Aerodynamic Analysis and Drag-reduction Design for Ultra-low-orbit Satellite

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Abstract. When the satellite is operating at an orbital height of 120-300 km, aerodynamic drag becomes the most important factor affecting ultra-low orbital attenuation and attitude disturbance. Based on the theory of free-molecular flow, the model of aerodynamic drag of a panel in free-molecular flow is established firstly, and then the influence of the angle of attack, adaptation coefficient, and the molecular velocity ratio on the drag coefficient of the panel is analysed. Finally, A reduced drag design method for a ultra-low-orbit satellite is proposed based on the analysis results. And it is validated by the simulation results. The approaches presented in this paper can be applied to aerodynamic design and calculation of ultra-low-orbit satellites.

Key words: Ultra-low-orbit satellite, Free-molecular flow, Aerodynamics analysis, Reduced drag design, Satellite configuration.

1. Introduction

Ultra-low orbit usually refers to satellite orbits outside the dense atmosphere but below the height of ordinary spacecraft orbits. In this paper, ultra-low orbits are defined as flight orbits with a spatial range of more than 120 kilometres and less than 300 kilometres from the earth's surface[1]. Satellites operating in this orbit have the advantages of high resolution, high cost efficiency, and low launch cost[2]. In the space range of the ultra-low orbit, the atmosphere is very thin, but compared with the flying height of traditional satellites, there are a large number of gas molecules. When the satellite is operating in ultra-low orbit, these gas molecules collide with the surface of the satellite to generate aerodynamic drag. The aerodynamic drag perturbation has become the most important factor affecting the attenuation and attitude disturbance of ultra-low orbit. Currently, the ultra-low orbit satellite has attracted the attention of the United States, Japan, ESA and so on. The major Aerospace countries have successively formulated the ultra-low orbit satellite project plan, and actively carried out feasibility study, key technology research and flight test[3-5].

The aerodynamic problem of ultra-low orbit satellite belongs to the field of free-molecular flow. At present, there are four methods to simulate the movement and action process of free-molecular flow: Panel method, Ray-Tracing Panel method, Direct Simulation Monte Carlo method and Test-Particle Monte Carlo method[6]. The Panel method does not consider the problem of occlusion and multiple reflections, and considers that the aerodynamic forces generated by each part of the satellite do not interfere with each other, so It can be divided into several parts, and the aerodynamic force is calculated...
by distribution. This paper focuses on the configuration design and optimization of satellites. When calculating the aerodynamic forces of satellites, Ray-Tracing Panel method, Direct Simulation Monte Carlo method and Test-Particle Monte Carlo method need a lot of computing resources and take a long time, while Panel method has the advantages of small amount of computation and high efficiency, and can analyze and optimize the configuration parameters through analytical solutions. Therefore, this paper chooses Panel method.

In this paper, firstly, based on the theory of free-molecular flow, the aerodynamic drag model of the panel is established, and the aerodynamic drag coefficient of the panel is analyzed systematically. Then, the cross-sectional shape, slenderness ratio, and head configuration of the ultra-low orbit satellite are calculated and analyzed by the Panel method, and the design method of the drag reduction configuration of the ultra-low orbit satellite is proposed.

2. Aerodynamic drag model of panel in free-molecular flow

2.1. Judgment of free-molecular flow

According to the degree of leaniness, the flow of lean gas can be divided into four zones[7], as shown in Table 1.

| Mobile Field               | Knudsen number ($K_n$) |
|---------------------------|------------------------|
| Continuous medium zone    | $K_n < 0.01$           |
| Slipstream zone           | $0.01 < K_n < 0.1$     |
| Transition zone           | $0.1 < K_n < 10$       |
| Free-molecular flow zone  | $10 < K_n$             |

Where $K_n = \lambda/L$ is the ratio of the mean free path ($\lambda$) of the molecule to the value of the flow characteristic length ($L$).

2.2. Density properties of ultra-low orbit atmosphere

The atmospheric density of the area where the ultra-low orbit is located changes drastically with the influence of solar activity, geomagnetic activity, season and other factors[8]. Based on the NRLMSISE atmospheric model, the changes in atmospheric density with orbital height in different years of solar activity are shown in Figure 1.

