Analysis of the Post-flutter Aerothermoelastic Characteristics of Hypersonic Skin Panels Using a CFD-Based Approach

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Abstract

The present work aims to investigate the post-flutter aerothermoelastic behaviours of the hypersonic skin panels by using the integrated aerothermoelastic analysis framework developed in this paper. The aerodynamic loading and heating are computed simultaneously by solving Reynolds-averaged Navier-Stokes equations (RANS). The structural and thermal finite element models of a hypersonic skin panel are built and solved numerically to model the structural dynamics and thermal conduction. An implicit predictor-corrector scheme is employed to address the fluid-thermal-structural interactions. The aerothermoelastic characteristics of a two-dimensional hypersonic panel obtained using both one-way and two-way coupling strategies are systematically compared and discussed. The results show that: 1) The air viscosity delays the onset of flutter significantly, albeit aggravates thermal effect on the flutter instability; 2) The buckled panel can be similarly pre-
dicted by both the one-way and two-way coupling strategies. In contrast, the two-way coupling captures shockwave/boundary layer interactions leading to high local temperature; 3) The modal transition is predicted when structural displacement feeds back into the aerothermoeastic analysis. 4) The variation of temperature gradient along the panel thickness is analogous to the time-domain displacement response as revealed by two-way coupling strategy; 5) One-way coupling predicts lower maximum Von Mises stress as compared with the two-way coupling counterpart under the conditions employed in the present study.

Keywords: Aerothermoeasticity, Buckling, Transition, Chaos

Nomenclature

\( \alpha_s \)  thermal expansion coefficient, /K
\( \beta \)  \( (Ma^2 - 1)^{1/2} \)
\( C_T \)  thermal capacitance matrix
\( ds \)  outer normal vector to the boundary
\( F_c \)  inviscid convective flux
\( F_v \)  viscous convective flux
\( F_T \)  heat load vector
\( K \)  stiffness matrix
\( K_T \) thermal conductivity matrix

\( M \) mass matrix

\( P \) mechanical load vector

\( P_T \) thermal load vector

\( Q \) conserved variables

\( T \) temperature vector, \( K \)

\( u \) displacement vector, \( m \)

\( \Delta T \) temperature differential, \( K \)

\( \Delta t \) time step, \( s \)

\( \Delta T_{cr} \) critical temperature differential, \( K \)

\( \epsilon \) relative error

\( \frac{\partial c(\Delta T)}{\partial t} \) temperature gradient changing rate throughout the thickness

\( \lambda \) non-dimensional dynamic pressure, \( \rho U^2_{\infty} a_s^3/\beta D \)

\( \mu \) mass ratio

\( \nabla(\Delta T) \) temperature gradient throughout the thickness

\( \nu \) Poisson’s ratio

\( \Omega, \partial\Omega \) control volume and boundary of control volume
ρ  air density, $kg/m^3$

ρ$_s$  structural mass density, $kg/m^3$

a$_s$  panel length, $m$

c$_p$  specific heat, $J/(kg \cdot K)$

D  plate stiffness, $Eh^3_s/12(1 - \nu^2)$

E  Young’s modulus, $GPa$

h$_s$  panel thickness, $m$

k  thermal conductivity coefficient, $W/(m \cdot K)$

Ma  Mach number

$p, p_\infty$  static pressure and free-stream static pressure, $Pa$

$p_0, q_0$  stagnation-point pressure ($Pa$) and heating rate ($W/m^2$)

q  non-dimensional heat flux

Re  Reynolds number

t  time, $s$

$T_\infty$  free-stream temperature, $K$

$T_w$  wall temperature, $K$

$U_\infty$  free-stream velocity, $m/s$
1. Introduction

Development of reusable launch vehicles for cost-effective space exploration and rapid response to global military threats in hypersonic flow has been an intermittent area of research for decades [32]. Compared with the classic aeroelastic problems which pose a major safety-critical factor in the qualification of aircraft into service due to the strong interaction between the flexible aircraft and surrounding flow [25, 41, 1, 51, 53], the situation becomes more severe for aerothermoelastic problems [46, 3]. On the fluid side, the structural deformation alters the characteristics of the flow, such as the shockwave position, aerodynamic pressure distribution, heat flux distribution, etc. On the structural side, aerodynamic heating leads to degradation of material properties in hypersonic flight. The temperature gradient inside the structure introduces the thermal load, which is combined with aerodynamic pressure and adversely impact on the structural integrity. Therefore, accurate simulation of fluid-thermal-structural interactions (FTSIs) over a substantial period of time is imperative for the analysis of the performance, stability, and reliability of hypersonic aircraft.

Considering that the aerothermoelastic problem is very complex due to the different coupling mechanisms between and within the underlying aerothermal and aeroelastic subsystems [32, 31, 28], a partitioned approach [17] with loosely coupling [16] is widely adopted, whereby separate solvers are used to obtain the responses of diverse physical domains and the coupling is achieved through the exchange of boundary data at the interfaces of the
domains. Furthermore, the loosely coupling only requires the exchanging information between solvers once per time step. It is, therefore, computationally efficient compared to the strong coupling as it does not require subiterations. However, the loosely coupled scheme needs to be carefully implemented to achieve desirable accuracy and maintain numerical stability. For fluid-thermal-structure analysis, Miller and McNamara et al are among the first to layout the coupling method, they developed a loosely coupled time-marching procedure for FTSI analysis using time-accurate CFD simulation [34, 35]. The results indicate that the scheme is second-order temporal accuracy. In [36], they compared several coupling schemes and found that the predictor implicit scheme proposed in [34, 35] retains second-order accuracy and provides significant computational savings compared to the other schemes.

Aerothermoelastic analyses with varying levels of simplification using the loosely coupled partitioned scheme have also been extensively carried out. In the early 1980s, Thornton and Dechaumphai [42, 9] applied a partitioned approach to couple quasi-static flow, thermal and structural models for panels and leading edges. Tran and Farhat [43] developed a serial staggered procedure with trivial predictors, then the aerodynamic heating of a F-16 fighter airfoil and the aerothermoelastic stability of a clamped flat panel were studied. A fully coupled FTSI computational framework is developed by Culler and McNamara [6] and FTSI's analysis for a simply supported panel is carried out. Third-order piston theory is adopted to obtain aerodynamic force and Eckert’s reference enthalpy method is used to predict heat flux. It was
found that two-way coupling is required to obtain accurate thermal stresses and flutter onset boundary. Furthermore, two simplified treatments are also investigated for reducing the computational cost and numerical simulations indicate that these approaches yield nearly identical flutter boundary predictions. The same computational framework is used to study a stiffened composite panel [5, 7], in [5], fluctuating pressure loads are included and its effects are studied in the simulation. In another work carried out by Crowell and McNamara et al [4], a CFD surrogate model is used in lieu of piston theory for aerodynamic modelling. The surrogate model is a combination of steady CFD results and piston theory, whereby the viscosity is omitted. However, theoretical study indicates that the effect of boundary layer is significant in aeroelastic modelling [12, 11, 20]. Brouwer and McNamara enhanced the CFD surrogate framework to include the capability of capturing the unsteady viscous effects [2]. Quasi-static simulation results showed that the enhanced model agrees well with the steady RANS loads and thermo-structural response while reduces the computational costs significantly.

