SIMULIA Community Conference
May 2015
Berlin

A study of Jumper FIV due to multiphase internal flow: understanding life-cycle fatigue

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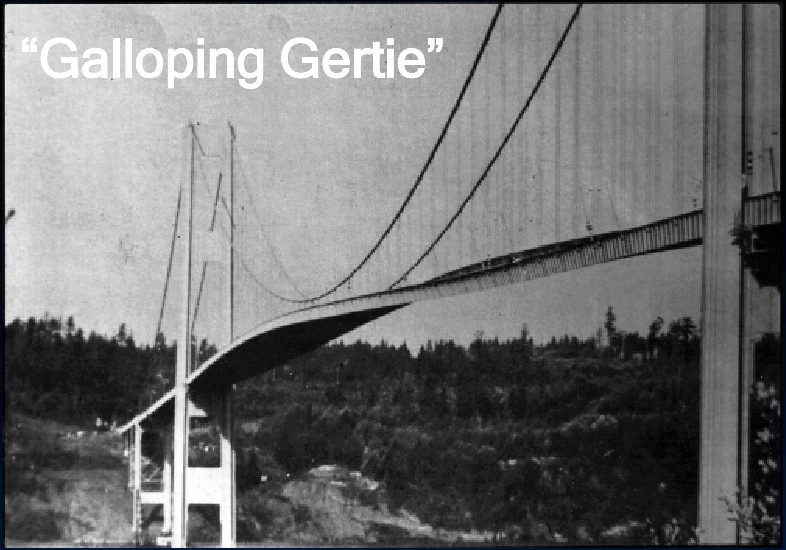
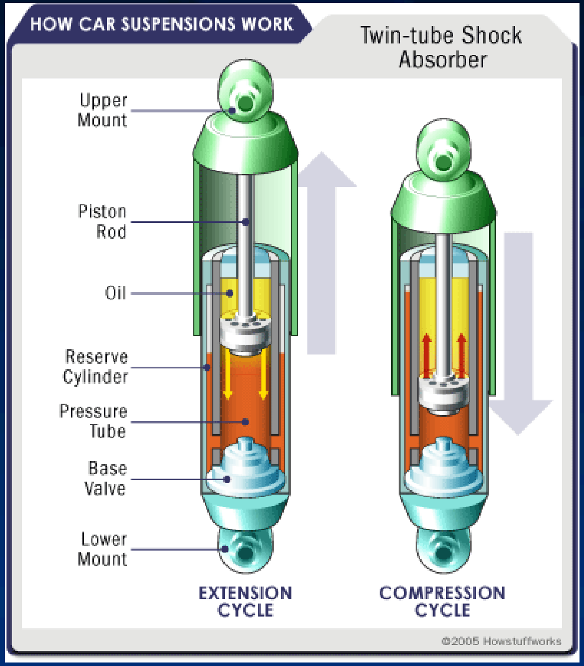
Does a fluid excite or damp a structure?

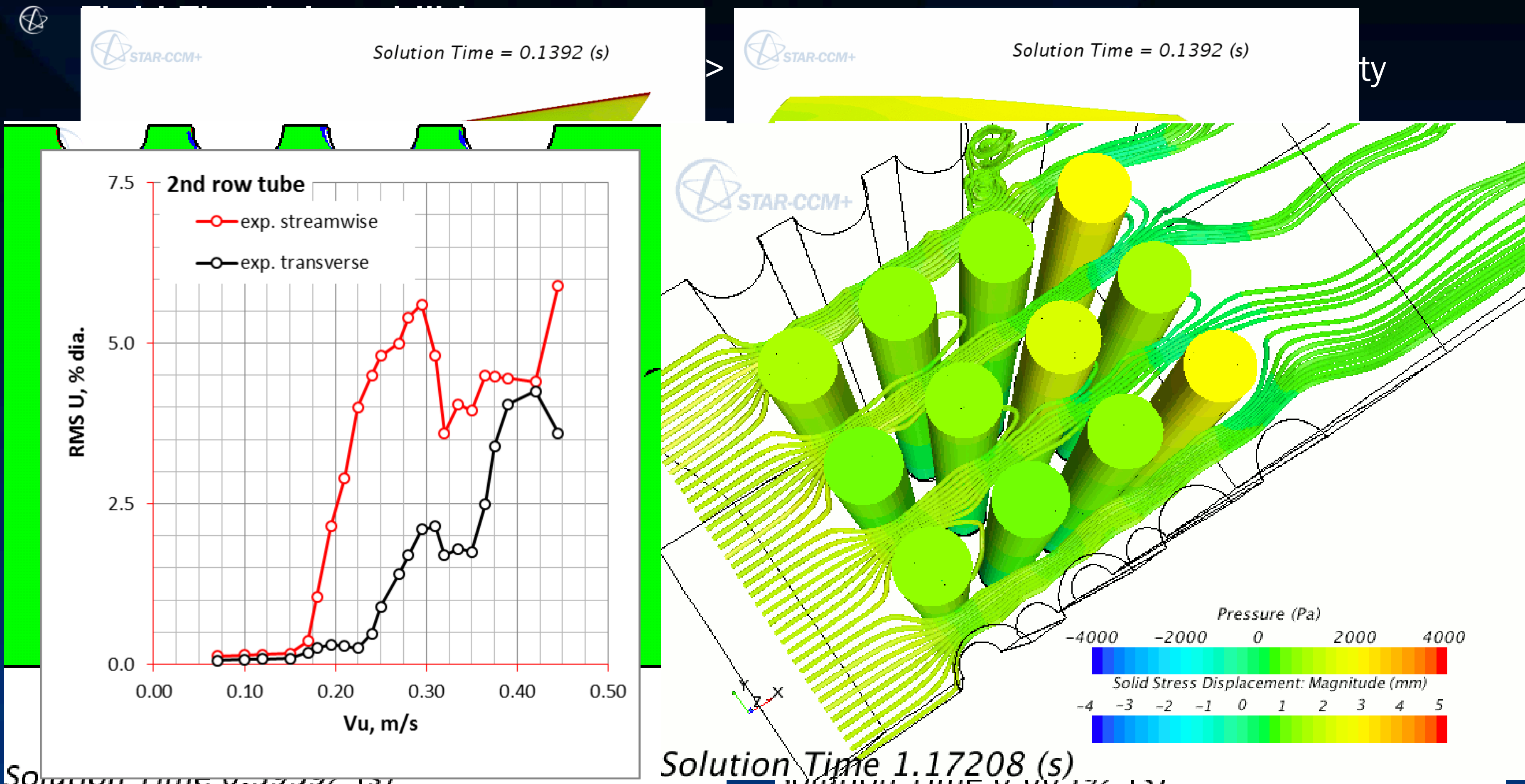
- Fluid excites the structure
  - Resonance
  - Flow Induced Vibration
  - Aeroelastic Flutter
- Fluid damps the structure
  - Dashpot





