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Abstract We present a numerical study on the uncertainty quantification (UQ) of aerodynamic forces acting on a hypersonic trailing-edge flap model, as a result of input uncertainties in the experimental boundary conditions. The complex fluid-thermal-structural interaction on aerodynamic surfaces of a hypersonic flight vehicle and fluctuations in flow conditions result in uncertainties in their aerodynamic characteristics. We run the numerical simulations in US3D to quantify these uncertainties. Altogether four input uncertain parameters—inlet flow velocity, density, temperature, and the model wall temperature—are considered. We obtain the aerodynamic forces from the primal solve, as well as gradient information from a dedicated sensitivity solver. We compare the surrogate-based UQ analysis using kriging as well as gradient-enhanced kriging (GEK), accounting for significant observation errors in the gradients, and quantify the accuracy of the output probability density function (PDF). The accuracy of the predicted output PDF converges faster for GEK than for kriging, implying the importance of the gradient information in order to reduce the computational cost—in the present case, the computational cost is reduced by a median speed-up of roughly 3.0 by exploiting the gradient information available from the sensitivity solver.

Keywords Hypersonic · Control surface · CFD · Uncertainty quantification · Gradient-enhanced kriging

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1 Introduction

The quantification of uncertainty (UQ) of the quantity of interest (QoI) of computational fluid dynamics (CFD) simulations has received much interest in recent literature. Given the high computational cost of Monte Carlo simulations [1], many studies have looked into surrogate-based UQ. However, the cost of a surrogate-based UQ analysis can still increase rapidly with an increasing number of uncertain variables, an effect known as the 'curse of dimensionality' [2].

In a review paper on UQ for computer predictions, Oden et al. [3, 4] state that:

> "A promising approach for addressing these computational [cost] issues is to use more information about the structure of the physical model than is available from simple point evaluations of the input-output map. In particular, algorithms now being developed use derivatives of the QoI's with respect to the uncertain inputs."

As an approach to utilise such derivative information, gradient-enhanced kriging (GEK) aims to improve the accuracy of the kriging surrogate prediction. This potentially improves computational efficiency when the gradients are obtained from an adjoint solver [5–14],