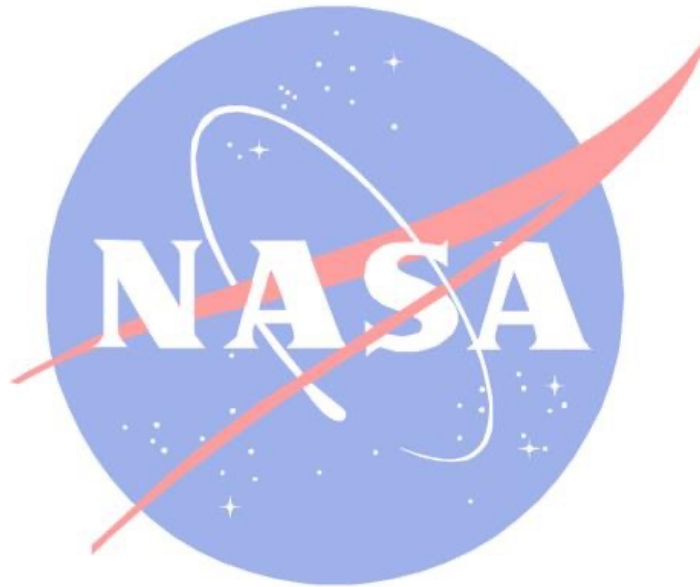


Gradient-Enhanced Reliability Analysis of Transonic Aeroelastic Flutter

AIAA SciTech Conference: Jan. 4th, 2022



Bret Stanford: NASA LaRC, Aeroelasticity Branch

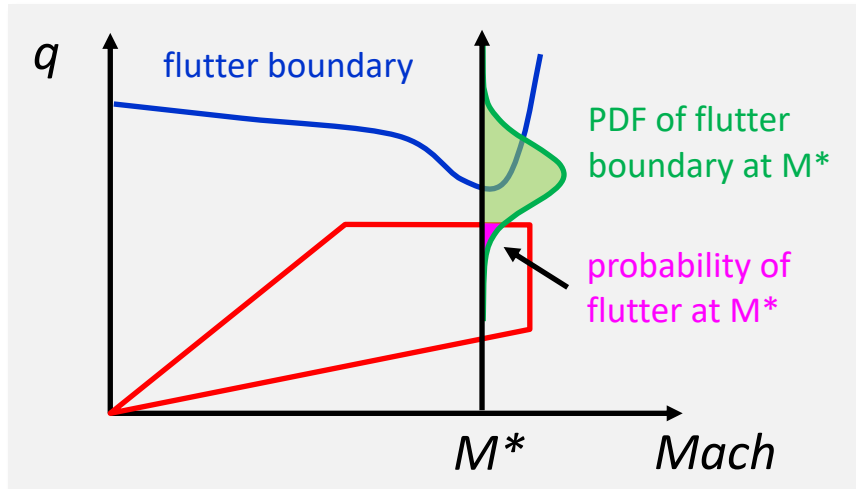
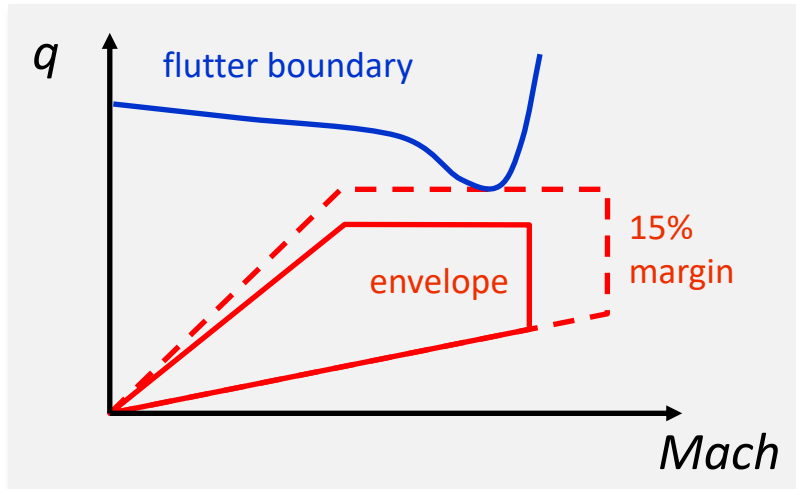
Annie Sauer: Virginia Tech, Department of Statistics

Kevin Jacobson : NASA LaRC, Aeroelasticity Branch

Jim Warner: Durability, Damage Tolerance, and Reliability Branch



Flutter Margin



- ◆ 15% flutter margin is empirical
 - Too conservative sometimes, other times not conservative enough
- ◆ Transonic flutter dip is very sensitive to parametric uncertainties and modeling uncertainties

