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Studying the Temperature Field of Hypersonic Vehicle Structure with Aero-Thermo-Elasticity Deformation

Geng Xiangren, Liu Lei, Gui Ye-Wei, Tang Wei, Wang An-ling

***Abstract*—**The malfunction of thermal protection system (TPS) caused by aerodynamic heating is a latent trouble to aircraft structure safety. Accurately predicting the structure temperature field is quite important for the TPS design of hypersonic vehicle. Since Thornton's work in 1988, the coupled method of aerodynamic heating and heat transfer has developed rapidly. However, little attention has been paid to the influence of structural deformation on aerodynamic heating and structural temperature field. In the flight, especially the long-endurance flight, the structural deformation, caused by the aerodynamic heating and temperature rise, has a direct impact on the aerodynamic heating and structural temperature field. Thus, the coupled interaction cannot be neglected. In this paper, based on the method of static aero-thermo-elasticity, considering the influence of aero-thermo-elasticity deformation, the aerodynamic heating and heat transfer coupled results of hypersonic vehicle wing model were calculated. The results show that, for the low-curvature region, such as fuselage or center-section wing, structure deformation has little effect on temperature field. However, for the stagnation region with high curvature, the coupled effect is not negligible. Thus, it is quite important for the structure temperature prediction to take into account the effect of elastic deformation. This work has laid a solid foundation for improving the prediction accuracy of the temperature distribution of aircraft structures and the evaluation capacity of structural performance.

***Keywords*—**Aero-thermo-elasticity, elastic deformation, structural temperature, multi-field coupling.

I. INTRODUCTION

AS aerospace vehicles progress into the hypersonic regime, the aerodynamic heating rates become higher and higher, which is a new challenge that design engineers will have to face. The huge rise in structure temperature will cause the characteristics of materials change dramatically, and an inhomogeneous temperature distribution with inhomogeneous temperature gradients will surely induce structural thermal stress. As a result, the structural stiffness will also change, leading to the changes of structural deformation, and temperature distribution. Accurate prediction of the structure temperature field is essential for the thermal protection system design of hypersonic vehicle.

For the long-endurance hypersonic flights, the structural deformation caused by aerodynamic and temperature rise cannot be neglected. The deformations have a direct impact on the aerodynamic heating and structural temperature field. If the coupled effect is neglected, the structure temperature field may be predicted with remarkable error margin.

The coupled fluid-thermal-structural method formed in 1960s [1]. It becomes matured gradually, and has been used in a lot of engineering applications [2]-[6]. Despite years of focused research, with the existing level of knowledge and the computational capability of the current computers, it is still rather difficult to solve aerodynamic- thermal-structural problems in fully coupled way for engineering design.

Up till now the influence of structural deformation on aerodynamic heating and structural temperature field has not been paid much attention to, and has not been included in most of these studies. As more and more vehicles are designed to fly in hypersonic regime with the prolonged flight, and take the slim shape to get a higher lift-drag-ratio. The slenderization reduces the whole structure stiffness, raises the local aerodynamic heating rates on the sharp leading -edge regions. The structural deformation and its coupled effect with structural temperature field can't be neglected anymore. In this paper, based on the method of static aero-thermo-elasticity [7], the aerodynamic heating and heat transfer of hypersonic aircraft wing model were calculated in coupled way, considering the influence of aero-thermo-elasticity deformation. The result has displayed that, in the sharp leading-edge region, coupled calculation gives a lower temperature peak than the decoupled calculation does, while in the center-wing region with low curvature, there is not remarkable difference between two methods. This work has laid a foundation for improving the prediction accuracy of the temperature field of aircraft structures and evaluation capacity of structural performance.

II. COMPUTATION METHODS

A. Flowchart of Aero-Thermo-Elastic Computation

Aero-thermo-elasticity, which is a typical multi-disciplinary issue, is defined as the mutual interaction of aerodynamic, structural dynamic and thermal forces in a system. Fig. 1 illustrates the coupled relations between the different disciplines [8], [9].

By the method of static aero-thermo-elasticity proposed in [10], [11], the aero-thermo-elasticity characteristic, including the influence of deformation, is calculated along the flight trajectory. In that way, the aerodynamic and aerothermodynamic are all recomputed based upon the results of structural elastic deformation, and then the calculation for the temperature field is updated.

