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LOOSELY COUPLED FLUID-THERMAL ANALYSIS STRATEGY BASED ON DYNAMIC FLIGHT TRAJECTORY

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ABSTRACT

In the design of supersonic and hypersonic missiles, aerodynamic heating analyses are inevitable to perform. To obtain detailed and high fidelity aerothermal data, time dependent conjugate heat transfer analyses have to be conducted which are time-consuming analysis process. In this study, a time efficient, loosely coupled fluid-thermal analysis strategy is proposed based on time dependent flight trajectories. Proposed approach applied to an axisymmetric generic missile geometry. Present method is validated using tightly coupled analysis conducted with commercial Fluent CFD code. Time dependent temperature data compared with tightly coupled approach. Very promising results have been obtained by using loosely coupled analysis strategy.

INTRODUCTION

In the design of supersonic and hypersonic missiles, aerodynamic heating analysis are essential. The accurate prediction of thermal variations in the structure is important since high-speed vehicles experience severe aerothermal effects. Accordingly, structural rigidity and instrumentations affected strongly at high temperatures. Trajectory based time dependent aerodynamic heating analyses have to be performed to overcome this situation. However, these analyses take too much time. If different trajectories have to be concerned, total analysis time increases much more.

The coupling mechanism of fluid-thermal coupling problem is a physical process of interaction between aeroheating within the fluid and the heat transfer within the solid through the fluid-solid coupling interface [Chen F., Zhang S. and Liu H., 2017]. There are generally two different approaches exist for coupling; tightly-coupled and loosely-coupled analysis. In tightly-coupled approach, temperature at the fluid and solid coupling interface have to be predicted using inner iterations since only one temperature value satisfies the transferred heat flux data and due to nature of physics very small time step values are selected. However in loosely-coupled approach, calculated heat flux data from flow solver transferred to the solid solver and calculated temperature field transferred back to the flow solver as a boundary condition. The latter approach is comparatively simple because fluid and solid equations can solved separately without need of inner iterations and large time steps can used.

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Tightly-coupled and loosely-coupled aerodynamic heating approaches are studied extensively. Crowell, Millery and McNamaraz investigated the coupling methods of separate fluid and thermal response analyses [Crowell, A., R., Millery, B., A., and McNamaraz, J., J., 2011]. Authors applied loosely coupled approach between CFD code and FEM solver for compliant skin panels, since loosely coupled schemes are efficient per time step. Wuilbaut T. applied different coupling methods between fluid and solid solvers for flat plate [Wuilbaut,T, 2008]. Flux Forward Temperature Backward (FFTB), Temperature Forward Flux Backward (TFFB), heat transfer coefficient Forward Temperature Backward (hFTB) and heat transfer coefficient Forward Flux Backward (hFFB) methods used to calculate temperature variation on the solid body. Since it showed good convergence properties, hFTB method selected to calculate aerodynamic heating effects on Expert reentry vehicle. Chen, F., Zhang S. and Liu H. integrated independently developed Hypersonic Computational Fluid Dynamics (HyCFD) code and heat transfer analysis software (ANSYS Mechanical APDL) to solve hypersonic aerothermodynamic simulations using tightly and loosely coupled approaches [Chen F., Zhang S. and Liu H., 2017]. Jie Huang, Wei-Xing Yao, Xian-Yang Shan and Cheng Chang studied aerothermal analysis of thermal protection system at hypersonic Mach number. Authors investigated the effect of coupling approach on surface temperature distribution [Huang J., Yao W., Shan X. and Chang C. 2019].

Objective of this paper is to propose a time-efficient trajectory based aerothermal analysis approach. A generic missile geometry and generic flight path is used as a test case. Proposed loosely-coupled approach results are compared with tightly-coupled analyses results. Satisfactory temperature results obtained with respect to fidelity of results.

METHOD

Fluid and thermal response analyses are performed using commercial Fluent solver. Loosely-coupled coupling approach is applied for the data exchange procedure.

