Title: Reconstruction and Uncertainty Quantification of Atmospheric Entry Heat Loads Using a Green's Function Approach

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Abstract

During the post-flight analysis of atmospheric entry spacecraft, reconstructions of the surface heating conditions are critical to investigate aerothermal phenomena, evaluate the performance of thermal protection systems (TPS), and validate computational models. In this work, a novel Green's function inverse heat transfer (IHT) algorithm is used to analyze the heating conditions on atmospheric entry spacecraft from TPS-embedded temperature probe measurements. The approach efficiently couples the subsurface temperature time-history with the surface heat flux boundary condition, allowing for direct calculation of the surface heating conditions in only a few ($\mathcal{O}(10)$) operations [1]. As a result of the algorithm's low computational overhead, reconstructed heating conditions can be generated up to 3 orders-of-magnitude faster than current IHT methods, positioning it well for use in computationally intensive analyses, such as uncertainty quantification, where current methods are often resource-limited [2,3].

The Green's function approach was used to reconstruct the heating conditions on the backshell of the Mars 2020 entry spacecraft and characterize the dynamic uncertainty contributions of the input parameters to the total reconstruction uncertainties. The reconstructed heating conditions were benchmarked against those calculated using a state-of-the-art IHT code, FIAT_Opt [3], and showed excellent agreement. A Monte Carlo simulation was used to calculate the total uncertainties of the reconstructed heating conditions subject to uncertainties in the algorithm input parameters. The individual contributions of the input parameter uncertainties to the uncertainties of the reconstructed heating conditions were quantified by calculating total Sobol indices via a Monte Carlo estimator. The input parameters included the thermal conductivity, specific heat, density, and emissivity of the TPS and the temperature probe depth. Notably, total Sobol indices were calculated for the full flight duration, exposing regions of both steady and dynamic behavior of the input parameter uncertainty contributions.

The uncertainties of the reconstructed heating conditions are maximum within the peak heating region, with 95% confidence interval margins as high as 2.3 W/cm^2 (46% peak heat flux). Up to the peak heating region, the reconstruction uncertainties are dominated by the uncertainty in the specific heat. This is attributed to a large sensitivity of the transient thermal response of the TPS to its thermal mass. Beyond the peak heating region, the uncertainty contributions vary significantly; as the heat loads decrease, the reconstruction uncertainties become strongly influenced by the uncertainty in the thermal conductivity. This region is characterized by a significant rate of diffusion of thermal energy from the near-surface hot region into the inner TPS, governed by the thermal conductivity. As the TPS cools, the uncertainty in the emissivity begins to dominate the reconstruction uncertainties, with peak contributions coinciding with adiabatic wall conditions.

These results highlight how the post-flight reconstruction uncertainties of atmospheric entry heating conditions are dynamically sensitive to uncertainties in the different input parameters throughout the entry heat pulse. Furthermore, they show how the main drivers of the reconstruction uncertainties correspond with different heating regimes, which can be used to inform similar analyses in different mission architectures.

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References

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