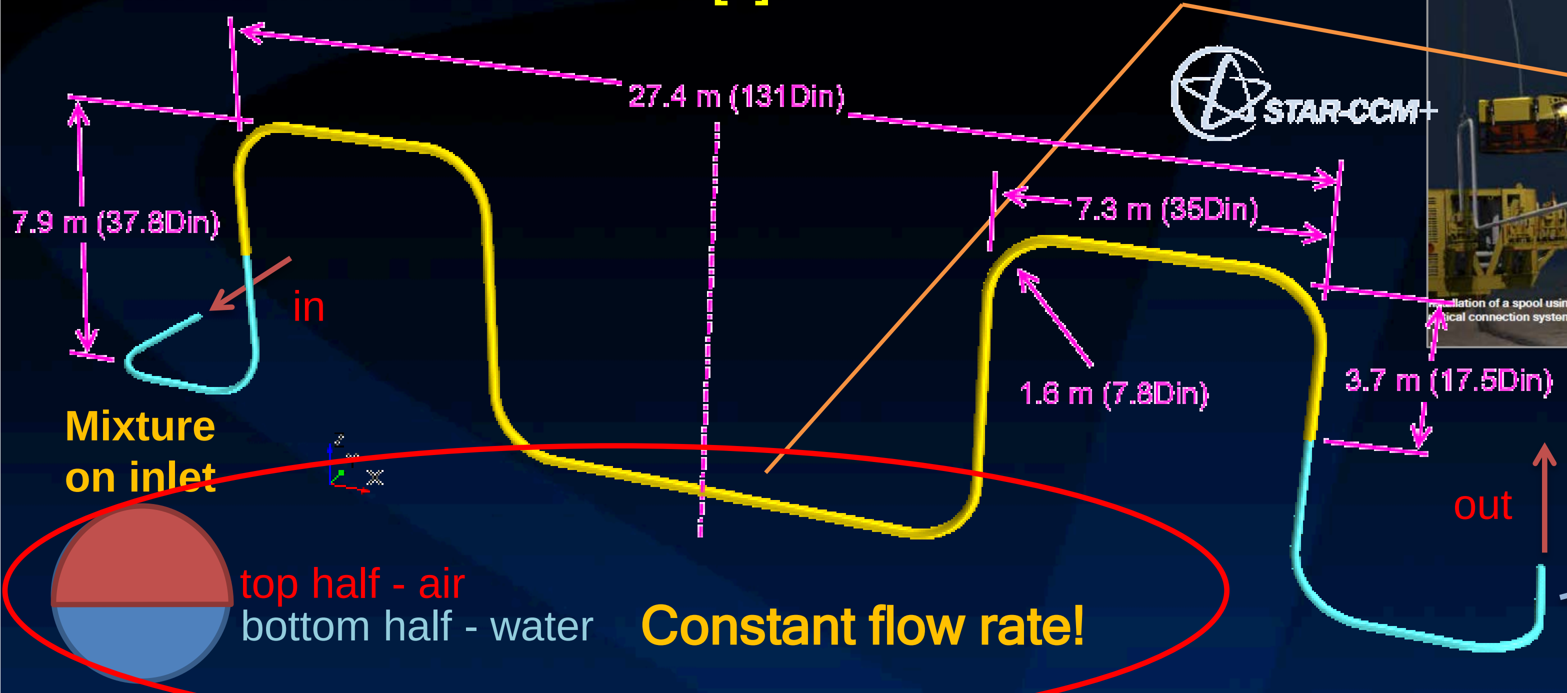
Fluids Damp *and* Excite!!

- Flutter
  - When cyclic positive fluid work (excitation) > negative work (damping) then flutter ensues
  - Balance of fluid excitation and damping leads to Limit Cycle Oscillation



Subsea Jumper Flow-Induced Vibration

Main structural dimensions [1]:



Case set-up:

1) water-air (50/50 % volume) mixture flow inside jumper;
2) the deformable jumper is clamped on its ends;
3) outside water is accounted as added mass and added damping.

[1] L. Chica. Fluid Structure Interaction Analysis of Two-Phase Flow in an M-shaped Jumper. University of Houston, College of Technology, Mechanical Engineering Technology. Star Global Conference 2012. January 28, 2012.

[2] Tie-in and structures. Brochure. Aker Solutions, 2010.

Applied physics & characteristic parameters

Fluid (STAR-CCM+):

Models:

- Segregated flow, 2-order time
- Eulerian Multiphase : VOF
- URANS k-omega SST turbulence
- Gravity: [0,0,-1g]

Flow parameters:

- V_{in} = 3.048 m/s
- water (incompressible):
  - μ = 0.001 Pa·s;
  - ρ = 1000 kg/m³;
  - $Re(D_{in}, V_{in}) = 6.4e+5$;
- air (ideal gas, isothermal):
  - μ = 2e-5 Pa·s;
  - ρ(P = 0) = 1.2 kg/m³;
  - Re(Din, Vin) = 3.8e+4;

Structure (Abaqus/Standard):

Step options:

- Implicit Dynamic,
- 2-order time;

Geometric parameters:

- Circular pipe;
- D_{out} = 10.75” (0.273 m);
- D_{in} = 8.25” (0.210 m).

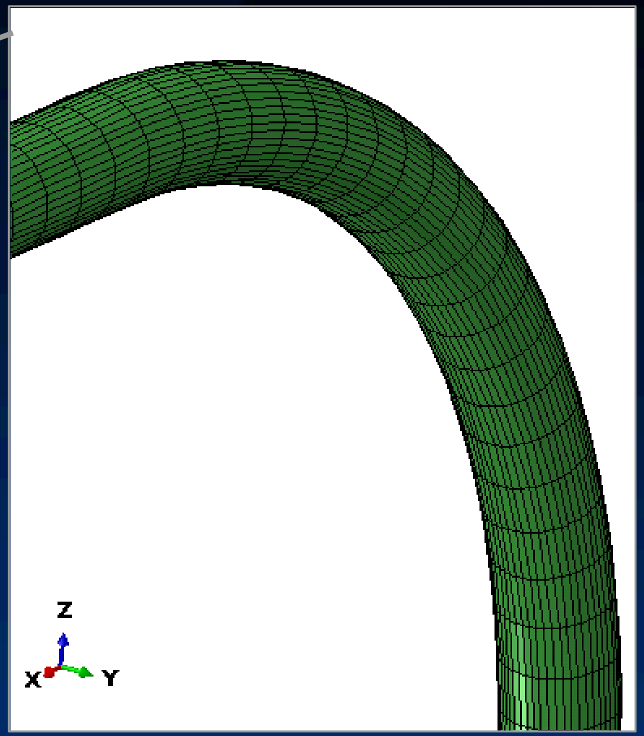
Mechanical characteristics:

- Steel:
  - E = 205 GPa;
  - ν = 0.29;
  - ρ = 7800 kg/m³.

Multi-phase internal flow leads to forcing frequencies not found in single phase flows

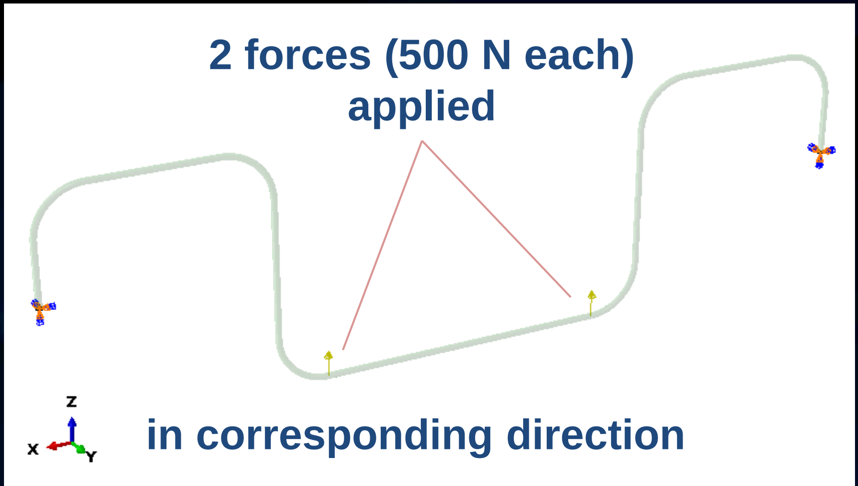
Abaqus Standalone Analysis: Stiffness

- Static analysis to evaluate stiffness
  - 21K shell elements (S4), 126K DoF



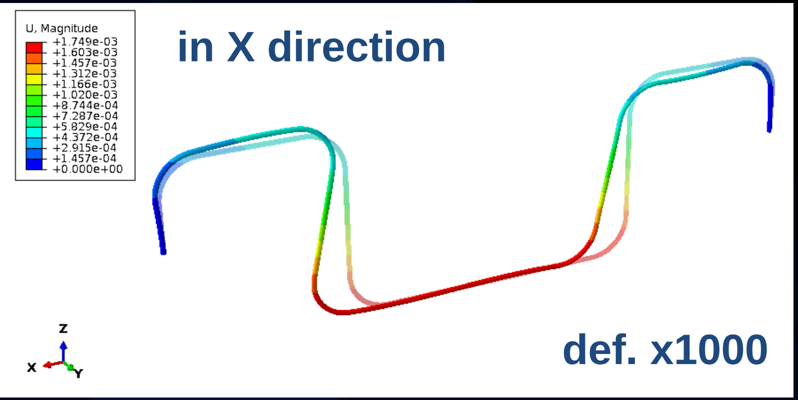
Abaqus v6.13-1:
4 cpu: 31.5k dof per cpu;

