Simulating cavitation bubbles near elastic structures in OpenFOAM

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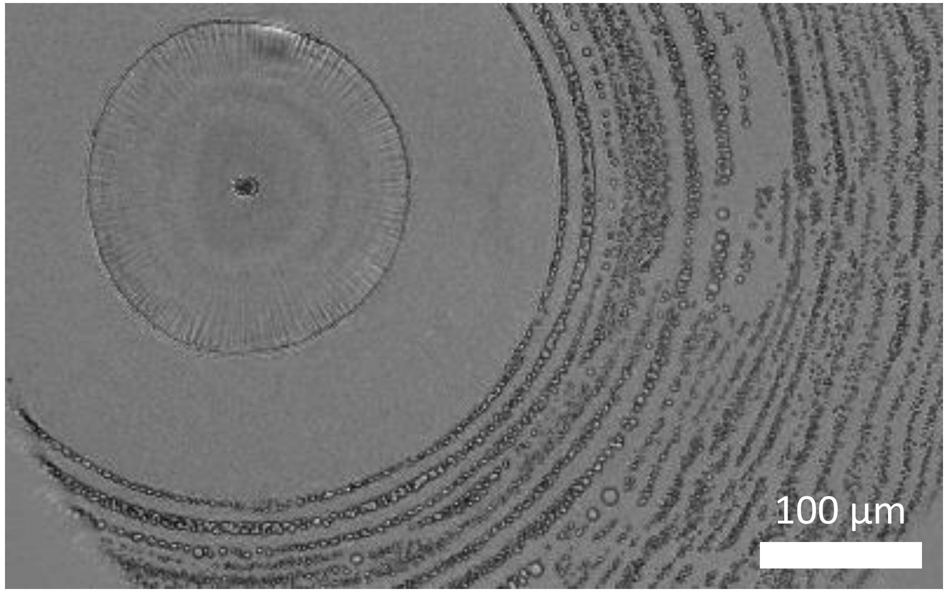
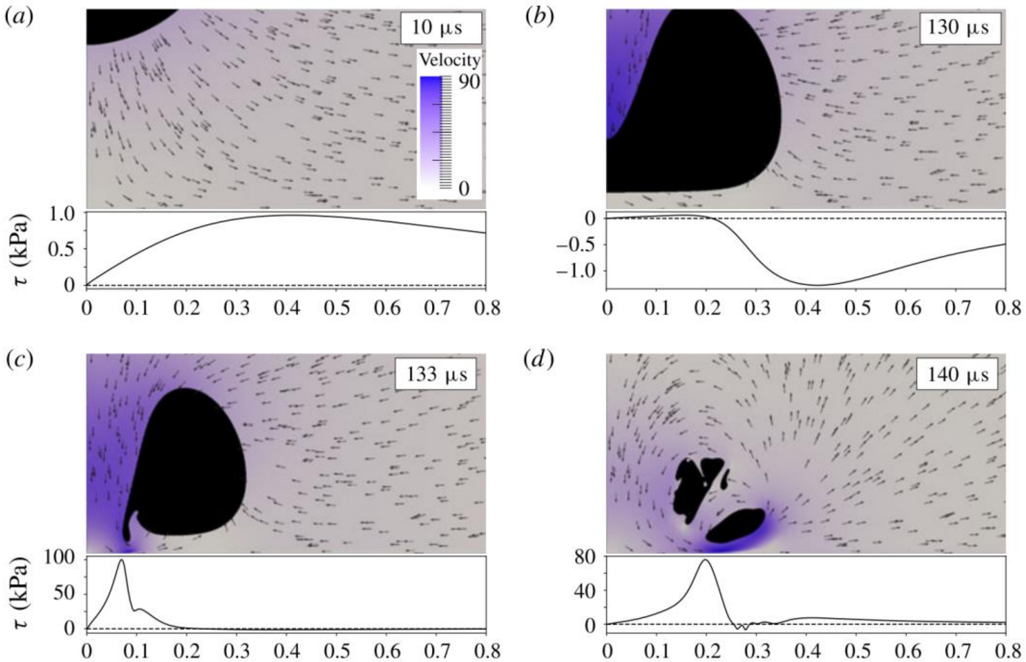
Motivation

- single cavitation bubbles near elastic solid
- quantify wall shear stress that causes damage/cleaning effect
- shear wave propagation



Patricia Pfeiffer, Otto-von-Guericke-University Magdeburg, Germany



Zeng et. al.: “Wall shear stress from jetting cavitation bubbles”, 2018, Fig. 5

Fluid Structure Interaction

- short: FSI
- interaction between movable or deformable structure and fluid flow
- fluid acts on structure through pressure p and viscous stresses $\mu \nabla \circ \vec{u}$
- structure acts on fluid through deformation D and velocity $\dot{D}$

