Complementary but Changing Roles of Computational and Experimental MODSIM

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Future Directions in CFD Research
Hampton, Virginia
August 6-8, 2012

Outline

- Introduction
- Design Practices – Past and Present State
- Examples of Current use of Computational M&S in Aerodynamic Design of Aerospace Systems
- Future (Desired) State
- What will it take to arrive at Future State?
- Summary Remarks

Modeling and Simulation (M&S)

- **In general, very few real world problems can be solved exactly and, therefore, most require approximations to arrive at an acceptable solution**

- **Any activity that attempts to model and simulate the reality can be defined as M&S**
  - Physical experimentation (e.g., wind tunnel or flight testing)
  - Numerical simulations (e.g., Computational Fluid Dynamics)
  - Both type entail errors and uncertainties that must be understood and adjusted for to get closer to actual solution

Aerospace Systems Design – Past State

Design mostly anchored on physical experimentation with some computational analysis to fill gaps (knowledge/experience played a major role to achieve successful designs)

Benefit:

- Confidence relatively high since designs were grounded in experiments

Limitations:

- Inadequate computational capability resulted in expensive design, long design cycle times, and limited design space
- Test data only at certain conditions, a lot of interpolation/extrapolation required
- Many times, testing not possible at the intended use conditions
- Knowledge and experience base important for successful designs, so difficult to explore new advanced/radical designs with substantial performance changes

Aerospace Systems Design – Current State

- **Initial design cycles done with computational M&S**
- **Design refinement and verification by physical experimentation**

Benefits:

- Reduces cost, cycle time, and time to market
- Allows exploration of larger design space, especially in conceptual design stage
- Allows quick insertion of advanced technologies on systems
- Allows exploration of advanced systems concepts on which only limited knowledge and experience base exist

Limitations:

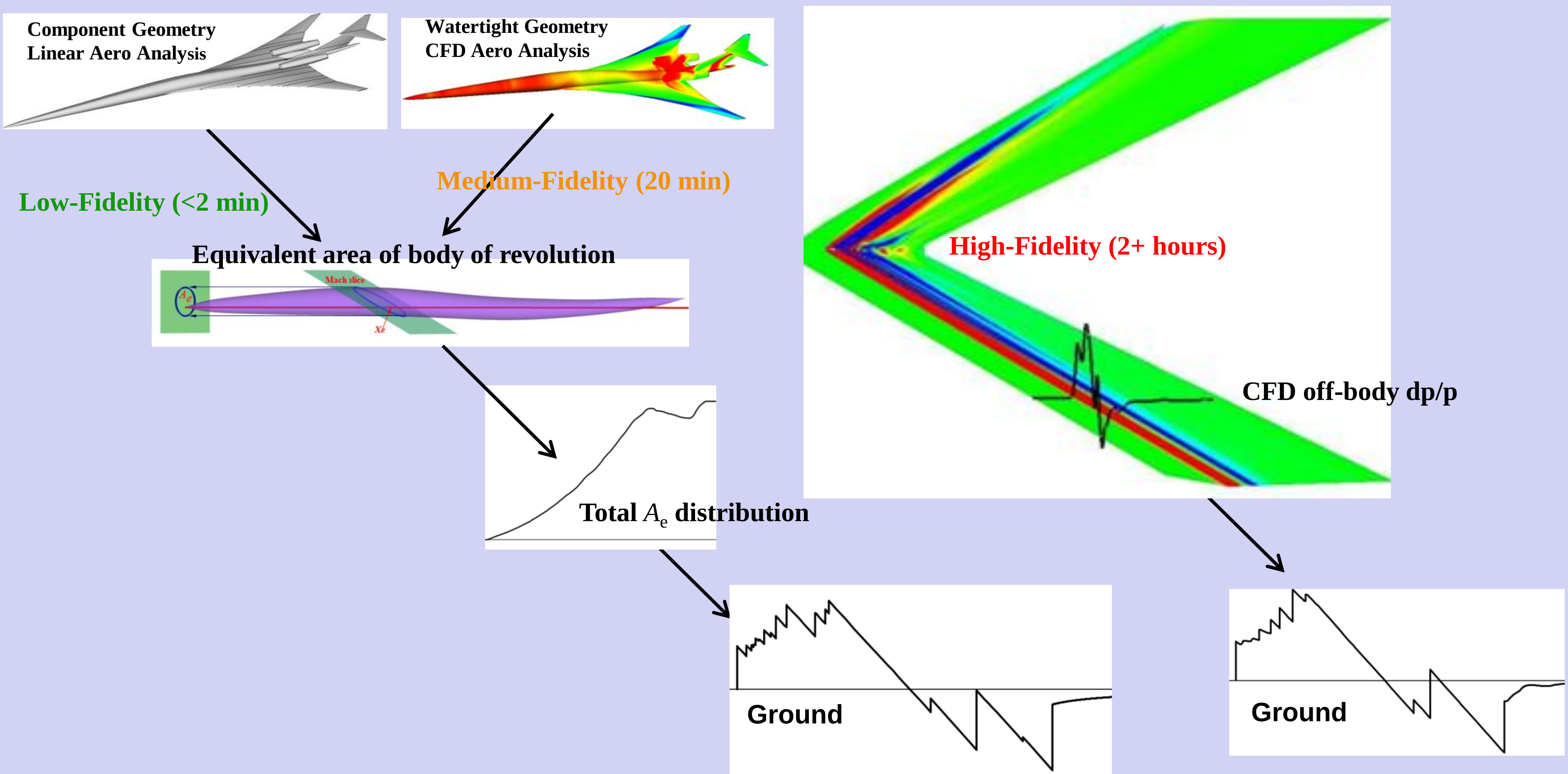
- Computational tools too slow to compute large number of cases over the design space
- Unknown uncertainty quantification leading to limited prediction capability and lack of confidence in design – require a lot of high-quality test data to calibrate and validate computational tools
- Computational tools mostly being used to generate delta in performance due to inability to simulate physical conditions in experiments (e.g., delta in performance from wind tunnel to flight Reynolds numbers)
- Knowledge/experience base still needed for successful designs