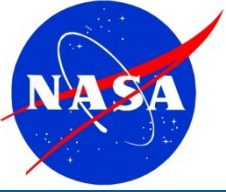


Goals and Challenges

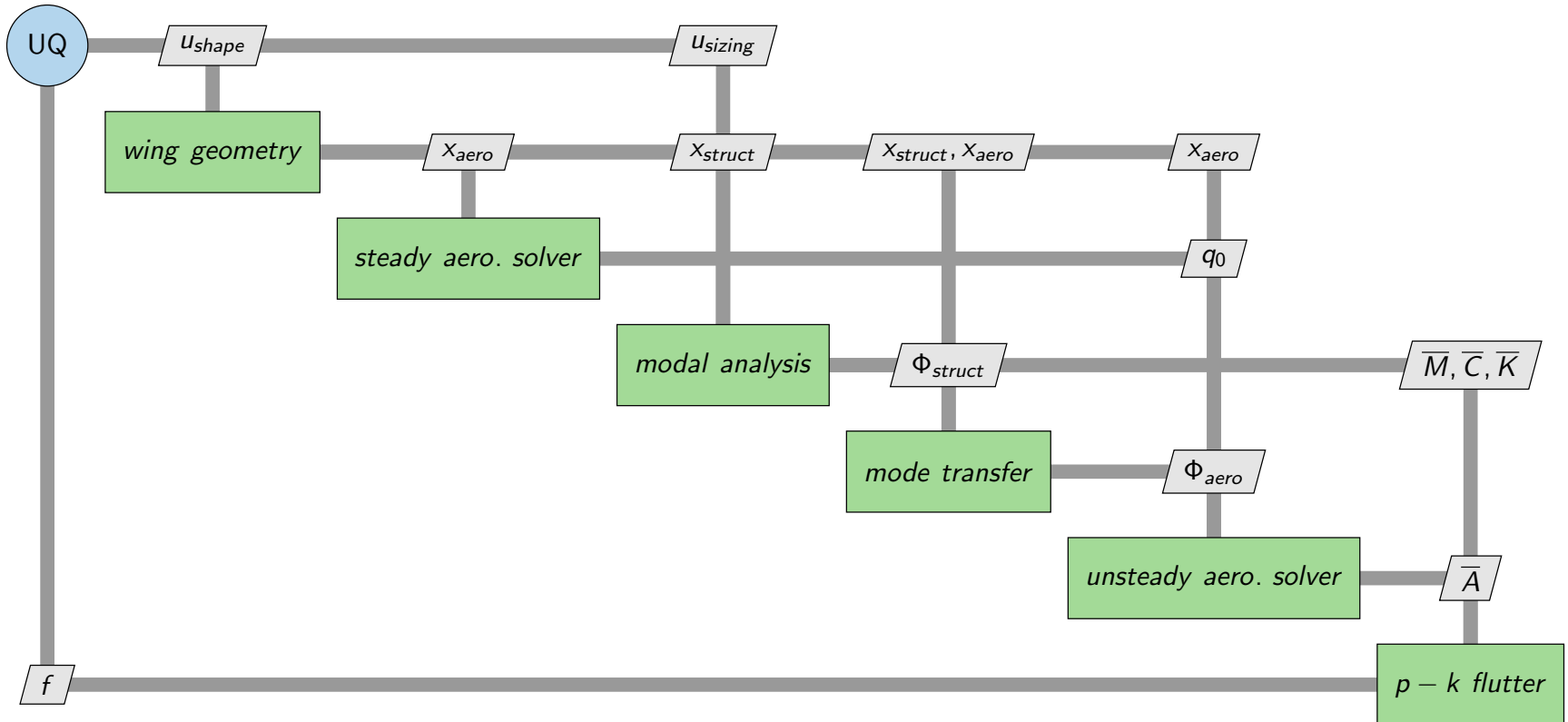


1. Difficult and expensive to efficiently predict transonic flutter
2. Uncertainty quantification is expensive
3. Difficult to predict small probabilities of failure

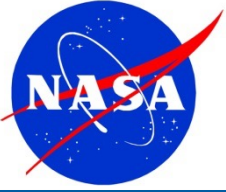
Focus on UQ tools that can utilize gradient information (derivative of flutter boundary with respect to random variables)



Transonic Aeroelastic Computations



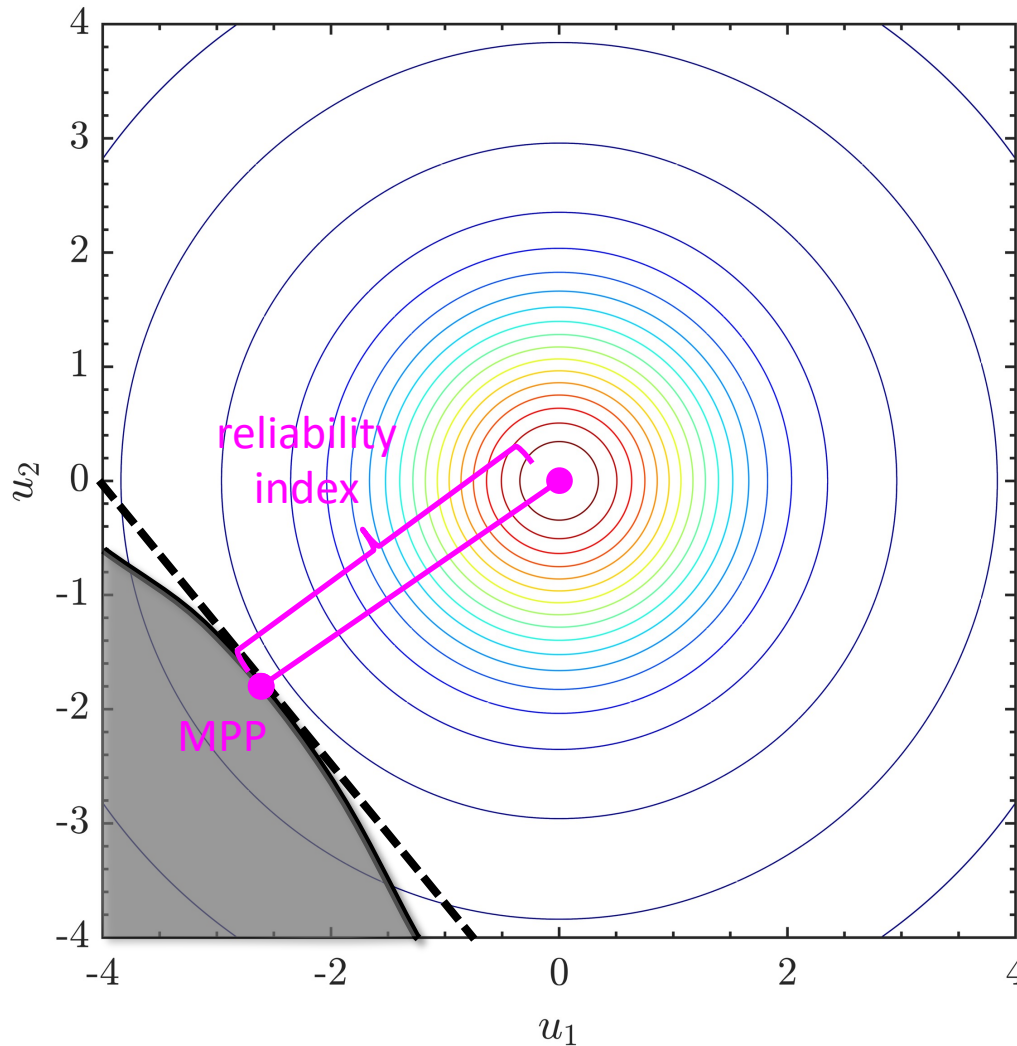
Aeroelastic coupling and derivatives handled with OpenMDAO and Mphys



- ◆ Two fidelities for the aerodynamics:
 1. Low fidelity: doublet lattice method (DLM)
 - ~1 minute wall time
 2. High fidelity: computational fluid dynamics (CFD)
 - Linearized frequency domain (LFD) solver in FUN3D / SFE
 - ~1 hour wall time
- ◆ Two fidelities are never used at the same time
 - Just two different testbeds for exercising UQ tools



