The research on the influence of multi-physical effect on the dynamic stability of high speed vehicle

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Abstract. In this paper, a kind of high speed vehicle similar to HTV-2 configuration is taken as the research object, and the influence of chemical non-equilibrium effect and rarefied flow effect on the vehicle's three-channel dynamic derivative and yaw channel free motion stability is studied by using the dynamic numerical simulation method based on rigid dynamic grid. The sensitivity of three-channel dynamic stability to multi-physical effects is analyzed, and the influence of multi-physical effects on the dynamic stability of high speed vehicle is obtained. The research results show that the rarefied flow effect and chemical non-equilibrium effect have a small impact on the dynamic derivatives of pitch and roll channels, and a relatively significant impact on the dynamic derivatives of yaw. Compared with the dynamic derivatives of yaw under the condition of complete gas without slip, the deviation of slip results is - 45.2%, and that of chemical non-equilibrium gas with slip results is - 65.9%; The yaw channel has dynamic stability under the condition of complete gas with slip, and the yaw dynamic stability under the condition of chemical non-equilibrium gas with slip is further enhanced, which is consistent with the stability trend represented by the dynamic derivative results; Under the condition of complete gas without slip, the result of dynamic derivative is characterized by dynamic stability, while the result of free yaw oscillation is characterized by dynamic instability; The dynamic derivatives of yaw and the numerical simulation results of free yaw under different inflow conditions show that the dynamic stability of yaw channel is more sensitive to multi-physical effects than that of pitch and roll channels.

Keywords: multi-physical effect, high speed vehicle, dynamic stability.

1. Introduction

In April 2010 and August 2011, the United States conducted two flight tests of HTV-2, both of which failed. The failure of the first flight test was due to the fact that during the flight, the yaw exceeded the expectation, accompanied by the rolling beyond the controllable range, which led to the aircraft losing control [1]. It can be seen that the problem of dynamic stability of high speed vehicles is very prominent, which brings severe challenges to flight safety [2], [3]. When the high speed vehicle represented by HTV-2 flies at high Mach number in the near space, the high altitude multi-physical effects (mainly including the high temperature real gas effect caused by Mach number and the rarefied flow effect caused by low density space) faced by the vehicle will have a great impact on its local flow pattern and overall aerodynamic performance [4], and will have an impact on the dynamic stability of the vehicle.

At present, scholars at home and abroad have carried out a lot of research on the multi-physical effects of high speed vehicles. Because of the high cost of wind tunnel test methods and the high requirements for test technology and measurement methods, the research mainly adopts CFD method [5]. Maus [6] et al. used CFD method to study the influence of viscous interference effect and real gas effect on the aerodynamic performance of space shuttle in 1983. Ye Youda [7] and other researchers have shown that the balance gas effect has a significant impact on the lift-drag ratio, pressure center position and centroid pitching moment of the vehicle when the high speed vehicle is flying at an altitude of 50~80km. The research of Tian Hao [8] and others shows that the real gas effect has a great impact on the shock layer thickness, the distribution of physical quantities in the boundary layer, and the flow separation and other local flow patterns of the hypersonic vehicle with

lift-body shape, which will affect the overall aerodynamic performance of the aircraft, reduce the lift-drag ratio of the aircraft, reduce the low-head torque, and move the pressure center forward. The above research mainly focuses on the impact of multi-physical effects on the static aerodynamic characteristics and static stability of aircraft, and does not involve the dynamic stability research.

Zhao Wenwen [5] and others have carried out research on pitching stability of blunt cones under multi-physical effects, and the results show that the influence of rarefied gas effect and chemical nonequilibrium effect on conventional aerodynamic and pitching stability parameters cannot be ignored. The rarefied flow effect leads to dynamic instability of pitching motion of blunt cone, and the instability increases with height. At the same time, the chemical nonequilibrium effect will also have an adverse effect on the pitching dynamic stability of the blunt cone, and the dynamic stability of the blunt cone will be weakened under the chemical nonequilibrium effect. However, the object of this study is a relatively simple blunt cone, whose shape is quite different from that of a high speed vehicle with a symmetrical slender body configuration, so its research results can only provide partial reference. The influence of multi-physical effects on the dynamic stability of high speed vehicles needs further study.

