AERO-THERMAL-ELASTIC ANALYSIS OF A PANEL IN SUPERSONIC FLOW WITH COUPLED NONUNIFORM HEAT TRANSFER

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ABSTRACT

Introduction

Aero-thermal-elasticity (ATE) deals with flexible structures exposed to significant thermal stress due to cooling or heating of the structure. In supersonic and hypersonic flows, the high stagnation temperature causes strong aerodynamic heat flux and ATE analyses become essential to capture the full extent of the physical phenomena. In its most basic form, ATE analyses are conducted in two stages. First the aero-thermal problem is solved for the rigid structure to obtain the temperature field over time. Then, the aeroelastic problem is solved using the temperature field at different time steps as input. A range of more elaborate approaches can be found in literature [1, 2]. The time-dependent nonuniform temperature field complicates the aeroelastic analysis and raises questions about the accuracy and computational efficiency of existing methods. For example, it is not always clear whether the flexible motion of the structure affects the aerodynamic heat flux. That is, can we assume the aero-thermal problem is one-way coupled to the aeroelastic system? If so, how large can the structural deformation or local wall velocity be for this assumption to still apply? The present work covers the first steps towards addressing these questions by applying the one-way aero-thermal analysis to the RC-19 thin panel test case [3].

Figure 1 shows the temperatures measured by Brouwer et al. [3] at the RC-19 wind tunnel (this set of results is from personal communications, but similar results were used in [3]). The temperature of the panel was measured near the spanwise edge and expected to be lower than the maximum temperature of the panel. The calculated temperature differential between the panel and the support are shown in green with a separate y-axis. It is shown that during the first 50 seconds of the test run, there is a rapid growth of temperature differential which is expected to buckle the thin panel. After the 50 seconds mark, the thermal stress is gradually alleviated as the support frame temperature catches up to the temperature of the panel. During this long test run, the panel is expected to buckle and reach a nonlinear static equilibrium which causes a shift in the structural natural frequencies. The combined ATE analysis to be conducted in this work is aimed at capturing this effect considering the nonuniform temperature distribution over the panel and the heat loss into the closed shallow cavity behind the panel.

The two key contributions of the present work are: (1) the RC-19 test case will be analysed from the start of the supersonic flow inside the test section to capture the possible hysteretic behaviour cause by the buckling and nonlinear deformation. Existing analyses of the RC-19 case typically consider the temperature field as input to the aeroelastic analysis however the results might be sensitive to the history of the aeroelastic system. We aim to analyze the gradual change from a panel in stable flat state to a post-buckled deformed state with flutter instability that appears during the test run [3]. And (2) the temperature field we consider for the thermal stress is spatially nonuniform and obtained by solving the heat transfer FEM problem across a 2.5D panel and a 3D cavity. The temperature obtained with our solver will be validated with the experimental data shown in Figure 1. The ATE analysis results obtained for the nonuniform thermal fields will be compared with the more common analysis in the literature of a uniform temperature differential.

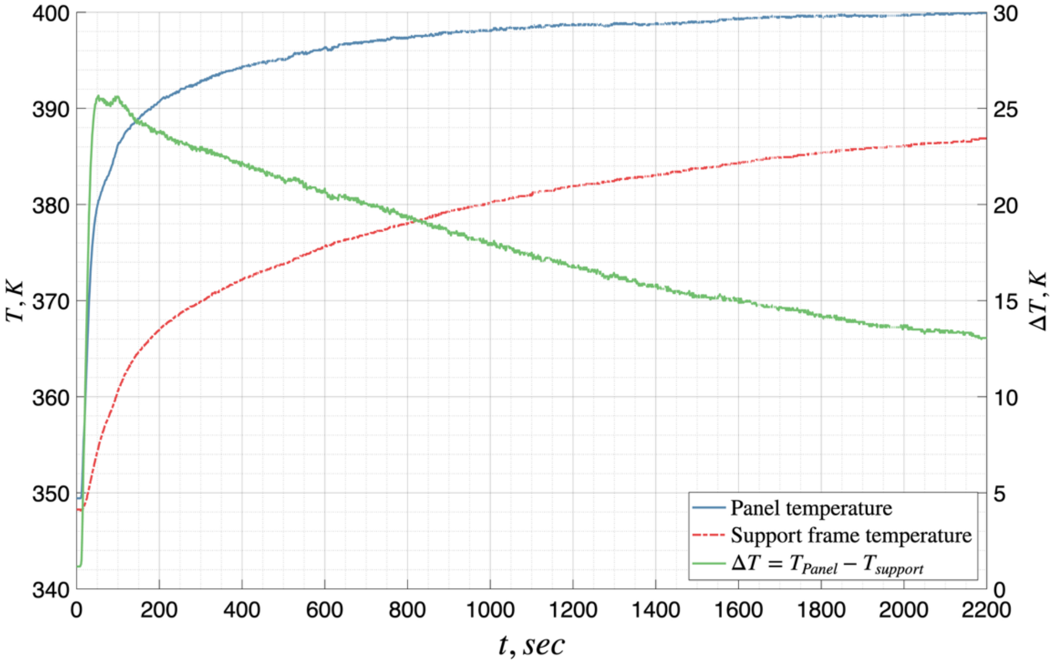

Figure 1 – Measured Panel (near the edge) and support temperature, and the calculated temperature differential vs. time for the RC-19 panel at Mach 2 and stagnation temperautre of 420K [3].

Methodology and Results

The following are the different components of our ATE analysis.

- **Heat transfer inside the panel** – a Finite Element (FE) model will be formulated as a 2.5D problem for the heat conduction in the x and y directions across the plate with heat flux into the panel from the high-speed flow and heat loss into the closed shallow cavity.
- **Heat transfer inside the cavity** – a 3D FE model for the shallow cavity will be formulated with temperature continuity condition at the elastic panel wall. The two FE models are combined into a single system of equations and time marched simultaneously.
- **The aerodynamic heat flux** from the Mach 2 flow will be modelled in two levels of complexity. The first is Eckert's reference temperature method, and the second is from Computational Fluid Dynamics (CFD) simulations. The EZAir solver will be used to obtain the aerodynamic heat flux distribution across the panel. EZAir a structured RANS solver developed by ISCFDC.
- **Structural model –** a thin elastic panel in Rayleigh-Ritz formulation with geometric nonlinearity will be used.
- **Unsteady aerodynamics** – the linear Piston Theory (LPT) will be used for the aeroelastic analysis.

The following analyses and investigations are planned to be conducted.

- **Thermal model validation by comparison to experimental data from RC-19 –** the accuracy of Eckert’s reference temperature method will be compared with RANS CFD. The effect of heat radiation from the panel to the cavity will be investigated. The effect of cavity depth on heat loss will be investigated.

- **ATE analysis** – with the solution of the thermal problem, the temperature fields at different time steps will be used as input to the frequency domain aeroelastic analysis with nonlinear static equilibrium. The thin panel is expected to buckle at a relatively low temperature differential due its small thickness. **Thus, a nonlinear static solution will be obtained for each thermal problem time step.** The structure will be analysed about its deformed equilibrium with coupled aerodynamics to obtain the aeroelastic natural frequencies, damping ratios, and mode shapes. The ATE analysis will be carried out for the different configurations of the thermal problems (cavity depths, aerodynamic heat flux models) to investigate the sensitivity of the coupled system to those parameters.

The above results will support our future work in which we aim to study the sensitivity of the aerodynamic heat flux to structural motion. The goal is to develop an ATE analysis framework that adapts the level of coupling (one or two way) of the thermal problem as the structure undergoes different phases (stable, buckled, large deflections, etc.).

References

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