The initial heat transfer coefficient values w.r.t. x-axis heat flux calculated by the first flow solution and transferred to the thermal solution in step 1, temperature variation in the structure obtained by thermal solution in step 2, calculated wall temperature at t=Δt is transferred back to the flow solution in the step 3, and the wall heat flux and heat transfer coefficient at t=Δt can be obtained by the CFD analysis in step 4. So, the heat transfer coefficient and temperature variations at t=Δt are obtained by the calculation in steps 1–4. Step 5 starts a new cycle for calculating the wall heat transfer coefficient and the temperature values at t=2Δt, and the analysis results of all time points can be obtained by repeating the calculations in steps 1–4. This scheme named as conventional serial staggered (CSS) scheme [Crowell, A., R., 2011] and shown in Fig. 1. The wall temperature is frozen in CFD solutions, and the wall heat transfer coefficient is frozen in the thermal response solutions.

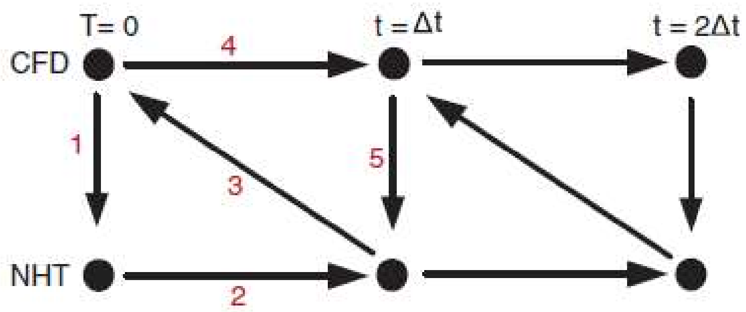

Figure 1. Conventional Serial Staggered (CSS) aerothermal coupling scheme

The loosely coupled method is simple and easy to apply in engineering. However, the freeze of boundary conditions causes the time lag effect in the analysis process, which affects the coupling time accuracy and causes an analysis error. As the analysis time t increases, the error will accumulate gradually. Therefore, the time-step size must be very small in the loosely coupled analysis to reduce the time lag effect.

Improved serial staggered (CSS) scheme [Crowell, A., R., 2011], shown in Fig. 2, improves data transfer between flowfield and thermal response analyses. This scheme ensures second order data transfer by shifting time steps Δt/2 value between fluid and thermal solutions.

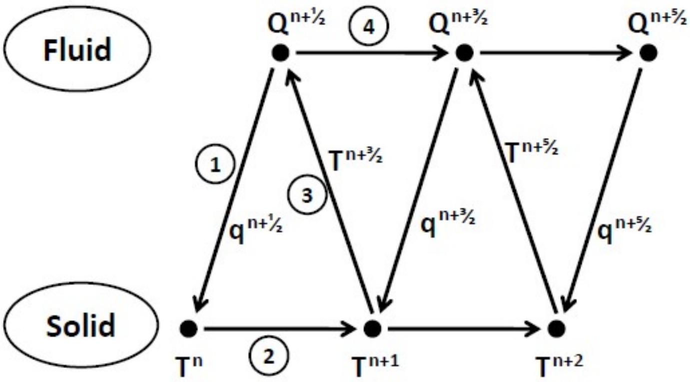

Figure 2. Improved Serial Staggered (ISS) aerothermal coupling scheme.

In order to maintain second order accuracy of the fluid from time n + 1/2 to n + 3/2, the wall temperature data must be specified at time n + 3/2. The wall temperature at n + 3/2 is estimated using a second order accurate extrapolation:

$$T^{n+3/2} = \frac{3}{2}T^{n} - \frac{1}{2}T^{n-1} + O(\Delta t^{2})$$

For verifying the developed new method, an aerodynamic heat transfer analysis is performed with a generic missile with a conical nose shown in Fig. 3. Generic missile model dimensions can be seen in Fig. 4. Meshes for fluid and solid cases and their sizes are shown in Fig. 4 and Table 1. Material properties for solid case are shown in Table 2.

