Modelling of fluid-structure interactions for wind energy applications

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Vortical structures and wall turbulence: In honour of Paolo Orlandi
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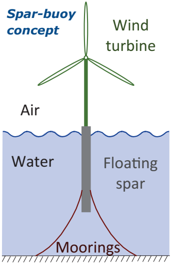
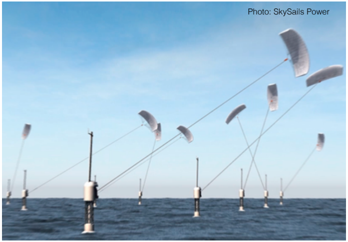
Motivation

Placing offshore renewable energy devices on fixed and floating supports (deep sea)

Photo: Trude Refsahl/Statoil





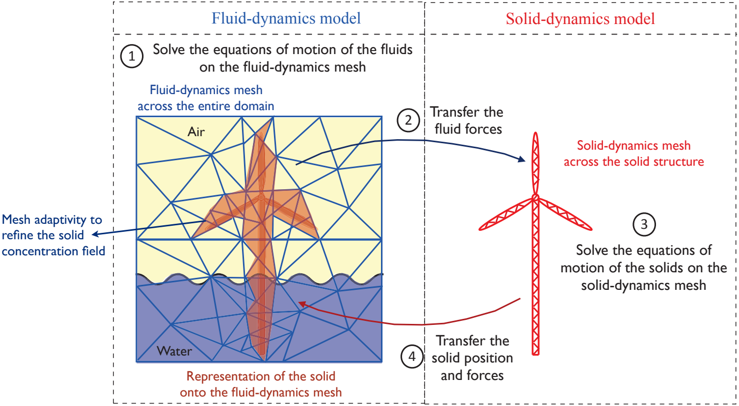
Scope of the project:

- Couple two finite-element models for modelling fluid-structure interactions
- Apply them to the various components of the offshore wind turbine

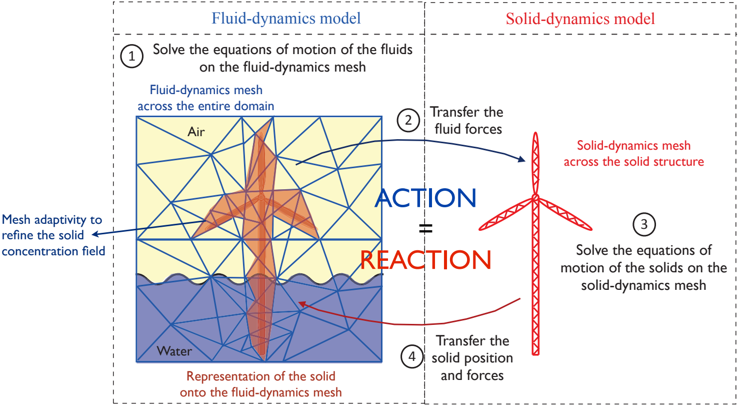
Outline

1. General formalism
2. Equations of motion
3. Coupling algorithm
4. Results
   - Hydrodynamics: wave-pile interactions
5. Conclusion

1. General formalism



1. General formalism



- Conservative projection scheme at a discrete level
- Integration in a Navier-Stokes fluid/wave model

2. Equations of motion

Fluid-dynamics model: Fluidity-ICOM

$$\bar{\nabla} \cdot \bar{u} = 0$$

$$\rho_f \frac{\partial \bar{u}}{\partial t} + \rho_f \left(\bar{u} \cdot \bar{\nabla} \right) \bar{u} = -\bar{\nabla} p + \bar{\nabla} \cdot \bar{\bar{\tau}} + \bar{F}_f \qquad (\rho_f = \text{constant})$$

- The equations are solved for a monolithic velocity: $\bar{u} = \alpha_f \bar{u}_f + \alpha_s \bar{u}_s$
- An additional force accounts for the presence of the solids:

$$\bar{F}_f = \beta \left(\alpha_s \bar{u}_s - \alpha_s \bar{u} \right) = \bar{F}_2 - \bar{F}_1 \qquad \beta = \text{fct}\left(\frac{\rho_f}{\Delta t}, \frac{\nu}{L^2} \right)$$

