Simulation at Aeronautics Test Facilities
A University Perspective
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1500-1640

Questions

- How has the ability to do increasingly accurate modeling and simulation (M&S) changed the way aeronautics test and evaluation (T&E) facilities are used? How has it changed the way we do flight test?
- From a T&E standpoint, are U.S. M&S capabilities sufficiently mature and reliable? How well are NASA facilities meeting the needs of industry regarding advanced M&S capabilities for aeronautics T&E?
- How well is NASA working with other government entities and academia to enhance M&S capabilities for aeronautics T&E?

Verification & Validation

- Verification – "Are you solving equations right?"
  - Confirming accuracy and correctness of code" (i.e. is grid resolved, are there any programming errors in codes, etc.)
- Validation – "Are you solving right equations?"
  - Verification, <u>and</u>
  - Confirming adequacy of equations used to model physical problem. Strictly speaking, code can only be validated by comparison with quality experimental data.

Rationale

- Accurate modeling/testing of relevant operational physics for manageable uncertainties, efficient design and control, reduced design-cycle time
  - Example: Maneuvering reentry vehicle
    - Flight profile introduces large heat transfer rates and viscous heating loads requiring substantial TPS (new materials, added shielding mass)
      - Heat transfer in turbulent boundary-layer can vary from laminar flow by a factor of five or more
    - Unexpected transition
      - Early: Substructure failure due to excessive temperatures
      - Asymmetric: Adverse effects on flight dynamics and aerostability
    - Before: Large uncertainty in transition when empirical methods used
    - After: Use of physics-based stability theory models, design strategies, control strategies – validated and enabling – <u>but need more</u>
      - Reason: advances in CFD and experiments

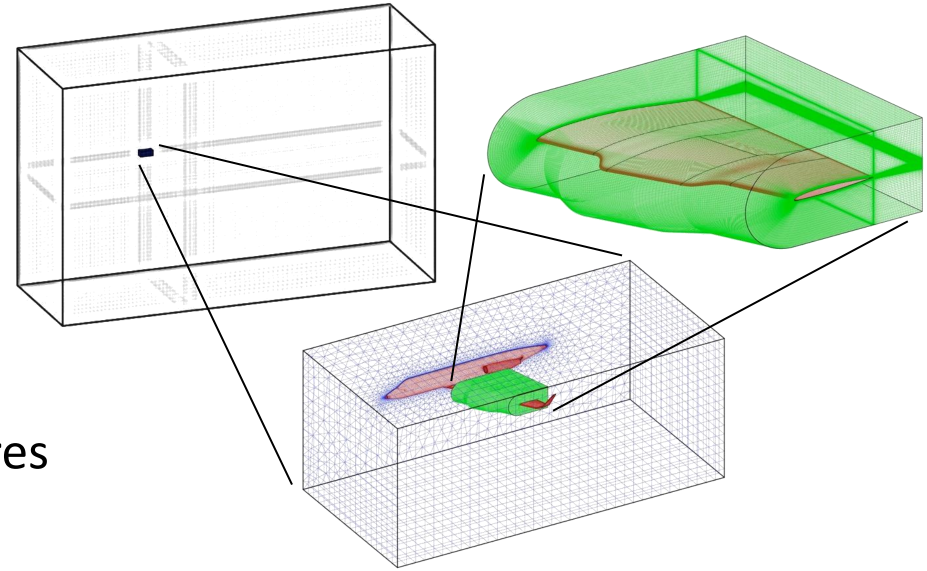
Rationale

- Operational vehicle or system – complex geometry, 3D effects, high Reynolds numbers, high enthalpy, surface imperfections such as skin-panel or leading-edge lift-device gaps and steps, bug-strikes, paint chips, ice accretion, etc.

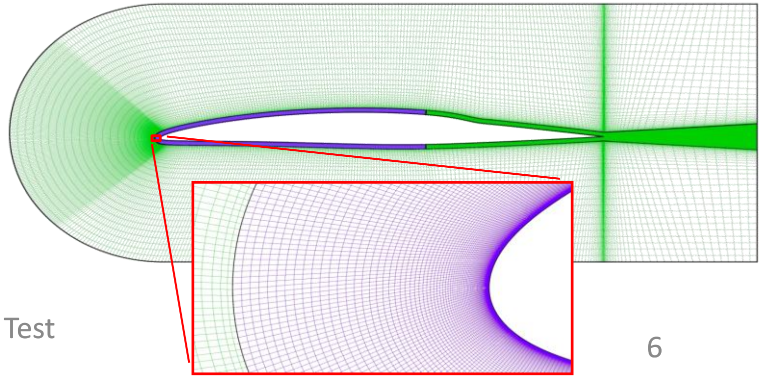
- Transition, separation, drag (shear stress, pressure drag), heating, aerostability, control authority, propulsive efficiency, … all sensitive to operating conditions
  - Re, M, flow angularity/uniformity, 3D effects, pressure gradients, surface conditions/features/curvature, chemistry, wall temperature, freestream disturbances, … – and the <u>interactions</u> among these