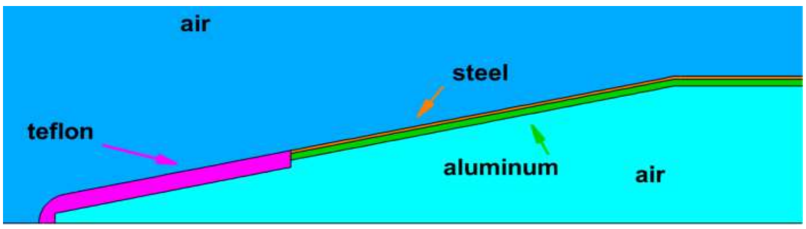

Figure 3. Generic missile model

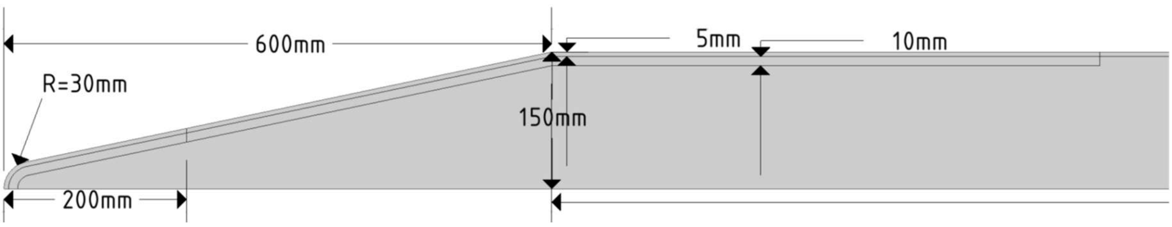

Figure 4. Generic missile model dimensions

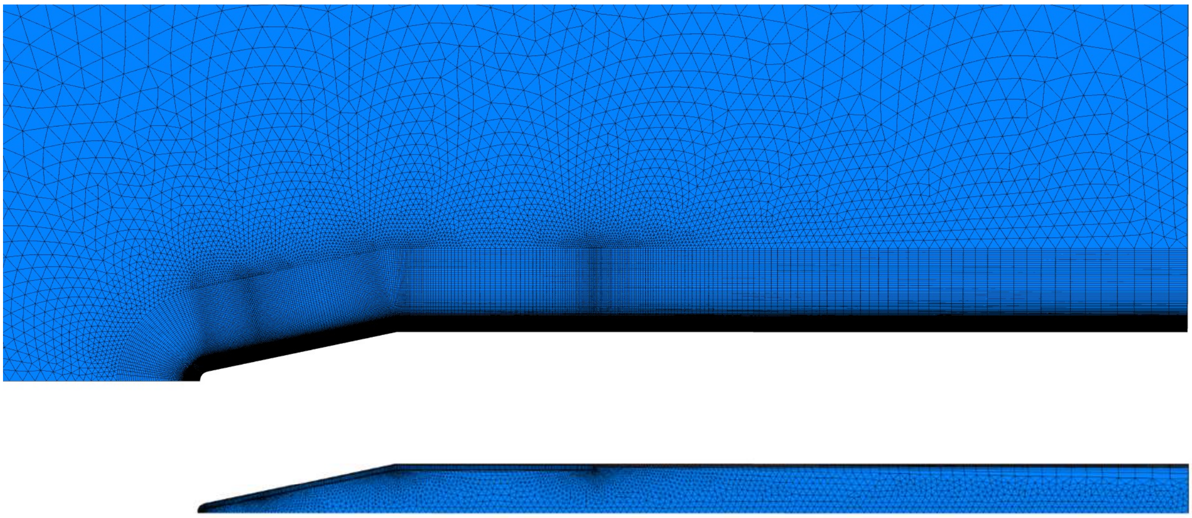

Figure 4. Fluid and solid mesh

Table 1. Mesh size

	Fluid Case	Solid Case
Mesh Size	121108 cells	35347 cells

Table 2. Material properties

Material	Density (kg/m^3)	Specific Heat J/(kg.K)	Thermal Conductivity W/(m.K)
Aluminum	2719	871.00	202.40
Steel	8030	502.48	16.27
Teflon	2200	1300.00	0.25

Using this model, for a 40 sec. scenario, analyzes were carried out with traditional and new methods using the ambient temperature and pressure changes obtained by using the time-dependent altitude and Mach number information shown in Fig. 5 as boundary conditions. As a result of these analyzes, the comparison of the temperature data obtained from the sensor points in Fig. 6 with traditional tightly coupled (TC) and new loosely coupled (LC) methods is presented in Fig. 7.