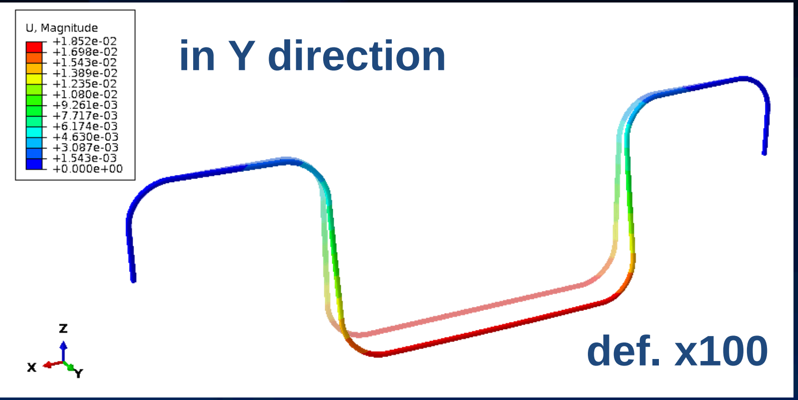
Abaqus Standalone Analysis: Stiffness

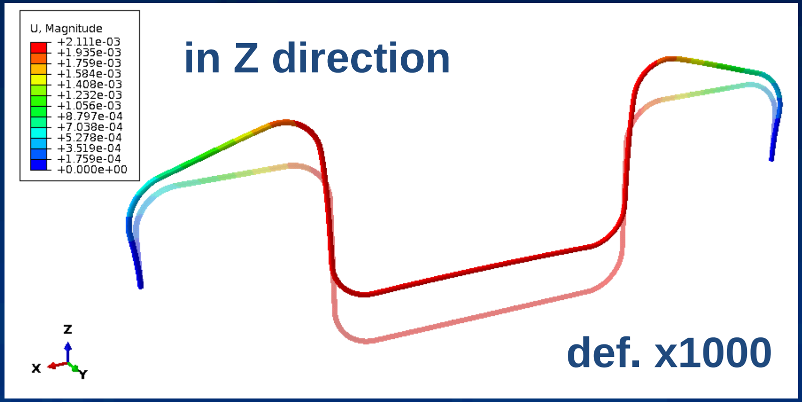


	X	Y	Z
St., N/mm	575	56.5	489

Considerably weaker in Y (cross) direction





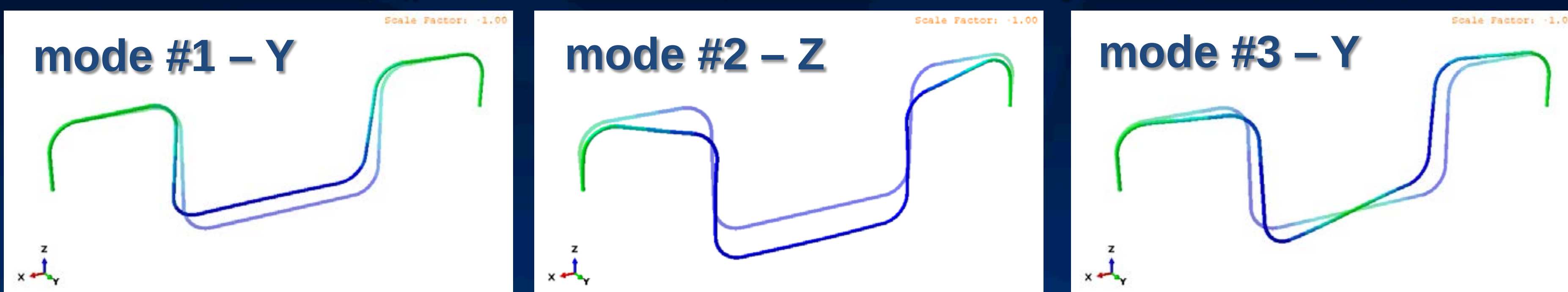


Abaqus Standalone Analysis: Natural Modes

- Eigenvalue analysis to evaluate mode shapes and fundamental frequencies

Accounted mass:

1) structural mass (M_s);
2) mass of internal mixture (M_{im}):
   in assumption of uniform 50/50% air/water vol. fraction;
3) added mass of surrounding water:
   $M_e/M_w = m^* + Ca$, $m^* = (M_s + M_{im})/M_w$, $Ca \approx 1$ [3], [4],
   M_w – mass of displaced water; M_e – effective structural ma



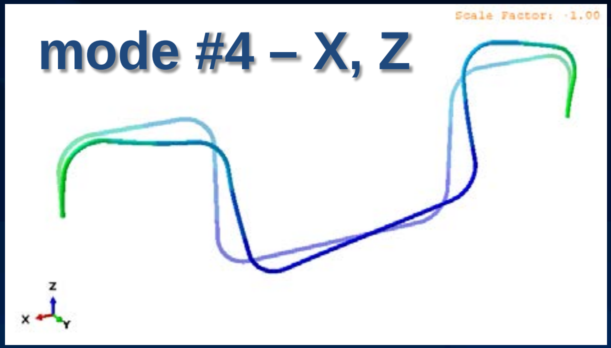
[3] J.P. Pontaza, B. Abuali, G.W. Brown, F.J. Smith. Flow-Induced Vibrations of Subsea Piping: A Screening Approach Based on Numerical Simulation. Shell International Exploration and Production Inc., Shell U.K. Limited. SPE 166661. 2013.
[4] J.P. Pontaza, R.G. Menon. Flow-Induced Vibrations of Subsea Jumpers due to Internal Multi-Phase Flow. Shell Projects & Technology. OMAE2011-50062.

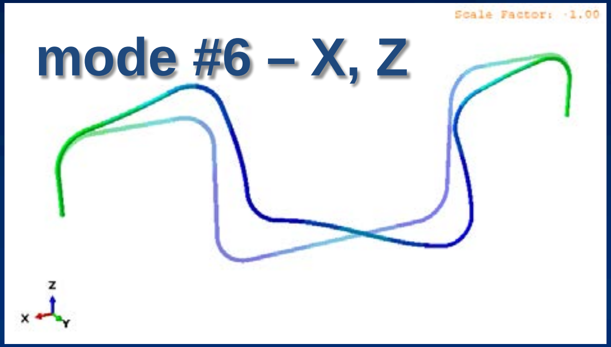
Structural mode shapes & natural frequencies

Natural frequencies:

Mode	1	2	3	4	5	6	7	8	
f, Hz	0.59	1.30	1.70	1.77	2.06	2.07	2.82	6.07	…

Considered in dynamic simulations

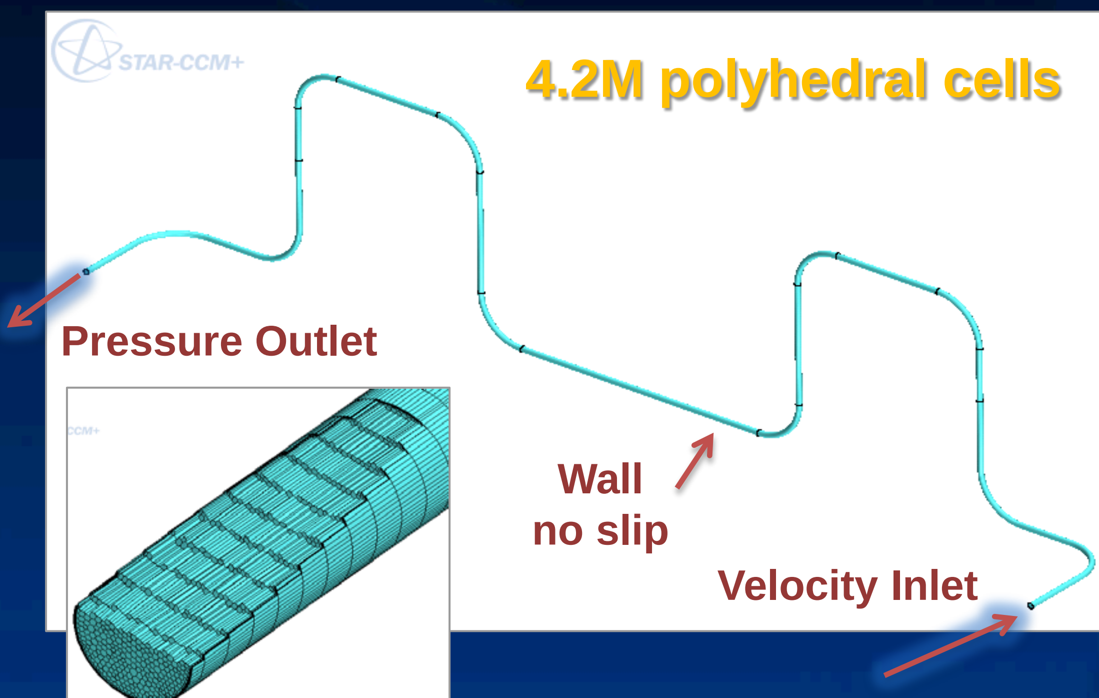


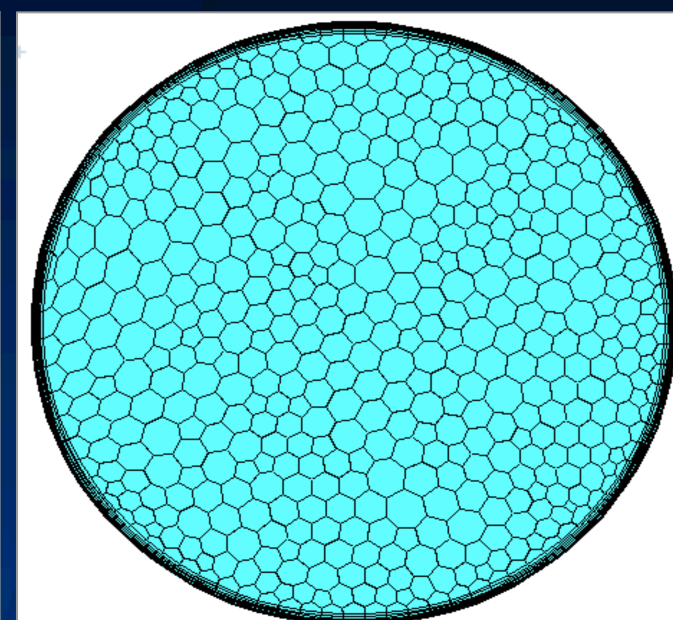


STAR-CCM+ VOF Standalone

STAR-CCM+ v9.02:
52 cpus: 82k cells per cpu;

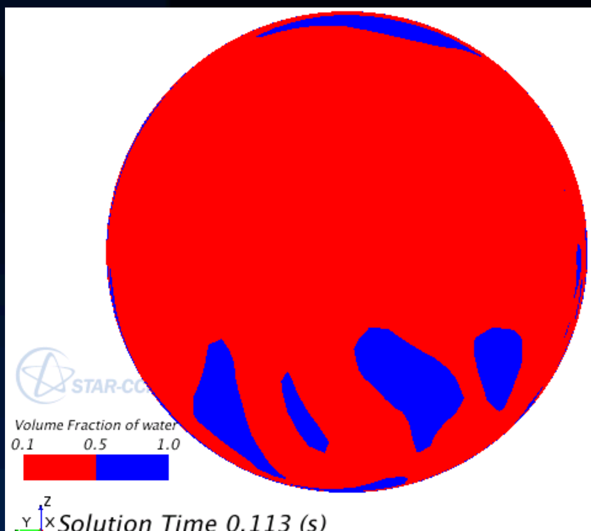
- Structure is rigid
- Spatial resolution sufficient to reasonably capture water/air interface surface
- Y+ near 1 to resolve boundary layer
- Time step limitation : free surface moves less than 1 cell in 1 time step
  - $\Delta t_f \approx T_7/50$ (small fraction of highest mode considered)
  - Larger times step possible but leads to significant numerical diffusion

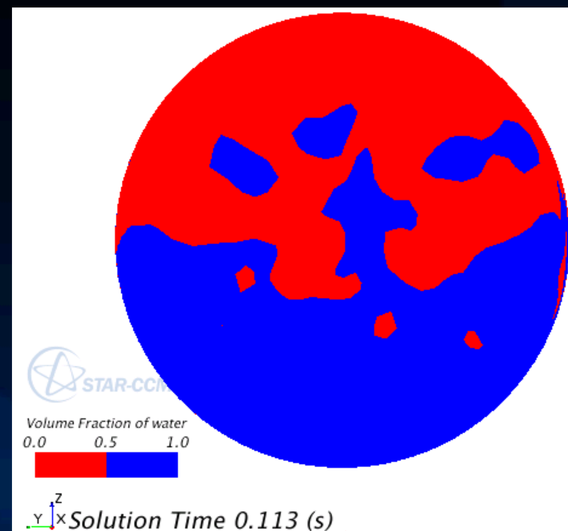


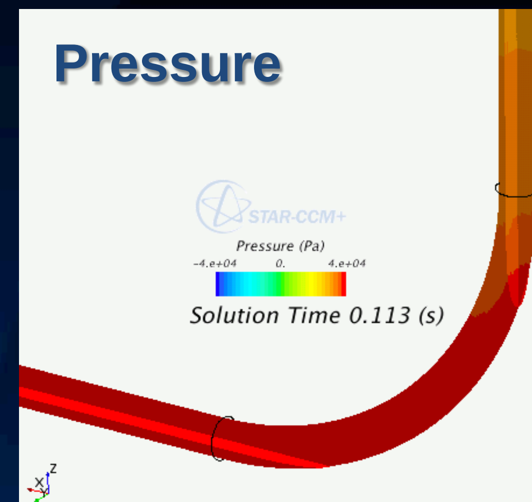


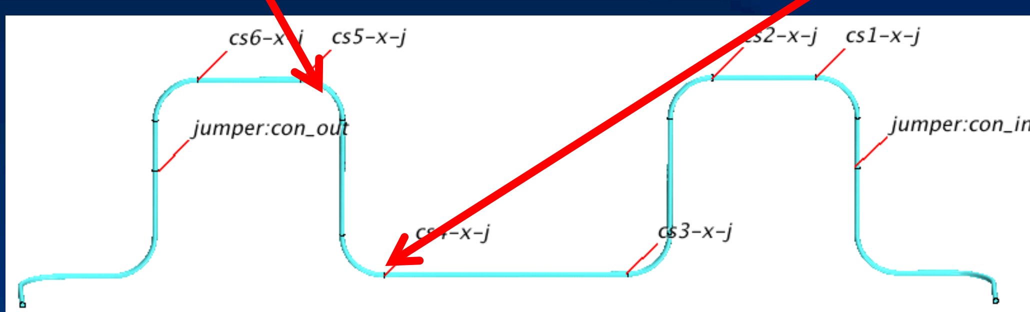
Fluid Standalone: Volume Fraction & Pressure

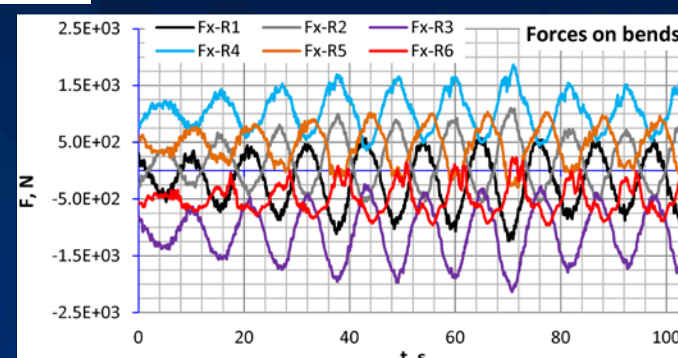
- Dominate Frequency 0.09 Hz << Mode 1 Frequency 0.59 Hz