Monolithic method:

- solve governing equations of the fluid and the solid simultaneously with a single solver

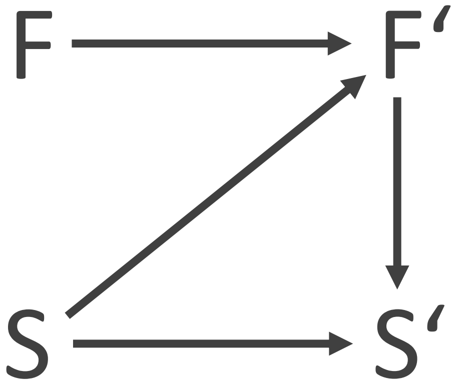
Partitioned method:

- solve flow equation and elasticity equation with two separate, coupled solvers

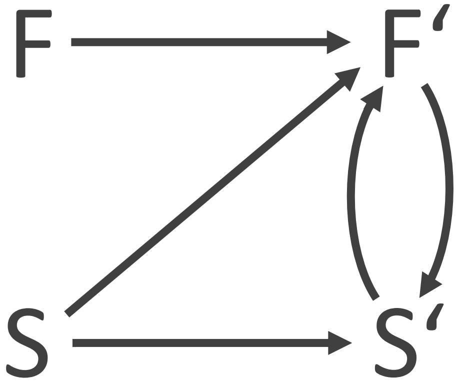
Fluid Structure Interaction

Partitioned method

Explicit coupling:
- weak FSI
- equations are only solved once, first fluid, then solid



Implicit coupling:
- strong FSI
- equations are solved iteratively



Governing equations - fluid

- compressible Navier-Stokes-equation:

$$\rho \frac{D\vec{u}}{Dt} = \rho\vec{f} - \nabla p + \mu(\Delta\vec{u} + \frac{1}{3}\nabla(\nabla\cdot\vec{u}))$$

- continuity equation:

$$\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\vec{u}) = 0$$

- equation of state (Tait equation):

$$p = (p_0 + B)\left(\frac{\rho}{\rho_0}\right)^{\gamma} - B$$

- stress tensor:

$$\overleftrightarrow{\sigma} = -p\overleftrightarrow{1} + \mu\left[\nabla\circ\vec{u} + (\nabla\circ\vec{u})^T\right]$$

- force on a surface:

$$\vec{F}\,dS = \overleftrightarrow{\sigma}\cdot\vec{n}$$

	gas	liquid
p_0 in Pa	10320	101325
ρ_0 in kg/m^3	0.12	998.2061
γ	1.33	7.15
B in Pa	0	4.046e8

Governing equations - solid

- equation of motion for Deformation $\vec{D}$ (linear elasticity):

$$\frac{\partial^2(\rho\vec{D})}{\partial t^2} - \nabla\cdot\overleftrightarrow{\sigma} = 0$$

- stress tensor:

$$\overleftrightarrow{\sigma} = 2\,G\,\overleftrightarrow{\varepsilon} + \lambda\,\mathrm{tr}(\overleftrightarrow{\varepsilon})\,\overleftrightarrow{1}$$

- strain tensor:

$$\overleftrightarrow{\varepsilon} = \frac{1}{2}\left[\nabla\vec{D} + (\nabla\vec{D})^T\right]$$

- Lamé parameters:

$$\lambda = \frac{\nu}{1-2\nu}\frac{1}{1+\nu}E\,,\quad G = \frac{1}{2}\frac{1}{1+\nu}E$$

