An Overview of ASME V&V 20: Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer

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OUTLINE

• Origin of the approach; background

• ASME V&V 20 -- Overview
Origin of this V&V Approach

  • Could unsteady RANS research codes be implemented with confidence in the design of the next generation of naval vessels?
  • Experiments on models in 3 towing tanks in U.S. (David Taylor, IIHR) and Italy (INSEAN)
  • Two RANS codes used by (a) code developers and (b) other groups
  • Classified program

• A quantitative V&V approach was proposed based on error and uncertainty concepts in experimental uncertainty analysis (ISO GUM, 1993, international standard).
  • Hugh Coleman (UAHuntsville) and Fred Stern (Iowa) published initial version in ASME Journal of Fluids Engineering, Dec 1997.
**V&V 20 Development**

ASME Performance Test Codes Committee PTC 61:

**V&V 20: Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer**

Approach is based on experimental uncertainty analysis concepts of error and uncertainty. Committee formed in 2004; Draft document completed; peer review comments received early June 2008; publication probable in late 2008.

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How Does V&V 20 Fit With Previously-Published V&V Guides?


– **Error**: A recognizable deficiency in any phase or activity of modeling and simulation that is not due to lack of knowledge.

– **Uncertainty**: A potential deficiency in any phase or activity of the modeling process that is due to lack of knowledge.
- **Error**: A recognizable deficiency in any phase or activity of modeling or experimentation that is not due to lack of knowledge.

- **Uncertainty**: A potential deficiency in any phase or activity of the modeling or experimentation process that is due to inherent variability or lack of knowledge.
• The objective of V&V 20: the specification of an approach that quantifies the degree of accuracy inferred from the comparison of solution and data for a specified variable at a specified validation point.

• The scope of V&V 20: the quantification of the degree of accuracy for cases in which the conditions of the actual experiment are simulated.

“How good is the prediction? What is the modeling error?” --- at the validation point --- when the experiment itself is simulated.
Experimental Uncertainty Concepts: Error and Uncertainty

An error \( \delta \) is a quantity with a sign and magnitude. A specific error \( \delta_i \) is the difference (caused by error source \( i \)) between a quantity (measured or simulated) and its true value. (We assume there has been a correction made for any error whose sign and magnitude is known, so the errors that remain are of unknown sign and magnitude.)

An uncertainty \( u_i \) is an estimate of an interval \( \pm u_i \) that should contain \( \delta_i \). (A standard uncertainty \( u \) is an estimate of the standard deviation of the parent distribution of \( \delta \): ISO GUM)

For example, for an (unknown) error \( \delta_d \) in the data, \( u_d \) would be the standard uncertainty estimate.
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Example for V&V 20 Nomenclature and Approach

Validation variables of interest are $T_o$ and $q = \rho Q(T_i - T_o)$.

Note: Fins are square in profile, not circular.
A Validation Comparison

Reynolds Number, Re

Outlet Bulk Fluid Temperature, T₀

Validation Point

Value

Value

True (but unknown)

Experiential Data Value

Error

Simulation Value

E

S

Q₀

Q₀
Real|ity of Interest (Truth): Experiment “as run”

Experimental Errors

Experimental Data, D

Comparison Error, E = S - D

Validation Uncertainty, u_{val}

Simulation Result, S

Modeling Assumptions

Simulation Inputs (Properties, etc.)

Numerical Solution of Equations

E = (\delta_{model}) + (\delta_{input} + \delta_{num} - \delta_{D})

V&V Overview – Sources of Error Shown in Ovals
Strategy of the Approach

• Isolate the modeling error, having a value or uncertainty for everything else

\[ E = \delta_{\text{model}} + (\delta_{\text{input}} + \delta_{\text{num}} - \delta_D) \]

\[ \delta_{\text{model}} = E - (\delta_{\text{input}} + \delta_{\text{num}} - \delta_D) \]

• If \( \pm u_{\text{val}} \) is an interval that includes \( (\delta_{\text{input}} + \delta_{\text{num}} - \delta_D) \), then \( \delta_{\text{model}} \) lies within the interval

\[ E \pm u_{\text{val}} \]
Uncertainty Estimates Necessary to Obtain the Validation Uncertainty $u_{val}$

$$u_{val} = \left( u_D^2 + u_{num}^2 + u_{input}^2 \right)^{1/2}$$

- Uncertainty in simulation result due to numerical solution of the equations, $u_{num}$ (code and solution verification)

- Uncertainty in experimental result, $u_D$

- Uncertainty in simulation result due to uncertainties in code inputs, $u_{input}$

Propagation by
(A) Taylor Series
(B) Monte Carlo
Uncertainty Estimates Necessary to Obtain the Validation Uncertainty $u_{val}$

$$u_{val} = \left( u_D^2 + u_{num}^2 + u_{input}^2 \right)^{1/2}$$

- **Code verification**: establishes that the code accurately solves the conceptual model incorporated in the code, i.e. that the code is free of mistakes for the simulations of interest. (MMS, ....)

