Numerical study on aerodynamic characteristics of rotating missile launched vertically under strong transverse wind

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Abstract. Numerical simulation of low speed high Angle of attack rotating missile was carried out by using different turbulence models, and the numerical simulation results were compared with the experimental results. The results show that the SST-DDES model can well simulate the aerodynamic characteristics of the rotating missile at low speed and high Angle of attack. Under the condition of low speed and high Angle of attack, the difference of the lateral force produced by the missile's tail fin is small, and the variation of the total missile lateral force mainly depends on the variation of the projectile body lateral force. When the Angle of attack increases from 40.1° to 60.1°, the direction of the missile's lateral force changes. This is because with the increase of the Angle of attack, the fluid velocity perpendicular to the projectile increases, resulting in the interaction and fusion of asymmetric vortexes on the leeward side, resulting in the change of lateral force direction.

1. Introduction

The vertical launch missile has the advantages of fast reaction speed and short response time against incoming missile, for stealth, more and more shipborne terminal defensive rotating missiles begin to adopt vertical launch mode. For the shipboard terminal defense weapon, the missile must complete the quick and wide angle turn within a short time after the vertical launch. Especially when the cross wind of the sea is very strong (such as a large typhoon), the missile has a low velocity at the initial moment and a high cross wind velocity, which results in the missile being at a high angle of attack for a short time after launch. At present, many scholars have studied the aerodynamic characteristics of large Angle of attack non-rotating projectile at low speed. Flow asymmetry was initially observed in experiment by Mead[1]. Further experimental studies[2] confirmed the existence of flow asymmetry and the resulting side force. Wardlaw[3] described the variation of maximum side force with Mach number and Reynolds number. The dependency of side force on Mach number was substantial while Reynolds number effect was minor. As the Mach number increases, the maximum side force is decreased. Osama Obeid[4] shows that grid resolution and solution scheme have a profound effect on the validity of the simulation of flow around slender bodies at high angles of attack. Computations were then carried out at seven angles of attack $\alpha=30^\circ$, $40^\circ$, $50^\circ$, $52.5^\circ$, $55^\circ$, $57.5^\circ$ and $60^\circ$. The total normal force increased with increasing angle of attack. On the other hand, the total side force started to increase rapidly for angles of attack $\alpha>50^\circ$ and reached a maximum at $\alpha=57.5^\circ$ before decreasing at $\alpha=60^\circ$. However, there are few studies on the aerodynamic characteristics of large Angle of attack rotating missile at low speed. In this paper, the navier-stokes equations were solved by using the SST-DDES model based on the SST $k-\omega$ turbulence model coupled with delayed-vortex simulation technology.
The flow field around Finner missile was simulated, and the influence of aerodynamic interference between components on magnus effect and the internal flow mechanism were studied.

2. Numerical method

2.1. Turbulence models
The integral form\(^5\) of SST \(k-\omega\) two-equation turbulence model is:

\[
\frac{\partial}{\partial t} \int_{\Omega} W_T d\Omega + \oint_{\partial \Omega} (F_{c,T} - F_{v,T}) dS = \int_{\Omega} Q_T d\Omega
\]  
(1)

Where, \(W_T\) is the conserved variable; \(F_{c,T}\) and \(F_{v,T}\) are the convection term and the viscosity term respectively. \(Q_T\) is the source term of the turbulent transport equation.

For high Reynolds number and large separation flow, DES scale \(\bar{l}\) was defined based on SST \(k-\omega\) two-equation turbulence model:

\[
\bar{l} = \min (l_{k-\omega}C_{DES}\Delta)
\]  
(2)

Among them

\[
l_{k-\omega} = \frac{k^2}{\beta^* \omega} \quad \Delta = \max \left(\Delta_x, \Delta_y, \Delta_z\right)
\]  
(3)

Grid scale \(\Delta\) space for three largest direction grid step length, \(C_{DES}\) for adaptive parameters:

\[
C_{DES} = (1 - f_1) C_{DESK-\varepsilon}^{k-\varepsilon} + f_1 C_{DESK-\omega}^{k-\omega}
\]  
(4)

Where: \(f_1\) is given by the turbulence model, \(C_{DESK-\varepsilon}^{k-\varepsilon} = 0.61, C_{DESK-\omega}^{k-\omega} = 0.78\).

