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Hypersonic Waveriders Aerodynamic Performance Studies

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Abstract : Aerodynamic performance of hypersonic waveriders aircraft basing on cone-derived waveriders with the consideration of volumetric efficient and thermal protection is being studied by computational fluid dynamic (CFD) and wind tunnel experiment (WTE) . Both the results from CFD and WTE proved that , waveriders with design condition Mach number 6 and attack angle 4°, at off-design conditions that Mach number vary within 5～7 , attack angle vary within 4°～6°, it can maintain excellent aerodynamic performance. The lift-to-drag ratio is only a little below 4. At the same time , a simple viscous drag analysis method basing on reference temperature method is being given to cooperate using the results of CFD and WTE. It can be used to give viscous drag that can not be got from WTE directly , and it can be used to validate viscous drag of CFD , which is hard to be calculated accuracy too. Though it is very coarse , it is very useful for engineer application.

Key words : Hypersonic waveriders ; Computational fluid dynamic ; Wind tunnel experiment ; Viscous drag analysis ; Reference temperature method

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0 Introduction

The waveriders concept to design hypersonic aircraft was first introduced by Nonweiler[1] in 1959. It uses the sharp leading edge to catch the shock wave , and then the higher pressure at lower surface and lower pressure at upper surface is being separated. At the design Mach number and attack angle , no pressure spillage takes place around the sharp leading edge ; hence the lift-to-drag barrier of hypersonic aircraft is being broken successfully. By the development near half a century , the theory and design method of waveriders have became more and more maturity , the application of this method to design real hypersonic aircraft is an inevitable tendency[10].

Now , the key problems that waveriders aircraft designers facing are to solve the contradictory of volumetric efficient and thermal protection with lift-to-drag ratio , the aerodynamic performance of lower speed and off-design condition are the key problems must be resolve too. In this article , we pay attention to the aerodynamic problems of waveriders at off-design conditions.

Whether the leading edge is catch the shock properly or not is crux to the aerodynamic performance of waveriders aircraft. Because it is unavoidable to flight at off-design conditions in real flight , the study of waveriders aerodynamic performance at off-design conditions is become very meaningful. In this article , basing on cone-derived waveriders[2,3] , with the consideration of volumetric efficient and thermal protection , we get the waveriders aircraft show in figure 1 , which is a hypersonic missile concept powered by rocket engines. Table 1 gives out the basic parameter of aircraft showing in figure 1. L、W、H、Su、Sl、Sb、V is length、width 、height、upper face area、lower face area、base face area and volume of the aircraft respectively. The aerodynamic performance of that aircraft is being studied by CFD and WTE respectively. At last , we introduce a simple method basing on reference temperature method to analysis viscous drag which is hard to be calculated accuracy in CFD and to gauge in WTE separately from total drag is very hard too. Though it is very coarse , it is very useful for engineer application.

Table 1 Basic parameter of vehicle model

L(m)	W(m)	H(m)	Su(m^2)	Sl(m^2)	Sb(m^2)	V(m^3)
6	3	1	7.30	11.79	1.47	3.57

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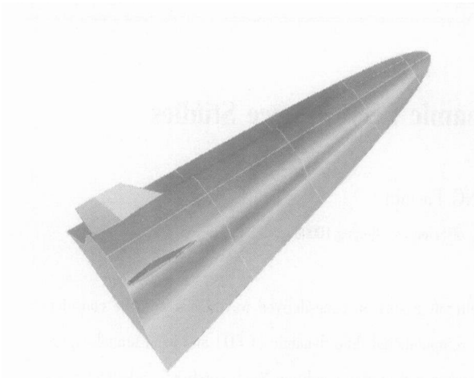

Fig. 1 Waveriders configure

1 Areaodynmacic Performance CFD Analysis

At design condition, waveriders have excellent aerodynamic performance such as lower drag、higher lift-to-drag ration etc. At off-design conditions, because the change of flow field and shock waves structure, it makes the waveriders characters of waveriders aircraft at design condition become weaker. The study of waveriders aerodynamic performance at off design conditions is very meaningful to push waveriders hypersonic aircraft design method from a design theory to real application.

