Influence of bubble size distribution on acoustically cavitating flows

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Acoustic cavitation

Source: Industrial Sonomechanics, LLC
Acoustic cavitation: multiscale problem

Source of figures: University of Göttingen, Drittes Physikalisches Institut
Motivation

- **State of the art**
  - fundamental physics of microscopic phenomena well understood
  - macroscopic computations: only linear bubble oscillations with homogeneous distribution

- **Goals**
  - relatively large geometries (~1-10dm³)
  - spatially inhomogeneous polydisperse bubble distribution
  - predict flow and bubble motion
  - current study: sensitivity to
    - void fraction
    - bubble population
Model

Source of figures: University of Göttingen, Drittes Physikalisches Institut

Ultrasound: Helmholtz Eqn.

Bubble Motion

Model Coupling

Radial Bubble Dynamics
Radial bubble dynamics (RBD)

- Toegel model: 3 ODEs
  - Keller-Miksis eqn. ($R$ – bubble radius)
    \[ \left(1 - \frac{\dot{R}}{c}\right) R \ddot{R} + \left(1 - \frac{\dot{R}}{3c}\right) \frac{3}{2} \dot{R}^2 = \frac{1}{\rho} \left[ \left(1 + \frac{\dot{R}}{c}\right) (p_g - |P_{ac}| \sin(\omega t) - p_0) + \frac{R \dot{p}_g}{c} - \frac{4 \mu \dot{R}}{R} - \frac{2 \sigma}{R} \right] \]
  - energy transfer ($\theta$ – temperature)
  - mass (vapor) transfer ($n$ – amount of substance)
- Stiff system
- Solution as pre-processing step in python
- Usage in solver as interpolation 2D table ($f(R_0, P_{ac})$)

Time period
$T = 50 \mu$s
($f = 20$ kHz)

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Time period
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Helmholtz equation (HE)

- Wave equation in frequency domain
  - $P_{ac}$ - complex sound pressure amplitude
  - $k_m$ - complex wave number of the gas-liquid mixture
- Solution in foam-extend
  - block-coupled solver
  - direct linear solver (MUMPS)
  - Newton-Raphson method for coupling to non-linear bubble dynamics

\[
\nabla^2 P_{ac} + k_m^2 P_{ac} = 0
\]

\[
k_m^2 = \int_T f(R, T, n, t, ...) dt
\]
Bubble motion

- Lagrangian
- Force balance

\[ m_b \frac{dU_b}{dt} = F_G + F_{Am} + F_D + F_{Bj} \]

- \( m_b, U_b \) - bubble mass and velocity
- Forces:
  - \( F_G \) - gravitation
  - \( F_{Am} \) - added mass
  - \( F_D \) - drag
  - \( F_{Bj} \) - Bjerknes, due to interaction of non-linear oscillation and acoustic pressure gradient

\[ F_{Bj} = \langle V_b \rangle_T \nabla P_{ac} \]
Bubble populations

Bubble populations implementation

- Assumptions:
  - void fraction at walls is kept above a threshold (injection)
  - bubbles jet when touching walls (escape condition)
  - initial homogeneous void fraction

- Dynamic Load Balancing (foam-extend)
  - $\beta = 10^{-5} \Rightarrow 1$ to $100$ Mio bubbles ($\beta$ – void fraction / bubble density)
  - due to cavitation forces bubbles may accumulate at stagnation points $\Rightarrow$ performance issues in parallel runs
  - rebalance mesh if imbalance is high such that every processor has similar number of bubbles
Overview

**OpenFOAM**

- **RBD**
  - 1D Model
  - Python

- **Tabulated integrals**

- **Helmholtz eqn.**
  - Eulerian

- **Bubble Motion**
  - Lagrangian

- **Liquid Motion**
  - Eulerian
  - URANS

- **Interpolate** $\nabla P_{ac}$

- **Momentum transfer**
Geometry

- Sonotrode immersed in a cylindrical geometry
  - typical setup also for large scale reactors
  - axisymmetric
  - tank
    - 18cm tall
    - 24cm diameter
- sonotrode
  - 3cm beneath water surface
  - 12cm diameter
Cylindrical tank
Velocitiy with glyphs

- Quasi-stationary after 3s
- Periodic fluctuations
- Velocity magnitude fits experimental results
Acoustic pressure contours

- In the area of the cone structure $|P|$ is fluctuating
- Bubbles are driven by $\nabla P$
- Thus, bubbles form clusters and disturb the flow, which leads to fluctuations
Fluid velocity

Reference
\begin{align*}
\beta &= 1.2 \cdot 10^{-5}, \\
R_0 &= \text{Jet distribution}
\end{align*}

\begin{align*}
\beta &= 10^{-4}, \\
R_0 &= \text{Jet distribution}
\end{align*}

\begin{align*}
\beta &= 1.2 \cdot 10^{-5}, \\
R_0 &= \text{Cluster distribution}
\end{align*}

\begin{align*}
\beta &= 1.2 \cdot 10^{-5}, \\
R_0 &= 2\mu m, \text{ monodisperse}
\end{align*}
Void fraction

Reference

$\beta = 1.2 \cdot 10^{-5}$, $R_0$ Jet distribution

$\beta = 10^{-4}$, $R_0$ Jet distribution

$\beta = 1.2 \cdot 10^{-5}$, $R_0$ Cluster distribution

$\beta = 1.2 \cdot 10^{-5}$, $R_0 = 2\mu m$, monodisperse
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\]
Summary

- Computation of cavitation flows in large scale reactors
  - solution agrees qualitatively with experiments
- Fluctuation of the flow, which is also seen in experiments, is explained by interaction between bubbles and acoustic pressure
- Bubble populations
  - generally: the flow and acoustic pressure structure show low sensitivity due to the population type
  - flow velocity may alter by up to 50%
Source code for Helmholtz solver (MUMPS interface):
https://github.com/technoC0re

Questions?

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