Computational Flow Assurance
Recent progress in modelling of multiphase flows in long pipelines

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Agenda

• Background
• Validation studies
  - Espedal – stratified flow
  - TMF - slug flow
  - StatOil – wavy-slug flow
• 3D application
  - Long pipeline
• Co-simulation
  - 1D-3D coupling
• Summary
The Importance of Simulation in Engineering Design

- “The deeper you go, the less you know”
  - Engineers need to know if proposed designs will function properly under increasingly harsh operating offshore/subsea conditions
  - Experience and “gut feel” become less reliable in new environments
  - Physical testing is increasingly expensive and less reliable due to scaling assumptions

- Simulation is rapidly moving from a troubleshooting tool into a leading position as a design tool: “Up-Front” numerical/virtual testing to validate and improve designs before they are built and installed
The Importance of Using the Right Numerical Tools

- To be effective, simulations must be
  - Fast enough to provide answers within the design timeframe
  - Accurate enough to provide sufficiently insightful answers for better design decisions

- Choice and use of a judicious mix of tools for **Multi-Fidelity Simulation** to meet these effectiveness requirements, e.g.
  - 1-D simulations (OLGA) for long pipeline systems
  - 3-D simulations (STAR) for equipment, transition regions
  - A user-friendly computing environment for activating the right mix of tools for the situation being examined: *co-simulation*
Multi-Fidelity Simulation Effort

Higher fidelity (= more *detailed* insight) requires increasing computational time *(wall-clock)*
Stratified flow in a pipe - Espedal (1998)

- Experimental data provided by Dag Biberg, SPT.
- Air-water stratified flow in near horizontal pipe.
- Reference data for pipe flow analysis.

- $L=18\text{m}$, $D=60\text{mm}$
Comparison with Espedal data

Pressure gradient

Liquid level
CPU requirement

- Cell count: 97416
- Time step: 1e-2
- 4 processors, 1 day to simulate ~100 s.
- Statistically steady state reached around 80 seconds.
Slug flow test case from TMF

- Slug flow benchmark case selected by Prof Geoff Hewitt, Imperial College.
- $L=37\text{m}$, $D=77.92\text{mm}$
- Air/water, $P=1\text{atm}$, $T=25^\circ\text{C}$, inlet fraction 50/50
- $U_{sl}=0.611\text{m/s}$, $U_{sg}=4.64\text{m/s}$
Mesh

- 384 cells in cross plane.
- 2.5 cm in axial direction.
- Total cell count 568,512.
CFD model

- Volume of Fluid (VOF).
- High Resolution Interface Capture (HRIC) scheme used for volume fraction.
- Momentum: Linear Upwind scheme (2nd order).
- Turbulence: k-ω SST model with interface damping.
- Gas phase: compressible.
- Liquid phase: incompressible.
- Time step: 8e-4 s
TMF - Slug Flow Benchmark: Slug Origination and Growth
 Slug frequency - liquid height at middle of pipe

Experiment

STAR-CD

CD-adapco
 Slug frequency - liquid height at end of pipe

**Experiment**

**STAR-CD**
Slug length along pipe

- CFD results show the initial development length. I.e. Initial 5m is needed for the instabilities to develop into waves and slugs.
- Slug length growth rate agrees well with measured data.
CPU requirement

- Cell count: 568,512
- Time step: 8e-4 s
- 20 processors, 10 days to simulate 100 s.
- Experimental measurement taken over 300 seconds.
Statoil-Hydro pipe

- Horizontal straight pipe: 3” diameter, 100m long.
- Measuring plane: 80m from inlet.

- Real fluids (gas, oil, water) at $P = 100$ bar, $T = 80^\circ C$. 
Mesh

- 370 cells in cross plane.
- 3330 cells in axial direction of 3 cm each.
- Total cell count is 1,232,100.
Gas-Oil: Density/Oil density

\[ U_{sg} = 1.01 \text{ m/s}, \quad U_{si} = 1.26 \text{ m/s} \]

Experiment

Density/Density-oil calculated as density of 2 phase mixture/density of oil
Gas-Oil: Power FFT

