Online Uncertainty Propagation via Monte Carlo Simulation in the AEDC Wind Tunnels

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Arnold Engineering Development Complex (AEDC)

- Most advanced and largest complex of flight simulation test facilities in the world
- 28 test cells (wind tunnels, rocket/turbine cells, space chambers, etc…)
- 14 test cells are unique in the world

Propulsion Wind Tunnel (PWT) Facility

- 16T – Continuous flow, 16’x16’ test section, Mach 0.05-1.6
- 16S – Continuous flow, 16’x16’ test section, Mach 1.5-4.75
- 4T – Continuous flow, 4’x4’ test section, Mach 0.05-2.5
- Primarily used for stability and control, aerodynamic, propulsion integration, and store/stage separation testing

Von Kármán Facility (VKF)

- Tunnel A – Continuous flow, 40”x40” test section, Mach 1.5-5.5
- Tunnel B – Continuous flow, 50” diam., Mach 6 or 8
- Tunnel C – Continuous flow, 50” diam., Mach 4, 8, or 10
- Primarily used for stability and control, aerodynamic, propulsion integration, and aerothermal testing

Motivation

- Next generation aerospace systems driving the need for improved test processes
  - Tighter performance margins
  - Increased budgetary constraints
  - Less testing, more simulation
  - Combined test types
- Industry/government demand for statistically defensible test and evaluation techniques
  - Design of Experiments
  - Repeatability analyses
  - Uncertainty quantification

NextGen Air Dominance Concept

Hypersonic Weapons Concept

Uncertainty Propagation

- A typical uncertainty propagation problem is of the form:

Known inputs with known uncertainty distributions → **Mathematical Model** → **Calculated output with unknown uncertainty distribution**

$$\boldsymbol{X} = \begin{Bmatrix} X_1 \\ X_2 \\ \vdots \\ X_N \end{Bmatrix}, \quad g_{\boldsymbol{X}} \quad \Rightarrow \quad f(\boldsymbol{X}) \quad \Rightarrow \quad Y, \; g_Y$$

- The most mathematically rigorous means of propagating the distributions is via

$$g_Y(\eta) = \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} g_{\mathbf{X}}(\xi)\delta(\eta - f(\xi))d\xi_N \ldots d\xi_1$$

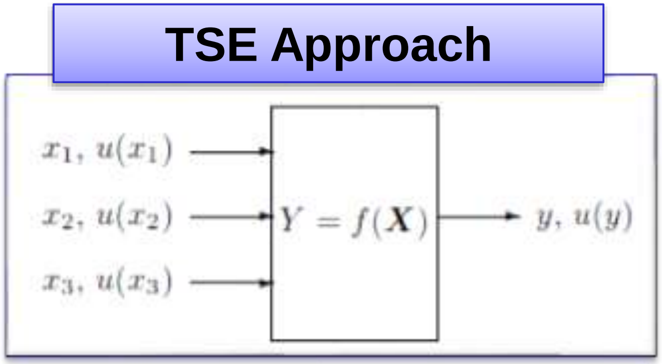
- Impossible/impractical to solve analytically for most real problems

Uncertainty Propagation at AEDC

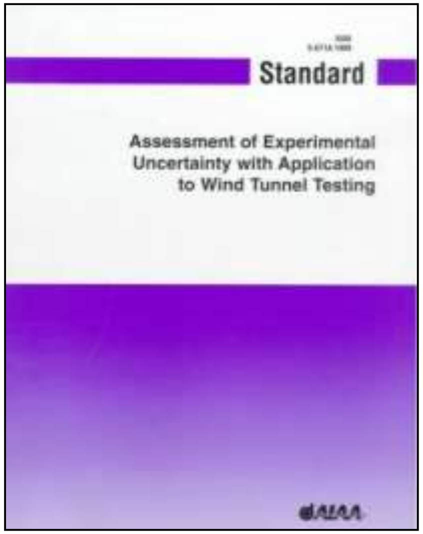
- A Taylor Series Expansion (TSE) of $f(\boldsymbol{X})$ can be used to approximate $g(Y)$ given $g(\boldsymbol{X})$
  - Propagates scalar descriptors
  - Requires calculation partial derivatives