CFD

- Many advances in algorithms, grid resolution, computer power. Ongoing work in big data: data mining and possibility of creating virtual databases of configurations for others to model or verify against



- Possible Concerns
  - Configuration codes typically have limited points in boundary layer or unable to model critical features
    - Experiments report critical features order 10^{-4} meter (100 microns)
    - Boundary layer thickness order 10^{-3} meter
    - Chord of model order 1 meter
    - Aircraft is order 10 meters
    - Farfield must be order 100 meters



CFD

- Possible Concerns
  - Codes with detail near the wall or in critical locations or able to include receptivity are geometry limited
    - Simple geometries (flat plates, infinite wings, parabolic leading edges, …)
    - Need to understand the effects of whole flowfield (flight or tunnel), include actual finite-thickness leading edges with bluntness, curvature, flow angularity/uniformity, any blockage, shocks, ….
  - Relevant upstream conditions and surface conditions, wall temperature, appropriate chemistry models, … are <u>required</u> for CFD
    - Operations (turbomachinery, flight) vs. test, appropriate freestream elements (sound vs vorticity, spectra), and <u>interactions</u>

Ground Tests

- Quiet tunnels (reduce freestream disturbances, eliminate noise radiated from turbulent side walls)
  - Turbulence scales of atmospheric boundary layer and upper atmospheric shear layers: microscale that may influence fluid mechanics in flight of order of viscous dissipation scales and is practically nonexistent.
  - Results can be opposite or non-representative to flight if conventional
- Improved instrumentation and diagnostics
- Best practices published by several

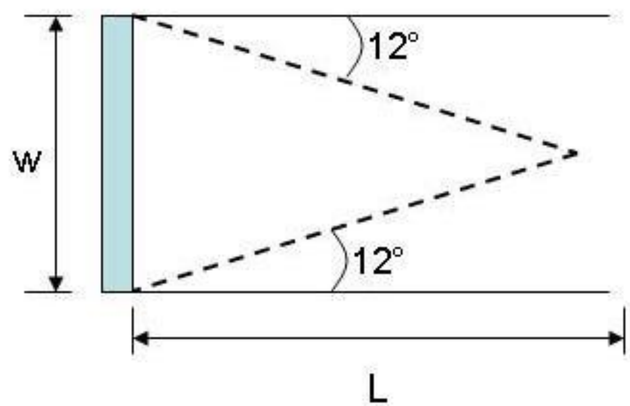
- Possible Concerns
  - Inherent tunnel effects
  - Full documentation of physical properties (surface roughness, operating conditions, wall temperature, coordinate system, local pressure gradients, …), background disturbances, initial amplitudes, spatial variations (including flow angularity/uniformity) should be made

Ground Tests

- Possible Concerns
  - Very important to measure, whenever possible, freestream environment separating freestream turbulence and sound. Not advisable to just quote “freestream turbulence level” as freestream turbulence and sound affect different features of the boundary layer in different ways.
  - Reynolds number effects are an issue. Typical low speed wind tunnels achieve only a maximum chord Reynolds number of $3x10^6$ – $16x10^6$. A typical cruise flight chord Reynolds number is much higher.
  - Related, scale effects are an issue. Even though a physical model can be scaled smaller, relevant roughness and feature lengths/heights which are likely related to boundary-layer thickness or laminar sub-layer thickness often are difficult to relatively reduce in size.
  - Mach number effects may be an issue especially if transonic conditions are expected in operation.

Ground Tests

- Possible Concerns
  - Issues with test section size are the potential for 1) blockage effects which may introduce streamwise pressure gradients, 2) too narrow width which may cause unexpected spanwise variations, and 3) too narrow width which may contaminate downstream measurements if model is too long.



$$\frac{L}{w} \approx 2.3$$

  - Test section flow angularity and uniformity may be issues in causing an unexpected effective angle of attack on the model and unexpected non-spanwise-uniform flow, respectively.