The realization of SST-DDES mode only needs to replace the dissipation term in \(k\) equation, that is, \(D_{RNAS}^k = \beta^* pk \omega\) is replaced by \(D_{DES}^k = \beta^* pk \omega F_{DES}\). Among them, \(F_{DES} = \max \left(\frac{l_{k-\omega}}{C_{DES} \Delta} (1 - f_{SST}), 1\right)\), \(f_{SST}\) is the switching function.

2.2. Numerical conditions and physical models
The international standard model Finner missile was selected for the calculation, and the calculated results were compared with the experimental results of AEDC\(^6\). The calculation condition is: \(p_\infty = 49329.9\)Pa, \(T_\infty = 308.127\)K, reference length \(L_{ref} = 0.4572\)m, reference area \(S_{ref} = 0.00164\)m\(^2\).

![Figure 1. Geometric model.](image-url)
2.3. Meshing

As shown in figure 2 and 3, the three-dimensional structure hexahedral mesh extends forward 10 times the elastic length, backward 10 times the elastic length, radial about 40 times the elastic diameter. The spin of the missile is realized by sliding the mesh motion in the mesh region. The grid height of the first layer was set as $1.8 \times 10^{-6}$ to ensure $y^+ < 1$, and the inner boundary of the grid was set as a sliding-free adiabatic wall. The XY plane is the angle of attack plane. The projectile revolved around the vertical axis that rejoined the X axis. The rotation direction of the missile is positive x axis and the dimensionless speed is $0.02(pd/2V_\infty)$.

11 million, 23 million and 32 million grids were selected for grid-independence verification. The calculated results showed that the lateral force coefficient difference between 23 million and 32 million grids on the surface was less than 1%, while the lateral force coefficient difference between 11 million and 23 million grids was 13%, so 23 million grids were selected for calculation.

3. Numerical simulation results

Figure 4 shows the calculation results of different turbulence models. Although the calculated result using SST-DDES model is larger than the experimental value, compared with other turbulence, the lateral force obtained by using SST-DDES model has the same trend with the Angle of attack. In particular, the SST-DDES model was used to capture the change of the lateral force direction from $40^\circ$ to $60^\circ$. 

![Figure 4. Results of different turbulence models](image-url)
Figure 5 and 6 show the variation curves of the lateral force coefficient of the missile components with the spin Angle. By comparing the lateral force coefficient of missile components with an Angle of attack of 40.1° and 60.1°, it can be seen that the lateral force coefficient generated by the tail fin is roughly the same, while the variation of the lateral force coefficient of the projectile body is the reason for the variation of the lateral force direction. When the Angle of attack is 40.1°, the lateral force generated by the projectile body is positive. However, when the Angle of attack increases to 60.1°, the lateral force of the projectile body changes from positive to negative, and the lateral force generated by the projectile body is larger, resulting in a change in the direction of the lateral force of the whole projectile body.

Figure 7 and 8 show the vorticity diagram of the flow field around the missile with an Angle of attack of 40.1° and 60.1°. Due to the rotation of the missile, the flow field around the missile body is asymmetric, so the vorticity distribution is uneven. It is because of this change that the lateral force of the body changes suddenly. Because the missile body has a larger Angle of attack, the body wash has less influence on the tail fin. Therefore, the variation of the lateral force of the whole projectile depends on the variation of the lateral force of the projectile.

4. Conclusion
Numerical simulation of low speed high Angle of attack rotating missile was carried out by using different turbulence models, and the numerical simulation results were compared with the
experimental results. The results show that the SST-DDES model can well simulate the aerodynamic characteristics of the rotating missile at low speed and high Angle of attack. Through the analysis of the simulation results, the following conclusions are obtained:

1) Under the condition of low speed and high Angle of attack, the difference of the lateral force produced by the missile's tail fin is small, and the variation of the total missile lateral force mainly depends on the variation of the projectile body lateral force.

2) When the Angle of attack increases from 40.1° to 60.1°, the direction of the missile's lateral force changes. This is because with the increase of the Angle of attack, the fluid velocity perpendicular to the projectile increases, resulting in the interaction and fusion of asymmetric vortexes on the leeward side, resulting in the change of lateral force direction.

Acknowledgments
Due to the reason of computing resources, this paper only calculates some representative feature points. We will add more calculation results in the following work. Secondly, we will continue to pay attention to the aerodynamic characteristics of the rotating missile with duck layout under strong transverse wind in the following work.

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