- AEDC's current uncertainty propagation tool is based upon a TSE approach
  - In compliance with the AIAA standard S-071A-1999
  - Extensive process to develop and implement
  - Invaluable in test planning and data quality analysis

- Current TSE implementation has limitations
  - Cumbersome to implement on large scale
  - Excel spreadsheet-based, slow
  - Difficult to extend to test specific equations
  - Results not available in real-time



Scalar descriptors


Standard

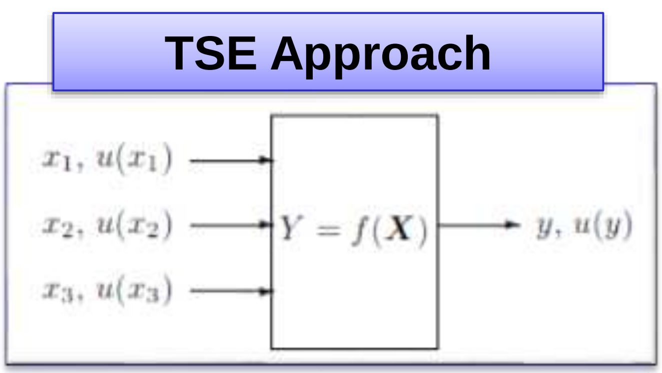
Assessment of Experimental Uncertainty with Application to Wind Tunnel Testing

AIAA

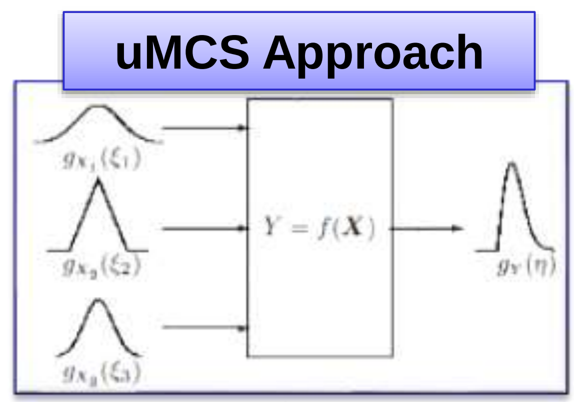
Uncertainties via Monte Carlo Simulation (uMCS)

- uMCS *approximately* propagates the uncertainty distributions of the fundamental measurements rather than just a scalar descriptor
- uMCS has a broader region of applicability than the TSE approach:
  - Contributory uncertainties are not of approximately the same magnitude
  - Difficult to provide the partial derivatives of the model
  - PDF of the output is not Gaussian (or t-distribution)
  - Output quantity and uncertainty are approximately same magnitude
  - Models are arbitrarily complicated
  - PDFs of the input quantities are asymmetric
- Implementation guidance given by the GUM, Supplement 1*

* "Evaluation of Measurement Data – Supplement 1 of the 'Guide to the Expression of Uncertainty in Measurement'," Joint Committee for Guides in Metrology, 2008.

