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Fluid-Thermal-Structural Interactions on a Fin in Hypersonic Flow

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Abstract

The focus of this paper is to investigate a range of parameters that may potentially make the incorporation of a fully coupled two-way FTSI simulation essential, for the representative case of a 2D fin in hypersonic cruise flight, undergoing static structural deformation due to aerothermodynamic effects. To this end, a procedure is adopted in which shock-expansion theory is used to predict the flow properties over the fin, with the Eckert reference temperature method then being used to predict the heat transfer into the surface. Thereafter, a 1D finite element implementation is used to determine the temperature distribution of the fin and the structural deformation due to the pressure and shear loading. Two way fluid-thermal-structural interactions are modelled by incorporating updates to the wall temperature, and establishing a flow turning angle between adjacent displaced elements that is then transferred to the fluid side. Results compare the difference in fidelity between one-way, one way+CHT and full two-way systems, and examine the effect of varying parameters such as the Mach number, altitude, fin/plate thickness, angle of attack and heating time.

Introduction

Flexible structures that travel through a fluid at hypersonic speeds are subject to a number of complex interactions that take place between the two domains. These interactions, termed fluid-structure interactions (FSI) in the field of aeroelasticity, involve a complex coupling mechanism between fluid and structure that has the potential to severely degrade the performance of flight-critical components to the point of structural failure. The effects of the fluid pressure force may be exacerbated by thermal effects at hypersonic speeds, due to the high enthalpy of the flow. This was seen to great effect during the SHEFEX-I hypersonic flight test program, where onboard cameras on the vehicle captured significant distortion of the second stage booster fins, as a result of differential thermal expansion due to significant thermal gradients (figure 1). Such distortion can severely impact the control authority and performance of the fin, and the wider vehicle, and as such, fluid-thermal-structural interaction (FTSI) within aerothermoelasticity represents an important consideration in the design of hypersonic vehicles.

Figure 1. Cameras onboard the SHEFEX-I flight experiment captured the structural deformation of the fins due to severe aerothermodynamic loading during re-entry [1].

Despite the importance of FTSI, its inherent complexity has prevented the drivers surrounding such interactions from being properly understood. As a result, aerothermoelastic effects have tended to be be treated rather haphazardly in literature. Frequently, these interactions have been deemed either negligible, or too difficult to incorporate. At other times, one-way effects are assumed to be the primary interactions at play, with two-way coupling considered either unnecessary, or included only as two-way thermal effects. More recent studies that incorporate full two-way thermal and structural effects have predominantly focused on the effect that these interactions have on dynamic phenomena such as flutter in a hypersonic context. Therefore, the aim of this paper is to determine the range of conditions that make incorporation of two-way coupling effects necessary. As such, it modifies the procedure outlined in [4] to analyse the comparative fidelity of one-way, one-way with conjugate heat transfer (CHT) and full-2 way implementations, and understand the relative importance of parameters such as Mach number, altitude, fin thickness, angle of attack (AOA) and heating time, on a 2D representive fin in hypersonic cruise flight.

Levels of Aerothermoelastic Fidelity

A key focus of this paper is an analysis of the different levels of fidelity possible in modeling the aerothemoelastic phenomenon. Traditionally, the favoured solution process has been sequential in nature, with the flow over a body first modelled, and the heat flux passed to a transient thermal solver. This solver then determines the temperature distribution of the body and transfers this to the structural solver, which also receives the pressure and shear stress load from the fluid solver. This process, termed here as 'one-way' aerothermoelastic modelling is shown in figure 2 as solid lines connecting the fluid, thermal and structural solvers. However, it assumes that a hot, deforming structure has negligible effects on the subsequent aerodynamic heating or pressure/shear loading.

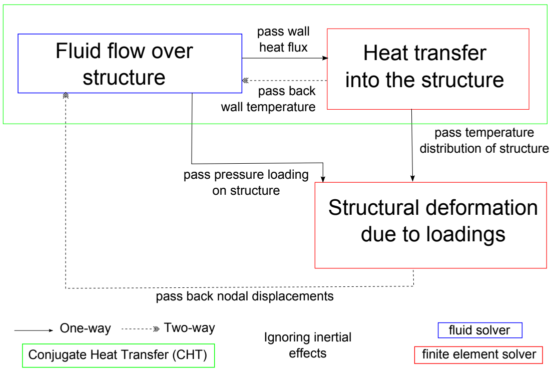


Figure 2. A schematic showing the various interactions at play in aerothermoelasticity.

