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Effect of Thrust Vectoring Technology on Taking-Off Performance of Hypersonic Vehicle

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Abstract. Owing to the high sweep angle and the slender structure, much less taking-off lift is produced by the horizontal taking-off hypersonic vehicle compared with general aircrafts. This paper aims at introducing the thrust vectoring technology into the taking-off stage of hypersonic vehicle, and discussing the effect of thrust vectoring technology on taking-off performance. The nonlinear hypersonic model with the thrust vectoring nozzle and retractable canard wings is firstly established in this paper. Then the taking-off process is divided into three parts, and the thrust vectoring technology is applied to these three parts respectively. Last, the simulation results indicate that the thrust vectoring technology obviously improves the taking-off performance of the hypersonic vehicle and effectively solves the problem of lacking lift.

1. Introduction

A hypersonic vehicle, with either rockets or scramjets as its main power source, generally refers to a vehicle flying at Mach 5 or above [1], which has become a popular research topic in air vehicles [2].

The object in this paper is a horizontal taking-off hypersonic vehicle, which cause a much smaller lift coefficient. The near space vehicle has two taking-off methods in general [3]. Although the vertical launching method can effectively avoid the problem of lacking lift, the cost and the reliability can hardly be given into consideration [4]. The horizontal taking-off method is capable to achieve vehicle reproducibility as well as the cost reduction. Nevertheless, bad taking-off performance are the problems need to be solved urgently.

Thrust vectoring is the ability of an aircraft to manipulate the direction of the thrust from its engine or motor in order to control the attitude or angular velocity [5]. Thrust vectoring technology has been applied to a double-engine fighter in literature [6] and the simulation qualitatively illustrates that thrust vectoring technology is capable to improve the taking-off performances. Thrust vectoring technology coordinated with canard wings has been applied to a fighter aircraft in literature [7] to improve the taking-off performances. Thrust vectoring technology coordinated with corresponding control surfaces has been applied to a general aircraft to testify the taking-off performances in literature [8].

literatures on thrust vectoring technology applied to the hypersonic vehicle are rare. In addition, hypersonic vehicle model with thrust vector nozzles and retractable canard wings is much more complex than general hypersonic vehicle. Rare literatures discuss this complex nonlinear model before.

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2. NONLINEAR MODEL

The object discussed in this paper is the hypersonic vehicle with retractable canard wings and thrust vector nozzles. The force diagram of the vehicle is shown in fig.1.

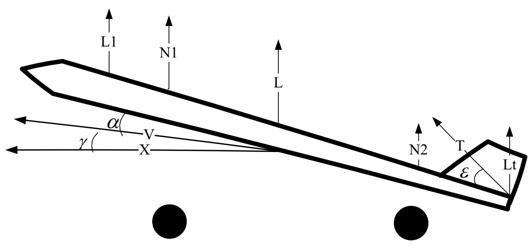


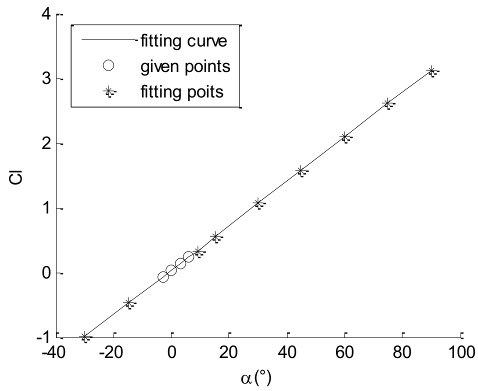
Fig.1 force diagram of the hypersonic vehicle at taking-off stage

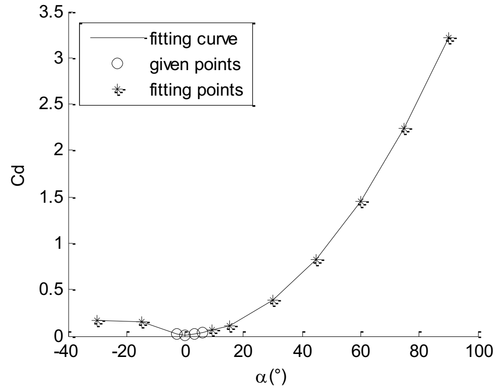
The sixth-order longitudinal equations of the hypersonic vehicle are,

