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Effect of a Jet Control Device on the Process of Missile and Internal Weapons Bay Separation

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ABSTRACT

To ensure that the missile is safely separated from the internal weapons bay, the jet is used to control the process of missile separation, which is mounted on the front edge of the bay. The length-to-depth ratio of the bay was L/D=8, the diameter of the missile was d_1=0.178 *m*, the diameter of the jet was d_2=0.05 *m* . The FLUENT software was combined with our group-developed code under the platform of a user-defined function (UDF) to solve the flow field and the six-degrees-of-freedom (6DOF) of missile. The detached eddy simulation method and dynamic mesh technology were used in the numerical calculations. The boundary condition of missile, bay, and aircraft was no-slip wall condition. The boundary condition of the jet was the pressure-inlet. The pressure far-field boundary was selected as other boundaries. The constraint of the ejection device on the missile was considered. It was found that the jet control device thickens the shear layer, so the shear layer with more gradual velocity gradients, which is beneficial to the separation of missile. The distance between the internal weapons bay and the missile in the positive *z*-direction with the jet is 1.74 times that without the jet at t=0.5 s. In the case of the jet control device, the pitching angle of the missile ranged from 0.93° to -3.94° , the angular motion range of the missile with the jet is smaller than that without. The jet can make the characteristics of the flow field friendly, and enable the missile to separate from the bay quickly, stably, and safely.

Keywords: Missile separation; Compressible flow; Internal weapons bay; Jet; User-defined function

1. INTRODUCTION

To reduce the flight resistance and radar signature, it has become common for modern fighters to utilise an internal weapons bay[1-3]. However, internal weapon bays also cause many complicated aerodynamic problems, such as boundary layer separation, aerodynamic noise, and shock waves, occur when high-speed airflow passes through the bay[4-6]. When the missile is released from the bay of fighter aircraft, it may bounce back to the bay under certain flight conditions[7]. However, the separation of missile and aircraft cannot pose any threat to the flight of aircraft, and the separation process must be absolutely safe[8]. To avoid disadvantages caused by the internal weapons bay, some active and passive control methods are used to ensure the safety of missiles during the release process, such as mounting spoilers, rods, and microjets on the internal weapons bay[9,10].

To reduce the flow instability caused by the internal weapons bay, Zhuang[11], *et al.* adopted the method of adding supersonic microjets to the cavity; the microjet changes the mixing layer, significantly reducing the flow instability in the cavity. The effects of two passive control devices, fence and cylinder, were studied by Lawrence[12], *et al*. to explore how the passive control device reduces the fluctuating pressure load in the cavity. The effectiveness of a subcavity and a triangular bump installed in the cavity to suppress the pressure oscillation of a supersonic cavity was numerically studied by Lee[13], *et al.*. Song[14], *et al*. used the wind tunnel drop test method to confirm that the cuboid control device installed in the bay can improve the flow field characteristics to allow the missile to traverse through the interferential flow field easily. To compensate for the limitations of passive control devices at Mach numbers between 2 and 4, Bower[15], *et al.* used the active control method to study the separation of high-speed weapon and bay. Guo[16], *et al.* proposed two strategies for flow control that are suitable for a supersonic internal bay with a large curvature contour, under the condition of Mach number $Ma > 3$; the flow control via a rod spoiler is beneficial for safe separation and the jet screen flow control method has application potential. Wu[17], *et al.* experimented with a high-speed wind tunnel to investigate internal weapon separation characteristics and passive and active control methods were explored to improve internal weapon separation characteristics; however, they did not consider the constraints of the ejection device on the weapon.

Theoretical analysis, wind tunnel tests, numerical simulations, and flight tests are the main methods used to study the separation process of aircraft and missiles[18,19]. With the development of computer technology, numerical calculation methods have seen wider application[20]. In this study, a numerical calculation method was employed to study missile separation. The jet flow control can eliminate flow separation[21], so, the jet

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control device at the leading edge of the bay can be used to control the separation of missile and aircraft. The constraint of the ejector configuration to the missile was considered, and the mechanism of the jet control device during the separation process was studied in the calculation.

