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Optimal design of the aerodynamic parameters for a supersonic two-dimensional guided artillery projectile

Ke Liang [a,*], Zheng Huang [a], Jing-min Zhang [b]

[a] Xi'an Institute of Electromechanical Information Technology, Norinco Group, No.99 Jixiang Road, Xi'an 710065, Shaanxi, China
[b] No.208 Research Institute of China Ordnance Industries, 1023 Changping, Beijing 102202, China

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ABSTRACT

An optimization method is introduced to design the aerodynamic parameters of a dual-spin two-dimensional guided projectile with the canards for trajectory correction. The nose guidance component contains two pairs of canards which can provide lift and despin with the projectile for stability. The optimal design algorithm is developed to decide the profiles both of the steering and spinning canards, and their deflection angles are also simulated to meet the needs of trajectory correction capabilities. Finally, the aerodynamic efficiency of the specific canards is discussed according to the CFD simulations. Results that obtained here can be further applied to the exterior ballistics design.

1. Introduction

As improving artillery projectile accuracy is obviously beneficial for the fire efficiency, nowadays the precision-guided munitions are of interest to the Army as a means of both reducing collateral damage and increasing the chance of desired effect with the first round fired [1,2].

In this paper, some fundamental studies on the structural and aerodynamic features for the guided projectile in the preliminary design of its exterior ballistics were discussed. There were many previous works that were contributed to the methods involved in this paper. Theodoulis et al. introduced the guidance and control modules for a class of spin-stabilized fin-controlled projectiles[[3–6], and the complete nonlinear dynamical model is developed and analyzed. Chang et al. analyzed the impact of the spin-rate on the forward section of the trajectory, their results indicated that the spin-rate property is influenced by the canards actuation [7–9]. As the dual-spin guided projectiles are fundamentally less stable than the conventional ballistic spin-stabilized projectiles, Wernert et al. modelled and analyzed the stability conditions of the guided projectiles [10,11]. Hamel, Youn, Sahu and et al. studied the aerodynamic characteristics of different kinds of trajectory correction projectiles [12–14]. Those studies gave us the ideas to design, model and analyze the complicated dynamics of the guidance and control system of the guided projectile. In particular, they provided some helpful references to investigate the aerodynamic characteristics in the preliminary design.

The purpose of this work is to design the control canards for the dual-spin two-dimensional guided projectile. An optimal design method was developed in this paper to obtain the aerodynamic parameters of the control canards for trajectory correction. Numerical simulations were performed to study the aerodynamic efficiency of the guided projectile with control canards.

2. Model and method

2.1. Model of the 2-D guided artillery projectile

The two-dimensional guided projectile in this study includes a conventional 155 mm projectile body and a nose guidance component which is used for trajectory correction. The design model the two-dimensional guided projectile is shown in Fig. 1. There are two pairs of canards fixed on the nose component of the projectile. The first pair of canards, called the steering canards, is mounted in the same direction on the nose component to create lift

* Corresponding author.
E-mail addresses: liangke3039@163.com (K. Liang), huangzheng82369@163.com (Z. Huang), zjm_208suo@163.com (J.-m. Zhang).
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Fig. 1. Two-dimensional guided projectile.

force. Meanwhile, the second pair of canards, named the spin canards, is differentially canted in a manner to create a sufficient amount of moment to rotate the head component in an opposite direction of the projectile spin.

2.2. Optimal design method

In design of the Two-dimensional guided projectile, it is absolutely essential that the aerodynamic parameters for different canard wings' structures are analyzed and optimized. Therefore, the optimal aerodynamic configuration can be obtained, and as well as the required correction forces and moments can be guaranteed. In detailed design, several designed parameters, such as the wing area, the profile, the aspect ratio, the sweepback angle and the taper ratio, are indispensable for influencing the aerodynamic configuration of the projectile.

The general guideline of the wing area design is to provide the necessary trajectory correction ability as much as possible in the limited shape space. As the changes of aerodynamic configuration are comparatively limited due to the restraints both from the shape of the projectile and the lift force of the canard wing, the study of the trajectory correction ability is focused on the calculations of additional force and additional moment about the projectile with corrective canards. By adding the additional forces and moments to the equations of motion [15], the trajectory correction abilities with respect to the different wing areas can be investigated.

