Dynamic analysis on the drag sail device of micro-satellite during the deploying process

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Abstract. In order to satisfy the requirements of the drag sail for the future micro-satellite, the drag sail device and the dynamic research of the process are carried out. A mathematical model is established, and the static and dynamic performance of the deployable mechanism are analyzed at different temperature. The results show that there is enough moment for deployable mechanism to start the deployment at the temperature range of -70 to 100 °C, and there is enough starting torque to realize the deployment of the sail, the acceleration reaches 1905 rad/s² at the moment of deployment, and the angular velocity tends to be stable at 0.4s. In addition, the reverse resistance of the damper becomes the key to restrict the deployment in the process of deployment. In order to ensure the smooth deployment of deployable mechanism, the reverse moment of it in deployed process should be less than the deployed bending moment of the boom. This study provides a theoretical basis for the design of the deployable mechanism of the drag sail device.

Keywords: Micro-satellite, the drag sail device, Force analysis, Static performance, Dynamic performance

1. Introduction
With the development of space science and technology, micro-satellites have gradually become one of the engines leading during the development of space technology. The number of micro-satellites has increased explosively in recent years. If these small satellites are not processed, the spacecraft in low earth orbit will exceed 500% in the next 200 years, which will seriously threaten the future space activities [1-2]. In order to slow down the growth of space debris, Inter-Agency Space Debris Coordination Committee (IADC) suggests that the spacecraft should leave orbit within 25 years after completing the mission or 30 years after entering orbit [3]. At present, for the small satellites with low cost, short cycle and high function density, it is a very important development trend to add the drag sail device in the design [4-5]. At the end of the life of the micro satellite, the drag sail device can use its stored mechanical energy to drive the sail to expand, improve the atmospheric resistance of the satellite in orbit flight, and accelerate the satellite off orbit. The whole device has the characteristics of light weight, simple structure, low cost, no fuel consumption and no need of attitude control, especially suitable for micro satellites in low earth orbit [6-8]. At present, a lot of researches on the design, analysis and verification of the drag sail device have been carried out abroad, but the research on this kind of device has just begun in China. During the deployment process of the drag sail device, there are many
kinds of reverse torques, and the total torque of the system is one of the key factors affecting the deployment performance of the drag sail device. In this paper, the design of the drag sail device is carried out, the force condition of the deployment mechanism is analysed, the dynamic model of the force is established, and the static and dynamic performance of the deployment mechanism at different temperatures is analysed by numerical method, which lays a theoretical guidance for the design of the satellite the drag sail device.

2. Force analysis of the drag sail device during deployment

The schematic diagram of the deployment mechanism of the satellite the drag sail device is shown in Fig. 1. During the deployment process, the mechanism will be subject to the friction generated by the compression mechanism, roller guide rail, flange plate and other structures, which will produce reverse torque. In order to ensure the smooth deployment of the deployment mechanism of the satellite the drag sail device, the deployment bending moment of the mast must be greater than the reverse torque generated by various friction forces. The stress of the deployment mechanism is shown in Fig. 2.

![Figure 1. Schematic diagram of unfolding mechanism and the device](image)

![Figure 2. Force analysis of the system in the deployment process of the drag sail device](image)

The total moment $\tau_E$ applied to the central axis and coil includes the unfolding moment $\tau_{UW}$ of the elastic mast and the reverse resistance moment $\tau_R$ from various sources, i.e

$$\tau_E = \tau_{UW} - \tau_R$$

The reverse resistance moment $\tau_R$ includes the following sources:

1) The reverse torque $\tau_e$ produced by the friction force of the clamping mechanism depends on the load on the clamping mechanism.

2) The resistance moment of the damper $\tau_d$ depends on the rotational angular velocity.

3) The friction torque $\tau_a$ generated on the center reel bearing depends on the load on the center reel.
Therefore, the resistance moment can be expressed as:

$$\tau_R = \tau_e + \tau_d + \tau_a$$  \hspace{1cm} (2)

The unfolding moment $\tau_{UW}$ is composed of the steady moment of forward bending $M^*$ and the steady moment of reverse bending of elastic mast $M^*$.

$$\tau_{UW} = M^* + M^* = -M^* + M^*$$  \hspace{1cm} (3)

The unfolding moment of the elastic mast depends on the basic parameters of the spring, and it is a constant value in the whole unfolding process.