Aerothermal coupling effects can be modelled by what is known as conjugate heat transfer (CHT), where the thermal solver passes information about the structure's wall temperature back to the fluid solver, in effect, moderating the heating as the latter uses the increasing wall temperature in it's heat flux calculations. When paired with a one-way aeroelastic solution, the combined model is known here as a 'one-way+CHT' analysis. Lastly, the effect of the deforming structure can be taken into account by passing nodal displacements back to the fluid solver, which uses this new geometry to update the flow properties over the body. Combined with CHT, this is known here as a 'two-way' analysis and is depicted in figure 2 through both solid and dashed lines. In this study, the fin is undergoing hypersonic cruise flight and the flow is inherently steady, apart from the effects due to nodal displacements and temperature. As a result, a quasi-static assumption is adopted for the structure, where the load is time dependent but slow enough that only elastic effects are considered and inertial effects neglected.

Methodology

Model Geometry

The fins seen undergoing distortion under severe aerothermodynamic loads in figure 1 served as the basis for the geometry of the model used in this paper. The fins in question were those of the second stage Improved Orion booster that was still attached to the SHEFEX vehicle during its re-entry. The present paper conducts a 2D analysis of this fin by taking a cut at the root along the chord and analysing the simplified transverse bending of this section. It is assumed that the fin acts as an all-moving elevator. As such, the fin is free to assume an AOA governed by the flight control software, but once this has been dialled in, is then fixed at this angle about the 55% chord position and free to bend about this point. The section has a chord length of 0.53m and currently is assumed to be made of aluminium Al6061. Although the melting point of aluminium is below the temperatures likely to be achieved in hypersonic flight, it was retained here in this preliminary analysis because its relatively high conductivity and low modulus would likely highlight any differences between one-way, one-way+CHT and full two-way implementations. It is envisaged that different materials, including stainless steel and titanium, will be used in future versions of the code.

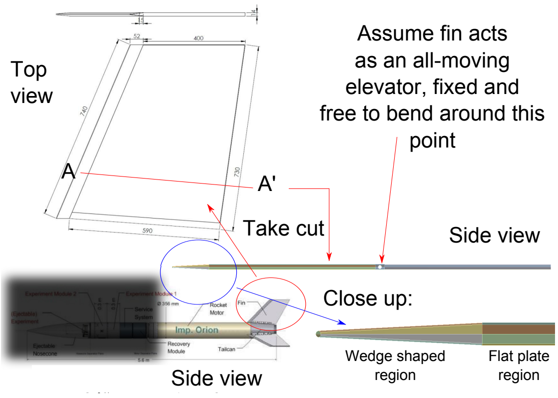


Figure 3. The 3D fin of the Improved Orion booster is converted to a 2D section by taking a cut and analysing the simplified bending of this section due to aerothermodynamic loads. It is assumed that it operates as an all-moving elevator fixed about a point 55% along the chord. The payload attached to the booster is not the focus of this paper and is therefore grayed out in the above diagram [3].

Model Implementation: Aerothermal

The aerothermal model begins with a calculation of the fluid properties on the geometry, at a specified AOA. In order to achieve this, flow turning angles along the chord are calculated for both the upper and lower surfaces, and are used with the shock-expansion model to determine the Mach number, pressure and temperature of the fluid. At the first timestep, the fin is undeformed and the flow turning angle is zero at all points along the chord, except for the first element, where it must account for the AOA and the wedge angle. It is also non-zero at the element where the body transitions from a wedge shape to a flat plate cross-section. Note that the flow is assumed to remain attached to the fin at all points along the chord.

Aerodynamic heating of the structure is calculated using the Eckert reference temperature method for a flat plate detailed in [2]. The Eckert reference temperature method provides an engineering level approximation of the heat flux, using flow conditions found through shock-expansion theory and a wall temperature that can be updated periodically if two-way aerothermal CHT effects are to be simulated. Heat transfer into the wedge shaped region at the front of the fin section is modelled by assuming the top and bottom surfaces are flat plates inclined at the wedge angle and calculating the flow conditions using a flow turning angle that incorporates this wedge angle. In this implementation of the model, both stagnation heating and radiation effects have been ignored, but will be incorporated in future versions.

Model Implementation: Thermal-Structural

Finite element thermal modelling of the fin starts with the use of the 1-D heat conduction formula, governed by the following equation:

$$\frac{\partial}{\partial x}(k_x\frac{\partial T}{\partial x})+Q=\rho c\frac{\partial T}{\partial t} \tag{1}$$

where k_x is the thermal conductivity in the x direction, Q represents a potential internal heat source, ρ is the mass density and c the specific heat. In addition, $\frac{\partial T}{\partial x}$ and $\frac{\partial T}{\partial t}$ represents the rate of change of temperature with respect to space and time respectively. A 1-D implementation was used because the long, slender nature of the fin means that temperature gradients in the through-thickness direction can be assumed to be negligible.