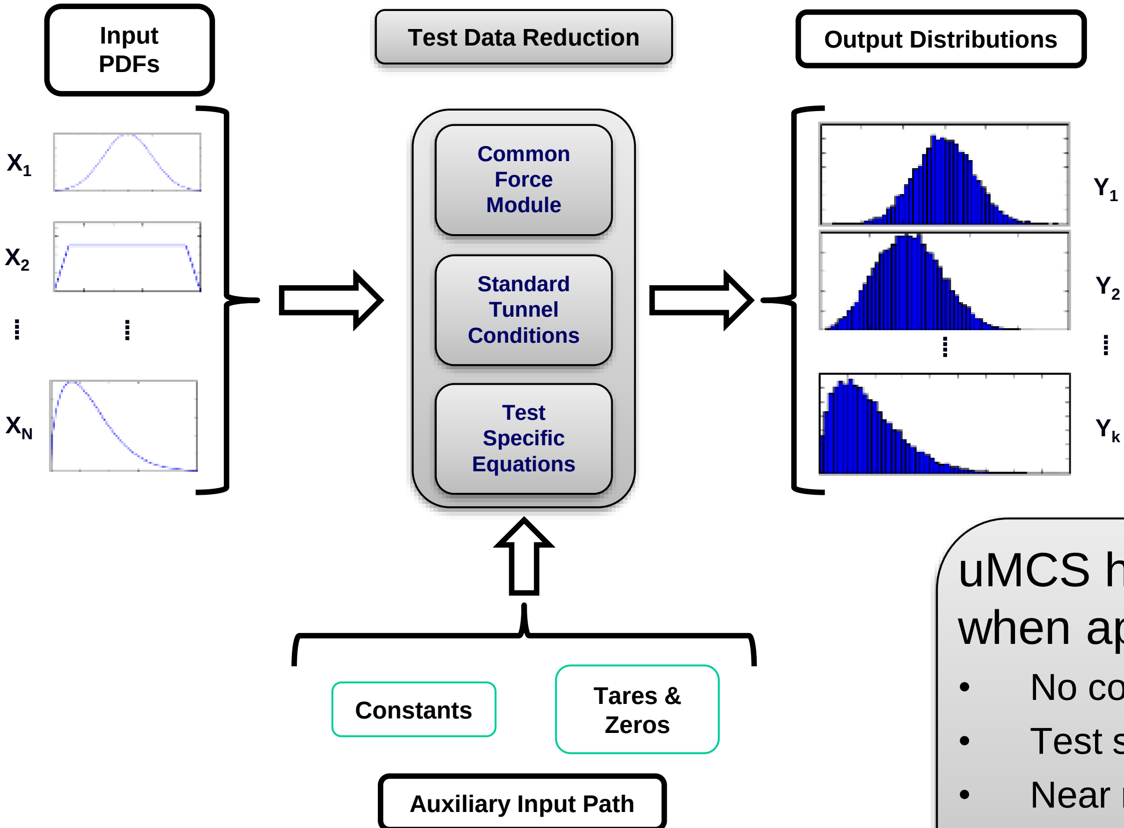


Scalar descriptors



Distributions

AEDC Implementation of uMCS



Common Force Module (CFM)

Core data reduction routines common to VKF and PWT

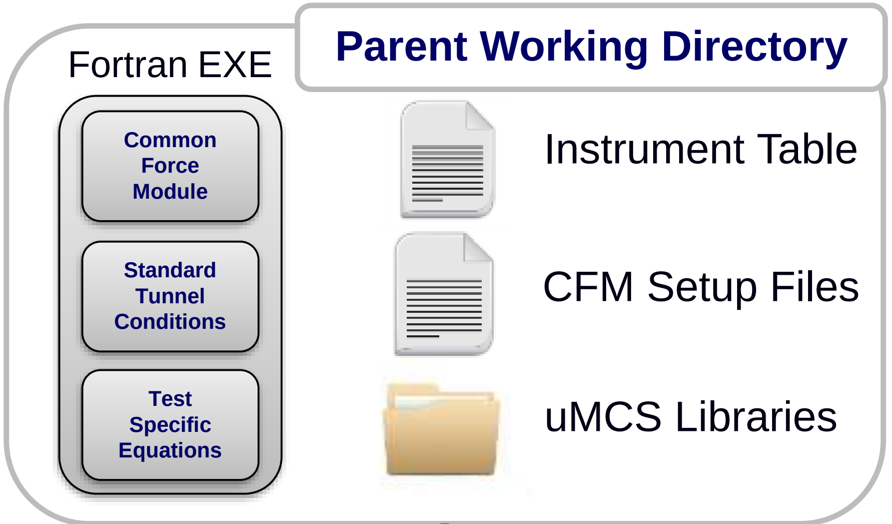
- Maintained by programmers
- Common input/output file structure
- Combined with facility/test specific code to make total data reduction

uMCS has many practical advantages when applied to the CFM:

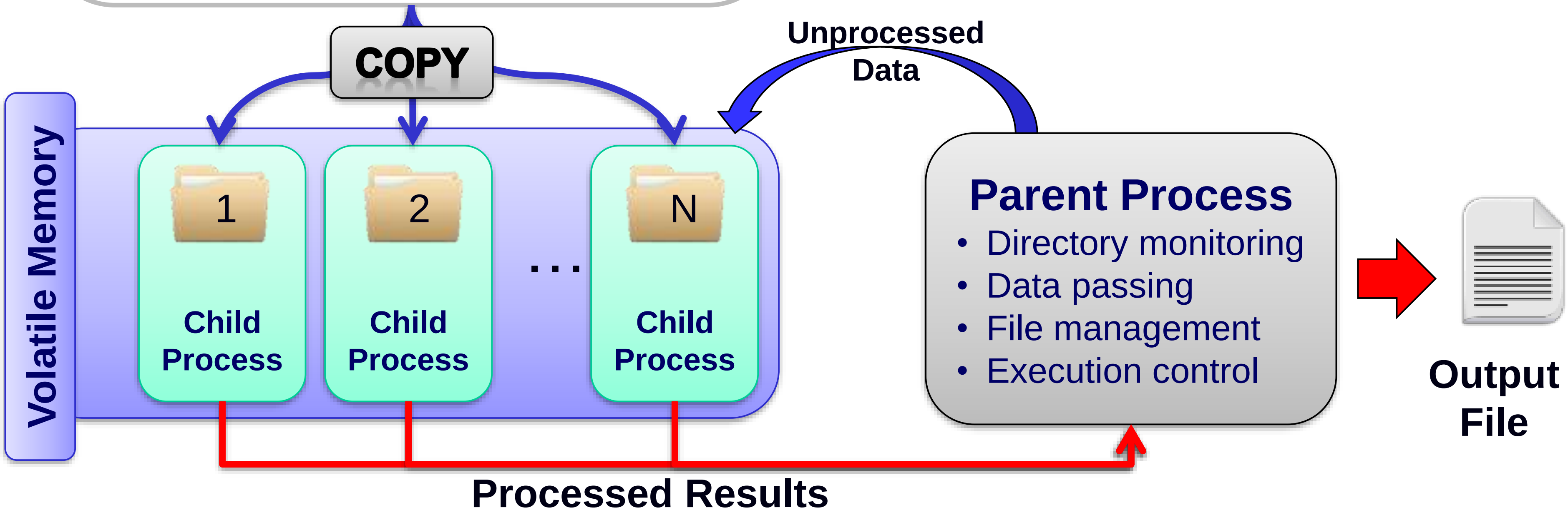
- No code changes/workflow disruption
- Test specific changes implicitly captured
- Near real time point-by-point results*
- Integrates into analysis workflow
- Easy wrapping/course-parallelization in Python