2. COMPUTATIONAL METHODS AND VALIDATION EXAMPLE

2.1 Computational Methods

The FLUENT software was combined with our group-developed code under the platform of a UDF to solve the flow field calculation domain and the six-degrees-of-freedom (6DOF) of the missile. The UDF was used to input and output the parameters of the missile, such as the mass, moment of inertia, trajectory, and aerodynamic parameters of the missile. The detached eddy simulation (DES) was used in this study. The realizable k-ε model was used in the calculation domain near the wall; the large eddy simulation was used in the computation domain far from the wall.

To calculate the relative motion between the missile and the internal weapons bay, two dynamic mesh technologies, smoothing method, and remeshing method were used in this study. In a time step, when the displacement of the missile is less than the size of the adjacent mesh, the smoothing method can be used to move the positions of some mesh nodes to represent the motion of the missile. The remeshing method must be used to generate new meshes near the missile, when the displacement of the missile is larger than the size of the adjacent mesh.

2.2 Verification Example

The numerical method used in this study can be validated by a typical example[22,23,27]. Figure 1 shows the computational model. The mass of the store was $m = 907\ kg$. The wing is a 45° clipped delta with an NACA-64A010 airfoil section. The angle of attack was 0°, the altitude was $11600\ m$, and the Mach number was 1.2. The ejection separation method was used; the ejector forces disappear when the separation time between the store and wing was $0.054\ s$. More details about geometric properties and calculation conditions can be found in references[22,23,27].

Figure 2 compares the experimental and numerical results of variations in the center of gravity (CG) location and euler angles of the store. It is evident that our numerical results agree well with the experimental[22] and numerical simulation[23] results.

3. COMPUTATIONAL MODEL AND CONDITIONS

3.1 Geometric Model

The geometric model of the air-to-air missile and the bay are shown in Fig. 3. The width, length, and depth of the internal weapons bay were $W = 0.8\ m$, $L = 4.2\ m$, and $D = 0.525\ m$, respectively. The length-to-depth ratio of the bay was $L/D = 8 \leq 10$, hence, the internal weapons bay belongs to the category of open cavity flow[24], it is beneficial to the separation of missile and aircraft[25]. The missile used in the calculation was similar to the AIM-120C air-to-air missile of the United States. The AIM-120C is a standard aerodynamic layout with a large slenderness ratio, small wingspan, and tail control. It has the advantages of small volume, lightweight, and small flight resistance[26], and the missile was stable in the pitch direction[3]. Therefore, the parameters such as mass, length, and diameter of the missile used in the numerical calculation are similar to those of AIM-120C. The missile's length was $3.65\ m$, the diameter of the missile was $d_1 = 0.178\ m$, and the center of gravity location of the missile was $1.816\ m$ behind the tip of the missile. The distances between the center of gravity location of the missile and the bottom and front of the bay were $0.2625\ m$ and $2\ m$, respectively.

In the numerical calculation, the bay was assumed to be stationary; the global coordinate system was based on the internal weapons bay. The origin was at the center of gravity