- E - Young's/elasticity modulus, $\nu = 0.4$ - Poisson's ratio

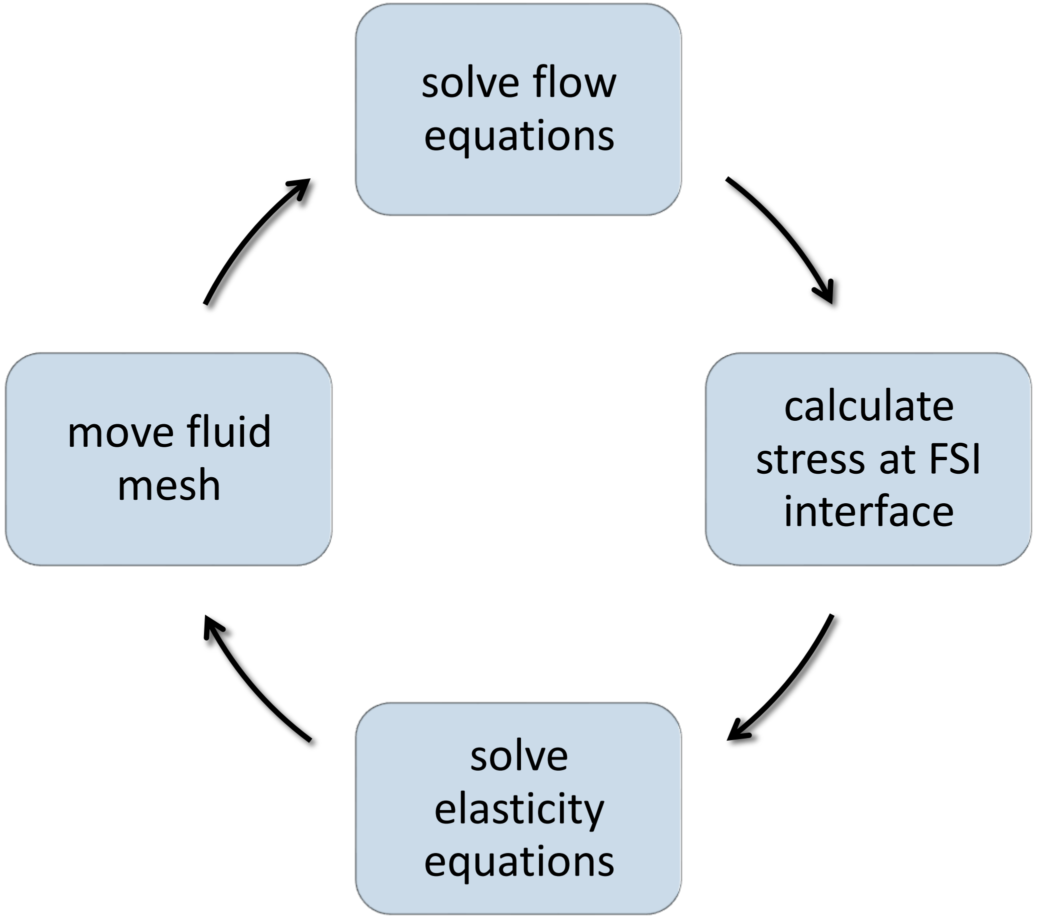
$$\Rightarrow \frac{\partial^2(\rho\vec{D})}{\partial t^2} - \nabla\cdot\left[G\nabla\vec{D} + \underline{G(\nabla\vec{D})^T + \lambda\,\mathrm{tr}(\nabla\vec{D})\,\overleftrightarrow{1}}\right] = 0$$

coupling between components

→ iterative solution required

Solver (OpenFOAM®) - base solver

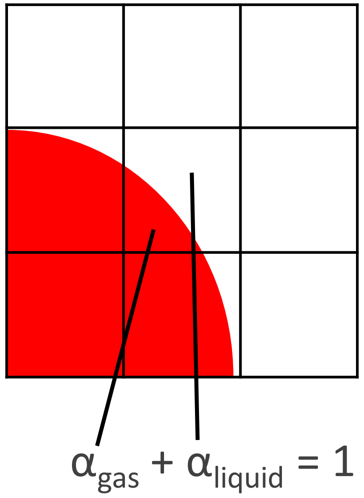
- OpenFOAM version: foam-extend-4.0
- base solver: fsiFoam
- “Finite volume fluid structure interaction solver based on partitioned approach and strong coupling. PIMPLE algorithm (Pressure-based Implicit Method for Pressure Linked Equations)“
- dynamic mesh in both the solid and fluid domains to handle solid deformation
- includes viscosity
- does not include: compressibility, multiphase flow



Solver (OpenFOAM®) - new solver

- new solver: CavBubbleFsiFoam
- implemented features from compressibleInterFoam:
  phase fraction (α), density (ρ), compressibility (κ) and viscosity (μ) fields and surface tension coefficients (σ)

$$\kappa \overset{\text{Tait}}{=} -\frac{1}{V}\frac{\partial V}{\partial p} = \frac{1}{\gamma\,(p + B)}$$