The post-flutter occurs beyond the flutter onset due to structural and aerodynamic nonlinearities in the form of LCOs, which may exist even below the flutter onset condition. Although there has been extensive work in aerothermoelastic computation for the prediction of flutter onset, some key questions with regard to the characteristic of post-flutter need to be addressed, such as how the coupling strategy influences the post-flutter of hypersonic panels? what the characteristics of the long duration response
in post-flutter regime? These questions are imperative for structural health monitoring [14] and uncertainty quantification [8, 26]. We therefore attempt to address the questions via an aerothermoelastic analysis framework developed in the present work. The long duration aerothermoelastic responses of a simply supported panel is obtained using two-way coupling strategy. The post-flutter characteristics including the evolution of the vibration forms, the variations of structural characteristics like temperature differentials, Von Mises stress and the flow mechanisms involved in the FTSIs problem are investigated in detail.

The paper is organized as follows. Section 2 introduces the formulation of fluid, thermal and structural system and the standard FTSI coupling strategies used in this paper. Validation of the aerothermoelastic analysis framework is provided in Section 3. A systematic analysis of the post-flutter aerothermoelastic characteristics of hypersonic panels are presented and discussed in Section 4. The conclusions are drawn in Section 5.

2. Mathematical modeling

For the sake of completeness, we recapitulate the flow governing equations of the CFD system and describe the implementation of the numerical schemes used for the CFD solver. Later, we present the general formulation of the thermal model in Section 2.2 and structural model in Section 2.3.
2.1. Flow Governing Equations

In this study, the aerodynamic force and the heat flux are obtained by solving time-dependent compressible Navier-Stokes equations:

\[
\frac{\partial}{\partial t} \int_{\Omega} Q \, d\Omega + \int_{\partial\Omega} (F_c - F_v) \cdot ds = 0
\]  

(1)

where \( Q \) is the vector of conserved variables, \( \Omega \) is the control volume and \( ds \) represents the outer normal vector to the boundary of the control volume \( \partial\Omega \).

\( F_c, F_v \) are the inviscid convective flux vector and the viscous convective flux vector, respectively. Detail expressions can be referred in Ref. [47]. The interface flux function is determined by the advection upstream splitting method (AUSM) scheme [30], and the second order accuracy is achieved with the Monotonic Upstream-Centered Scheme for Conservation Laws (MUSCL) [29] interpolation and the Minmod limiter. Geometric conservation law (GCL) [40] is applied to modify the grid velocity when propagating the solid wall deformation to the fluid domain. Lower-upper symmetric-gauss-seidel (LU-SGS) implicit time-stepping scheme [50] together with the second order dual-time-step method [24] is employed to solve unsteady problems. The Menter \( k - \omega \) SST turbulence model [33] is chosen for turbulence modelling in the present work.

2.2. Thermal Model

Based on the basic heat transfer theory and by carrying out the finite element discretization, the structural heat transfer finite element solution equation can be expressed as:

\[
C_T \dot{T} + K_T T = F_T
\]  

(2)
where $C_T$, $K_T$, $F_T$, $T$ are the thermal capacitance matrix, thermal conductivity matrix, nodal heat load vector and temperature vector, respectively. Eq. 2 is solved using the central difference method (Crank-Nicolson method) and a modified Newton method [13] is used when Eq. 2 becomes a nonlinear function of temperature.

2.3. Structural Model

A variational structure finite element formulation based on Lagrangian framework is adopted by considering the Saint-Venant-Kirchhoff material and geometric nonlinearity in this section. The Euler-Bernoulli beam theory (EBT), which neglects the Poisson effect and transverse strains, is considered to model the skin panel in the present work. The two-node beam element and Hermite cubic interpolation function are used to discretize the structural model. The scaling laws used to generate a beam that is structurally equivalent to a panel are as follows:

$$E^b = \frac{E^p}{1 - \nu^2} \quad and \quad \alpha_s^b = \alpha_s^p (1 + \nu) \quad (3)$$

where $E^p$ and $\alpha_s^p$ denote the Young’s modulus and thermal expansion coefficient of the skin panel. $E^b$ and $\alpha_s^b$ are the equivalent values, respectively.

The variational approach of the governing equations of the nonlinear bending beams leads to the structural dynamic equations in matrix form:

$$M\ddot{u} + K(u)u = P + P_T \quad (4)$$

where $M$, $K(u)$, $P$, $P_T$ are the mass, stiffness matrix, mechanical load vector and thermal load vector. Detailed expressions of the nonlinear stiffness
matrix can be found in [38]. The structural damping is neglected in the current study and the equations of motion in Eq. 4 are time-marched using an implicit scheme names HHT-α method [21]. In this paper, a little numerical damping of $-0.05$ is used to quickly remove the high-frequency noise. Similarly, modified Newton method [13] is used to solve the geometrically nonlinear equation 4 for convergence.

2.4. Fluid-Thermal-Structural Coupling Strategy

Fig. 1 shows the degree of coupling between the fields in aerothermoelasticity [39]. By neglecting the “weak” couplings, the aerothermoelastic analysis is carried out using the one-way coupling, whereby the aerothermal conduction is first solved to obtain the structural temperature distribution. Subsequently, the aeroelastic solution is obtained based on the resulting temperature distribution. The method heavily relies on assumptions such as the structural deformation is sufficiently small and negligible in aerodynamic heating [39, 7]. When these assumptions are violated, the two-way coupling strategy is required to feed the structural deformation into thermal conduction. The process of aerothermoelastic modelling is depicted in Fig. 1(b), which consists of aerothermal and aeroelastic steps. Path 1 represents that the aerothermal solution is passed to the aeroelastic step and feedback of structural deformation is transferred along path 2. Two-way coupling strategy is used if path 2 is included when carrying out the aerothermoelastic analysis.

In the present work, the loosely coupled scheme proposed by Miller and
(a) Degree of coupling in aerothermoelasticity [39] 

(b) Aerothermoelastic modelling approach

Figure 1: Basic relationship and modelling approach in aerothermoelasticity.

Mcnamara et al [34] is adopted for the aerothermoelastic analysis. As illustrated in Fig. 2, the loosely coupled scheme combines the aerodynamic predictors and the temperature interpolation to achieve the second-order temporal accuracy. The simulation is initiated at the same physical time $t_f^n = t_s^n = t_T^n$. In this paper, the same time step ($\Delta t_T = \Delta t_s = \Delta t_f$) is used in both aerothermal and aeroelastic solution currently. Detailed procedures are given below [34, 36]:

1. The aerothermal step:
   
   (a) Heat flux from the fluid solver is extrapolated and passed to the thermal solver:
   
   $$q^{n+\frac{1}{2}} = \frac{3}{2}q^n - \frac{1}{2}q^{n-1}$$  \hspace{1cm} (5)

   (b) The thermal solution $T$ is updated to step $n + 1$.