An overview of the method for solving static aero-thermo-elasticity problem is shown in Fig. 2. The dotted line represents the aerothermodynamic calculation based on the

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elastic deformation when the static aero-thermo-elasticity calculation has been finished. By this way, the cumulative influence of elastic deformation on the structure temperature distribution along the trajectory has been included.

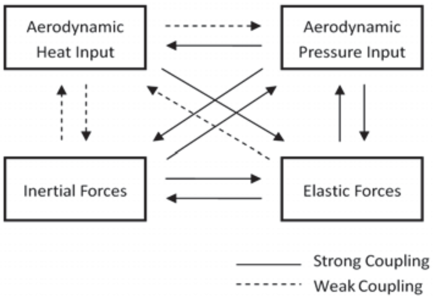

Fig. 1 Coupling diagram of aero-thermo-elastic problem

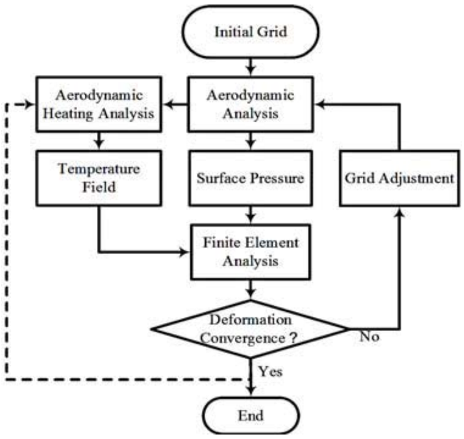

Fig. 2 Flowchart of the computation of static aero-elastic problem with deformation effects considered

B. *Computation Method*

1) Approximate Hypersonic Aero-Thermo-Dynamic

The engineering methods for predicting aerodynamic heating rates can be divided into two major types. One is for the stagnation region, and the other is for fuselage and center wing with low curvature. The Fay-Riddell correlation has been widely used in predicting stagnation aerodynamic heating rates. For the low-curvature region, the engineering methods can be classified as that for laminar flow and turbulent flow. The development of the aerodynamic heating engineering methods for laminar flow is already mature. The amendatory Lees formula is commonly used. For turbulent flow, using Blasius surface friction formula and amendatory Reynolds analogy, the momentum integral equation and the energy integral equation can be solved to give the results.

2) Approximate Hypersonic Aerodynamic

There are a lot of engineering correlations for the prediction of hypersonic aerodynamic [12], such as Newtonian theory, embedded Newtonian theory, piston theory and shock-expansion theory. Considering the characteristics of the computational models in this paper, the embedded Newtonian theory is used in the prediction of the windward aerodynamic force.

$$C_p = C_{p_0} + C_{p_{\max}} f\left(x^* M_\infty\right)\left(V_\perp / V_\infty\right)^2 \qquad (1)$$

The Prandtl-Meyer expansion relation is used for the calculation of the leeward aerodynamic force.

$$C_p = -\frac{\gamma+1}{2}\delta^2\left(\sqrt{1+\left(\frac{4}{(\gamma+1)M\delta}\right)^2}-1\right) \qquad (2)$$

3) Heat Transfer

The finite volume method is used in the calculation of heat transfer. The heat conduction equation is discretized at time-level n using second-order TVD-Runge-Kutta scheme. The convective heat flux on the hot wall (temperature Tw) needs to be amended, as a cold-wall heat flux is given, supposing the wall temperature equals 300K. The amendatory formula is given by:

$$q_h = \frac{H_{re} - H_w}{H_{re} - H_{300}} q_c \qquad (3)$$

where, H_{re} is the recovery enthalpy, H_w the wall enthalpy, H_{300} the enthalpy when the wall temperature is 300K, and q_c the cold-wall heat flux.