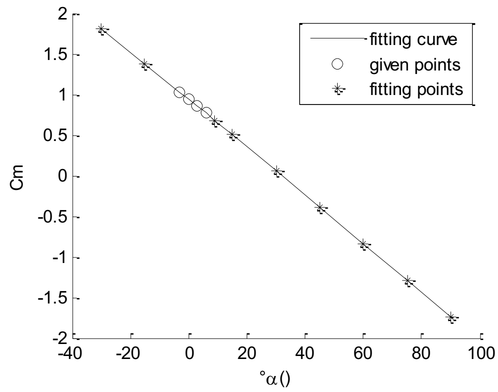
$$
\begin{aligned}
\dot{V} &= \frac{T_1\cos\alpha + T_2\cos(\alpha+\varepsilon) - D}{m} - \\
&\quad \frac{\mu(N1+N2)\cos\gamma - (N1+N2)\sin\gamma}{m} - g\cdot\sin\gamma \\
\dot{\gamma} &= \frac{T_1\sin\alpha + T_2\sin(\alpha+\varepsilon) + L + L1 + L_t}{mV} + \\
&\quad \frac{(N1+N2)\cos\gamma + \mu(N1+N2)\sin\gamma}{mV} - \frac{g\cdot\cos\gamma}{V} \\
\dot{h} &= V\sin\gamma \\
\dot{\alpha} &= q - \dot{\gamma} \\
\dot{q} &= \frac{M_{yy} + N1\cdot l_1\cdot\cos\alpha - N2\cdot l_2\cdot\cos\alpha}{I_{yy}} - \\
&\quad \frac{T_2\cdot\sin\varepsilon\cdot l_t - L_1\cdot l_y\cdot\cos\alpha + L_t\cdot l_t\cdot\cos\alpha}{I_{yy}} \\
\dot{m} &= -\frac{T}{I_{sp}g_0}
\end{aligned}
\tag{1}
$$

Where, μ is the rolling friction coefficient, l_1 is the distance between the front wheel and the aerodynamic center, l_2 is the distance between back wheels and the aerodynamic center, l_y is the distance between canard wings and the aerodynamic center, l_t is the distance between nozzles and the aerodynamic center, ε is the deflection angle of the nozzle.

In order to build an accurate model at taking-off stage, C_L, C_D , C_M and are Taking-off thrust T replaced with curve-fitted approximation based on the relationship and given points. The fitting curves are shown in fig.2.







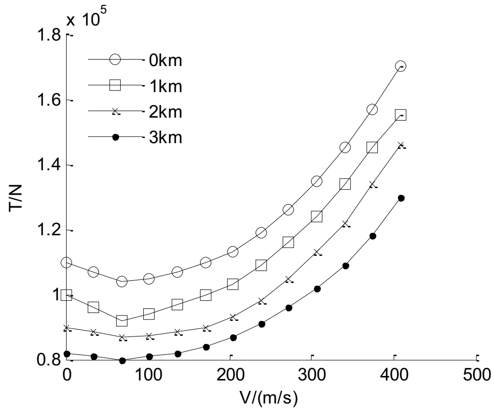


Fig.2 Fitting curve of aerodynamic coefficients at $Ma = 0.3$ and Fitting curve of T

3. TAKING-OFF PROCESS DIVIDING

Taking-off stage is a significant stage for horizontal taking-off hypersonic flight. The hypersonic vehicle starts to taxiing first, then the nozzle starts to deflect. Canard wings start to deflect at the same time to offset the nose-down moment produced by the nozzle. Ultimately, the direct force is produced to reduce the friction as well as to improve the taking-off performance.