   (c) The panel surface temperature $T_{nw}^{n+1}$ from the thermal solver is passed to the fluid solver.
2. The aeroelastic step:

(a) The pressure from the fluid solver is extrapolated and passed to the structural solver:

\[ p^{n+1,E} = 2p^n - p^{n-1} \]  

(b) The structural temperature of the flexible panel \( T^{n+1} \) from the thermal solver is passed to the structural solver.

(c) The structural solution \( u \) is updated to step \( n + 1 \).

(d) The displacement from the structural solver is passed to the fluid solver:

\[ u^{n+1,E} = u^{n+1} \]  

(e) The fluid solutions \( p \) and \( q \) are updated to step \( n + 1 \).

3. The proceeding steps are repeated until the simulation is completed.

The displacement \( u \) and temperature \( T \) are interpolated between the solid and fluid domains using the consistent interpolation based scheme [15], whereas the node projection scheme is used to interpolate the pressure \( p \) and heat flux \( q \) to satisfy the conservation of energy [15, 23]. It is worth noting that the two-way coupling strategy degenerates into the one-way coupling counterpart if the aerothermal analysis is first carried out to obtain the temperature without updating the structural deformation.

3. Validation of Aerothermoelastic framework

In this section, a cylinder and simply supported semi-infinite panel are considered to verify the aerothermal and aeroelastic solvers separately.
3.1. Verification of Aerothermal Analysis Module

The model considered is a cylinder subjected to aerodynamic heating from a Mach 6.47 flow studied by Allan R Wieting in the NASA Langley 8-ft High Temperature Tunnel in 1987 experimentally. The flow conditions are considered as follows:

\[ Ma = 6.47, \quad Re = 1.31 \times 10^6, \quad p_{\infty} = 648.1 Pa, \quad T_{\infty} = 241.5 K \] (8)

The length, diameter and thickness of the stainless steel 321 cylinder are 0.6096m, 0.0762m and 0.0127m, respectively. The material properties of the cylinder are listed in Table 1 and the initial structural temperature is \( T_w = 294.5K \). The heat flux from the fluid model is prescribed on the outer surface...
of the cylinder, while the other surfaces are assumed perfectly insulated. The experiment lasts for 5s and details of the experimental configurations, the tunnel flow conditions, and the experimental results can be referred in Ref. [44, 45].

Table 1: Material properties for the aerothermal model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>( \rho_s )</td>
<td>8030 kg/m(^3)</td>
</tr>
<tr>
<td>( \alpha_s )</td>
<td>1.7 \times 10^{-5}/K</td>
</tr>
<tr>
<td>( E )</td>
<td>193 GPa</td>
</tr>
<tr>
<td>( \nu )</td>
<td>0.275</td>
</tr>
<tr>
<td>( k )</td>
<td>16.27 W/(m \cdot K)</td>
</tr>
<tr>
<td>( c_p )</td>
<td>502.48 J/(kg \cdot K)</td>
</tr>
</tbody>
</table>

Only one-half of the flow domain and one-fourth of the cylinder are modelled due to the symmetry of the flow above and below the cylinder. Fig. 3 shows the figure of the computational domain which consists of the fluid domain and the structural domain. As can be seen in Fig. 3, the smallest height of aerodynamic grid is 10\(^{-6}\)m in order to get accurate heating rate, and the structural grid in cylinder is also refined near the interface while the smallest grid height is 10\(^{-4}\)m, respectively.

Fig. 4 illustrates the pressure and temperature distribution along the centerline of the upstream flow domain. The predicted location of the shockwave is at \( x = -0.055m \), and the predicted pressure and temperature behind the shockwave are 31345 Pa and 2182.70 K, which agree well with the results in...
Figure 3: Fluid-thermal model for flow over a cylinder.

[9, 52].

The undisturbed aerodynamic pressure and heating rate distribution along the cylinder surface are compared with the experimental results, as shown in Fig. 5. The predicted and experimental results are normalized by their respective stagnation-point pressure ($p_0$) and heating rate ($q_0$), which were within 1% for heating rate. By observing Fig. 5 it can be obviously seen that excellent agreement is achieved, which indicates that the fluid solver can accurately predict the aerodynamic pressure and heating rate.
(a) Fluid pressure distribution along the centerline
(b) Fluid temperature distribution along the centerline

Figure 4: Pressure and temperature distribution along the centerline.

(a) Comparative surface pressure distributions
(b) Comparative surface heating rate distributions

Figure 5: Comparison of surface pressure and cold-wall heating rate distributions.

Fig. 6 gives the comparison between the surface temperature within 5 seconds and the experimental data. In Fig. 6(a), the experimental data points
are located between the curves at $t = 4s$ and $t = 5s$, and the error between the computed stagnation-point temperature at $t = 5s$ and the experimental results [44] is within 1%. The smooth temperature contour at 2s is shown in Fig. 6(b), which is quantitatively agree with the contour obtained by Dechaumphai et al [9].

![Figure 6](image_url)

(a) Comparative surface temperature distributions (b) Temperature contours on the cylinder at 2s

Figure 6: Comparative surface temperature distributions and temperature contours on the cylinder.

Generally, the above results show that the present aerothermal analysis component of the aerothermoelastic analytical framework established in this paper performs well.

3.2. Verification of Aeroelastic Analysis Module

In order to verify the present aeroelastic analysis module, a simply supported semi-infinite panel, as shown in Fig. 7, is considered in this paper.
The parameters used are listed in table 2 to meet $\mu/.Ma = 0.01$, whereby $\mu = \rho a_s/\rho_s h_s$ is the mass ratio. The non-dimensional dynamic pressure $\lambda$ is computed using $\rho U_\infty^2 a_s^3/\beta D$, whereby $D = Eh_s^3/12(1 - \nu^2)$ is the plate stiffness. Once the non-dimensional dynamic pressure $\lambda$, Mach number $Ma$, and Reynolds number $Re$ are determined, the free-stream static pressure $p_\infty$, velocity $U_\infty$, temperature $T_\infty$ can be computed based on the ideal gas law.

