Two-Way-Coupling Method for Rapid Aerothermoelastic Analyses of Hypersonic Wings

Wan Zhiqiang[1,2], *Yi Nan*[1,2], *Li Guoshu*[3], *Yang Chao*[1,2*]

1. School of Aeronautics Science and Engineering, Beihang University, Beijing 100191, P. R. China;

2. Key Laboratory of Aircraft Advanced Design Technology (Behang University), Ministry of Industry and Information Technology, Beijing 100191, P. R. China;

3. Beijing Institute of Nearspace Vehicle′s Systems Engineer, Beijing 100076, P. R. China

(Received 17 November 2016; revised 3 February 2017; accepted 8 February 2017)

Abstract: Several types of coupling methods for resolving aerothermoelastic problems associated with hypersonic wings are summarized, and the appropriate coupling methods for engineering calculations are selected. Then, the calculation and analysis methods for the subdisciplines in this field are introduced, and the time step issue is discussed. A two-way-coupling rapid static aerothermoelastic method for analyzing hypersonic wings is proposed. This method considers thermal effects and is used to conduct an aerothermoelastic response analysis for a hypersonic wing. In addition, the aerodynamic force, heat flux, structural deformation and temperature field are obtained. The following three conclusions are drawn. First, the heating effect has a significant impact on the static aeroelastic response of hypersonic wings; therefore, thermal protection shields are essential. Second, the application of thermal protection shields reduces the differences in the calculation results between the one- and two-way-coupling methods. Third, hypersonic wings exhibit large thermal deformation under high-temperature environments, and in certain cases, the thermal deformation is even larger than the deformation caused by aerodynamic force.

Key words: hypersonic; aerothermoelastic; two-way-coupling; aerodynamic heating; thermal deformation

CLC number: V211.47 **Document code**: A **Article ID**: 1005-1120(2018)01-0135-11

0 Introduction

Hypersonic vehicles operate at a Mach number ranging from 5 to 15, and they can fly in and across the atmosphere at hypersonic speeds[1]. Hypersonic vehicles can fly at high speeds, they are capable of long voyages, and they present good maneuverability and quick reactions. In addition, these vehicles can adapt to technologically advanced warfare and will be able to satisfy future high-speed transportation requirements. Therefore, research on hypersonic vehicles has become popular in recent years.

The aerodynamic shapes of most hypersonic vehicles include slender bodies, lifting bodies or waverider configurations. To reduce weight, the fuselage, wing and control surface always have large elasticity. Therefore, the aeroelastic effect of hypersonic vehicles must be considered. Hypersonic vehicles must fly at hypersonic velocity in the atmosphere, which causes a drastic aerodynamic heating effect on the vehicle surface. The structural stiffness and the aeroelastic response are influenced by the aerodynamic heating effect. Thus, owing to the impact of aerodynamic force and aerodynamic heating, hypersonic vehicles encounter an aero-thermal-structural coupling problem. During the design stage of this type of air vehicle, the influence of aerodynamic heating on the aeroelastic response must be considered[2].

So far, relatively few studies have focused on the aerothermoelastic effect of hypersonic vehicles

* Corresponding author, E-mail address: yangchao@buaa.edu.cn.

How to cite this article: Wan Zhiqiang, Yi Nan, Li Guoshu, et al. Two-way-coupling method for rapid aerothermoelastic analyses of hypersonic wings[J]. Trans. Nanjing Univ. Aero. Astro., 2018,35(1):135-145.

http://dx.doi.org/10.16356/j.1005-1120.2018.01.135

and the coupling relationship between the heating effect and static aeroelastic response[3]. In the past, researchers have typically focused on the aeroelastic response in the thermal environment[4]. Particularly, domestic researchers often assumed the temperature field in their calculations and neglected the variations in the structure temperature field induced by the aerodynamic heating of hypersonic flow[5]. In general, limited systematic research has been performed to develop an aerothermoelastic analysis method for hypersonic vehicles, and a uniform and rapid method for this problem has not yet been established.

Due to increasing demands in engineering fields, the concepts underlying a rapid aerothermoelastic analysis method are addressed here. Thus, strong couplings and weak couplings are explained, and one- and two-way-coupling methods are illustrated and compared. The findings indicate that the two-way-coupling method is appropriate for this problem. The aerothermoelastic analysis method proposed in this paper covers several disciplines, i. e., aerodynamic calculation, aerodynamic heat flux calculation, heat transfer calculation, and static aeroelastic analysis. When introducing the calculation methods for each discipline, rapid calculation methods that are widely used in engineering are implemented to improve the computational efficiency. Based on the aforementioned concepts, a rapid aerothermoelastic analysis method is established. This method utilizes a two-way-coupling method and simultaneously considers the calculations required for each discipline, such as aerodynamic force, aerodynamic heat flux, heat transfer, and static aeroelastic response calculations. In the following sections, an aerothermoelastic simulation of the wing of a hypersonic vehicle is performed using this method. The simulation results obtained by the one- and two-way-coupling method are compared and analyzed.

1 Coupling and Calculation Methods for Each Discipline

1.1 Introduction and selection of coupling method

In general, the hypersonic aerothermoelastic problem can be divided into two categories conceptually: One is the aerodynamic heating problem, and the other is the aeroelastic problem. The aerodynamic heating problem contains the calculations of aerodynamic heat flux and heat transfer. After solving this problem, the temperature field of the structure can be obtained. The aerodynamic heat flux is a function of the surface temperature; therefore, the interaction between the aerodynamic heat flux and heat transfer must be considered. Furthermore, the surface geometrical shape of the vehicle can also influence the aerodynamic heat flux by affecting the aerodynamic force distribution. Thus, various coupling relationships are involved in the hypersonic aerothermoelastic problem, which are focused on by this paper.

