Compressible multi-scale Euler-Lagrange simulations of cavitating flows

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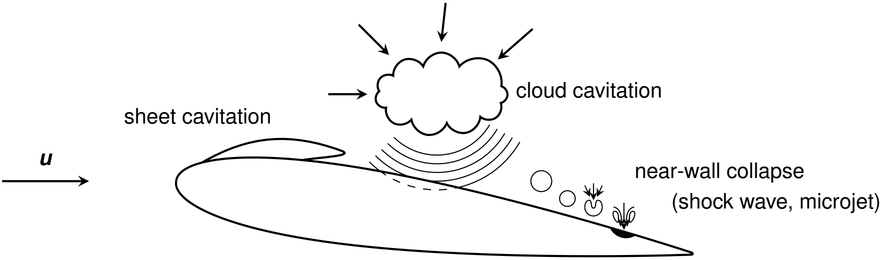
- **Motivation of present work:**
  - Development of hybrid multi-scale Euler-Lagrange methods to simulate cavitating flows including details of single bubble dynamics
  - Prediction of cavitation erosion from Lagrangian single bubble collapses
  - Using *OpenFOAM* © as CFD toolbox

Cavitation and Erosion

Cavitation erosion mechanisms

- Collapsing cavitation bubbles near a solid wall cause erosion



$\Rightarrow$ **How to deal with the different temporal and spatial scales involved in cavitation and cavitation erosion?**

Eulerian and Lagrangian Methods

Euler-Euler – homogeneous mixture approach

- Liquid phase and vapour phase are both treated as continuum on Eulerian grid
- Behaviour of flow from mass and momentum conservation
- Volume of Fluid (VoF) method to capture interface between the phases
- Compressibility of liquid phase: additional derivatives in volume fraction and pressure equations; liquid density and speed of sound according to Tait equation of state
- Source terms from a cavitation model account for vaporisation and condensation processes
- **Advantage**: Computational efficiency
- **Disadvantage**: Details about behaviour of single bubbles missing

Euler-Lagrange

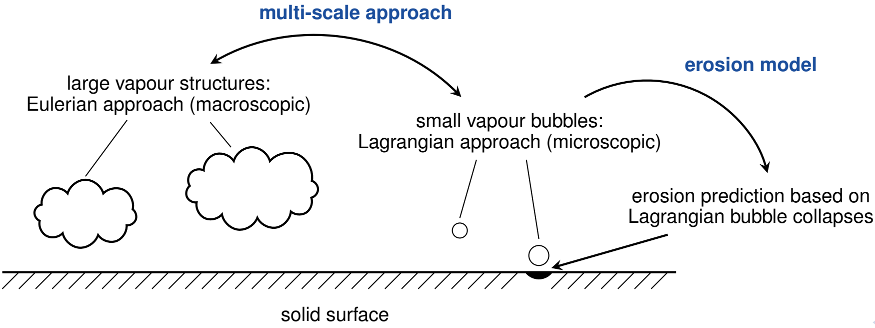
- Liquid phase treated as continuum; vapour phase consists of a discrete number of spherical bubbles; different levels of coupling (1-, **2-**, 4-way)
- Motions of each single bubble are calculated using a Lagrangian equation of motion
- Bubble dynamics calculated for each bubble (Rayleigh-Plesset, Gilmore, Tomita-Shima)
- **Advantage**: Detailed information about spherical single bubbles
- **Disadvantage**: High computational resources needed

$\Rightarrow$ **combine the advantages of both methods**

Multi-Scale Euler-Lagrange Approach

Basic Concept: Multi-Scale Euler-Lagrange

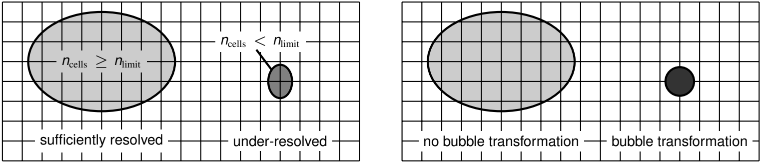
- Basic Concept – Multi-Scale Euler-Lagrange Method, Peters and el Moctar (2020):
  - Liquid phase: treated as continuum in Eulerian frame
  - Large vapour volumes: treated as continua in Eulerian frame
  - Small vapour volumes: treated as spherical Lagrangian bubbles
- Erosion Prediction:
  - Based on collapses of Lagrangian bubbles near solid-surfaces

