Numerical Simulation Calculation and Analysis of the Effect of Rocket and Duck Rudder on Its Aerodynamic Characteristics and Flexible Deformation

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Abstract. Based on inertia relief and CFD/CSD two-way coupling methods, the static aeroelasticity numerical simulation of a simply guided rocket with duck rudder actuator has been done, and the influence of duck rudder on aerodynamic characteristics and flexible deformation has been analyzed. Firstly, the lift, drag force and pitch moment coefficients, etc. had been calculated by using CFD method based on SST k-\omega turbulence model, the error was less than 10 percent compared with the experimental data, and it verified the accuracy of fluid domain numerical method. Then, the two-way fluid-structure interaction simulation on the rocket and the contrastive analysis were done based on ANSYS Workbench multi-physics coupling simulation platform. The results show that duck rudder has a larger influence on rocket aerodynamic characteristics, by analysing the rocket aerodynamic coefficients under the conditions of without duck rudder, 0° rudder angle and 10° rudder angle, and it shows that the lift force and pitch moment coefficients change 5 to 30 percent with or without duck rudder and angle. Considering the influence of flexible deformation on aerodynamic coefficients, the flexible deformation has a more influence on the lift force and pitch moment coefficients, it reflects that the flexible deformation leads to the lift force coefficients smaller and pitch moment coefficients absolute value smaller, the maximum influence can reach to 5 to 10 percent. Meanwhile, the results show that the maximum deformation of rocket occurred in the middle of the rocket body, and the maximum equivalent stress occurred in the em pennage of the rocket. Therefore, in the design of simply guided rockets, it’s very important to consider the influence of duck rudder on the aerodynamic characteristics and flexible deformation.

1. Introduction

The accuracy of conventional bullets can be improved by simple guidance. In order to improve the firing accuracy of projectiles and rockets, a detection device is installed on conventional projectiles and a relatively simple guidance technology is adopted to correct the actual flight trajectory \cite{1, 2}. Usually, the main guidance devices are pulse engine and duck rudder actuator \cite{3}. The research object of this paper is a simple guided rocket based on duck rudder actuator. Accurate prediction of aerodynamic coefficients is very important for the study of control law of simple guided rocket. The modification of
guidance and control equations contain parameters such as drag coefficient, lift coefficient and pitching moment coefficient. Without the specific values of these aerodynamic coefficients, it is impossible to calculate the aerodynamic forces and aerodynamic moments, thus the scheme trajectory cannot be determined, and the simple guidance cannot be achieved by comparing the deviation with the actual trajectory.

In many cases, the model needs to be assumed as a flexible body. If the model is assumed as a rigid body, many engineering problems will arise. With the development of material science and processing technology, light alloys and composite materials are widely used in rocket structure. The shell is thinner and thinner. The ratio of thrust to mass and the ratio of length to diameter of projectile are larger and larger. Therefore, "large slenderness ratio" and "high flexibility" are the important characteristics of rocket projectile development in the future. The flexible rocket with large slenderness ratio will produce elastic deformation in the air. The bending deformation of the projectile will change the size and distribution of aerodynamic force. In turn, the change of aerodynamic force will change the deformation of the projectile. Therefore, there is a coupling relationship between the airflow and the structure, which is called aeroelastic phenomenon. Therefore, aeroelastic problems need to be considered in the preliminary work of rocket design, and the fluid-solid coupling method is becoming more and more important in the practical application of engineering. By using the method of calculating aeroelasticity, the number of flight and wind tunnel experiments can be reduced, and the design cost can be greatly saved. With the continuous improvement of CFD technology and computer computing ability, computer aided engineering (CAE) analysis which integrates CFD flow analysis [4-8] and computational structural mechanics (CSD) analysis [9] has developed rapidly in the field of aeroelastic design of aircraft.

2. Geometric Model
A geometric model of a simple guided rocket projectile without a duck rudder, with a duck rudder and a duck rudder at a rudder angle of 0 degrees and a duck rudder at a rudder angle of 10 degrees is established. As shown in Figures 1, 2 and 3.

