Validation of CFD Model of Smooth Seal using V&V 20-2009

Presented by Madeline Collins
In Collaboration with Houston Wood, Cori Watson-Kassa, Neal Morgan
Who’s presenting?

Madeline Carlisle Collins

- BS in Mechanical Engineering from Louisiana Tech (2017)
- Pursuing PhD in Mechanical Engineering at University of Virginia
  - Research in ROMAC

ROMAC

- Rotating Machinery and Controls Lab
- Research Consortium supported by ~30 industry members
- Develop software for engineering design of turbomachinery
  - Tribology (bearings and seals)
  - Codes are numerical solvers
  - CFD is our “gold standard” and sanity check
What I’ll be talking about

• Problem Statement
• Case Study
• Validation Procedure
Problem Statement

- How validation is done in ROMAC
- ROMAC’s plans for the future
- How this study fits in that plan
How ROMAC currently validates codes

• Compares code output to experimental data
  • Sparse data problem
• Compares code output to CFD models

Problems with this method

• Research shows that model output varies significantly between code developers
  • Variation likely due to model assumptions and solution techniques [1]
• **Accuracy & uncertainty of codes unknown**
ROMAC plans for validation improvements

Develop formal method to assess accuracy of our codes with

- Generalized method for types of problem ROMAC solves
- Demonstrated on example case

1. Validate CFD model (this presentation)
   - Case study: smooth seals

Future steps: Unclear and open to suggestions
Case Study

• About seals
• About experiment validated against
• About CFD model being validated
Why model a seal?

- Machine component contains fluid at high pressures (greater than ambient)
  - Ex: pumps, compressors
- Component is on a rotor
- Seal keeps fluid from leaking out of component with minimal power loss to system (friction)
Experimental data validated against

“Experimental Study on Static and Dynamic Characteristics of Liquid Annular Convergent-Tapered Damper Seals With Honeycomb Roughness Pattern” [3]

- By Satoru Kaneko, Takashi Ikeda, Takuro Saito, Shin Ito
- Published in 2003
- ASME Journal of Tribology

Validation Point

- Working fluid: water
- 3000 rpm
- Inlet pressure: 784 kPa
Experiment: Rig for measuring seal performance [3]
Region of experiment test rig to be modeled [3]
CFD Model

ANSYS CFX

Structured mesh

SST turbulence modeling

massFlow = Leakage = QOI
Validation Study

• Following V&V 20-2009
• 3 sources of uncertainty addressed
  • Experimental, numerical, & input
• Result: estimate of model error
Overarching idea behind V&V 20-2009 (sec. 1)

Error: Deviation from truth

Simulation error

\[ E = \delta_S - \delta_D = S - D \]

- \( \delta_S \) = sum of various types of errors due to simulation
- Numerical \( \delta_{num} \)
- Input parameters \( \delta_{input} \)
- Model assumptions \( \delta_{model} \)

Experimental error

\( \delta_D \) = sum of errors from experiment

Comparison error is known

\[ E = \delta_S - \delta_D = S - D \]
Overarching idea behind V&V 20-2009 (sec. 1)

Simulation error: \( \delta_S = \delta_{num} + \delta_{input} + \delta_{model} \)

Comparison error: \( E = \delta_S - \delta_D = \delta_{num} + \delta_{input} + \delta_{model} - \delta_D \)

Model error \( \Rightarrow \delta_{model} = E - (\delta_{num} + \delta_{input} - \delta_D) \)

Define uncertainty \( u_i \) to be an estimation of error, \( \delta_i \)

\[
\delta_{model} \in E \pm \sqrt{u_{num}^2 + u_{input}^2 + u_D^2}
\]

Validation uncertainty: \( u_{val} \equiv \pm \sqrt{u_{num}^2 + u_{input}^2 + u_D^2} \)

This estimate of model error is the final result of the validation study. It represents the contribution of modeling assumptions to the model’s error.
EXPERIMENTAL UNCERTAINTY (sec. 4)

$u_D$ uncertainty of experiment
Experimental uncertainty without enough data

V&V 20-2009 method requires Validation Experiment data

• Perturbations of control parameters for uncertainty quantification

ROMAC typically uses retrospective experiments and validates with already published data

V&V 20-2009 Foreword

• Ideally, “those responsible for the simulations and those responsible for the experiments should be involved cooperatively in designing the V&V effort.”
• The sources of uncertainty in this standard “can be studied independently.”
Experimental uncertainty calculations

For this study, the reported experimental uncertainty for leakage in [3] will be used here.