In this paper, a kind of high speed vehicle similar to HTV-2 configuration is taken as the research object, and the dynamic numerical simulation method based on rigid dynamic grid is used to study the influence of chemical non-equilibrium effect and rarefied flow effect on the vehicle's three-channel dynamic derivatives and the yaw channel free motion stability, and the sensitivity of the three-channel dynamic stability to multi-physical effects is analyzed, thus the influence law of multi-physical effects on the dynamic stability of the high speed vehicle is obtained, The research results can provide a reference for the stability evaluation of high speed vehicles.

2. Numerical method and calculation model

2.1 Numerical method

The flow field control equation involving the real gas effect is three-dimensional chemical nonequilibrium Navier-Stokes equation. The finite volume method based on unstructured grid is adopted for the space discretization of the control equation. The viscous term uses the central difference, the inviscid term uses the TVD scheme, the implicit time discretization uses the LU-SGS method, the unsteady time advancement uses the double time step method, the dynamic grid generation uses the rigid dynamic grid technology, and the whole flow field is assumed to be laminar. In the simulation, the wall is set as isothermal wall and the temperature is set as 1000K.

2.2 Kinetic model of chemical reaction

Park [9] chemical nonequilibrium gas model is adopted, including 7 components (N2, O2, NO, N, O, NO+, e -) and 6 elementary reactions. The specific parameters are shown in Table 1. Among them, M in the first three reactions is the third collider, and the three-body effect factor parameters (third-body collider coefficient) involved are shown in Table 2.

Table 1. Chemical nonequilibrium reaction model.

No.	Reaction	Frequency factor $(s^{-1}(m^3/kmol)^{N-1})$	Temperature exponent	Activation energy (J/kmol)
1	$N_2+M<->2N+M$	7.0e18	-1.6	9.411448e8
2	$O_2+M<->2O+M$	2.0e18	-1.5	4.94683e8
3	$NO+M<->N+O+M$	5.0e12	0.0	6.27707e8
4	$NO+O<->O_2+N$	8.4e9	0.0	1.617073e8
5	$N_2+O<->NO+N$	6.4e14	-1.0	3.192576e8
6	$N+O<->NO^++e$	8.8e5	1.0	2.652166e8

Table 2. Three-body effect factor parameter.

Reaction	Species (e)	Species (N)	Species (O2)	Species (NO)	Species (O)	Species (NO+)	Species (N2)
1	1750	4.286	1.0	1.0	4.286	1.0	1.0
2	0.0	5.0	1.0	1.0	5.0	1.0	1.0
3	0.0	22	1.0	22	22	1.0	1.0

2.3 Treatment of slip boundary conditions

With the increase of flight altitude, due to the effect of rarefied gas, slip flow will occur in the surface flow. At this time, the non-slip condition will fail, and the slip velocity boundary condition and slip temperature boundary condition need to be introduced. The slip velocity boundary condition and slip temperature boundary condition equations of Beskok[10] adopted in this project are as follows:

$$u_s = u_w + \left(\frac{2-\sigma_v}{\sigma_v}\right)\left(\frac{Kn}{1-bKn}\right)\left(\frac{\partial u}{\partial n}\right)_w \tag{1}$$

Including:

u_s is the dimensionless sliding wall velocity;

u_w is the dimensionless non-slip wall velocity;

σ_v is the tangential momentum adaptive coefficient;

Kn is Knudsen number, $Kn = \frac{\lambda_v}{L}$, λ_v is the mean free path of momentum and L is the characteristic length;

b is the coefficient of the equation. The first order is 0, and the second order is -1. The second order is used in this project to ensure the calculation accuracy;

n is the dimensionless wall normal coordinate;

$$T_s = T_w + \left(\frac{2-\sigma_T}{\sigma_T}\right)\left(\frac{2}{\gamma+1}\right)\lambda_T\left(\frac{\partial T}{\partial n}\right)_w \tag{2}$$

Including:

T_s is the dimensionless sliding wall temperature;

T_w is the dimensionless wall temperature;

σ_T is the thermal adaptation coefficient;

γ is the specific heat ratio;

λ_T is the mean free path of temperature, with $\lambda_T = \frac{2k}{\rho m c_v}$;

k is thermal conductivity;

m is the average molecular velocity;

c_v is the specific heat capacity at constant volume.

