An optimization method of separation parameters for pico-satellite by minimizing external moment

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Abstract. In this article, a direct and key factor which affects separation parameters of satellite-rocket separation mechanism called optimization method of minimizing external moment is introduced. By changing the positions of elastic launch devices, popping process is effectively controlled. This optimization method is proved by ground test which can offset gravity, and it particularly adapts to the fixed and non-stable status elastic parameters, the distribution of all kinds of elastic devices and bias aircrafts which are hard to make the correction. The method has successfully applied to prediction and optimization for the separation of “Zhejiang University BJ Pico-satellite”. It is widely used now in practice with its easy operation.

1.Introduction
Satellite-rocket separation mechanism can make reliable connection for satellite and rocket during launch. After satellite and rocket enter the orbit, it gives the function of reliable separation. Many experts have made studies on the separation system of satellite and rocket and also the optimization of separation parameters. Xie [1] has designed and analyzed the movement system of satellite-rocket separation mechanism for “Zhejiang University Pico-satellite 1 A” and they have made on orbit satellite and rocket separation possible; Wu [2] has designed the satellite and rocket system for “Zhejiang University Pico-satellite 2” and they have proved the feasibility of the system from theory aspect; Teng [3] utilized an orthogonal optimization method to directly optimize the angular velocities of ZDPS–2 and ensure that they meet separation accuracy requirements. In addition, the optimization results were proved through ground tests and on-orbit separation. Hu [4] has optimized the separation velocity and angular velocities of “Tiantuo-1” and the verification on test and on orbit have been achieved; Tayefi [5] has optimized the separation velocity and separation distance by utilizing the response surface method and the practical verification of it has been realized.

However in literature [1] and [2], they have not taken the effects the separation system exerted to separation performance[6-10] into consideration and the analysis on dynamics of satellite-rocket separation system[11-16] is not given. In the literature [3], the angular velocities of the satellite are optimized directly, and the key factors that cause the angular velocities are not analyzed and optimized. In literature [4], they have calculated the potential energy corresponding to coordination for every potential energy device and the overlay summation of potential energy, and they have chosen one of the minimum value groups of potential energy as the launching and installation scheme. However this method is not applicable for the fixed spring parameters or the changed spring position. Also, the test method mentioned has big limitations, because it needs more test room and it is not easy to make test on launching site. In literature[5], the optimization method which is given in terms of satellite mass, spring quantity and spring parameters, but the optimal separation parameters could be obtained after carrying out 100 times of calculation at least.
In this article, we have given an optimization method for minimizing external moment to enrich the insufficient in literatures [1] - [5] in terms of the method. We also have redesigned the separation mechanism for “Zhejiang University BJ Pico-satellite” and made theoretical analysis and optimization so that the separation parameters meet with the technical specification. We have verified the optimization results through simulation and test.

2. Separation dynamics theory

In order to avoid stuck caused by redundant constraints during the separation of satellite, we adopt the six degrees of freedom and non-redundant constraints locking scheme. By arranging two supporting bars on opposite angles of satellite, five degrees of freedom is limited. The pre-tightening force of locking bars arranged in opposite angles could press the satellite tightly on separation mechanism. The constrained degree of freedom formed on separation mechanism and the relative positions of locking, supporting and pushing bars are shown in Fig. 1 and Fig. 2. We arrange the explosive cutters on locking bars, when unlocking, the explosive cutters cut the two locking bars at the same time, and the satellite releases under the function of the four pre-compressed springs.

