

Sensitivity of Predicted Ablation Rates to Uncertain Parameter Variation

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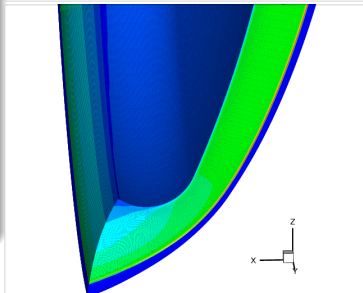
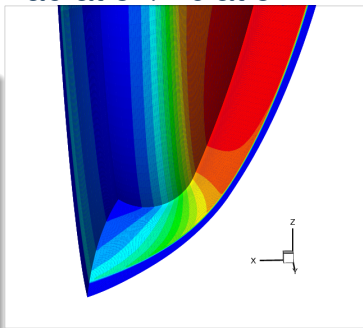
September 30, 2009

Uncertainty in Coupled Flow/Radiation/Ablation

Submodel Uncertainties

- Hypersonic Flow
 - ▶ Trajectory peak heating point
 - Velocity
 - Freestream conditions
 - ▶ Chemical reaction rates
 - ▶ Diffusive fluxes
 - ▶ Turbulent mixing
- Radiation
 - ▶ Absorptivity
 - ▶ Model Error
- Ablation
 - ▶ Virgin, char densities
 - ▶ Reaction rates, equilibria

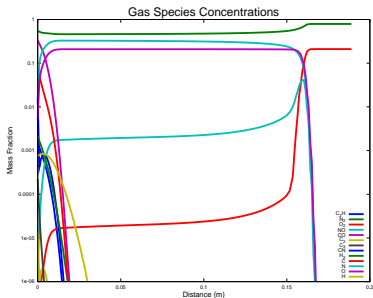
~ 300 *independent parameters*



Parameter Sampling and Coupling

Simulation Coupling

- Coupled
 - ▶ Submodel sensitivities amplified or dampened
 - ▶ Sensitivities to parameters absent from submodels
- Fully Coupled
 - ▶ Changes in radiation, ablation feed back to flow solver
 - ▶ Every parameter change requires full re-solve
- Loosely Coupled
 - ▶ Convergence to off-baseline solution is linear
 - ▶ Automatic discretized adjoints are unavailable



Parameter Study Automation

Parametric Study Setup

- Off-baseline perturbations resume from hand-converged baseline
- Custom build script creates samples
- Modified Dakota preprocessor builds input files
- Makefile-based job submission, lonestar/hera options
- Automatic detection/resumption of failed runs

Postprocessing

- Quantities of interest from DPLR, coupling enhancements, `postflow`
- “make summarize” - extraction, collection, calculations
- Makefile-based job submission, lonestar/hera options

Insensitivities

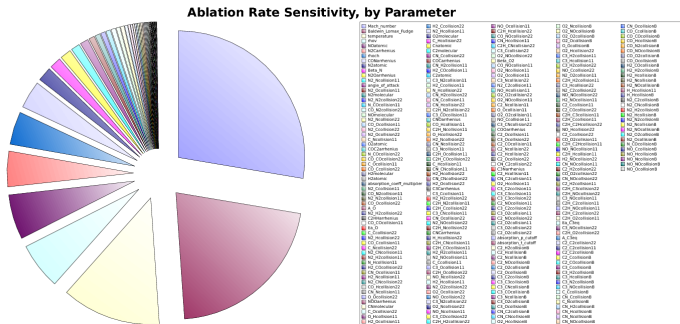
“Curse of Dimensionality”

- Advanced UQ techniques can converge much faster than Monte Carlo
- But cost is exponential in number of independent parameters!
- With a priori knowledge we could:
 - ▶ Truncate parameter series
 - ▶ Sample anisotropically

Calibration/Validation

- Data \rightarrow Model \rightarrow Prediction
- Equally uncertain parameters may not be equally important
- Parameter sensitivities inform model development, data collection

Insensitivities

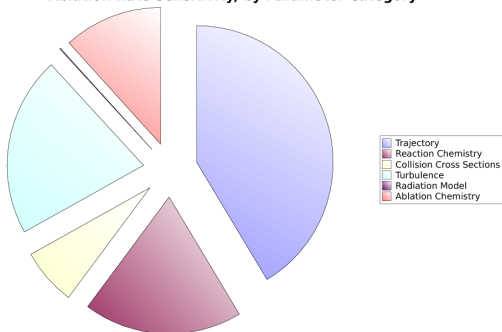


Not all uncertain parameters are equal

- ~ 300 parameters
- > 150 parameters negligible to within numerical error
- < 30 parameters account for 95%+ uncertainty

Sensitivities

Ablation Rate Sensitivity, by Parameter Category



Current Questions:

- Trajectory Uncertainty?
- Radiation: $\mathcal{O}(V^8)$?
- Model error: radiation, turbulence

Adjoint-based Sensitivity Analysis

Primal Problem

$$\mathcal{R}(u(p), v; p) \equiv 0 \quad \forall v$$

$$\frac{d\mathcal{R}}{dp} = 0$$

$$\frac{\partial \mathcal{R}}{\partial p} + \frac{\partial \mathcal{R}}{\partial u} \frac{\partial u}{\partial p} = 0$$

Adjoint-based Sensitivity Analysis

Primal Problem

$$\begin{aligned} \mathcal{R}(u(p), v; p) &\equiv 0 \quad \forall v \\ \frac{d\mathcal{R}}{dp} &= 0 \\ \frac{\partial \mathcal{R}}{\partial p} + \frac{\partial \mathcal{R}}{\partial u} \frac{\partial u}{\partial p} &= 0 \end{aligned}$$

Adjoint Problem

$$\begin{aligned} \frac{\partial Q(u; p)}{\partial u} &\equiv \frac{\partial \mathcal{R}(u, \phi(u, p); p)}{\partial u} \\ q' &\equiv \frac{dQ(u; p)}{dp} \\ &= \frac{\partial Q}{\partial p} - \frac{\partial \mathcal{R}(u, \phi(u, p))}{\partial p} \end{aligned}$$

Adjoint-based Sensitivity Analysis

Primal Problem

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Costs

- Forward solution expensive: One full solve per parameter
- Adjoint solution efficient: Just one linear solve
- Forward implementation simple: requires residual
- Adjoint implementation complicated: *requires full Jacobian*

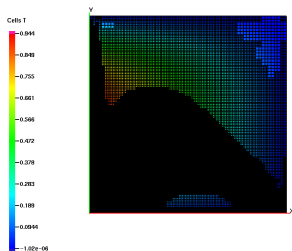
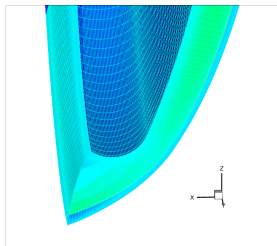
Ongoing activities

Sensitivity Studies

- Grid refinement, alignment studies
- Lunar return study

Sensitivity Capabilities

- Adjoint solver verification
- Flow, ablation adjoint solves



Thank you. Any questions?