### Table 2: Parameters for the aeroelastic model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Ma$</td>
<td>5</td>
</tr>
<tr>
<td>$Re$</td>
<td>$9.36 \times 10^6$</td>
</tr>
<tr>
<td>$\rho$</td>
<td>0.275 kg/m$^3$</td>
</tr>
<tr>
<td>$a_s$</td>
<td>1 m</td>
</tr>
<tr>
<td>$h_s$</td>
<td>0.002 m</td>
</tr>
<tr>
<td>$\rho_s$</td>
<td>2750 kg/m$^3$</td>
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<tr>
<td>$\alpha_s$</td>
<td>$2.34 \times 10^{-5}/K$</td>
</tr>
<tr>
<td>$E$</td>
<td>71 Gpa</td>
</tr>
<tr>
<td>$\nu$</td>
<td>0.3</td>
</tr>
<tr>
<td>$k$</td>
<td>200 $W/(m \cdot K)$</td>
</tr>
<tr>
<td>$c_p$</td>
<td>900 $J/(kg \cdot K)$</td>
</tr>
</tbody>
</table>

The fluid domain is discretized using a structured mesh which consists of 120 elements in the streamwise direction and 100 cells in the normal direction, illustrated in Fig. 9(a). 40 uniform distributed cells are located along the length of the panel. The wall normal spacing for the mesh is $10^{-6} m$ in order
Figure 7: Schematic diagram of the two dimensional panel configuration.

to get accurate heat flux.

In Fig. 8, the grid convergence and time-step sensitivity study with a sequence of grid refinements and a set of time steps are carried out at $\lambda = 400$. The $u(x)$ and $T_w(x)$ are given by Eq. 9 and Eq. 10, whereby the first four modes of the panel are considered. For the unsteady simulation, the panel is forced to oscillate with a frequency of 10 Hz.

$$u(x)/h_s = 1.25 \sin(\pi x) - 0.75 \sin(2\pi x) + 2.75 \sin(3\pi x) + 2 \sin(4\pi x) \quad (9)$$

$$T_w(x)/T_\infty = 0.25 \sin(\pi x) - 0.15 \sin(2\pi x) + 0.55 \sin(3\pi x) + 0.4 \sin(4\pi x) \quad (10)$$

The relative error of the steady pressure distribution is computed using the L1 norm (Eq. 11), whereas the relative error of the unsteady pressure and heat flux is computed using the L2 norm (Eq. 12).

$$\epsilon = \frac{\int |p(x) - p_{ref}(x)| \, dx}{\int |p_{ref}(x)| \, dx} \quad (11)$$
\[ \epsilon = \left( \frac{1}{N} \sum_{i=1}^{N} \left( \frac{1}{M} \sum_{j=1}^{M} (p_{ij} - p_{ij,\text{ref}})^2 \right)^{1/2} \right) \left/ \left( \frac{1}{N} \sum_{i=1}^{N} \sum_{j=1}^{M} (p_{ij,\text{ref}})^2 \right)^{1/2} \right) \]  

where \( p_{ij} \) is the pressure at element \( j \) and the \( i \) time step. The time steps are sampled from \( t = 0.25s \) to \( t = 0.35s \).

The steady results indicate that the 121 \times 101 mesh used in the current study achieves the convergence of the pressure distribution within 0.31\% and the heat flux distribution within 1.08\%. As for the unsteady simulation, the relative error of the time step size of \( \Delta t = 5 \times 10^{-5}s \) is 0.013\% for pressure and 0.211\% for heat flux, the response history also agrees well with the reference results. Therefore, the physical time step used for the present study is \( 5 \times 10^{-5}s \).

The thermal solver used by Miller and McNamara in [37] only models the panel and constant temperature is applied for the rigid wall. However, this
treatment will bring the problem of temperature discontinuity at the junction of the rigid wall and the flexible panel, which is unreasonable for the real case. Therefore, in this paper, the thermal solver models both chordwise and through-thickness heat transfer throughout the whole computational domain to avoid this problem, as shown in Fig. 9(b). Heat flux from the fluid model is prescribed on the upper face of both the flexible panel and the rigid wall, while the other surfaces are assumed perfectly insulated. The model consists of 120 elements in the streamwise direction and 10 elements through the thickness. The distribution along the length is the same as the computational grid for the fluid domain.

(a) Flow computational grid  (b) Local mesh near the wall

Figure 9: Computational grid of both the fluid domain and thermal domain.

For the structural modelling issue, finite element discretization is applied for the panel which also consists of 40 uniform distributed elements along the panel. For inviscid simulations, the free-stream pressure is specified as
the pressure of the backside of the panel. However, for viscous simulations, Dowell [10, 11] and Ye [49] have pointed out that even small pressure differentials across the panel can lead to significant changes in the panel response. As an example, Fig. 10 shows the non-dimensional pressure distribution on upper surface of the undeflected panel for $Ma = 5, \lambda = 100$, whereby a notable pressure variation along the upper surface can be seen. Therefore, the mean of the initial pressure obtained through steady CFD computation on the plate is specified as the pressure of the backside of the panel to minimize this effect on viscous flutter computations [18] at the beginning of the simulation. The flutter computations are initiated by providing a small vertical velocity to the first mode of the plate, $\delta \dot{u} = \dot{u}_0 \sin(\frac{\pi x}{a_s}), \dot{u}_0 = 0.001$. The critical temperature is defined as $\Delta T_{cr} = \frac{\pi^2 h_s^2}{12(1 + \nu)\alpha_s a_s^2}$.

Fig. 11 gives the stability-region boundaries and the amplitudes of limit cycle oscillation (LCO) of present panel model. Noticed that Euler CFD solver is used in order to compare with the values in [10, 48, 6] since the air viscosity is omitted in their study. Furthermore, the viscous results at $Ma = 1.2$ are computed and compared with the work of Gordnier et al [19].

For the inviscid case, from Fig. 11(a) we can find that the stability-boundary data points from the present model agree well with the stability-region boundaries given in [10] and the data set in [6]. Similarly, Fig. 11(b) compares the LCOs at $x/a = 0.75$ from the present model to the results in [10, 48, 6] at four values of the thermal load ($\Delta T/\Delta T_{cr} = 0, 1, 2, 3$). Close agreements between present data and the reference data sets can also be observed, which indicate that the aeroelastic analysis module performs well.
Figure 10: Pressure distribution on upper surface of the undeflected rigid panel: $Ma = 5, \lambda = 100$.

For the viscous case, the LCO amplitudes computed at $Ma = 1.2$, $Re = 10^5$, $\delta/a_s = 0.025, 0.05$ agree well with the literature [19]. In addition, in order to investigate the unsteady viscous effect under hypersonic flow, the numerical results under $Ma = 5$ are also computed and plotted in Fig. 11(a) and Fig. 11(b) with red dashed dot line, it can be found that due to the influence of air viscosity, the onset of flutter is significantly delayed. In addition, from the results in Fig. 11(b) it can also be found that the spacing
between the viscous results at different values of thermal load is larger than the inviscid results. For example, the difference between the flutter boundary of $\Delta T/\Delta T_{cr} = 1$ and $\Delta T/\Delta T_{cr} = 0$ is 145 for viscous case, which is larger than that of inviscid case (80). This indicates that the effect of thermal load is aggravated due to the existence of boundary layer. The calculated results show that it is necessary to use RANS CFD solver to get unsteady aerodynamic forces in order to accurately simulate aeroelastic/aerothermoelastic problems.