Examples of Current Use of Computational M&S in Aerodynamic Design

- **Conceptual design of low-boom supersonic aircraft**
  - Ref: Li, Shields & Geiselhart: A mixed fidelity approach for design of low-boom supersonic aircraft, AIAA Paper 2010-0845, Jan. 2011
- **Development of large subsonic transport**
  - Ref: Johnson, Tinoco &Yu: Thirty years of development and application of CFD at Boeing Commercial Airplanes, Seattle, J. of Computers and Fluids, 2005.
- **Uncertainty in aerodynamic database for a launch vehicle**
  - Ref: Hemsch & Walker: The crucial role of error correlation for uncertainty modeling of CFD-based aerodynamic increments, AIAA Paper 2011-0173, Jan. 2011.

Multi-Fidelity Sonic Boom Analyses

1. Ground signature for low-fidelity equivalent area (*Ae*) distribution
2. Ground signature for CFD equivalent area distribution
3. Ground signature for CFD off-body pressure distribution



Multi-Fidelity Low-Boom Design Process

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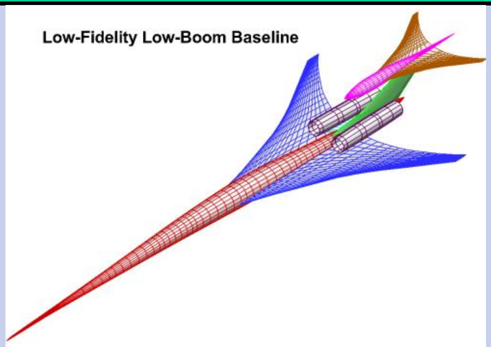
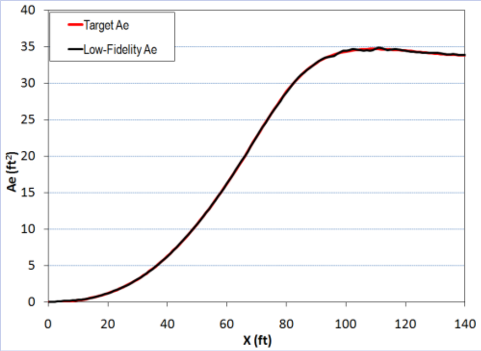
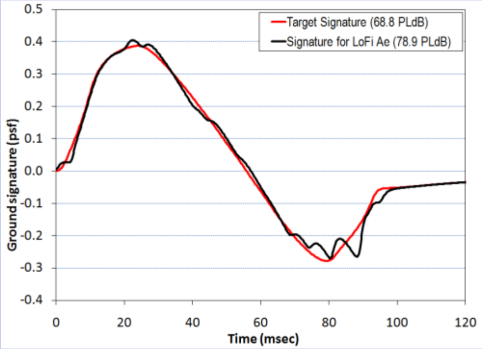
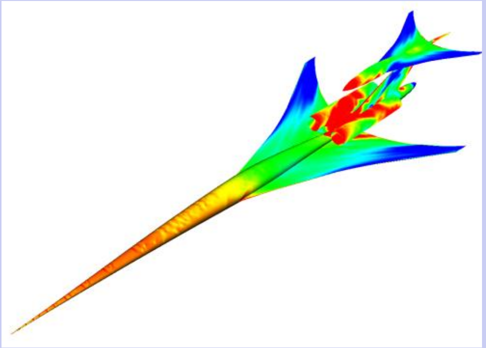
Low-Fidelity Ae Matching

