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Numerical Investigations on Wedge Control of Separation of a Missile from an Aircraft

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ABSTRACT

To make the missile safely separate from the internal weapons bay, a wedge flow control device is mounted on the front of the bay to control the variation of flow during the separation. The numerical simulations of missile separation without and with wedge flow control device under different sizes are carried out. The flow fields of different separation processes are obtained and discussed; the aerodynamic parameters and trajectory parameters of missile of different cases are illustrated and compared. Results show that, the wedge flow control device can accelerate the missile separation and has the effect of regulating the angular motion of missile. The influence of the wedge height is stronger than that of its length on the center of gravity motion and angular motion of missile.

Keywords: Missile separation; Flow control; Wedge device; Internal weapons bay; Six-degrees-of-freedom

1. INTRODUCTION

The modern fighter aircraft usually adopts the internal weapons bay to reduce the radar reflection characteristics and drag[1,2]. However, the use of the internal weapons bay may lead to a series of complex flow phenomena for missile launch, such as flow separation, shear layer instability[3,4]. These phenomena may lead to unexpected movement of missiles in the separation process, even hitting the carrier, therefore, it is of great significance to study the separation process of missiles from the internal weapons bay, and the effects of flow control devices during the separation process.

To study the flow characteristics of the internal weapons bay, researchers usually simplify the bay into a rectangular cavity, and cavity flow has been studied since the implementation of internal weapons bay into aircraft in the 1950s[5]. As found before, after its release, the missile may return back[6]. To avoid this, some control methods have been applied to ensure a safe separation, such as mounting spoilers[7], rod[2], blowing[1], microjets[6] at the leading edge of the bay. However, research on the wedge flow control device and the influence of the wedge size on the control effect is rare. Therefore, in this paper, we investigate the missile separation from the bay under the control of a wedge. Based on the computational fluid dynamics (CFD), six-degrees-of-freedom (6DOF) rigid-body motion equations and the application of dynamic mesh technique, the numerical studies of the separation process with wedge flow control device under different sizes are carried out. The variations of flow fields with different wedge devices are studied, and the influences of the length (Δx) and height (Δz) of the wedge on missile motion have also been discussed.

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2. NUMERICAL METHODS

With the development of powerful computers and advanced numerical algorithms, CFD has revolutionised the aerodynamic and propulsion design of aerospace vehicles[8], such as missile separation from aircraft[9,10,]. Based on the commercial FLUENT software and user-defined function (UDF), the fluid dynamic equations and 6DOF rigid-body motion equations of the missile is simulated. The coupled numerical calculation process for each time step is as follows: firstly, the aerodynamic force (moment) parameters of the missile are obtained by solving the flow field; secondly, according to the aerodynamic force (moment) parameters of the missile, the 6DOF motion process of the missile is solved, and the trajectory parameters of missile are obtained; finally, according to the trajectory parameters of the missile, the dynamic mesh technique is used to update the flow field meshes. In our previous work, we have validated the above calculation method[11,12].

The three-dimensional, unsteady *Navier-Stokes* (N-S) equations are solved by using a higher precision detached eddy simulation method (DES). The advection upstream splitting method (AUSM) is used for the convection term and the second order central difference scheme for the viscosity term. In order to obtain the 6DOF trajectory parameters of missile, the mass and moment of inertia of missile are given using UDF. Two dynamic mesh methods, smoothing and remeshing method, are used to describe the move of the missile. When the missile displacement is smaller than the mesh size, the smoothing method is used to move the nodes of mesh. With this method, the mesh topology is always stable, and the computational accuracy can be guaranteed. When the missile displacement is large, the remeshing method is applied to regenerate the mesh with better quality. More details about dynamic mesh method can be found[13].