1.1.1 Strong coupling and weak coupling

The hypersonic aerothermoelastic problem usually involves two different types of coupling relationships among the aerodynamic heat flux, aerodynamic force, inertial force, and elastic force. These two different types of coupling relationships are strong and weak couplings, as shown in Fig. 1.

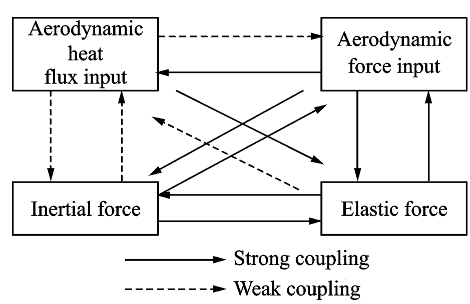


Fig. 1 Strong and weak couplings in aerothermoelastic analyses

The strong couplings include the following three aspects:

(1) The coupling relationships among aerodynamic, inertial and elastic forces.

(2) The direct influence of the aerodynamic heating on stiffness and elastic force.

(3) The impact of aerodynamic force on aerodynamic heating.

The weak couplings include the following three aspects:

(1) The direct impact of aerodynamic heating on aerodynamic force.

(2) The direct impact of elastic force on aerodynamic heating.

(3) The coupling relationship between aerodynamic heating and inertial force.

Since the weak couplings have little effect on aerothermoelastic properties, only the strong couplings are evaluated, as indicated by the solid lines in Fig. 1[6]. Therefore, the following three assumptions are made to resolve the proposed problem:

(1) Aerodynamic heating does not impact aerodynamic force.

(2) Structural deformation does not directly impact aerodynamic heating.

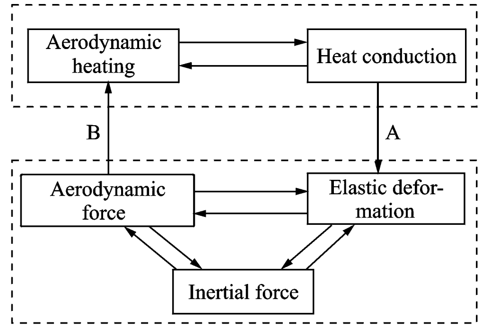
(3) The coupling relationship between aerodynamic heating and inertial force does not exist.

Thus, in the rapid aerothermoelastic analysis method, only strong couplings should be considered.

1.1.2 One-way-coupling and two-way-coupling methods

In coupling analyses, aerodynamic heating is considered to impact structural stiffness in two ways. On the one hand, the mechanical properties of the material will change with variations in the thermal environment. On the other hand, aerodynamic heating will generate external thermal stress on the structure. Furthermore, variation in the aerodynamic force induced by structural deformation can influence the aerodynamic heating.

Concerning the complexity of this problem, only the effects of aerodynamic heating on structural mechanical properties and aerodynamic force, in addition to that of structural deformation on aerodynamic force, have previously been studied. The feedback effect of aerodynamic force on aerodynamic heating has been neglected. In the one-way-coupling method, only the former effects are considered, whereas in the two-way-coupling method, all of the aforementioned effects are considered, as shown in Fig. 2[7].



One-way-coupling: Only A is considered and B is not considered.
Two-way-coupling: Both A and B are considered.

Fig. 2 One- and two-way-coupling methods

In the two-way-coupling method, the feedback impact of aerodynamic force on aerodynamic heating is considered based on the one-way-coupling method, and it provides a more complex analysis that remains consistent with actual conditions. Thus, the two-way-coupling method can reduce errors.

To analyze the aerothermoelastic problem of a hypersonic wing more effectively and obtain a better understanding of the coupling relationships of each discipline involved in the aerothermoelastic problem, the two types of coupling methods are applied for the same model, and the results are compared.

1.2 Calculation method for each discipline

1.2.1 Structural static/dynamic equation in a thermal environment

The static/dynamic equation of the structure of a hypersonic wing based on the finite element method (FEM) in the physical coordinate is expressed as follows [8]

$$\boldsymbol{M}_s \ddot{\boldsymbol{q}} + \boldsymbol{K}_s^* (T) q = \boldsymbol{F}_s (t) \tag{1}$$

where $\boldsymbol{M}_s$ is the mass matrix, $\boldsymbol{F}_s$ the load vector, q the displacement vector, and $\boldsymbol{K}_s^* (T)$ the stiffness matrix.

1.2.2 Aerodynamic force calculation

Here, aerodynamic force is calculated by the shock expansion method and local piston theory. First, the local airflow parameters are calculated by the shock expansion method. The method is illustrated as follows [9].

When air flows past the rhombic wing, as shown in Fig. 3, an oblique shock wave appears at the leading edge of the wing, and an expansion

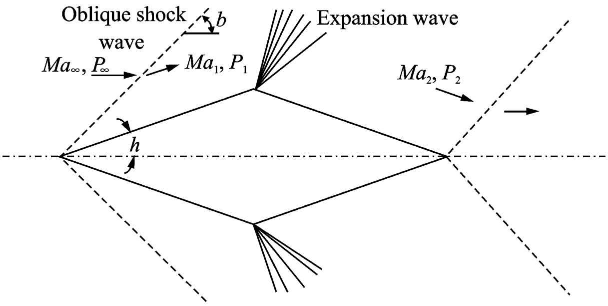


Fig. 3 Oblique shock wave and expansion wave

wave appears at the middle of the wing chord.