The design condition of waveriders aircraft in figure 1 is Mach number 6 with attack angle 4°. In order to study aerodynamic performance at different Mach number and attack angle, we choose Mach number 5, 6, 7, attack angle 0°, 2°, 4°, 6°, 8°, use CFD code to calculate aerodynamic respectively. Use atmosphere[4] condition of 32km high altitude as free stream condition, the static pressure is 889pa and static temperature is 228.5k. Reference length is choosing the waveriders aircraft length 6m. Viscosity is calculated use Sutherland law. Reynolds number of different calculate conditions are: 0.86×10^7 (Mach number 5), 1.01×10^7 (Mach number 6), 1.18×10^7 (Mach number 7).

Figure 2 gives out pressure contour of a section in the flow field at design condition with Mach number 6 and attack angle 4°. From figure 2, we can see that, when waveriders hypersonic aircraft is flight at design condition, higher pressure gas is at the lower surface and lower pressure is at the upper surface of waveriders, this character can make waveriders hypersonic aircraft gets higher lift-to-drag ratio at design condition.

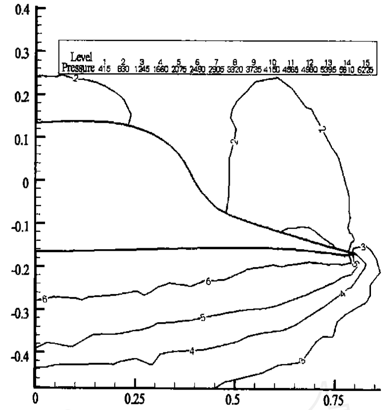

Fig. 2 Pressure contour of a section (Ma = 6, α = 4°)

Figure 3 gives out the pressure contour of the same section at off design condition Mach number 6 and attack angle 8°. From figure 3, we can see that, waveriders have very well ability to adapt to the change of attack angle; it almost has no pressure spillage of lower surface higher pressure to upper surface lower pressure.

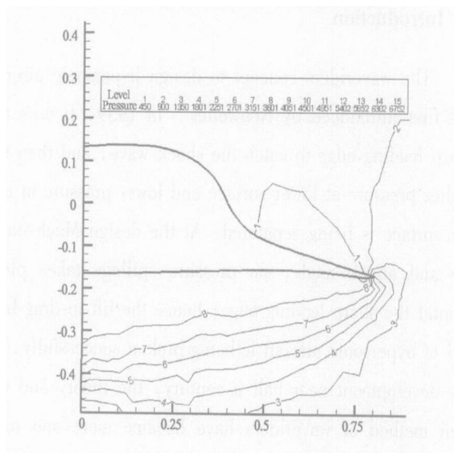

Fig. 3 Pressure contour of a section (Ma = 6, α = 8°)

Figure 4 gives out the pressure contour of the same section at off design condition Mach number 5 and attack angle 4°, Figure 5 gives out the pressure contour of the same section at off design condition Mach number 7 and attack angle 4°. Form figure 4 and 5, we can see that, at off design Mach number, hypersonic waveriders aircraft can maintain the higher pressure gas in lower surface spillage less. This makes waveriders aircraft at off design Mach number within a certain range maintain excellent aerodynamic performance such as higher lift-to-drag ratio.

Table 2 gives out the aerodynamic result of CFD at

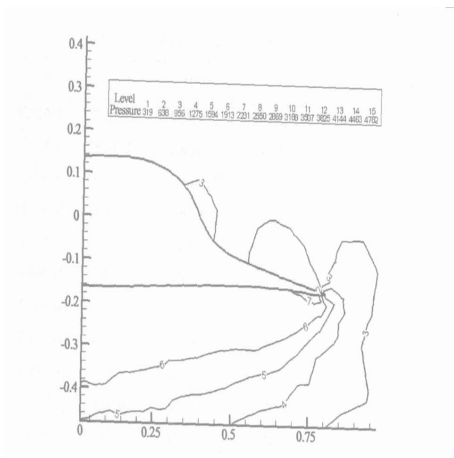

Fig. 4　Pressure contour of a section (Ma = 5 , α = 4°)

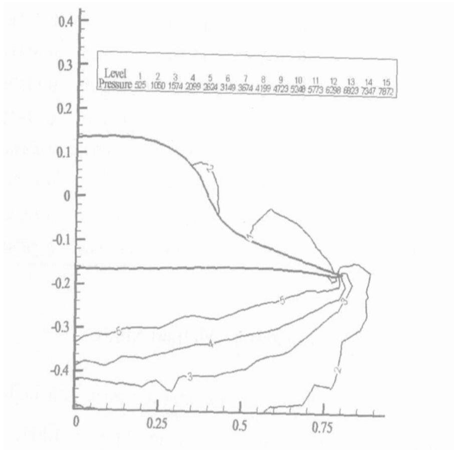

Fig. 5　Pressure contour of a section (Ma = 7 , α = 4°)