3. Establishment of mathematical model

The deployment mechanism of the drag sail device is equivalent to a system composed of two main bodies. The body 1 composed of the central axis and the elastic mast wound on the central axis carries out one-dimensional rotation motion; the body 2 composed of two supporting arms carries out one-dimensional translation motion. The two subjects move synchronously, and mass exchange occurs in the process of motion.

The motion equations of the central axis and the elastic mast wound on the central axis are as follows:

$$\tau_e + \tau_a(t) = (I_{red} + I_{coil}) \frac{d^2\theta(t)}{dt^2}$$  \hspace{1cm} (4)

Where, $\tau_e$ is the total moment applied to the central axis and coil, $\tau_a(t)$ is the external moment generated by the support arm, $I_{red}$ is the moment of inertia of the central axis, $I_{coil}$ is the moment of inertia of the elastic mast wound on the central axis, and $\theta(t)$ is the rotation angle coordinate.

The motion equation of the support arm is as follows.

$$F_e + F(t) = m_{boom} \frac{d^2x(t)}{dt^2}$$  \hspace{1cm} (5)

Where, $F_e$ is the total external force generated by the deployment system, $F(t)$ is the external force generated by the central axis and coil, $m_{boom}$ is the mass of the two support arms, and $x(t)$ is the deployment length of the support arms.

In order to ensure that the total moment of the drag sail device deployment is greater than the total reverse moment, the reverse moment and friction force are calculated.

(1) Reverse torque of pressing mechanism

The formula of the reverse moment generated by the pressing mechanism is as follows:

$$\tau_e = \mu \frac{\tau_{UW} d_r}{r_r}$$  \hspace{1cm} (6)

Of the equation, $\mu$ is the lubricant friction coefficient, which is related to the temperature $T$, its empirical formula is $\mu = g_1 e^{g_2 T}$, and $g_1$, $g_2$ are the empirical coefficients. $F_e$ is the total external force produced by the unfolding system, $\tau_{UW}$ is the unfolding bending moment, $d_r$ is the inner diameter of the bearing and $r_r$ is the radius of the pressing mechanism.
(2) Reverse friction torque of central shaft assembly
The reverse torque of central shaft assembly is:

\[ \tau_a = \mu_r \left[ M^* + M^* \right] \frac{d_a}{r_i} \]

(7)

Where, \( \tau_a \) is the reverse moment of the central shaft assembly; \( r_i \) is the inner radius of the elastic mast winding; \( d_a \) is the inner diameter of the central shaft bearing; \( M^* \) is the forward unfolding moment; \( M^* \) is the reverse unfolding moment.

(3) Moment of damper
The empirical formula for the moment of the damper is as follows:

\[ \tau_d(T, \omega) = a_1 + a_2 \omega + a_3 T + a_4 \omega^2 + a_5 T^2 \]

(8)

The moment of the damper \( \tau_d \) depends on the speed \( \omega \), temperature \( T \) and the corresponding coefficient \( a_1, a_2, a_3, a_4, a_5 \).

(4) Force analysis of support arm
The resistance exerted on the supporting arm \( F_R \) is composed of the friction between the supporting arm and the structure \( F_{BS} \), and the resistance during the expansion of the sail surface \( F_s \):

\[ F_R = F_{BS} + F_s \]

(9)

The friction between the support arm and the structure, \( F_{BS} \), can be expressed as:

\[ F_{BS} = \frac{\mu_s M^*}{l_{inner}} + \frac{\mu_s M^*}{l_{outer}} \]

(10)

Where, \( \mu_s \) is the friction coefficient between the elastic mast and the structure, \( l_{inner} \) is the reserved length of the inner elastic mast, \( l_{outer} \) is the reserved length of the outer elastic mast, \( M^* \) is the forward unfolding bending moment, \( M^* \) is the reverse unfolding bending moment.