(a) Stability regions of a simply- (b) Comparison of limit cycle amplitudes for a simply-supported, semi-infinite panel with and without viscosity ($\mu/Ma = 0.01$) infinite panel with and without viscosity ($\mu/Ma = 0.01$)

Figure 11: Verification of aeroelastic model.
3.3. Verification of Aerothermoelastic analysis framework

The aerothermoelastic analysis framework is verified in this section using the benchmark case taken from [27]. The geometrical parameters are \( h_s = 0.0025\, m \) and the flight conditions are \( Ma = 4.0, p_\infty = 2087.2\, Pa, T_\infty = 266.7\, K \). The material properties are function of temperature and the initial temperature is \( T_w = 300\, K \) as shown in Table 3 [27]. The time step is 100 \( \mu s \), which is consistent with [27].

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<td>72.87 GPa</td>
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<td>2.236 \times 10^{-5}/K</td>
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<tr>
<td>( \nu )</td>
<td>0.325</td>
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<tr>
<td>( k )</td>
<td>132.05 W/(m \cdot K)</td>
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<tr>
<td>( c_p )</td>
<td>850.94 J/(kg \cdot K)</td>
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</tbody>
</table>

The numerical results are compared with the work of Daning et al [22], as shown in Fig. 12, whereby the midpanel displacement is nondimensionalized by the thickness. It can be seen in the figure that the aerothermoelastic responses with different boundary-layer thickness match quite well with the literature [22], but some discrepancy can be observed in the average heat flux. The reason for this discrepancy is believed to be the different types of turbulence models.
Figure 12: Aerothermoelastic responses of the 2-D panel at $Ma = 4.0, p_\infty = 2087.2 \, Pa, T_\infty = 266.7 \, K$. 
4. Results and Discussions

In this section, the aerothermoelastic framework is utilized to investigate the evolution process of the post-flutter aerothermoelastic characteristics. The semi-infinite panel in section 3.2 is considered. Fig. 11(a) indicates when the non-dimensional dynamic pressure $\lambda$ is relatively small, the panel responses will gradually enter the dynamic stability region with the increase of structural temperature. On the contrary, the panel responses will cross the stability region into the flutter region for large $\lambda$. Therefore, two representative dynamic pressure $\lambda = 100, 400$ are chosen in the present study. Two-way coupling strategy is used to simulate the aerothermoelastic problem more accurately and the numerical simulations of the one-way coupling method is also included for comparison. For all simulations in this section, at the beginning of the simulation, the wall temperature is set equal to the free-stream temperature, and the duration of the simulation is $t = 15s$. Three characteristic points (P1: $x/a = 0.25$, P2: $x/a = 0.5$, P3: $x/a = 0.75$) are selected to investigate the response characteristics.

4.1. Buckling

The structural responses at the characteristic points are compared in the Fig. 13. It can be found that buckled response is predicted, but the slight differences between one-way and two-way coupled results suggests that the coupling strategy has little influence on the prediction of buckled response.

The structural Von Mises stress contours are plotted and compared in Fig. 14. It can be seen that the maximum Von Mises stress appears at the
(a) time domain displacement responses    (b) displacement distributions

Figure 13: Displacement responses at the characteristic points and the displacement distributions at different times.

Figure 14: Structural Von Mises calculated using two types of fluid-thermal-structural coupling strategies (left: one-way, right: two-way).

position of maximum deformation. Through numerical data it can be known that the maximum Von Mises value of two-way coupling strategy (9.23 MPa) is larger than the other one (9.21 MPa), which indicates that the onset of
panel failure will be earlier.

Fig. 15 shows the upper surface temperature contours during the simulation. It can be found that the temperature differential distribution alters with time when the two-way coupling strategy is utilized, but the one-way coupled result remains a relatively uniform distribution since the surface deformation is not considered. The maximum value appears at about $x/a = 0.3$ of the panel while the minimum value appears at about $x/a = 0.95$. It can be further confirmed through Fig. 16, the values of the front half of the panel is obviously higher than that of the back half. Considering that the distribution of surface temperature is closely relevant to the design of thermal protection system, the importance of involving the structural deformation is highlighted by this significant difference. For example, for this issue, only the first half of the panel needs to be protected instead of the whole panel, which can help reduce the cost spent on the thermal protection.

![Figure 15: Temperature differential contours calculated using two types of fluid-thermal-structural coupling strategies (left: one-way, right: two-way).](image)

30
Figure 16: Temperature differential variations at the characteristic points and the temperature differential distributions at different times.

Figure 17: Heat flux distributions on the upper surface of the panel, nondimensionalized by the maximum value of the steady CFD result on the panel.
Next, the flow field characteristics under this issue are studied. Fig. 17 shows the non-dimensional heat flux applied on the upper surface of the panel, the heat flux is nondimensionalized by the maximum value of the steady surface heat flux. It can be discovered that although the two results decrease steadily, the heat flux of the two-way coupled case is larger than that of one-way coupled case on the front half of the panel and smaller on the back half. The phenomenon shown in Fig. 15 and Fig. 17 can be reason-
ably explained by observing Fig. 18, which is the typical pressure distribution nondimensionalized by the free-stream pressure. From the paragraph it can be found that there is a shockwave and an expansion wave due to the buckled panel, and as it is known to all that the temperature as well as the temperature gradient near the panel will increase after the shockwave and decrease after the expansion wave. Therefore, the position of the maximum temperature of two-way coupled case appears after the shockwave and the minimum temperature appears after the expansion wave.

4.2. Flutter

In this section, the aerothermoelastic characteristics under $\lambda = 400$ will be displayed in three aspects. The overall view of structural displacement responses at the characteristic points are firstly illustrated, then the structural characteristics such as the temperature distribution, the Von Mises stress are investigated. Finally, the flow field characteristics and the flow mechanism are explored.

To explore how the initial condition influences the structural response, the initial disturbance with different amplitudes, e.g. $\dot{u}_0 = (0.001, 0.0015, 0.002)$ are chosen and the aerothermoelastic structural responses are computed as shown in Fig. 19. The figure clearly shows that a similar trend is observed in the responses computed by the two coupling strategies with the initial condition $\dot{u}_0 = (0.0015, 0.002)$. In contrast, a significant discrepancy appears in the responses computed with $\dot{u}_0 = 0.001$. Further exploration on this issue is needed for the aerothermoelastic system, which is highly nonlinear.
and sensitive to the initial conditions.

![Figure 19: Aerothermoelastic structural responses computed using different initial disturbance ($\dot{u}_0 = 0.001, 0.0015, 0.002$) at Point P3.](image)

4.2.1. Structural Displacement Response

The structural displacement responses at the characteristic points are presented in Fig. 20. It can be seen that, unlike the situation in Section 4.1, the structural responses obtained using two-way coupling strategy are completely different from that of one-way coupled results. Combining with the Hilbert-Huang Spectrum shown in Fig. 21, it can be concluded that the one-way coupled result is a periodic LCO solution, while the structure response is a chaotic motion when two-way coupling strategy is applied. Furthermore,
the maximum amplitude predicted using the one-way coupling strategy is almost twice that of the two-way coupled results, which suggests that the structural deformation is over predicted when the one-way coupling method is applied.