Oblique shock wave formulas are applied to calculate the airflow parameters after the wave, and the following is obtained.

$$\tan\eta = 2\cot\beta \frac{Ma_\infty^2 \sin^2\beta - 1}{Ma_\infty^2(\gamma + \cos 2\beta) + 2} \tag{2}$$

where η represents the angle between the wedge leading edge and the horizontal plane, and β the shock wave angle. Then, the following relationships can be obtained.

$$\frac{p_1}{p_\infty} = 1 + \frac{2\gamma}{\gamma + 1}(Ma_\infty^2 \sin^2\beta - 1) \tag{3}$$

$$Ma_1^2 = \frac{Ma_\infty^2 + \frac{2}{\gamma - 1}}{\frac{2\gamma}{\gamma - 1} Ma_\infty^2 \sin^2\beta - 1} + \frac{Ma_\infty^2 \cos^2\beta}{\frac{\gamma - 1}{2} Ma_\infty^2 \sin^2\beta + 1} \tag{4}$$

where p_1 and p_∞ represent the pressure between and after the shock wave, respectively, and Ma_1 and Ma_∞ represent the Mach number between and after the shock wave, respectively.

The Prandtl-Meyer expansion wave formulas and isentropic formulas are applied to calculate the airflow parameters for two arbitrary Mach numbers, Ma_1 and Ma_2

$$\frac{p_2}{p_1} = \left(\frac{1 + \frac{\gamma - 1}{2} Ma_1^2}{1 + \frac{\gamma - 1}{2} Ma_2^2}\right)^{\frac{\gamma}{\gamma - 1}}, \quad \frac{\rho_2}{\rho_1} = \left(\frac{1 + \frac{\gamma - 1}{2} Ma_1^2}{1 + \frac{\gamma - 1}{2} Ma_2^2}\right)^{\frac{1}{\gamma - 1}}$$

$$\frac{T_2}{T_1} = \frac{1 + \frac{\gamma - 1}{2} Ma_1^2}{1 + \frac{\gamma - 1}{2} Ma_2^2} \tag{5}$$

The airflow parameters have been obtained.

Then, local piston theory can be applied to obtain the pressure coefficient c_p [10].

$$c_p(x,t) = \frac{2}{Ma_{\text{local}}^2}\left[\frac{v_n}{a_{\text{local}}} + \frac{(\gamma + 1)}{4}\left(\frac{v_n}{a_{\text{local}}}\right)^2 + \frac{(\gamma + 1)}{12}\left(\frac{v_n}{a_{\text{local}}}\right)^3\right] \tag{6}$$

where a_{local} represents the local sound velocity, and γ is the specific heat ratio.

$$v_n = \frac{\partial Z(x,t)}{\partial t} + V_\infty \left\{\frac{\partial Z(x,t)}{\partial x}\right\} \tag{7}$$

The meaning of the variables is shown in Fig. 4.

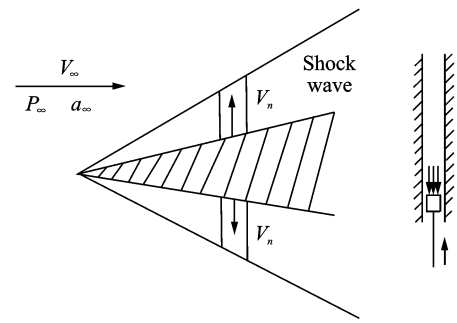


Fig. 4 Sketch map explaining local piston theory

1.2.3 Aerodynamic heat flux calculation

The Eckert reference temperature method, which is widely applied in engineering, is applied to the aerodynamic heat flux calculation. The theory of the Eckert reference temperature method is elaborated here[11]. When air flows past a wall, the temperature of the incoming flow T and other related parameters are corrected, and a reference temperature T^* is used to replace the original temperature T. Therefore, if the shear stress calculated by inserting T^* into the equation of incompressible fluid is equal to the shear stress calculated by the equation for compressible fluid, then the fluid friction equation of incompressible fluid can be used to calculate the compressible fluid value[7]. In the incompressible fluid calculation, the variables related to temperature must be obtained from T^*.

$$T^* = T + 0.5(T_w - T) + 0.22(T_r - T) \tag{8}$$

where T_w is the wall temperature, and T_r the recovery temperature. In a turbulent flow, T_r can be calculated as

$$T_r = T\left(1 + 0.88(\gamma - 1)\frac{Ma^2}{2}\right) \tag{9}$$

Once the reference temperature T^* is obtained, c_f, which is the coefficient of friction resistance in the boundary layer of turbulent flow, can be calculated[12]

$$c_f = c_f^* \frac{T}{T^*} = \frac{0.0592}{\sqrt[5]{Re_x}} \left(\frac{T}{T^*}\right)^{-0.648} \tag{10}$$

where Re_x is the local Reynolds number, $Re_x = \frac{\rho v x}{\mu}$.

The Stanton number St represents the heat transfer coefficient of heat convection[13], and it is equivalent to $St = \frac{c_f}{2} \times 0.82$ in turbulent flow.