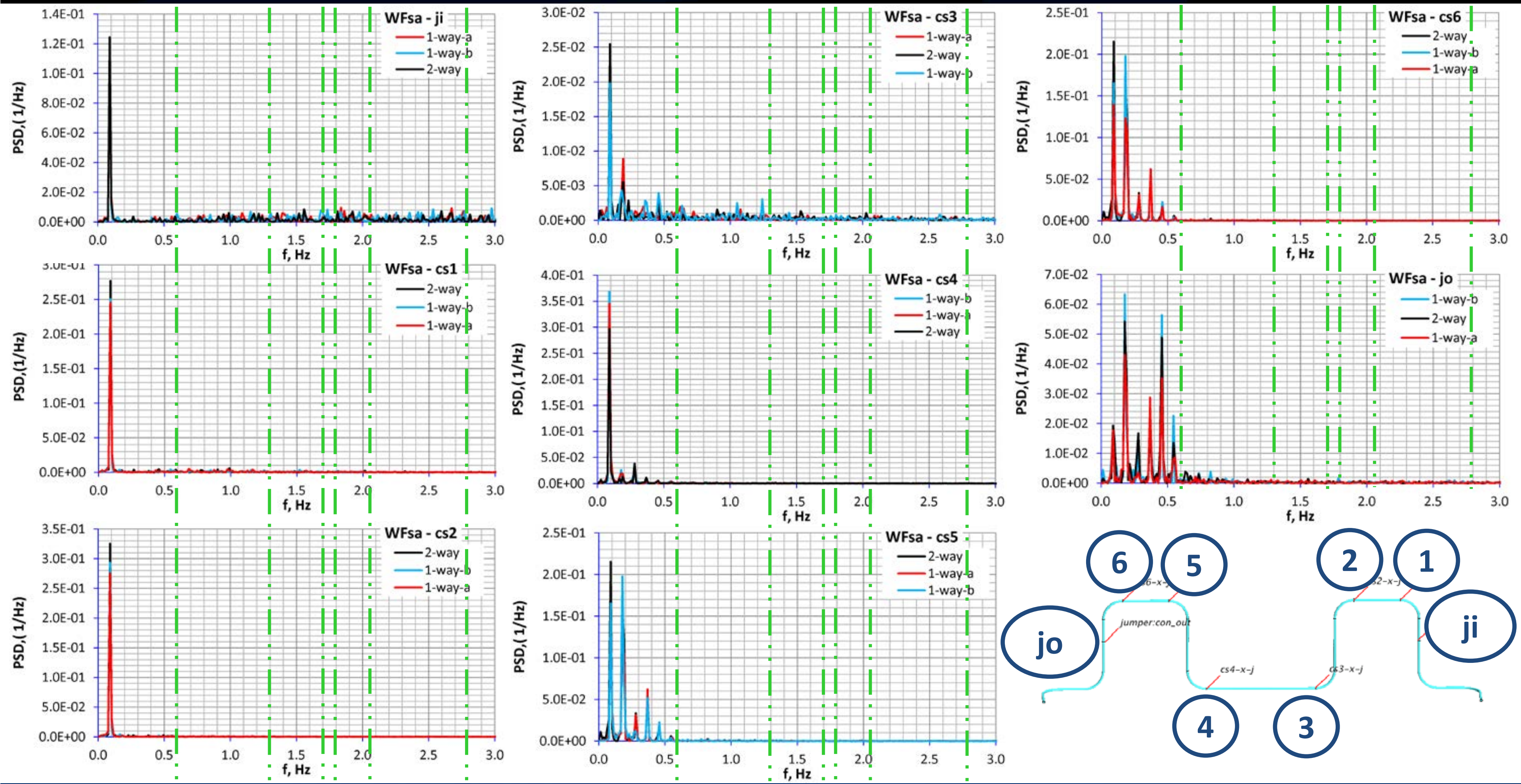






Force history on bends

Water volume fraction (section averaged)



Dominant (slug) frequencies, Hz

#	1	2	3	4	5	6
f, Hz	0.089	0.18	0.28	0.37	0.46	0.54

Possible coupled solution approaches

CD-adapco

1-way coupled

- transient forces from the fluid solution are transmitted to the structural solution;
- doesn't account for vibration of the structure in the fluid solution;
- requires application of added mass and damping for internal vibrations;

two variants

Damping is applied as mass proportional

Damping is applied as stiffness proportional

- commonly used practice;
- needs minimum computational effort;
- What is a reasonable amount of added damping due to multiphase flow?

2-way coupled

- forces from the fluid side are transmitted to the structural side and displacements of the structure are passed back to the fluid side;
- requires implicit coupling for stability;
- added mass and damping from internal flow is applied in a natural manner as a reaction for movement of the structure;

- computationally more expensive;
- potentially more accurate;
- How large is the difference in effort & accuracy from the 1-way coupled?

1-way coupled

- **Fluid**
  - Same setup as in fluid standalone $\Delta t_f \approx T_7/50$
- **Structure**
  - Structure resolution as in structure standalone
  - Same added mass for internal and external flow as in Eigenmode analysis
  - Time step chosen to resolve well 7th mode $\Delta t = T_7/60$
  - External fluid added damping
  - Internal fluid added damping
    - To correct for rigid assumption in fluid model
- **Explicit Coupling**
  - Fluid loads to structure once per fluid time step
- **Simulation over 10 fundamental fluid forcing periods**

One-Way Coupling : Internal Damping

- **Choice of Damping**
  - Mass Proportional $C=\alpha*M$
  - Stiffness Proportional $C=\beta*K$
- **Size α,β to give damping in Mode 1**
  - as measured in 2-way coupling
  - **ln(D) = 0.09** => $\xi = \ln(D)/\mathrm{sqrt}[4\cdot pi^2 + \ln(D)^2]$

Stiffness proportional: $2\xi=\beta\omega$

Mass proportional: $2\xi=\alpha/\omega$

	Mode	1	2	3	4	5	6	7
	f, Hz	0.59	1.30	1.70	1.77	2.06	2.07	2.82
α=0.106Hz	ξ:	1.43e-2	6.50e-3	4.97e-3	4.77e-3	4.10e-3	4.08e-3	3.00e-3
β=7.71e-3s	ξ:	1.43e-2	3.16e-2	4.13e-2	4.30e-2	5.00e-2	5.03e-2	6.85e-2

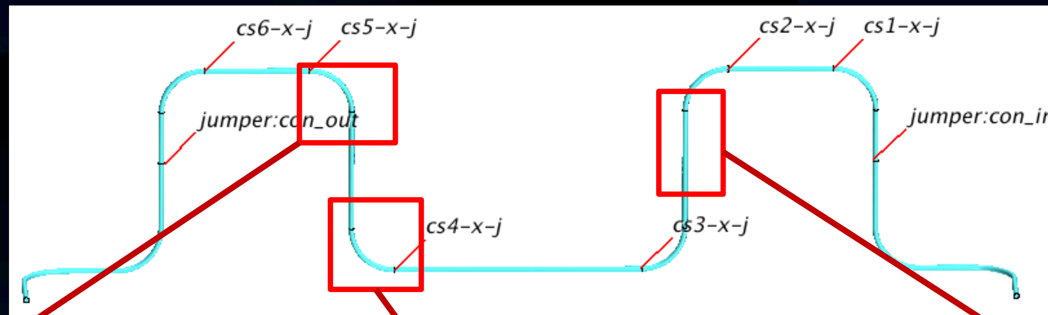
2-way coupled

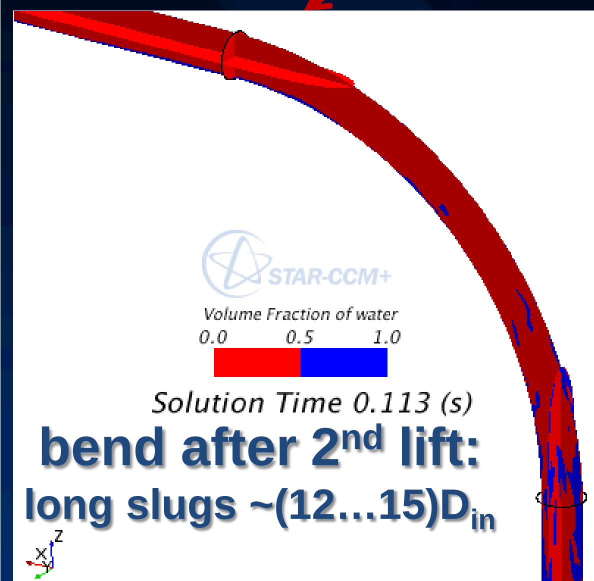
- Fluid
  - Same conditions as in 1-way except fluid time step same as solid time step: $\Delta t_f = T_7/60$
- Structure
  - Same as 1-way but no added mass and damping for internal flow
- Implicit Coupling
  - Data Exchange once per iteration in a time step
    - Fluid loads sent to structure
    - Structure displacements sent to fluid
  - Fluid and structure use identical time steps
  - Move to next time step when both structure and fluid residuals converge

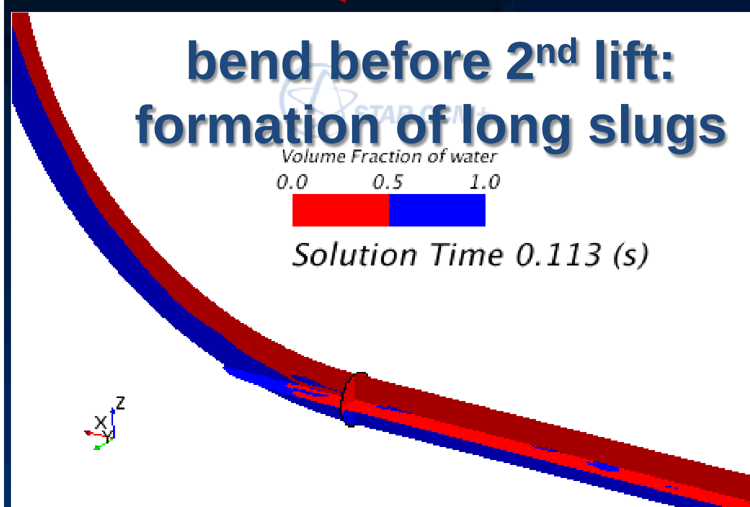
- Simulation over 10 fundamental fluid forcing periods