![Figure 1](image.jpg)

**Figure 1.** Variation of atmospheric density in different solar activity years.

It can be seen that when the orbit height is 120km, the magnitude of atmospheric density is $10^{-8}$, when the orbit height is 300km, the magnitude of atmospheric density is $10^{-11}$ in the low year of solar activity and $10^{-10}$ in the high year of solar activity. When the orbit is low, the influence of solar activity on the atmospheric density is small. With the increase of orbit, atmospheric density ratio of high and
low solar activity also increase, and the ratio is 8.76 at the height of 300km. In the calculation in this paper, the average density at a specific height is taken as the calculated value.

2.3. Gas-surface interaction model

The aerodynamics force beating for the panel in the free molecule flow is shown in Figure 2. Where \( p_n \), \( \tau \) respectively represent the normal and tangential momentum flow components; the subscript \( i \) indicates that the quantity belongs to the incoming flow, and the subscript \( r \) indicates that the quantity belongs to the reflected flow.

\[
\begin{align*}
\alpha & \quad U \\
p_n & \quad \tau \\
p_i & \quad \tau_i
\end{align*}
\]

**Figure 2.** The aerodynamics force beating for the plate in the free molecule flow

According to the Maxwell model[9], the expressions of the positive pressure and shear force on the surface of the object are calculated as:

\[
P_a = \frac{\rho_\infty U^2}{2S^2} \left\{ \frac{2 - \sigma}{\sqrt{\pi}} \left( S \sin \theta + \frac{\sigma}{2} \sqrt{\frac{T_e}{T}} \right) e^{(S \sin \theta)^2} + \left( 2 - \sigma \right) \left[ (S \sin \theta)^2 + \frac{1}{2} \right] + \frac{\sigma}{2} \sqrt{\frac{\pi T_e}{T}} S \sin \theta \right\} \left[ 1 + \text{erf}(S \sin \theta) \right] \tag{1}
\]

\[
\tau_a = -\frac{\sigma \rho_\infty U^2 \cos \theta}{2 \sqrt{\pi} S} \left\{ S \sin \theta \left[ 1 + \text{erf}(S \sin \theta) \right] \right\} \tag{2}
\]

Where \( \rho_\infty \) is the inflow density, \( U \) is the inflow velocity, \( S = \frac{U}{\sqrt{2RT}} \) is the molecular velocity ratio, \( R \) is the gas constant, \( T \) is the inflow temperature, \( T_e \) is the reflected gas temperature, which is considered equal to the wall temperature, \( \text{erf}(a) = \frac{2}{\sqrt{\pi}} \int_0^a \exp(-x^2)dx \) is the error function; \( \theta \) is the angle between the inflow \( U \) and the normal direction of the surface.

Taking the area of one side of the panel as the characteristic area, the aerodynamic drag coefficient with the angle of attack \( \alpha \) can be calculated from equations (1) and (2) as:

\[
C_d = \frac{2}{\rho_\infty U^2} \left[ P_0 \left|_{\theta = \frac{\pi}{2} - \alpha} \right. \right. - \left. \left. \tau_0 \left|_{\theta = \frac{\pi}{2} - \alpha} \right. \right. \right] \cdot \cos \alpha \\
= \frac{1}{S^2} \left\{ \frac{2S}{\sqrt{\pi}} \sin^2 \alpha + \frac{\sigma S}{\sqrt{\pi}} \cos 2\alpha + \frac{\sigma}{2} \sqrt{\frac{T_e}{T}} \sin \alpha \right\} \cdot e^{-(S \sin \alpha)^2} + \sin \alpha \cdot \left[ 1 + \text{erf}(S \sin \alpha) \right] \cdot \left[ \sigma S^2 \cos 2\alpha + 2S^2 \sin^2 \alpha + 1 - \frac{\sigma}{2} \sqrt{\frac{\pi T_e}{T}} S \sin \alpha \right] \tag{3}
\]