Then, the heat flux can be defined as[7]

$$q_{\text{aero}} = St \rho U_e c_p (T_r - T_w) \tag{11}$$

where ρU_e represents the mass of airflow, which flows past the unit area in the unit time, and c_p the constant-pressure specific heat of the air.

Based on the relational expression of isentropic flow, a one-to-one correspondence occurs between the local pressure p and the local parameters ρ, Ma, v and T, separately. Therefore, a one-to-one correspondence occurs between the local pressure p and local heat flux q_{aero}.

High temperatures occur at the surface of hypersonic vehicles; therefore, thermal radiation must be considered. Assuming that the surface is not a black body, the radiation equation is as follows

$$Q_{\text{rad}} = \sigma \varepsilon (T_w^4 - T^4) \tag{12}$$

where σ is the Stanford constant, which has a value of 5.669E−8 W · m^{-2} · T^{-4}, and ε the radiation heat dissipation rate.

Finally, the heat flux conducting into the structure is

$$Q = Q_{\text{aero}} - Q_{\text{rad}} \tag{13}$$

2 Analysis Framework

Based on the coupling relationships and calculation methods introduced in the previous sections, the rapid aerothermoelastic analysis method for hypersonic wings is presented here. In this method, only strong coupling is considered, and the two-way-coupling method is used. When each discipline is considered, the FEM is used to calculate the structural deformation and heat transfer, the shock expansion method and local piston theory are used to calculate the aerodynamic force, and the Eckert reference temperature method is used to calculate the aerodynamic heat flux. Fig. 5 presents the framework of the hypersonic aero-thermal-structural coupling analysis[14].

The analysis steps are the following:

(1) At the beginning of the analysis, the initial parameters of the air flow, the initial structural parameters and the initial temperature field are given. The steady aerodynamic force is calculated by the shock expansion method and local piston theory. This steady aerodynamic force is loaded on the structure via the FEM, and then the deformation is also obtained via the FEM. Then, the deformation is utilized in the aerodynamic calculation mode. Solving iteratively until convergence, the static aeroelastic response of the structure at moment t is obtained.

(2) Based on the aerodynamic force distribution, the aerodynamic heat flux is calculated by the Eckert reference temperature method. The aerodynamic force is redistributed with structural deformation. When the two-way-coupling method is used, the redistributed aerodynamic force must be used. Otherwise, the redistribution of aerodynamic force can be neglected.

(3) The FEM is applied to analyze the heat transfer, and the temperature field of the structure at the next time step $t + \Delta t$ can be obtained. The updated wall temperature, which is the initial condition of the aerodynamic heat flux calculation, can also be obtained. At the same time, the structure temperature field, which is the initial condition of the heat transfer calculation, can be obtained.

(4) Based on the temperature field obtained in the previous step, the FEM is used to perform a stress analysis for a structure in a thermal environment. Then, the stiffness matrix and thermal deformation of the heated structure are obtained.

(5) If the final time is reached, then the calculation ends. Otherwise, the stiffness matrix in the aeroelastic analysis and the structural deformation will be updated. The process returns to the aeroelastic calculation, where the aeroelastic response at moment is obtained, and the loop continues.

Aero-thermal-structural coupling is focused on in this paper; therefore, the aeroelastic analysis is considered to be completed instantaneously. Furthermore, since the aerodynamic heat flux calculation is performed via the Eckert reference temperature method, the method is fast. Thus, the time steps of the aerodynamic heat flux and heat transfer calculations can be equivalent to simplify the code. Therefore, the time step of each discipline in this paper can be equivalent.

