Analysis Method for the Mass Center of Low Earth Orbit Remote Sensing in Orbit

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Abstract. A real-time method for estimating the mass center of low earth orbit (LEO) remote sensing satellite in orbit is introduced in this paper. LEO remote sensing satellite requires highly on calculating the position of its mass center, due to the need of precise orbit determination and attitude control. This article offers an analysis method for the factors that play a leading role in the change of the centroid of satellite in orbit, which are the consuming of satellite fuel, the circulation of satellite-to-ground data transmission antenna and rotation of solar arrays. The parameters for calculating the centroid of LEO remote sensing satellite are defined, and a formula for computing the position of the satellite mass center in orbit is proposed.

1. Introduction
Generally, the orbit accuracy of LEO remote sensing satellite could reach tens of centimeters level. Dual frequency GPS is wildly used for geometric orbit determination and its accuracy can be improved by dynamic orbit determination[1-6]. Therefore it is necessary to analyze the change of the satellite centroid while it is in orbit, in order to provide specific date for dynamic orbit determination. An on-line method to identify the mass properties of satellite such as centroid, inertia matrix based on recursive least square (RLS) algorithm was proposed by Wang Shuting in Harbin Industrial University, and an alternative structural total least square algorithm to figure out the mass center of satellite through structural propulsive model was introduced by Lin Jiawei in Beijing Institute of control Engineering. All the algorithms above need to use sensors and thrust devices on the satellite, which would increase fuel and resource consumption, and are hardly to obtain real-time data of satellite mass center.
This paper presents an estimation method to calculate the position of the satellite mass center directly, according to the position change of the equipment including large antenna, solar panels and fuel on the LEO remote sensing satellite.

2. Analysis of the influence of satellite-to-ground data transmission antenna on the position of the mass center
Two satellite-to-ground data transmission antennas A and B were carried on a LEO sensing satellite. The head of the antenna A and B could rotate round X-axis and Y-axis direction, and the relation between X-axis and Y-axis to the satellite coordinate system can be seen in Fig.1, which shows the simplified mass model of two satellite-to-ground data transmission antennas.
The position and mass distribution of antenna’s deployable arm relatively to the zero position of the satellite-to-ground data transmission antennas A and B, let the rotation angles of the reflector assembly about Y-axis are $\alpha_1$, $\alpha_2$, the rotation angles of Y-axis rotating joint and the reflecting surface assembly around X-axis are $\beta_1$, $\beta_2$, and the calculation process of the change of the satellite centroid could be computed as follows:

- **The influence of satellite in X direction**
  When the reflector assembly rotates round Y-axis, it will affect the position of satellite mass center in X direction. The weight of the reflector assembly is about 1.7kg, the distance between the centroid of reflector and Y-axis of the antenna is about 170mm, as a result the change of the centroid of satellite in X direction is:

  $$\Delta r_{x1} = \frac{1.7 \times 170 \sin \alpha_1}{M}$$

  $$\Delta r_{x2} = \frac{-1.7 \times 170 \sin \alpha_2}{M}$$

  Where, M is the weight of satellite.

- **The influence of satellite in Y direction**
  The distance between X-axis and Y-axis of the satellite-to-ground data transmission antenna is 148mm, the distance between the mass center of the relative fixed part between X and Y-axis to X-axis is 115mm, and weighted 2.8kg. The change of the position of satellite centroid in Y direction relative to the zero position of the antenna is:

  $$\Delta r_{y1} = \frac{2.8 \times 115 \sin \beta_1 + 1.7 \times (148 \cos \alpha_1 + 170 \cos \alpha_1 \cos \beta_1)}{M}$$

  $$= \frac{(573.6 + 289 \cos \alpha_1) \sin \beta_1}{M}$$

  $$\Delta r_{y2} = \frac{-2.8 \times 115 \sin \beta_2 - 1.7 \times (148 \cos \alpha_2 + 170 \cos \alpha_2 \cos \beta_2)}{M}$$

  $$= -\frac{(573.6 + 289 \cos \alpha_2) \sin \beta_2}{M}$$

  (2)