3. Analysis of influencing factors of panel aerodynamic drag coefficient

3.1. Change law of aerodynamic drag coefficient with angle of attack
From the formula (3), it can be seen that the magnitude of the panel aerodynamic drag coefficient $C_D$ is closely related to the angle of attack ($\alpha$), the adaptation coefficient ($\sigma$), and the molecular speed ratio ($S$). In order to analyze the relationship between them, $C_D$ is divided into:

$$C_D = C_{D\sigma} + C_{D'}$$  (4)

Where $C_{D\sigma}$ is related to the adaptation coefficient:

$$C_{D\sigma} = \frac{\sigma}{S^2} \left\{ \cos 2\alpha \left( \frac{S}{\sqrt{\pi}} \cos 2\alpha + \frac{1}{2} \frac{T_e}{T} \sin \alpha \right) e^{-(S\sin \alpha)^2} + \sin \alpha \left( 1 + \text{erf}(S\sin \alpha) \right) \right\}$$  (5)

$C_{D'}$ is uncorrelated to the adaptation coefficient:

$$C_{D'} = \frac{1}{S^2} \left\{ \frac{2S}{\sqrt{\pi}} \sin^2 \alpha \cdot e^{-\left(S\sin \alpha\right)^2} + \sin \alpha \left[ 1 + \text{erf}(S\sin \alpha) \right] \right\}$$  (6)

Taking the adaptation coefficient $\sigma = 0.9$, the orbit height is 200 km, the incoming temperature is 841K, the wall temperature is equal to the incoming temperature, and the change law of the drag coefficient with the angle of attack is analysed, as shown in Figure 3.

It can be seen that as the angle of attack increases, $C_D$ and $C_{D'}$ gradually increase, while $C_{D\sigma}$ increases firstly and then decreases, and a critical angle ($\beta$) appears, so that $C_{D\sigma}$ is 0, that is, the angle of attack is at $\beta$, the change of the adaptation coefficient has no effect on the aerodynamic drag. In addition, when the angle of attack is 0, the total aerodynamic drag coefficient is not 0. This is due to the thermal motion of the molecules, and the airflow produces a shearing force on the plate, and the shearing force is $\tau_0 = \frac{C_{D\sigma}U^2}{2\sqrt{\pi}S}$.

3.2. Change law of aerodynamic drag coefficient with adaptation coefficient

When the angle of attack is 30° (less than $\beta$) and 60° (more than $\beta$), the change rule of aerodynamic drag coefficient with the adaptation coefficient is shown in Figure 4. It can be seen that when the angle of attack is 30° (less than $\beta$), the drag coefficient increases with the increase of adaptation coefficient; when the angle of attack is 60° (more than $\beta$), the drag coefficient decreases with the increase of adaptation coefficient. In the satellite configuration design, the angle of attack of the windward side is...
generally large. As the adaptation coefficient increases, the aerodynamic drag decreases. Therefore, the windward side can use ordinary industrial processing technology, and the general adaptation coefficient is about 0.9. But the side attack angle is small, the side smoothing technology should be used to reduce the side drag.

3.3. Change law of aerodynamic drag coefficient with molecular velocity ratio
From the definition of the molecular speed ratio, it can be seen that the molecular speed ratio is directly proportional to the satellite's operating speed and inversely proportional to the square of the incoming gas temperature. Taking the adaptation coefficient $\sigma = 0.9$, and the angle of attack of $90^\circ$, the change law of the panel drag coefficient and critical angle with the molecular velocity ratio is analyzed, as shown in Figure 5.

It can be seen that as the molecular velocity ratio increases, the drag coefficient and the critical angle both decrease, because the drag coefficient decreases with the increase of the molecular speed ratio, indicating that after the molecular speed ratio increases, the influence of the adaptation coefficient on the drag coefficient will be reduced.