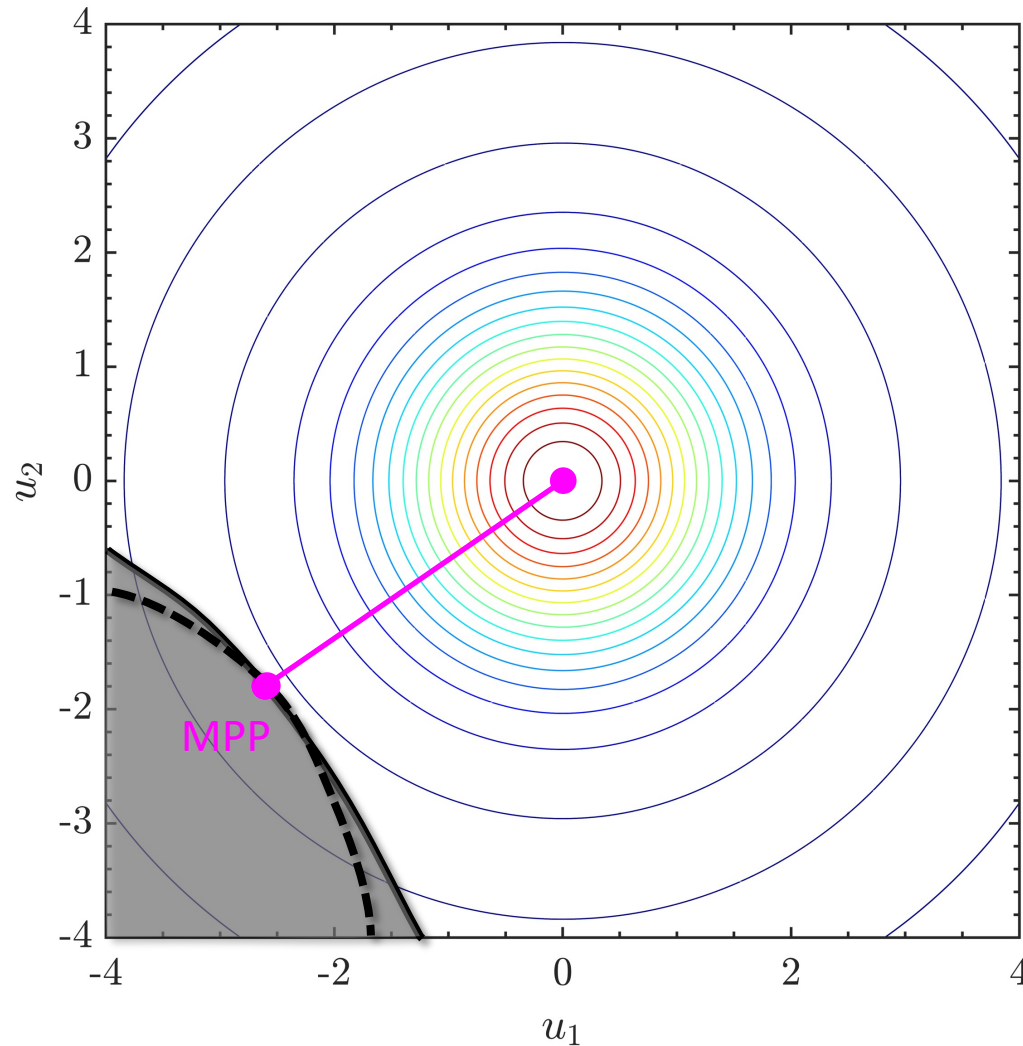
First-Order Reliability Method



1. Locate MPP in standard normal space (gradient search)
2. Distance between origin and MPP is the reliability index = β
3. $P_f = \text{CDF}(-\beta)$
4. Assumes failure surface is linear