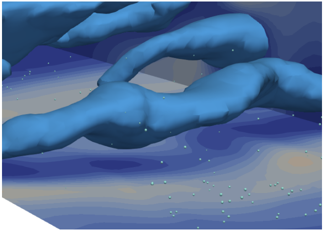


Multi-Scale Euler-Lagrange: Transformation

How to transform vapour volumes between Eulerian and Lagrangian frame?

- Transformations based on criteria: (vice versa for Lagrange to Euler)
  - Absolute size of vapour volume: $V_{\text{ref}} < V_{\text{limit}}$ or
  - Relative size of vapour volume to numerical grid: $n_{\text{cells}} < n_{\text{limit}}$
- Transformation of vapour volume from Euler to Lagrange:





- Calculation of total vapour volume from both frameworks:

$$\alpha_{\text{v,total}} = \alpha_{\text{v,Euler}} + \alpha_{\text{v,Lagrange}}$$

Multi-Scale Euler-Lagrange: Erosion Assessment

Erosion Model

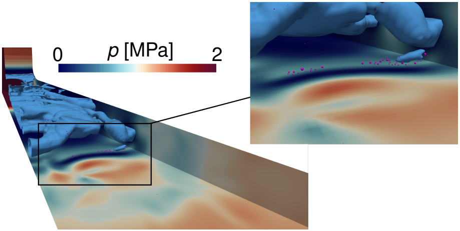
- **Aim:** predict erosion using Lagrangian bubble collapses near solid wall
- Erosion potential depends on properties obtained from Lagrangian bubble collapses:
  - Maximum bubble radius prior to collapse R_{max}
  - Distance of bubble centre to surface H
  - Pressure at end of collapse p_{coll}
  - Number of bubble collapses affecting regarded face n_{coll}
- Lagrangian damage potential, c_{dam}, for every face of a surface:

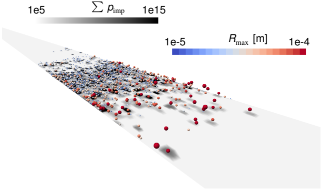
$$c_{\mathrm{dam}} = \frac{\sum_t^T \left(\frac{n_{\mathrm{coll}} p_{\mathrm{coll}} R_{\mathrm{max}}}{H} \right)_t}{\sum_n^N \left(\sum_t^T \left(\frac{n_{\mathrm{coll}} p_{\mathrm{coll}} R_{\mathrm{max}}}{H} \right)_t \right)_n}$$

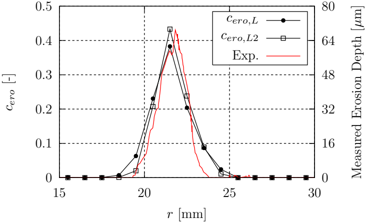
$\Rightarrow$ Part of erosion compared to total erosion on surface (qualitative)

Multi-Scale Euler-Lagrange: Validation Case

- Validation of multi-scale Euler-Lagrange approach to predict cavitation erosion, Peters and el Moctar (2020)
- Benchmark based on experiments of Franc and Riondet (2006); Franc et al. (2011)







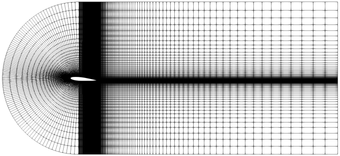
Sources: Peters and el Moctar (2020); Peters (2020)