And according to the satellite-rocket separation system mentioned above, the coordination system is setup like what is shown in Fig. 3. The equations of gesture dynamics are:
where \( I_x, I_y, I_z \) are moment of inertia of satellite corresponding to the three axes, \( \omega_x, \omega_y, \omega_z \) are the angular rates of three directions of satellite, \( \omega_x, \omega_y, \omega_z \) are the angular velocities of three directions of satellite, \( M_x, M_y, M_z \) are the external moment of the three axes. As for satellite \( I_x \approx I_y \), the disturbing force is low, so we have:

\[
\begin{align*}
I_x \dot{\omega}_x + (I_z - I_y) \omega_y \omega_z &= M_x \\
I_y \dot{\omega}_y + (I_x - I_z) \omega_x \omega_z &= M_y \\
I_z \dot{\omega}_z + (I_y - I_x) \omega_x \omega_y &= M_z
\end{align*}
\]

(1)

So the equations of angular velocities are:

\[
\begin{align*}
\omega_x &= \int_0^t \frac{M_x}{I_x} \, dt \\
\omega_y &= \int_0^t \frac{M_y}{I_y} \, dt \\
\omega_z &= \int_0^t \frac{M_z}{I_z} \, dt
\end{align*}
\]

(3)

When the center of mass of satellite is at the original point, the external moment can be expressed as: Taking moment from \( x \) axle, we could get:
\[ M_x = F|y_1| - F|y_3| \]  
(4)

Taking moment from axle, we could get:

\[ M_y = F|x_2| - F|x_4| \]  
(5)

When the center of mass of satellite is bias, the coordinate system like what is shown in Fig. 4 is established. The equations of external moment can be expressed as:

Taking moment from \( cx' \) axle, we can get:

When \( y_2 > y_c \):

\[ M_x = F|y_1 - y_c| + F|y_2 - y_c| - F|y_3 - y_c| - F|y_4 - y_c| \]  
(6)

When \( y_4 > y_c \):

\[ M_x = F|y_1 - y_c| - F|y_2 - y_c| - F|y_3 - y_c| + F|y_4 - y_c| \]  
(7)

Other situations:

\[ M_x = F|y_1 - y_c| - F|y_2 - y_c| - F|y_3 - y_c| - F|y_4 - y_c| \]  
(8)

Taking moment from \( cy' \) axle, we can get:

When \( x_1 < x_c \):

\[ M_y = -F|x_1 - x_c| + F|x_2 - x_c| + F|x_3 - x_c| - F|x_4 - x_c| \]  
(9)

When \( x_3 < x_c \):

\[ M_y = F|x_1 - x_c| + F|x_2 - x_c| - F|x_3 - x_c| - F|x_4 - x_c| \]  
(10)

Other situations:

\[ M_y = F|x_1 - x_c| + F|x_2 - x_c| + F|x_3 - x_c| - F|x_4 - x_c| \]  
(11)

From Eq. (3)-Eq. (11), we can get that the angular velocities at separation is caused by mass bias and external moment unbalance. By optimizing the positions of pushing bars, we could have the minimum value of external moment, and the angular velocities of separation reach to its lowest value. This gives theoretical evidence for optimization of angular velocities of separation.

3. Optimization method

Due to the limited energy on pico-satellite, its gesture control ability is weak. Sub system of gesture control gives some corresponding requirements on the initial gesture in order for satellite runs into orbit. The detail demands are in Table 1.

| No. | Technical specification                  | Design value |
|-----|------------------------------------------|--------------|
| 1   | Separation velocity/(m·s⁻¹)              | \( v = 1 \pm 0.1 \) |
| 2   | Mass of separation mechanism /kg         | \( m \leq 4.5 \) |
| 2   | Rolling angular velocity/(°·s⁻¹)         | \( |\Delta w_\gamma| \leq 2 \) |
| 3   | Pitch velocity /°·s⁻¹                    | \( |\Delta w_\phi| \leq 2 \) |
| 3   | Yaw velocity /°·s⁻¹                      | \( |\Delta w_\psi| \leq 2 \) |

3.1 Initial separation parameters analysis

The mass characters of pico-satellite is shown in Table 2. According to Fig. 3, the separation system coordinate system, we input the separation system into ADAMS software; we could get the angular
velocities of satellite separation when the spring pushing bars are in full symmetry, and the simulation results are shown in Table 3.

