Numerical analysis of the influence of the front heat shield separation process from the descent module on their aerodynamic characteristics

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Abstract. This paper considers aerodynamic characteristics of the descent module and the separable front heat shield (FHS) during its separation. FlowVision software was used to perform a numerical analysis of the flow around the front heat shield and descent module. The calculations were performed using dynamic and static meshes. The trajectory of the front heat shield after separation was calculated using dynamic mesh. The aerodynamic characteristics of the front heat shield in several positions on calculated trajectory were determined using static mesh. The results of the calculations using different kind of grids are compared.

1. Introduction
During the descent module moving in the Earth’s atmosphere, some its structural elements are being separated. After separation, when structural element in the immediate vicinity of the descent module, there is mutual aerodynamic interference, which significantly affects the separation safety [1]. As a result of this effect, changing the total aerodynamic characteristics of both the descent module and structural components occurs, which can lead to oscillations and collision. In most cases, such structural elements are the front heat shield and the parachute container hatch cover. These elements protect the descent module from high thermal loads during flight in the dense layers of the atmosphere.

Nowadays, methods of numerical modeling are paid a lot of attention in the aerodynamic characteristics determine taking into account the aerodynamic interference in the process of elements separation from aircrafts. The reasons for these are the following:

1. Numerical modeling takes less time and costs less than experimental investigations;
2. The scope of experimental investigations is severely limited. For instance, experiments in a wide range of conditions may not be possible;
3. Contrary to a mathematical model, a flight experiment is very risky for the pilots and the aircrafts [1].

Numerical modeling of the elements separation from an aircraft can done using a steady-state solver with static mesh [2, 3], as well as a non-steady state solver with moving [4, 5] or oversetting [6,7,8] meshes.

In this paper we focus on the front heat shield aerodynamic characteristics determining during separation from descent module. Earlier, numerical modeling of the flow around the descent module and the front heat shield was carried out [9], however, the effect of the front heat shield motion on the aerodynamic characteristics during separation was not taken into account in the work.

2. Methods

FlowVision software was used to solve this task. The objects considered were the descent module and the front heat shield (See Fig. 1(a)). Firstly, the aerodynamic characteristics of the descent module before frontal heat shield separation were determined. Then the separation process and moving in the flow of the front heat shield using dynamic mesh was modeled. In result aerodynamic characteristics of the moving front heat shield and fixed descent module were calculated. Besides, the frontal heat shield trajectory and kinematic parameters were obtained. Please follow these instructions as carefully as possible so all articles within a conference have the same style to the title page. This paragraph follows a section title so it should not be indented.

![Figure 1](image-url)  
**Figure 1.** Descent module and the front heat shield (a - coordinate systems, mesh near the models before separation of the front heat shield)  
(dashed line - FHS position before separation)

Aerodynamic characteristics of the front heat shield and descent module were determined in wind coordinate system $O_aX_aY_a$. Point $O$ is located on the symmetry axis of the front heat shield on the external surface before the moment of separation. The mass-inertial characteristics of the front heat shield are set in the associated coordinate system $O_1X_1Y_1$. Point $O_1$ is located in the front heat shield mass center. The gravitational acceleration vector coincides with the direction of the axis $OX_a$.

The descent module and front heat shield drag coefficients $C_{DMx} = \frac{x_{DM}}{q_1s_m}$, $C_{FHSx} = \frac{x_{FHS}}{q_2s_m}$, lift coefficients $C_{DMy} = \frac{y_{DM}}{q_1s_m}$, $C_{FHSy} = \frac{y_{FHS}}{q_2s_m}$, front heat shield pitching moment with respect to the center $C_{DMz} = \frac{z_{DM}}{q_1s_m}$, $C_{FHSz} = \frac{z_{FHS}}{q_2s_m}$.
of mass $m_z^{FHS} = \frac{M_z^{FHS}}{q_2s_m l_m}$, descent module pitching moment with respect to the O-point $m_z^{DM} = \frac{M_z^{DM}}{q_2s_m l_m}$ were calculated. The value of the characteristic length equal to the descent module model length $L = 0.85D_m$ and the value of the midsection area of $S_m = \frac{\pi D_m^2}{4}$, were used in calculations. During the descent of the descent module by parachute, the speed of the incoming flow can vary in the range of 5 - 20 $[m/s]$. The value $V_\infty = 16 [m/s]$ was assumed in the calculations. Velocity head was calculated according to the equations $q_1 = \frac{\rho_\infty V_\infty^2}{2}$, $q_2 = \frac{\rho_\infty (V_\infty + V_{FHS})^2}{2}$, where $\rho_\infty$ - air density, $V_\infty$ - free stream velocity, $V_{FHS}$ - front heat shield relative speed at the current time. The angle of attack may vary due to the descent module oscillatory motion. In the calculations, we take $\alpha = 43^\circ$, and the amplitude of the change in the angle of attack $\Delta\alpha = \pm 15^\circ$. Aerodynamic characteristic at angles of attack $\alpha = 28^\circ$, $\alpha = 43^\circ$, $\alpha = 58^\circ$ were calculated.