4) Thermal Stress/Strain

The finite element method is used in the calculation for thermal stress/strain. The thermo-elastic equations can be transformed into the classic finite element equation by the variation principle.

$$Ka = P \qquad (4)$$

where K is the structure stiffness matrix, P the structure load vector, a the displacement vector which needs to be solved. Because the thermal expansion results in linear strain only, the deformation generated by the heating can be regarded as the initial deformation ε_0:

$$\varepsilon_0 = \alpha(\phi - \phi_0) \qquad (5)$$

The stress-strain relationship can be expressed as:

$$\sigma = D(\varepsilon - \varepsilon_0) \qquad (6)$$

where α is the coefficient of thermal expansion, ϕ_0 the initial temperature, and ϕ the final temperature. For anisotropic materials, the coefficients of thermal expansion are usually different along different direction. The final temperature ϕ is obtained in advance, as a known condition.

III. COMPUTATIONAL RESULTS

A. Model

Fig. 3 is the geometries of all-moving rudder of hypersonic aircraft. The structure of bearing at the wing root has been ignored in this study. The root length, wingspan, and leading edge sweep angle are 2.67m, 1.27m, and 30 degree respectively. The material is GH1015, a kind of high-temperature alloy. The structural initial temperature is supposed to be 300K. The aircraft cruises at an altitude of 20Km. The Mach number is 5, and the angle of attack is 10 degree.

In order to reduce structure mass and improve payload, the hollow structure usually are used in practical design, without any loss of structural safety and flight performance. In this paper, the thickness of model "skin" is 5mm. the computing grid diagram of hollow all-moving rudder model is shown in Fig. 4.

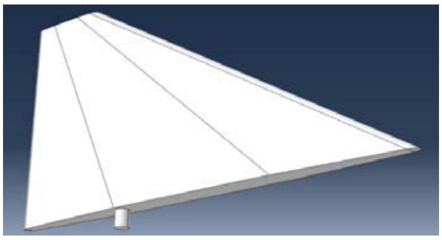

Fig. 3 All-moving rudder model of hypersonic vehicle

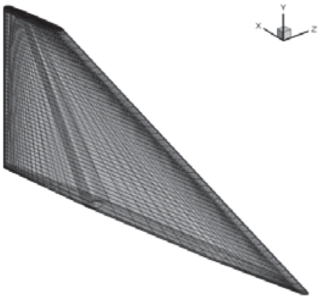

Fig. 4 Computing grid of hollow full-motion rudder

B. Results and Analysis

The coupled method (Method 2: Approximate Hypersonic Aerodynamic) is used in the prediction of surface heat flux, temperature distributions, and structure deformation.

Fig. 5 is the heat flux contour of rudder model, and the heat flux distributions along the axial direction are shown in Fig. 6. It displays that, the max heat flux, which is 1500 approximately, is located near the leading edge. The phenomenon of transition, from laminar flow to turbulent flow, appeared on the windward surface of center rudder. A significant rise in heat flux of the turbulent zone can be seen, compared with that of laminar zone. The maximum heat flux is close to 300.

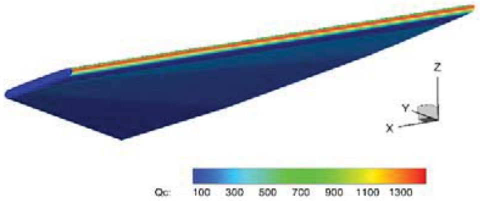

Fig. 5 Heat flux contour of all-moving rudder

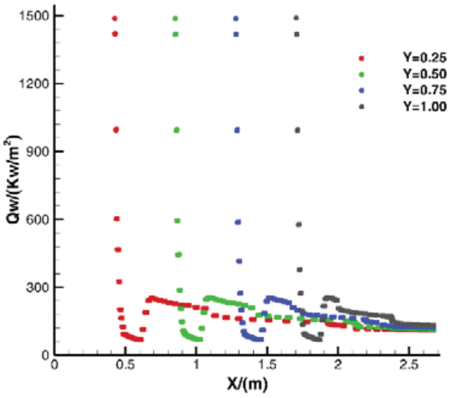

Fig. 6 Heat flux curves of all-moving rudder model along the axial direction

In order to show the influence of coupled effect on prediction precision of the structural temperature field in detail, three monitoring points, based on the geometry characteristics of the rudder model, are chosen and shown in Fig. 7 They are point A near the leading edge, point B on the windward side surface, and point C near the trailing edge. The coordinate value of monitoring points is provided in Table I.