The taking-off process is divided into three stages:

1. three-point ground taxiing;
2. Taxiing with the front wheel lifting;
3. Climbing with the track angle increasing and the attack angle maintaining.

Next, the thrust vectoring technology is applied to each stage above and simulation results are shown below.

4. THREE-POINT GROUND TAXIING

In this taxiing stage, both the front wheel and back wheels are touching the ground simultaneously. The terminal condition of this stage is when the front wheel leaving the ground: $N1 = 0$. Then, $\alpha = \alpha_0$, $\dot{\alpha} = 0$, $q = 0$, $h = 0$.

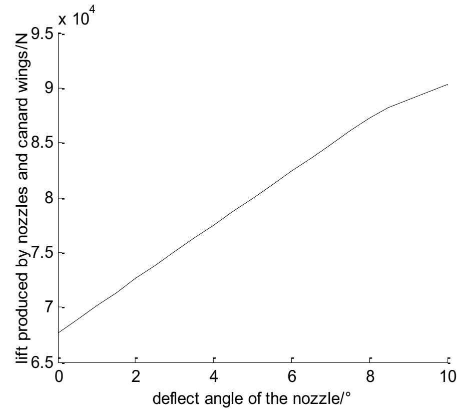


Fig.3 varying lift with deflect angle of the nozzle

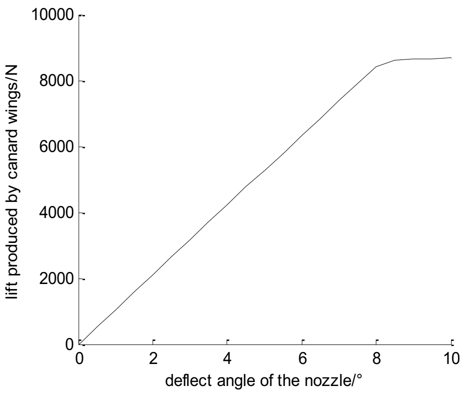
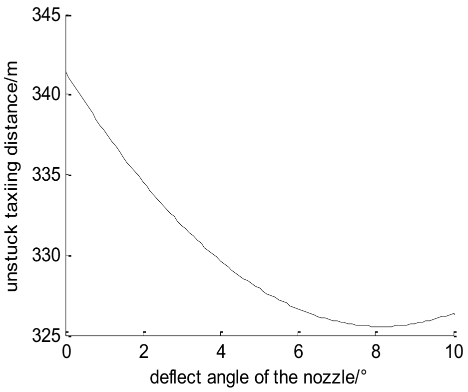
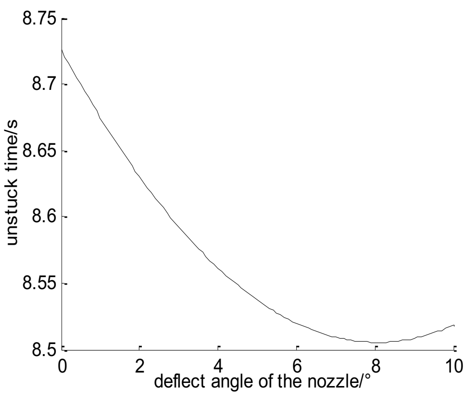


Fig.4 varying lift generated from canard wings with deflect angle of the nozzle





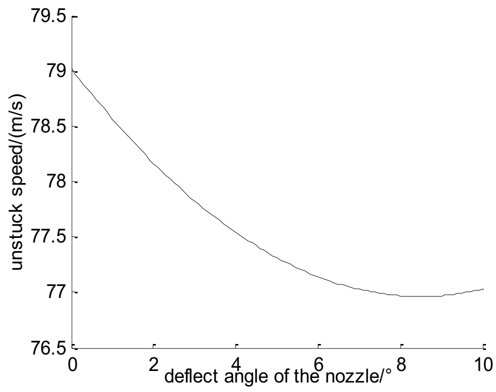


Fig.5 varying front wheel unstuck speed/ time/ taxiing distance with deflect angle of the nozzle

As shown in figure 3, the direct lift generated from canard wings and the deflect nozzle has a progressive increment which helps to provide more lift that the hypersonic vehicle needs during three-point ground taxiing stage.

