditions as follows:

(1) The lengths of the four slings between the hoist device and the spacecraft are the same. Stress deformations of the slings are negligible.

(2) The hoist device and the spacecraft are regarded as rigid bodies, and their stress deformations can be ignored during hoisting.

(3) Based on the actual engineering requirements, the mass of the payload is unknown and the COG position is uncertain either.

(4) The leveling adjustment does not begin until the system stops swing.

B. Modeling and Analysis

Because of the contact between spacecraft and the supporting equipment during the hoisting process, it exists unknown supporting force which makes the hoisting process more complicated as shown in Fig.3(b). So the horizontal work condition and the inclination work condition without supporting force are analyzed firstly as easy cases, shown in Fig. 3 (a), (c).

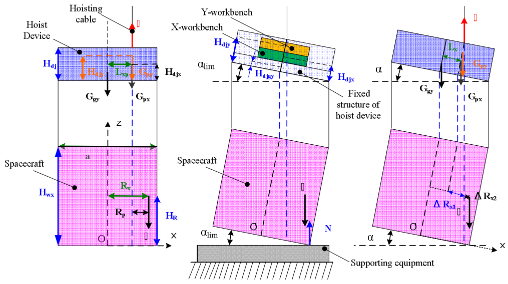

Fig.3 Mechanical analysis for spacecraft-Hoist Device system

According to Fig.3(a), the geometric relationship, and moment equilibrium equation, can be described as follows:

$$\begin{cases} L_{xp} = R_x - R_p \\ GR_p = G_{gy} L_{xp} \end{cases} \quad (1)$$

Where,

L_{xp} as theory center to keep X-workbench balance, m; R_x as X direction projection of spacecraft COG, m; R_p as constant distance between balance position and R_x, m; G as gravity of spacecraft, N; G_{gy} as gravity of the fixed structure of hoist device, N.

It is general obtained through (1):

$$\begin{cases} L_{xp} = \dfrac{GR_x}{G + G_{gy}} \\ R_p = \dfrac{G_{gy} R_x}{G + G_{gy}} \end{cases} \quad (2)$$

According to Fig.3(c), the geometric relationship, and moment equilibrium equation, can be described as follows:

$$\begin{cases} \Delta R_{x1} = H_{dj} \tan\beta + (H_{wx} - H_R)\tan\beta \\ G\Delta R_{x2} \cos\beta = G_{gy}[L_x \cos\beta + (H_{dj} - H_{djgy})\sin\beta] \\ +G_{px}(H_{dj} - H_{djx})\sin\beta + G_{py}(H_{dj} - H_{djy})\sin\beta \\ R_x = L_x + \Delta R_{x1} + \Delta R_{x2} \end{cases} \quad (3)$$

Where,

H_{dj} as total height of the hoist device, m;

H_{wx} as total height of the spacecraft, m;

H_R as COG height of spacecraft, m;

H_{djgy} as COG height of the fixed structure of the hoist device, m;

H_{djx} as COG height of X-workbench, m;

H_{djy} as COG height of Y-workbench, m;

G_{px} as gravity of X-workbench, N;

G_{py} as gravity of Y-workbench, N;

L_x as current location X-workbench, m;

ΔR_{x1} as projection of inclination height of spacecraft and hoist device in the R_x direction, m; ΔR_{x2} as difference among R_x, L_x and ΔR_{x1}, m; α as the angle between axis X and horizontal surface, rad.

We can obtain that

$$\begin{aligned} R_x &= L_x + H_{dj}\tan\beta + (H_{wx} - H_R)\tan\beta \\ &+ \frac{1}{G\cos\beta}\{G_{gy}[L_x\cos\beta + (H_{dj} - H_{djgy})\sin\beta] + \\ &G_{px}(H_{dj} - H_{djx})\sin\beta + G_{py}(H_{dj} - H_{djy})\sin\beta\} \end{aligned} \quad (4)$$

According to (2), (4), L_{xp} is shown as in (5).