There are two types of profile that can be divided as the supersonic profile and the subsonic profile in application. For the frequently used supersonic profiles, such as diamond shape, lens shape, hexagon and blunt trailing edge, their features are simply shaped airfoils with sharp leading edges to cut down the shock wave. For the subsonic profiles, such as symmetric arc, asymmetric arc and laminar flow, they are usually streamlined with relatively smooth leading edges to enhance the leading-edge suctions and to reduce the atmospheric drags.

While increasing the aspect ratio, generally, the slope of lift curve will be elevated. For a specific length of the wing root, both the span and the aspect ratio will be raised at the same time. However, the span must not exceed the caliber of the artillery. The length of mean chord will decrease while the friction will increase, and the wave drag will also increase for a low mach number during the supersonic flying.

The sweepback angle will mainly impact the resistance property of the projectile. The reasons for using the sweepback angle are to increase the critical mach number, delay the shock wave, decrease the peak value of the drag coefficient and make the drag coefficient change smoothly with the increasing of the mach number. The taper ratio has less influence on aerodynamics of the projectile when the other geometric parameters had been finalized.

Changing of any mentioned parameters above will affect its aerodynamic efficiency of the 2-D guided projectile. In order to obtain the optimal aerodynamic configuration, both the constraint of the structural strength and the adjustment of the canard's aerodynamic shape should be considered. In this study, the optimal design algorithm is developed by coupling of the fluid and solid, as shown in Fig. 2, which make sure the aerodynamic efficiency to be optimized under all the given requirements.

From Fig. 2, there are two types of parameters need to be optimized for selecting the canards, which are structure parameters and aerodynamic parameters. Meanwhile, there are strong connections between these two types of parameters. Firstly, we calculated the structure parameters, such as parameters of the profile, by using engineering prediction methods, and made those results as the initial inputs of the optimization process. Then, the aerodynamic parameters are simulated and optimized to meet the trajectory correction capability of the guided projectile. During the optimizing process, both the structure parameters and aerodynamic parameters might be redesigned under their boundary conditions. And finally, the local optimal solution can be obtained as well as the canards can be selected.

After the optimization method is used to obtain the profiles of steering or spinning canards, the relationship between the deflection angle of control surface and the angle of attack can be