As figure 4 shows, the lift generated from canard wings begins to increase at first and stay still later. It is because the canard wing can offset the nose-down moment when there is only a small deflection of the nozzle. With increasing deflection of the nozzle, canard wings have already deflected to a limited angle.

As figure 5 shows, the speed at which the front wheel lifts off the ground decreases at first and increases later. It is because the direct force helps increasing the lift when canard wings can offset the nose-down moment. As a result, the front wheel can lift off the ground at a lower speed. When the deflection angle of the nozzle increases to a given value, the moment generated from canard wings is not sufficient to offset the nose-down moment and needs force compensation. So the supporting force from the front wheel increases to offset the nose-down moment. Consequently, the higher speed is needed to nose up the vehicle. The unstuck time and the unstuck taxiing distance have the similar trend with the unstuck speed.

5. TAXIING WITH THE FRONT WHEEL LIFTING

In this taxiing stage, the front wheel is lifting to increase the attack angle until the back wheels leave the ground.

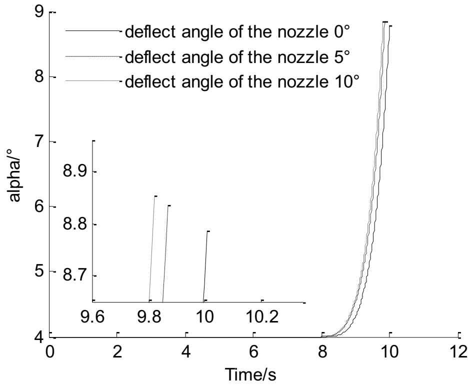


Fig.6 varying α with deflect angle of the nozzle

Fig.7 varying unstuck speed with deflect angle of the nozzle

Fig.8 varying unstuck time with deflect angle of the nozzle

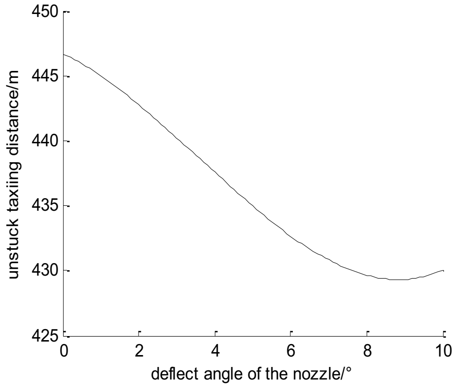


Fig.9 varying unstuck taxiing distance with deflect angle of the nozzle

As figure 6 shows, the attack angle increases continuously until back wheels lifting off the ground. Meanwhile, the greater the downward deflection degree of the deflect nozzle is, the greater the unstuck attack angle would be. It is because the hypersonic vehicle with relaxed static stability (RSS) is studied in this paper, the aerodynamic center locates before the center of gravity. When the moment generated from canard wings can hardly offset the nose-down moment generated from the deflect nozzle, the fuselage lift is required. The greater the downward deflection degree of the deflect nozzle is, the greater the fuselage lift is required.

As figure 7 shows, the speed at which the vehicle lifts off the ground decreases at first and increases later with downward deflection of the nozzle. The reason is the same with the previous stage.

As shown in figure 8 and 9, the unstuck time and the unstuck ground taxiing distance decreases at first and increases later with downward deflection of the deflect nozzle.

6. CLIMBING WITH THE TRACK ANGLE INCREASING AND THE ATTACK ANGLE MAINTAINING

The hypersonic vehicle starts to climb when leaving the ground. In this stage, The attack angle maintains the same, therefore, $\dot{\alpha} = 0$. The track angle γ keeps increasing until reaching the assumed value.