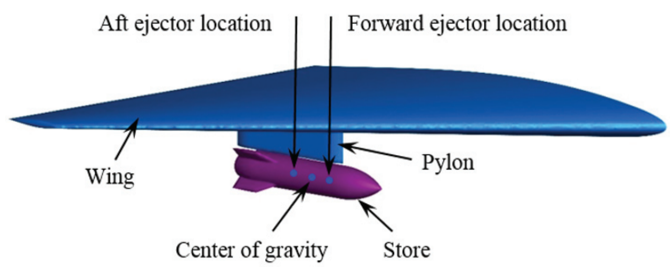


Figure 1. Geometric model

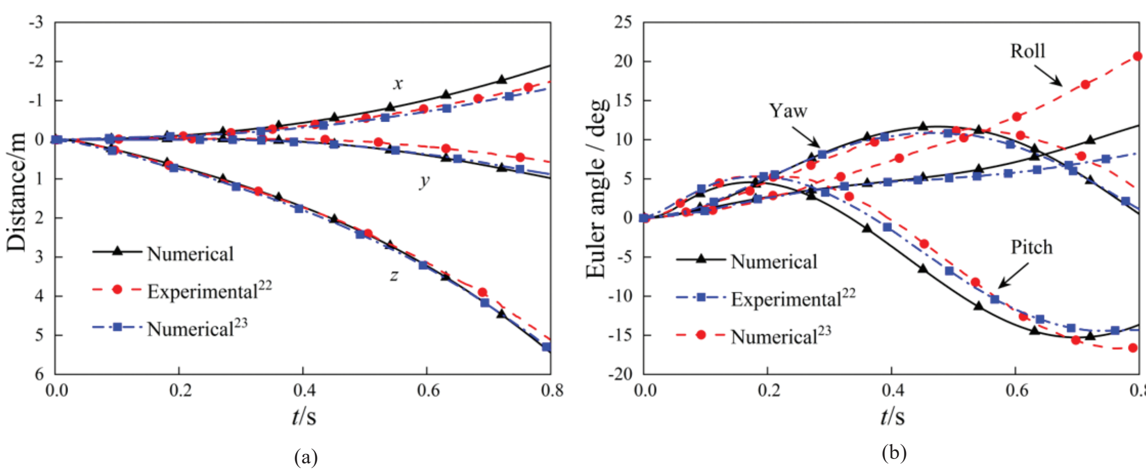


Figure 2. Result of the store: (a) center of gravity location and (b) angular orientation.

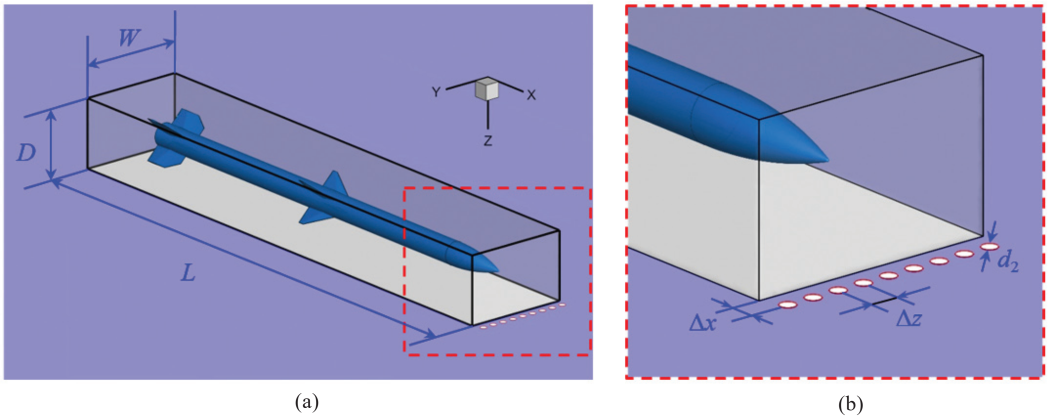


Figure 3. Geometric model: (a) model of internal weapons bay, missile, and jet hole and (b) size of jet hole

of the missile before missile separation. The center line of the missile was coincident with the x-axis, and the tip direction was positive. The z-axis coincided with the positive direction of gravity. The y-axis can be obtained by the right-hand rule. The location and size parameters of the jet are shown in Fig. 3(b). The diameter of the jet was $d_2 = 0.05\ m$, the distance between the center of the jet and the front edge of the bay was $\Delta x = 0.08\ m$, and the distance between the two jets was $\Delta z = 0.09\ m$. Figure 4 presents the mesh of the missile, and the convergence of the mesh was studied. The unstructured tetrahedral mesh was used in the computational domain.

3.2 Computational Conditions

The boundary conditions and computational domain are illustrated in Fig. 5. The boundary condition of the missile and bay was no-slip wall conditions. The boundary condition of the jet was the pressure-inlet. The jet direction was perpendicular to the jet hole, the angle between the jet and incoming gas was $\theta = 90^\circ$, and the gauge total pressure of the jet flow control device was $5\ atm$, the initial gauge pressure was $0.2615\ atm$. The jet control device began operation at $t > 0\ s$. The pressure far-field boundary conditions were selected as other boundaries. The mass of the air-to-air missile was $m = 156.8\ kg$ and the moments of inertia were $I_{xx} = 1.0708\ kg \cdot m^2$ and $I_{yy} = I_{zz} = 199.59 kg \cdot m^2$. The missile separated from the bay at an altitude of $10\ km$, the angle of attack was 0°, and the Mach number was 2. The velocity of the air-to-air missile was 0 at $t = 0\ s$. The ejection separation was used, but the ejector model was ignored; the constraint of the ejector configuration to the missile was considered in the numerical calculation. The ejector force was $F_t = 20\ kN$, acting on the center of gravity of the missile along the gravity direction. When the distance of missile moving in the positive z-direction is greater than $0.15\ m$, the power and constraint of the ejector on the missile disappeared. Within the action time of ejection device, the missile could only move in a straight line along the z-direction.