Experiment

STAR-CD
Gas-Water: Density/Water density

$U_{sg}=1.01 \text{ m/s}, U_{sl}=1.50 \text{ m/s}$
Gas-Water: Power FFT

Experiment

STAR-CD

CD-adapco
## Comparison of results

<table>
<thead>
<tr>
<th>Density / Density liquid</th>
<th>Experiment</th>
<th>STAR-CD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas-oil</td>
<td>0.63</td>
<td>0.656</td>
</tr>
<tr>
<td>Gas-water</td>
<td>0.55</td>
<td>0.68</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Power (FFT) Dominant period</th>
<th>Experiment (s)</th>
<th>STAR-CD (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas-oil</td>
<td>2.7</td>
<td>2.23</td>
</tr>
<tr>
<td>Gas-water</td>
<td>1.34</td>
<td>1.57</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wave speed</th>
<th>Experiment (m/s)</th>
<th>STAR-CD (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas-oil</td>
<td>2.8</td>
<td>2.58</td>
</tr>
<tr>
<td>Gas-water</td>
<td>3.2</td>
<td>2.7</td>
</tr>
</tbody>
</table>

- CFD wave speed obtained by comparing holdup trace at 2 locations of known distance and time delay between the signals.
CPU requirement

- Cell count: 1,232,100
- Time step: 7e-4 s
- 40 processors, 1 day to simulate ~55 s
- Each case requires around 300 s (~ 3 residence time) can be done within 1 week.
• Simulation of oil-gas flow in a pipeline where wavy, slug, churn, and annular flow may occur.

• Slug Flow Types:
  - Hydrodynamic slugging: induced by growth of Kelvin-Helmholtz instabilities into waves then, at sufficiently large heights, into slugs.
  - Terrain slugging: induced by positive pipeline inclinations, such as section A.
  - Severe slugging: induced by gas pressure build-up behind liquid slugs. It occurs in highly inclined or vertical pipeline sections, such as section B, at sufficiently low gas velocities.
Mesh Details

- 1.76M cells (352 cross-section x 5000 streamwise) → butterfly mesh
- Streamwise cell spacing $\Delta x \approx 22$ mm $\approx 0.3D$
- Run on 64 cores (rogue cluster) $\Rightarrow$ 27500 cells/core
Problem Setup

- **Boundary Conditions**
  - Inlet: Velocity
    - $U_{\text{liq}} = 1.7 \text{ m/s}$
    - $U_{\text{gas}} = 5.4 \text{ m/s}$
    - Liquid Holdup $\alpha_L = 0.5$
    - $\rho_{\text{liq}} = 914 \text{ kg/m}^3$
  - Outlet: Pressure
    - $p = 10^5 \text{ Pa}$

- **Initial Conditions**
  - $\alpha_L = 0.5$, $\alpha_G = 0.5$
  - $U = V = W = 0.0 \text{ m/s}$

- **Fluid Properties**
  - $\mu_{\text{liq}} = 0.033 \text{ Pa.s}$
  - $\mu_{\text{gas}} = 1.5 \times 10^{-5} \text{ Pa.s}$
Run Controls

- Run for about two flow passes, based on inlet liquid velocity of 1.7 m/s
  - Total Physical Time = 132 s
  - Start-up run physical time, $t_1 \approx 74.5$ s
  - Restart run physical time, $t_2 \approx 57.5$ s
- A variable time step size based on an Average Courant Number criterion
  - $\text{CFL}_{\text{avg}} = 0.25$
- Run on 64 cores (Rogue cluster)
  - 27500 cells per core – expected linear scalability
## Performance Data

<table>
<thead>
<tr>
<th></th>
<th>Start-up</th>
<th>Restart</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of Time Steps</strong></td>
<td>174036</td>
<td>138596</td>
<td>312632</td>
</tr>
<tr>
<td><strong>Physical Time (s)</strong></td>
<td>74.534</td>
<td>57.610</td>
<td>132.144</td>
</tr>
<tr>
<td><strong>CPU time (s)</strong></td>
<td>834523</td>
<td>664441</td>
<td>1498964</td>
</tr>
<tr>
<td><strong>Elapsed time (s)</strong></td>
<td>866038</td>
<td>690601</td>
<td>1556639</td>
</tr>
<tr>
<td><strong>CPU time (d/h/min/s)</strong></td>
<td>9d 15h 48min 43s</td>
<td>7d 16h 34min 1s</td>
<td>17d 8h 22min 44s</td>
</tr>
<tr>
<td><strong>Elapsed time (d/h/min/s)</strong></td>
<td>10d 0h 33min 58s</td>
<td>7d 23h 50min 1s</td>
<td>18d 0h 23min 59s</td>
</tr>
<tr>
<td><strong>CPU (s) / TimeStep</strong></td>
<td>4.80</td>
<td>4.79</td>
<td>4.79</td>
</tr>
<tr>
<td><strong>CPU / Physical</strong></td>
<td>11197 (3.11 h/s)</td>
<td>11533 (3.20 h/s)</td>
<td>11343 (3.15 h/s)</td>
</tr>
<tr>
<td><strong>Elapsed / Physical</strong></td>
<td>11619 (3.23 h/s)</td>
<td>11987 (3.33 h/s)</td>
<td>11780 (3.27 h/s)</td>
</tr>
<tr>
<td><strong>TimeStep size (ms)</strong></td>
<td>0.43</td>
<td>0.42</td>
<td>0.42</td>
</tr>
<tr>
<td><strong>Outer ITERmax</strong></td>
<td>9.69</td>
<td>9.42</td>
<td>9.55</td>
</tr>
<tr>
<td><strong>CFLmax</strong></td>
<td>31.45</td>
<td>26.45</td>
<td>28.95</td>
</tr>
</tbody>
</table>
Transient Data