The characteristic length of the Knudsen number in the slip velocity boundary condition adopted in this project is taken as the total length of the aircraft of 4m.

2.4 Calculation method of dynamic stability derivative

In this paper, the numerical forced harmonic oscillation method is used to calculate the dynamic derivatives to evaluate the single degree of freedom dynamic stability of the aircraft. The following is a brief introduction to the calculation method. The numerical forced harmonic oscillation method is to solve the flow control equation and flight dynamics equation by numerically simulating the simple harmonic oscillation of the aircraft, and identify the dynamic derivatives according to the history of the aircraft's motion parameters and the unsteady aerodynamic parameters obtained by numerical simulation.

Taking the pitching dynamic derivative as an example, a small amplitude pitching forced oscillation motion is added to the reference motion of the aircraft with constant centroid velocity, and its motion form meets the following requirements:

$$\theta(t)=\alpha(t)=\alpha_0+A\sin(\omega t) \tag{3}$$

$$\dot{\alpha}=q=\dot{\theta}=\omega A\cos(\omega t) \tag{4}$$

Where A is amplitude, α_0 is the initial angle of attack, ω is pitch angle frequency.

Define the reduction frequency k as:

$$k=\frac{\omega L_r}{2V_\infty} \tag{5}$$

Where L_r is the reference length and V_∞ is the incoming flow speed.

After the pitching angle history $\theta(t)$ and the corresponding pitching moment coefficient history $C_m(t)$ are obtained by numerical simulation, the static derivative $C_{m\theta}$ and dynamic derivative $C_{m\dot{\theta}}$ can be obtained by numerical integration with the following formula:

$$\begin{aligned} C_{m\theta}&=\frac{\omega}{A\pi}\int_{t_0}^{t_0+T}C_m(t)\sin(\omega t)dt \\ C_{m\dot{\theta}}&=\frac{\omega}{kA\pi}\int_{t_0}^{t_0+T}C_m(t)\cos(\omega t)dt \end{aligned} \tag{6}$$

2.5 The aircraft shape and grid

The aircraft shape and grid are shown in Figure 1. The total length of the model L=4m, the centroid position X_{cg}/L=60%, the reference length L_r=4m, and the reference area S_r=1m^2. For the model, a number of structural grids are used for topology. In order to ensure the grid quality near the boundary layer, the body surface adopts an O-type grid. The dimensionless height of the first layer of grid on the wall is around 1, and the number of grids is about 1.85 million.

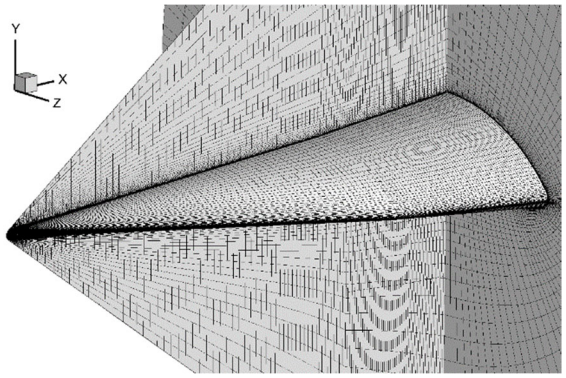

Figure 1. Aircraft shape and grid.

3. Results and analysis

3.1 Influence of multi-physical effects on pitching dynamic stability

Under the condition of Mach number Ma=20 and flight altitude h=70km, numerical simulation is carried out for the pitching dynamic characteristics of the model at 15° and 30° angles of attack. The static calculation results are taken as the starting conditions for dynamic calculation. The forced pitching motion reduction frequency is k=0.05, and the amplitude A=1°.