| Table 2 Pico-satellite mass characteristics |
|-----------------|-----------------|-----------------|
| \( m \) (kg) | Center of mass (mm) | Moment of inertia (kgm^2) |
| 19.08 | (-3.134,4.711,214.799) | \( I_x = 0.72 \) |
| | | \( I_y = 0.72 \) |
| | | \( I_z = 0.23 \) |

| Table 3 Separation angular velocities before optimization |
|----------------|----------------|----------------|----------------|----------------|----------------|
| \( x_1 \) (°/s) | \( y_1 \) (°/s) | \( x_2 \) (°/s) | \( y_2 \) (°/s) | \( x_3 \) (°/s) | \( y_3 \) (°/s) | \( x_4 \) (°/s) | \( y_4 \) (°/s) |
| 0 | 118.5 | 118.5 | 0 | 0 | -118.5 | -118.5 | 0 | -9.812 | -7.188 | -0.0047 |

From Table 3, we can get that the value of \( \omega_x \) and \( \omega_y \) are beyond of the technical specification, we must optimize \( \omega_x \) and \( \omega_y \) to make them meet with the specification.

### 3.2 Angular velocities optimization

Based on the contact range between four pushing bars and satellite, we take the boundary position of pushing bars as the constraint condition of coordinate. We select the relative position coordinate for four pushing bars and take them as the factors for optimization, and \( M_x \) and \( M_y \) are the optimization targets. We establish parameters levels table for position coordination of spring pushing bars, like what is shown in Table 4.

Without considering the interaction of all factors, we established an orthogonal test table of 8 factors and 5 levels. By calculating \( M_x \) and \( M_y \), we can have the external moment results for 49 schemes, like what is shown in Table 5. It can be seen from Table 5 that \( M_x \) and \( M_y \) can be optimized to a great extent. By method of least minimum squares, we optimize \( M_x \) and \( M_y \), less than 10-4Nmm, at this time, the optimization results of \( M_x \) and \( M_y \) can be found in Table 6. By entering the optimization results data into ADAMS software, we get the final optimization results in Table 7.

| Table 4 Coordinate parameters levels table |
|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Leve 1 | Factor \( x_1 \) (mm) | Factor \( y_1 \) (mm) | Factor \( x_2 \) (mm) | Factor \( y_2 \) (mm) | Factor \( x_3 \) (mm) | Factor \( y_3 \) (mm) | Factor \( x_4 \) (mm) | Factor \( y_4 \) (mm) |
| 1 | -6 | 112.5 | 112.5 | -6 | -6 | -124.5 | -124.5 | -6 |
| 2 | -3 | 115.5 | 115.5 | -3 | -3 | -121.5 | -121.5 | -3 |
| 3 | 0 | 118.5 | 118.5 | 0 | 0 | -118.5 | -118.5 | 0 |
| 4 | 3 | 121.5 | 121.5 | 3 | 3 | -115.5 | -115.5 | 3 |
| 5 | 6 | 124.5 | 124.5 | 6 | 6 | -112.5 | -112.5 | 6 |

| Table 5 Orthogonal test table and calculation results |
|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| No. | \( A \) | \( B \) | \( C \) | \( D \) | \( E \) | \( F \) | \( G \) | \( H \) | \( M_x \) | \( M_y \) | \( M_z \) |
| 1 | 2.00 | 5.00 | 2.00 | 2.00 | 1.00 | 4.00 | 5.00 | 3.00 | -2.106416 | 1.071904 | 0 |
| 2 | 2.00 | 1.00 | 1.00 | 1.00 | 2.00 | 2.00 | 3.00 | 1.00 | -6.534416 | 0.087904 | 0 |
| 3 | 2.00 | 1.00 | 5.00 | 1.00 | 3.00 | 4.00 | 2.00 | 5.00 | -3.582416 | 2.055904 | 0 |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| \(x_1\) (mm) | \(y_1\) (mm) | \(x_2\) (mm) | \(y_2\) (mm) | \(x_3\) (mm) | \(y_3\) (mm) | \(x_4\) (mm) | \(y_4\) (mm) | \(M_1\) | \(M_{y_1}\) | \(M\) |
|---|---|---|---|---|---|---|---|---|---|---|
| -3.134 | 124.5 | 114.3 | 6 | 0.799 | -112.5 | -124.5 | 0.845 | 0.000164 | 0.000164 | 0 |