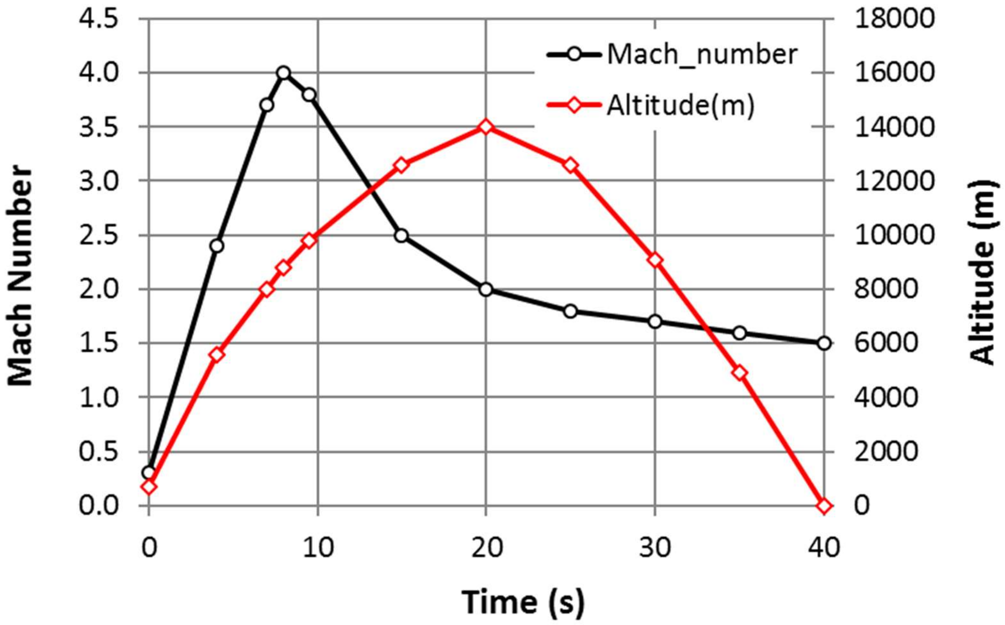

Figure 5. Time dependent change of Mach number and altitude in the flight scenario