The results of pitching dynamic derivatives obtained by numerical simulation under different working conditions are shown in Table 3, where PG is the result of complete gas without slip, PG-slip is the result of complete gas with slip, and RG-slip is the result of chemical non-equilibrium gas with slip. It can be seen that the pitching dynamic derivative is less than 0 under all working

conditions, indicating that the pitching dynamic stability is available. The results of pitching dynamic derivatives under different gas models have little difference. The deviation of the results of different gas models under 15° angle of attack is not more than -3.3%, and the deviation of the results of different gas models under 30° angle of attack is not more than -5.2%, indicating that the chemical non-equilibrium effect and the rarefied flow effect have no significant impact on pitching dynamic stability.

Table 3. Pitch dynamic derivative results under different conditions.

α/°	PG	PG-slip	RG-slip	PG-slip and PG deviation $(C_{PG-slip}-C_{PG})/\lvert C_{PG}\rvert$	RG-slip and PG deviation $(C_{RG-slip}-C_{PG})/\lvert C_{PG}\rvert$
15	-0.72321	-0.73141	-0.74701	-1.13342%	-3.28991%
30	-1.38837	--	-1.46109	--	-5.2378%

3.2 Influence of multi-physical effects on rolling dynamic stability

Under the condition of Mach number Ma=20 and flight altitude h=70km, numerical simulation is conducted for the rolling dynamic characteristics of the model at 15° and 30° attack angles. The static calculation results are taken as the starting conditions for dynamic calculation. The forced rolling motion reduction frequency is k=0.05, and the amplitude A=1°.

The rolling derivative results obtained by numerical simulation under different working conditions are shown in Table 4. It can be seen that the rolling derivative is less than 0 under all working conditions, indicating that it has rolling stability. The results of the rolling derivatives of different gas models have little difference. The deviation of the results of different gas models at 15° angle of attack is not more than 1.2%, and the deviation of the results of different gas models at 30° angle of attack is not more than - 5.6%, indicating that the chemical non-equilibrium effect and the rarefied flow effect have no significant impact on the rolling stability.

Table 4. Roll dynamic derivative results under different conditions.

α/°	PG	PG-slip	RG-slip	PG-slip and PG deviation $(C_{PG-slip}-C_{PG})/\lvert C_{PG}\rvert$	RG-slip and PG deviation $(C_{RG-slip}-C_{PG})/\lvert C_{PG}\rvert$
15	-0.13571	-0.13449	-0.13414	0.8975%	1.15834%
30	-0.22661	--	-0.23938	--	-5.63489%

3.3 Influence of multi-physical effects on yawing dynamic stability

Under the condition of Mach number Ma=20 and flight altitude h=70km, numerical simulation is conducted for the dynamic characteristics of yaw of the model at 15° and 30° angles of attack. The static calculation results are taken as the starting conditions for dynamic calculation. The forced yaw reduction frequency is k=0.05, the amplitude A=1°, and the vertical main lift of the model body axis y is upward, so the positive yaw direction is the left deviation of the nose.

The results of yaw dynamic derivatives obtained by numerical simulation under different conditions are shown in Table 5. It can be seen that the yaw dynamic derivative is less than 0 under all operating conditions, indicating that it has yaw dynamic stability. The results of yaw dynamic derivatives under different gas models are significantly different. At 15° angle of attack, compared with the results of complete gas without slip, the deviation of slip results is -44.6%, and that of chemical non-equilibrium gas with slip results is -59.7%. At 30° angle of attack, the deviation of slip results is -45.2%, and that of chemical non-equilibrium gas is -65.9%. The results show that the lean flow effect will significantly enhance the yaw dynamic stability, and the chemical non-equilibrium effect will further enhance the yaw dynamic stability. The yaw moment hysteresis curve is shown in Figure 2 and Figure 3 respectively. Compared with the results of complete gas without slip, the envelope area of the hysteresis curve under slip condition is increased, and the envelope area of the hysteresis curve under chemical non-equilibrium gas with slip condition is further increased,

indicating that the chemical non-equilibrium effect and rarefied flow effect have a significant impact on the dynamic yaw moment.