Mach number 5 ,6 ,7 with attack angle 0 °,2 °,4 °,6 °,8 °. Cd、L/D、Cmz、Xcp is drag、lift-to-drag ratio、pitch moment coefficient respectively. In table 2 , the reference length is 6m , and reference area is 11. 79 m^2. When Mach number varies within 5～7 and attack angle varies within 4 °～6 °, the lift-to-drag ratio is always higher , just a little below 4.

For a Mach number 6 hypersonic waverides aircraft with the consideration of volumetric efficient and thermal protection , such aerodynamic result like that is quite desirable. It demonstrates that point-design waveriders do not suffer any marked off design problems , waveriders aircraft has excellent off design ability. The pitch moment is negative with a positive angle of attack , shows its static stability ability in pitch direction. The pressure center is nearly 0. 6 with the change of angle of attack and Mach number , because the projection of the lower face is almost isosceles triangle. This character is very useful to stability and control too.

Table 2　Aerodynamic result of CFD

Mach	Aoa (0)	Cd	L/D	Cmz	Xcp
5	0	0.01810	1.37735	- 0.0162	0.61631
5	2	0.02170	2.94378	- 0.0387	0.60842
5	4	0.02852	3.62938	- 0.0631	0.61001
5	6	0.03864	3.73835	- 0.0843	0.59832
5	8	0.05243	3.56037	- 0.0105	0.58640
6	0	0.01464	1.48634	- 0.0133	0.62290
6	2	0.01791	3.11893	- 0.0355	0.61130
6	4	0.02396	3.79299	- 0.0572	0.61512
6	6	0.03241	3.93366	- 0.0740	0.59840
6	8	0.04379	3.80817	- 0.0933	0.58537
7	0	0.01302	1.52765	- 0.0137	0.62630
7	2	0.01601	3.21799	- 0.0336	0.61832
7	4	0.02185	3.86270	- 0.0549	0.61973
7	6	0.03036	3.93083	- 0.0750	0.60213
7	8	0.04024	3.89115	- 0.0899	0.58928

2　Aerodynamic Performance WTE Analysis

In order to analysis waveriders aircraft aerodynamic performance more credible , and validate the CFD result too , the wind WTE fore measure is being carried out with the waveriders aircraft configure given by figure 1.

Figure 6 gives out the test model with computer aid design (CAD) software. Figure 7 gives out the test model after manufactured by number control (NC) machine to maintain the configuration more accuracy.

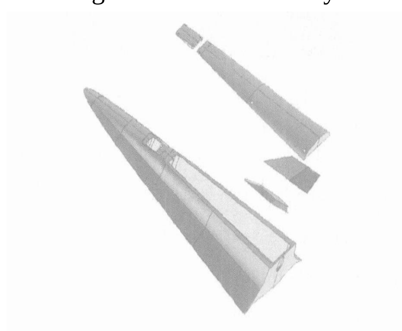

Fig. 6　WTE model of CAD

This test is being finished in the hypersonic wind tunnel of China Academy of Aerospace Aerodynamics (CAAA) .

Figure 8 is the schlieren of model in wind tunnel when test is being carried out.

We choose Mach number 5 , 6 , 7 , attack angle 0 °, 1 °,2 °,4 °,5 °,6 °,8 ° as test condition. Table 3 gives out the wind tunnel parameter corresponding to different Mach

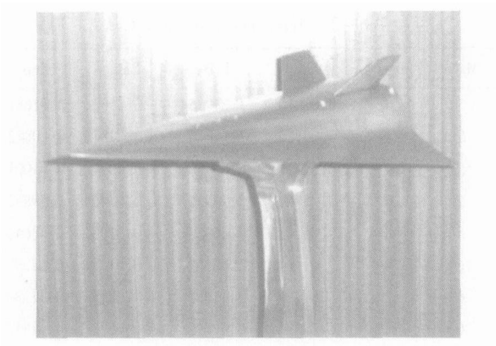

Fig. 7 Model photo of WTE

number. Reynolds number in table 3 is choosing 1m as reference length to get.