Ground Tests

- Possible Concerns
  - Appropriate instrumentation needs to be available and capable of quality and conclusive relevant measurements.
  - Be careful that the measuring device is applied in such a way as to be non-intrusive and not locally influencing the measurement and increasing drag by itself. Probe/sting interference (too large/too close) can be a concern, creating local unexpected pressure gradients in the vicinity of the measurements. Measurement surface coatings can themselves introduce nontrivial surface roughness.

Flight Tests

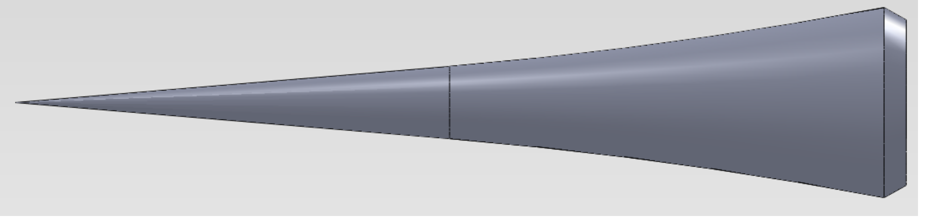
- The purpose of flight test is to demonstrate technology in operational environment (including atmospheric scales, bugs, dust, clouds, particles…) at relevant Reynolds numbers and Mach numbers.
- Only go to flight if ground test not sufficient
  - Even best tunnels are challenged with increasing Mach number
  - Some phenomenon are very sensitive: transition, separation, unsteadiness, …. – need right operational environment content and scales
- Possible Concerns
  - Cost, aircraft and pilot availability, weather
  - Safe operating range of test aircraft - limit range of data
  - If a model or test article or technology, will the scale be sufficient to achieve a meaningful result? Will the flow parameters in situ be relevant to the final application (3D effects, pressure gradients, …)?

Flight Tests

- Possible Concerns
  - Will instrumentation be sufficient to achieve meaningful result? One should also maintain and monitor test conditions including trajectory, speed, alpha, beta, and disturbance environment. Other relevant parameters (surface conditions, wall temperature, …).
  - Proper flight experiment must have clearly articulated objective, one that is not possible to realize in a ground based facility. Don't try to accomplish too many objectives in the campaign – this costs more in money and time to design and often requires compromises that diminish ability to isolate results. Goal should be operationally relevant, repeatable, and sustainable high-quality data.

