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Forward and backward uncertainty quantification for atmospheric reentry flows

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Simulation of aerospace applications, such as atmospheric entries of spacecraft, are challenging problems involving many complex physical phenomena, including rarefied gas effects, aerothermochemistry, radiation, and the response of thermal protection materials to extreme conditions. Reliable predictions require sophisticated physico-chemical models as well as a systematic and comprehensive treatment of model calibration and validation, including the quantification of a very large set of uncertainties inherent in such models. In fact, several sources of uncertainties have to be considered: chemistry model parameters and freestream conditions have to be considered as uncertain input parameters in the forward problems. Moreover, in reacting flows, several constitutive relations are required to describe the chemical mechanism characterizing the gas mixture, each of which contains a large number of parameters. Another challenge is to handle experimental data, since some could be difficult to obtain, especially in-flight measurements of entering space vehicles. For example, during the reentry trajectory of a space vehicle, it is extremely challenging to obtain direct measurements of freestream quantities (velocity and thermodynamic state of the atmosphere), due to the presence of a strong bow shock in front of the vehicle nose. However, these quantities are of relevant importance in both post-flight analysis, to get accurate values of the actual flight trajectory and atmospheric conditions, and during the flight to be able to make adequate real-time corrections in case of manned flights.

The focus of the study presented here is to assess the interest in using heat flux measurements, which are available in recent space missions, for rebuilding freestream conditions, requiring the set-up of multiple numerical tools for tackling several issues which are analyzed and cured here. In this talk, we will first introduce and apply two techniques for tackling this problem featuring a large number of uncertainties and expensive high-fidelity numerical simulation. The first technique relies on a sparse Polynomial Dimensional Decomposition approach. Due to the intimate connection between the PDD and the Analysis of Variance (ANOVA) approaches, PDD is able to provide a simpler and more direct evaluation of the Sobol' sensitivity indices, when compared to the Polynomial Chaos expansion (PC). The second technique is based on the construction of an Active Subspaces, in order to find a low-dimensional dependence structures in the input-to-output map of the forward numerical solver. Here, we will present a different angle on the active subspace-based approach. Instead of using the gradient of the log-likelihood to define the active subspace, we find an independent subspace for each of the parameter-to-observable maps, that we combine for a data-informed subspace. Finally, a Bayesian calibration of the free stream parameters of a hypersonic flow will be performed using both experimental and synthetic data, by exploiting active subspaces for the reduction of the dimensionality of the input space. Bayesian inversion will be then used to assess the feasibility in using measurements of pressure and heat flux at the stagnation point for rebuilding freestream velocity and density.

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