4. RESULT AND DISCUSSION

4.1 Control Mechanism of the Jet

To study the effect of the jet on the separation of missile and bay, a comprehensive comparative study was conducted for the cases with and without a jet. The case without a jet control device was studied in our previous work[27]. The pressure distribution in the xoz plane ($y = 0$) of the separation process at six different times are illustrated in Fig. 6. Figure 6(a) presents the case without a jet control device. Figure 6(b) shows the case with the jet, and the pressure of the jet control device was $5\ atm$. In the case without the jet control device,

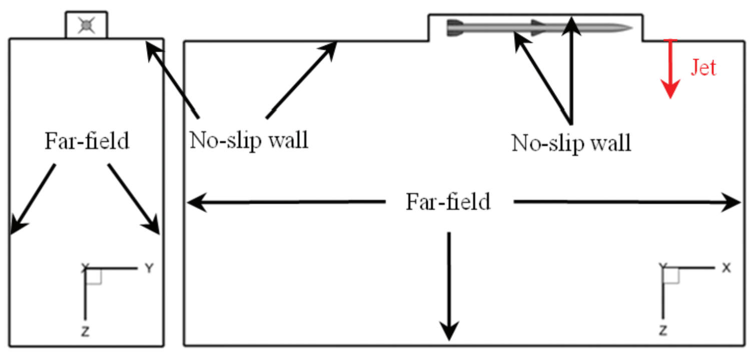


Figure 5. Boundary conditions and computational domain.

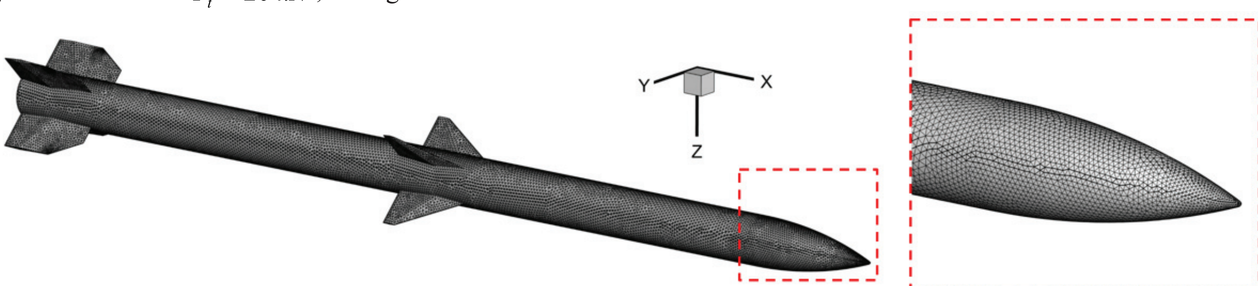


Figure 4. Mesh of the missile.

the pressure in the back of the internal weapons bay is greater than that in the front, causing the missile to pitch up first when it leaves the bay. If the time of the missile pitch up is long, the missile may collide with the bay, which makes the separation process dangerous.

When $t > 0\ s$, the jet control device of the internal weapons bay turns on, and the gas of the jet will meet with the incoming gas and generate shock waves (Fig. 6(b)), which is similar to the research of others[7,11]. Since the jet is perpendicular to the freestream, the shock wave is initially normal and then turns toward the cavity a small distance in the downstream direction. Because the size of the jet is very small compared with the size of the internal weapons bay, the normal shock wave is smaller than the oblique shock wave[7]. The shock wave hinders the freestream to the downstream of the bay, so the high pressure of the jet changes the flow characteristics of the bay and lowers the pressure in the bay compared to the case without a jet. The jet has a significant influence on the separation process and changes the trajectory of missile. The head of the missile is affected by the high pressure of the jet at $t = 0.1\ s$. Under the action of the high-pressure of jet, the head of missile moves to the positive z-direction; simultaneously, due to the high pressure of jet, the force on the missile increases, accelerated the missile departure from the bay; this is beneficial for the separation process. During the separation of missile and aircraft, the high pressure of the jet first comes into contact with the head of the missile. As time passes, when $t = 0.4\ s$, the action position of the high pressure gradually moves toward the rear of the missile, and the missile is unaffected by the bay and jet control device at $t = 0.5\ s$.