Due to the complex characteristics of the sail deployment process, it is difficult to accurately model the resistance in the deployment process. A rough test shows that the resistance of the sail decreases from an initial value to zero as it unfolds. It can be expressed by piecewise function:

\[ F_s = \begin{cases} F_{s,i} - \frac{F_{s,i}}{l_{boom}} x, & x \leq l_{boom} \\ 0, & x > l_{boom} \end{cases} \]

(11)

And, \( l_{boom} \) is the total length of the unfold drag sail device,

(5) Analysis of moment of inertia of winding coil assembly of central axis and elastic mast
When the center reel and the coil of the elastic mast rotate, the mass of the coil decreases and the mass of the extended support arm increases.
The moment of inertia of the center reel and coil includes the moment of inertia of the center reel assembly and the moment of inertia of the coil of the elastic mast. The moment of inertia of the coil can be expressed as:

\[ I_{\text{coil}} = \frac{1}{2} m_{\text{coil}} \left( r_i^2 + r_o^2 \right) \tag{12} \]

Where, \( r_i \) is the inner radius of the winding coil, \( r_o \) is the outer radius of the winding coil, and \( m_{\text{coil}} \) is the mass of the winding coil. The outer ring of the spring coil always keeps in contact with the pressing mechanism, and the outer radius of the spring coil is constant. The inner diameter will expand with the expansion of the support arm, and depends on the length of the spring \( l_{\text{coil}} \) and the thickness \( t \) of each layer.

\[ r_i = \sqrt{\frac{r_o^2 - l_{\text{coil}} t}{\pi}} = \sqrt{\frac{r_o^2 - (l_{\text{boom}} - x) t}{\pi}} \tag{13} \]

The quality of winding coil is as follows:

\[ m_{\text{coil}} = n_B \kappa l_{\text{coil}} = n_B \kappa (l_{\text{boom}} - x) \tag{14} \]

In equation, \( n_B \) is the number of support arms, \( \kappa \) is the mass per unit length of a single support arm, \( x \) is the unfolded length, and \( l_{\text{boom}} \) is the total length of the elastic mast.

Equations (1) ~ (14) constitute the dynamic model of the deployment process of the derailment device. By solving the differential equations, the functional relationship \( \omega = F(t) \) and \( \tau = F_\tau(t) \) can be obtained. It is helpful to analyze the static and dynamic performance of the deployment mechanism of the derailment device. According to the application requirements of microsatellite, the design of the off orbit device is carried out. Considering the light and miniaturization of the device, high reliability and elastic driving, the design parameters are shown in the following table.

| Element Style | Element Style | Element Style |
|---------------|---------------|---------------|
| \( F_r \)     | 0.2 N         | \( \mu_r \)   | 0.1           |
| \( \tau_{\text{UW}} \) | 8.9×10^{-2} N m | \( d_r \) | 0.003m        |
| \( l_{\text{boom}} \) | 1.5 m         | \( r_i \)    | 0.004m        |
| \( F_{\text{SS}} \) | 0.5767 N     | \( d_o \)    | 0.007m        |
| \( r_o \)     | 0.0175 m     | \( r_o \)    | 0.015m        |
| \( I_{\text{reel}} \) | 3.37×10^{-6} kg/m^2 | \( M_r \) | 26 N mm      |
| \( n_B \)     | 2            | \( \mu_B \) | 0.4           |
| \( M_r \)     | 63 N mm      | \( l_{\text{outer}} \) | 0.048 m |
| \( \kappa \)  | 0.02 kg      | \( \mu_{\text{ss}} \) | 0.07 m |
| \( l_{\text{inner}} \) | 0.048 m | \( l_{\text{outer}} \) | 0.07 m |

In addition, in the empirical formula of damper torque, the coefficients of \( a_1 \sim a_5 \) are 0.0068904, 0.93264, - 0.11931, - 4.7225 and 6.629 respectively.

Through the above design parameters, the static and dynamic performance of the device in the deployment process can be obtained, and the deployment bending moment of the device under different
conditions can be analyzed to ensure the reliability of the deployment of the device and provide reverse resistance for the micro satellite.

4. Dynamic performance analysis of deployable mechanism

4.1. Static performance analysis

Micro satellite works in space environment, the temperature changes greatly day and night. In order to ensure the smooth deployment of the drag sail device under large temperature changes, this paper analyzes the static performance of the deployment mechanism under different temperatures. To ensure the smooth deployment of the device, the static reverse moment, $\tau_{Rs}$, must be less than the deployment moment, $\tau_{UW}$. According to the designed parameters and the established dynamic model, the safety margin is used as the index to measure the deployment performance:

$$MS = \frac{\tau_{UW}}{\tau_{Rs}} - 1$$  \hspace{1cm} (15)

The curve of safety margin versus temperature is shown in the figure below:

![Figure 3. Curve of safety margin versus temperature](image)

It can be seen from the Fig.3 that in the temperature range of -70 °C ~ 100 °C, the deployment mechanism has enough torque to start the deployment, and at about - 80 °C, the safety margin becomes negative.