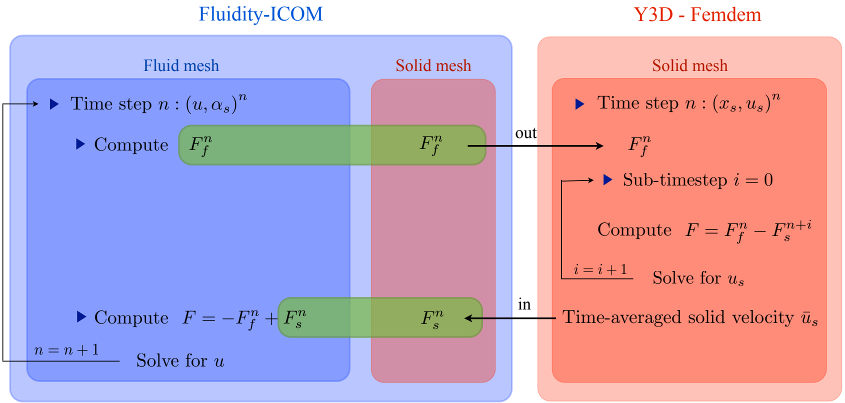
Solid-dynamics model: Y3D-Femdem

$$\frac{D}{Dt}(\rho_s \bar{u}_s) = \bar{\nabla} \cdot \bar{\bar{\tau}}_s + \bar{F}_s \qquad \bar{F}_s = \bar{F}_1 - \bar{F}_2$$

Conservation

$$\int_V F_f dV = -\int_{V_s} F_s dV_s$$

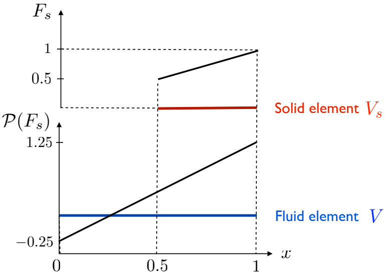
3. Coupling algorithm



Viré *et al.*, Ocean Dyn. 62 (2012); Viré, Xiang, Pain, submitted to Phil. Trans. R. Soc. A (2014)

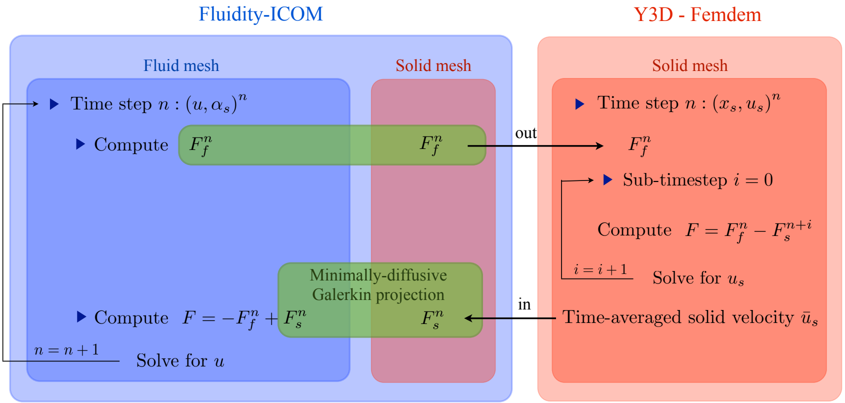
3. Coupling algorithm

Galerkin projection
from solid to fluid mesh



$$\int_{V_s} F_s dV_s = \int_V \mathcal{P}(F_s) dV$$

3. Coupling algorithm



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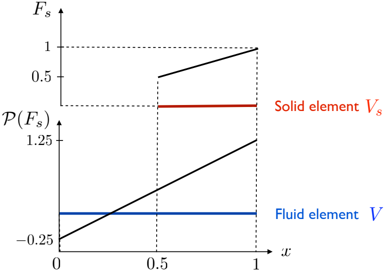
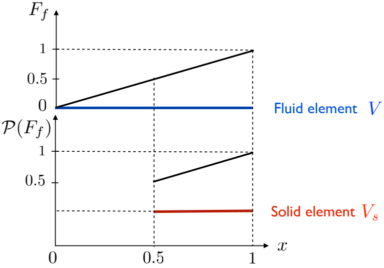


$$\int_{V_s} F_s dV_s = \int_V \mathcal{P}(F_s) dV$$

Galerkin projection
from fluid to solid mesh



$$\int_{V \cap V_s} F_f dV_\cap = \int_{V_s} \mathcal{P}(F_f) dV_s$$

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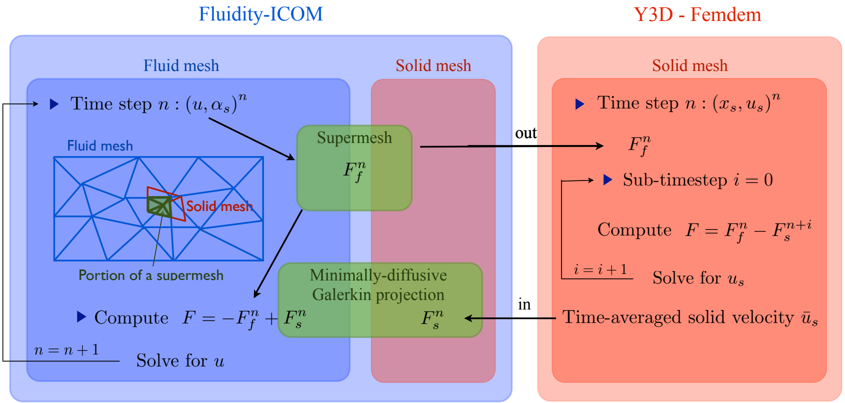
3. Coupling algorithm