![Figure 1. Rocket without duck rudder](image1)
![Figure 2. Rocket with a rudder angle of 0](image2)
![Figure 3. Rocket with a rudder angle of 10](image3)

2.1. CSD Control Equation
Static Equation of Structures:

\[
[K]\{\delta\} = \{F\}
\]

Among them, \([K]\) is a stiffness matrix and constant. \(\{\delta\}\) is the displacement vector and \(\{F\}\) is the pressure calculated by CFD. The rocket material is 30CrMnSi and the wall thickness is 4mm. Two kinds of shell elements, triangle and quadrilateral, are used to divide the grids. The number of solid domain elements of the three sets of rockets is about 5200. As shown in Figures 4:
In this paper, the method of inertial release [10] is used to ensure that the free-flying rocket has no rigid body displacement in structural statics analysis. Its basic idea is to set up a virtual support in the structure to provide full constraints for the structure and make the equation solvable. Then, the program calculates the acceleration of each node in each direction under the action of external force, and then converts the acceleration into inertia force which is applied to each node in the opposite direction. Thus, a balanced force system is constructed. At this time, the reaction force of the support is zero. Finally, the displacement of the relative virtual support is obtained by solving the equation. This method will affect the display value of displacement, but the relative value remains unchanged.

2.2. Dynamic Mesh Method and Coupled Surface Boundary Conditions

In this paper, a mesh diffusion smoothing method based on cell volume is used. The velocity of mesh nodes is calculated by diffusion equation (2), and the displacement of mesh nodes is updated by velocity.

$$\nabla \cdot (\gamma \nabla \bar{u}) = 0$$

(2)

Among them, $\bar{u}$ is the velocity of mesh nodes and $\gamma$ is the diffusion coefficient. The diffusion coefficient is obtained by solving equation (3), where $\alpha$ is the diffusion parameter, where $\alpha = 1.9$ and $V$ are the regular volume.

$$\gamma = \frac{1}{V^{\alpha}}$$

(3)

Then, the node position is updated and the equation (4) is derived.

$$\bar{x}_{new} = \bar{x}_{old} + \bar{u} \Delta t$$

(4)

Here, $\Delta t$ represents a coupling step.

The following conditions need to be satisfied at the interface of fluid-solid coupling:

$$d_f = d_s$$

(5)

$$n \cdot \tau_f = n \cdot \tau_s$$

(6)

Among them, $d$ is the displacement field, $\tau$ is the stress field, $n$ is the normal direction, and subscripts $f$ and $s$ are the fluid and solid respectively.

2.3. Two-way Coupled Flow Chart of Aeroelasticity

Considering not only the influence of the pressure calculated by the flow field on the structure field, but also the influence of the structural deformation on the flow field, the surface pressure distribution of rocket projectile is obtained by the steady CFD calculation and used as the initial boundary condition of the CSD analysis. Then, the displacement calculated by the CSD is transferred to the flow field grid calculated by the CFD through the data exchange platform, and the moving grid technology is used to make the grid deform. Then the pressure distribution is calculated by CFD, and the results are convergent by iterating with each other until the rocket structure no longer deforms. This method is called static
aeroelastic bidirectional coupling. The static-aeroelastic two-way coupling process adopted in this paper is shown in Fig. 5:

![Flow chart of loosely coupled method](image)

**Figure 5.** Flow chart of loosely coupled method

The two-way coupling calculation method is as follows:
1) Transfer the displacement $W^n_f$ of the structure boundary of the nth coupling step to the flow field.
2) Update flow field grid.
3) The fluid governing equation is solved under the current grid state and boundary conditions, and the flow field conservation variable $Q^{n+1}$ with n+1 coupling steps is obtained.
4) The flow field pressure $P_{d}^{n+1}$ of n+1 coupling step is transformed into the equivalent load of the structure.
5) Solving the static equation of the structure, obtaining the static deformation of the structure, and advancing to the n+1 coupling step.
6) Enter the next cycle.
7) Inter-iteration until the rocket structure no longer deforms and the aerodynamic coefficients no longer change. It is considered that the calculation is completed.

