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
Uncertainty Propagation

• A typical uncertainty propagation problem is of the form:

\[ X = \begin{pmatrix} X_1 \\ X_2 \\ \vdots \\ X_N \end{pmatrix}, \quad g_X \rightarrow f(X) \rightarrow Y, \quad g_Y \]

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

\[ g_Y(\eta) = \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} g_X(\xi) \delta(\eta - f(\xi)) d\xi_N \cdots d\xi_1 \]

• Impossible/impractical to solve analytically for most real problems
Uncertainty Propagation at AEDC

• A Taylor Series Expansion (TSE) of \( f(X) \) can be used to approximate \( g(Y) \) given \( g(X) \)
  – 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
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*

*TSE Approach

TSE Approach

Scalar descriptors

- $x_1, u(x_1)$
- $x_2, u(x_2)$
- $x_3, u(x_3)$

$Y = f(X) \rightarrow y, u(y)$

*uMCS Approach

uMCS Approach

Distributions

- $g_{x_1}(ξ_i)$
- $g_{x_2}(ξ_2)$
- $g_{x_3}(ξ_3)$

$Y = f(X) \rightarrow g_y(η)$

AEDC Implementation of uMCS

Test Data Reduction

Input PDFs

Output Distributions

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?