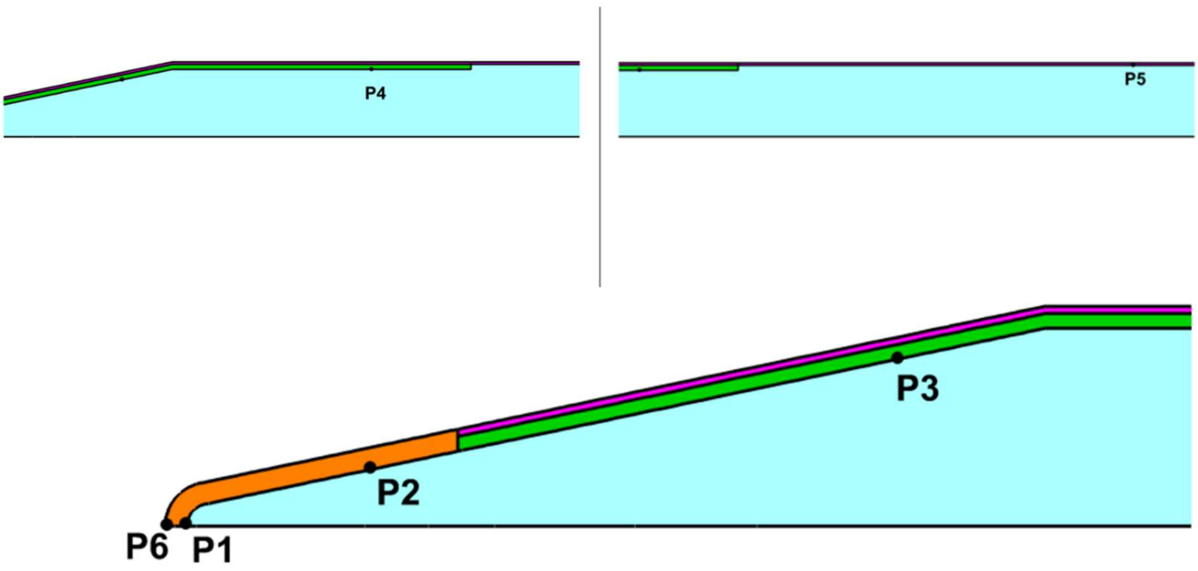

Figure 6. Sensor points on the missile where data is collected

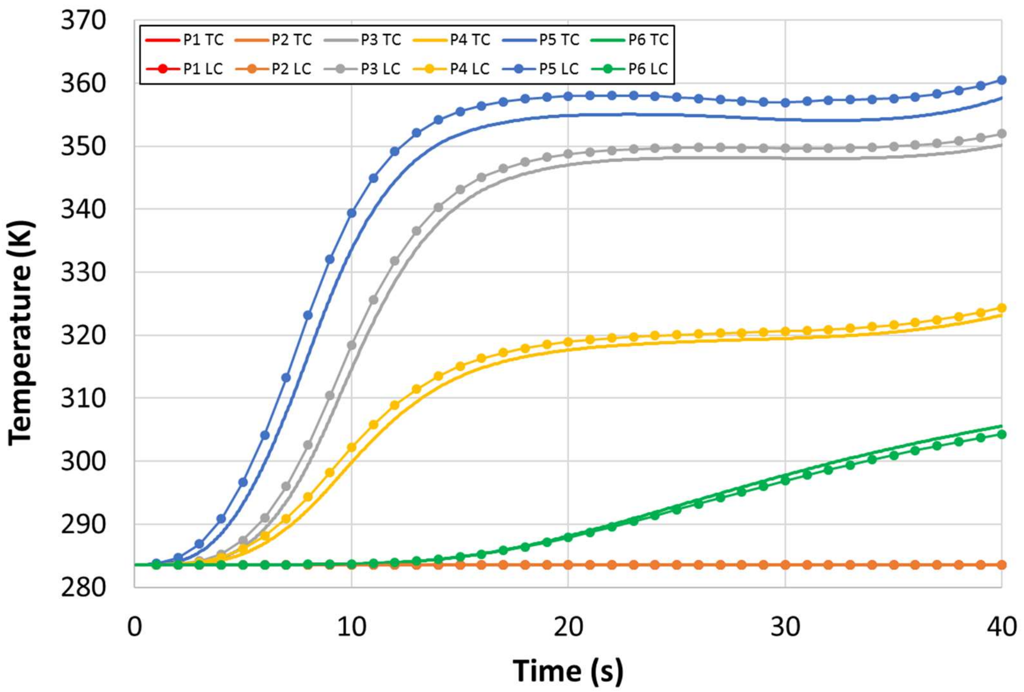

Figure 7. Time-dependent temperature data obtained from the sensor points

When the results in Figure 7 are compared, it is revealed that there is no significant difference between the methods. In addition, the analysis times at which the results were obtained are also presented in Table 3. The analysis performed with the loosely coupled method using 80 CPU's showed a 94.7% reduction in time compared to the analysis performed with the same number of CPU's using the tightly coupled method.

Table 3. Comparison of computation time between analysis methods for generic missile

Analysis	Mesh Element #	CPU #	Time (Hours)
Tightly Coupled	156455	80	57.75
Loosely Coupled	156455	80	3.02

References

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