3. Results Analysis

Firstly, the drag coefficient, lift coefficient and pitch moment coefficient of the simple guided rigid rocket projectile without duck rudder, with duck rudder and rudder angle of 0 and with duck rudder angle of 10 are calculated and compared with the experimental data. The error is less than 10%, which verifies the accuracy of the CFD method. Fig. 6(a) is a diagram of the drag coefficient varying with Mach number in three cases. It can be seen from the diagram that the drag coefficient in the case of rudder angle of 10 degrees is 2%~20% larger than that in the case of no duck rudder and rudder angle of 0 degrees. This is due to the larger drag area caused by duck rudder when rudder angle is 10 degrees.

Fig. 7 (a) shows the variation of lift coefficient with Mach number in three cases. It can be seen from the figure that the lift coefficient in the case of rudder angle of 10 degrees is 5%-30% higher than that in the case of no duck rudder and rudder angle of 0 degrees. It shows that the existence of duck rudder has a great influence on the drag and lift coefficient of rocket. When duck rudder has rudder angle, it has a greater influence on the drag and lift coefficient of rocket. Fig. 8 (a) is the pitching moment coefficient distribution diagram of rocket projectile in three cases, which is just opposite to the distribution law of the lift coefficient in Fig. 7 (a). When calculating the pitching moment coefficient, the top of the projectile is taken as the reference point. Then the drag coefficient, lift coefficient and pitching moment coefficient of flexible rocket projectile under these three conditions are calculated and compared with the aerodynamic coefficients of rigid rocket projectile, as shown in figs. 6 (b), 7 (b) and 8 (b). It can be seen from the figure that when the velocity of incoming flow is less than Mach and the angle of attack is 4 degrees, the aerodynamic coefficients caused by the flexible deformation of rocket projectiles change little in three cases. With the increase of Mach number, the influence of flexible deformation on aerodynamic coefficients increases gradually. Among them, the flexible deformation
has little effect on the drag coefficient, and the flexible deformation causes the drag coefficient of rocket to decrease slightly. Flexible deformation has great influence on lift coefficient and pitch moment coefficient. Flexible deformation leads to smaller lift coefficient and smaller absolute value of pitch moment coefficient. The maximum influence on lift coefficient and pitch moment coefficient can reach 5%~10%.

Figure 6. Drag coefficient vs. Mach number

(a) Rigid rocket drag coefficient  
(b) Rigid and flexible rocket drag coefficient

Figure 7. Lift coefficient vs. Mach number

(a) Rigid rocket lift coefficient  
(b) Rigid and flexible rocket lift coefficient
Figure 8. Pitching moment coefficient vs. Mach number

(a) Rigid rocket Pitching moment coefficient  (b) Rigid and flexible rocket Pitching moment coefficient

Figure 9 shows the max total deformation of rocket with Mach number in three cases. It can be seen from the figure that the max total deformation of rocket without canard rudder is larger than that with canard rudder, and the max total deformation of rocket with rudder angle of 10 degree is larger than that with rudder angle of 0 degree. From Fig. 10, it can be seen that the lift coefficient of rocket with rudder angle of 10 degrees is larger than that of the other two cases, but its maximum total deformation is not the largest. This is because the rocket head without duck rudder is lighter than that with duck rudder, and the head of the rocket has added duck rudder, which makes the rigidity of the rocket head bigger, and it is not easy to deform when there is no duck rudder. Fig. 9-12 is the total deformation and equivalent stress nephogram of rocket projectile under three conditions: incoming velocity 4.45 Ma, angle of attack 4 degrees without duck rudder, rudder angle 0 degrees, rudder angle 10 degrees. It can be seen from the figure that the maximum total deformation of rocket projectile in three cases basically occurs in the middle of rocket projectile, and the equivalent force in the middle of rocket projectile in three cases is larger.