Observations

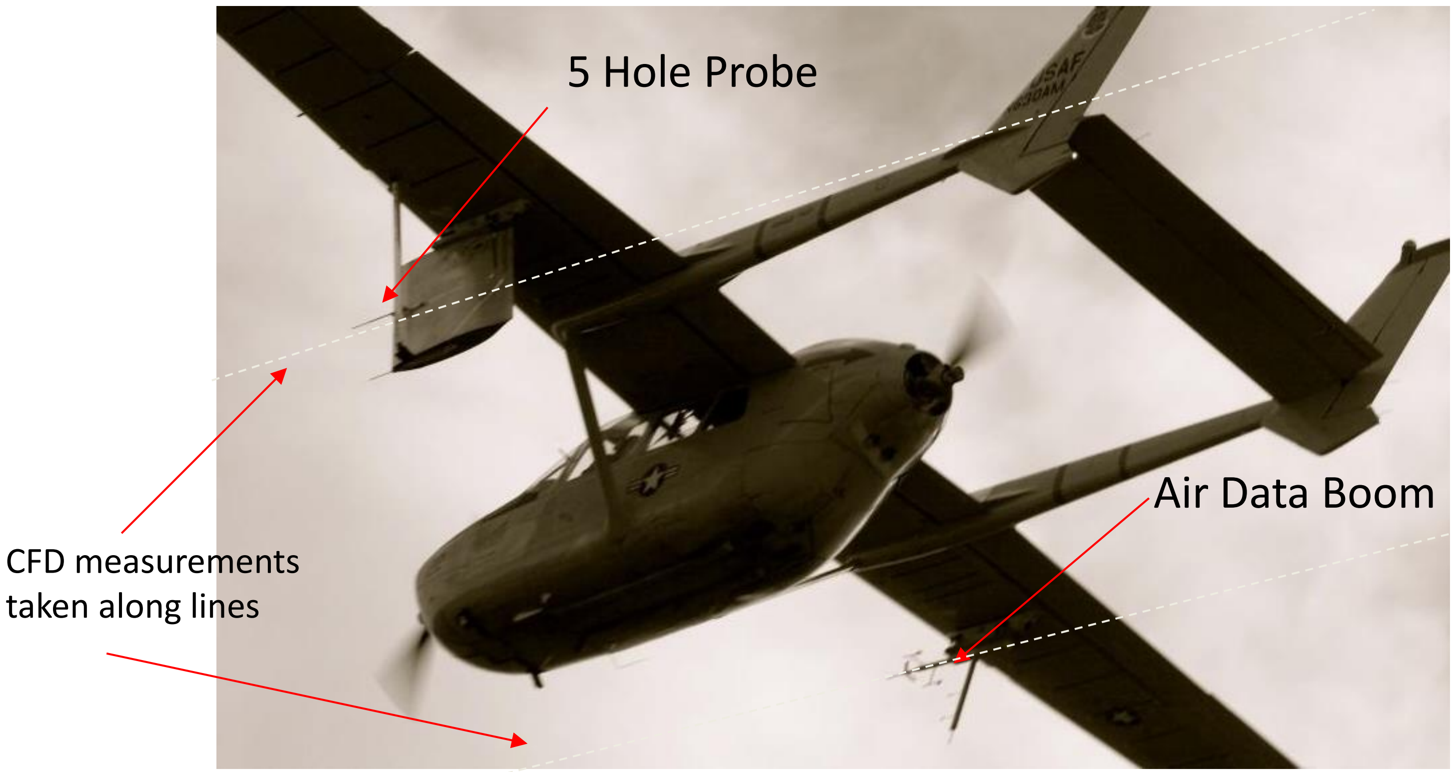
- Both CFD and testing (ground and flight tests) have limitations
- Both will always be needed
- Both must work hand-in hand as equal partners on the same geometries and operating conditions, and confirm it. Each validates the other.
  - Example – Mach 6 flared cone
    - Computations predict slope on order of *6.5 kHz* per *0.1˚*, with experiments showing similar effect!



Reed et al., *AIAA JSR* 2014:10.2514/1.A32825:1-9.

Observations

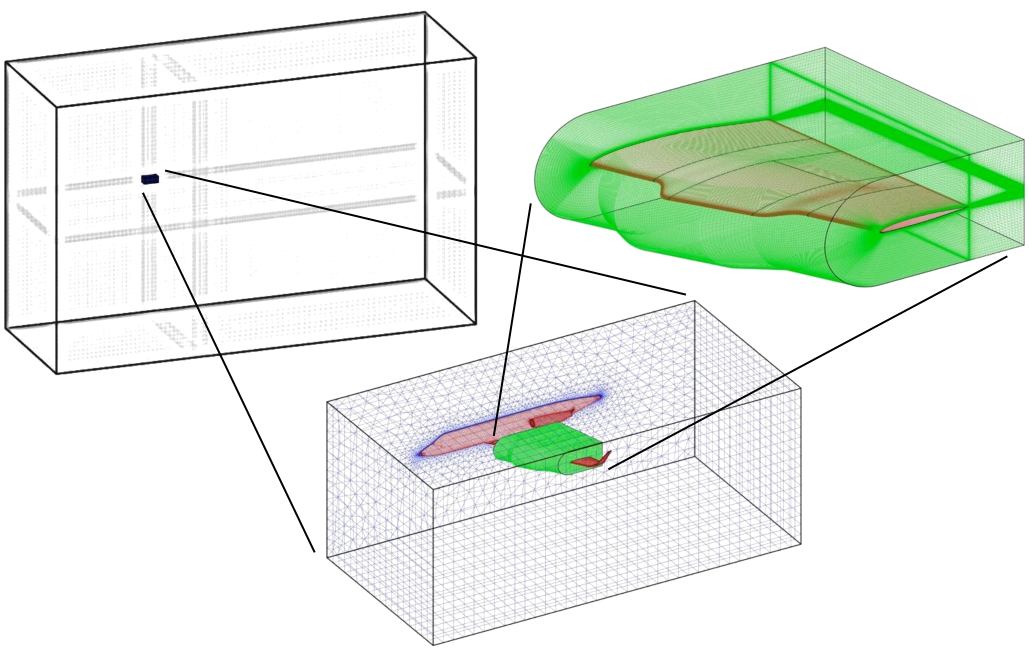
– Example – Swept wing model in flight
  - Flow angularity around fuselage induced unexpected AoA strongly affecting results