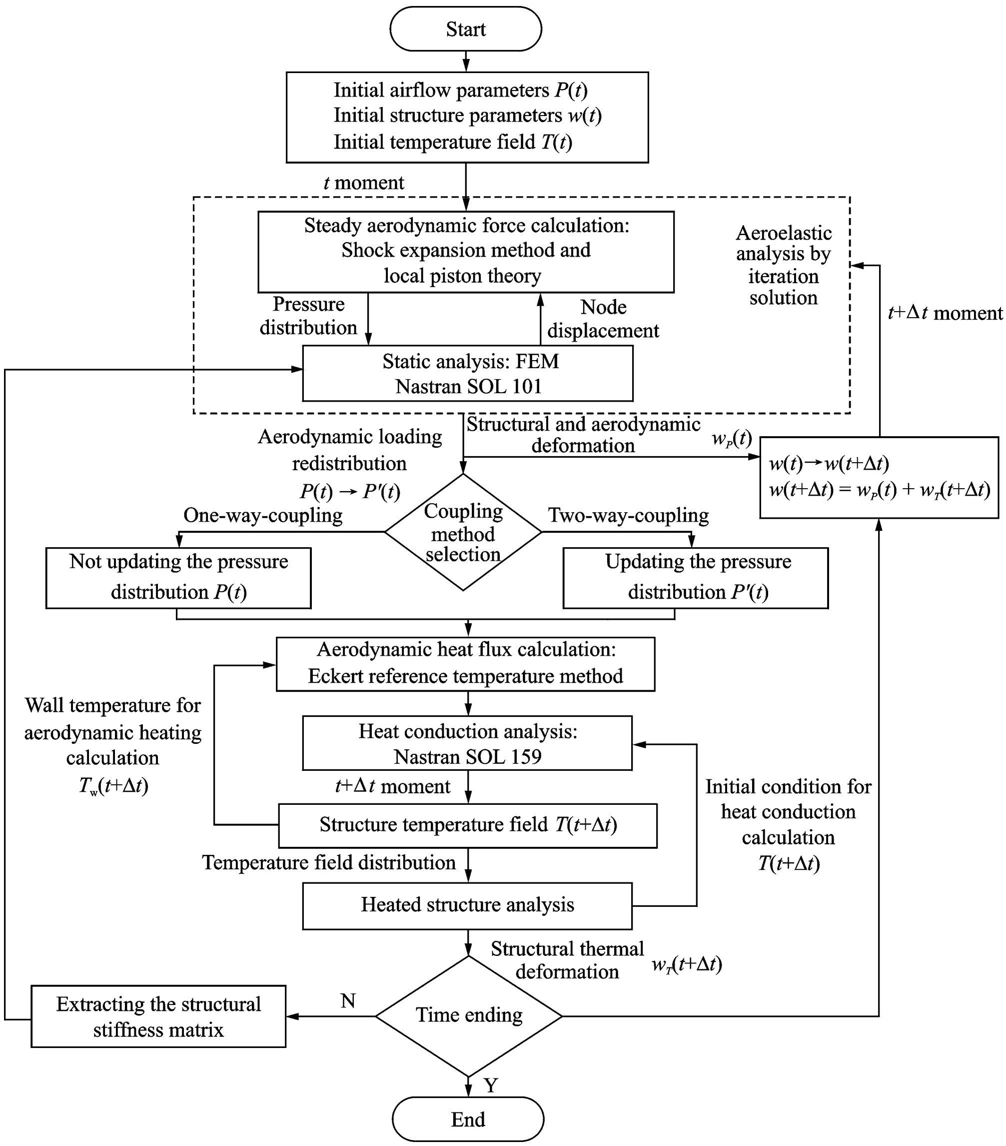


Fig. 5 Analysis framework

3 Calculation Model

The model proposed in this paper is the low-aspect-ratio wing of a hypersonic aircraft, and the wing span, chord length and thickness of the wing are shown in Fig. 6[15].

Hypersonic aircrafts usually encounter severe thermal environments in flight; therefore, a series of thermal protection measures are required to protect the wing structure, as shown in Fig. 7.

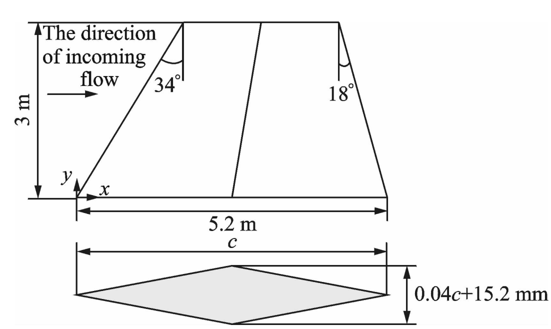


Fig. 6 Configuration of the hypersonic aircraft wing

In the proposed model, 7. 6-mm-thick thermal protection shields are added on the upper and low-

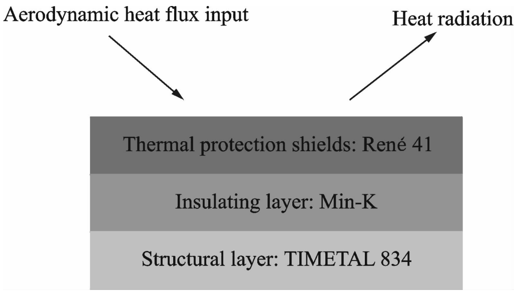


Fig. 7 Scheme of thermal protection shields and structural layers on aircraft surface[14]

er surfaces of the wing to achieve this goal[15].

Table 1 presents the material properties of the model, including the thermal and mechanical material property parameters of the three layers. "T-dep" indicates that the parameter depends on temperature, and "—" indicates that the parameter is not considered.

Table 1 Material property parameters of the three layers

Material	$\rho/(\mathrm{kg\cdot m^{-3}})$	E/Pa	μ
René 41	8 240	T-dep	0.31
Min-K	256	—	—
TIMETAL 834	4 550	T-dep	0.31
$\alpha_T/(\mu\mathrm{m\cdot m^{-1}\cdot K^{-1}})$	$k_T/(\mathrm{W\cdot m^{-1}\cdot K^{-1}})$	$c_p/(\mathrm{J\cdot kg^{-1}\cdot K^{-1}})$	h/mm
T-dep	18	541	3.8
—	0.052	858	3.8
11	7	525	3.175

The finite element model of the hypersonic wing used for the structural deformation calculation and the heat transfer calculation is shown in Fig. 8.

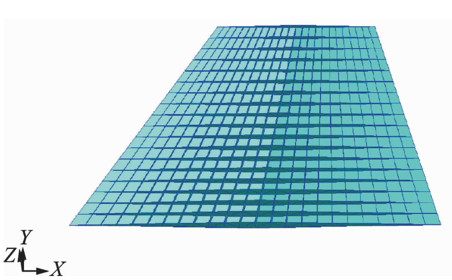


Fig. 8 Finite element model of hypersonic wing

4 Calculation and Results Analyses

4.1 Method verification

To verify the proposed method, a comparison between the results of this paper and those of Ref. [15] is provided in Table 2, which shows the lifting forces of four cases.