![Figure 5. Variation of drag coefficient and critical angle of attack with molecular velocity ratio.](image)

4. Ultra-low orbit satellite drag reduction configuration design

4.1. Satellite cross-section shape design
The slender body configuration satellite is selected to study the aerodynamic drag effect. Inscribed quadrilateral, Inscribed hexagon, Inscribed octagon, and circle with a diameter of 1 meter in cross section are taken as slender bodies with a length of 4 meters. Solar sails are not considered. When the solar array and other expansion devices are not considered, calculate the aerodynamic drag and volume drag ratio under the ultra-low orbit, as shown in Table 2.

| Cross-section | Dynamic pressure ($P_a$) | Cross-sectional area ($m^2$) | Volume ($m^3$) | Aerodynamic drag ($N$) | Volume drag ratio ($m^3/N$) |
|---------------|--------------------------|----------------------------|----------------|------------------------|-----------------------------|
| Quadrilateral | 0.007945                 | 0.500                      | 2.000          | 0.01742                | 114.8                       |
| Hexagon       | 0.007945                 | 0.650                      | 2.827          | 0.02158                | 125.5                       |
| Octagon       | 0.007945                 | 0.707                      | 2.828          | 0.02195                | 128.8                       |
| Circle        | 0.007945                 | 0.785                      | 3.142          | 0.02364                | 132.9                       |

It can be seen that with the increase of the number of sides of the cross-sectional shape (the circle has an infinite number of sides), the aerodynamic drag of a satellite operating in an ultra-low orbit increases, the volume increases, and the volume drag ratio also increases. Considering only the aerodynamic drag and volume, the slender satellite with a circular cross section has the best aerodynamic performance.
4.2. Satellite slenderness ratio design
Select the shape of the satellite section as a circle, the circle diameter is $D$, the volume is $V$, and the total length is $L$. The total aerodynamic drag of the satellite is expressed as:

$$ F_D = F_1 + F_2 = q C_{D1} S_1 + q C_{D2} S_2 = \frac{1}{2} \rho \infty U^2 \cdot \left( \frac{\pi D^2}{4} + \frac{C_{D2} 4V}{C_{D1} D} \right) $$

(7)

Where $F_1$ is the windward drag, $F_2$ is the side drag, $C_{D1}$ is the windward drag coefficient, $C_{D2}$ is the side drag coefficient, $S_1$ is the windward area, $S_2$ is the side area.

It can be found that when the slenderness ratio is $L/D = C_{D1}/2C_{D2}$, the total aerodynamic drag of the spacecraft is the smallest.

Take a cylindrical satellite with a volume of 1 Cubic meter and the adaptation coefficient is 0.9. The variation rule of aerodynamic drag with the slenderness ratio of the satellite is calculated when the orbit height of the satellite is 200 km, as shown in Figure 6.

![Figure 6. Variation of aerodynamic drag with satellite slenderness ratio.](image)

It can be seen that: (1) with the increase of slenderness ratio, the aerodynamic drag decreases first and then increases; when the slenderness ratio of satellite is small, the side area has little influence on the total drag of satellite, and the total drag of spacecraft tends to be the drag only considering the windward area, so the aerodynamic drag decreases with the increase of slenderness ratio; when the slenderness ratio increases to a certain extent, the drag effect of side area is obvious, The total drag of the spacecraft increases with the increase of slenderness ratio; (2) when slenderness ratio of the cylindrical spacecraft is about 23, the aerodynamic drag is the smallest, and the aerodynamic drag on the side is about twice that on the windward side. (3) In the practical design of ultra-low orbit satellite, considering the limitation of launch vehicle and the maneuverability of satellite in orbit, the actual slenderness ratio of ultra-low orbit satellite is generally far less than 23, so it is only necessary to reduce the windward side of spacecraft to reduce its aerodynamic drag.

