A Reduced Order Modeling Approach to the Dynamic Stability Analysis of Blunt-Body Entry Vehicles

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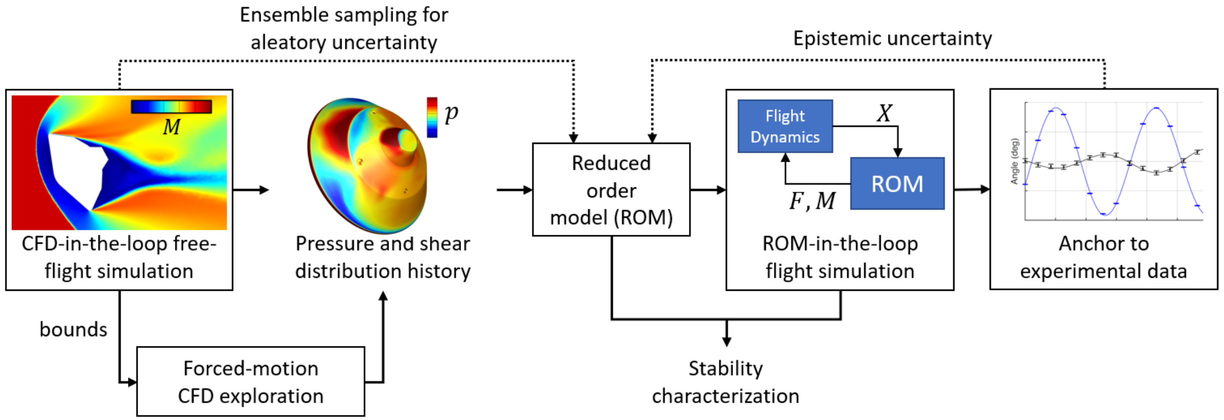

Figure: ROM-based methodology accounting for both aleatory and epistemic uncertainty

Approach:

1. Sampling from CFD-in-the-loop flight simulation
   - Free-flight runs to bound design of experiments
   - Forced motion CFD simulations to explore design space
2. Dimensionality reduction and regression
   - Train ROMs on pressure and shear distributions
   - Construct regression map to state variables (M, α, $\hat{q}$, etc.)
3. Dynamic Stability analysis
   - Implement ROMs in POST2 trajectory propagator
   - Direct differentiation of ROMs to obtain instantaneous stability characteristics
4. Bayesian calibration for uncertainty quantification
   - Calibration against wind tunnel and ballistic range data

Research Objectives:

- Improve the state of the art for understanding and predicting the dynamic behavior of entry vehicles
- Create reduced order models (ROMs) of the fore- and afterbody pressure and shear force distributions
  - Recover physically consistent flow fields from proper orthogonal decomposition (POD) modes
- Replace linearized aerodynamic databases with ROMs, preserving more aerodynamic information and eliminating linearization assumptions
- Capture the effects of physically-correlated aleatory and epistemic uncertainty
- Advance the methodology incorporating POD, ROM, and Bayesian calibration from initial TRL 2 to TRL 3

Impact:

- Validate the use of ROMs for entry vehicle aerodynamic prediction
- Eliminate linearized derivatives and simplifying assumptions from aerodynamic model
- Enable the direct evaluation of dynamic stability as a function of vehicle state and flow conditions
- Improve the ability to analyze/visualize coherent structures
- Understand the underlying coherent structures in the flow that drive dynamic responses
- Demonstrate applicability to aerodynamic modeling of forces and moments beyond pitch damping