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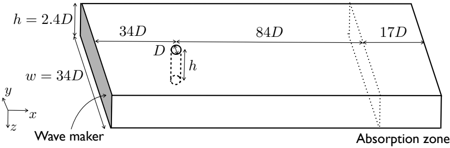
4. Results

Hydrodynamics: wave-pile interaction with regular waves

- Wave modelling with CFD
  - Maguire, PhD. Edinburgh, 2010
  - Viré et al., Proceedings of ISOPE 2013



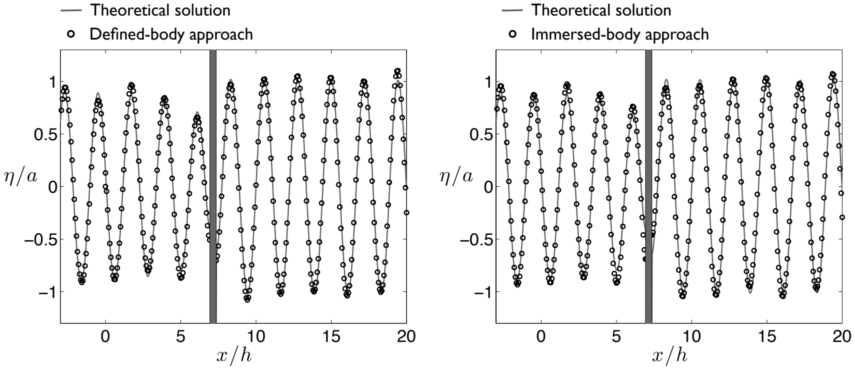
- The flow is inviscid
- Regular waves are generated at the inlet:

$$ak = 0.001 \quad \text{where} \quad gk\tanh(kh) = (2\pi T)^2 \quad \text{and} \quad T = 1$$

- The water depth is intermediate between shallow and deep, i.e. $h/\lambda_0 = 0.45$ $(\lambda_0 = 2\pi g/\omega^2)$
- A mixed finite-element pair is used: $P1_{DG}$ in velocity and $P2$ in pressure
- The mesh has approximately 30,000 nodes in the x-y plane and is extruded vertically in 7 layers
- Defined-body and immersed-body methods are compared
- Reference: linear diffraction theory (MacCamy and Fuchs, Tech Memorandum, US Beach Erosion Board, 1954)

4. Results

Hydrodynamics: wave-pile interaction with regular waves



4. Results

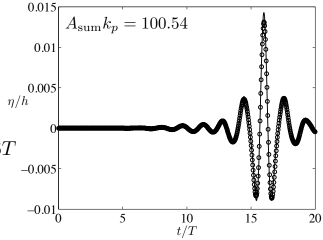
Hydrodynamics: wave modelling for irregular waves

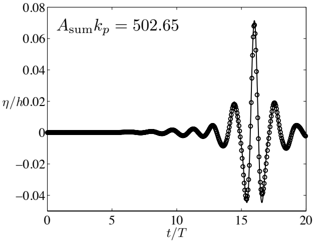
- Irregular waves are generated at the inlet
- 3 amplitudes of the focused event are considered:

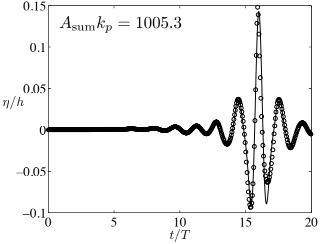
  $A_{\text{sum}} k_p = 100.54 \quad A_{\text{sum}} k_p = 502.65 \quad A_{\text{sum}} k_p = 1005.3$

  where k_p corresponds to the peak in Jonswap spectrum
- The maximum amplitude occurs at: $x_f = 10h$ and $t_f = 16T$
- Reference: second-order calculation

  (Sharma and Dean, Society of Petroleum Engineers Journal, 1981)

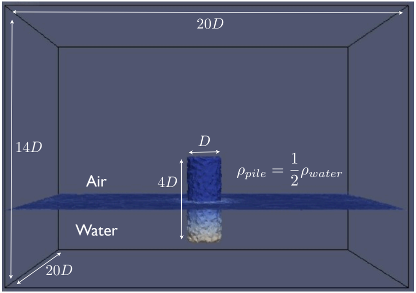






4. Results

Hydrodynamics: dynamics of a floating pile



5. Conclusion

- Coupling between two finite-element models based on unstructured meshes
- Validation on flows of fundamental interest in offshore engineering

Next steps

- Increase the level of turbulence... in the wake of Paolo Orlandi

Acknowledgements

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All the best to Paolo Orlandi