$$\begin{aligned} L_{xp} &= \frac{G}{G + G_{gy}}[L_x + H_{dj}\tan\beta + (H_{wx} - H_R)\tan\beta] \\ &+ \frac{1}{(G + G_{gy})\cos\beta}\{G_{gy}[L_x\cos\beta + (H_{dj} - H_{djgy})\sin\beta] \\ &+ G_{px}(H_{dj} - H_{djx})\sin\beta + G_{py}(H_{dj} - H_{djy})\sin\beta\} \end{aligned} \quad (5)$$

Generally, the tilt angle between spacecraft and supporting equipment is no more than 3°, so (5) can be simplified as follow:

$$L_{xp}=L_x+\frac{\beta}{G+G_{gy}}[G(H_{dj}+H_{wx}-H_R)+G_{gy}(H_{dj}-H_{djgy})+G_{px}(H_{dj}-H_{djx})+G_{py}(H_{dj}-H_{djy})] \quad (6)$$

As shown in the Fig.3 (b), before spacecraft leaves the supporting equipment, supporting equipment makes a restrictive effect to prevent spacecraft from inclining further, compared with the steady state shown in Fig.3(c), just like a limiting switch. The maximum amplitude is the maximum tilt angle ~ allowed when spacecraft is still on the supporting equipment, as shown in Fig. 4.

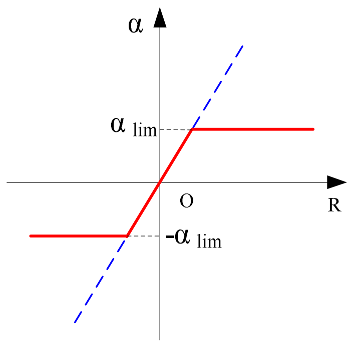

Fig. 4 Schematic chart of limiting switch

IV. Design for Leveling Adjustment Controller

For this situation, incremental adjustment algorithms can be adopted. The (6) can be shown as in (7):

$$\begin{cases}\Delta L_{x(k+1)}=L_{x(k+1)}-L_{x(k)}=C_x\alpha_{(k+1)}\\ L_{x(k+1)}=L_{x(k)}+\Delta L_{x(k+1)}=L_{x(0)}+\sum_{i=1}^{k+1}\Delta L_{x(i)}\\ =L_{x(0)}+C_x\sum_{i=1}^{k+1}\alpha_{(i)}\end{cases} \quad (7)$$

Where,

$$C_x=\frac{1}{G+G_{gy}}[(H_{dj}+H_{wx}-H_R)G+G_{gy}(H_{dj}-H_{djgy})+G_{px}(H_{dj}-H_{djx})+G_{py}(H_{dj}-H_{djy})]$$

$L_{x(i)}$ as location of X-workbench, m;

$\Delta L_{x(i)}$ as adjustment displacement of X-workbench, m ;

$\alpha_{x(i)}$ as tilt angle between X-axis of hoist equipment and horizon surface, rad.

Control strategy of X-direction is as follows:

(1) Initialization. XY-workbench is located at center of hoist device, so the threshold value $L_{x(0)}=0$, $\alpha_{(0)}=0$.

(2) At the first hoisting, $\alpha_{(1)}=\alpha_{\lim}$, we can calculate $\Delta L_{x(1)}$ according to (7), then X-workbench moves $\Delta L_{x(1)}$ along with X-axis to $L_{x(1)}=L_{x(0)}+\Delta L_{x(1)}$.

(3) At the second hoisting, $\alpha_{(2)}=\alpha_{\lim}$, we can calculate $\Delta L_{x(2)}$ according to (7), then X-workbench moves $\Delta L_{x(2)}$ along with X-axis to $L_{x(2)}=L_{x(0)}+\Delta L_{x(1)}+\Delta L_{x(2)}$.

(4) At the k*th* hoisting, $\alpha_{(k)}<\alpha_{\lim}$, we can calculate $\Delta L_{x(k)}$ according to (7), then X-workbench moves $\Delta L_{x(k)}$ along with X-axis to $L_{x(k)}=L_{x(0)}+\Delta L_{x(1)}+\Delta L_{x(2)}+\ldots+\Delta L_{x(k)}$.

At the (k+1)*th* hoisting, check whether α(k+1) meets horizontal degree requirement or not. If α(k+1) does not meet the horizontal degree requirement, repeat the circle above. If α(k+1) meets the horizontal degree requirement, adjustment is completed, then spacecraft will be hoisted directly.

