FLUID-THERMAL-STRUCTURAL INTERACTION ANALYSIS OF COMPLIANT PANELS UNDER HYPERSONIC FLOW WITH EXPERIMENTAL CORRELATION.

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ABSTRACT

The aeroelastic response of flexible structures subjected to hypersonic flow presents a complex multiphysics challenge, involving tightly coupled interactions among aerodynamics, structural dynamics, and thermal loads. With the increasing focus on high-speed vehicles operating under extreme conditions, the need for robust and accurate predictive models has become increasingly critical. Aeroelastic effects can compromise aerodynamic efficiency, accelerate structural fatigue, and reduce the operational lifespan of flight vehicles. Among these phenomena, flutter is particularly critical, as it can trigger dynamic instabilities that may ultimately lead to catastrophic structural failure.

This work is motivated by the fluid–thermal–structural interaction experiments conducted at the AFRL Mach 6 High Reynolds Number Facility (M6HRF) [1–2]. In the experiment reported in [1], the aeroelastic response of the panel is driven by pressure and temperature differentials, while the pressure induced by panel deformation has a negligible effect on the structural response. Consequently, the dominant effects to be captured are the thermal stresses and temperature variations resulting from aerodynamic heating. Numerical simulation of this experiment was performed as a preliminary step toward flutter analysis, enabling validation of the applied thermal loads and temperature-dependent material properties. For the conditions considered, the temperature dependence of the material properties was found to be insignificant.

The follow-on experiment reported in [2] introduced several improvements, including a longer wind tunnel run time, and a sealed and actively controlled cavity beneath the panel. The three different panel thicknesses, wide range of angles of attack, reduced panel width-to-length ratio, and various flow conditions (achieved by varying the freestream total pressure) explored in these experiments provide valuable data for exploring a range of aeroelastic phenomena. These measurements offer an opportunity to assess whether, and to what extent, the interplay between the flow boundary layer and the structural vibrations influences the aerothermoelastic response of thin panels in hypersonic flow.

This study seeks to bridge the gap between experimental observations and computational modeling by first considering a case in which thermal loads dominate the aerothermoelastic response [1], and subsequently incorporating aerodynamic unsteadiness to correlate with the experimental campaign reported in [2]. To this end, oblique shock relations and piston theory aerodynamics are coupled with Mindlin plate theory and nonlinear von Kármán strain–displacement relations. This formulation enables the structural model to capture nonlinear effects associated with large deflections of thin plates, while accounting for stresses induced by thermal expansion due to aerodynamic heating. The temperature field is obtained through conjugate heat transfer analyses to approximate the experimental results.

Therefore, this work expands the existing computational database through comparison with experimental results on the aeroelastic behavior of compliant panels undergoing both steady-state, large-amplitude oscillatory responses, and flutter. The results may improve the understanding of these phenomena and inform the design of future high-speed vehicles.

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[1] Riley, Z. B., Perez, R. A., & Ehrhardt, D. A. (2021). Response of a Thin Panel to Aerothermal Loading at Mach 6. *AIAA Journal*, *59*(9), 3787–3793.

[2] Riley, Z. B., Perez, R., & Brouwer, K. R. (2023, January 23). Design of Aerothermoelastic Experiments in the AFRL Mach 6 High Reynolds Number Facility. *AIAA SCITECH 2023 Forum*. AIAA SCITECH 2023 Forum, National Harbor, MD & Online.