3. PHYSICAL MODEL AND COMPUTATIONAL CONDITIONS

3.1 Physical Model and Mesh

The model of the internal weapons bay, missile and the wedge device used in the calculation are as shown in Figs. 1(a) and 1(b). All dimensions of the internal weapons bay, missile and the wedge device are non-dimensionalised using the cavity width $W = w$. The length and depth of the bay is $L = 5.25w$ and $D = 0.65625w$, respectively. The missile with a length of $4.5625w$ and a diameter of $0.2225w$, the CG location of the missile is $2.27w$ from the missile tip. The distance between the CG location of missile and the front, bottom of the internal weapons bay is $2.5w$ and $0.328125w$, respectively. It is assumed that the internal weapons bay is stationary, and the global coordinate system is built based on the bay. The centerline of the missile lies along the x axis with the positive direction toward the missile tip. The z axis is along the direction of gravity, and the y axis is determined by the right hand rule. The origin of the coordinate system is located at the CG location of missile. Figure 1(c) shows the mesh distribution of missile of the case with $\Delta x = 0.09375w$, $\Delta z = 0.1875w$, $W = 1w$. The unstructured mesh is adopted in the computational fluid domain.

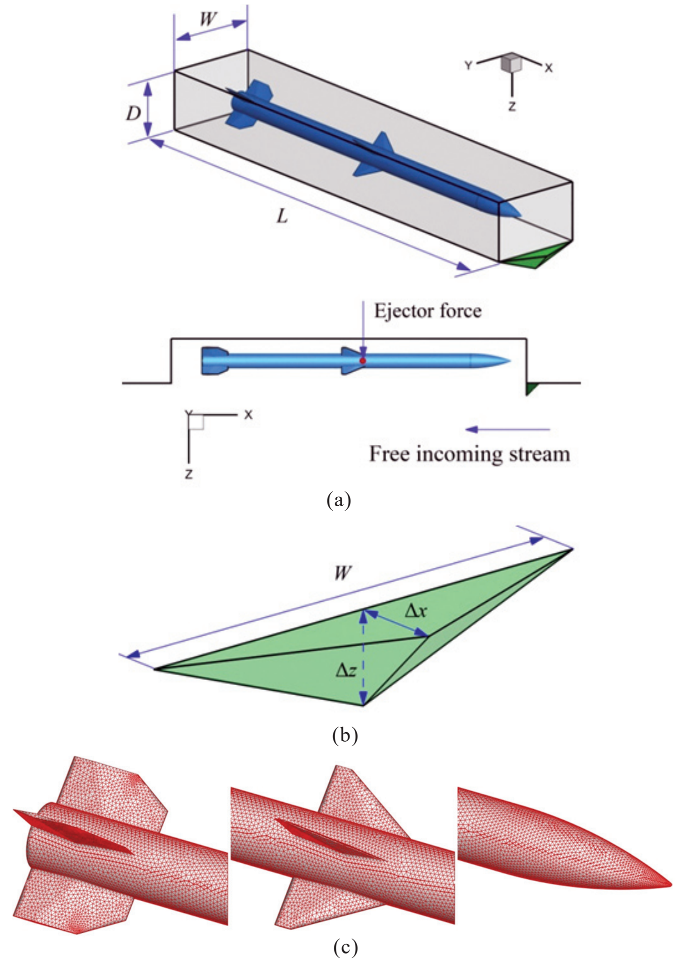


Figure 1. Geometric model and mesh (a) Geometric model, (b) Wedge device, and (c) Mesh distribution of missile.

3.2 Computational Conditions

The surface of missile, wedge device, internal weapons bay and nearby aircraft structures are subjected to no-slip wall conditions. Other boundaries are chosen to be pressure far-field boundary conditions. The mass of missile is 156.8 kg, and the moment of inertia $I_{xx} = 1.0708 kg \cdot m^2$, $I_{yy} = I_{zz} = 199.59 kg \cdot m^2$. The free incoming stream conditions for this simulation are given as Mach number of 2, angle of attack of 0°, and altitude of 10 km, the gravitational acceleration is $g = 9.8 m/s^2$. The initial velocity and angular velocity of the missile are zero. The ejector force is taken as $F_t = 20kN$, and given by UDF, acts on CG of the missile along gravity direction. When the missile distance $z \geq 0.1875w$ in the direction of z, the ejector force disappears, but when $z < 0.1875w$, the missile is constrained to move along z direction only.

4. RESULTS AND DISCUSSIONS

4.1 Control Mechanism of the Wedge

In order to understand the control mechanism and effect of the wedge, cases with and without wedge device are simulated and compared. Figure 2 shows the pressure contours in the symmetry plane (*xz* plane). Without wedge control, the pressure at the rear of the internal weapons bay is higher than the pressure at the front, which makes the missile head rise, which has the potential risk for the missile separation.