*Computing resource dependent

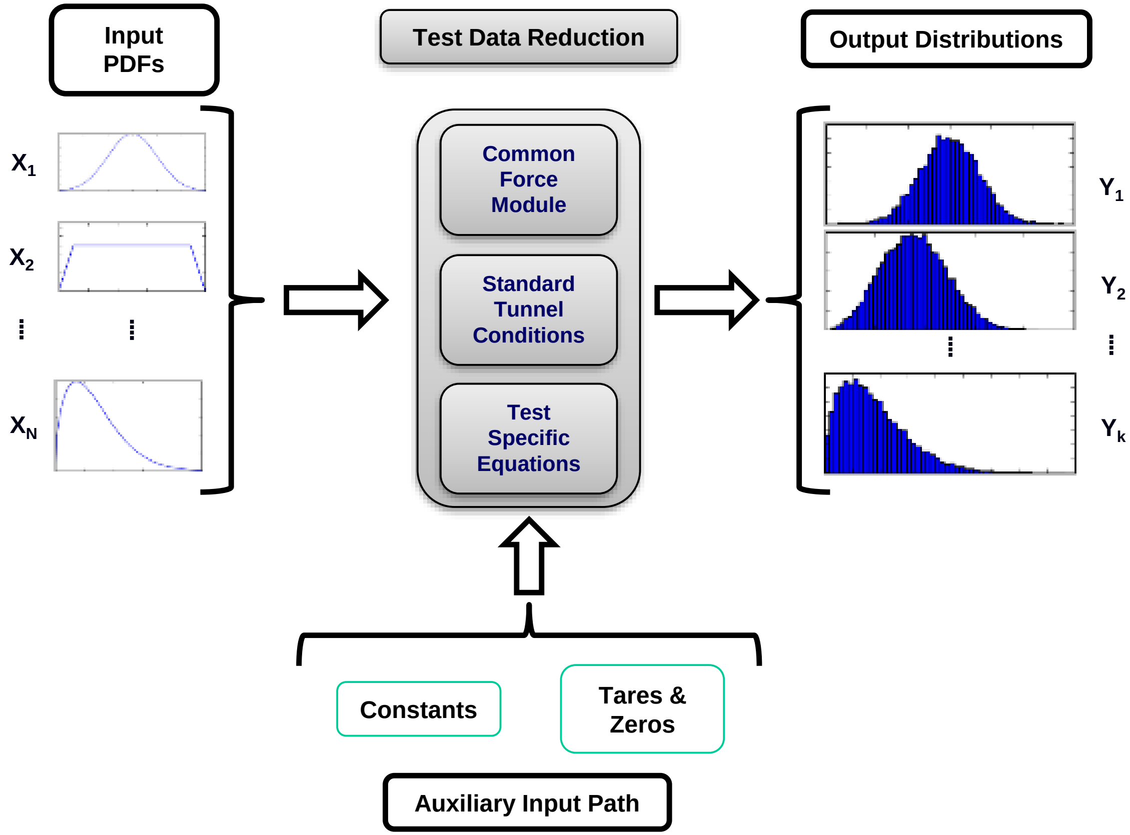
Python Implementation



- Every Monte Carlo trial is independent
- Course-parallelization implemented via Python
- Operations conducted in RAM to minimize File I/O impact
- 1000-trial simulation executes in a few hundredths of a second