Figure 9. Maximum total deformation vs. Mach number
Figure 10. 4.45Ma, Total Deformation and Equivalent Stress Clouds of Rockets without Duck Rudder at 4.45 Ma and 4 Degree of Attack

Figure 11. 4.45Ma, Total Deformation and Equivalent Stress Clouds of Rocket Projectile with 4.45Ma and 4 Angle of Attack and 0 Angle of Rudder

Figure 12. 4.45Ma, Total Deformation and Equivalent Stress Clouds of Rocket Projectile with 4.45Ma and 4 Angle of Attack and 10 Angle of Rudder

Figure 13 shows the max stress of the simple guided rocket with Mach number in the case of no duck rudder, rudder angle of 0 and rudder angle of 10. It can be seen from the figure that the maximum equivalent stress of rocket projectile with rudder angle of 10 degrees is larger than that without duck rudder and rudder angle of 0 degrees after 2.5 Ma. Fig. 13-16 are Max equivalent stress nephograms of rocket projectiles with inflow velocity of 4.45 Ma and attack angle of 4 degrees without duck rudder, rudder angle of 0 degrees and rudder angle of 10 degrees respectively. It can be seen from the figure that the maximum equivalent stress occurs on the tail of the rocket projectile. The material used for
rocket projectile is 30CrMnSi, and the yield stress of the material is $\sigma_y \geq 885\text{MPa}$. From figs. 13 to 16, it can be seen that the maximum equivalent stress of the rocket under the given flight conditions is 167 MPa, which does not exceed the yield limit.

![Figure 13. Maximum von-Mises stress vs. Mach number](image)

![Figure 14. 4.45Ma, Equivalent force nephogram of rocket without duck rudder at 4.45 Ma angle of attack](image)

![Figure 15. 4.45Ma, Equivalent force nephogram of rocket projectile with rudder angle of 0 degree at 4.45 Ma and attack angle of 4 degree](image)
Fig. 16. 4.45Ma, Equivalent force nephogram of rocket projectile with rudder angle of 10 degree at 4.45 Ma and attack angle of 4 degree

Fig. 17 is the velocity cloud of rocket projectile with inflow velocity of 4.45 Ma and rudder angle of 10 degrees at angle of attack of 4 degrees. From Fig. 17, it can be seen that the head, rudder blade and tail leading edge form a clear oblique shock wave, and a low pressure zone is formed in the shoulder and bottom area of the projectile. The simulation results accord with the aerodynamic law. Fig. 18 is an integrated image of total deformation and velocity of rocket projectiles with inflow velocity of 4.45 Ma and rudder angle of 10 degrees at attack angle of 4 degrees. Compared with the velocity nephogram of rigid rocket projectile without considering static aeroelasticity, it can be seen from Fig. 18 that the elastic deformation of the projectile has an effect on the flow field distribution of the rocket projectile, which is more obvious in the nose and tail of the projectile.

Fig. 17. 4.45Ma, Velocity nephogram of rigid rocket projectile with rudder angle of 10 degrees at 4.45 Ma and attack angle of 4 degrees

Fig. 18. 4.45Ma, Total Deformation and Velocity Nephogram of Rocket Projectile with 4.45Ma and 4 Degree of Attack and 10 Degree of Rudder Angle
4. Summary
Based on CFD/CSD two-way coupling method, the static aeroelastic numerical simulation of a simple guided rocket with duck rudder actuator was carried out, and the influence of duck rudder on its aerodynamic characteristics and flexible deformation was analyzed. The calculation results show that the duck rudder has a great influence on the aerodynamic characteristics of rocket projectiles. By analyzing the aerodynamic coefficients of rocket projectiles without duck rudder, rudder angle is 0 degree and rudder angle is 10 degree, it is found that the lift coefficient and pitch moment coefficient can be changed by 5%~30% with or without duck rudder. Considering the influence of flexible deformation on aerodynamic coefficients, flexible deformation has great influence on lift coefficient and pitching moment coefficient. Flexible deformation leads to smaller lift coefficient and smaller absolute value of pitching moment coefficient. The maximum influence on lift coefficient and pitching moment coefficient can reach 5%~10%. At the same time, it is found that the maximum deformation of the rocket basically occurs in the middle of the rocket body, and the maximum equivalent stress occurs in the tail part of the rocket. Therefore, in the design of simple guided rocket, it is very important to consider the influence of duck rudder on its aerodynamic characteristics and flexible deformation.

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