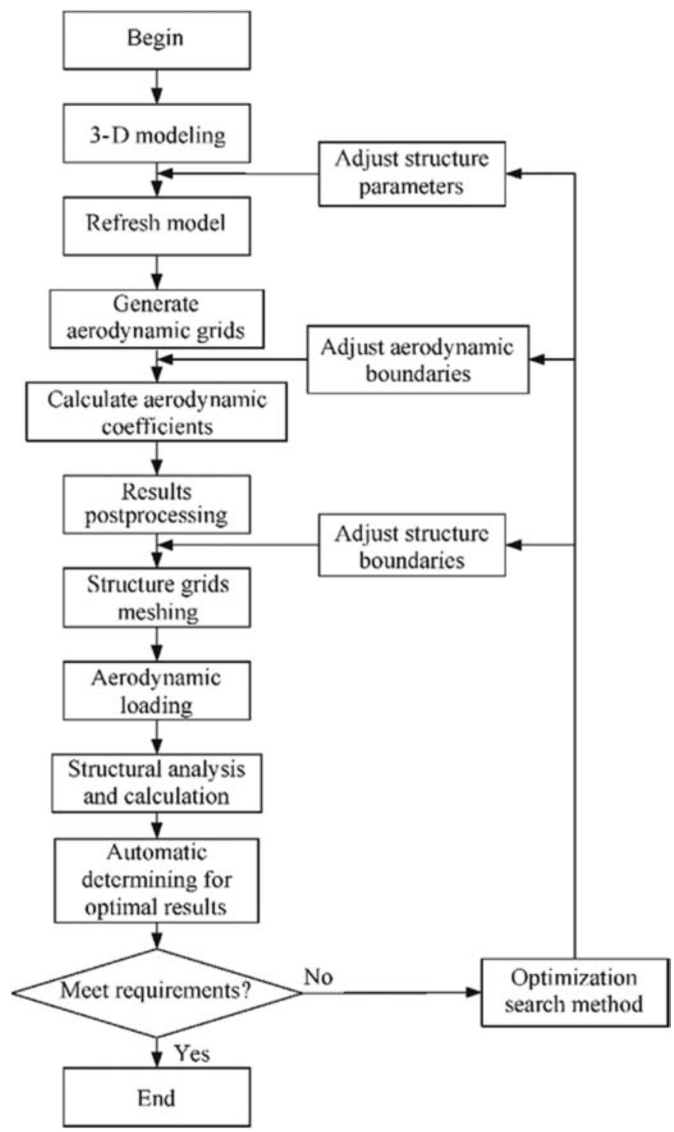

Fig. 2. Optimal design algorithm of 2-D guided projectile with high aerodynamic efficiency canards.

numerically simulated by CFD method. Then, the aerodynamic efficiency of the designed canards can be analyzed.

3. Simulations and results

Increasing of the wing area will be benefit to improve the trajectory correcting capability of the aerodynamic controlling canards. However, it will be caused not only the loss of firing range but also the flight instability of the spinning projectile. In order to obtain the optimal aerodynamic shape of the canard, its aerodynamic efficiency should be simulated and analyzed to optimize the structure of the canards. Both the correction capability and the flight stability for the 2-D guided projectile were considered during the whole simulation process.

3.1. Selecting for the canard profile

In the preliminary design, the engineering prediction methods [16,17] are used to get the values of the aerodynamic characteristics from the determined structure parameters. There are eight types of profiles have been evaluated, and their structure specific parameters are shown in Table 1. By applying all the profiles to the guided projectile, their aerodynamic characteristics can be obtained. And these parameters can be used as the initial inputs of the optimization process. The selecting criteria of the best profile are large lift-to-drag ratio, little changes of pressure center and small deflection angle.

The requirements of the lifts for the steering canards and the spin moments for the spin canards were estimated from the simulations of the 6-DOF external ballistics model, as seen in Table 2. The values of the lifts and the spin moments with different Mach numbers must meet the capability of trajectory correction for the guided projectile on its entire ballistic trajectory. Therefore, it can be the final criterion to verify the capability of the designed canard.

According to the capabilities both of lift force and spin moment, the No. 8 canard profile in Table 1 is selected as the best matching profile to meet the demands of trajectory correction capabilities. Results of the comparison between the requirements and capabilities can be seen in Fig. 3 and Fig. 4. The required value curves in Figs. 3 and 4 are obtained by using the curve fitting method from the data in Table 2.

Simulation results of the aerodynamic parameters indicate that their capabilities will meet the design requirements with an eleven degree deflection angle for the pair of steering canards and the plus or minus six degrees deflection angles for the spin canards.

3.2. CFD numerical simulation

UG is used to construct the three dimensional model of the 2-D guided projectile, and the Pointwise software also used for the CFD meshing. As seen in Fig. 5, the boundaries of the computational domains for the external flow fields are set up with reference to the length of projectile. They are ten times of the length in the *X* direction, and four times of the length in the *Y* direction and *Z* direction. The meshing details at the head and tail of the projectile can be seen in Fig. 6. The amount of total grids in this CFD simulation is around 9 million units. To insure the convergence of the results, the grid quality has been checked, and it shows the nice grid qualities with very low cell squish and skewness.

As shown in Fig. 6, the coordinate system is defined as follows: The origin of the coordinate is fixed at the head of the projectile, the *X* axis is pointing to the projectile tail along its body, the *Z* axis is pointing to the direction of the normal force which is vertical with respect to the steering canards, and the *Y* axis is vertical with respect to the pair of the spin canards.

The points of reference in the calculation are described as follows: The reference point to calculate the center of pressure coefficient, the center of Magnus pressure coefficient, pitching moment coefficient and yawing moment coefficient is the apex of the head; the reference point to calculate pitch-damping moment coefficient is the center of mass.