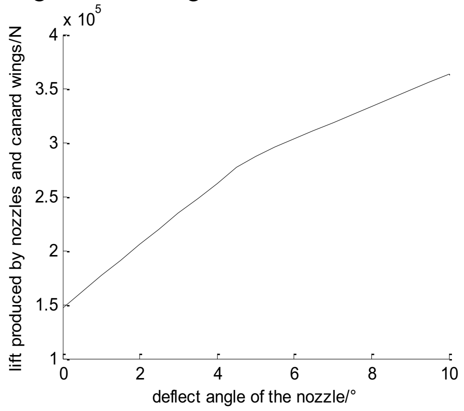


Fig.10 varying lift with deflect angle of the nozzle

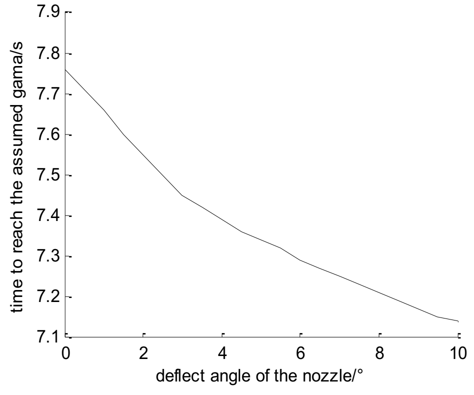
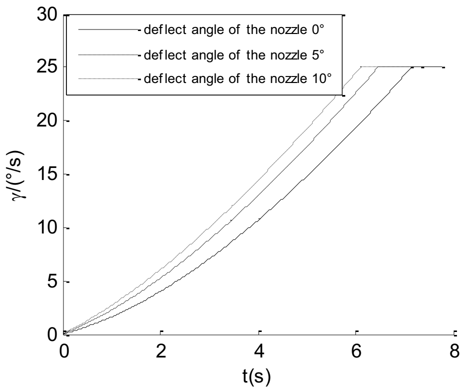


Fig.11 varying reach time with deflect angle of the nozzle



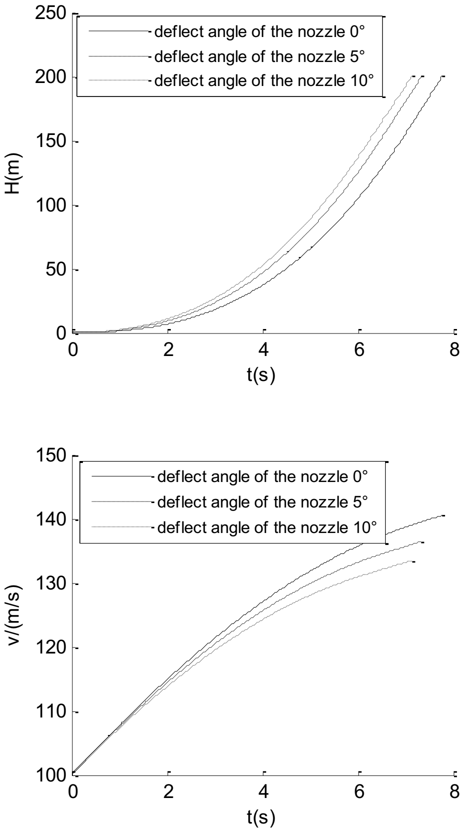


Fig.12 γ / Height/ velocity response with different deflect angle of the nozzle

As figure 10 shows, the direct lift generated from canard wings and the deflect nozzle has a progressive increment as downward deflection degree of the deflect nozzle increases progressively, which helps to provide more lift during the climbing stage.

As figure 11 shows, the time to reach the designated γ gets shorter as downward deflection degree of the nozzle increases progressively.

Figure 12 show that the greater downward deflection of the nozzle is, the shorter the time to reach the designated track angle would be, and the shorter the time to reach the designated height would be. Also the speed is increasing constantly. Nevertheless, the increasing tends is shown to slow down with increasingly downward deflection degree of the nozzle. This is the result from the fact that the thrust along the velocity direction decreases with increasingly downward deflection degree of the nozzle.

Acknowledgements

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