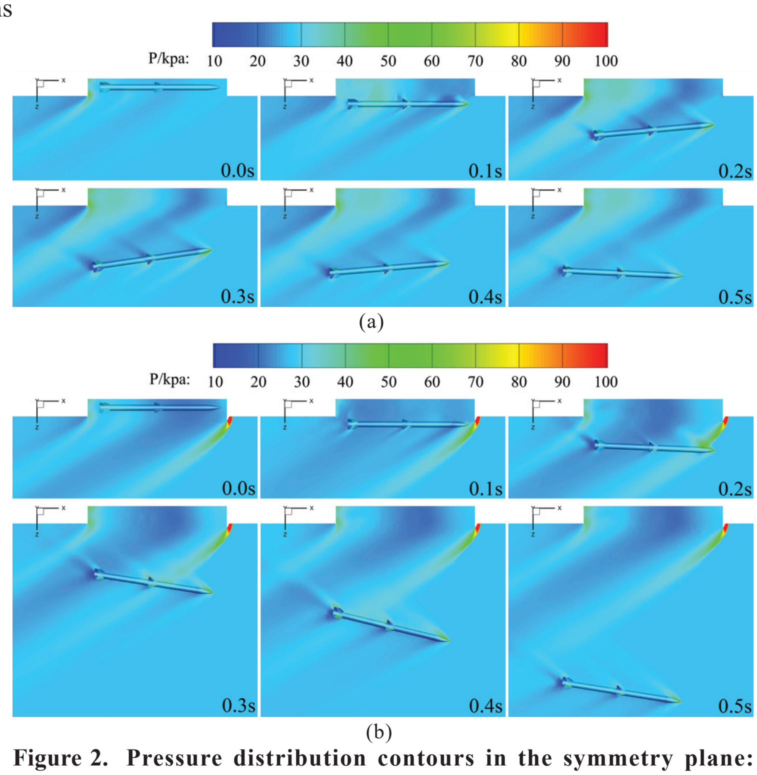
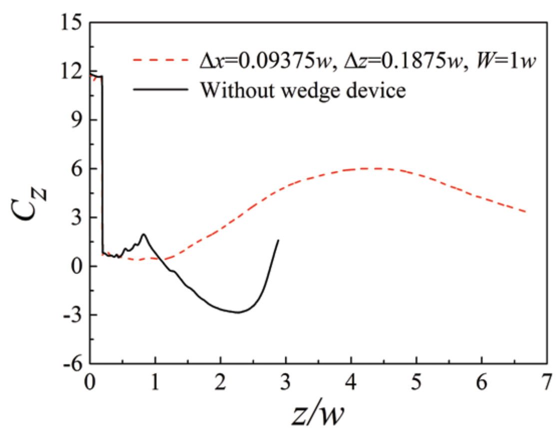


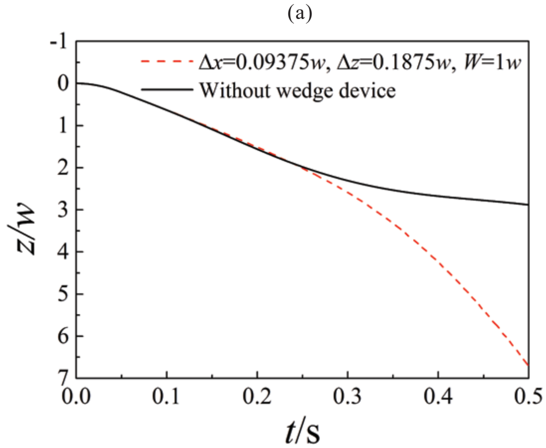
Figure 2. Pressure distribution contours in the symmetry plane: (a) Without wedge control and (b) With wedge control ($\Delta x = 0.09375w$, $\Delta z = 0.1875w$, $W = 1w$).

For separation with the wedge device, the bow shock wave forms in front of the leading edge of wedge which has a great influence on the movement of the missile. When $t > 0.1s$, the head of missile passes the bow shock wave, and its head is down under the action of shock wave. And the aerodynamic force of missile along z direction increases, therefore, the missile accelerates away from the bay. During the separation process, the shock wave firstly acts on the missile head. With time goes on, the acting point moves to the missile tail, its intensity becomes weak, until the missile is completely moved out of the influence of the wedge (Fig. 2(b), $t = 0.5s$).