![Displacement responses calculated by one-way and two-way coupling strategies.](image)

(a) One-way coupling strategy  (b) Two-way coupling strategy

Figure 20: Displacement responses calculated by one-way and two-way coupling strategies.

In the following section, the aerothermoelastic responses are investigated in detail. First, the aerothermoelastic responses obtained using the one-way coupling strategy is illustrated and described. Fig. 22 gives the typical time-domain aerothermoelastic responses at $t \in [2s, 3s]$, the corresponding Fast Fourier Transform (FFT) results, the phase portraits and the Poincaré maps at point P3 ($x/a = 0.75$). In this paper we map out the Poincaré plot based on the occurrence of an event that when the time response of an event point P2 ($x/a = 0.5$) reaches its positive maximum deflection, the deflection and velocity of point P3 are recorded.
By observing Fig. 22(a) it can be found that the one-way coupled responses have two vibration frequency peaks while its corresponding values are about [193 Hz, 384 Hz]. The second frequency component is smaller and its value is twice that of the fundamental frequency value, which indicates that the aerothermoelastic response of this issue is a double periodic motion. It is confirmed by the phase portrait and the Poincaré map, where the phase portrait is symmetric about the zero-velocity plane which indicates the response contains even multiple frequency components and there are two clusters of points on the Poincaré map which means a 2-period motion. Noticed that the structural temperature is still rising, therefore the phase portrait is still expanding outward and the points on the Poincaré map cannot completely coincide. Periodic characteristics can be observed from Fig. 22(b), which corresponds to the deformation variation in time pe-
period [2.7s, 2.8s]. As the simulation goes on, the vibration form has changed from a 2-period motion into a 3-period motion, as shown in Fig. 23. It can be seen that a new vibration frequency component appears and the values of vibration frequencies have increased to [235 Hz, 470 Hz, 705 Hz].

![Displacement response and corresponding FFT result, phase portrait and Poincaré map](image)

Figure 22: Structural responses at $t \in [2s, 3s]$ and the displacement distributions at $t \in [2.7s, 2.8s]$ for one-way coupled case.

In summary, harmonic periodic oscillation is predicted when using the one-way coupling strategy, the major evolutionary phenomenon is that the vibration frequencies rise due to the increase of structural temperature differential.

Next, the evolution of the post-flutter aerothermoeelastic characteristics computed using two-way coupling strategy is studied. Considering that the total physical time of numerical simulation is quite long and there are con-
(a) Displacement response and the corresponding FFT result, phase portrait and Poincaré map

(b) Displacement distribution contour

Figure 23: Structural responses at \( t \in [9.5s, 13.5s] \) and the displacement distributions at \( t \in [12s, 12.1s] \) for one-way coupled case.

versions of different motion forms. Therefore, several typical time ranges \( ([t_1, t_2]) \) are presented for the convenience of analysis, the method used here is to observe the responses and the corresponding Hilbert-Huang Spectrum in Fig. 20(b) and Fig. 21 carefully and then distinguish the time period with a similar motion form.

Figure 24(a) shows the structural displacement responses at three characteristic points in the first 2 second. It can be seen that the structural deformation responses calculated using both one-way and two-way coupling strategies are consistent in the early stage of the numerical simulation, but the responses quickly begin to take different forms. As time goes on, the one-way coupled result exhibits periodicity but the two-way coupled result
exhibits chaos. Furthermore, it is obviously that the vibration frequency of one-way coupled result is larger than that of two-way coupled result, FFT results (Fig. 25) show that the fundamental frequency of the one-way coupled responses rapidly rises to 180 Hz, but the frequency values of two-way coupled result are basically lower than 100 Hz. This indicates that the two-way coupling strategy can simulate the gradual process of system characteristics, but the one-way coupling strategy cannot. By observing Fig. 24(b), which represents the variation of the temperature ratio, we can find that the temperature differentials obtained using two-way coupling strategy differ from that of one-way coupling strategy obviously as time grows.

Figure 24: Structural responses calculated by one-way and two-way coupling strategies at $t \in [0s, 2s]$.

Fig. 26 shows the structural deformation contour in this time period, it can be manifestly seen that, the surface deformations calculated using...
Figure 25: FFT results of the structural displacement response in $t \in [0s, 2s]$.

Figure 26: Panel deformation distributions at $t \in [0s, 2s]$ (left: one-way, right: two-way).

Two diverse types of FTSI coupling strategies are almost the same at the early state of simulation. As the time goes on, periodic response is obtained when using one-way coupling strategy but the two-way coupled result exhibits chaotic motion.
In order to qualitatively analyze the aerothermoelastic responses, typical structural displacement responses in time range $[7s, 9s]$ and $[9.5s, 13.5s]$ are illustrated in Fig. 27. From the FFT results we can find that the frequency spectrum is in a continuous distribution, which suggests that the two-way coupled response is a chaotic motion. It is reaffirmed by the phase portrait which has no repeat character and a cloud of points in the corresponding Poincaré map.

![Displacement/m Velocity/(m/s)](image)

(a) Results in $7s - 9s$

![Displacement/m Velocity/(m/s)](image)

(b) Results in $9.5s - 13.5s$

Figure 27: Structural displacement responses and the corresponding FFT results, phase portraits and Poincaré maps (two-way).

The modal transition can be revealed by Hilbert-Huang transformation as shown in Fig. 28(b), whereby the “Periodicity” pattern is observed at $t \in [11s, 12.5s]$. Furthermore, four typical deformation contours, which correspond to time range $[5.9s, 6s]$, $[6.6s, 6.7s]$, $[7.8s, 7.9s]$, $[12s, 12.1s]$ respectively, are presented in Fig. 29. Obviously that there does exist “Periodicity”
pattern. As shown in Fig. 28 and Fig. 29, the vibration frequencies increase with time, which indicates that the motion form of the panel gradually shifts from low-order mode to higher-order mode. In order to clarify this, the corresponding FFT results are given in Fig. 30 and the values of the first twelve panel natural frequency are given in Table 4. The fundamental frequency of the vibration in [5.9s, 6s] is 191.31 Hz, which tells that the coupling mode in this time period is Mode 6 and Mode 7. As time grows, the value has increased to 381.33 Hz, 538.96 Hz, 599.40 Hz, which corresponds Mode 9, 10 and 11. However, this phenomenon of mode transfer is not observed when using one-way coupling strategy.

