The Validation of STAR-CCM+ Coupled to Abaqus for Analyzing Fluid-Elastic Instabilities in a Flexible Tube Bundle

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Objective is to apply STAR-CCM+ coupled to Abaqus to predict the fluid-elastic instabilities of a tube bundle in a turbulent water cross-flow

- Particularly important phenomena in large heat exchangers and fuel assemblies in the Nuclear industry

Compare the results to a well-documented experimental study

Difficult Validation Case
- Large amplitude vibrations of the tubes
- Strong coupling between water and structure that requires implicit, iterative coupling strategies
- Prediction of the critical flow velocity at which vibration instabilities ensue
  - Fluid damping is critical
- Prediction of the Limit Cycle Oscillations (LCO) above critical velocities
- Complicated transition of the fluid/structure behavior
Abaqus and STAR-CCM+ Models

Abaqus standard model : (37 K nodes)
- Acrylic rods attached to smaller steel rods
- Acrylic rods: 3d continuum elements
- Steel rods: b31 elements

STAR-CCM+ model : 1.47M cells
- K–omega SST model (RANS)
- Segregated solver
- Y+ near 1 (likely overkill)
- urfv=.95, urfp=0.4,
- 20 to 40 iteration per time step

implicit coupling
- Δt=T/100, T=1st eigenmode in air
- Default displacement urf
Vibration of single rod in air (Abaqus Standalone)

- Young's modulus, density, steel rod length chosen to give measured frequency 25.5Hz
- Rayleigh Damping tuned to measured damping in air
  - $\beta = 0.000205$;
  - $\ln(D) = 0.014$, $D = A(k)/A(k+1)$
- Stiffness alone was not measured!

\[ f_1 = 25.51 \text{Hz} \quad f_2 = 231.7 \text{ Hz} \]
Natural frequency and damping of single rod in quiescent water (Coupled Simulations)

- Measured damping \( \ln(D) = 0.037 \)
- Apply impulse load to excite mostly the 1\(^{st}\) mode and observe free motion
- 2\(^{nd}\) order in both Abaqus & STAR-CCM+
  - 1\(^{st}\) order gridflux \( \ln(D) = 0.074 \)
  - 1\(^{st}\) order gridflux, \( \Delta t = T/200 \) \( \ln(D) = 0.067 \)

Predicted \( f_1 = 18.0 \text{ Hz} \)
Fluid Flow over Rigid Rods (STAR-CCM+ Standalone)

Simulations run sufficiently long to reach pressure RMS steady-state

\[ Vu = 0.24 \text{m/s} \quad \text{Spectra} \quad Vu = 0.39 \text{m/s} \]

Frequency (HZ)

Solution Time 0.00394 (s)
Fluid Flow over Flexible Rods (STAR-CCM+/Abaqus)

Fluid velocity

Velocity: Magnitude (m/s)

Solution Time 0.39592 (s)

Vu=0.25m/s  Velocity Mag  Vu=0.31m/s
Fluid Flow over Flexible Rods (STAR-CCM+/Abaqus)

**Vortex Shedding**

- **Vorticity**
  - $V_u = 0.25\text{m/s}$
  - $V_u = 0.31\text{m/s}$

*Solution Time*: 0.39592 (s) for $V_u = 0.25\text{m/s}$ and 0.00392 (s) for $V_u = 0.31\text{m/s}$

*Z-Vorticity*
Comparison of Experimental and Simulated Spectra:
2\textsuperscript{nd} row tubes

Vu = 0.19 m/s

Vu = 0.35 m/s

Vu = 0.37 m/s
Fluid Flow over Flexible Rods (STAR-CCM+/Abaqus)

- displacement RMS (% diameter) as function of inlet velocity
  - Streamwise (red and orange) and transverse (black and gray)
fluid-elastic instability phenomena of the tube bundle was detected by the FSI Simulations

critical velocity is over predicted slightly using current models
- 0.24m/s in simulation vs. 0.17 m/s in the experiment
- Many possible reasons and needs additional investigation

LCO amplitude growth trend satisfactory corresponds to the experimental data in the range of inlet velocities [0.24; 0.28-0.29] m/s especially in transverse direction;

LCO frequencies satisfactory correspond to the experimental spectra;

main phases of the tube bundle behavior described in the reference documentation are detected in the coupled solutions.
Future studies with current model

- Examine other turbulence models
- Compute inlet velocity dependent damping
  - Apply impulse load to current simulation at given Vu
  - Observe how long it takes to come back to statistical steady-state RMS
- Inlet velocity at other angles to the tubes
- Effects of material stiffness and damping
Have demonstrated a robust tool for studying fluid-elastic instabilities in strongly coupled systems

Although results are not perfect, they show correct trends
  – Very reasonable given that stiffness is still not tuned

To our knowledge this study using STAR-CCM+/Abaqus simulation is the 1st
  – to demonstrate the fluid instability critical velocity, and
  – to analyze limit cycle oscillations beyond the critical velocity, and
  – to show strong transverse vibration amplitudes