Investigation on the use of a hybrid CFD solver to simulate breaking waves

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Introduction
Offshore wind farms in the future

- Multi-use platform (wind farms, aquaculture and exploitation of wave energy)
- Massive development in the intermediate depth region (20 - 60 m)

EU Project 'MERMAID - Innovative Multi-purpose offshore platforms: planning, design and operation'.
Spilling breaking waves impact on secondary structures

- Waves often break as spilling breakers in the intermediate depth area under storm conditions.
- Spilling waves are characterized by a mixture of dispersed air bubbles and water traveling with the wave front.
- Impact on secondary structures (external access platforms, boat-landings, railings..) can cause severe damages.

![Spilling and plunging waves](image)

![Breaking waves impact at a Horns Rev wind turbine](image)
Model set-up
Which are the characteristics of the problem?

- A breaking wave is an unsteady multiphase flow
- Wide range of interfacial lengths scales occurring between air and water
- Largest scales are localized at the free surface during the wave propagation
- Smallest scales are generated as soon as the wave breaks and the air bubbles are entrained
Which approach to model the different length scales?

- Wave propagation: a moving sharp interface larger than the grid size \(\rightarrow\) **Model with interface capturing capabilities for immiscible phases** (Volume Of Fluid is the most common)

- Breaking event: disruption of the sharp interface and entrainment of air bubbles smaller than the grid size \(\rightarrow\) **Eulerian multi-fluid methodology for dispersed phases**
What does hybrid model mean?

- **Hybrid** means that a solver with interface capturing capabilities is coupled with one based on the Eulerian methodology.

- Explicit coupling: both solvers are implemented, but employed in a mutually-exclusive way according to a local criterion.

- **Adopted coupling**: numerical interface sharpening within the Eulerian framework.
Interaction of: water, air above the free surface and entrained bubbles.

- Entrained bubbles with different size $\rightarrow n$ different air phases $\rightarrow n$ different diameters smaller than the grid size

- The phase representing the air above the free surface has diameter larger than the grid size (continuous air)

- Total number of phases = $(n + 1)$ air phases + 1 water phase = $n + 2$

- The interface between continuous air and water is the free surface to be sharpened

- Mass and momentum transfers among phases are not solved but modeled
Can a VOF-based model simulate the air entrainment process?

- A VOF-based model can reproduce the air entrainment process as long as the domain is discretized very finely → computational demanding!

- Two examples:

  Vortical structures underneath a plunging breaking wave. **Grid size = 0.1 mm.**

  Hydraulic jump. **Grid size = 0.625 mm**
Description of the model
The Eulerian approach: governing equations

- Averaged mass and momentum conservation equations:

\[
\frac{\partial (\alpha_i \rho_i)}{\partial t} + \nabla \cdot (\alpha_i \rho_i \mathbf{u}_i) = S_i
\]

\[
\frac{\partial (\alpha_i \rho_i \mathbf{u}_i)}{\partial t} + \nabla \cdot (\alpha_i \rho_i \mathbf{u}_i \otimes \mathbf{u}_i) = -\alpha_i \nabla p - \nabla \cdot (\alpha_i \rho_i \mathbf{T}_i^{\text{eff}}) + \alpha_i \rho_i \mathbf{g} + \mathbf{M}_i
\]

- Each phase \( i \) is essentially defined via the density, the viscosity and the diameter of bubbles

- The \((n + 1)\) air phases share the same density and viscosity but they have different diameter

- \( S_i \) and \( \mathbf{M}_i \) represent mass transfer and interfacial forces among phases respectively
Mass transfer modeling

- Mass transfer among the $n$ bubble classes: binary breakage (regulated by the intensity of turbulence).
  
  $$S_{i, \text{breakup}} = \beta_i^+ - \beta_i^-$$

- Mass transfer between the dispersed bubbles and the continuous air
  - from continuous air into the $n$ classes → air entrainment (not modeled yet)
  - from the $n$ classes into continuous air → escaping of bubbles

- Escaping of bubbles modeled with:  
  $$S_{i, \text{merging}} = (1 - \varphi_s) \varphi_{\text{morph}} \rho_i \alpha_i / (a_t \Delta t)$$

- For all phases:
  
  $$S_{i, \text{bubble}} = S_{i, \text{breakup}} - S_{i, \text{merging}}$$

  $$S_{\text{continuous Air}} = \sum_{i=1}^{n} S_{i, \text{merging}}$$

  $$S_{\text{water}} = 0$$
Interfacial forces modeling

- \( \mathbf{M}_i \) decomposed into three contributions: drag, virtual mass and surface tension force