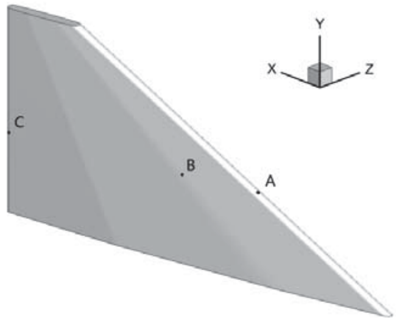

Fig. 7 Monitoring points for temperature field

TABLE I
THE COORDINATE VALUE OF MONITORING POINTS

Monitoring points	Coordinate value
A	（0.855，0.500，-0.146）
B	（1.390，0.500，-0.300）
C	（2.650，0.500，-0.496）

Fig. 8 is the contour of structure temperature field at 500s. The figure shows that the temperature on the windward surface is all over 900K, close to the equilibrium state. The decoupled method (Method 1: Approximate Hypersonic

Aero-Thermo-Dynamic) is also used to predict the temperature distribution for comparison. The main difference between two methods is that, in Method 1 the influence of structure deformation on structure temperature distribution has been neglected.

Fig. 9 shows the curves of temperature versus time on the structural monitoring points. For the point A, near the leading edge, there is a remarkable difference between temperature distributions by two methods. The maximum temperature drops from 1164K of Method 1 to 1137K of Method 2, due to coupled effect. But for point B and Point C, the temperature differences are negligible. For point B, the temperature rise due to coupled effect is 4K, from 992K to 996K. For point C, the temperature rise due to coupled effect is 2K, from 923K to 925K.

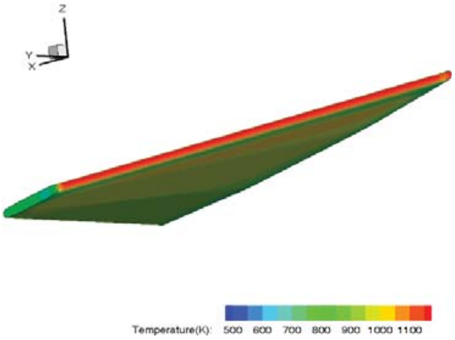

Fig. 8 Contour of structure temperature field at 500s

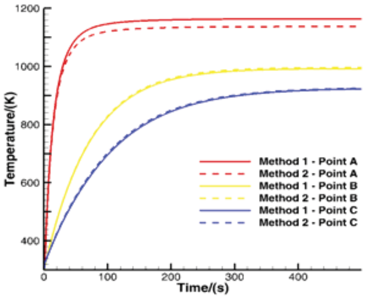

Fig. 9 Temperature versus time of the structural monitoring points

Generally, the structure deformation is on the magnitude of 1.0 percentage of the characteristic length of vehicles. For the all-moving rudder considered in this paper, the deformation is on the magnitude of 1mm or so. The thermal deformation contributes to the temperature change in two ways. First, it changes the local angle of attack, thus the local heat flux will surely change, especially on the region with small local curvature radius, such as the sharp leading-edge. Second, the deformation will make a small shift on the stagnation point, reducing to a mild aerodynamic heating on the moving stagnation region, which gives the reason for why the stagnant temperature given by coupled Method 2 is less than by decoupled Method 1.

For those regions with large curvature radius, such as fuselage or center wing, the difference on results between two methods is quite negligible.

In general, the coupled thermal deformation is quite important for the structure temperature field prediction, especially on those regions with small local curvature radius, such as the nose-cone, and the sharp leading-edge. The coupled computation will generally give temperature results less than the decoupled method will. If the local curvature radius is on the magnitude of mm, the thermal deformation may change the prediction results remarkably.

IV. CONCLUSION

Based on the calculation method of static aero-thermo-elasticity, the aerodynamic heating and heat transfer coupled calculation for hypersonic aircraft wing model were performed, considering the influence of aero-thermo-elasticity deformation. The results show that, for those regions with large local curvature radius, such as fuselage and center wing, the deformation of structure has little effect on temperature field. But, for the stagnation point region where the local curvature radius is quite small, the structure temperature will surely change remarkably. Thus, the elastic deformation is important for the prediction of structure temperature field, especially for those advanced and smart hypersonic vehicles. This work has laid a foundation for improving the prediction accuracy of the temperature field of aircraft structures and the evaluation capacity of structural performance.

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