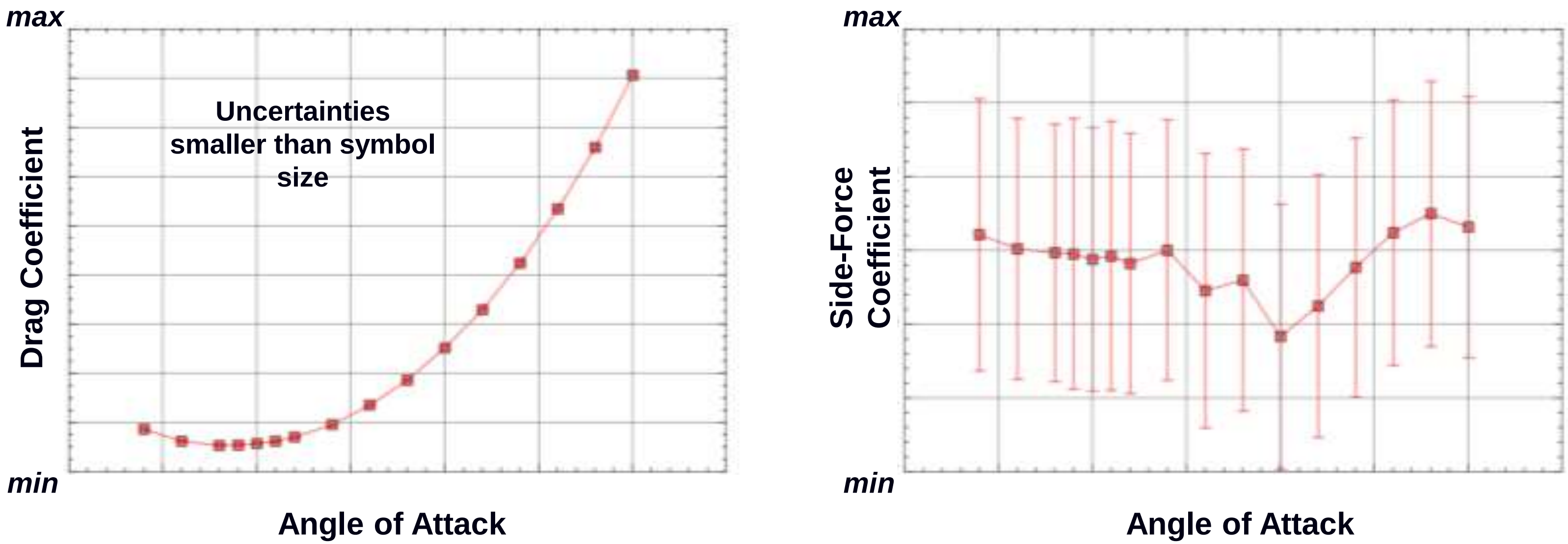
AEDC Implementation of uMCS



Implementation Challenges

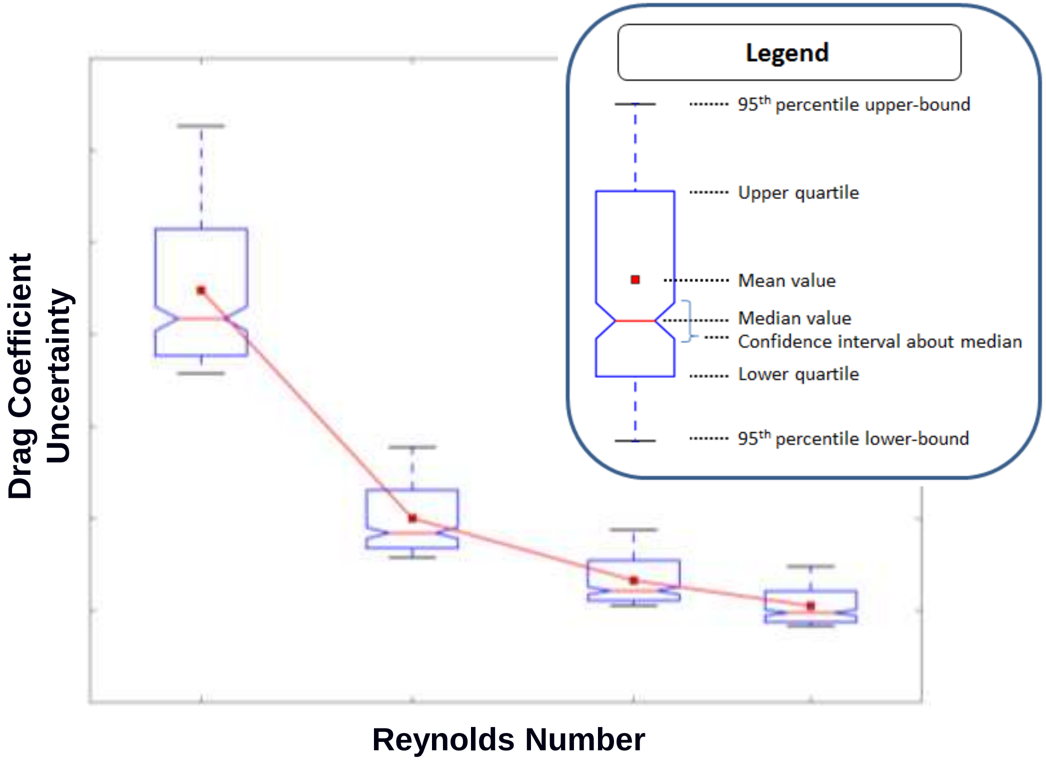
- uMCS is still in the development stage
- Many challenges remain:
  - Improve handling of auxiliary inputs
  - Development of a pre-test interface
  - Expansion to other test types (CTS, inlet)
  - Dynamic data acquisition
  - Upgrade computational resources in the tunnel

Example Results – Error Bars



- Example results from a typical force & moment test using an internal balance
- uMCS provides real-time point-by-point uncertainties for display in Datamine_qt
- Enables real-time data quality assessments
- Helps identify significant features in the results
- Computed for all selected output parameters, including test specific parameters