Figure 7 shows the Mach number in the $y = 0$ (xoz) plane at $t = 0.05\ s$. In the case without the jet control device, a strong flat shear layer is formed below the bay. So, the missile is subjected to a large lift force (negative z-direction force coefficient) when passing through the shear layer; the missile has the risk of being bounced back into the bay. In the case with jet control device, the shear layer under the bay becomes thicker. Thicker shear layers, with more gradual velocity gradients[11], which is beneficial to the separation of the missile.

In addition, when the incoming gas meets the high pressure of the jet, a shock wave is formed under the jet control device and the shear layer of the bay widens. The lift force received by the missile when it separates through the shear layer became smaller, which is conducive to the separation movement of the missile.

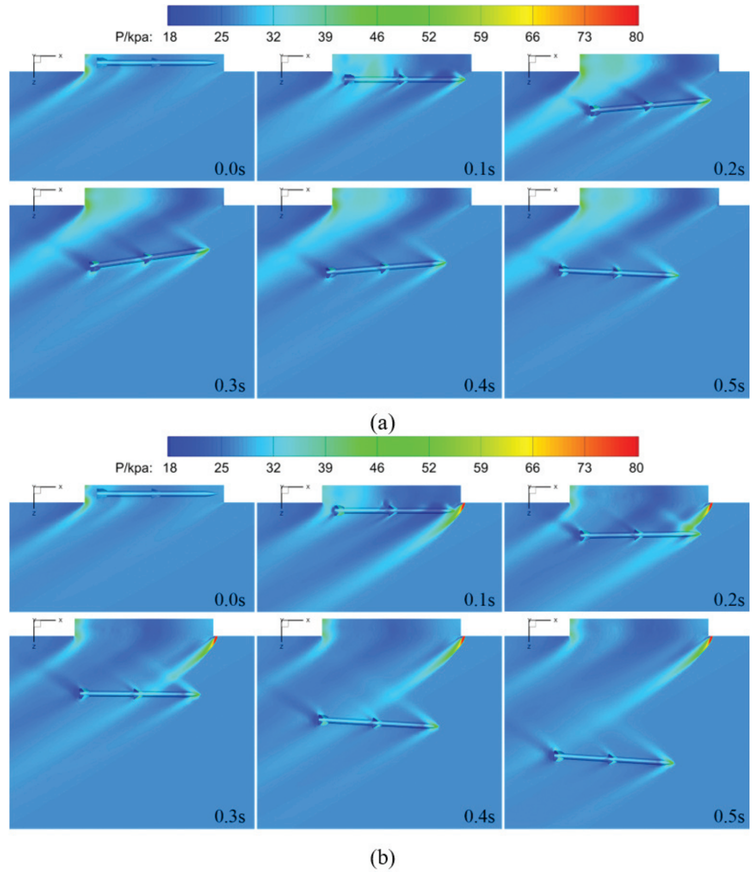


Figure 6. Pressure distribution: (a) without jet control device and (b) with jet control device.

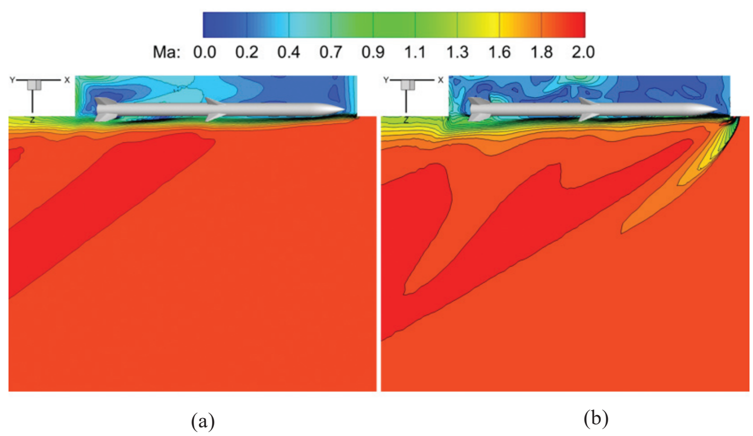


Figure 7. Mach number in the xoz plane at *t*=0.05 *s*: (a) without jet control device and (b) with the jet control device.