Similarly, the control strategy of Y-direction is as follows:

$$\begin{cases}\Delta L_{y(k+1)}=L_{y(k+1)}-L_{y(k)}=C_y\beta_{(k+1)}\\ L_{y(k+1)}=L_{y(k)}+\Delta L_{y(k+1)}=L_{y(0)}+\sum_{i=1}^{k+1}\Delta L_{y(i)}\\ =L_{y(0)}+C_y\sum_{i=1}^{k+1}\beta_{(i)}\end{cases} \quad (8)$$

Where,

$$C_y=\frac{1}{G+G_{gy}+G_{px}}[(H_{dj}+H_{wx}-H_R)G+G_{gy}(H_{dj}-H_{djgy})+G_{px}(H_{dj}-H_{djx})+G_{py}(H_{dj}-H_{djy})]$$

$L_{y(i)}$ as location of Y-workbench, m;

$\Delta L_{y(i)}$ as adjustment displacement of Y-workbench, m ;

$\beta_{y(i)}$ as tilt angle between Y-axis of hoist equipment and horizontal surface, rad.

V. Simulation and Hoisting Test

A. Simulation analysis

A simplified model including spacecraft, hoist device, supporting equipment, and overhead crane is established by the simulation software ADAMS as shown in Fig.5.

The system simulation parameters are as follows: G =1500kg, R_x =30mm, R_p =40mm, G_{gy} =200kg, G_{px} =50kg, G_{py} =50kg. The linear deformation of sling is 1/1000 under rated load. The spacecraft is supported by the supporting equipment.

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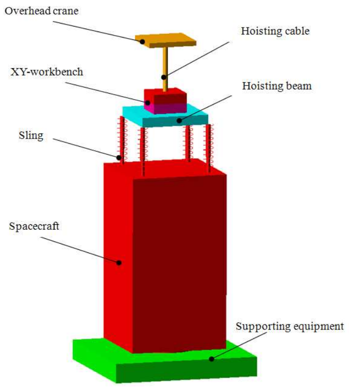

Fig. 5 Simulation model

One tilt sensor is set on the hoist device to measure the X-axis tilt angle α and Y-axis tilt angle β. According to (7) and (8), adjustment displacement of XY-workbench can be calculated, whose results can be used to optimize the parameters of the model. Another tilt sensor is set on the spacecraft to measure the actual tilt angle γ of X-axis and actual tilt angle δ of Y-axis.

Then we use ADAMS software to simulate the whole lifting course according to the adjustment algorithm. The simulation values of all the parameters are described in Table I. The adjustment displacements of XY-workbench are shown in Fig. 6. The relation between adjustment times and horizontal degree (H.D.) is shown in Fig. 7.

TABLE I
SIMULATION VALUE FOR THE PARAMETER MODEL

Times	α(°)	β(°)	γ(°)	δ(°)	H.D.(mm/m)	X(mm)	Y(mm)
0	0	0	0	0	0	0	0
1	0.1727	0.2302	0.1728	0.2303	7.04	7.2	9.3
2	0.1721	0.2296	0.1725	0.2301	7.03	14.3	18.5
3	0.169	0.2256	0.1698	0.2266	6.92	21.3	27.6
4	0.1153	0.1534	0.1164	0.1549	4.74	26.1	33.8
5	0.0077	0.01037	0.00898	0.01207	0.367	26.4	34.2
6	0.00043	0.000057	0.00133	0.00168	0.053	26.42	34.20
7	0.00012	0.000658	0.00141	0.00238	0.066	-	-