Some other specific values that involved in the simulation can be found as below. Noted that the reference area is determined based on the projectile caliber.

Reference area: $S = 0.01897\ \mathrm{m}^2$;
Reference length: $l = 0.9365$ m;
Mach number: $Ma = 0.6, 0.7, 0.8, 0.9, 1, 1.1, 1.2, 1.5, 1.8, 2, 2.5, 3$;
Angle of attack: $\alpha = 0^\circ, 2^\circ, 4^\circ, 6^\circ, 8^\circ$.

3.3. Calculating formulas

The formulas for calculating the aerodynamic parameters are summarized in this section, and can be seen as bellow [16,18].

$$\text{Dynamic pressure}: \quad q = \frac{1}{2}\rho V^2 \tag{1}$$

$$\text{Lift force}: \quad L = C_L qS = N\cos\alpha - A\sin\alpha \tag{2}$$

$$\text{Drag force}: \quad D = C_D qS = N\sin\alpha + A\cos\alpha \tag{3}$$

N≡Normal force

A≡Axial force

α≡Angle of attack

$$\text{Lift coefficient}: \quad C_L = \frac{L}{qS} \tag{4}$$

Table 1
Structure parameters for eight types of profiles.

No.	Span/mm	Root chord/mm	Tip chord/mm	Sweepback angle/(°)	Aspect ratio	Taper ratio	Area/mm^2
1	54.00	40.00	18.00	22.20	1.86	2.22	1566
2	59.00	40.00	16.00	22.20	2.11	2.50	1652
3	49.00	45.00	20.00	27.03	1.51	2.25	1593
4	54.00	45.00	17.50	27.03	1.73	2.57	1688
5	59.00	45.00	15.00	27.03	1.97	3.00	1770
6	49.00	50.00	20.00	31.47	1.40	2.50	1715
7	54.00	50.00	17.00	31.47	1.61	2.94	1809
8	59.00	50.00	14.00	31.47	1.84	3.57	1888

Table 2
Requirements of the lift and spin moment.

Parameter	Value						
Ma	0.8	0.95	1.05	1.2	1.5	2.0	2.5
Lift/N	47.04	87.95	102.71	123.44	162.94	270.56	334.97
Spin moment/(N·m)	0.17	0.27	0.41	0.61	0.87	1.47	1.86

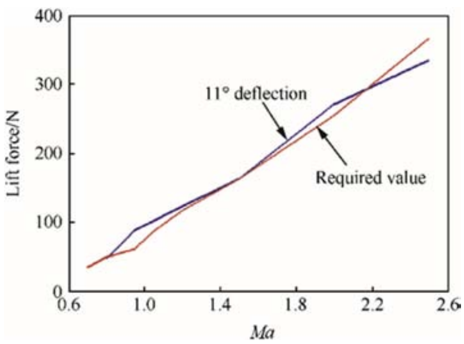

Fig. 3. Requirements and capabilities of the steering canards.

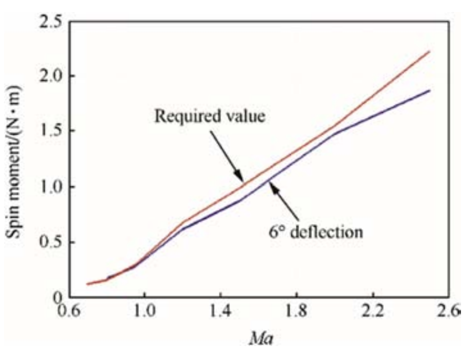

Fig. 4. Requirements and capabilities of the spin canards.