Figure 3(a) illustrates the total force coefficient (C_z) of missile in the z direction. Figure 3(b) shows the missile CG location in the z direction. Due to the disappearance of ejector force at $z \geq 0.1875w$, then, C_z decreases rapidly, and the variation trend of C_z for both with and without control become completely different. In the case of without wedge, C_z increases firstly till $z = 0.82w$, then it decreases rapidly till $z = 2.4w$, and C_z is negative most of time, which means C_z becomes a lift and hinder the missile's moving away from the bay. With wedge applied, the variation of force coefficient C_z increases slowly after the ejector force disappeared, then it decreases at about $z = 4.5\ w$, but the value is always positive, therefore, the missile is accelerated away from the bay. In the same time, its displacement of missile in the z direction is much greater than the case without wedge (Fig. 3(b)). Thus, the wedge device has the effect of make the missile leave quickly.



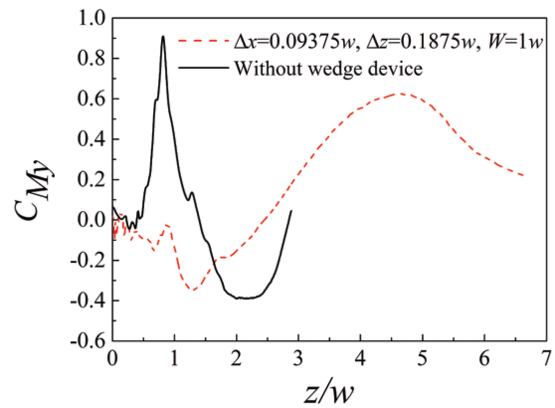
(a)



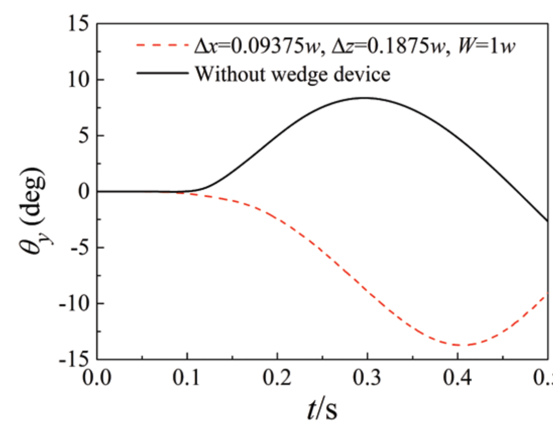
(b)

Figure 3. Force coefficient and CG location of missile in the z direction: (a) Force coefficient and (b) CG location.

Figure 4(a) illustrates the pitching moment coefficient of missile in z direction, Fig. 4(b) shows the variation of the pitch angle versus time. Without wedge, the pitching moment coefficient C_{My} increases rapidly after the missile separating from the bay, and makes the missile nose-up, this may lead to the collision of the missile and the aircraft and should be avoided. However, with wedge control, when $z < 2.5w$, C_{My} does not change greatly, and it is a small negative value, this means that the attitude of the missile is stable and its nose will be downward slowly (Fig. 4(b)). When the distance become large ($z > 2.5w$), the C_{My} begins to increase and become positive, then it decreases again. Since the variation of C_{My} is not intense, the missile attitude does not change much. Therefore, the wedge can improve the pitch motion of missile.



(a)



(b)

Figure 4. Pitching moment coefficient and pitch angle of missile: (a) Pitching moment coefficient and (b) Pitch angle.

4.2 The Effects of Length (Δx) of the Wedge on the Separation

Three different cases with wedge length $\Delta x = 0.09375w$, $0.1875w$ and $0.28125w$ are chosen to investigate their effects on the flow control during separation, respectively. For all three cases $\Delta z = 0.1875w$, $W = w$.