The numerically discretised finite element formulation can then be found to be:

$$(\frac{1}{\Delta t}\underline{\mathrm{M}}+\beta\underline{\mathrm{K}})\underline{\mathrm{T}}_{i+1}=[\frac{1}{\Delta t}\underline{\mathrm{M}}-(1-\beta)\underline{\mathrm{K}}]\underline{\mathrm{T}}_i+(1-\beta)\underline{\mathrm{F}}_i+\beta\underline{\mathrm{F}}_{i+1} \tag{2}$$

where $\underline{\mathrm{M}}$, $\underline{\mathrm{K}}$ and $\underline{\mathrm{F}}$ represent the global mass, stiffness and force matrices respectively. In addition, the subscripts i and $i+1$ represent conditions at the current and next time step. The solution to the temperature distribution of the fin at the next timestep, $\underline{\mathrm{T}}_{i+1}$ can be determined using equation (2) by substituting in the global matrices $\underline{\mathrm{M}}$, $\underline{\mathrm{K}}$ and $\underline{\mathrm{F}}$, the current known temperature distribution $\underline{\mathrm{T}}_i$, and adopting an appropriate value for the stability criterion β. In the present analysis, the Galerkin model is used, which sets $\beta=\frac{2}{3}$ and is unconditionally stable. For the first iteration, the initial wall temperature is set to $T_{i=0}=298K$.

On the structural side, the static bending of the fin is given by Euler-Bernoulli theory:

$$EI\frac{d^4\hat{v}}{d\hat{x}^4}=0 \tag{3}$$

assuming constant EI, where E is the modulus of the material and I is the second moment of area. In addition, $\hat{v}$ represents the transverse displacement of the beam at position $\hat{x}$.

The finite element implementation of this equation is given by

$$\underline{\mathrm{F}}=\frac{EI}{L^3}[\underline{\mathrm{K}}][\underline{\mathrm{D}}] \tag{4}$$

where $\underline{F}$ is the global force vector containing the force (pressure and shear load multiplied by element area) and moment applied to each node, $\underline{D}$ is the global displacement vector containing the displacement and rotation degrees of freedom for each node, and $\underline{K}$ is the global stiffness matrix. Applying a fixed boundary condition at the 55% chord position, the remaining displacements (and rotations) can be solved. Thereafter, the flow turning angle is determined as shown in figure 4 and passed to the shock-expansion model for calculation of the fluid properties at the next timestep.

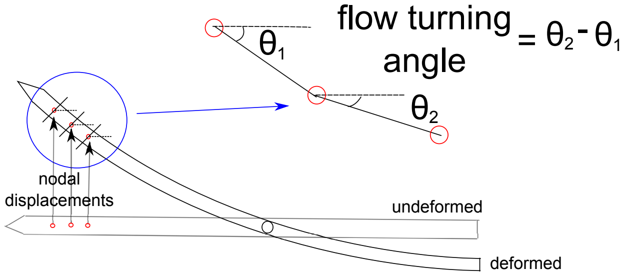


Figure 4. A schematic showing the calculation of the flow turning angle from nodal displacements.

Equations (2) and (4) assume constant parameters in their derivation that are not constant in this application. In particular, the cross-sectional area and second moment of area in the wedge-shaped region is changing with chord, as are the material properties. As a result, proper discretisation of the fin is very important to minimise the error due to these assumptions, and therefore the model has separate independent discretisation levels for the wedge-shaped and flat plate regions of the fin. This allows elements to be concentrated in the wedge shaped zone, without excess elements then being used in the flat plate region.

Results

A grid and time independence study was carried out to determine the element count and timestep that balance accuracy and efficiency; based on Table 1, a timestep of $\delta t = 0.1s$, and an element count of 30 and 75 were chosen for the wedge shaped and flat plate regions respectively.

Time step	$Parameter_{\%\Delta}$	Name of parameter
$\delta t = 1 -> \delta t = 0.01$	20.9%	Pressure$_{\text{upper surface}}$
$\delta t = 0.1 -> \delta t = 0.01$	7.4%	Pressure$_{\text{upper surface}}$

(a) Table outlining the parameter most influenced by a change in timestep

# elements	$Parameter_{\%\Delta}$	Name of parameter
$30 -> 60$	3.1%	Structural deformation
$40 -> 60$	1.6%	Structural deformation
$50 -> 60$	0.7%	Structural deformation

(b) Table outlining the parameter most influenced by a change in the number of elements in the wedge shaped region.