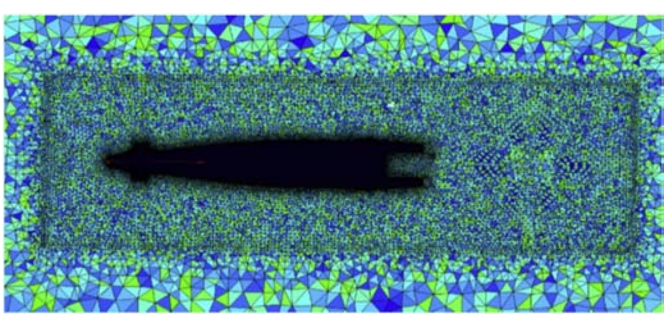

Fig. 5. Grid distribution of the symmetric section.

$$\text{Drag coefficient}: \quad C_D = \frac{D}{qS} \tag{5}$$

$$\text{Normal force coefficient}: \quad C_N = \frac{N}{qS} \tag{6}$$

$$\text{Axial force coefficient}: \quad C_A = \frac{A}{qS} \tag{7}$$

$$\text{Center of pressure}: \quad X_{cp} = \overline{X}_{cp} l \tag{8}$$

$$\text{Dimensionless roll rate}: \quad \overline{\omega}_x = \frac{\omega_x l}{2V} \tag{9}$$

$$\text{Dimensionless pitch rate}: \quad \overline{\omega}_z = \frac{\omega_z l}{2V} \tag{10}$$

$$\text{Roll} - \text{damping moment}: \quad M_{x\_\text{damping}} = \frac{m_x^{\overline{\omega x}} qSl^2 \omega_x}{2V} \tag{11}$$

$$\text{Pitch} - \text{damping moment}: \quad M_{z_{\text{damping}}} = \frac{m_z^{\overline{\omega z}} qSl^2 \omega_z}{2V} \tag{12}$$

$$\text{Roll moment}: \quad M_x = m_x qSl \tag{13}$$

$$\text{Pitch moment}: \quad M_z = m_z qSl \tag{14}$$

$$\text{Magnus force}: \quad R_Z = qSc_z \tag{15}$$

$$\text{Magnus moment}: \quad M_y = qSDm_y \tag{16}$$

3.4. *Aerodynamics coefficients results*

FLUENT is used to calculate the aerodynamics coefficients of the guided projectile that with the preferred canards. Results for different attack angles ($\alpha = 0°, 2°, 4°, 6°, 8°$) are shown from Figs. 7–11.

In Figs. 7–11, it was shown that how the deflection angle affects with the normal force of the projectile under the specific attack angles and Mach numbers. From these results, the efficiency of the canards can be approximately evaluated when the deflection angle and the normal force have a linear relationship.

3.5. *Efficiency analysis of the canards*

The aerodynamic efficiency of the control canards is analyzed from the results shown in Figs. 7–11. When the Mach number is greater than one ($Ma > 1$), the normal force coefficient of the whole projectile is increasing linearly during the deflection angle of the steering canards growth. It is indicated that the aerodynamic efficiency of the canards had changed linearly in this supersonic segment.

When the Mach number is equal to one ($Ma = 1$), the normal force coefficient is shown irregular alterations with respect to the changes of both the deflection angle of canards and the attack angle of projectile. The aerodynamic efficiency of canards is influenced by the angle of attack. For detailed discussion, (1) when $\alpha = 0°$ and $Ma = 1$, the normal force coefficient is raising linearly as the deflection angle $\delta < 15°$; (2) when $\alpha = 2°$ and $Ma = 1$, the normal force coefficient is raising linearly as the deflection angle $\delta < 15°$; (3) when $\alpha = 4°$ and $Ma = 1$, the normal force coefficient is raising

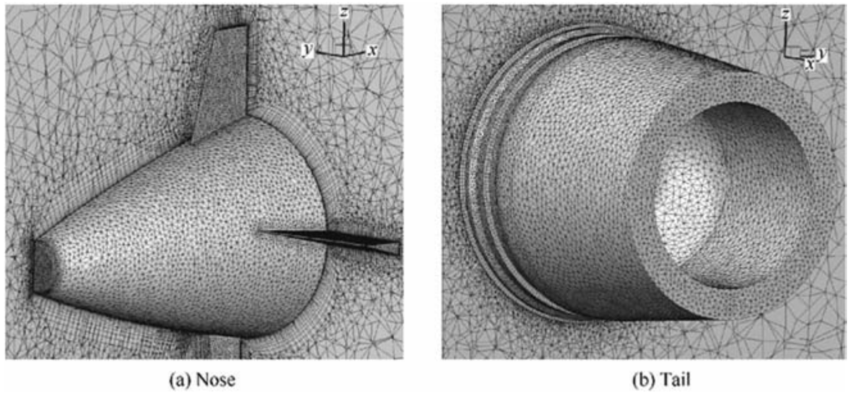

Fig. 6. Meshing at the head and tail of the 2-D guided projectile.