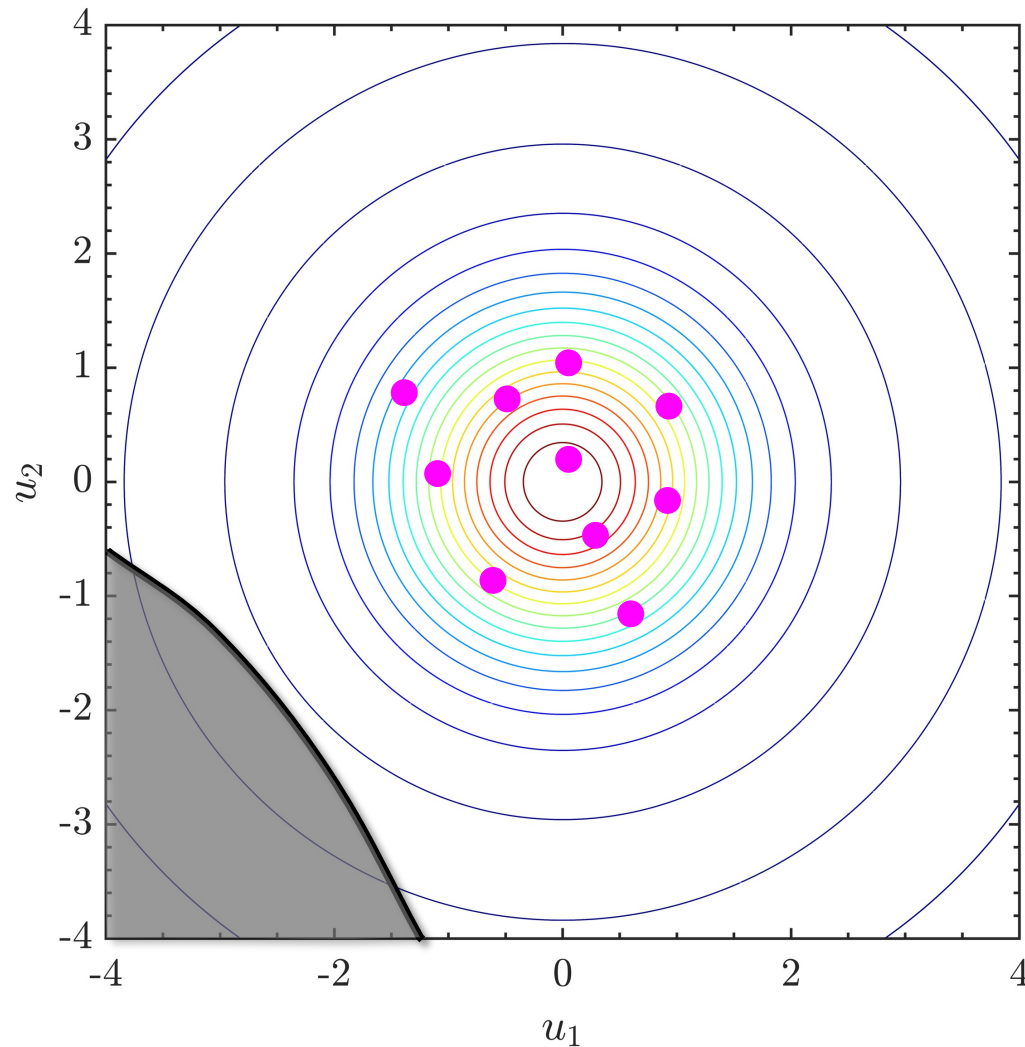
Second-Order Reliability Method



1. Corrects P_f computation with Hessian curvatures
2. Hessian approximated during MPP search



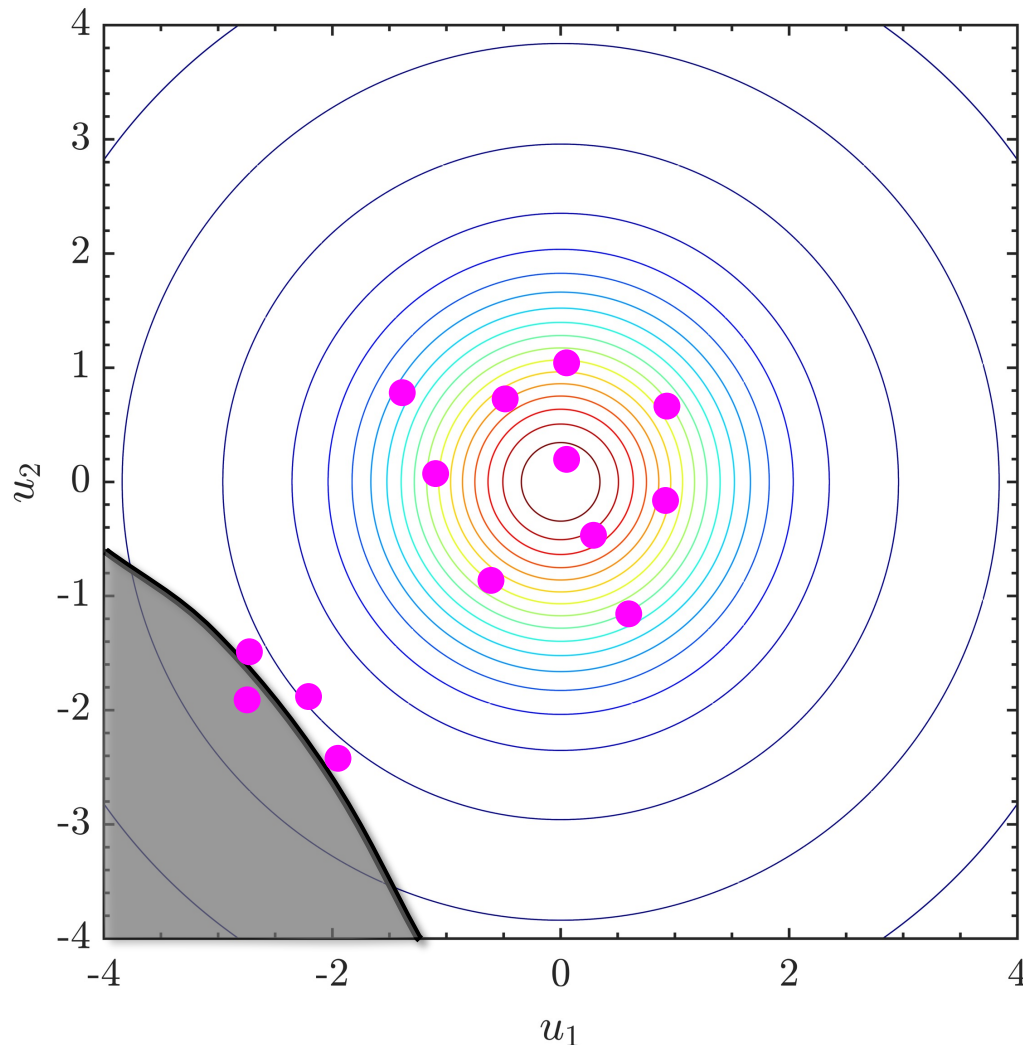
Polynomial Chaos Expansion (NIPC)



1. Sample data through RV space: LHS
2. Fit data with basis functions (Hermite polynomials)
 - Least squares
 - Gradient-enhancements
3. Use surrogates to estimate statistics
 - Mean-centered, so P_f predictions may be poor



Gaussian Process w/ ECL



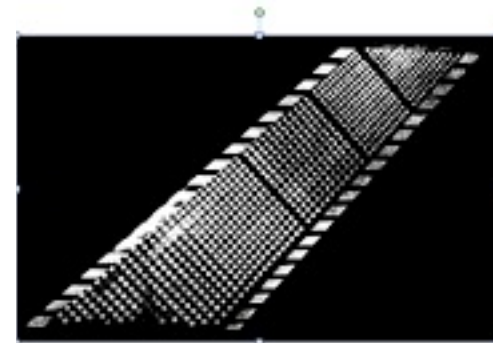
1. Sample data through RV space: LHS
2. Fit data with a GP
 - Gradient-enhancement
3. Closed-form expression for P_f available throughout the u -space
4. Compute entropy:
 - $E(u) = -P_f(u) \cdot \log(P_f(u)) - (1-P_f(u)) \cdot \log(1-P_f(u))$
5. Find the point in the u -space which maximizes E , add it to the samples
6. Repeat



- ◆ ECL samples are added until process converges, or sampling budget is expended
- ◆ Final P_f computed by a MCS of the inexpensive GP surrogate, and averaging the P_f at every sample
 - ...unless P_f is really small, in which case multifidelity importance sampling is used
- ◆ Final P_f computation will be better than PCE, since we have samples near the failure boundary