- **The influence of satellite in Z direction**
  Relative to the zero position of the satellite-to-ground data transmission antenna, the change of the position of the satellite centroid in Z direction is as follows:

  $$\Delta r_{z1} = \frac{2.8 \times 115 (1 - \cos \beta_1) + 1.7 \times (148 (1 - \cos \beta_1) + 170 (1 - \cos \alpha_1 \cos \beta_1))}{M}$$

  $$= \frac{743.6 - 573.6 \cos \beta_1 - 170 \cos \alpha_1 \cos \beta_1}{M}$$

  $$\Delta r_{z2} = \frac{2.8 \times 115 (1 - \cos \beta_2) + 1.7 \times (148 (1 - \cos \beta_2) + 170 (1 - \cos \alpha_2 \cos \beta_2))}{M}$$

  $$= \frac{743.6 - 573.6 \cos \beta_2 - 170 \cos \alpha_2 \cos \beta_2}{M}$$

  (3)

3. **Analysis of the influence of solar array on the position of the centroid of satellite**
Double symmetry structure of solar arrays is adopted in LEO remote sensing satellite. The mass distribution of each side of the solar panel is shown in Figure 2:

![Figure 2 The position of the centroid of deployed solar panel](image)

In the working orbit, the solar arrays rotate round the axis of its driving mechanism 360 degrees per orbit. The mass center of the solar panel will change constantly when it rotates, if the mass center of the solar panel deviates from the axis of its driving mechanism, or the axis of the solar panel driving mechanism deviates from Y-axis of satellite, which would affect the centroid of the satellite. The mass center of the solar panel is about 12.5mm away from its axis, the angle between the centroid and the long side of the solar panel is about 34.5°, and each deployed solar panel weighs 39kg approximately.

If the rotation angle of the solar array is \( \theta \) relative to its zero position, it can be calculated that the position variation of satellite centroid caused by the rotation of solar array is:

The change of the centroid of satellite in X direction:

\[
\Delta x_{yy} = \frac{[10.31 - 12.5 \cos(\theta + 34.5)] \times 39 \times 2}{M}
\]

(4)

The change of the centroid of satellite in Z direction:

\[
\Delta z_{yy} = \frac{12.5 \sin(\theta + 34.5)] \times 39 \times 2}{M}
\]

(5)

There is no change of the centroid of satellite in Y direction.

4. Analysis of the influence of fuel distribution on the position of satellite centroid

The fuel tank of the satellite has a capacity of 100 liters. There are 75L liquid (75kg) and 25L gas when launching, due to the gravity effect, the fuel is at the bottom of tank, distributed in lower hemisphere and column area. After entering the orbit, the surface tension becomes the key factor to determine the distribution of fuel instead of gravity. Since there are many fuel collection devices on the inner surface of the tank column and in the hemispheres at both ends, the fuel is preferentially located at the above area. Affected by the consumption of fuel and acceleration by track maintaining, the fuel distribution becomes complex and uncertain.

When the satellite is flying stably in a static environment, the orbit angular velocity (along the pitch axis of satellite), the revision control of bias angular velocity (along the roll axis of satellite), and the side sway maneuver (along the heading axis of satellite) will lead to the linear acceleration of fuel in the tank. At this point, the angular velocity of orbit is 0.06°/S, the side sway angular velocity is 0.2°/S, and the bias angular velocity is 0.004°/S approximately, considering the influencing radius of the above disturbing force, the linear acceleration caused the above disturbances is:

- The influence by orbit angular velocity: \( a_o = \omega_b^2 \times r_o = 1.6 \times 10^{-7} \) g;  \( \omega_b = 1.6 \times 10^{-5} \) rad/s

(6)

- The influence by side sway angular velocity: \( a_e = \omega_c^2 \times r_c = 0.7 \times 10^{-6} \) g;  \( \omega_c = 0.7 \times 10^{-1} \) rad/s

(7)