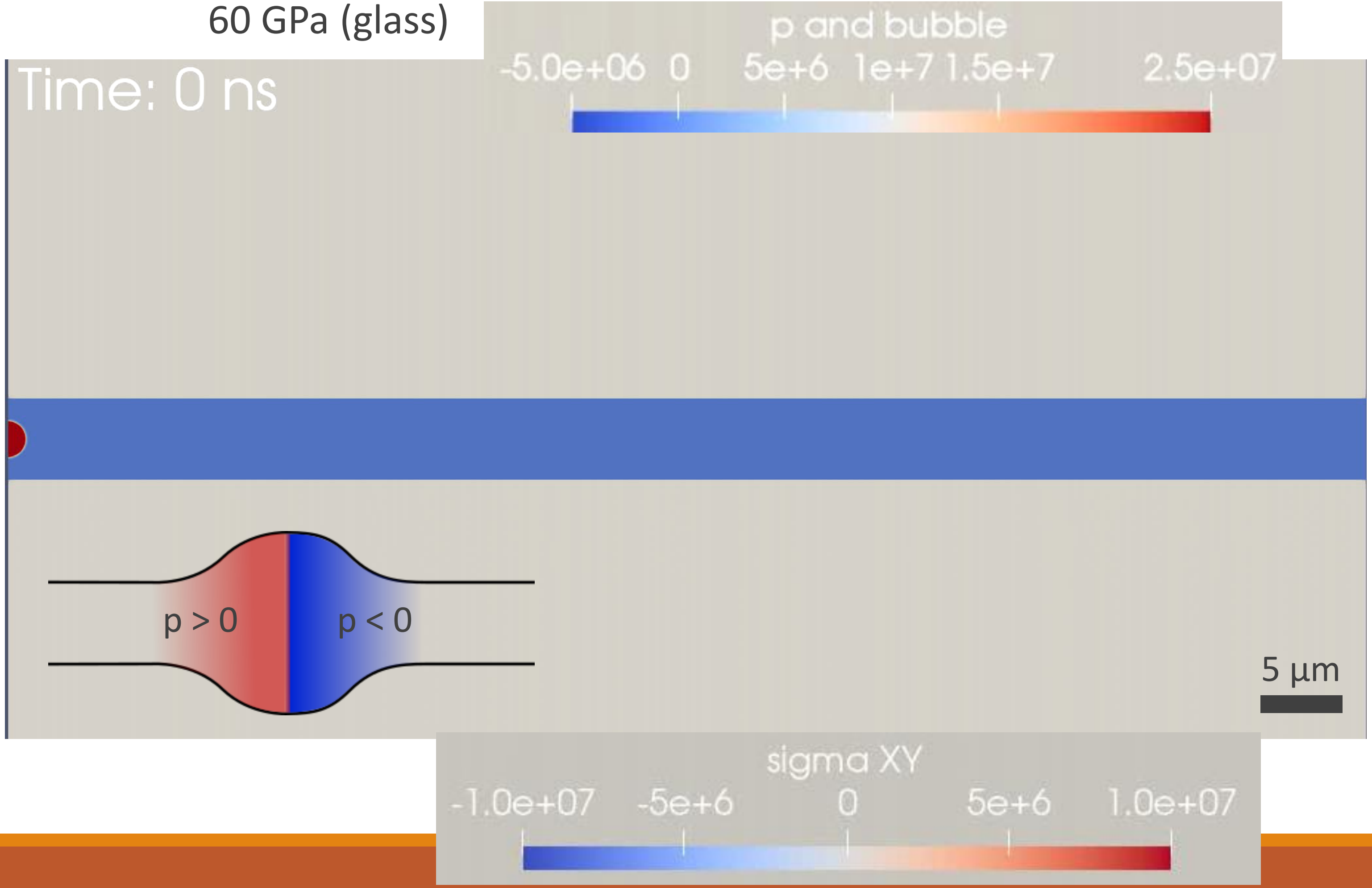


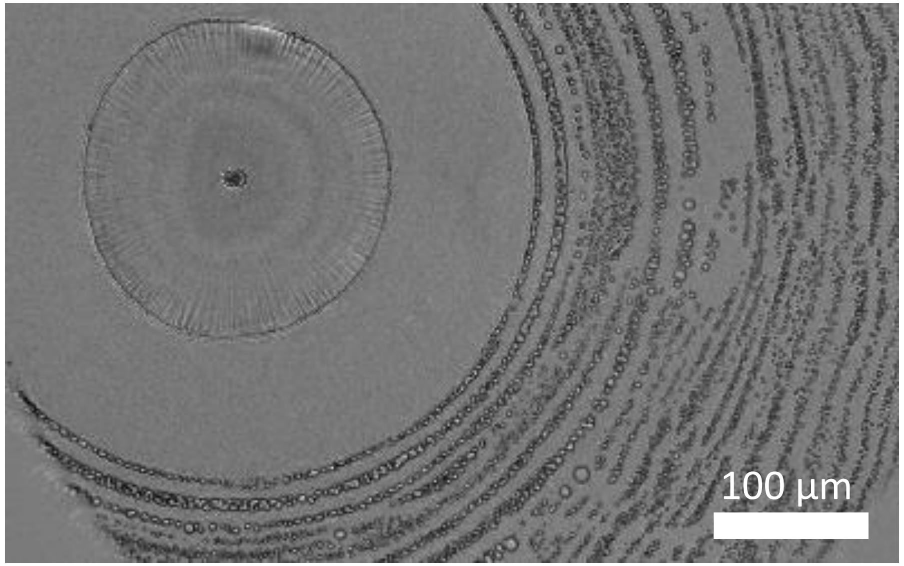
- adjusted forces onto solid accordingly
- corrected ρ for the bubble mass to stay constant (no phase transitions), $m = \sum_{i=1}^{n_{cells}} \alpha_{gas,i}\, \rho_{gas,i}\, V_i$
- corrected α fields to counteract numerical cavitation
  sets $\alpha_{gas} = 0$ if $\alpha_{gas} < 0.001$
- still not including: phase transitions, temperature equation