- **Drag force:**
  \[
  \mathbf{M}_{D,i} = \frac{3}{4} \rho_c \alpha_c \alpha_d C_D \| \mathbf{u}_d - \mathbf{u}_c \| (\mathbf{u}_d - \mathbf{u}_c) \frac{d}{d_d}
  \]

- **Virtual mass force:**
  \[
  \mathbf{M}_{VM,i} = \rho_c \alpha_c \alpha_d C_{VM} \left( \frac{D \mathbf{u}_c}{Dt} - \frac{D \mathbf{u}_d}{Dt} \right)
  \]

- **Surface tension force:**
  \[
  \mathbf{M}_{surf,i} = \sigma \kappa \nabla \alpha
  \]

- Interfacial forces defined between:
  - water and bubble classes
  - water and continuous air
Interface sharpening method

- The interface compression method (VOF-type) is employed:

\[
\frac{\partial (\alpha_i \rho_i)}{\partial t} + \nabla \cdot (\alpha_i \rho_i \mathbf{u}_i) + \nabla \cdot [\mathbf{u}_c \alpha_i (1 - \alpha_i)] = S_i
\]

- \(\mathbf{u}_c\) is the "compression velocity":

\[
\mathbf{u}_c = \min(C \| \mathbf{u}_r \|, \max(\| \mathbf{u}_r \|)) \frac{\nabla \alpha}{\| \nabla \alpha \|}
\]

- \(C\) is a coefficient that the user can flexibly specify for any phase pair:
  - \(C = 0\) → interface not compressed, phases dispersed (bubbles and water)
  - \(C > 0\) → interface compressed, phases segregated (continuous air and water)
A bubble column: simulation set-up

- Uniform 3D hexahedral mesh of size 0.01 m
- LES Smagorinsky model employed
- Flow simulated for 200 s
- Three cases:

- **A**
  - continuousAir
  - $d = 0.004$ m
  - free surface
  - water $d = 0.0001$ m

- **B**
  - continuousAir
  - $d = 0.04$ m
  - free surface sharpened
  - water $d = 0.0001$ m

- **C**
  - continuousAir
  - $d = 0.04$ m
  - free surface sharpened
  - water $d = 0.0001$ m
  - bubble class 2
  - $d = 0.002$ m

- bubble class 1
  - $d = 0.004$ m
Isosurfaces of $\alpha_{air}$ at $t = 200$ s

- Negligible effect of VM
- Lift force not modeled $\rightarrow$ Absence of transversal spreading $\rightarrow$ Large central peak
A bubble column: results case B

Isosurfaces of $\alpha_{\text{air}}$ at $t = 200$ s

$\alpha_{\text{continuousAir}}$ at $t = 200$ s

- No presence of introduced bubbles above the free surface
- Free surface quite sharp with either $C=0$ or $C=1$
- Velocity profiles similar to case A

A bubble column: results case C

- Turbulence was not intense enough to break the introduced bubbles
- Time history of the axial liquid velocity:

![Graph showing time history of axial liquid velocity](image)

- Smaller bubbles were not produced → results identical to case B
A plunging solitary wave

- 3D uniform mesh in the flat part (size 0.01 m). Aspect ratio, skewness and non-orthogonality minimized in the sloping part.

- LES Smagorinsky model employed

- Wave generated by imposing velocity and phase fraction on both water and air at the inlet

- Flow simulated for 20 s

- **Air entrainment not modeled → no bubble classes → only water and continuous air**

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![Diagram of the experiment with sections and distances]( attachment://diagram.png)
A plunging solitary wave: $C = 0$ vs $C = 1$

- Two cases: $C = 0$ and $C = 1$
- Drag and surface tension force taken into account. No virtual mass force.
- Water phase fraction at the simulated breaking point ($x = 5.35$ m)

Upper: $C=0$. Lower: $C = 1$
A plunging wave: free surface elevation when $C = 1$

- Good agreement with experiments
- Good agreement with VOF-type model
- Run-up underestimated

![Graph showing free surface elevation with different sections and time]
Conclusions
Main conclusions and on-going work

- A CFD simulation of the entire breaking wave process involves interfacial length scales both smaller and larger than the grid size.

- An Eulerian model coupled with a VOF-type interface capturing algorithm could have the capabilities of handling such multi-scale problem.

- A bubble column case study was used to test the momentum transfer modeling and the implemented mass transfer formulations. Both need further investigations.

- Simulation of a plunging solitary wave showed encouraging results for the free surface motion. The interface sharpening method was effective at the breaking point.

On-going work:
- modeling of the lift force and the bubble coalescence
- implementation of the sub-grid air entrainment formulation