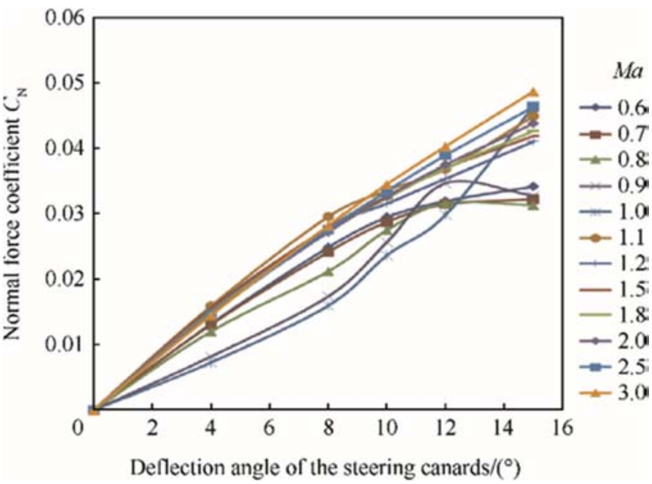

Fig. 7. Changes of the normal force for $\alpha = 0°$.

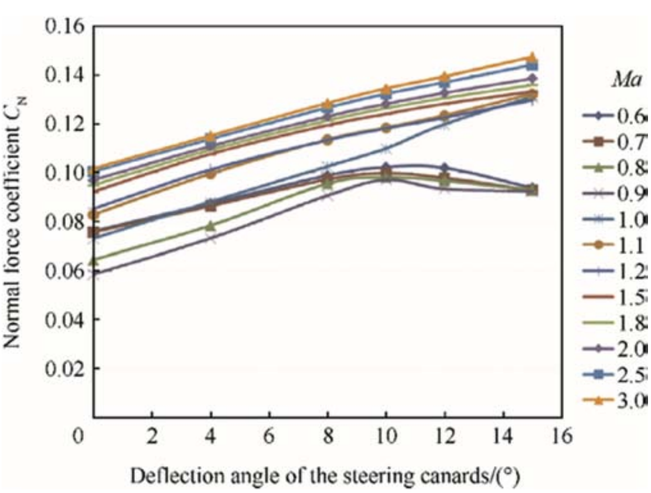

Fig. 8. Changes of the normal force for $\alpha = 2°$.

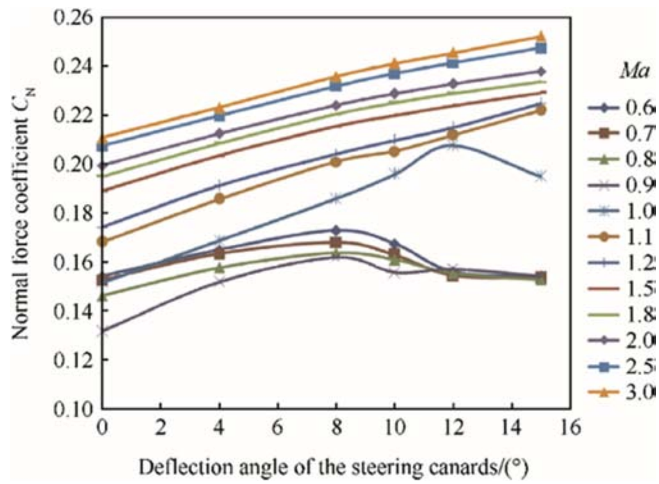

Fig. 9. Changes of the normal force for $\alpha = 4°$.