First results

Bubble in a thin gap

60 GPa (glass)



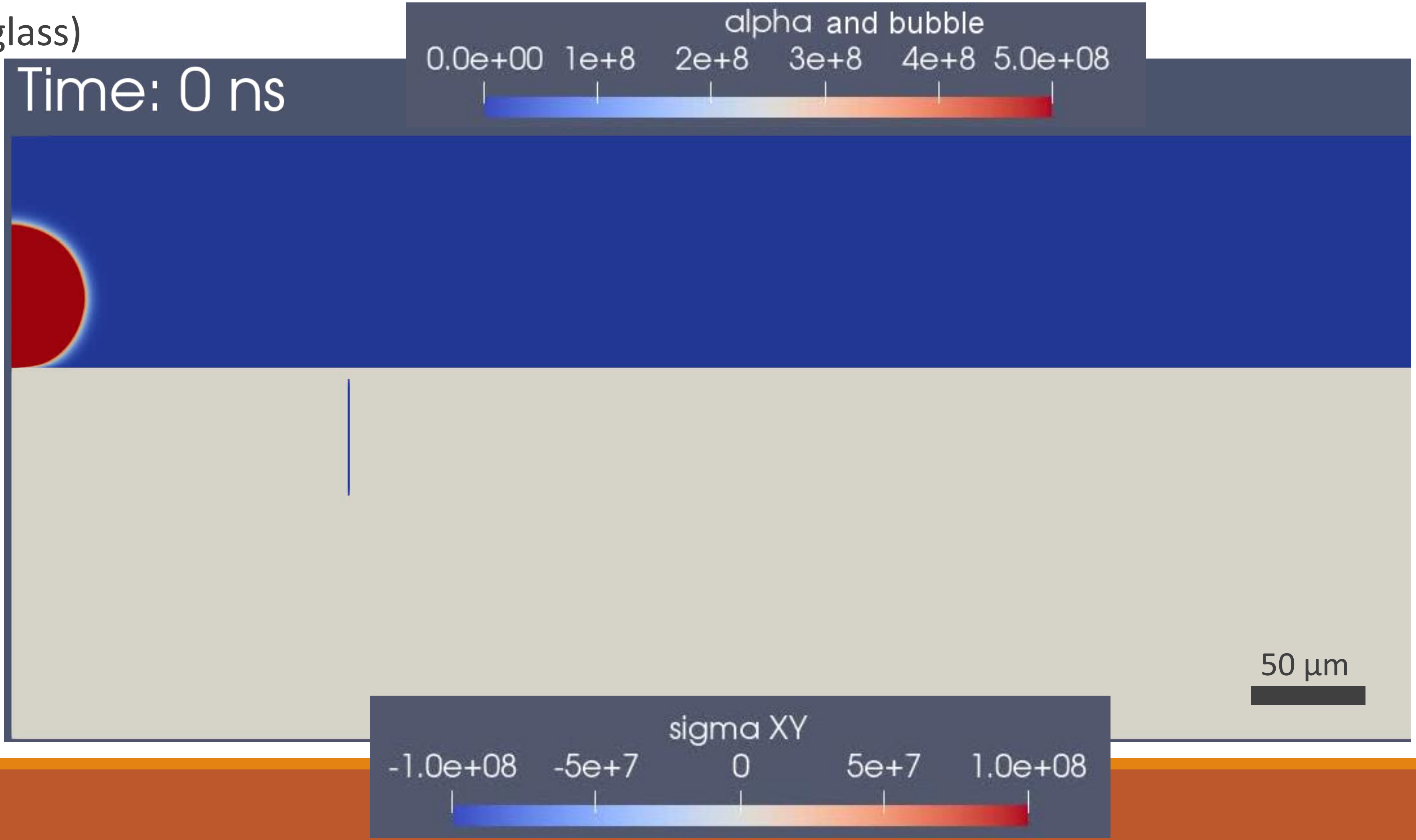


Secondary cavitation in a small gap

Patricia Pfeiffer, Otto-von-Guericke-University