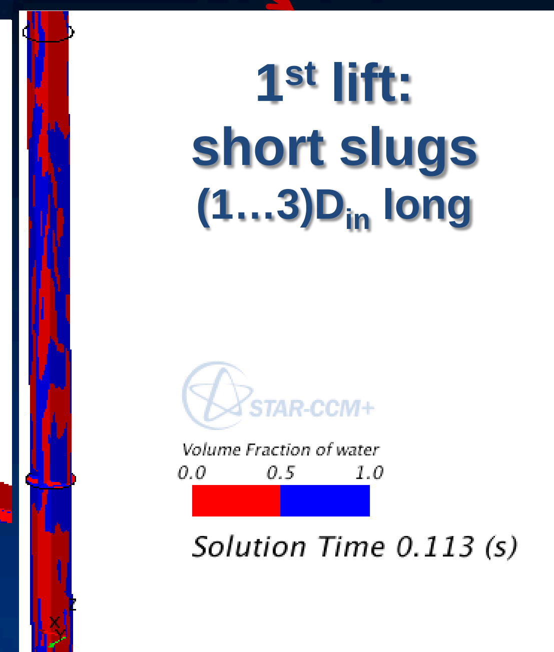
Under the stated conditions, the primary difference between 1-way and 2-way coupling: 2-way coupling requires more iterations within a time step: The elapsed time for 2-way is about 2 times the 1-way coupling