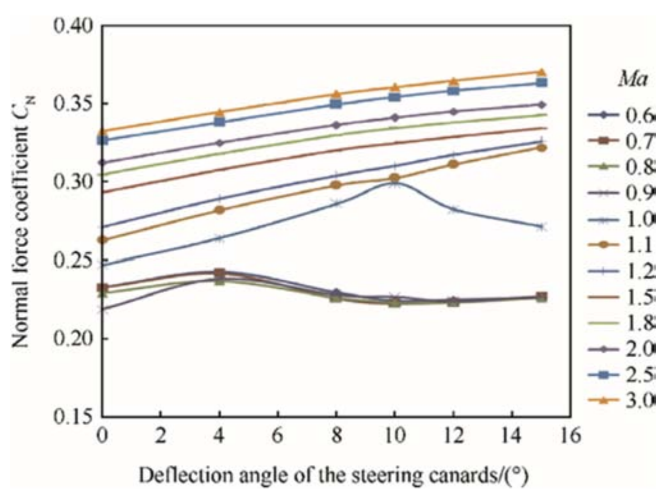

Fig. 10. Changes of the normal force for $\alpha = 6°$.

linearly as the deflection angle $\delta < 12°$; (4) when $\alpha = 6°$ and $Ma = 1$, the normal force coefficient is raising linearly as the deflection angle $\delta < 10°$; (5) when $\alpha = 8°$ and $Ma = 1$, the normal force coefficient is raising linearly as the deflection angle $\delta < 8°$.

When the Mach number is less than one ($Ma < 1$), the normal force coefficient is also demonstrated irregular variations by changing from both the deflection angle of canards and the attack angle of projectile. In this subsonic flight phase, the linear segments of the aerodynamic efficiency of canards are shortened during the angle of attack growth. For further discussion, (1) when $\alpha = 0°$ and $Ma < 1$, the normal force coefficient is increased linearly while $\delta < 12°$; (2) when $\alpha = 2°$ and $Ma < 1$, the normal force coefficient is

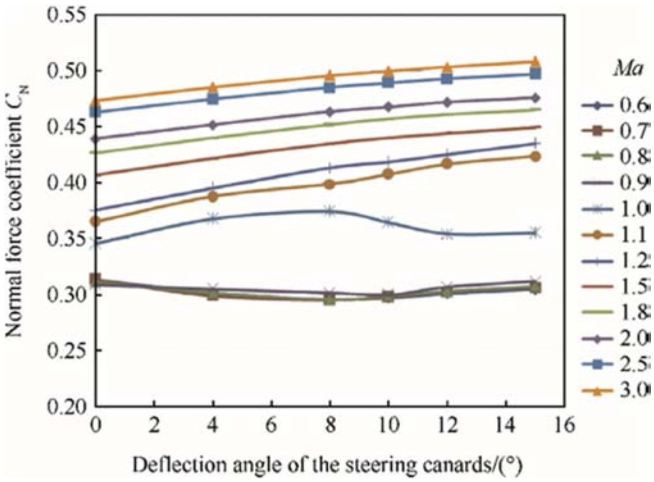

Fig. 11. Changes of the normal force for $\alpha = 8^\circ$.

increased linearly while $\delta < 10^\circ$; (3) when $\alpha = 4^\circ$ and $Ma < 1$, the normal force coefficient is increased linearly while $\delta < 8^\circ$; (4) when $\alpha = 6^\circ$ and $Ma < 1$, the normal force coefficient is increased linearly while $\delta < 4^\circ$; (5) when $\alpha = 8^\circ$ and $Ma < 1$, the normal force coefficient is weakened to be negative.

4. Conclusions

This study has shown some fundamental works in the preliminary design of exterior ballistics. An optimization method is developed to obtain the applicable aerodynamic parameters of the controlling canards for a 2-D guided artillery projectile. The optimal canard profile is designed to make the guidance component meet the needs of trajectory correction capabilities. And on this basis the efficiency of the canards is simulated and analyzed. The results of the aerodynamic parameters obtained in this study could be the valuable inputs for the further design of exterior ballistics.

While adding of the canards may improve the accuracy of the artillery projectile, the dynamical stability of the spinning projectile will be affected at the same time. Some basic suggestions from this study are: Firstly, the design of the canards must not destroy the spinning stability of the guided projectile during the entire time of flight; secondly, the accuracy of the guided projectile should be increased by optimizing the structure and aerodynamic parameters, not just by extending the size of the canards.

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