Table 2 Comparison between the results of previous studies and those of this study

Case	Case 1 (26 km altitude, Ma=8.0, 3.0°(attack angle)	Case 2 (36 km altitude, Ma=6.0, 1.5°(attack angle)
Reference result/N	30 000	2 510
Results in this paper/ N	30 553	2 481

Case 3 (24.97 km altitude, Ma=5.0, 3.0°(attack angle)	Case 4 (24.97 km altitude, Ma=5.0, 1.5°(attack angle)
21 403	10 439
21 618	10 726

The results obtained by the present method are consistent with the reference results, indicating that the method is feasible. Thus, an aerothermoelastic response analysis for the hypersonic wing will be performed using this method.

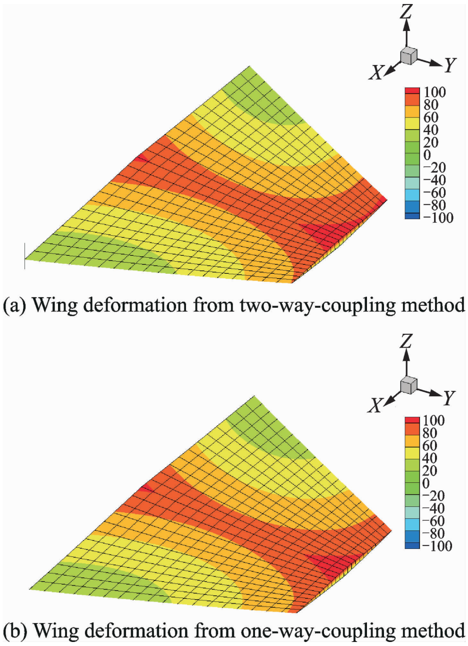
4.2 Example and result analysis

The static aerothermoelastic analysis of a wing under the aero-thermal-structural coupling frame is performed for a specific altitude, angle of attack, Mach number, and load factor. The specific parameter values used in the analysis are as follows: Ma =8, H=15 km, α = 6°, longitudinal overload=−1 g, initial temperature of the structure T_{ref} =293 K, Prandtl number Pr=0.86, and specific heat ratio of the atmosphere γ=1.4.

The radiant emissivity of the surface layer of the structure, i. e., the thermal protection shield, is 0.85; the time intervals for the aerodynamic heat flux and heat transfer calculations are both Δt = 4 s; and the total calculation time is t_{total} =600 s.

Figs. 9—12 show several structural deformation and temperature field results for the structural layer, upper surface, and lower surface. Each figure contains the one-way-coupling result and the two-way-coupling result.

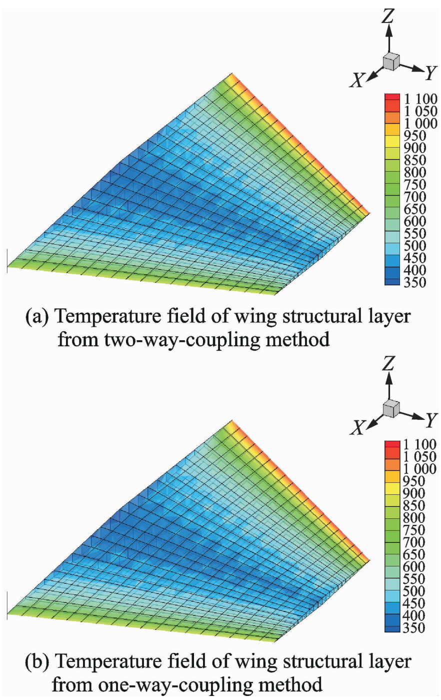
Because hypersonic vehicle experiments are difficult to conduct, the results of this paper are



(a) Wing deformation from two-way-coupling method

(b) Wing deformation from one-way-coupling method

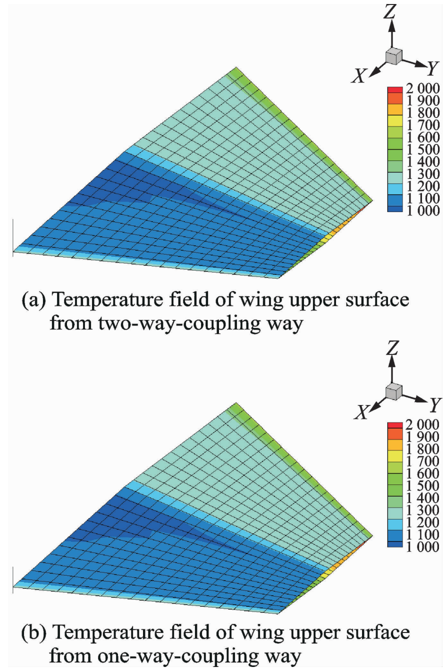
Fig. 9 Deformation of the wing structure at 600 s



(a) Temperature field of wing structural layer from two-way-coupling method

(b) Temperature field of wing structural layer from one-way-coupling method

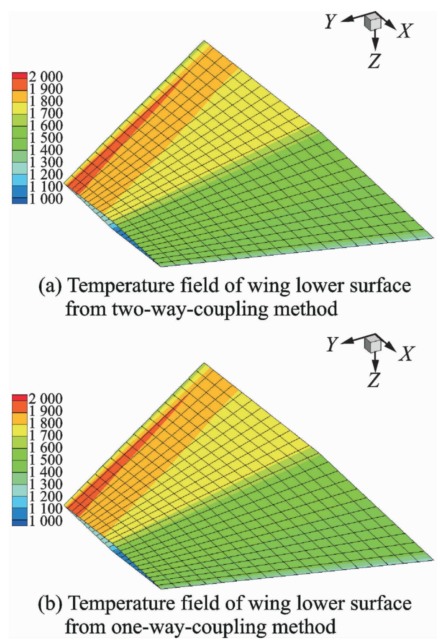
Fig. 10 Temperature field of the wing structural layer at 600 s