- Transient data monitored at 10 locations:
  - Inlet
  - Monitor (1): end of positive inclined section
  - Monitor (2): end of negative inclined section prior to riser
  - Monitors (3) to (8): as shown in schematic below
  - Outlet

- Type of data monitored:
  - Liquid hold-up (i.e., VOF scalar)
  - Pressure
  - Density
  - Velocity
Transient Data

Area-averaged liquid hold-up – Monitor (1)
The simulation of a two-phase oil-gas flow in a realistic geometry pipeline was carried out using STAR-CD

STAR-CD was able to successfully capture:

- Wavy flow
- Slug flow
- Severe slugging
- Churn flow
- Annular flow
The Next Step: Co-Simulation Using the STAR-OLGA Link

To seamlessly study 3D effects in in-line equipment: valves, junctions, elbows, obstacles, jumpers, separators, slug catchers, compressors, ...

Flow rates from OLGA to STAR
Pressure from STAR to OLGA
Flow rates from STAR to OLGA
Pressure from OLGA to STAR

Note: stratified flow becomes annular flow due to two circumferential pipe dimples
OLGA-STAR coupled model – example 1

Flow rates from OLGA to STAR
Pressure from STAR to OLGA
OLGA-STAR coupled model – example 1

OLGA pipe:
- 3 phase flow in pipe: gas, oil and water
- Pipe diameter: 0.254 m
- Pipe length is 1.5 km going up an incline of 15m
- Fixed mass source at inlet

STAR pipe:
- Same 3 phases
- Same physical properties as OLGA
- Same pipe diameter, 1 m long, small flow restrictions in flow area (valve, fouling/hydrate deposit,...)
OLGA-STAR: 1-way and 2-way coupling

- **One-way OLGA->STAR coupling:**
  - OLGA sends outlet mass flow rates to STAR for inlet conditions.

- **Two-way OLGA->STAR coupling:**
  - OLGA sends outlet mass flow rates to STAR for inlet conditions.
  - STAR returns computed pressure at inlet to OLGA for outlet pressure value.
OLGA-STAR-OLGA coupled model: Two-end Coupling

Flow rates from OLGA to STAR

Flow rates from STAR to OLGA

Pressure from STAR to OLGA

Pressure from OLGA to STAR

Note: Annular flow at outlet of STAR pipe.

One OLGA session with two independent pipelines.
OLGA-STAR-OLGA coupled model - example 2

Flow rates from OLGA to STAR

Note:
Annular flow at outlet of STAR pipe.

Pressure from STAR to OLGA

Flow rates from STAR to OLGA

Pressure from OLGA to STAR
OLGA-STAR-OLGA – mass flows in OLGA pipes

Upstream pipe

Downstream pipe - flows are getting through the STAR pipe into the downstream pipe
OLGA-STAR coupled model - example 3

Flow rates from OLGA to STAR

Pressure from STAR to OLGA
Summary

- 3D Flow Assurance tools have been validated and applied to long pipelines.
- Slug behaviour well captured but long calculation time (compared to traditional 1D methods).
- Successful development of coupling between OLGA and STAR for 1D analysis of long pipeline with detailed 3D simulation to study effects in local regions (the “3-D microscope”).
- Successful demonstration of OLGA-STAR-OLGA two-point two-way coupling.
- Very interesting preliminary results obtained. Further test cases and more detailed analyses will follow.
Discussion - Questions?

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