Dimensionless uncertainty for QOI (leakage) was reported

• $\frac{u_D}{D} = 5\%$

Dimensional

• $u_D = \left(\frac{u_D}{D}\right) D = (5\%) \left(0.528 \frac{L}{s}\right) = 2.64 \cdot 10^{-2} \frac{L}{s}$
NUMERICAL UNCERTAINTY (sec. 2)

$u_{num}$ simulation uncertainty due to numerical error
Grids for numerical uncertainty

1. Find 3 grids with representative grid size, \( h = \left( \frac{\text{fluid volume}}{\text{number of elements}} \right)^{\frac{1}{3}} \)
   - \( h \) is the average size of a cell in one dimension
   - Ratio between grids: \( r = \frac{h_{\text{coarse}}}{h_{\text{fine}}} \geq 1.3 \)
   - Order grids: \( h_1 < h_2 < h_3 \)

2. Run simulation for all grids
   - Collect Quantity of Interest
   - QOI = leakage = \( \varphi_i \) (for \( i^{\text{th}} \) grid)

<table>
<thead>
<tr>
<th>Grid</th>
<th>Num. Elements</th>
<th>Element Size</th>
<th>Ratio</th>
<th>Leakage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N (#)</td>
<td>h (mm)</td>
<td></td>
<td>( \varphi ) (L/s)</td>
</tr>
<tr>
<td>1</td>
<td>9.74E+04</td>
<td>0.21637</td>
<td></td>
<td>0.50748</td>
</tr>
<tr>
<td>2</td>
<td>3.23E+04</td>
<td>0.31250</td>
<td>1.44</td>
<td>0.50728</td>
</tr>
<tr>
<td>3</td>
<td>1.08E+04</td>
<td>0.44991</td>
<td>1.44</td>
<td>0.49174</td>
</tr>
</tbody>
</table>
Numerical uncertainty calculation

3. Find order of convergence, \( p = \frac{\ln|\varepsilon_{32}/\varepsilon_{21}|+q}{\ln(r_{21})} = 12 \)
   - Relative error between grids \( \varepsilon = \varphi_{\text{coarse}} - \varphi_{\text{fine}} \)
   - If grid ratios \( r \approx \text{constant} \), then \( q \approx 0 \)

4. Find grid convergence index, \( GCI = \frac{F_s|\varepsilon_{21}|}{r_{21}^p-1} = 0.001 \% \)
   - \( F_s = \) factor of safety = 1.25 for structured grid

5. Find numerical uncertainty, \( u_{num} = \frac{GCI}{k} \varphi_1 = 3.00 \cdot 10^{-6} \frac{L}{s} \)
   - \( k \) = expansion factor = 1.15 for well-behaved problems

- Note: Ran simulation on 16 different grids and performed calculations for all appropriate combinations of 3 grids (47 uncertainty calculations).
INPUT UNCERTAINTY (sec. 3)

$u_{input}$ simulation uncertainty due to CFD input parameters
Input Uncertainty, formulaic definition

Consider all $n$ input parameters ($X_i$). Define input uncertainty

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

- $u_{X_i}$ = **standard uncertainty** of input parameter $X_i$
- $\frac{\partial S}{\partial X_i}$ = **sensitivity coefficient** = rate of change in simulation output per change in input parameter $X_i$
  - With second-order finite difference, $\frac{\partial S}{\partial X} \approx \frac{\Delta S}{\Delta X} = \frac{S(X+\Delta X) - S(X-\Delta X)}{2 \Delta X}$

For standard uncertainty $u_{X_i}$: When unreported, refer to “expert opinion”
  - ROMAC industry member and colleagues
Input Uncertainty Calculation

For sensitivity coefficient \( \frac{\Delta S}{\Delta X_i} \):

Try various deviations of each parameter. Choose deviation \( \Delta X_i \) where the effect on CFD output is approximately constant

- If \( \Delta X_i \) too small, output is unchanging – subtractive cancellation
- If \( \Delta X_i \) too large, output is not representative of the validation point – parameter discretization

Input Uncertainty

\[ u_{\text{input}}^2 \approx \sum_{1}^{10} \left( u_X \frac{\Delta S}{\Delta X} \right) \Rightarrow u_{\text{input}} = 1.01 \cdot 10^{-1} \frac{L}{s} \]
MODEL ERROR

\( \delta_{\text{model}} \) error in simulation from truth due to model assumptions and approximations
Validation uncertainty & interpretation (sec. 5 & 6)