(a) Temperature field of wing upper surface from two-way-coupling way

(b) Temperature field of wing upper surface from one-way-coupling way

Fig. 11 Temperature field of the upper surface of the wing at 600 s



(a) Temperature field of wing lower surface from two-way-coupling method

(b) Temperature field of wing lower surface from one-way-coupling method

Fig. 12 Temperature field of the lower surface of the wing at 600 s

compared with those of Ref. [15] for verification. The comparison shows that the temperature field distributions of the wing surfaces between the two studies are consistent.

From Figs. 9—12, the differences between the results of the two methods can be identified. However, the differences are not very clear. In Table 3, the differences are more obvious.

Table 3 shows that the different coupling methods primarily influence the surface temperature of the hypersonic vehicle. Although the maximum difference in surface temperature is close to 100 K, if the thermal protection shields are effective, then the difference is eliminated, and the temperature fields of the structural layer in two situations are similar.

Table 3 Differences between the two methods

Method	Maximum deformation at the wing tip/mm	Maximum temperature at the structural layer/K	Average temperature at the structural layer/K	Maximum temperature at the upper surface/K	Average temperature at the upper surface/K	Maximum temperature at the lower surface/K	Average temperature at the lower surface/K
One-way-coupling	106.1	1 119	551	1 347	1 124	2 040	1 663
Two-way-coupling	97.1	1 133	552	1 439	1 134	1 938	1 656

Fig. 13 shows the initial heat flux distribution at the lower surface of the wing; the temperature of the wing is 293 K. Fig. 14 shows the heat flux distribution at the lower surface of the wing at 600 s; the average temperature at 600 s is 1 833 K. The comparison of the initial heat flux distribution with the heat flux distribution at 600 s shows that the initial heat flux input is far larger than that at 600 s. Therefore, the effect of thermal radiation is obvious based on Eq. (13).

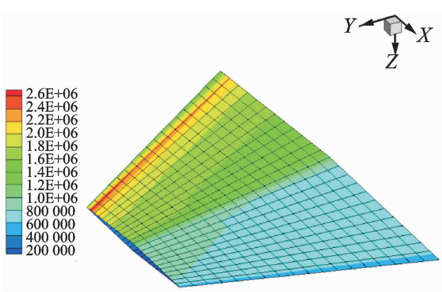


Fig. 13 Initial heat flux distribution at the lower surface of the wing

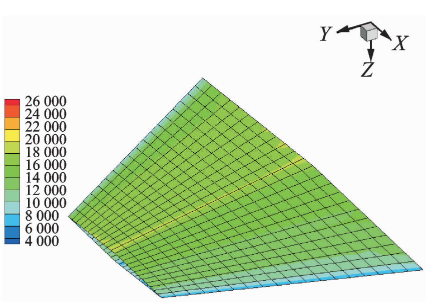


Fig. 14 Heat flux distribution at the lower surface of the wing at 600 s

In previous research, only the change in stiffness was considered, whereas the impact of thermal deformation on aerodynamic force was neglected, which would generate considerable errors.

Thermal deformations are calculated in this paper. When the temperature is high, the thermal deformation is remarkable. In certain situations, the thermal deformation is even larger than the deformation induced by aerodynamic force, as shown in Figs. 15, 16. This finding also validates the rationality of considering the influence of thermal deformation on aerodynamic force in the analysis process presented in this paper.

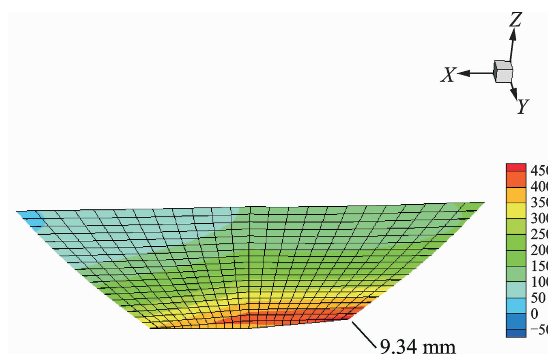


Fig. 15 Deformation caused by aerodynamic force

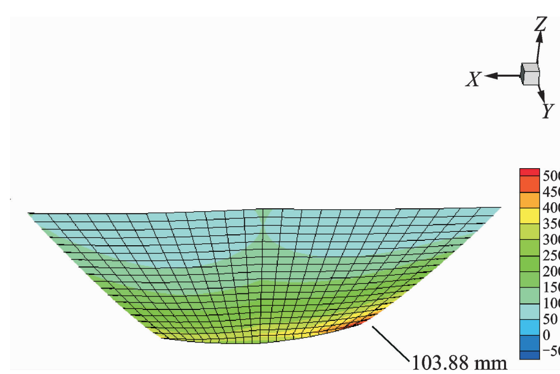


Fig. 16 Deformation caused by thermal stress

5 Conclusions

The aero-thermal-structural coupling problems for hypersonic wings are discussed. The coupling and calculation methods are introduced and selected. Then, the aerothermoelastic analysis framework is presented, and an example is simulated. The deformation, temperature field, pressure distribution and heat flux distribution of a hypersonic wing while cruising are calculated. Furthermore, the results of the one-method and two-way-coupling method are compared. The following conclusions have been obtained:

(1) The high Mach numbers and severe thermal environments experienced by hypersonic vehicles cause obvious aero-thermal-structural coupling effects that should be considered when related issues are studied.