- The influence by bias angular velocity: \( a_p = \omega_p^2 \times r_p = 0.7 \times 10^{-10} \) g;  \( \omega_p = 0.7 \times 10^{-7} \) rad/s

(8)
Therefore it can be shown that the orbit angular velocity is considered as the main influencing source of satellite in normal flight, since the impact by bias angular velocity is too limited to take into account. The VOF two-phase flow model can be introduced in quantitative analysis of the distribution of fuel centroid during the stable flight of satellite in orbit. Each wall could be set as solid wall boundary condition, which means the boundary condition without penetrating and sliding is adopted in the calculation. This kind of tank can be mainly used in monopropellant propulsion system, anhydrous hydrazine therefore is used as simulated medium, its surface tension coefficient is 0.07476N/m, and contact angle is 0°. In initial state, it is assumed that the simulated propellant settles to the bottom, and the calculation domain includes two parts: gas and liquid. The initial volume distribution in the calculation domain is set to be the initial condition of the gas-liquid two-phase distribution in the calculation domain. The height of liquid level is set at initialization, and the volume of the simulated propellant in this region is 1, and 0 in rest regions.

Figure 3 Fuel distributions when the flight of satellite tends to be stable

From the numerical results, eight coordinates of the mass center could be given; hence the position curve for the distribution of remaining fuel mass center in tank can be obtained in Figure 4 when the satellite is in a stable flight.
Figure 4 The position of the mass center of remaining fuel in Y-axis direction

The trend of the change of satellite centroid caused by fuel consumption is shown in Figure 5 (assuming that the coordinate value of satellite centroid in X-direction is 1685 (mm), and the total weight of satellite when launching is 2650kg).

Figure 5 Effect of fuel consumption on the centroid of satellite in X direction

5. Conclusion and Prospect
Based on the analysis of large antenna, solar arrays and fuel, which are three main factors that affect the change of the centroid of LEO remote sensing satellite in orbit, a method that could obtain real-time information of the mass center of satellite is introduced. With the help of the information which could be applied to satellite orbit determination system, the calculation precision of the satellite orbit position would be improved. Subsequently, practical data of the satellite in orbit need to be applied to the analysis above, experimental data of satellite orbit determination with high accuracy can be acquired by increasing the real-time position data of the centroid of satellite.

6. Conclusion
Based on the analysis of large antenna, solar arrays and fuel, which are three main factors that affect the change of the centroid of LEO remote sensing satellite in orbit, a method that could obtain real-time information of the mass center of satellite is introduced. With the help of the information which could be applied to satellite orbit determination system, the calculation precision of the satellite orbit position would be improved. Subsequently, practical data of the satellite in orbit need to be applied to the analysis above, experimental data of satellite orbit determination with high accuracy can be acquired by increasing the real-time position data of the centroid of satellite.

7. References
[1] Wang Shuting, Cao Xibin on-line Mass-property Identification Algorithm Research for Satellite, Proceedings of the 25th Chinese Control Conference, 8.2006
[2] Lin Jiawei, Wang Ping on Orbit Estimation of Satellite Mass Center Based on STLS. Chinese Space Science and Technology ,4. 2010
[3] Li Xiansheng, Meng Xiangyu, Zhang Xuelian, Gheng Zhuqing, Ren Yuanyuan. Dynamic characteristics of liquid sloshing in partially-filled tank. Journal of Jilin University (Engineering and Technology Edition), Vol.47, No.3.
[4] Wang Chao, Zhang Ruiliang, Wang Tie, Chen Haoli. Analysis of the Dynamic Change of the Fluid Mass in the Tank of the Mixing Truck. Science Technology and Engineering, Vol.16, No.30.
[5] Chen Minnian, Lei Zhiguo, Xu Jianquan. Calculation of the Liquid Center of Mass Coordinates when the Tank Truck is Parked on the Ramp. China Automotive Engineering Society Annual Conference,2003.
[6] Wang Zhanqi. Research on Braking Stability of Vehicle with Partially Loaded Liquid Tank. Journal of Jilin University of Technology. Vol.3,1990.