Water volume fraction: evolution of slugs

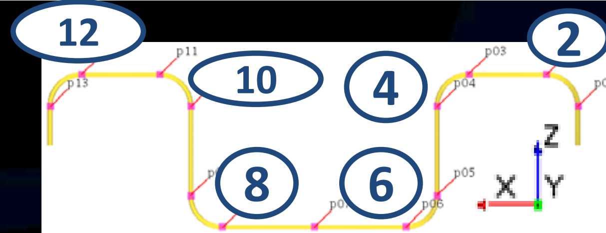


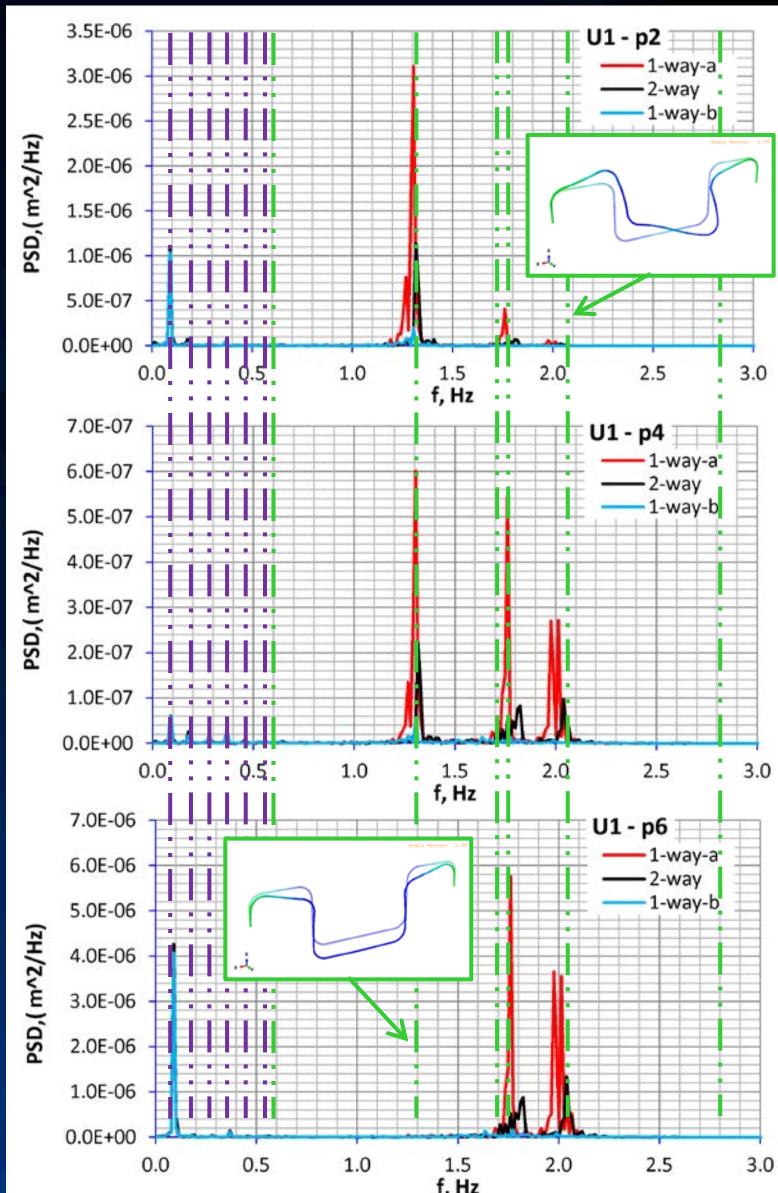


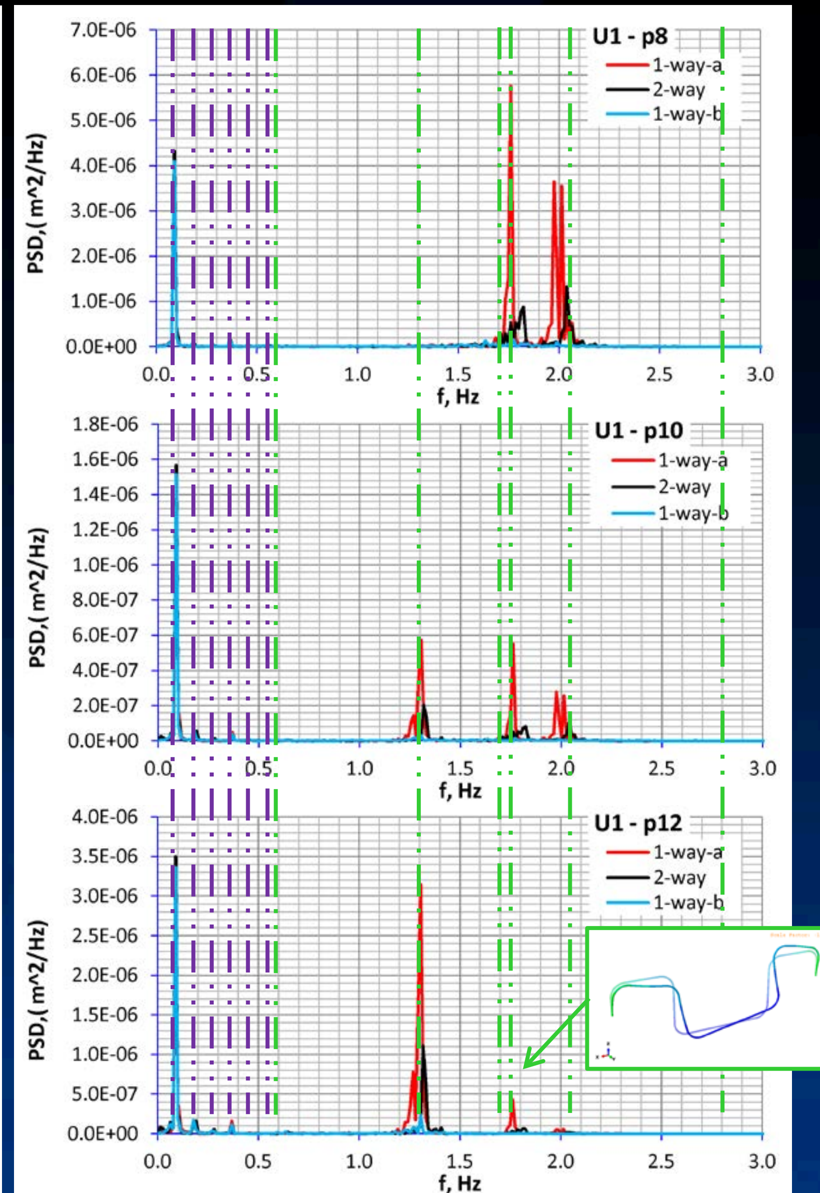




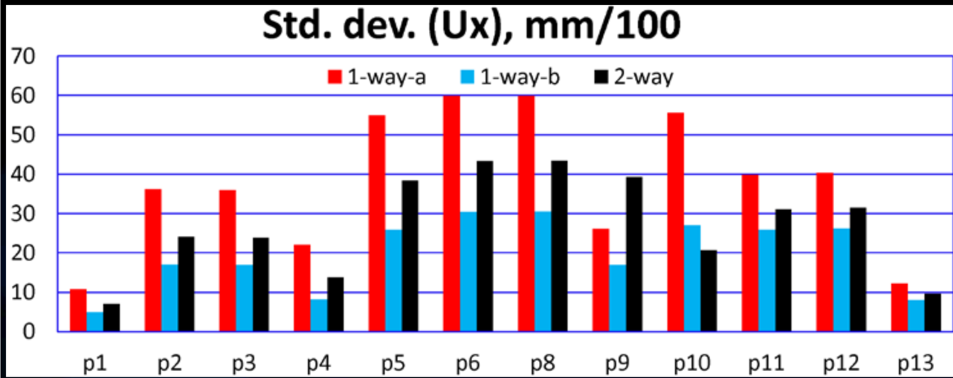
Pipe vibrations
FFT (Ux), [25 s, tmax]

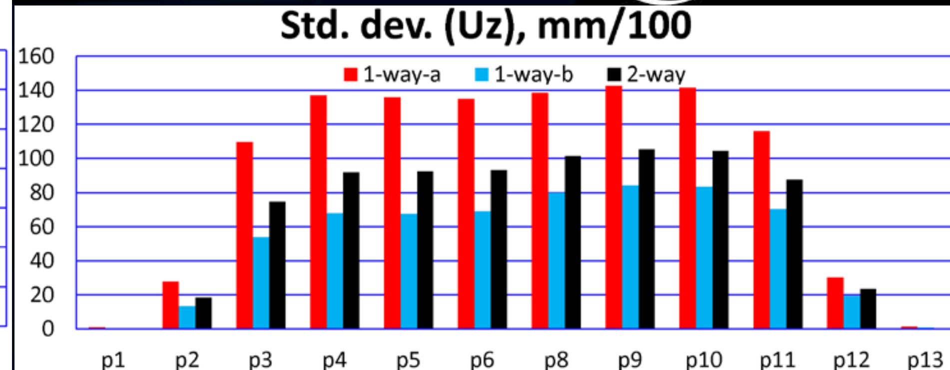


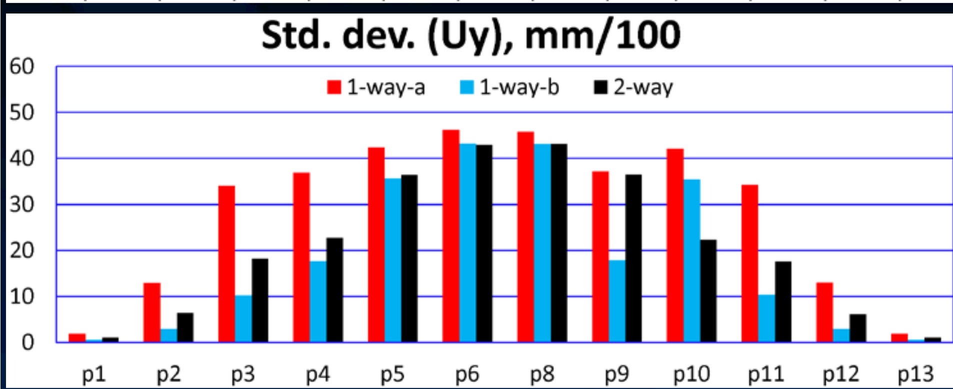


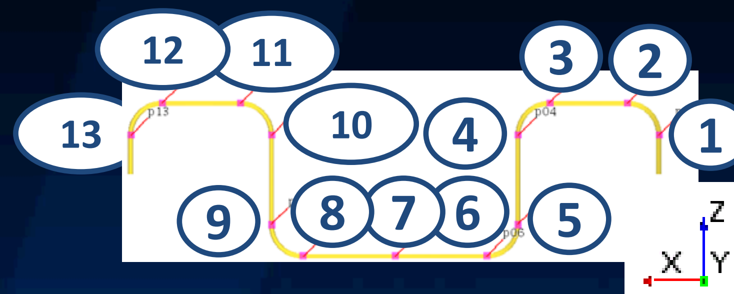


Pipe vibrations



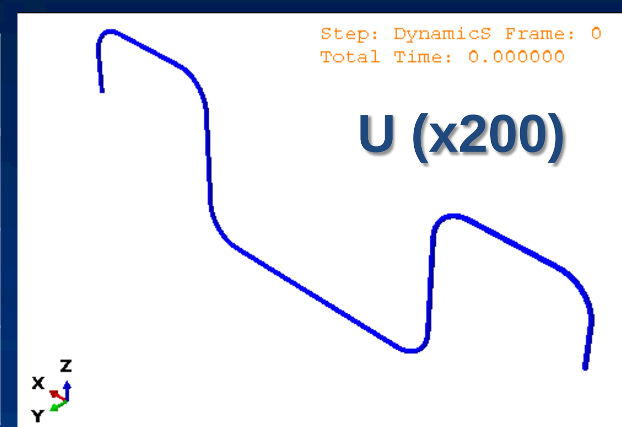




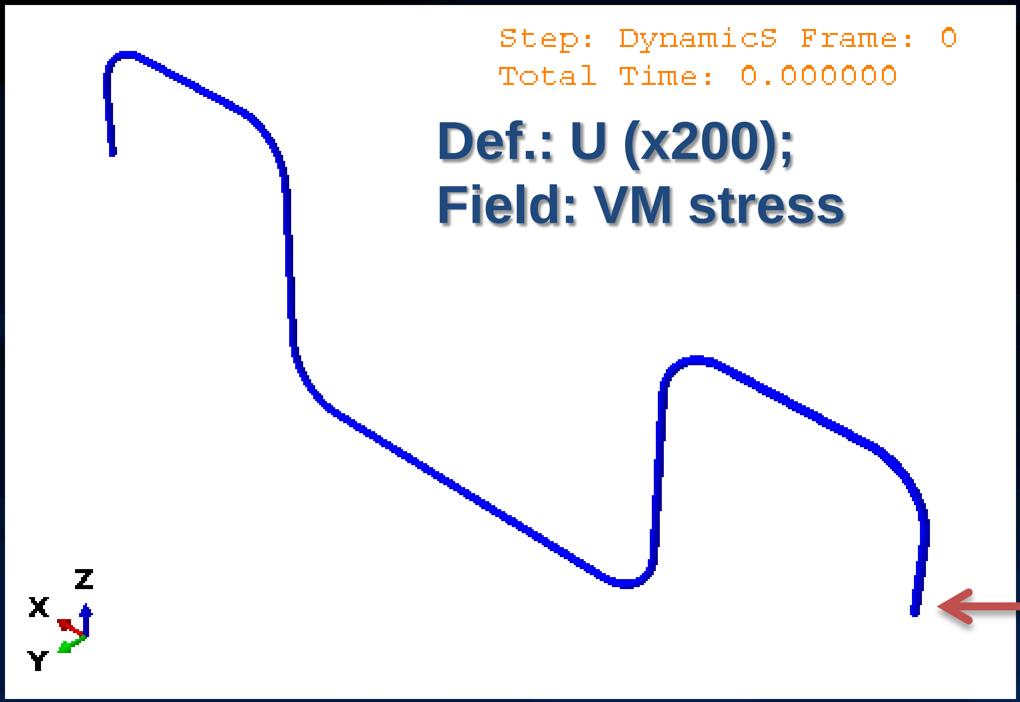


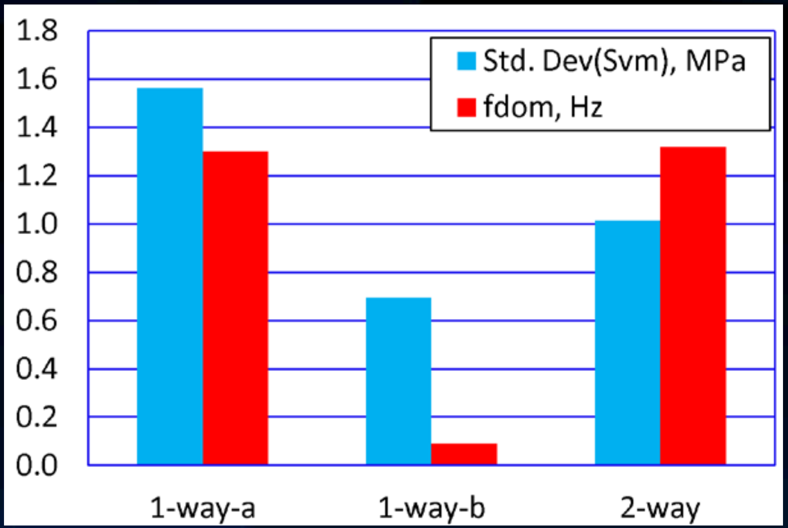
Dominant frequencies, Hz

Mode	-	1	2	3	4	5, 6	7
U1-x	0.089	-	1.32	-	1.7-1.8	2.04	-
U2-y	0.089	0.56	-	1.6-1.7	-	2.06	2.77
U3-z	0.089	-	1.32	-	-	2.04	-