Table 6  The optimization results of external moment

| \(x_1\) | \(y_1\) | \(x_2\) | \(y_2\) | \(x_3\) | \(y_3\) | \(x_4\) | \(y_4\) | \(\omega_x\) (°/s) | \(\omega_y\) (°/s) | \(\omega_z\) (°/s) |
|---|---|---|---|---|---|---|---|---|---|---|
| -3.134 | 124.5 | 114.3 | 6 | 0.799 | -112.5 | -124.5 | 0.845 | 0.0276 | -0.329 | -0.0026 |

Table 7  The final optimization results of separation angle velocities

4. Experiment preparation

The springs arrangement on separation mechanism have been changed based on the optimization results in Table 7. By establishing the test system which can offset gravity, shown in Fig. 5, we can carry out the separation test and get separation parameters. This test system includes pico-satellite, satellite-rocket separation mechanism, high speed camera, three axis angular velocity sensor, hanging rack, roller wheel, synchronize unlocking device, tools etc. High speed camera is used to measure separation velocity and to observe whether separation is steady; Three axis angular velocity sensor is used to measure angular velocities of three axes during separation; Hanging rack can offset gravity, and roller wheel can reduce the separation resistance; Synchronize unlocking device is used to realize synchronous unlocking.

5. Results and Discussion

Separation result is shown Fig.6. At the time of releasing, spring force is bigger than external disturbing force and roller wheel is at slide friction, so we can ignore the effects from external disturbing force and from friction. After thousands of ground separation tests, it proves that satellite could separate successfully. Satellite separates steadily with any hooking or interference on satellite-rocket separation mechanism. The results of simulation and test are shown in Table 8, and the results comparison before and after optimization are shown Fig.7. From the results, we can make conclusion that the simulation and test results are basically in line with each other, and angular velocities are greatly improved. The
relative errors of rolling angular velocity, pitch velocity and yaw velocity individually are 15.38%, 13.5% and 9.4%. The separation parameters of satellite meet with requirements from satellite-rocket separation.

Figure 6. (a) Design figure (b) Experiment figure after separation in offset gravity test system.

Figure 7. The results comparison between before and after optimization.

Table 8 The comparison of simulation results and test results

| Technical specification       | Simulation results | Test results | Relative errors |
|------------------------------|-------------------|--------------|-----------------|
| Time(s)                      | 0.0459            | 0.047        | 2.34%           |
| Separation velocity (m·s⁻¹)  | 1.082             | 1.123        | 3.78%           |
| Rolling angular velocity (°·s⁻¹) | -0.0026         | -0.003       | 15.38%          |
| Pitch velocity (°·s⁻¹)       | -0.329            | -0.373       | 13.5%           |
| Yaw velocity (°·s⁻¹)         | 0.0276            | 0.03         | 9.4%            |
6. Conclusions
In this article, a direct and key factor which affects separation parameters of satellite-rocket separation mechanism called optimization method of minimizing external moment. By changing the positions of elastic launch devices, popping process is effectively controlled. Through utilizing the offset gravity scheme, this optimization method is verified. This method particularly adapts to the fixed and non-stable status of elastic parameters, the distribution of all kinds of elastic devices and bias aircrafts which are hard to adjust. Through the optimization method for separation parameters described in this article, satellite separation accuracy is greatly enhanced. High separation angular velocities which are beyond the scope of satellite gesture control is avoided, and a solid foundation is laid for gesture control.

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