Fig. 4 shows the variation curve of the moment of the elastic mast with the temperature. It can be seen from the figure that the resistance moment of the elastic mast increases significantly under the condition of low working temperature, which also leads to the decrease of the safety margin. Below -50 °C, the reverse moment of the compression mechanism component increases. When the temperature is above -50 °C, the resistance torque caused by the static friction between the support arm and the structure is dominant, and the overall state is relatively stable.
4.2. Dynamic performance analysis

The dynamic performance of the micro satellite's drag sail device is mainly reflected in the angular velocity and acceleration when it is deployed in space. Based on the displacement and time variables in the deployment process, the angular velocity and angular acceleration change process in the deployment process are obtained, which is conducive to the analysis of the force changes in the deployment process and plays a guiding role in the design and analysis of safety margin.

As can be seen from Fig. 5, at the moment of deployment, the internal elastic drive of the device forms a larger driving force, and the angular acceleration in the initial state can reach 1905 rad/s². During the release process, the reverse torque generated by the damper also increases, and the total torque decreases continuously during the deployment process, and releases rapidly, so that the angular velocity reaches 83 rad/s in 0.2s, and tends to be stable quickly.

Fig. 6 shows the change curve of unfolding moment and total resistance moment in the process of system. It can be seen that in the process of deployment, the unbalanced torque of the system is very small, the maximum torque is only 0.089 N·m, and with the increase of deployment time, the unbalanced torque is getting smaller and smaller, so does the acceleration of the system deployment, and gradually tends to zero, at the ending, the deployment speed of the system gradually tends to an equilibrium value.
In addition, the response time of deployment moment is also very short, which tends to be stable only in 0.4s, it also meets the demand of fast response deployment of the derailment device.

![Image](image1.png)

**Figure 6.** Curve of the unfolding moment and total resistance moment changes with time at 20 °C

Fig. 7 shows the curves of various torques of the system during the deployment process with the time. During the deployment process, according to the mapping relationship between the damping torque and the angular velocity of the damper, it increases rapidly with the change of the angular velocity and becomes the total resistance torque rapidly. Relatively, other resistance torques are stable and far lower than the resistance torques produced by dampers. In addition, the resistance torque generated in the process of sail deployment fluctuates, which may be the main reason for the change of resistance torque caused by the continuous change of deployment area.

![Image](image2.png)

**Figure 7.** Curve of the torque on the system when temperature is 20 °C

Fig. 8 described the change of the deployment speed of the system with time under different temperatures. It can be seen from the figure that the deployment speed increases significantly with the increase of temperature. The angular velocity is only 19 rad/s at -70 °C, when the temperature rised at 80 °C, the angular velocity reached 89 rad/s. This is because, with the increase of temperature, the friction coefficient of the bearing and the friction torque produced by the damper in the system gradually
decrease. When the total driving torque is fixed, the effective driving torque becomes larger and larger, and the deployment speed also increases.

![Figure 8. Curve of system deployment speed at different temperatures](image)

5. Conclusion
In order to meet the strong demand of micro satellite after long-term failure in orbit, the design and dynamic analysis of the drag sail device are carried out, and the dynamic model of the deployment process of the device is established, and the static and dynamic performance of the device is analyzed. The results show that in the temperature range from -70°C to 100°C, there is enough starting torque for the deployment mechanism to realize the deployment of the sail. At the moment of deployment, the acceleration reaches 1905 rad/s², and the angular velocity increases rapidly, and tends to be stable at 0.4s. In addition, in the process of deployment, the reverse resistance of the damper becomes the key to restrict the deployment of the device. Finally, with the constant change of temperature, the material properties of the elastic device and the friction resistance produced in the deployment process are obviously different. In order to ensure the adaptability of space environment, the reverse resistance torque in low temperature environment should be fully considered. Through the performance analysis of the above dynamics, it can provide some technical guidance for the design of the moment and margin of the derailment device.

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