# elements	$Parameter_{\%\Delta}$	Name of parameter
$25 -> 200$	2.6%	Structural deformation
$75 -> 200$	1.8%	Structural deformation
$125 -> 200$	1.64%	Structural deformation
$175 -> 200$	1.57%	Structural deformation

(c) Table outlining the parameter most influenced by a change in the number of elements in the flat plate shaped region.

Table 1: Time and grid independence studies (Two-way model)

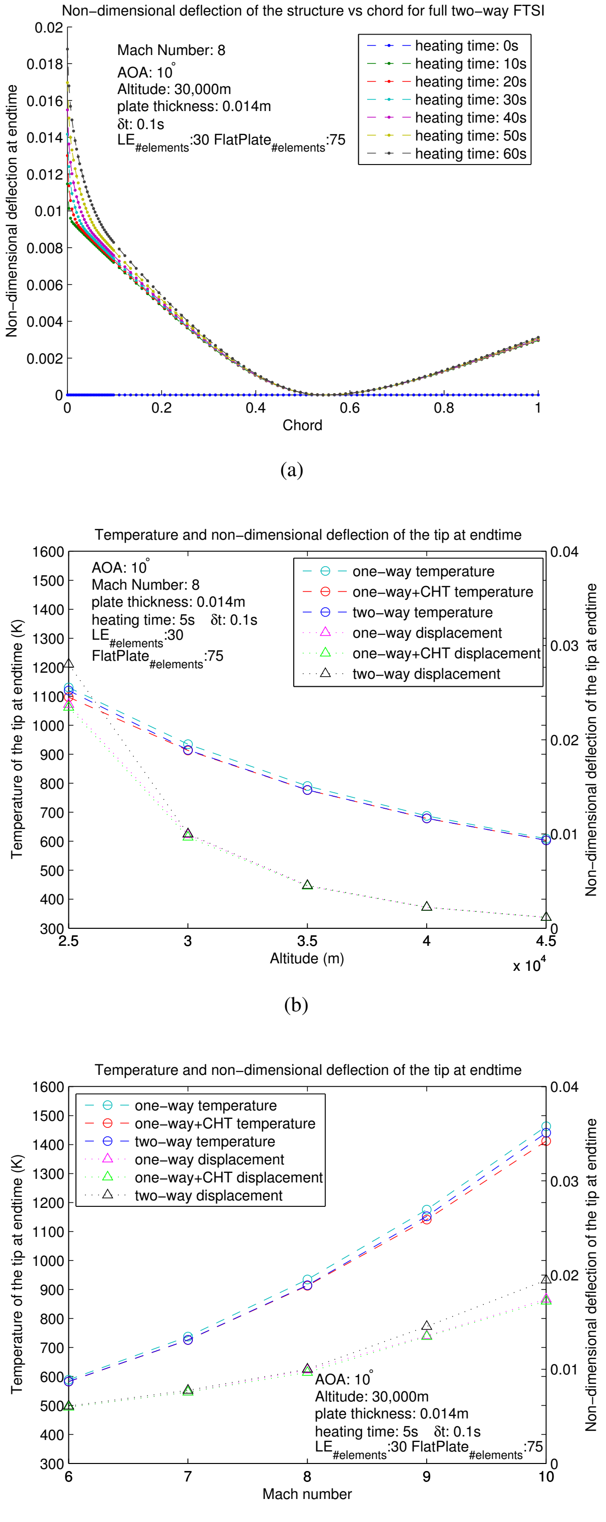
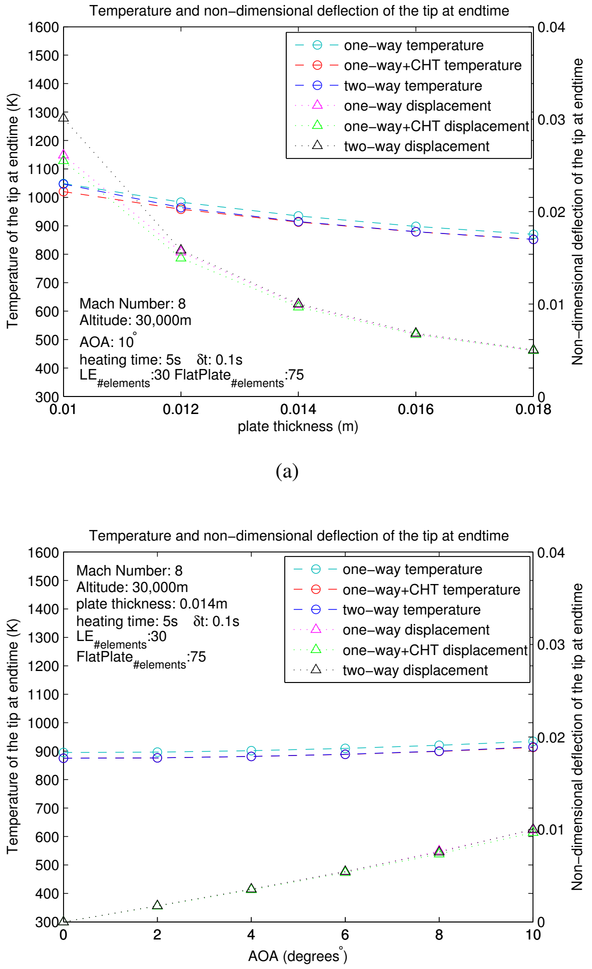