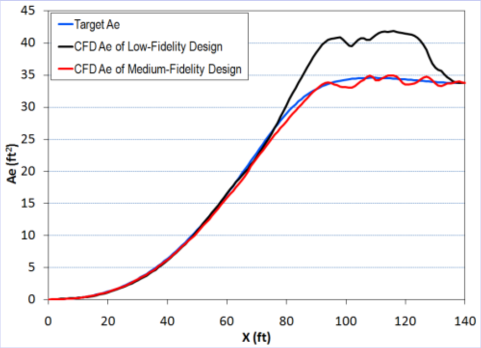


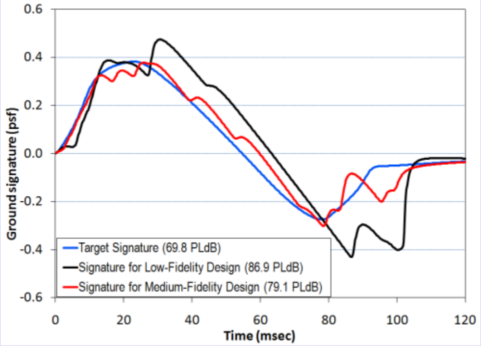




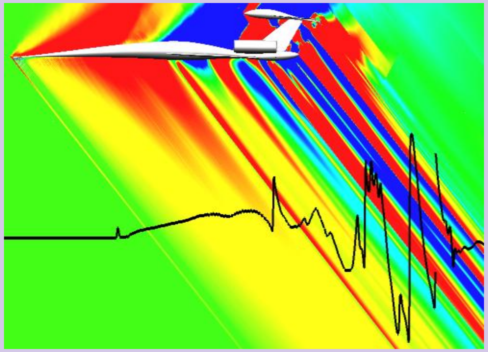
Medium-Fidelity Ae Matching

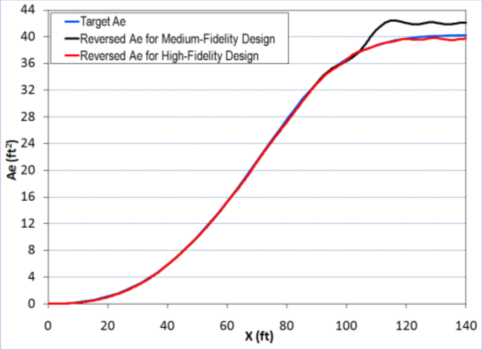


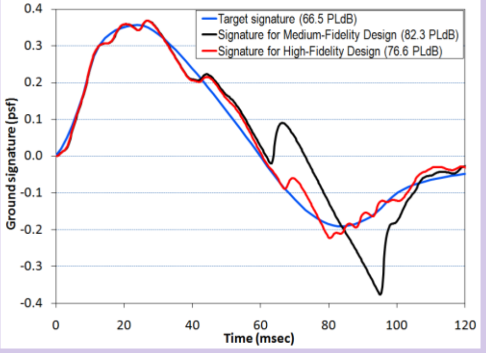




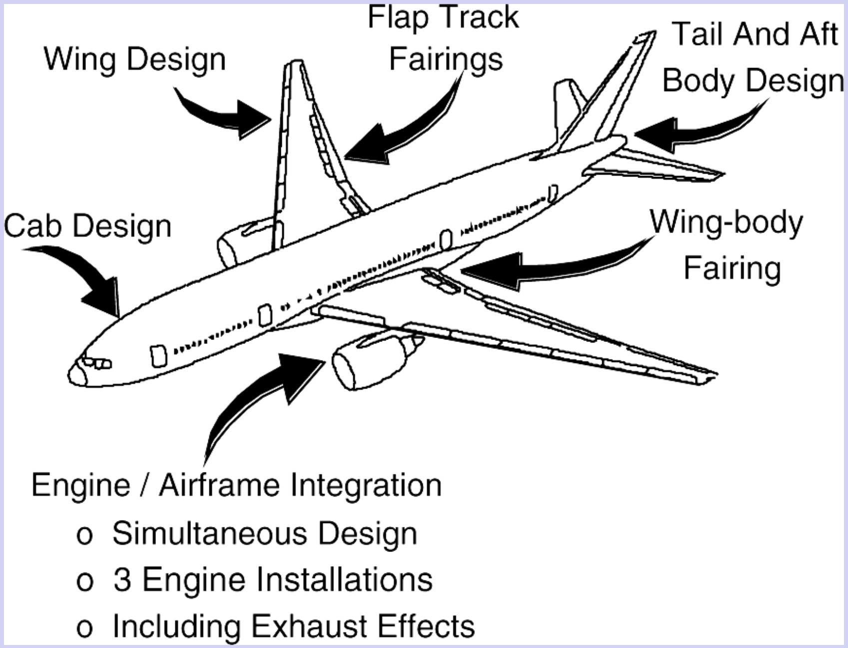
High-Fidelity Aft Tailoring



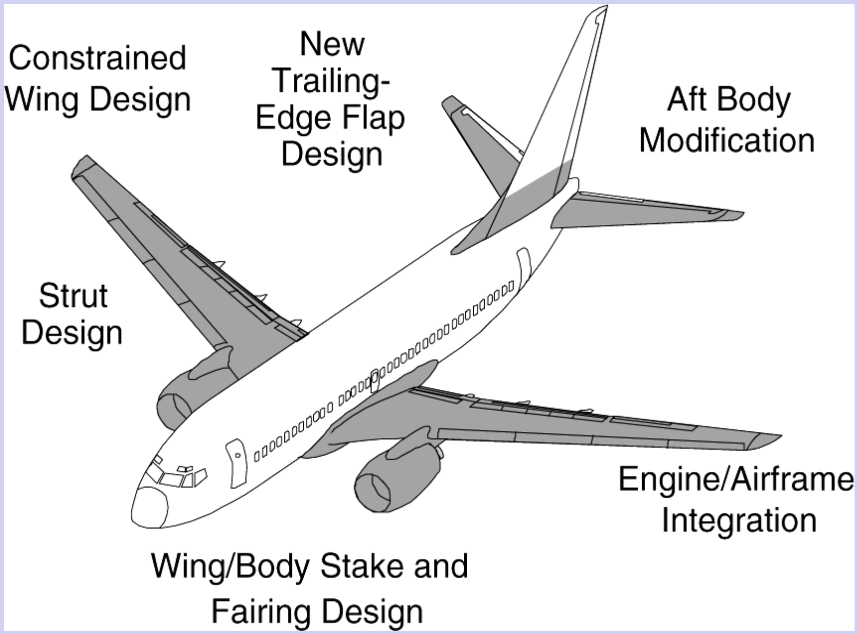




CFD Contributions to Boeing 777 and 737NG

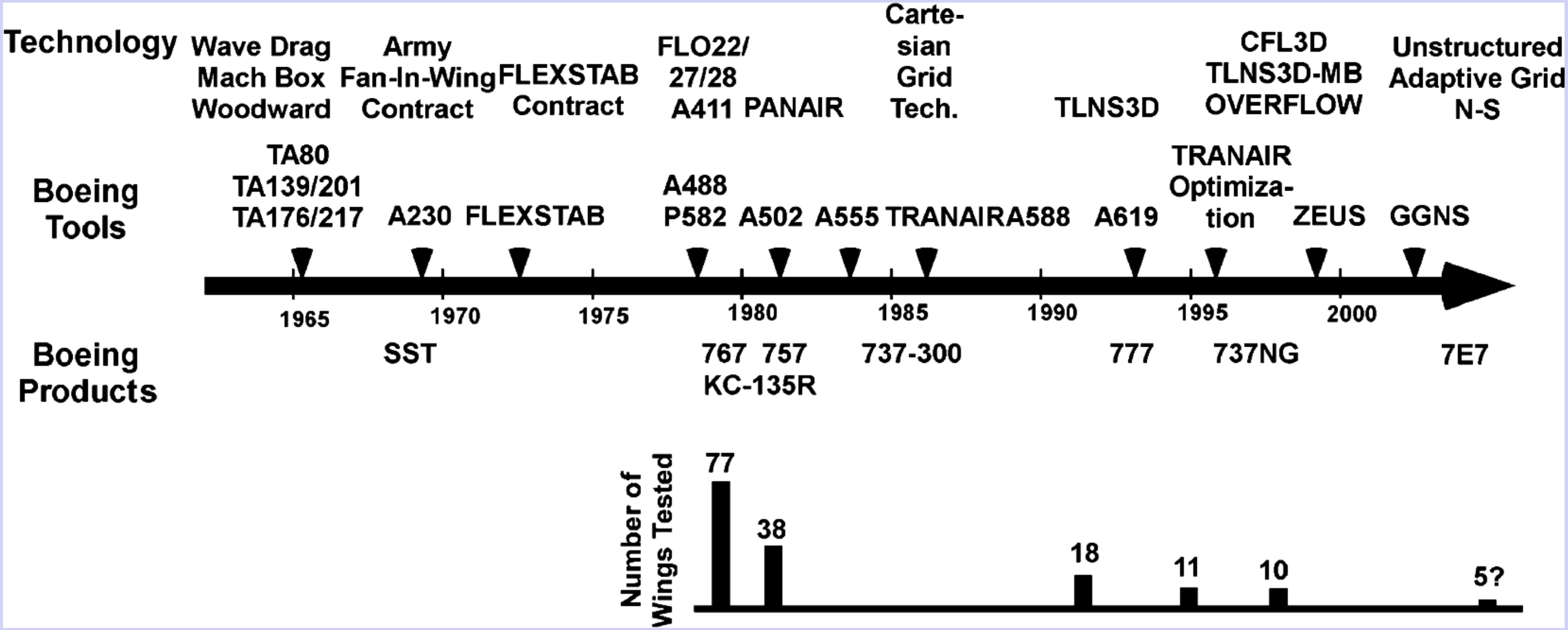


B 777



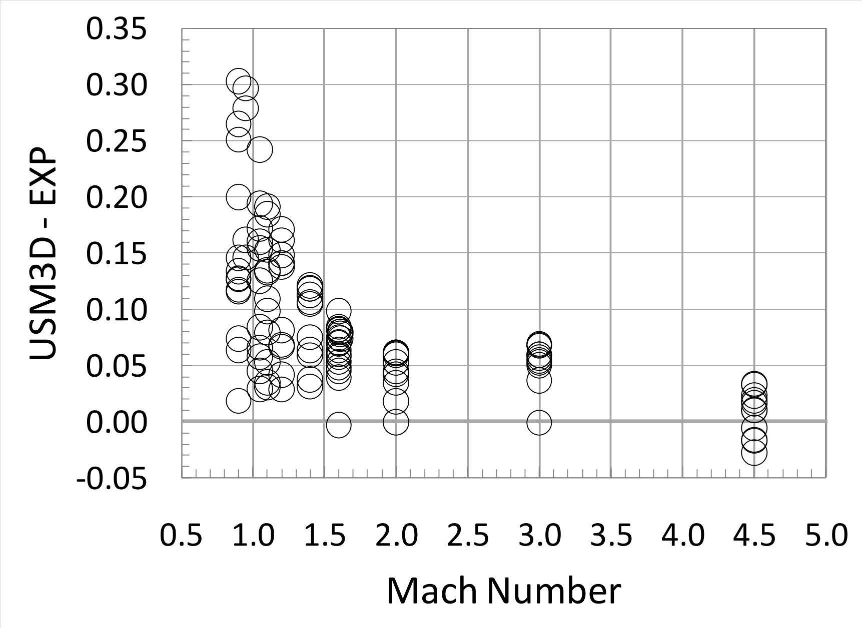
B 737NG

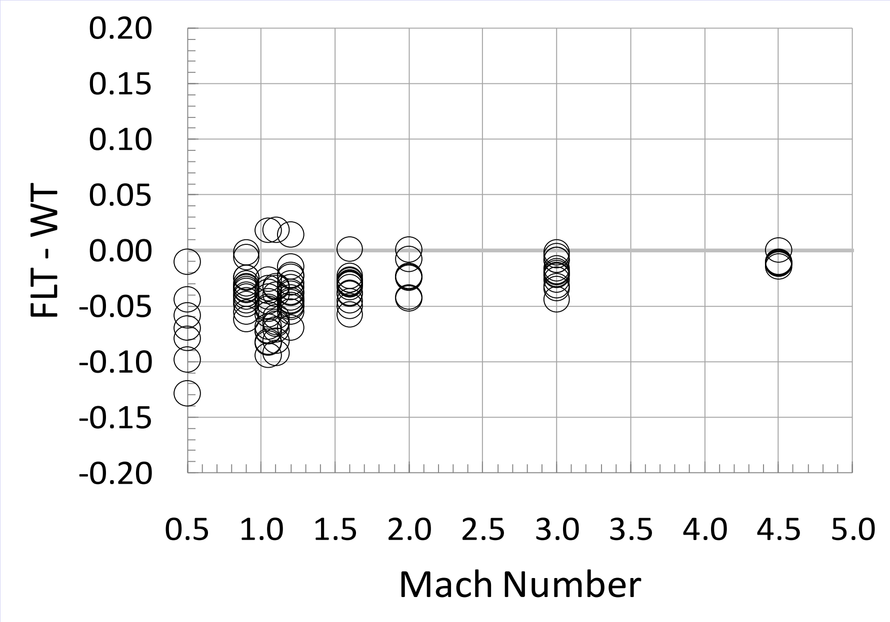
Impact of CFD on Wing Development