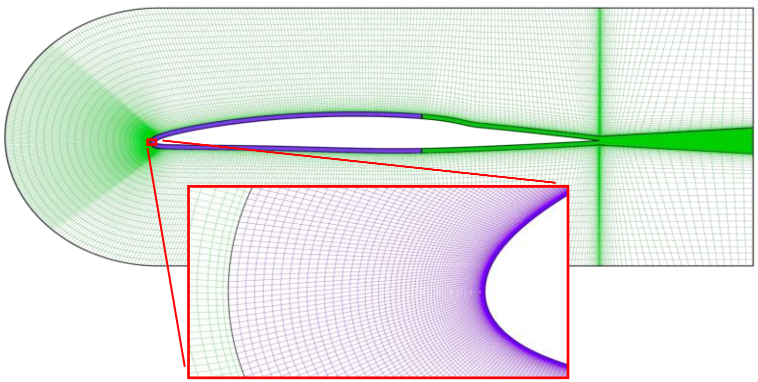


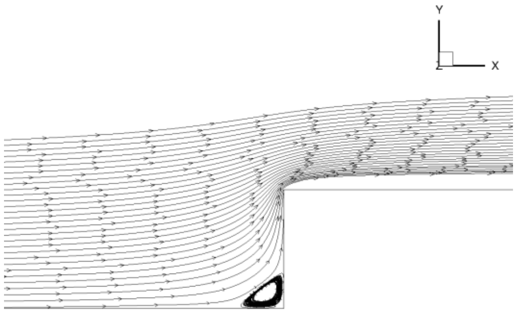
Rhodes, Reed, Saric, Carpenter, Neale, *IJESMS,* 2:1/2, 139-148, 2010.

Observations

- Testing a common test article in multiple facilities is optimal way to identify inherent local tunnel effects.
- CFD can use a tiered approach to modeling features at different scales.







Observations

- With the limitations, the purpose of a flight test should additionally be to validate predictive computational models to then extend the range of results.
- If in using a test article it is going to be difficult to determine an objective (e.g. amount of drag reduction) because relevant detailed measurements in flight are a challenge, then perhaps if certain key and conclusive features can be validated with the computations, then perhaps the computations can infer the final result.

Ground Testing/CFD

- Review ground facility feasibility – Will there be good, meaningful, and conclusive measurements?
  - Critique flowfield angularity, spanwise uniformity, scales (width), freestream, accessibility for data collection, available instrumentation (uncertainty, quality), and so forth
- Design representative scaled model including facility flowfield considerations
- Conduct companion CFD/testing of model installed in ground facilities (validation with CFD as well as other facilities) – work together!
  - Smooth-surface model
  - Model with roughness, any ultra small surface features
  - In both instances, compare with computations – determine why results are different between the computations and experiments and fix
- Use validated CFD and any updated simplified computational analyses/ predictive models to extend results for other conditions

Flight Testing/CFD

- Review aircraft test feasibility
  - Conduct survey of available and feasible aircraft platforms.
  - Computational simulation of complete aircraft flowfield and validation with measurements (VERY IMPORTANT) – determine why results are different between the computations and experiments and fix
  - Can a good, relevant, and conclusive test even be conducted? Are good and relevant measurements even possible to proceed?
- Design representative model/test article
  - Include aircraft flowfield considerations from above
  - Are good and relevant measurements even possible to proceed?

Flight Testing/CFD

- Conduct companion computational simulation/testing of model/test article installed on aircraft (validation with CFD) – work together!
  - Smooth-surface model
  - Model with roughness, any ultra small surface features
  - In both instances, compare with computations – determine why results are different between the computations and experiments and fix
- Use validated CFD and any updated simplified computational analyses/ predictive models to extend results for other conditions

Observations

- Both CFD and testing (ground and flight tests) can have limitations/concerns
- Both will always be needed
  - Over the past decades, it has become apparent that it is critically important for CFD and experiments to work very closely together on same geometries and operating conditions and confirm it. Advances in prediction methods have come from working together. Various fluid mechanics phenomena are highly sensitive to possibly many facets of operating conditions. Computations provide validation of experiments and vice versa.
  - Determine the important effects, model them, validate the CFD, and then extend the range with CFD
- We have made a lot of good progress and can continue to do so. We must keep moving forward.
- Problems are not solved overnight but on the scale of years.
- Threat: Uncertainty in federal funding – lack of continuity to support research facilities/CFD teams and maintain expertise