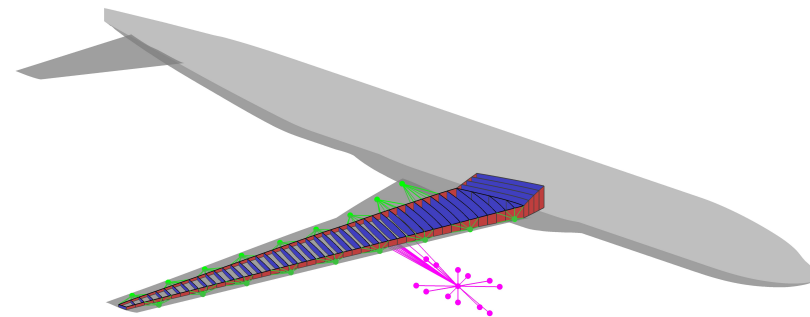
1. AGARD 445.6

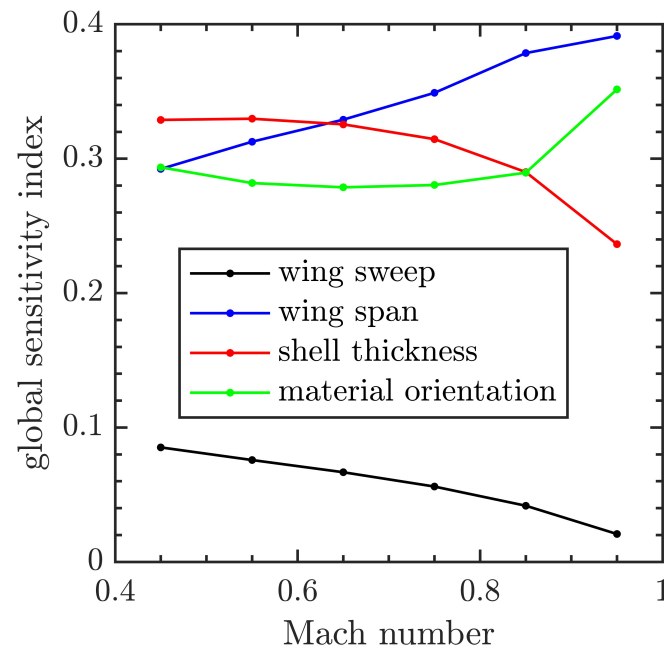
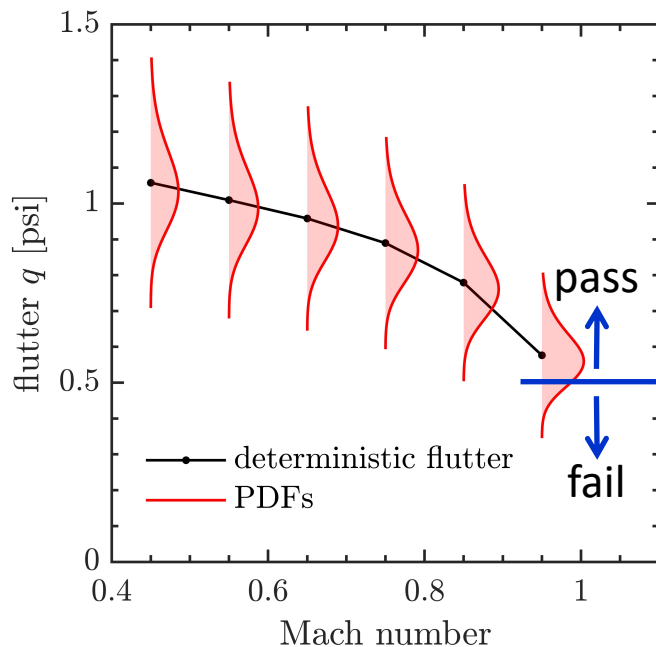
- DLM-based results
- CFD-based results
- All UQ methods exercised



2. Common Research Model

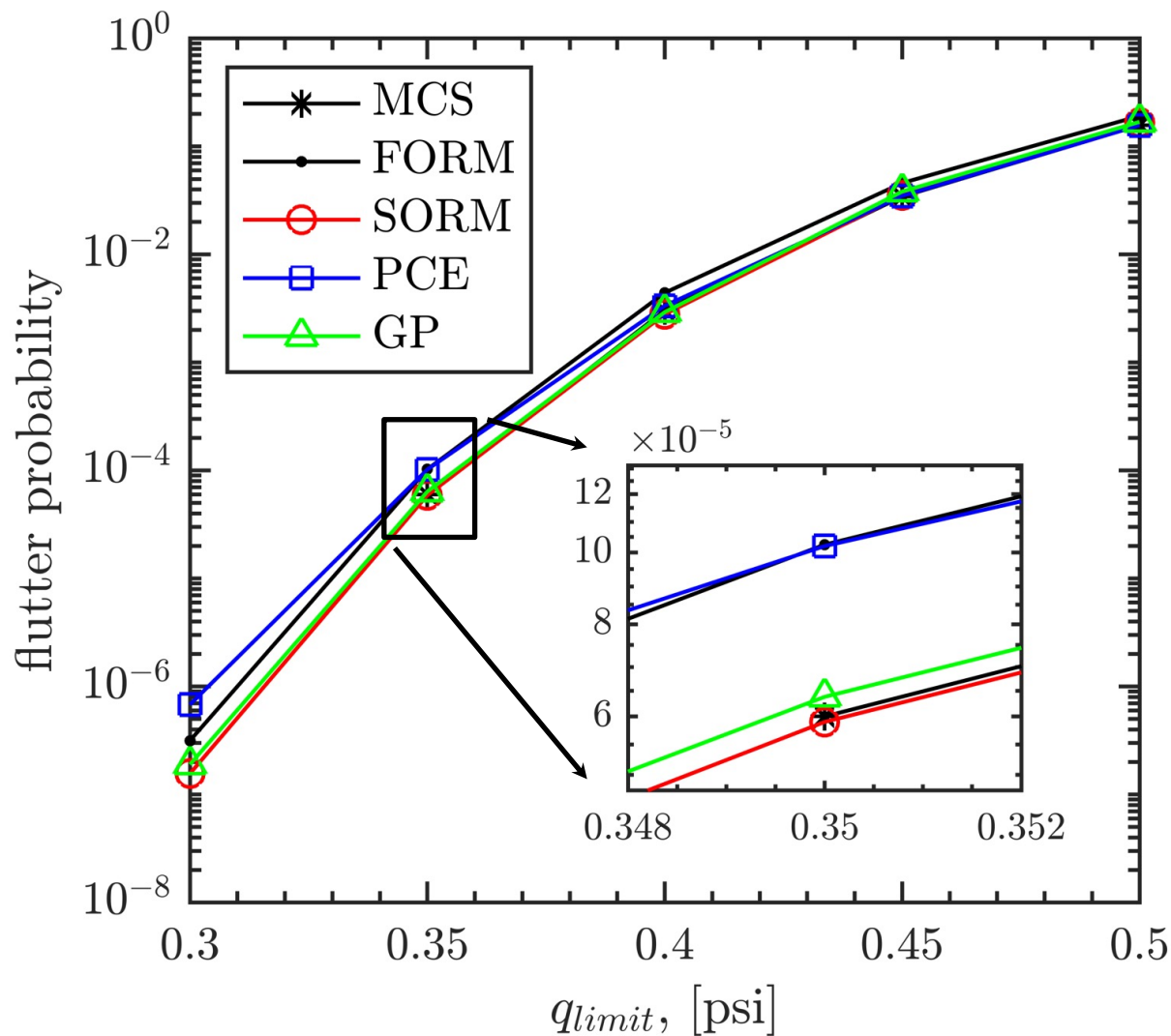
- CFD-based results only
- PCE-based results only