Artist's Sketch of an Ares I Configuration just after Launch

Validation Errors and CFD Performance Increments due to WT to Flight Reynolds Number





Normal force coeff. for various values of angle of attack (0 to 8 deg) and roll angle (0 to 360 deg)

Observations from the Three Examples

- Increasing use of computational M&S (CFD) in actual aerodynamic design of aerospace vehicles is reducing the requirement for physical testing
- Computational M&S could allow exploration of expanded design space in conceptual design stage of advanced aerospace systems
- With proper calibration over a range of parameters of interest, computational M&S could be used reliably in predicting delta in performance

Aerospace Systems Design - Desired Future State

- **Design and certification of advanced systems and technologies done by computational M&S (requires highly reliable, predictive capability)**
- **Physical experimentation used primarily to generate reliable and high quality database to calibrate and validate (C&V) computational M&S tools**

Benefits:

- Faster and cheaper approach to system design and certification
- Ability to explore larger design space for robust designs
- Faster integration of advanced technologies in systems (e.g., HLFC)
- Development of advanced systems for which knowledge and experience base is limited
- Faster time to market

Limitations:

- Need a lot of advances in creating reliable prediction capability with credible uncertainty estimates
- Need 4 to 6 orders or more reduction in computational time to operate at the speed of the designer
- Need large sustained investment in physical experimentation to develop high-quality databases for physical model development and C&V of computational tools

This is the state in which the computational M&S plays the dominant role with physical experimentation as being complementary