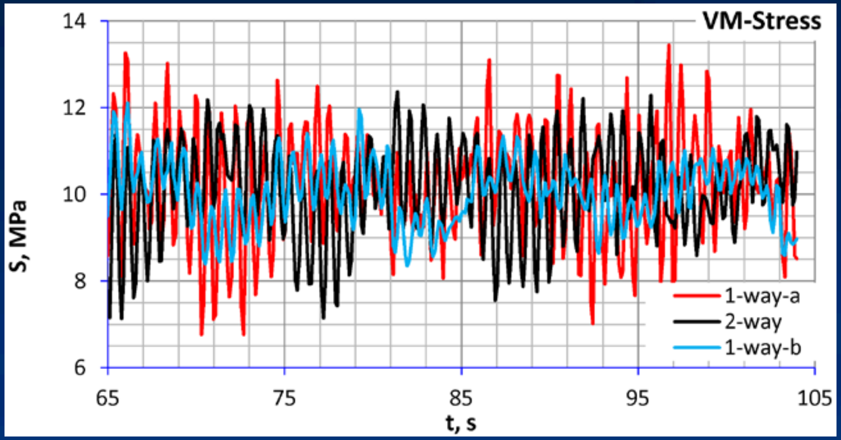
Stress signal

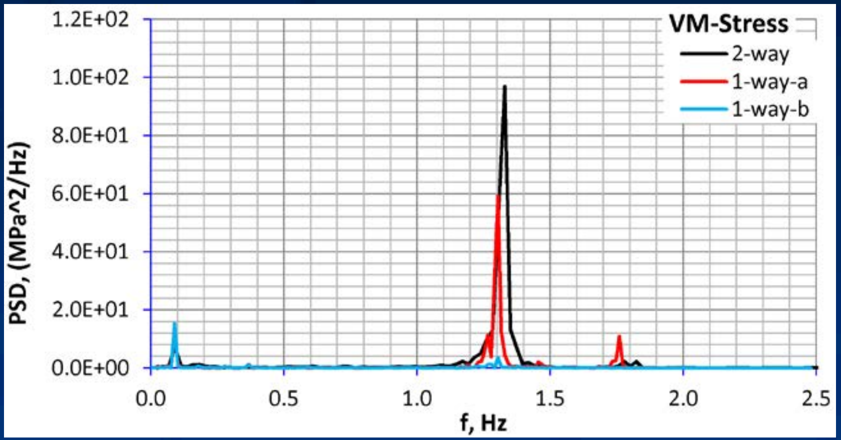




σ_{max} **(tension), max. amplitude**

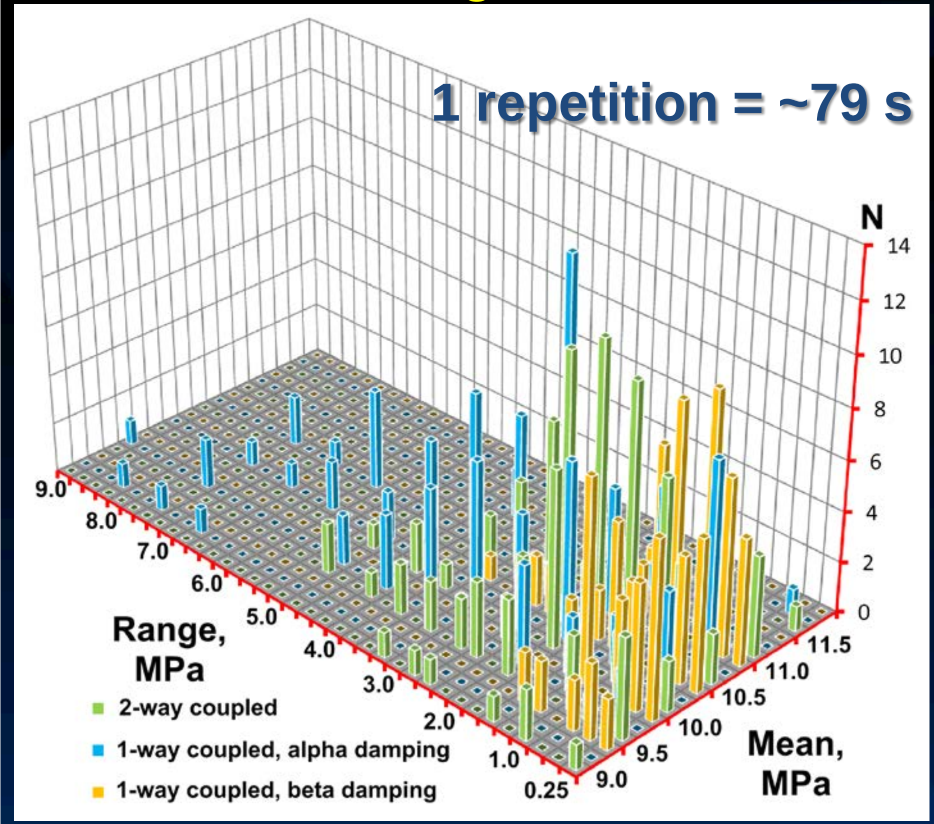
Input for fatigue life calculation





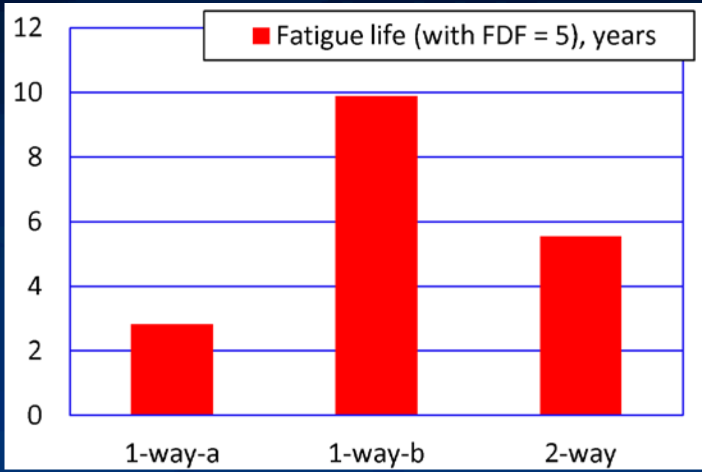
Fatigue life estimate

Rain flow counting results



S-N curve [5]

Applied modifications:
- thickness effect;
- stress gradient (bending);
- surface roughness.



Palmgren-Miner rule to compute the damage and life estimate

[5] Guide for the fatigue assessment of offshore structures. American Bureau of Shipping, Houston, TX, USA. November 2010.

Conclusions

- STAR-CCM+ VOF coupled to Abaqus successfully applied to Jumper FIV
  - Simulations run “out of the box”
- Two methods for assessing the response of the structure to internal multiphase flow
  - 2-way coupling
  - 1-way coupling
- 2-way coupling naturally accounts for added mass and added damping due to the internal multiphase flow
- 1-way coupling requires estimates of added mass and damping
  - Lifetime estimates are sensitive to these approximations
  - 2-way coupling can be used to estimate the added mass and added damping applied in 1-way coupling simulations
- Under the conditions studied, the 1-way coupling is not significantly faster than 2-way coupling

Questions?

Thank You!