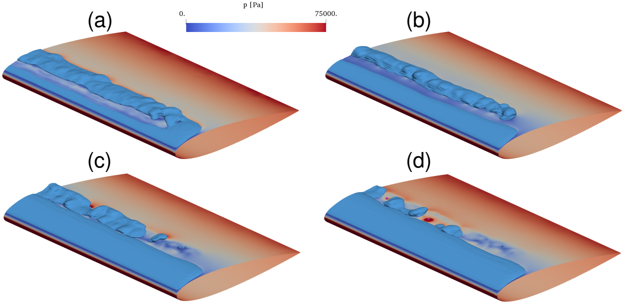
Numerical Results –

Cavitating Flow over NACA 0015

Multi-Scale Euler-Lagrange: NACA 0015 (1)

- Simulation of cavitating flow over NACA 0015 at $AoA = 5°$, $U_{\text{in}} = 10\,\text{m/s}$, $\sigma = 1.19$ using multi-scale Euler-Lagrange method, Peters et al. (2020)



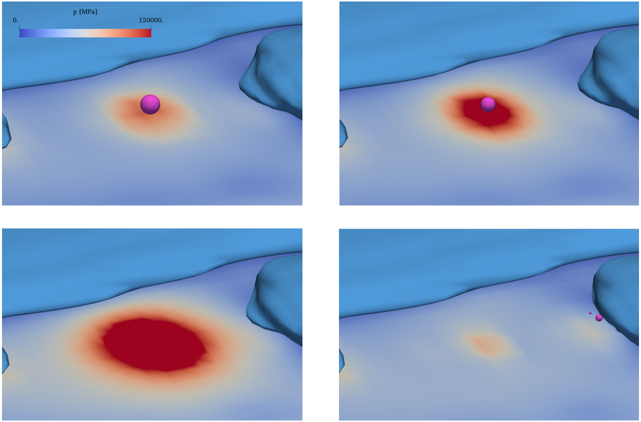


Multi-Scale Euler-Lagrange: NACA 0015 (2)

- Transformations of Eulerian vapour volumes into Lagrangian bubbles (and vice versa)
- Collapse of Lagrangian bubbles in vicinity of surface

Multi-Scale Euler-Lagrange: NACA 0015 (3)

- Collapse of a Lagrangian bubble near the hydrofoil's surface

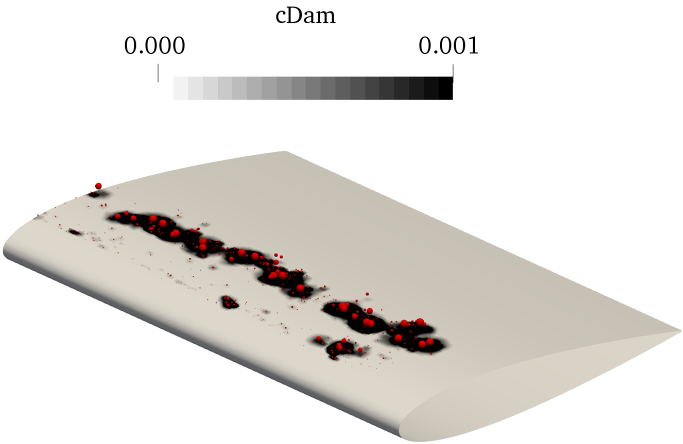


Multi-Scale Euler-Lagrange: Bubble Collapse (4)

- Two Eulerian vapour structures are transformed into Lagrangian bubbles, which collapse consecutively
- Collapse of larger bubble radiates a noticable shock wave

Multi-Scale Euler-Lagrange: NACA 0015 (4)

- Information from bubble collapses is used to assess erosion potential



Conclusions and Outlook

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Conclusions

- Multi-scale approach connects macroscopic with microscopic scales
- Lagrangian bubble collapse information can be used to predict erosion

Outlook

- Comparison with further experimental measurements
- Implementation of bubble break-up processes
- Considering three-phase carrier flow (including non-condensable gases)

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Thank you!