(2) The differences between the one-way-coupling method and the two-way-coupling method are in the surface heat flux calculations. However, the application of effective thermal protection shields can nearly eliminate the differences between the methods; thus, the final results are similar.

(3) Thermal deformation is obvious, and in certain situations, it is even larger than the deformation caused by aerodynamic force. As thermal deformation can obviously alter aerodynamic force, this factor should be considered in future studies.

Acknowledgements

This work was supported partly by the National Natural Science Foundation of China (Nos. 11302011, 11402013, 11372023, 11672018); the National Key Research and Development Program (No. 2016YFB0200703); and the Fundamental Research Funds for the Central Universities (No. YWF-14-HKXY-006).

References:

[1] DU Z L, WAN Z, YANG C. Robust aeroelastic design optimization of hypersonic wings considering uncertainty in heat flux[J]. Transactions of the Japan Society for Aeronautical & Space Sciences, 2017, 60(3):152-163.

[2] MCNAMARA J J, FRIDMANN P P. Aeroelastic and aerothermoelastic analysis of hypersonic vehicles: Current status and future trend: AIAA 2007-2013[R]. USA:AIAA,2007.

[3] MCNAMARA J J, FRIDMANN P P, THURUTHIMATTAM B J. Aeroelastic and aerothermoelastic behavior in hypersonic flow[J]. AIAA Journal,2008, 46(10) :2591-2610.

[4] THURUTHIMATTAM B J, FRIEDMANN P P, POWELL K G. Aeroelasticity of a generic hypersonic vehicle:AIAA 2002-1209[R]. USA:AIAA, 2002.

[5] WU Z G, HUI J P, YANG C. Hypersonic aerothermoelastic analysis of wings[J]. Journal of Beijing University of Aeronautics and Astronautics,2005,31(3):270-273. (in Chinese)

[6] MCNAMARA J J, FRIDMANN P P. Aeroelastic and aerothermoelastic analysis in hypersonic flow: Past, present, and future[J]. AIAA Journal, 2011, 49(6):1089-1122.

[7] CULLER A J, MCNAMARA J J. Studies on fluid-thermal-structural coupling for aerothermoelasticity in hypersonic flow[J]. AIAA Journal, 2010, 48(8): 1721-1738.

[8] LI G S, WAN Z Q, YANG C. Integrated analysis of aerothermal-aeroelastic wings in hypersonic flow[J]. Journal of Beijing University of Aeronautics and Astronautics,2012,38(1):53-58.

[9] WU Z N, WANG B, ZHOU R. Aerodynamics (Volum 1)[M]. Beijing: Tsinghua University, 2007:61-65. (in Chinese)

[10] MCNAMARA J J, CROWELL A R, FRIDMANN P P, et al. Approximate modeling of unsteady aerodynamics for hypersonic aeroelasticity [J]. Journal of Aircraft, 2010, 47(6):1932-1945.

[11] ECKERTE R G. Engineering relations for heattransfer and friction in high-velocity laminar and turbulent boundary-layer flow over surfaces with constant pressure and temperature [J]. Transactions of the ASME, 1956, 78(6):1273-1283.

[12] BERTIN J J, CUMMINGS R M. Fifty years of hypersonics: Where we've been and where we're going [J]. Progress in Aerospace Sciences,2003,39(6/7): 551-536.

[13] QIAN Y J. Aerodynamics [M]. Beijing: Beihang University, 2004:260-268.

[14] WAN Z Q, WANG Y K, LIU Y Z, et al. A high-efficiency aerothermoelastic analysis method[J]. Science China, 2014, 57(6):1111-1118.

[15] FALKIEWICZ N, CESNIK C E S, CROWELL A R, et al. Reduced-order aerothermoelastic framework for hypersonic vehicle control simulation[J]. AIAA

Journal, 2011, 49(8):1625-1646.

Prof. **Wan Zhiqiang** is currently a professor at School of Aeronautic Science and Engineer, Beihang University. He received his B. S. degree in engineer from Beihang University in 1998 and the Ph. D. degree in aircraft design from Beihang University in 2003. His major research interests are aircraft design and optimization, aeroelasticity, and adaptive structure. He is an AIAA Associate Fellow.

Mr. **Yi Nan** is currently a Ph. D. candidate at School of Aeronautic Science and Engineer, Beihang University. He received his B. Sc. degree in engineer from Xi′an Jiaotong University in 2011. His major research interests are aircraft design and optimization, aerothermoelasticity of hypersonic vehicle.

Mr. **Li Guoshu** is currently a senior engineer in Beijing Institute of Nearspace Vehicle′s Systems Engineer. His research interests include aircraft overall design, aerothermoelasticy, and aircraft loads/vibration.

Prof. **Yang Chao** is currently a professor at School of Aeronautic Science and Engineer, Beihang University. His major research interests are aircraft design and optimization, aeroelasticity, and adaptive structure. He is a senior member of AIAA.

(Production Editor: Zhang Tong)