The above results show that compared with pitch and roll channels, the dynamic stability of yaw channel is more significantly affected by the rarefaction effect and chemical non-equilibrium effect. The possible reason is that the aircraft model studied in this paper lacks vertical stabilizer, so the stability of the yaw channel is weaker than the other two channels, resulting in the yaw channel is more sensitive to the aerodynamic characteristics caused by the rarefied flow effect and chemical non-equilibrium effect.

In order to further verify the influence of multi-physical effects on yaw dynamic stability, numerical simulation is conducted for the free yaw motion of the model at 30° angle of attack. The rotational inertia of the model body axis y is I_y=44.6kg · m^2, and the initial yaw angle ψ=0° at initial yaw rate ω_y=10°/s as the initial disturbance.

The free yaw motion curves obtained by numerical simulation under different gas models are shown in Figure 4, and the phase diagram of free yaw motion is shown in Figure 5. The model appears yaw oscillation motion after initial disturbance, while the motion trend under different gas models is significantly different. The oscillation amplitude of yaw angle gradually increases under the condition of complete gas without slip, and the yaw motion has a slow divergence trend. Therefore, the yaw channel is dynamically unstable under this condition, which deviates from the stability predicted by the dynamic derivative result. The possible reason is that the dynamic derivative is measured by small-amplitude forced motion, and the dynamic characteristics under small-amplitude forced motion are different from those under relatively large-amplitude free motion. The amplitude of yaw angle gradually attenuates and the yaw motion has a slow convergence trend under the condition of complete gas with slip, indicating that the yaw channel has dynamic stability under this condition. The amplitude of yaw angle decays faster when the chemical nonequilibrium gas has slip, indicating that the yaw dynamic stability is further enhanced. Therefore, the free yaw motion results of complete gas with slip and chemical nonequilibrium gas with slip are consistent with the stability trend represented by the dynamic derivative results.

Table 5. Yaw dynamic derivative results under different conditions.

α/°	PG	PG-slip	RG-slip	PG-slip and PG deviation $(C_{PG-slip}-C_{PG})/\lvert C_{PG}\rvert$	RG-slip and PG deviation $(C_{RG-slip}-C_{PG})/\lvert C_{PG}\rvert$
15	-0.12093	-0.17489	-0.19314	-44.6226%	-59.70794%
30	-0.14915	-0.21657	-0.24739	-45.20087%	-65.86435%

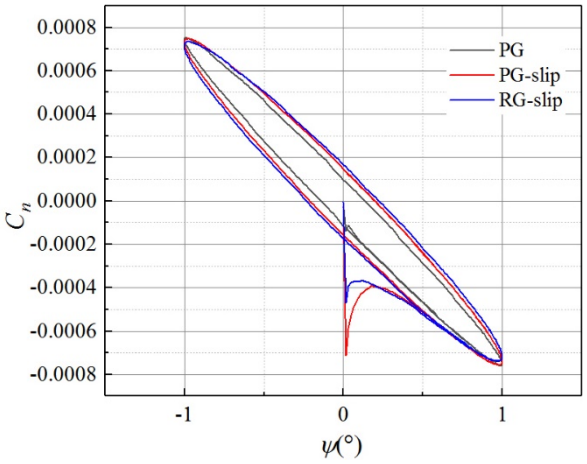

Figure 2. Yaw moment hysteresis curve at angle of attack 15°.

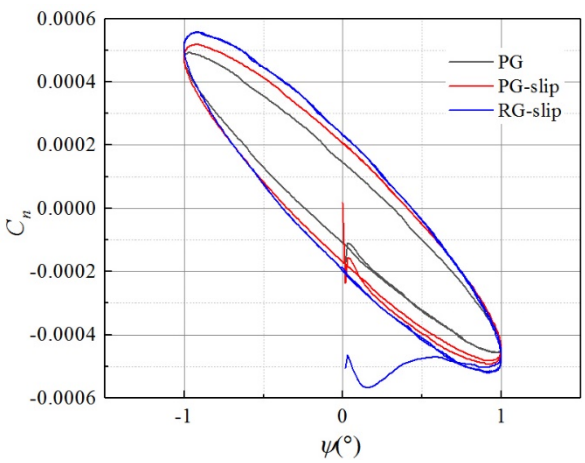

Figure 3. Yaw moment hysteresis curve at angle of attack 15°.