Magdeburg, Germany

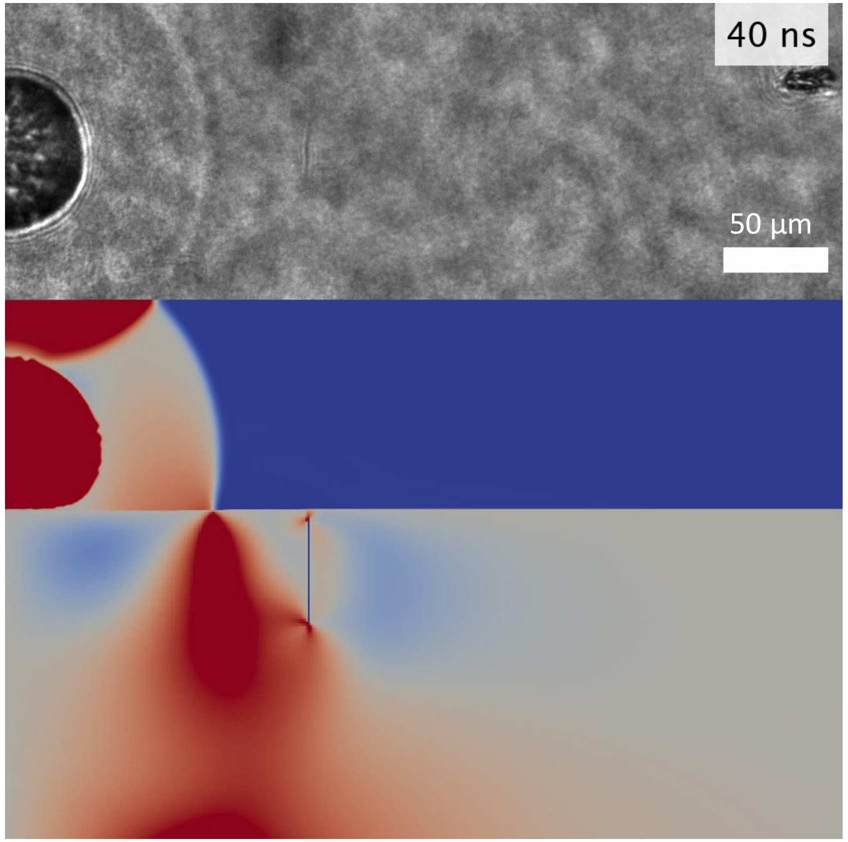
Bubble in a thin gap - wave propagation

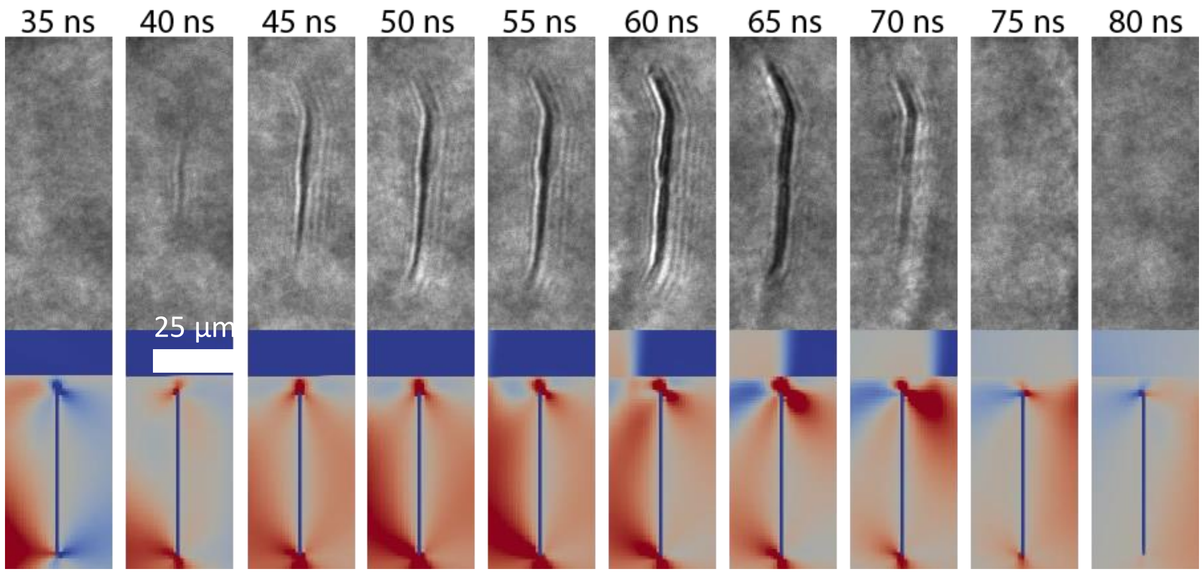
60 GPa (glass)



