

AEROTHERMOELASTIC RESPONSE ANALYSIS OF HYPERSONIC VEHICLES BASED ON A CFD-MODIFIED ENGINEERING METHOD

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ABSTRACT

The design of advanced hypersonic vehicles is characterized by highly coupled aerothermoelastic (ATE) problems. The complex fluid/thermal/structural interaction (FTSI) makes high-fidelity numerical simulations prohibitively expensive, while obtaining reliable data from wind tunnel tests remains challenging. Therefore, there is a pressing need to develop an efficient simulation method based on existing technical capabilities to meet practical engineering requirements. Such a method would allow numerical simulation to compensate, as far as possible, for the infeasibility of complex wind tunnel testing.

Traditional engineering methods for hypersonic flow have limited applicability and low accuracy for complex configurations, whereas high-fidelity computational fluid dynamics (CFD) methods severely compromise efficiency in coupled analyses requiring multiple iterative calculations. To effectively manage the dimensionality of the FTSI system while preserving its essential physics, balancing accuracy with efficiency, this paper establishes a component-level modified method for ATE response analysis that leverages full-vehicle-scale data. This approach integrates CFD-modified aerothermodynamic engineering methods (developed from our preliminary work, Reference [1]) with a thermo-structural analysis technique based on the finite element method (FEM). Its performance is validated against conventional simulation techniques using a representative rudder model.

Subsequently, time-domain ATE simulations along a flight trajectory are conducted for various assembly configurations. The analysis yields static response curves capturing critical properties such as deformation and aerodynamic performance under full-vehicle-scale flow effects. Based on these results, specific critical load moments are selected for further thermal flutter analysis. A reduction technique based on proper orthogonal decomposition (POD) and the Ritz method (developed from Reference [2]) is applied to simplify the flutter calculations. Stability margin profiles are plotted to illustrate the vehicle's stability variations along its flight path. The results demonstrate asynchronous force and thermal loading during flight. This phenomenon leads to a distinct ATE response that warrants researchers' attention.

This investigation examines the ATE response with respect to the mounting angles and internal structural configurations of control surfaces. By analyzing characteristic phenomena observed during hypersonic flight, the study explores the underlying force and thermal mechanisms acting upon control surfaces. These findings identify potential research directions and provide reference points and conceptual approaches for hypersonic vehicle design and ATE studies.

- [1] Ma, L., Wan, Z., and Wang, X., "Aerodynamic Load Characterisation of Hypersonic Rudders," In *2nd Aerospace Frontiers Conference*, Vol. II, Beijing, 2026.
- [2] Falkiewicz, N. J., Cesnik, C. E. S., Crowell, A. R., and McNamara, J. J., "Reduced-Order Aerothermoelastic Framework for Hypersonic Vehicle Control Simulation," *AIAA Journal*, Vol. 49, No. 8, 2011.