Figures 5(a) and 5(b) show the CG velocity and trajectory of missile in the z direction, respectively. As initialised, under the action of ejector force ($z \leq 0.1875w$), the missile is restricted by the ejector and only moves along z direction and its velocity is increased linearly. The CG velocity and trajectory in the z direction decrease with the increase of the

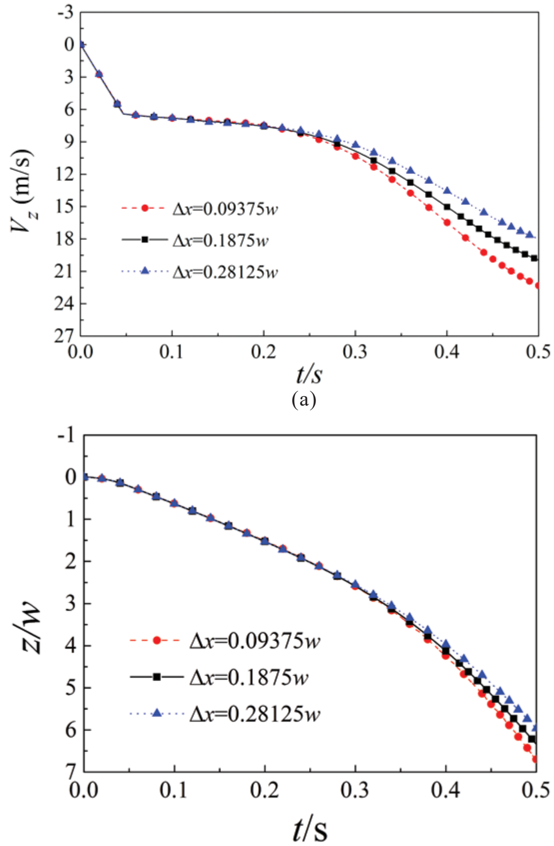


Figure 5. CG velocity and CG trajectory of missile in the z direction: (a) CG velocity and (b) CG trajectory.

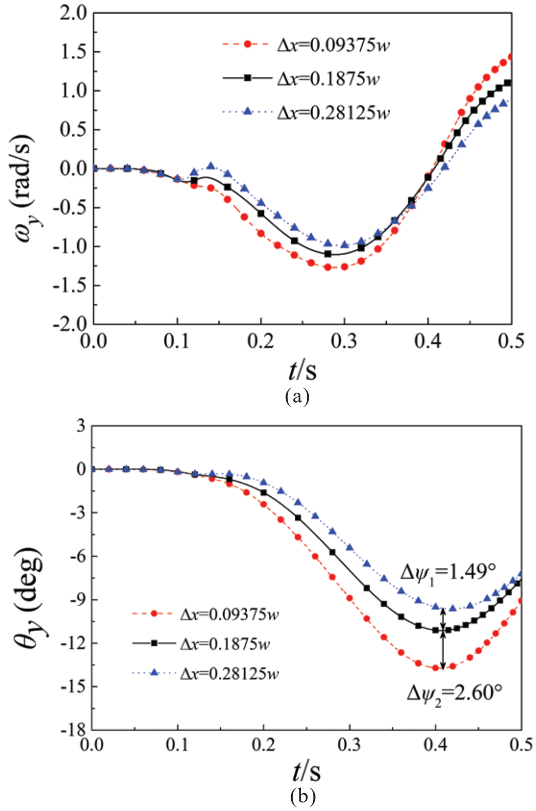


Figure 6. Variation of pitch angular velocity and pitch angle of missile: (a) Pitch angular velocity and (b) Pitch angle.

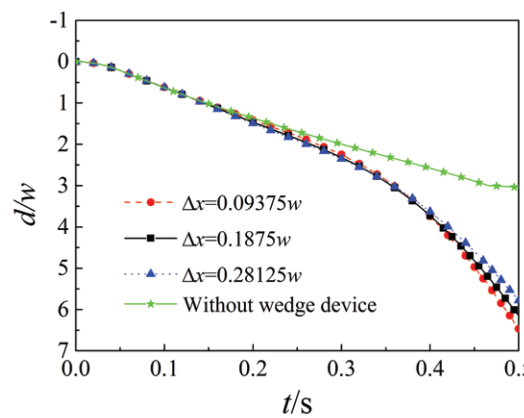


Figure 7. The minimum distance between the missile and the aircraft.

wedge length (Δx). Compared with the case without wedge in Fig. 3(b), the control devices ($\Delta x = 0.09375w$, $0.1875w$ and $0.28125w$) in this section all lead to a larger displacement. The shorter the wedge, the larger its displacement becomes. For all three cases, the smallest length ($\Delta x = 0.09375w$) of the wedge has the largest displacement of the missile. It is $6.71w$ in *z* direction, and it is beneficial for the missile separation.