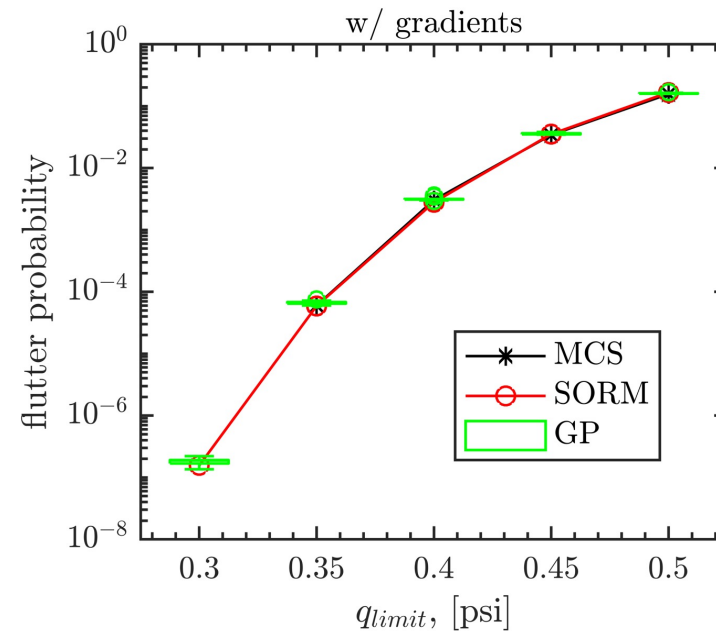
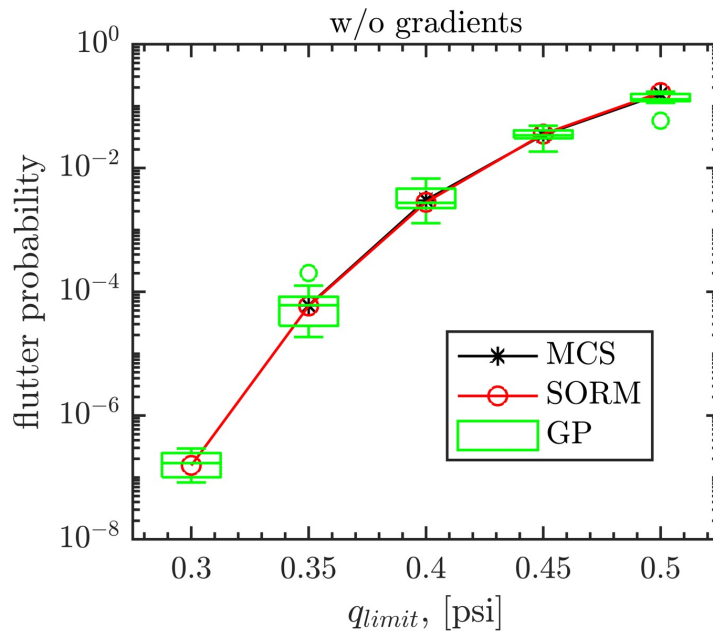
◆ Reliability analysis:

- Mach 0.95
- Flutter- q failure boundary swept between:
 - 0.5 psi (large P_f)
 - 0.3 psi (small P_f)

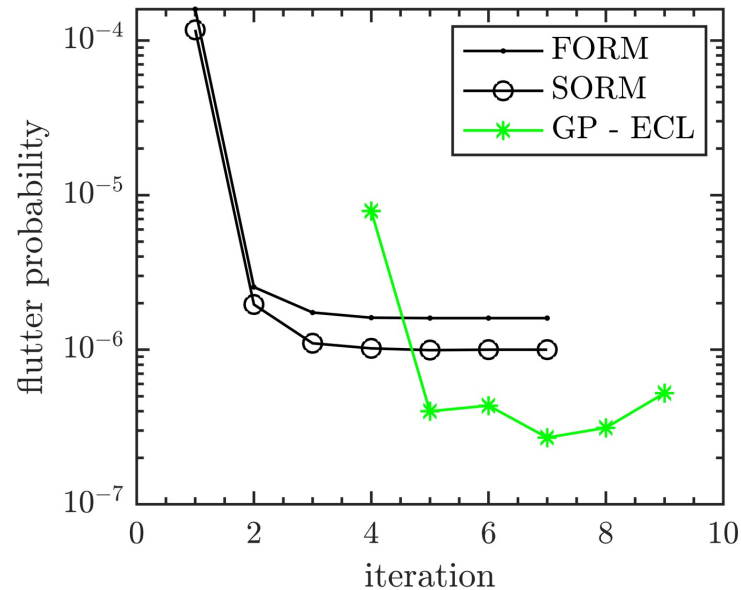
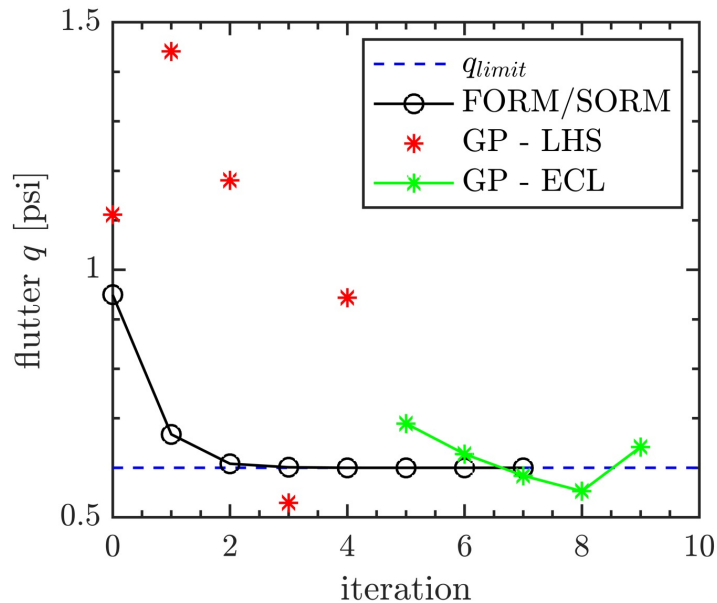