- **Solution verification**: estimates the numerical accuracy of a particular calculation, i.e., $u_{num}$. (RE, GCI, ....)

Uncertainty Estimates Necessary to Obtain the Validation Uncertainty $u_{\text{val}}$

$$u_{\text{val}} = \left( u_D^2 + u_{\text{num}}^2 + u_{\text{input}}^2 \right)^{1/2}$$

- $u_D$ can be estimated using experimental uncertainty analysis techniques.
Test Uncertainty

ASME PTC 19.1-2005
(Revision of ASME PTC 19.1-1998)

AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers

Experimentation and Uncertainty Analysis for Engineers
SECOND EDITION

Hugh W. Coleman • W. Glenn Steele

3rd Edition in 2009
Uncertainty Estimates Necessary to Obtain the Validation Uncertainty $u_{val}$

$$u_{val} = \left( u_D^2 + u_{num}^2 + u_{input}^2 \right)^{1/2}$$

Taylor Series propagation approach to estimating $u_{input}$

$$u_{input}^2 = \sum_{i=1}^{m} \left( \frac{\partial S}{\partial X_i} \right)^2 \left( u_{X_i} \right)^2$$

and the $u_{X_i}$ are the uncertainties in the m simulation inputs $X_i$

(This expression for $u_{input}$ is strictly true only when there are no shared variables in S and D. A more complex form is necessary if S and D contain shared variables, and is presented in detail in V&V 20)
Taylor Series approach for estimating $u_{val}$ when the validation variable $T_o$ is directly-measured ($T_{o,D}$) and predicted with the simulation ($T_{o,S}$) as

$$T_{o,S} = T_{o,S}(T_i, T_\infty, Q, \rho, u, C_P, h_i, h_2, h_f, h_c, k_f, k_l, d_1, d_2, L, a, w_f, w_{nf})$$

**Case 1**
Monte Carlo approach for estimating $u_{val}$ when the validation variable $T_o$ is directly-measured ($T_{o,D}$) and predicted with the simulation ($T_{o,S}$) as $T_{o,S} = T_{o,S}(T_i, T_{\infty}, Q, \rho, \mu, C_P, h_1, h_2, h_f, h_c, k_f, k_t, d_1, d_2, L, a, w_f, w_{nf})$.
Additional Cases Covered in V&V 20

- The experimental value $D$ of the validation variable is determined from a data reduction equation

$$q_D = \rho QC_P \left( T_{i,D} - T_{o,D} \right)$$

and the simulation value predicted as

$$q_S = \rho QC_P \left[ T_{i,D} - T_{o,S} \left( T_i, T_\infty, Q, \rho, \mu, C_P, h_1, h_2, h_f, h_c, k_f, k_t, d_1, d_2, L, a, w_f, w_{nf} \right) \right]$$

**V&V 20 Case 2:** $T_{i,D}$ and $T_{o,D}$ share no error sources, so there are no correlated systematic errors

**V&V 20 Case 3:** $T_{i,D}$ and $T_{o,D}$ are measured with transducers calibrated against the same standard, so there are correlated systematic errors
Case 4 considers a combustion flow with the validation variable being duct wall heat flux $q$ at a given location. The experimental $q$ is inferred from temperature-time measurements at the outside combustor duct wall using a data reduction equation that is itself a model. The predicted $q$ is from a simulation using a turbulent chemically-reacting flow code to model the flow through the duct.
Interpretation of Validation Results with No Assumptions Made about the Error Distributions

\[ \delta_{\text{model}} = E - (\delta_{\text{input}} + \delta_{\text{num}} - \delta_D) \]

If \( |E| \gg u_{\text{val}} \)
then probably \( \delta_{\text{model}} \approx E \).

If \( |E| \leq u_{\text{val}} \)
then probably \( \delta_{\text{model}} \) is of the same order as or less than \( (\delta_{\text{num}} + \delta_{\text{input}} - \delta_D) \).
Interpretation of Validation Results with Assumptions Made about the Error Distributions

\[ \delta_{\text{model}} = E - (\delta_{\text{input}} + \delta_{\text{num}} - \delta_D) \]

In order to estimate an interval within which \( \delta_{\text{model}} \) falls with a given probability or degree of confidence, an assumption about the probability distribution of the error combination \( (\delta_{\text{input}} + \delta_{\text{num}} - \delta_D) \) must be made. This then allows the choice of a coverage factor \( k \) such that

\[ U_{\%} = k \% u_{\text{val}} \]

One can say, for instance, that \( (E \pm k_{95}u_{\text{val}}) \) then defines an interval within which \( \delta_{\text{model}} \) falls about 95 times out of 100 (i.e., with 95% confidence) when the coverage factor has been chosen for a level of confidence of 95%.
Questions?