Table 3 Wind tunnel parameter

Mach	P0(pa)	PS(pa)	Pd(pa)	T0(K)	Re(x107)
5	964365	1962	33480	364	2.14
6	1997869	1355	33404	464	1.99
7	3503084	868	29553	598	1.60

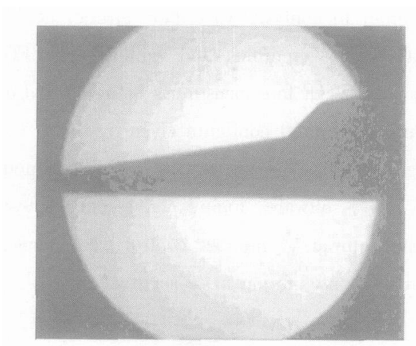

Fig. 8 Schlieren of model in WTE

Table 4 gives out the aerodynamic result of WTE at Mach number 5, 6, 7 with attack angle 0°, 1°, 2°, 4°, 5°, 6°, 8°. In table 4, the reference length is 0.5m, and the reference area is 0.0819m^2. From the WTE result data in table 4, we can see that, at Mach number within 5～7, attack angle within 4°～6°, waveriders aircraft maintain higher aerodynamic performance, the lift-to-drag ratio is very higher, just a little below 4. And pitch moment coefficient is always negative with a positive angle of attack and pressure center is near 0.6. Compare the CFD result in table 2 with WTE result in table 4, we can draw the conclusion that CFD result fits in well with WTE result. When comparison between wind WTE and CFD result, the viscous drag coefficient due to the different of Reynolds number must be considerate.

Table 4 Aerodynamic result of WTE

Mach	Aoa(0)	Cd	L/D	Cmz	Xcp
5	0	0.01788	1.63059	-0.0172	0.61826
5	1	0.01949	2.38564	-0.0282	0.60321
5	2	0.02149	3.03041	-0.0399	0.60670
5	4	0.02825	3.66461	-0.0641	0.60913
5	5	0.03269	3.74884	-0.0757	0.60595
5	6	0.03793	3.70458	-0.0857	0.59643
5	8	0.05067	3.48671	-0.1061	0.58329
6	0	0.01494	1.60257	-0.0142	0.62492
6	1	0.01636	2.53194	-0.0253	0.60789
6	2	0.01835	3.03041	-0.0364	0.61206
6	4	0.02447	3.81404	-0.0584	0.61615
6	5	0.02845	3.86225	-0.0680	0.60740
6	6	0.03238	3.84855	-0.0760	0.59725
6	8	0.04262	3.69180	-0.0942	0.58269
7	0	0.01349	1.65900	-0.0135	0.62956
7	1	0.01464	2.63945	-0.0239	0.61559
7	2	0.01665	3.31775	-0.0345	0.61872
7	4	0.02275	3.90977	-0.0560	0.62067
7	5	0.02690	3.93963	-0.0666	0.61784
7	6	0.03105	3.86315	-0.0741	0.60536
7	8	0.03980	3.78607	-0.0909	0.58794

3 Viscous Drag Analysis Method Study

How to calculate viscous drag accuracy is a problem need to pay more close attention to study in CFD. Via WTE, total drag can be got with wind tunnel balance, but we can not separate viscous drag and wave drag from total drag force directly. By CFD to solve NS equation with proper model to define viscous, turbulent, transition etc, we can get wave drag and viscous drag and total drag, and we can deem wave drag get by CFD as real wave drag, but viscous drag is very hard to calculate accuracy.

When aircraft is flight at a certain attack angle, lift and drag is the change of axial fore and normal force with the array formed by sine and cosine of attack angle. more definitely, the viscous drag and wave drag in this part is axial force. It is good to not confusion.

Total drag、wave drag and viscous drag coefficient get by CFD are D_{CFD}, $D_{w,CFD}$, $D_{v,CFD}$, total drag coefficient get by WTE is D_T, and wave drag and viscous drag coefficient $D_{w,T}$, $D_{v,T}$, they can not be got directly.