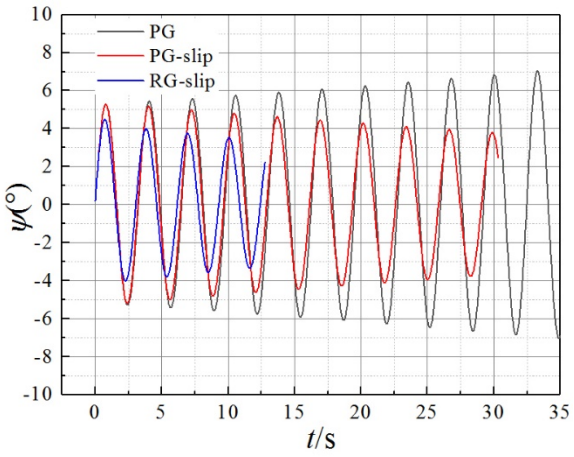

Figure 4. Free yaw motion curve with attack angle of 30 °.

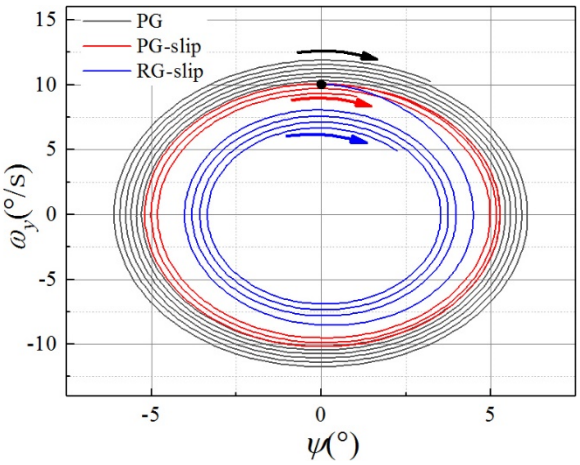

Figure 5. Phase diagram of free yaw motion with angle of attack of 30 °.

4. Conclusion

The above research shows that:

(1) The lean flow effect and chemical non-equilibrium effect have a small impact on the dynamic derivatives of pitch and roll channels, and a relatively significant impact on the dynamic derivatives of yaw. At an angle of attack of 30 °, compared with the dynamic derivatives of yaw under the condition of complete gas without slip, the deviation of the results of slip with slip is - 45.2%, and the deviation of the results of slip with chemical non-equilibrium gas is - 65.9%, indicating that the lean flow effect will significantly enhance the dynamic stability of yaw, The chemical non-equilibrium effect leads to further enhancement of yaw dynamic stability.

(2) The numerical simulation results of free yaw at 30 ° angle of attack show that the yaw channel has dynamic stability under the condition of complete gas with slip, and the dynamic stability of yaw under the condition of chemical non-equilibrium gas with slip is further enhanced, which is consistent with the stability trend represented by the dynamic derivative results; Under the condition of complete gas without slip, the dynamic derivative results are characterized by dynamic stability, while the free yaw oscillation results are characterized by dynamic instability, which indicates that the dynamic characteristics under small amplitude forced motion are different from those under relatively large amplitude free motion. Therefore, it is difficult to comprehensively evaluate the stability of the vehicle under large amplitude free motion only by using dynamic derivatives.

(3) The dynamic derivatives of yaw and the numerical simulation results of free yaw under different inflow conditions show that the dynamic stability of yaw channel is more sensitive to multi-physical effects than that of pitch and roll channels. The possible reason is that the aircraft model studied in this paper lacks vertical stabilizer, so the stability of the yaw channel is weaker than the other two channels, resulting in the yaw channel is more sensitive to the aerodynamic characteristics caused by the rarefied flow effect and chemical non-equilibrium effect. Therefore, the impact of multi-physical effects on the dynamic stability of the vehicle should be fully considered when evaluating the performance of the high speed vehicle.

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