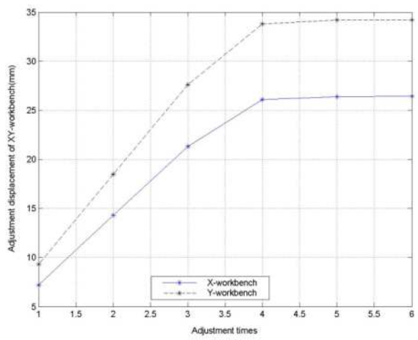

Fig. 6 Compared chart of adjusting quantities of XY-workbench

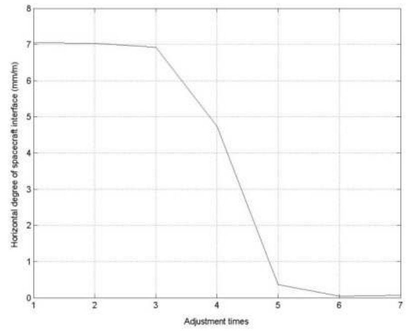

Fig. 7 Relation chart between adjustment times and horizontal degree

According to the analysis for Table I, we can make the conclusions as follows:

(1) Through the first, second, and third adjustments, it can be seen that the tilt angles measured on the hoist device are nearly the same, the tilt angle is the maximum angle, and the adjustment displacements of XY-workbench are orderly increasing. Furthermore, the tilt angle of the hoist device and the tilt angle of spacecraft are nearly the same. Simulation results show that supporting equipment has an amplitude restrictive effect to prevent spacecraft from inclining further, and the incremental adjustment strategy is very effective and reliable, which can avoid the problem of the same input leading to unchangeable output. From the fourth, fifth, sixth adjustment, it is shown that tilt angles on the hoist device decrease rapidly, and tilt angle of the spacecraft and tilt angle of the hoist device are the same. The adjustment displacement of XY-workbench is decreasing with a fixed value. All of these are explained that the tilt angle of spacecraft enters in the linear area, and the adjusting method algorithm has a better convergence.

(2) During the sixth adjustment, order of magnitude accuracy is intentionally increased, causing the result that there is no obvious change in the seventh tilt angle measured. It shows that the XY-workbench of 0.1mm precision has reached the limit of the adjustment method and met the operation requirement.

(3) From the first to fifth measurements, there is hardly any differences between the spacecraft actual tilt angle and that of hoist device. However, during the sixth and seventh measurements, the actual tilt angle of spacecraft has exceeded that of hoist device. No matter how to increase the adjustment precision, the actual tilt angle of spacecraft and horizontal degree cease from decreasing. On the contrary, they have little increase. It illustrates that the limit of this leveling adjustment is 0.05mm/m, which does meet the practical applications.

B. Hoisting Test Hoisting Test

To verify the horizontal degree, several hoisting tests have been conducted by lifting the actual spacecraft. The validity of control algorithm, and convergence speed of control system have been verified in detail, then the convergence times have also been tested and the algorithm has been optimized. The test data are described as Table II.

TABLE II
TEST VERIFICATION DATA OF THE HOIST DEVICE

No.	X(mm)	Y(mm)	Adjustment times	H.D. （mm/m）
1	23.8	-9.5	3	0.8
2	26.3	-7.5	3	4.0
3	-1.7	30.2	3	1.3
4	-2.5	-32.0	3	1.8
5	-4.6	-21.6	3	0.2
6	-3.5	-35.2	3	0.6
7	24.1	40.7	3	0.4
8	18.0	32.3	3	0.4
9	25.6	44.6	3	0.3
10	18.4	36.6	3	0.6
11	19.6	38.5	2	0.8
12	24.1	50	3	0.0
13	27.9	47.3	3	2.0
14	16.2	34.2	3	3.8

Table II is shown that 14 different hoisting processes can be completely adjusted through two or three times, the horizontal degree is less than 4.0mm/m, and the validity of control algorithm and convergence speed of control system have been well verified. To improve the precision of leveling adjustment, the adjustment times can be increased properly. Considering the efficiency and precision of hoisting, 3 adjustment times can be acceptable.

VI. CONCLUSION

Based on lifting point adjustment by utilizing XY-workbench, automatic leveling and equalizing hoist device for spacecraft is designed and developed. According to the spacecraft-hoist device system models, the leveling adjustment controllers based on self-adaptive control algorithm are designed to obtain the system running in high performance. Simulation results show that this system has higher adjustment precision and stronger reliability in the hoisting process. Then the technical parameters and control algorithm are optimized by lifting test using the engineering prototype. Experimental results demonstrate that the controller can easily accomplish the automatic leveling adjustment, and the adjustment precision can meet the requirements of practical applications for spacecraft.

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