4.2 Aerodynamic Force (Moment) and Missile Motion

Figure 8 shows the force coefficient of the missile, which includes the effects of ejection force, aerodynamic force, and gravity. Figure 9 illustrates the center of gravity location of the missile in the z-direction. For both cases (with and without jet control), when $t = 0.0465\ s$, the ejection force disappears and C_z decreases rapidly. After the ejection force disappears, the variation trend of the force coefficient C_z differs for each case. For the case without jet control, the force coefficient C_z increases, because the pressure acting on the upper side of missile is greater than that on the lower side (Fig. 6(a)), and a maximum value of C_z appears at the separation time is $0.12\ s$. Since the pressure in the latter part of the bay is greater than that in the front, the missile's angle of attack begins to be greater than zero. Therefore, when the force under the missile's head is greater than the force above the missile's tail ($t > 0.12\ s$), the force coefficient C_z begins to decrease. The force coefficient C_z is negative for most of the separation time, hindering the separation of the missile from the bay.

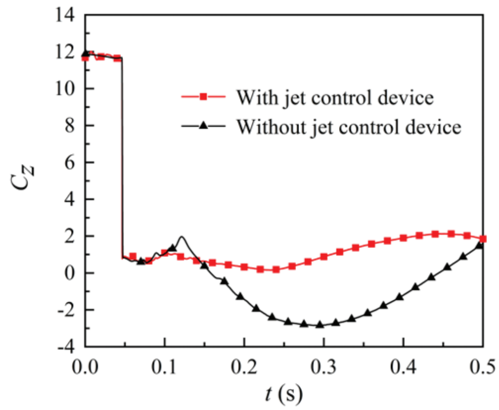


Figure 8. Force coefficients of missile in the z-direction.

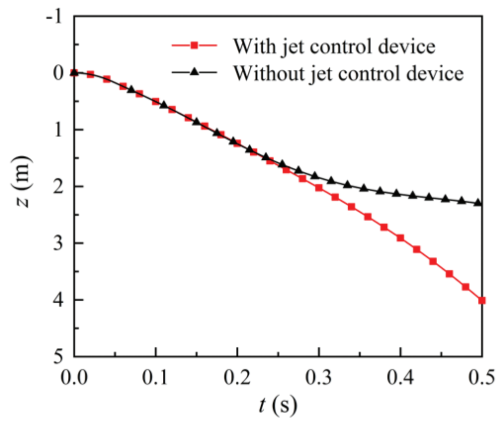


Figure 9. Center of gravity location in the z-direction of missile.

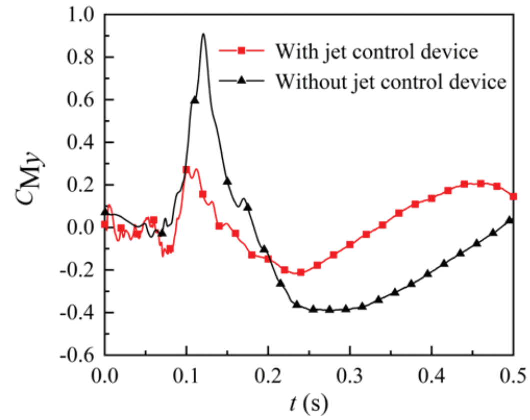


Figure 10. Pitching moment coefficients of missile.

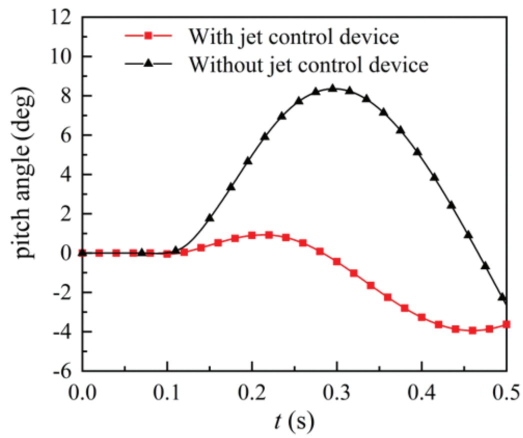
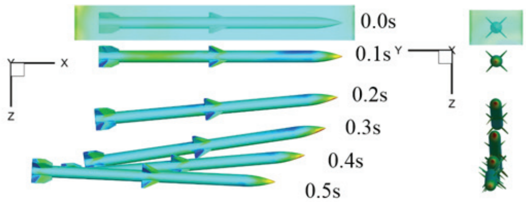


Figure 11. Pitch angle of missile.