Example Results – Box Whisker Trends

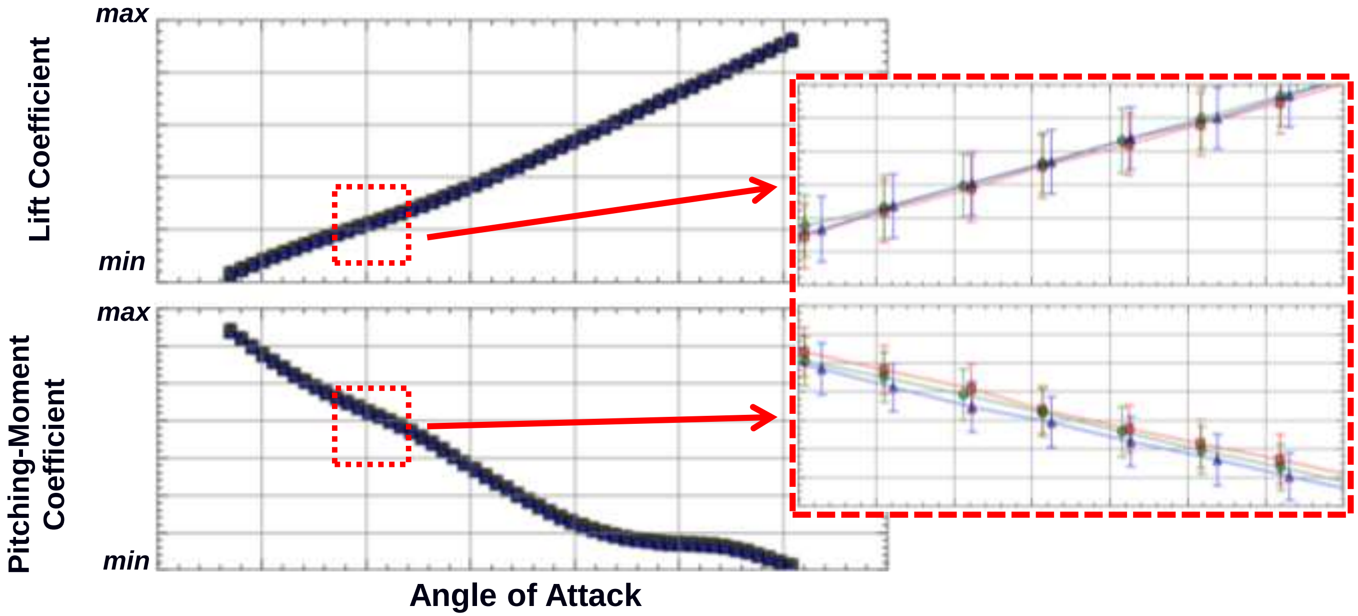


- uMCS results can also be used to visualize the distribution of uncertainty vs. a test condition
- Assists in conducting trade studies for condition selection
- Powerful pre-test planning tool*

*pre-test capabilities still in development

- In this example, each box illustrates the distribution of the drag-coefficient uncertainty at all vehicle attitudes versus Reynolds number
- Customer often must balance trade-off between uncertainty and tunnel conditions
- Tunnel conditions are strong drivers of utility cost and condition transition time

Example Results – Repeatability



- Uncertainty results are critical to a statistically defensible repeatability analysis
- Significant overlap in the error bars of repeated runs provides visual evidence that the facility and test hardware are performing satisfactorily
- Customer decisions to proceed with model configuration changes are often dependent upon real-time data quality analyses supported by uMCS results

Continued Development

- The AEDC uMCS tool is still a work in progress

- Planned improvements include:
  - Improved handling of auxiliary input uncertainties
  - Input-output sensitivity calculations
  - Pre-test uncertainty predictions based on standard models
  - Parametric study tools for instrumentation and tunnel condition selection
  - Maximum-likelihood methods for inlet distortion testing
  - Continued development of automated report generation

Conclusions

- uMCS has already been successfully demonstrated on a number of test programs
- Results have compared favorably with those from the established TSE approach
- Integrated into repeatability analyses and reporting process
- Positive customer feedback

Technical Impact

- Provide customers with more rigorous and robust uncertainty estimates
- Reduce pre- and post-test man-hours by automating many tasks
- Standardize the reporting and data format delivered to customers

Increased technical rigor, Decreased execution time, and Faster deliverables to Customer

QUESTIONS?