Figure 5. (a) Non-dimensional deflection of the fin along the chord length, shown at different heating times for the two-way implementation. (b) Altitude and (c) Mach number vs temperature of the fin (left y-axis) and transverse non-dimensional (by plate length) deflection of the tip (right y-axis). LE$_{\#\text{ elements}}$ refers to the number of elements in the wedge shaped region.



(a)

(b)

Figure 6. (a) Plate thickness and (b) AOA vs temperature of the fin (left y-axis) and transverse non-dimensional (by plate length) deflection of the tip (right y-axis). $\mathrm{LE}_{\#\,\mathrm{elements}}$ refers to the number of elements in the wedge shaped region.

These grid and time parameters were then used to plot the deflection of the fin along the chord, as shown in figure 5(a) for increasing heating times. As expected, the fin undergoes increased bending with heating time, and deforms around the fixed 55% chord boundary condition where displacement is zero. Deflection is particularly pronounced around the wedge shaped forward region, where both the reduced thermal mass and reduced second moment of area are causing significant bending to take place. Further insight into this bending is found by analysing the one-way, one-way+CHT and full two-way models, as shown in figures 5(b)-(c) and 6. Here, structural temperature and non-dimensional transverse displacement are plotted on the left and right y-axis respectively, against the parameters Mach number, altitude, AOA and plate thickness. A number of phenomena are noted here, one of which is the relative impact of the parameters themselves. From figure 5(b), it can be seen that changing the altitude has a moderate impact on temperature, and a significant impact on deflection at low elevations; density and therefore heating increase with decreasing altitude, reducing the elastic modulus of the material. When this is combined with the increased static pressure also found at decreased altitudes, significant deformation of the fin takes place. Similarly, the plate thickness has a notable influence on deflection (figure 6(a)), possibly due to the influence of a cubed relationship between the thickness and the second moment of area for a rectangular cross-section, used in equation (3). Furthermore, figure 5(c) suggests that Mach number also influences temperature and deformation, likely due to the fact that compression and expansion (and therefore the pressure differential acting on the fin) become more severe at increased Mach numbers. In contrast, the effect of AOA appears rather muted (figure 6(b)), with deformation linearly increasing with AOA, and temperature remaining near constant.

Figures 5(b)-(c) and 6, show the influence of coupling effects such as CHT. Temperatures reached by the fin are consistently higher in the one-way case, then for the one-way+CHT and full 2-way models, which both update the wall temperature and reduce the heat flux over time. It can also be seen that the incorporation of full 2-way aerothermoelastic effects consistently results in the most deflection at the tip, especially at conditions that are increasingly severe; namely rising Mach numbers, decreasing altitude and decreasing plate thickness. However, as established, the two-way model incorporates CHT and moderates the heat flux, in turn limiting the increase in temperature, and degradation of material elastic modulus when compared with the pure one-way case. Therefore, the increased deflection seen at the tip in the full two-way scenario must be at least partially due to the feedback to and from the flow. On the aerothermal side, Mach number and altitude have a larger effect on the relative temperature solutions between the three models, when compared against AOA and plate thickness.

Conclusion

In conclusion, a study was conducted incorporating one-way, one-way+CHT and full 2-way FTSI modelling, with the aim of establishing the influence that parameters such as Mach number, altitude, plate thickness, AOA and heating time had on a 2D hypersonic fin section, and its surrounding fluid. It was established that while changes in altitude, Mach number and plate thickness had the potential to significantly alter the deflection of the fin leading edge, variation in AOA was less influential. In addition, the paper found that two-way aerothermal and aeroelastic coupling effects did alter the structure's temperature and displacement. In particular, it was seen that the full two-way model produced the largest tip deflections when the driving parameters were altered appreciably, despite being cooler than the pure one-way case. This suggests that two-way coupling between the fluid loading and structure had an appreciable effect on the deflection.

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