Because wave drag coefficient is irrelevant to viscous effect, so the wave drag coefficient of CFD model and WTE model is the same. Because we can assume the wave drag get by CFD is accuracy wave drag , so :

$$D_{w,T} = D_{w,CFD} \tag{1}$$

Then :

$$D_{v,T} = D_T - D_{w,T} \tag{2}$$

The Reynolds number of CFD and wind WTE is flight Reynolds number and wind tunnel Reynolds separately , so we must consideration this different effect to the viscous drag coefficient. We assume a third condition , it has the same Reynolds number with WTE , free stream condition is the same as CFD , so we can calculate the model length of this third condition is :

$$L = \frac{R_{eT} L_{CFD}}{R_{eCFD}} \tag{3}$$

Now the third condition is satisfied geometry similarity、Mach number and Reynolds number the same , viscous drag coefficient of wind tunnel test result D_{vT} is the same as third condition. Then problem that analysis the difference and relation of viscous drag coefficient between WTE and CFD is change to study the viscous drag coefficient between third condition and CFD condition. Because the free stream condition of third condition is the same with CFD condition , the only different is the aircraft length , the length ration is $n_1 = L_{CFD}/L$, with reference temperature method[6,7] to calculate viscous drag , we get :

$$\frac{D_{v,CFD1}}{D_{v,T}} = \frac{\sum \int_{n_1 a_1}^{n_1 a_2} \mathrm{d}y \int_{n_1 b_1}^{n_1 b_2} \frac{G_1}{x^{1-G_2}} \mathrm{d}x / (n_1^2)}{\sum \int_{a_1}^{a_2} \mathrm{d}y \int_{b_1}^{b_2} \frac{G_1}{x^{1-G_2}} \mathrm{d}x} = (n_1)^{G_2 - 1} \tag{4}$$

a_1 , a_2 , b_1 , b_2 is a little viscous drag integral region. G_1 , G_2 is parameter used in reference method to calculate viscous drag , G_1 is being reduced , G_2 is 0.5 in laminar flow and 0.8 in turbulent flow.

Basing on the result of $D_{v,CFD1}$ get by reference temperature method , we can use it to analysis and validate the result $D_{v,CFD}$, D_{CFD} get by CFD.

4 Conclusions

Via the CFD and WTE analysis of a cone-derived hypersonic waveriders aircraft aerodynamic performance , we can draw the conclusions below :

(1) The waveriders aircraft with design condition Mach number 6 and attackangle 4° can maintain excellent aerodynamic performance when mach number varies within 5～7 and attack angle varies with 4°～6°. With the consideration of volumetric efficient and thermal protection , it has a lift-to-drag only a little below 4 , this is quite desirable result. The aerodynamic results get in this article can being a meaningful basic for the application of waveriders hypersonic aircraft design.

(2) Basing on reference temperature method , cooperate use CFD and WTE result can simple get the viscous drag that can not be got directly by WTE , and it can be used to validate the viscous drag that is hard to calculate accuracy in CFD too. It resolves the viscous problem that face by CFD and WTE. Though it is very coarse , for engineer application , it is very useful.

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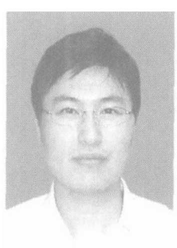

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高超声速乘波飞行器气动特性研究

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摘　要：用计算流体力学和风洞试验的方法对以锥导乘波体为基础生成的高超声速乘波飞行器的气动性能进行了研究。结果表明，以马赫数 6，攻角 4 度为设计状态的乘波体，在马赫数 5～7，攻角 4～6 度的范围内，都具有良好的气动特性，升阻比接近 4。最后，提出了一个简单的以参考温度方法为基础的粘性阻力分析方法。该方法配合使用风洞试验和计算流体的结果，可以用来验证计算流体中难以计算准确的粘性阻力，也可以用来分析在风洞试验难以直接得到的粘性阻力。对于工程上的粘性阻力分析是一个有用的办法。

关键词：高超声速乘波体；计算流体力学；风洞试验；粘性阻力分析；参考温度法

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Fuel-Time Optimal Rendezvous of an Inspector Satellite to its Master

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Abstract：The rendezvous of an inspector satellite to its master is one of the key techniques in formation flying. The diversity of the space missions demands minimization of both fuel and time. A stable time-fuel optimal spiral orbit for the rendezvous of an inspector satellite is put forward. Descriptions of the rendezvous problem based on Hill's equation are given，and the design intents and prerequisites of the transfer orbit are expounded. Then an effective spiral rendezvous control scheme is raised，and its characteristics and stability is discussed. At last，the tradeoff between fuel cost and rendezvous time and initial phase is investigated. Simulation results show that the spiral control sheme is efficient and feasible. It can accomplish rendezvous effectively，and can gain tradeoff between fuel and time.

Key words：Inspector satellite；Relative orbit control；Fuel-time tradeoff