Figures 6(a) and 6(b) show the variations of the pitch angular velocity and pitch angle of the missile, respectively. In all three cases, the variation tendencies of the missile pitch attitude are the same, the nose goes down first, then goes back. The smaller the wedge length, the larger the variation of the pitch angular velocity and angle become. Since the large variation of pitch angle may affect the balance of the missile, therefore, the wedge length should be set appropriately.

Figure 7 shows the time history of the minimum distance between the missile and the aircraft with different wedge lengths. It seems that the wedge length does not affect the minimum distance much, and at $t = 0.5s$, the minimum distances of all cases vary among $5.78 \sim 6.5w$, and they are all more than twice of that without wedge device, this also proves that the missile separation process is greatly enhanced with wedge devices.

4.3 The Effects of Height (Δz) of the Wedge on the Separation

Three different wedge heights $\Delta z = 0.09375w$, $0.1875w$ and $0.28125w$, are also chosen to investigate their effects on the separation flow control, respectively. For all three cases $\Delta x = 0.1875w$, $W = w$.

Figures 8(a) and 8(b) show the variations of CG velocity and location of missile in *z* direction, respectively. It is clear that the missile has the same movement as described in Sec. 4.2 during the ejection. When ejector force disappears, the variation of CG velocity and displacement of the missile with increase of height (Δz) along *z* direction is contrary to those described in Fig. 5. The CG velocity and displacement increase with the increase of wedge height, and its increased value is larger. For wedge height $\Delta z = 0.28125w$, the displacement of the missile

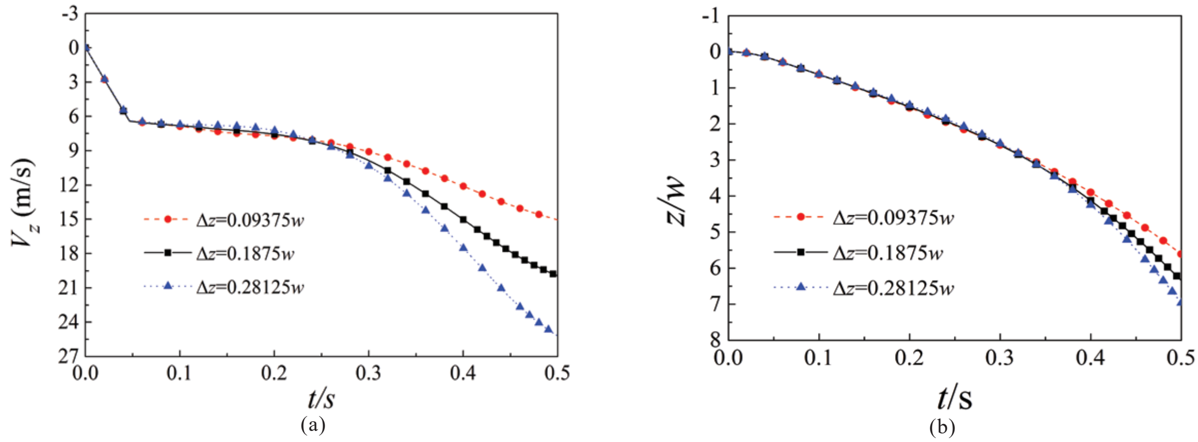


Figure 8. CG velocity and CG location of missile in the *z* direction: (a) CG velocity and (b) CG location