Another important discovery is that we find there exists stages which we call it transition stage when using two-way coupling strategy. In transition stage, the vibration frequencies of the structural deformation response
Figure 29: Four typical structural displacement contours with “Periodicity” pattern.

decrease and the vibration form returns to chaos with no “Periodicity” described above. A typical transition stage corresponding to time period [4.5s, 5s] is presented below. Fig. 31 shows the structural deformation responses and the corresponding FFT results before, in and after this time period. Obvious changes of vibration frequencies can be observed, the fundamental frequency (200 Hz) decreased to the value below 100 Hz first and then increased to about 180 Hz. In order to study it more clearly, Fig. 32 illustrates the deformation contour in time range [4.3, 5.2s]. It can be seen that, chaotic motion
accompanied by “Periodicity” appears before and after the transition stage and the response forms have also changed from one type to another one, but irregular motion appears between these two time period. This phenomenon suggests that, due to the joint influence of structural temperature rise, the changing of temperature distribution and the temperature gradient inside the structure, the panel motion changes from a stable state to a different one.

Finally, the aerothermoelastic responses from 14s to 15s are given in
Table 4: The first twelve panel natural frequency.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Value (Hz)</th>
<th>Mode</th>
<th>Value (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.8306</td>
<td>7</td>
<td>236.6994</td>
</tr>
<tr>
<td>2</td>
<td>19.3224</td>
<td>8</td>
<td>309.1584</td>
</tr>
<tr>
<td>3</td>
<td>43.4754</td>
<td>9</td>
<td>391.2786</td>
</tr>
<tr>
<td>4</td>
<td>77.2895</td>
<td>10</td>
<td>483.0600</td>
</tr>
<tr>
<td>5</td>
<td>120.765</td>
<td>11</td>
<td>584.5026</td>
</tr>
<tr>
<td>6</td>
<td>173.9016</td>
<td>12</td>
<td>695.6064</td>
</tr>
</tbody>
</table>

(a) time domain response       (b) FFT results of structural deformation response

Figure 31: Structural displacement responses with transition stage and its corresponding FFT results at $t \in [4s, 5.5s]$.

Fig. 33. In addition to the fact that the panel motion is still chaotic, both the vibration frequencies and the maximum amplitude have decreased, which suggests that a transition stage will appear if the simulation goes on. How-
ever, in addition to the reason mentioned above, there is another explanation which is that the structure and the flow field gradually enter the state of heat exchange, rather than the simple heat transfer from the flow field to the panel in the early stage of the numerical simulation. This brings a feature which is significantly different from the one-way coupling method, that is, although the structural temperature has been rising in general, it will decrease at some time points. Further confirmation will be shown in the following section 4.2.2.

So far, the evolution of structural vibration forms has been studied, har-
monic periodic motion is obtained when applying the one-way coupling strategy, and with the increment of the temperature differential, the vibration form gradually changes from a double period motion to a triple period motion. However, chaotic motion accompanied by “Periodicity” pattern is discovered when involving the effects of panel deformation. Furthermore, transition stages which represent the modal transition effect are observed while the one-way coupling strategy fails to capture this phenomenon.

(a) Displacement response and the corresponding FFT result, phase portrait and Poincaré map
(b) Displacement distribution contour

Figure 33: Aerothermoelastic responses and the corresponding displacement distribution contours at $t \in [14s, 15s]$.

4.2.2. Analysis of Structural Characteristics

In this section, we will explore why different panel motions are obtained when using two diverse types of FTSI coupling strategies and find out the
reasons why the structural deformation is over predicted when using the one-way coupling method. The temperature differential distributions on the upper surface are given in Fig. 34. It can be found that, because of the structural deformation, the temperature on the upper surface is wavy distribution rather than uniform distribution.

![Temperature differential variations on the upper surface of the panel.](image)

(a) One-way coupling strategy  
(b) Two-way coupling strategy

Figure 34: Temperature differential variations on the upper surface of the panel.

The time history of the upper surface temperature differentials obtained using two various types of FTSI coupling strategies and the upper surface temperature distributions at different times are shown in Fig. 35. As shown in Fig. 35(a), as time goes on, the surface temperature differentials are relatively very small, which means that the temperature gradient on the upper surface of the panel is small. For example, $\Delta T_{P1} - \Delta T_{P3} < 0.15K$ at $t = 15s$, which is about one critical temperature differential of the panel. However, for the two-way coupled case, $\Delta T_{P1} - \Delta T_{P3} \approx 1.5K$ at $t = 15s$, which is al-
most 10 times the panel critical temperature. Furthermore, from the zoom-in view at the upper left corner in Fig. 35(a) we will also find that, unlike the one-way coupled temperature curve which increases steadily, the two-way coupled temperature curve is fluctuating. Considering that the thermal load is induced by the temperature, therefore the relatively small surface temperature differentials of one-way coupled case will result in a uniform distributed thermal load and the large upper surface temperature gradient leads to a complex thermal load distribution. This explained why the aerothermoelastic behaviours of one-way coupling strategy is relatively simple but complex panel motions are obtained when using two-way FTSI coupling method.

(a) The difference between the temper- (b) Comparative temperature distribu-
ature of different characteristic points on tions at different times the upper surface

Figure 35: Comparisons of the temperature differential variations and distributions on the upper surface of the panel.

By observing the comparison of the upper surface temperature distri-
bution shown in Fig. 35(b), it can be seen that most of the temperature values obtained using the one-way coupling method is higher than that of the two-way coupled result, especially for the points at the back of the panel. Considering that the larger temperature differential, the larger the thermal load, the larger the response amplitude. Thus it explains why the maximum aerothermoelastic response amplitude is over predicted when applying the one-way coupling strategy.

The effect of the temperature gradient throughout the panel thickness is also investigated in this paper. Fig. 36 shows the temperature gradient and the corresponding temperature gradient changing rate at P3, where the temperature gradient is defined as $\nabla (\Delta T) = \frac{\Delta T_{top} - \Delta T_{bot}}{h}$ while the changing rate is calculated using first-order time difference method $\frac{\partial \nabla (\Delta T)}{\partial t} = \frac{\nabla (\Delta T)^{n+1} - \nabla (\Delta T)^n}{\Delta t}$. From the comparison of the temperature gradient it can be found that after going through the initial rapid heating stage, the one-way coupled result decreases slowly, combined with the changing rate shown in Fig. 36(b) it can be inferred that the values will tend to be constant. However, although the two-way coupled result is also slowly declining, the process is significantly fluctuating. Furthermore, it is quite important to notice that the trend of the temperature gradient changing rate curve is similar to the structural displacement response shown in Fig. 20. The above phenomenon leads to two enlightenments: the first one is that the traditional method which gives the temperature differential directly and then perform the aerothermoelastic analysis is similar to the one-way coupled method, therefore it do have some instructive significance in the preliminary study;
the second deduction is that the temperature gradient throughout the thickness is one of the main inducements that lead to the chaotic response of the panel, which highlights the importance of involving the effects of structural deformation.

\[
\nabla(\Delta T) = \frac{\Delta T_{\text{top}} - \Delta T_{\text{bot}}}{h_s}
\]

Figure 36: Comparative temperature gradient throughout the panel thickness and its corresponding changing rate.