Numerical modeling was done based on the control volume approach using SST turbulence model. The simulation domain is a cube with a side length of 20D. Figure 1 (b) shows an example of the mesh near the models. The number of cells was approximately about 7 million. The mesh was refined by a factor ranging from 1 to 5.

### 3. Results and discussions

The task of modeling the front heat shield separation process from descent module using a dynamic mesh is solved in two stages. First of all, the aerodynamic characteristics of the descent module before the front heat shield separation were calculated (Figure 2).

![Figure 2](image2.png)

**Figure 2.** Aerodynamic characteristics of the descent module before separation of the front heat shield

As can be seen from the graph, the drag force coefficient isn't changed much at the considered angles of attack. However, the coefficients of lift force and pitch moment change sign with increasing angle of attack. This effect is associated with the features of the flow around the descent module at the considered angles of attack (Figure 3). The negative sign of the lift force is caused by the pressure redistribution along the lateral surface of the descent module, in particular by reduced pressure at the lower leading edge. It can also be noted that at an angle of attack of approximately 54 degrees, the pitch moment sign is changed from negative to positive. We can conclude the descent module is statically unstable with respect to point O at such angle of attack.
The second stage of solving the task involves the movement of the front heat shield both along the guides and in free fall.

As a result of the numerical calculation of the descent module flow around during the front heat shield separation using a dynamic mesh, the motion trajectories were obtained (Figure 4). The front heat shield motion kinematic parameters, such as the mass center velocity (Figure 5), the angle of attack \( \alpha \) (Figure 6), and the angular velocity of motion around the mass center (Figure 7), depending on time, were obtained.
As can be seen from the graphs, there is no return movement of the front heat shield, as a result of which there is no collision of the heat shield and the descent module. During the front heat shield motion, its relative velocity increases and reaches a value of $V_{c.m.} \approx 18 \text{ [m / s]}$ (Figure 5). As can be seen from Figure 7, the larger initial angle of attack, the greater the amplitude of the angle of attack during the front heat shield oscillatory movement. The angle of attack amplitude values are decreased over time. This fact can testify to the dynamic stability of the front heat shield. However, for a more detailed study of this fact, it is necessary to carry out simulation for a longer period of time.

After the calculations taking into account the presence of front heat shield movement, several calculations were performed with the shield stationary. The front heat shield positions in the calculations were set based on the obtained trajectory of the shield at an initial angle of attack $\alpha = 43^\circ$. These positions were corresponded to times $t_1 = 1.5 \text{ s}$, $t_2 = 2.5 \text{ s}$, $t_3 = 3.5 \text{ s}$.

The descent module aerodynamic characteristics obtained by using various types of meshes are shown at Figure 8.
As can be seen from the plots, at the initial moment, the aerodynamic coefficients are very different from the aerodynamic coefficients of the descent module before the shield separation. When the shield is removed from the descent module, the values of the aerodynamic characteristics tend to values before separation. The changing in the descent module pitch moment coefficient is oscillatory, that is explained by the effect of the vortex wake on the descent module caused by the shield movement. This phenomenon can increase the oscillations amplitude of the descent module during moving by parachute.

When simulating a flow around using a fixed mesh, the descent module aerodynamic forces coefficients smaller slightly in modulus than in conditions of simulation a flow around using a dynamic mesh. However, this effect is opposite for the values of the pitch moment coefficient, which is due to the heat shield speed presence.

The velocity distribution fields in the OX,Y plane during the front heat shield separation using dynamic and fixed meshes are shown in figure 9. It's shown that the flow structures behind the front head shield are different using various types of meshes.
When calculating with a fixed front heat shield, the flow structure in the region behind it is similar to the flow structure in a free cavity. With a shield moving, the flow structure is rearranged. In the upper part there is a local region of the bottom flow with flow separation. One part of the flow is moved to the descent module frontal surface, and the other flow part is moved into the gap between the lower part of the heat shield and the descent module frontal surface.

The front heat shield aerodynamic coefficients are shown at Figure 10.
It can be seen some difference in the drag coefficients in the simulation of flow around using fixed and dynamic meshes at $t_1 = 1.5$ s. This effect is explained by the flow structure transformation between the descent module and the moving front heat shield in comparison with fixed shield (Figure 9, a, c). With further front heat shield moving away, its aerodynamic characteristics practically do not change using various types of grids (Figure 10). The front heat shield aerodynamic characteristics are oscillatory in nature due to its oscillatory motion.

4. Conclusion
As a result of the calculations, the aerodynamic characteristics of the descent module and the front heat shield using fixed and dynamic meshes are obtained. The front heat shield movement under the influence of gravity was considered. The physical features of the heat shield speed influence on the change in the flow between the front heat shield and the descent module are established compared with calculations in a stationary setting. It is noted the modeling of the front heat shield flow around during its motion effects on both in the aerodynamic characteristics changing and the flow structures restructuring, in comparison with calculations with a fixed shield. The influence of the separated elements movement speed can be taken into account when performing calculations using a dynamic mesh. As a result of investigations acceptable results for engineering practice are obtained.

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