Advances in M&S to Arrive at the Future Desired State

- **Require reliable prediction capability with credible uncertainty estimates and range of parameters over which the capability is validated**
- **Systems approach to tools development by simultaneously advancing**
  - Solution algorithms and gridding strategies for efficient solution of governing equations along with modeling equations
    - Higher order accuracy on non-uniform grids
    - Understanding of convergence errors
  - Physical model development
  - Calibration/validation over a range of parameters of interest
  - Uncertainty quantification
  - Efficient implementation on computers (i.e., compatibility with computer architecture)
  - Development and documentation of best practices for use of M&S tools in design
  - Automated intelligent interrogation of solution set for system performance
- **4 to 6 orders or more gains in computational speed**
  - 2 to 3 orders increase in computational speed due to algorithms, gridding strategies, and following best practices
  - 2 to 3 orders increase due to advances in computer technologies and efficient implementation

Sources of Uncertainties in M&S

Physical Experimentation

- Scaled model geometry of the system (may not capture true details such as gaps and steps, surface roughness, etc.)
- Simulated flow in the wind tunnel (may have free stream turbulence, non-uniformity, angularity, wall effects, model support effects, Reynolds number, etc.)
- Instrumentation

Computational Simulations

- Fidelity of governing equations (empirical to high fidelity)
- Numerical effects due to algorithms, grid, dissipation, etc.
- Models for physical phenomena such as transition & turbulence models
- Treatment of discontinuities in the flow such as shock waves
- Lack of convergence

When Can We Arrive at the Future State?

- **Require continuous investments over next 10 to 20 years in advancing technology for computational tools and developing necessary experimental databases for physical models and calibration & validation**
  - These advances have been limited over the last two decades due to lack of investment of funds due to premature declaration of maturity of M&S tools, expensive, no immediate return
- **Keep up with the advances in computer technology that continues to advance.**
  - In 70s and 80s these advances were driven by the needs of scientific computing but not any more. Over the last two decades, advances have come primarily from the needs of gaming industry, movie business, etc.

There are no short cuts if we want to advance the predictive capability of computational tools to perform at the speed of designer

Summary Remarks

- **The grand challenge for computational M&S is to arrive at "Design and Certification by Analysis"**
  - Require highly reliable and robust predictive capability
  - Capable of operating at the speed of system designers
- **Progress towards meeting this grand challenge has been slow due to limited investments**
  - Current high fidelity computational tools are still being used primarily to calculate delta in performance rather than absolute performance
- **Need continuous investments and a systems approach over next 10 – 20 years in**
  - Computer hardware research to exploit extremely high-speed computing
  - Algorithmic research to develop low dissipation/dispersion schemes and solution-adaptive grids
  - Advanced physical modeling
  - Fundamental experiments to validate physical modeling and computational tools
- **Role of physical experimentation is evolving to substantiating computational tools, probably even a more demanding role than before**

Additional References

- Kumar, A. and Hefner, J.N.: Future Challenges and Opportunities in Aerodynamics, The Aeronautical Journal, pp. 365-373, August 2000
- Malik, M. and Bushnell, D.M. (Editors): Role of CFD and Wind Tunnels in Aeronautics R&D, NASA Langley Report, 2012.
- Peterson, Carl W.: Modeling and Simulation-Based Engineering at Sandia, Jan. 2005

Enhancing Reliability and Predictive Capability of Computational M&S

- **Create necessary databases, capturing relevant physics, for calibration and validation over the desired range of parameters for design**
- **Quantify uncertainty**
- **Create standards/best practices for appropriate use of M&S tools such as use the tools over the parameter range where they have been adequately validated**
- **Fund research in physical model development**
  - Require high quality, detailed measurements with uncertainty limits to understand and model the underlying physics

Creating reliable and robust designs using M&S requires reliable and robust predictive capability with credible uncertainty estimates

Enhancing Quality of Experimental Databases

- Well understood and documented facilities with precisely defined operating conditions and flow quality (e.g., flow uniformity, flow angularity, free-stream turbulence, etc.)
- Highly reliable instrumentation, possibly nonintrusive, for detailed measurements of physical phenomena such as flow transition, separation, and interactions, etc.
- Highly defined test article geometry
- Uncertainty limits on measurements

Reliable and robust predicting capability requires high quality, detailed experimental database for physical models and calibration and validation