Combine uncertainties

- \[ u_{val}^2 = u_{exp}^2 + u_{num}^2 + u_{input}^2 = \left(2.64 \cdot 10^{-2} \frac{L}{s}\right)^2 + \left(7.20 \cdot 10^{-6} \frac{L}{s}\right)^2 + \left(1.01 \cdot 10^{-1} \frac{L}{s}\right)^2 \]
- \[ \Rightarrow u_{val} = 0.104 \frac{L}{s} \]

Validation comparison error, \( E = \left(0.50728 \frac{L}{s}\right) - \left(0.528 \frac{L}{s}\right) = 0.02072 \frac{L}{s} \]

With this, we estimate error due to model assumptions

- \[ \delta_{model} \in E \pm u_{val} = (0.02072 \pm 0.104) \frac{L}{s} \Rightarrow \delta_{model} \in \left(-0.083 \frac{L}{s}, 0.125 \frac{L}{s}\right) \]

Since \( E \leq u_{val} \), model is within the noise of the uncertainty sources. Model improvement opportunities are unclear.
References


Let’s introduce ASME V&V to Turbomachinery

Thank you

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Extra Slides

- Details
- Judgement calls
MY selection of this set of 3 grids

Simulated for 16 different grids. Followed procedure for all possible combinations of 3 grids with \( r_{12}, r_{32} > 1.3 \). ...47 combinations

1. Eliminate those with GCI above 1% in magnitude
   • Low GCI indicates stronger convergence
2. Among remaining, choose the remaining sets with the smallest middle grid
   • Future simulations will run faster
3. Among remaining, choose sets with larger ratio between grid sizes (\( r_{12}, r_{32} \))
   • Larger ratios test convergence more strongly
4. Among remaining, choose set with greatest uncertainty
   • To be conservative
Examples of varying deviation of parameters

Horizontal axis: $\log(\Delta X/X)$

Vertical axis: $\log(u)$

- Problem: For some parameters, it’s unclear what region to choose
### Input uncertainty calculations

**Input Parameter:**

<table>
<thead>
<tr>
<th>Term</th>
<th>Unit</th>
<th>Rotor Speed</th>
<th>Inlet Pressure</th>
<th>Seal Length</th>
<th>Seal Clearance</th>
<th>Inlet Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X$</td>
<td>[u]</td>
<td>3000</td>
<td>881.38</td>
<td>60</td>
<td>0.168</td>
<td>0.61</td>
</tr>
<tr>
<td>$\Delta X$</td>
<td>[u]</td>
<td>60</td>
<td>1.8</td>
<td>1.2</td>
<td>3.4E-3</td>
<td>6.8E-1</td>
</tr>
<tr>
<td>$S(X+\Delta X)$</td>
<td>[L/s]</td>
<td>0.506246</td>
<td>0.506817</td>
<td>0.504303</td>
<td>0.516016</td>
<td>0.506715</td>
</tr>
<tr>
<td>$S(X-\Delta X)$</td>
<td>[L/s]</td>
<td>0.506786</td>
<td>0.506217</td>
<td>0.509251</td>
<td>0.499424</td>
<td>0.506842</td>
</tr>
<tr>
<td>$\Delta S/\Delta X$</td>
<td>[L/s/u]</td>
<td>-9.0E-6</td>
<td>3.4E-4</td>
<td>-4.1E-3</td>
<td>4.9E+0</td>
<td>9.2E-4</td>
</tr>
<tr>
<td>$u_x$</td>
<td>[%]</td>
<td>10%</td>
<td>10%</td>
<td>5%</td>
<td>5%</td>
<td>20%</td>
</tr>
<tr>
<td>$u_x \ast \Delta S/\Delta X$</td>
<td>[L/s]</td>
<td>-1.3E-3</td>
<td>1.5E-2</td>
<td>-2.5E-2</td>
<td>8.3E-2</td>
<td>6.3E-3</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
  u_{input}^2 & \approx \sum_{1}^{6} \left( u_x \frac{\Delta S}{\Delta X} \right) \\
  \implies u_{input} & = 1.01 \cdot 10^{-1} \frac{L}{s}
\end{align*}
\]
Input uncertainty details

10 Input Parameters, 3 types

- Operating conditions ($u_{X_i} \sim 10\%$)
  - *Inlet pressure, Rotational speed of rotor*
- Dimensions of seal reported by experimentalists ($u_{X_i} \sim 5\%$)
  - *Seal Length, Seal Clearance, Rotor Radius*
- Dimensions estimated from test rig diagram ($u_{X_i} \sim 20\%$)
Numerical uncertainty - Well behaved problem

Asymptotic region