Bubble in a thin gap - wave propagation

60 GPa (glass), comparison of experiment with selected frames





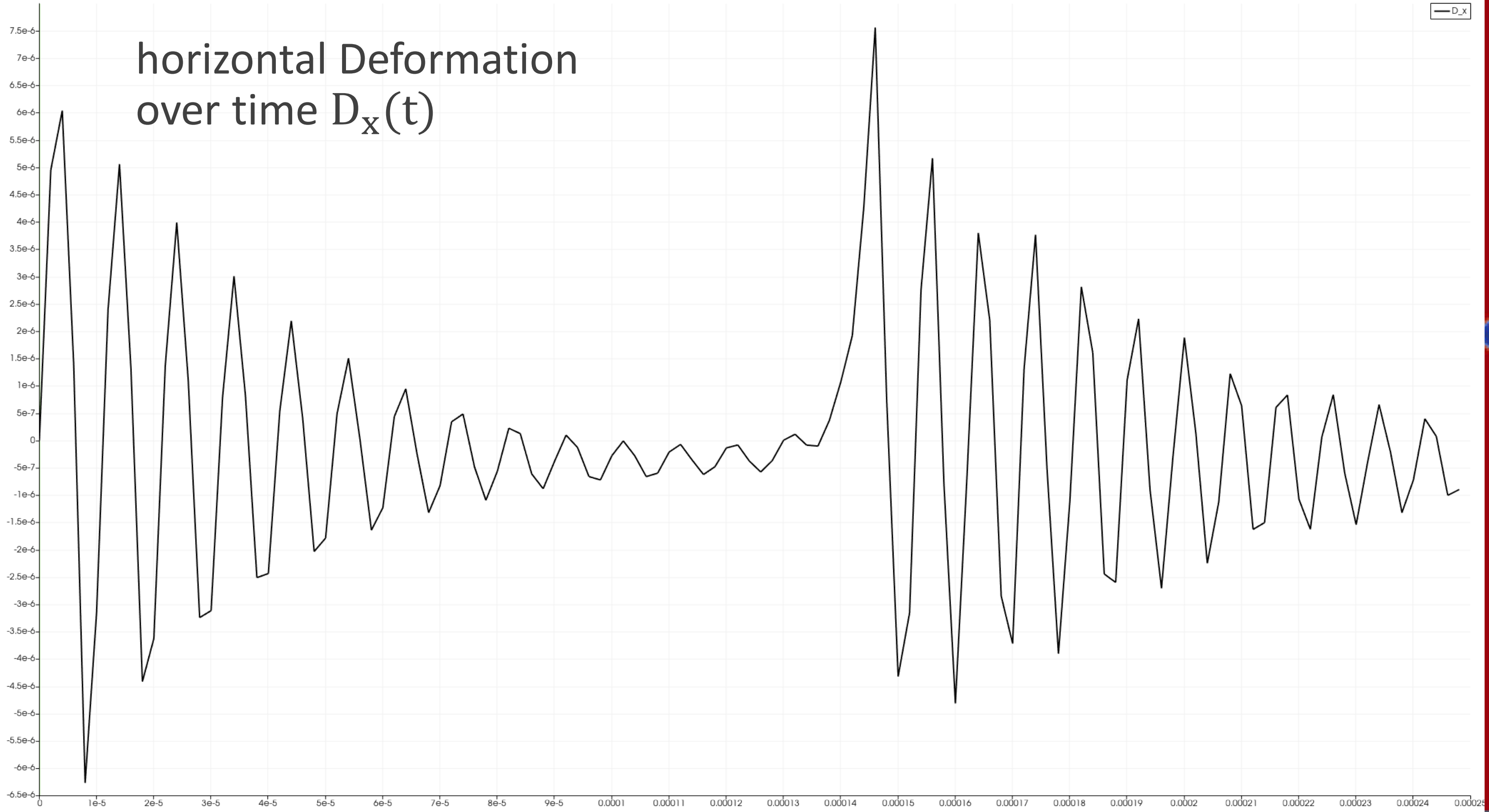
Pedro Quinto, Universidad Nacional Autónoma de México, Mexico

