A Surrogate-Based Uncertainty Quantification Framework for Hypersonic Cone–Flare RANS Simulations

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Deterministic CFD predictions of hypersonic cone–flare shock–boundary-layer interaction (SBLI) can vary significantly even for canonical benchmark cases. This work quantifies how aleatory variability in freestream conditions, wall temperature, transport parameters, and nose bluntness propagates to design-relevant quantities of interest (QoIs).

Seven inputs are treated as random:

$$\mathbf{x} = [M_\infty,\ p_\infty,\ T_\infty,\ T_w,\ Pr_l,\ Pr_t,\ b]\,.$$

Freestream quantities, wall temperature, and laminar Prandtl number Pr_l are modeled as lognormal, turbulent Prandtl number Pr_t as uniform on $[0.7, 1]$, and bluntness via a bounded beta distribution.

A non-intrusive uncertainty propagation framework couples SU2 (steady compressible RANS with SST turbulence model) to DAKOTA. Latin Hypercube Sampling generates 269 realizations of the seven-dimensional input space. From each simulation, six QoIs are extracted: maximum wall temperature and pressure (and their locations), flow separation location, and integrated wall heat flux.

Kriging (Gaussian process) surrogate models with Matérn kernels are constructed for each QoI and refined through Bayesian adaptive sampling. After validation ($R^2 > 0.98$), 75,000 Monte Carlo evaluations of the surrogate enable efficient estimation of probability distributions and Sobol global sensitivity indices.

Results show that peak pressure magnitude is dominated by Mach number, consistent with compressible shock scaling, with secondary influence from freestream pressure. Thermal responses exhibit stronger dependence on boundary-layer thermodynamics.

Flow separation location is highly sensitive to wall temperature, indicating that near-wall thermodynamic state governs boundary-layer robustness and detachment onset more than freestream variability within the explored range. For most QoIs, first-order and total Sobol indices are similar, suggesting predominantly additive effects.

This study demonstrates a reproducible surrogate-based UQ workflow for hypersonic cone-flare RANS simulations. The findings highlight the importance of boundary-layer thermodynamics in SBLI-dominated hypersonic flows and motivate future extension to epistemic model-form and numerical uncertainty.

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