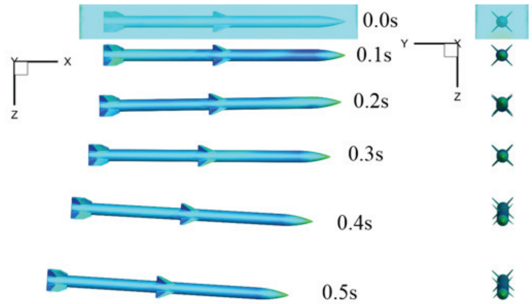
In the case of the jet control device, the pressure in the internal weapons bay was lower than that without jet control (Fig. 6). Therefore, in the case of a jet, the force coefficient C_z does not show an obvious increasing trend and does not exhibit a maximum value, as in the case without jet control. When the missile moves in the positive z-direction, the missile is within the range of the high pressure of the jet (Fig. 6(b)), the force coefficient C_z remains positive during the entire process, and the missile accelerates out of the bay. At the end of calculation ($t = 0.5\ s$), the displacement of the missile is $4.01\ m$ and $2.31\ m$ in the z-direction for the case with and without a jet, respectively. The distance for the case with a jet is 1.74-fold greater than that without. Therefore, for the same separation time, the distance of the missile with the jet is much greater than that in the case without the jet control device (Fig. 9).

Figure 10 illustrates the pitch moment coefficient of the missile. Figure 11 illustrates the pitch angle of missile. In the case without the jet, after the missile breaks away from the constraints of the ejection device, under the action of high pressure in the back of the bay and the incoming flow (Fig. 6(a)), the missile suffers a large pitching moment. The moment coefficient C_{My} of the missile increases rapidly and reaches a maximum value when the separation time is $0.12\ s$. When the separation time is greater than $0.12\ s$, the low-pressure area under the internal weapons bay gradually acts on the rear of the missile, causing the moment coefficient C_{My} to decrease accordingly until it becomes negative. In the case of the jet control device, when $t = 0.1\ s$, the missile enters into the influence of the jet at the front edge of the bay (Fig. 6(b)). When the head of the missile enters the effect of the jet, the upper side of the missile head bears greater pressure. Therefore, compared to the case without the jet, the pitch moment coefficient C_{My} does not significantly increase when the missile is out of the bay; the increase of C_{My} is restrained. During the entire process of missile separation, in the case without jet control device, the pitching moment coefficient C_{My} of the missile varies greatly, changing the pitching angle of the missile from $8.35°$ to $-2.67°$. The intense pitching motion of the missile may cause it to collide with the bay during the separation process, impeding safe separation. In the case of the jet control device, the moment coefficient, C_{My}, remains mostly unchanged; thus, the pitch motion of the missile is relatively gentle and the pitching angle of the missile ranges from $0.93°$ to $-3.94°$. Therefore, the jet control device installed at the front edge of the bay can change the angular motion of the missile and a reasonable setting of the parameters of the jet can improve the angular movement of the missile.

Figure 12 shows the relative position and attitude of the missile. Six typical separation moments visually show the separation process of the missile. As can be seen, in the case with jet, the missile leaves the bay quickly. At the end of calculation ($t = 0.5\ s$), the distance of the missile moving in positive z-direction is larger than the length of the missile and is much larger than the displacement of the missile in the case



(a)



(b)

Figure 12. Separation process of missile: (a) without jet control device and (b) with jet control device.

without the jet control device. Moreover, in the case of the jet control device, the pitch motion of the missile changes little and the attitude change of the missile is not obvious. Compared with the case without the jet control device, the separation motion of the missile is relatively safe.

5. CONCLUSIONS

The separation process of the missile with and without the jet control device was numerically simulated, and the role of the jet control device in the separation process was analysed in detail. The jet control device installed at the front edge of the bay can alter the shear layer, improve the flow field characteristics, and enable the missile to smoothly traverse the shear layer and separate from the bay.

Under the action of the high-pressure jet, the missile can quickly leave the bay. At the end of calculation ($t = 0.5\ s$), the distance of the missile moving in the z -direction with and without the jet is $4.01\ m$ and, $2.31\ m$, respectively. The displacement with the jet is 1.74 times that without the jet. In the case without the jet control device, the pitching angle of the missile ranged from $8.35°$ to $-2.67°$. In the case of the jet control device, the pitching angle of the missile ranged from $0.93°$ to $-3.94°$. The jet control device installed at the front edge of the bay can improve the pitch motion of the missile, and improve the safety of the missile separation.

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