4.3. Satellite head optimization
Select the satellite with a slender cylinder configuration as the research object. The diameter of the cylindrical cross section is 1 meter and the length is 4 meter. The first 5th of the length of the satellite is set as the satellite head. In order to study the influence of the satellite head on the aerodynamics of the satellite, the head is modified and designed into different shapes, as shown in Figure 7.
configuration I
configuration II
configuration III
configuration IV

**Figure 7.** Schematic diagram of satellite head optimization.

Taking the adaptation coefficient \(\sigma = 0.9\) and the orbital height of 200km, the aerodynamic drag and volume drag ratio of the four configurations under moderate solar activity conditions are calculated and analysed, as shown in Table 3.

| Configuration   | Volume \((m^3)\) | Head aerodynamic drag \((N)\) | Total aerodynamic drag \((N)\) | Volume drag ratio \(m^3/N\) |
|-----------------|-----------------|-------------------------------|-----------------------------|-------------------------|
| Configuration I | 3.142           | 0.01646                       | 0.02364                     | 132.9                   |
| Configuration II| 2.827           | 0.01439                       | 0.02158                     | 131.0                   |
| Configuration III| 2.875           | 0.01311                       | 0.02029                     | 141.7                   |
| Configuration IV| 2.723           | 0.01245                       | 0.01964                     | 136.7                   |

It can be seen that the optimization of the satellite head can effectively reduce the aerodynamic drag and increase the volume drag ratio. Configuration IV has the minimum drag, which can be reduced by 16.92% compared with configuration I when the orbit height is 200km; configuration III has the optimal volume drag ratio, which can be increased by 6.64% compared with configuration I when the orbit height is 200km. Thus, the rationality of the configuration of NanoEye satellite is proved.

From the analysis in Section 3.1, it can be concluded that the size of the adaptation coefficient directly affects the aerodynamic drag. Through the special treatment of the satellite head (improving the surface smoothness, using special materials, etc.), the adaptation coefficient of the head can be changed to achieve the drag reduction effect.

Taking the orbital height of 200km and the adaptation coefficient of the satellite main body as 0.9, the aerodynamic drag and volume drag ratio of the four configurations with different adaptation coefficients at the head are calculated and analyzed, as shown in Figure 8.
Figure 8. Aerodynamic drag and volume drag ratio of the four configurations under different adaptation coefficients.

It can be seen that with the increase of the adaptation coefficient, the configuration I and configuration II decrease the aerodynamic drag and increase the volume drag ratio; the configuration III and configuration IV increase the aerodynamic drag and decrease the volume drag ratio. This is because the head cone angles of configuration I and II are larger than the critical angle, and the head cone angles of configuration III and IV are smaller than the critical angle. Therefore, for the configuration I and the configuration II, the head can adopt ordinary processing technology, and the general adaptation coefficient is 0.9, and no special processing and processing technology is required. For Configuration III and Configuration IV the head should try to improve the surface smoothness and use special materials to reduce the adaptation coefficient.

5. Conclusion
Based on the theory of free-molecular flow, this paper uses the Panel method to calculate the aerodynamic drag of a simple-shaped satellite, the effects of the angle of attack, the adaptation coefficient, and the molecular velocity ratio on the panel drag coefficient are systematically analysed, and the configuration design method of ultra-low orbit satellite is proposed. The conclusion is as follows:

(1) The drag coefficient is closely related to the angle of attack, the molecular speed ratio, and the adaptation coefficient of the material. With the increase of angle of attack and molecular velocity ratio, the drag coefficient increases, and there is a critical angle, which makes the change of adaptation coefficient have no effect on aerodynamic drag.

(2) For a slender satellite, with the increase of the number of sides of the cross-section shape, the windward drag and side drag of the satellite increase, the volume of the satellite increases, and the volume drag ratio of the satellite also increases. Considering only drag and satellite volume, the circular section slender satellite has the best aerodynamic performance.

(3) For the slender satellite with circular cross section, the aerodynamic drag decreases first and then increases with the increase of slenderness ratio; When the slenderness ratio of satellite is small, the influence of side area on the total drag of satellite is small, and the aerodynamic drag decreases with the increase of slenderness ratio; when slenderness ratio is larger than \( C_{D1}/2C_{D2} \), the drag effect of side area is obvious, and the total drag of spacecraft increases with the increase of slenderness ratio;

(4) After the satellite head is optimized and improved, the drag decreases and the volume decreases, but the volume drag ratio increases. In the case of considering only drag and satellite volume, the configuration III proposed in this paper has the best aerodynamic performance, and its head should be as smooth as possible, which can effectively reduce aerodynamic drag.

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