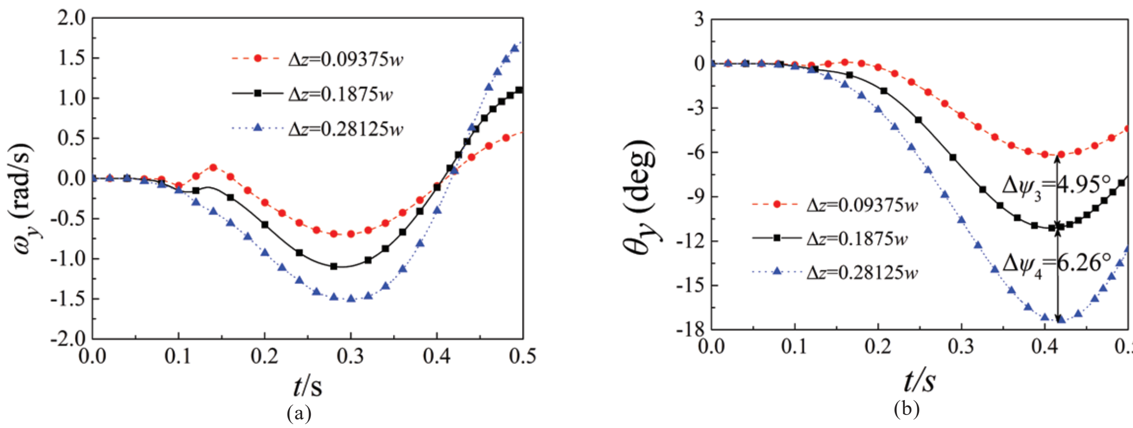


Figure 9. Variation of pitch angular velocity and pitch angle of the missile: (a) Pitch angular velocity and (b) Pitch angle.

is $6.963w$ at $t=0.5s$. Therefore, variation of wedge height (Δz) has greater impact on the missile downward motion than that of its length (Δx).

Figures 9(a) and 9(b) show the variation of the pitch angular velocity and pitch angle of the missile, respectively. Their variations with the height is also opposite to that of the wedge length as shown in Fig. 6, but the missile attitude during the separation has the same tendency. It leaves with nose down. The bigger the wedge height (Δz), the larger the changing gradient of the pitch angular velocity and angle become. Thus, the wedge height (Δz) also has a greater impact on the pitch motion of the missile than that of the length (Δx).

Figure 10 shows the time history of the minimum distance between the missile and the aircraft with different heights of wedges. Similar to earlier Sec. 4.2, It seems that the wedge height does not affect the minimum distance much, and at $t=0.5s$, the minimum distances of all wedges vary among $5.5 \sim 6.5w$, at $t=0.5s$, the minimum distance with control device is still more than twice of that without wedge device, it also validated that the missile separation process is much safer with device.

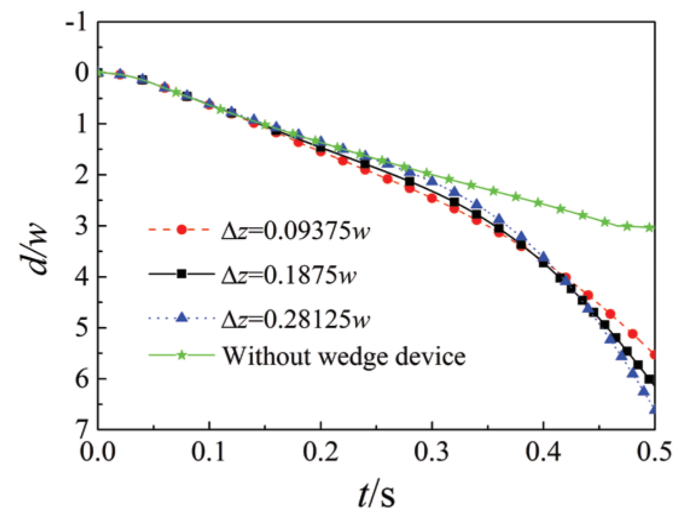


Figure 10. The minimum distance between the missile and the aircraft.

5. CONCLUSIONS

With the coupling of *N-S* equations, 6DOF rigid-body equations and dynamic mesh technology. The numerical simulation of missile separation from the bay which is mounted with different wedges are carried out and discussed.

Our results show that, with the wedge flow control device, the bow shock wave forms at the leading edge of the wedge. The shock wave acts on the missile head and make its head down during the separation, and the variation of attitude increases aerodynamic lift and the missile velocity, therefore, wedge device can enhance the missile separation.

The CG displacement of the missile in the *z* direction decreases with the increase of the wedge length (Δx), but increases with the increase of the height (Δz). And the same with that of its pitch angle, but the actual wedge length and height should be designed with other factors considered. Our results also show that the wedge height (Δz) variation has larger effect than that of its length (Δx) on the missile separation.

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In the current study, he revised the paper and provided overall guidance.