GP / ECL Repeatability



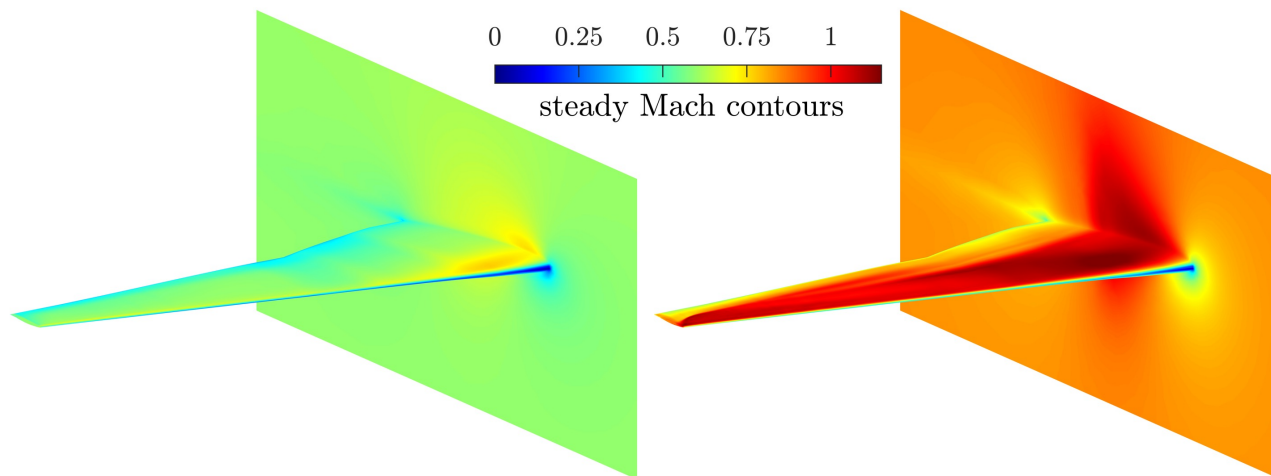
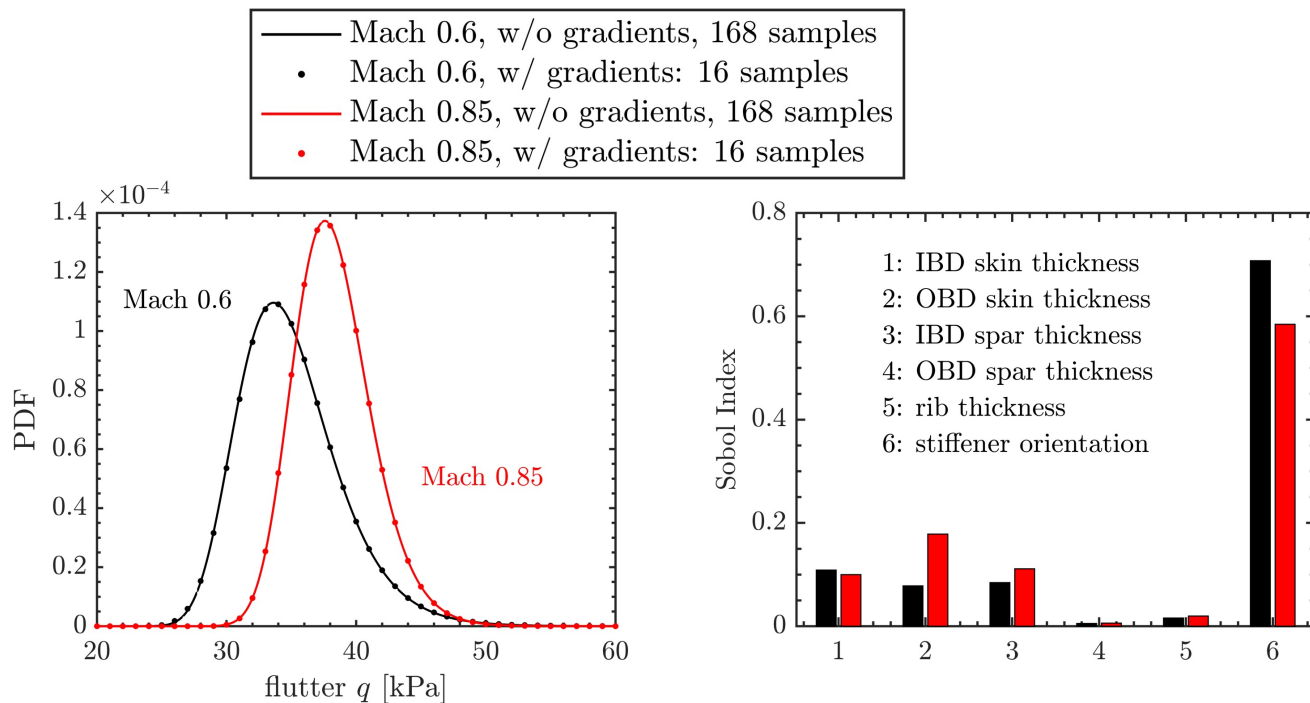
- ◆ 5 initial LHS samples, followed by 15 ECL steps
- ◆ 10 separate trials

