Validation Issues Associated with Unsteady Flows

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9th Annual Shock Wave/Boundary Layer Interaction Technical Interchange Meeting
Ohio Aerospace Institute, Cleveland, Ohio
24 – 25 May 2016
Outline

• Traditional vs. validation experiments
  – Goals of model validation
  – Trade-off in model validation
  – Design of validation experiments

• Structure of computational simulation
  – Non-deterministic simulation
  – Validation versus calibration

• Areas in need of improvement
  – Experimental activities
  – Computational activities

• Conclusion and recommendations
Traditional Experiments vs. Validation Experiments

Goals of three types of traditional experiments:

1. Improve the fundamental understanding of the physics:
   - Ex: fluid dynamic turbulence experiment; experiment for understanding evaporation and condensation in multi-phase flows

2. Improve the mathematical models of some physical phenomena:
   - Ex: experiment to determine reaction rate parameters in reacting flow; experiment for calibrating parameters in two-equation turbulence models

3. Assess subsystem or complete system performance:
   - Ex: performance of a new combustor design in a gas turbine engine; tests of a new multi-element flap design for a wing

• Model validation experiment
   - An experiment that is designed and executed to quantitatively estimate a mathematical model’s ability to simulate a physical system or process.

• The computational model developer or code user is the customer.
Goals of Model Validation

• Tactical goals of validation:
  – Quantification of the effects of mathematical modeling assumptions and approximations by comparison of simulation results with experimental measurements
  – Identification of the effect of physics modeling weaknesses, i.e., quantification of model form uncertain
  – Model form uncertainty is distinct from model parameter uncertainty

• Strategic goals of validation:
  – Improve the separation of model form uncertainty from all other forms of uncertainty, particularly model parameter uncertainty
  – Improve physics modeling to improve predictive capability

• What are the crucial elements of model validation?
  – Experimental measurement of the important input data for the model
  – Validation metrics: mathematical operators that quantify the difference between simulation and experimental results
Trade-Off in Model Validation Experiments

Design of Validation Experiments

• Key elements in the design of validation experiments:
  – Modelers and experimentalists jointly design the experiment
  – Experimentalist should measure all important model input data
  – Achievement of a blind prediction is the most effective approach
  – Experimentalist should estimate uncertainty on both input data and system response quantities measured

• Five categories of input data:
  – System geometry
  – Initial conditions
  – System physical parameters
  – Boundary conditions
  – System excitation

• What makes validation particularly difficult?
  – Connecting modelers and experimentalist, on the same time frame
  – Separation of input uncertainty and model form uncertainty
Structure of Computational Simulation

Uncertain inputs to the model

- System geometry, SG
- Initial conditions, IC
- Physical modeling parameters, PMP
- Boundary conditions, BC
- System excitation, SE

Propagation of uncertainties through the model

- Mathematical model, $M$, given by a set of primary PDEs, plus a set of equations for all sub-models

Uncertain outputs from the model

- System response quantities, SRQs

• Examples of uncertainty in input data for validation experiments:
  - Geometry; detailed measurement of the actual as-tested geometry
  - Initial conditions; flow field at the beginning of engine-unstart
  - Physical parameters; non-equilibrium chemistry in a high enthalpy facility
  - Boundary conditions; spatial and temporal characterization of inflow conditions in a wind tunnel
  - System excitation; acoustic excitation of a turbulent boundary layer
Where Do We Stand in Model Validation?

• Common approach to validation is actually **model calibration**:
  – Input data and parameters in the model (either scalars or probability distributions) are calibrated to improve agreement with experimental data
  – When model validation (i.e., model accuracy assessment) is mixed with model calibration, it underestimates model form uncertainty by adjusting input data uncertainty

• To improve confidence in our simulations, validation should:
  – Improve the separation of calibration and validation activities
  – Emphasize the assessment of simulation accuracy by using blind-predictions of experimental data
  – Improve cooperation and teamwork between experimentalists and computational analysts so as to conduct improved validation experiments
Areas in Need of Improvement: Experimental Activities

• Improved spatial and temporal characterization of inflow boundary conditions for CFD simulation

• Improved spatial and temporal measurement of flow in an empty test section of a wind tunnel, including the tunnel walls

• Improved measurement and documentation of time-dependent quantities, especially in high-enthalpy shock tunnels

• Comparison of measurements using different experimental techniques, e.g., PIV versus LDV

• Improved experimental uncertainty estimation by way of:
  – Comparison of run-to-run and facility-to-facility variability
  – Comparison of runs with the test article at different locations in the test section

• Improved assessment of experiments regarding completeness of information for model validation
Areas in Need of Improvement: Computational Activities

• Use of simulation to guide the design and execution of validation experiments, e.g., use of sensitivity analyses
• Improved code verification testing and documentation
• Improved quantification and documentation of numerical error due to temporal and spatial discretization
• Willingness to compute the flow in the entire test section
• Construction of improved validation metrics for unsteady flows
• Improve cooperation and teaming with experimentalists

This is the responsibility of management and funding sources
Conclusions and Recommendations

• “Quality” of a validation experiment should be ranked on the following characteristics (in priority order):
  – Measurement and documentation of important input data needed for the simulation
  – Estimation of experimental uncertainty on both input and output data
  – Assessment of model accuracy by way of a blind prediction
  – Separation of model calibration and model validation

• Validation is focused on simulation of the flow field inside the wind tunnel or in flight

• The burden of improving the quality of validation experiments falls primarily on experimentalists

• Sponsors should recognize the need to fund new validation experiments

This is the path to critically assessing our simulations


• Roache, P. J. (2009), *Fundamentals of Verification and Validation*, Hermosa Publishers, Socorro, NM.