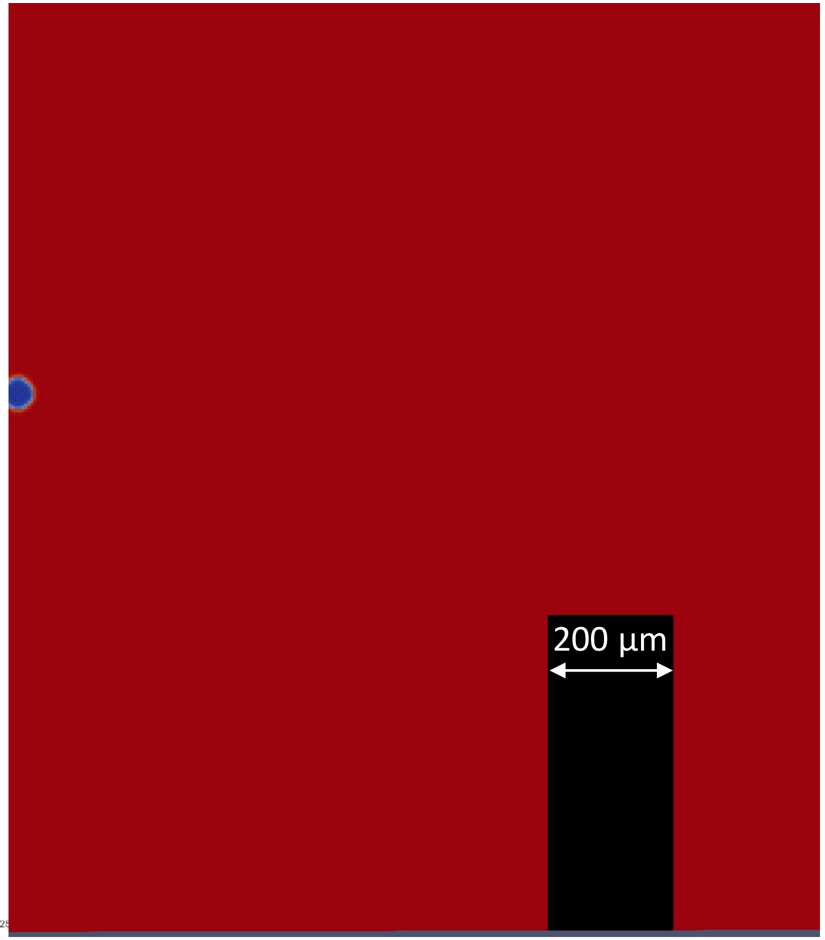
Ulisses Jesús Gutiérrez Hérnandez , Universidad Nacional Autónoma de México, Mexico

Bubble at an elastic wall - bubble collapse

20 MPa (Rubber)

Bubble at an elastic wall - bubble collapse





Conclusion and Outlook

- developed numerical solver for a single cavitation bubble and an elastic solid
- shows good agreement with experiments
- future work:
  - optimization of the solver
  - deeper understanding of cavitation erosion
  - deeper understanding of secondary cavitation

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Credit/prior work

- experiments by:
  - Patricia Pfeiffer, Otto-von-Guericke-University Magdeburg, Germany
  - Pedro Quinto, Universidad Nacional Autónoma de México, Mexico
  - Ulisses Jesús Gutiérrez Hérnandez , Universidad Nacional Autónoma de México, Mexico

- work on single bubble simulations using OpenFOAM done by:
  - Max Koch, Georg-August-University of Göttingen, Germany
  - Christiane Lechner, , Georg-August-University of Göttingen, Germany
  - Qingyun Zeng, Nanyang Technological University of Singapore

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Pictures

- [B1] “Ein- und Auslassventile mit Ultraschall reinigen im BANDELIN SONOREX Ultraschallreiniger“, BANDELIN, YouTube, URL: https://www.youtube.com/watch?v=7pL1UOLEjnQ
- [B2] F. Reuter, R. Mettin: “Mechanisms of single bubble cleaning“, Fig. 12, Georg-August-Universität Göttingen, Germany, Ultrasonics Sonochemistry, 2016
- [B5] OpenFOAM logo, https://www.openfoam.com/
- [B6] DFG logo, https://www.dfg.de/
- [B7] Otto-von-Guericke-University logo, https://www.ovgu.de/

compressibleInterFoam time loop

- calculate Courant number, adjust time step size
- pressure-velocity PIMPLE corrector loop
  - solve α equation (continuity equation for alpha field), $\frac{\partial(\alpha\rho)}{\partial t} + \nabla \cdot (\alpha\rho\vec{u}) = 0$
  - update ρ (continuity equation)
  - solve U equation (NSE without pressure term), pressure corrector loop
    - solve pressure equation
    - update compressibility and ρ
  - correct bubble mass
- write fields and output data

Bubble initiation

- mimicks a laser/spark produced bubble
- $\rho_{gas} = \rho_{liquid}$
- $p_g \approx 170$ kBar, $p_l \approx 1$ Bar
- U = 0 m/s
- solid: D = 0 m, σ = 0 Pa
- smearing to counteract Rayleigh-Taylor-Instability