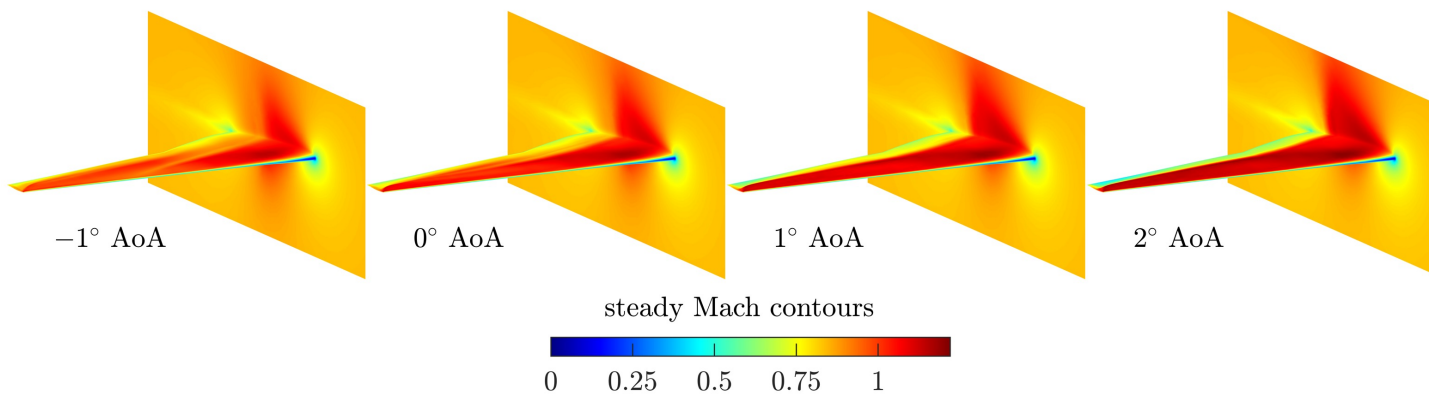
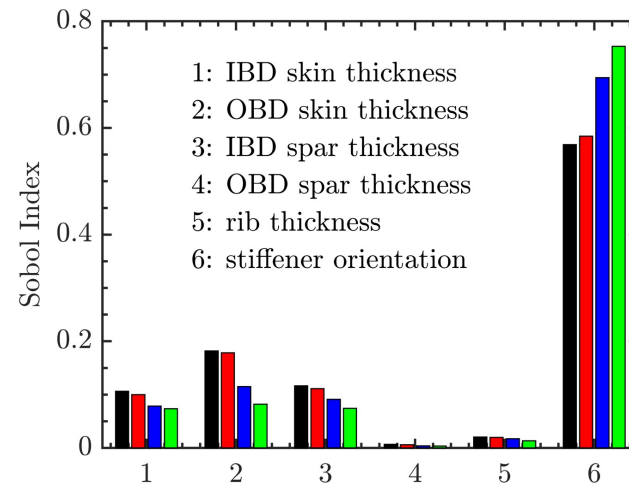
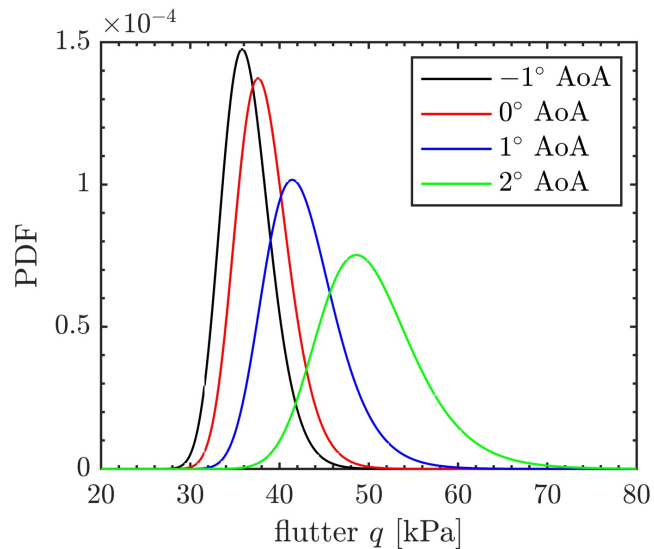


- ◆ GP/ECL: 5 LHS samples followed by 5 ECL steps
- ◆ FORM/SORM: largely converges in 5-6 steps
- ◆ Differences between SORM- P_f and GP- P_f
 - “True” answer is unknown, since CFD solver is too expensive for MCS



CRM PCE Results

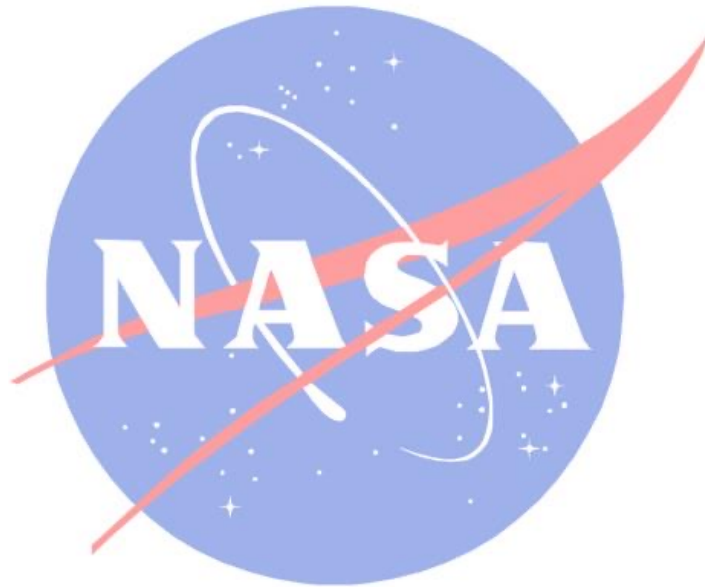






- ◆ AGARD and CRM UQ results
 - CRM results are more preliminary, no reliability computations yet
- ◆ Focus on UQ methods which can benefit from the existence of gradients (PCE, GP/ECL)
 - ...or rely entirely on the existence of gradients (FORM/SORM)
- ◆ SORM is giving the best results:
 - Converges quickly
 - Closest P_f values to the “truth” model (MCS), when MCS is available
- ◆ But: for future problems of interest with stronger nonlinearities in the flutter surface (transonic CRM), expectation is that GP/ECL will be superior
 - GP further can benefit from parallel computing environments (multiple entropy additions per step)
 - SORM is inherently sequential

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