(a) Temperature gradient throughout the thickness, \( \nabla(\Delta T) = \frac{\Delta T_{\text{top}} - \Delta T_{\text{bot}}}{h_s} \) throughout the thickness, \( \frac{\partial \nabla(\Delta T)}{\partial t} = \frac{\nabla(\Delta T)^{n+1} - \nabla(\Delta T)^{n}}{\Delta t} \)

(b) Temperature gradient changing rate

Considering that the temperature differentials inside the panel is closely relevant to the structural mechanical properties, the structural Von Mises stress results are therefore extracted and plotted in Fig. 37. From Fig. 37 it can be found that the distribution of the Von Mises stress are completely different, which indicates that the location where the panel may break will be significantly different. More importantly, the maximum Von Mises stress (540 Mpa) of the two-way coupled result is 42% higher than that of the
one-way coupled case (380 MPa), which tells that the dynamic pressure as well as the onset of panel failure predicted by two-way coupling strategy is smaller and earlier than the results predicted by one-way coupling strategy. Therefore, the one-way coupling method may underestimate hazardous situations, rather than assuming that this simplified treatment can cover the limit case, as commonly recognized.

![Figure 37: Structural Von Mises stress contours of the panel.](image)

4.2.3. Analysis of Flow Characteristics

In the following content, the evolutionary process of the flow characteristics is illustrated first, then the flow mechanism that leads to the occurrence of the transition stage during the simulation will be explored.

Figure 38 shows the non-dimensional surface heat flux on the panel. As can be clearly observed, the values computed using the one-way coupling strategy always decrease with time (less than 1). On the contrary, the surface
heat flux distribution of the two-way coupled result on the panel is changing over time. Due to the existence of shockwave and expansion wave induced by the panel deformation, the values not only less than 1 but also greater than 1 appear during the simulation. Furthermore, it can also be observed in Fig. 38(b) that there are also values below 0 in the later stage of the simulation and the minimum value is $\approx -0.85$. It tells that in the process of aerothermal analysis, not only heat is transferred into the panel from the flow field, but also heat is transferred into the flow field from the panel. That is to say, the heat transfer during the aerothermoelastic analysis is a dynamical exchange process that cannot be simulated by the one-way coupling strategy and this is critical to the design of thermal protection systems.

Figure 38: The variations of the nondimensional heat flux applied on the upper surface of the panel.

In order to explore the flow field mechanism that results in the differ-
ent response forms and the appearance of the transition stage. The typical flow field pressure contours when the displacement at Point P3 reaches the maximum and minimum values are extracted and presented below.

The contours calculated using the one-way coupling method when the displacement at P3 reaches maximum and minimum values are firstly presented in Fig. 39. From the pressure contours we will find that the distribution of the flow field characteristic does not change significantly. And the evolution of this issue is similar to a pure aeroelastic analysis with an additional temperature which is evenly distributed and slowly rising. The evidence is that the pressure contours shows a typical conversion of aeroelastic calculation, the flow field shows the alternation of shockwave and expansion wave.

![Typical pressure contours](image)

(a) maximum values  
(b) minimum values

Figure 39: Typical pressure contours calculated by the one-way coupling method when the displacement at P3 reaches maximum and minimum values.

Next, the flow field mechanism when using the two-way coupling strat-
ergy is explored. Similarly, Fig. 40 and Fig. 41 illustrate the typical pressure
distribution contours at the “Periodicity” regions. Unlike the contours of the
one-way coupled case, it can be found that the numbers of shockwaves and
expansion waves increase with time, which means that the distribution of
aerodynamic force is getting more complicated. In addition, the numbers of
peaks and valleys of the panel gradually increase over time, which indicates
the vibration frequency component in the response increases and the vibra-
tion form of the panel is also changing over time, this phenomenon is also
consistent with previous frequency domain results shown in Fig. 30. The spe-
cific evolution process that results in the phenomenon described above is that:
the structure is deformed by the initial disturbance and the aerodynamic
force, the distribution of heat flux is then altered; the distribution of struc-
tural temperature and temperature gradient is therefore changed through
aerodynamic heating simulation; due to the altered temperature differential,
the structural vibration forms as well as the characteristics of flow field are
changed; the above procedures is repeated during the simulation and this
complex three-field interaction finally lead to the complex chaotic response
of the panel.

The appearance of the transition stage can be reasonably explained from
the perspective of energy exchange. It is known to all that the essence of the
aerothermoelastic problem is the energy exchange process between the energy
consumed by the structure and the energy absorbed from the flow field. As
the structural temperature increases and accompanied by the change of the
structural temperature gradient, the energy obtained by the structure from
Figure 40: The two-way coupled typical pressure contours at the region that exhibits “Periodicity” when the displacement at P3 reaches maximum values.

Figure 41: The two-way coupled typical pressure contours at the region that exhibits “Periodicity” when the displacement at P3 reaches minimum values.

the current flow field is not enough to meet the capacity loss of structural vibration. Thus, the characteristics of the flow field need to be changed to adapt the new panel vibration form. In the process of this coupling, the flow
state gradually changes from a stable state to another new one.

5. Conclusions

In the present work, evolution analysis of the post-flutter characteristics of an aerothermoelastic system is carried out based on the integrated aerothermoelastic analysis framework developed in this paper. A CFD solver is used to obtain aerodynamic force and aerodynamic heating, structural dynamics and thermal conduction are computed using a finite element structural solver and a finite element solver, respectively. Verification of the framework is done by comparing with a cylinder subjected to aerodynamic heating and a simply supported hypersonic panel. Subsequently, the aerothermoelastic characteristics is systematically investigated. The following conclusions can be drawn.

1. The viscous effect significantly delays the flutter onset and aggravates the thermal load, which indicates the necessity of high-fidelity model in aerothermoelastic computation.

2. Buckled panel is predicted when applying the two various FTSI coupling strategies for small dynamic pressure. However, the panel deformation leads to high local temperature behind the shockwave and low temperature behind the expansion wave when using the two-way coupling approach. This observation provides important guidance for the design of thermal protection system.

3. Modal transition phenomenon is observed using two-way coupling under the circumstance investigated in this paper, whereby the vibration
changes from one type to another. However, the aerothermoelastic system in the present work is highly nonlinear and sensitive to the initial conditions. Therefore, this phenomenon may not be observed for arbitrary initial conditions.

4. An analogy, which is observed between the rate of temperature gradient throughout the panel thickness and the structural time-domain response, indicates the temperature gradient inside the panel is one of dominant factors that determines the vibration forms of the panel.

5. For the hypersonic panel in the flutter regime under the conditions investigated in the present study, the maximum value of Von Mises stress obtained by the two-way coupling method is approximately 42% larger than the one-way counterpart. This indicates that the onset of structural failure can be underestimated when using one-way coupling strategy in the aerothermoelastic computation.

Our future work is to further investigate the effect of material nonlinearity and further apply the framework to three dimensional models for aerothermoelastic analysis.

Acknowledgements

The first author gratefully acknowledges the support from the College of Astronautics, Northwestern Polytechnical University.
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