Modelling Transient Fluid Loading on Flexible Structures

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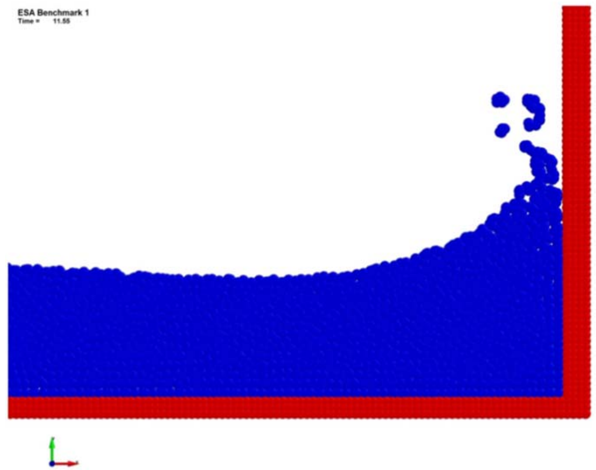
MAFELAP CONFERENCE

The Mathematics of Finite Elements and Applications

14 - 17 June, 2016



Overview

- Introduction / need for Fluid-Structure Interaction codes
- SPH Overview
- Contact in SPH
- Water Modelling
- Helicopter crash on water
- Fluid Sloshing

- Acknowledgements:
  - Rade Vignjevic, James Campbell, Tom De Vuyst, Nenad Djordjevic
  - Omkar Gulavani, David Munro, Lampros Papagiannis, Marcos Acin, Clement Legriel, Esther Comellas, Slavisia Milisavljevic, Luis Rubio Aparici, Paula Serrador, Maria Beneto Garcia, Paul-Andre Somazzi

Extreme fluid-structure interaction

- There are a number of engineering problems that combine transient non-linear structural and fluid behaviour.

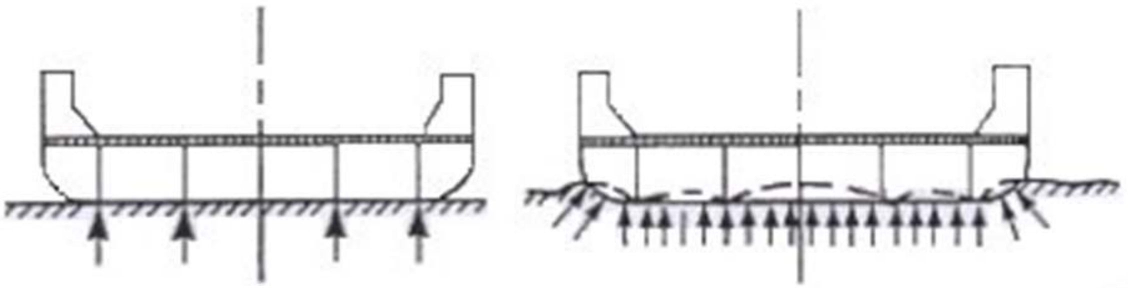


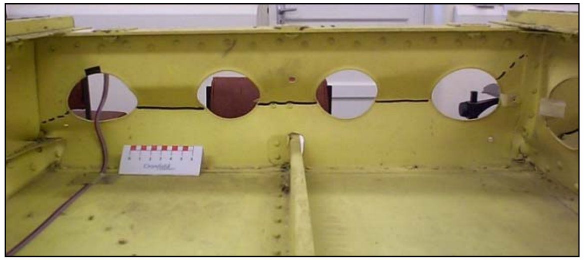
Image source:
http://www.btinternet.com/~derek.mackay/offshore/images/vessels/

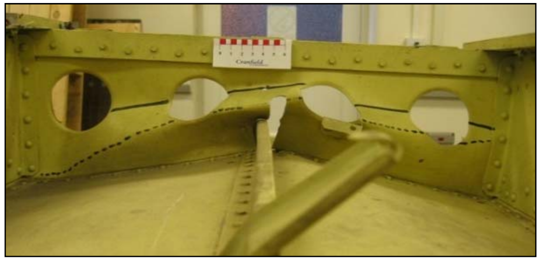
Airbus Ditching in Hudson – Jan 2009

- Modelling the behaviour present in these events is challenging:
  - Large structural deformation, including non-linear transient behaviour and potentially material failure,
  - Complex fluid behaviour,
  - Fluid-structure interaction

Structural modelling
- Case Study: Helicopter Impact on water







Differences in load transmission during a “flat” hard surface impact (left) and a fluid surface (right) at 8 m/s [1, 2].

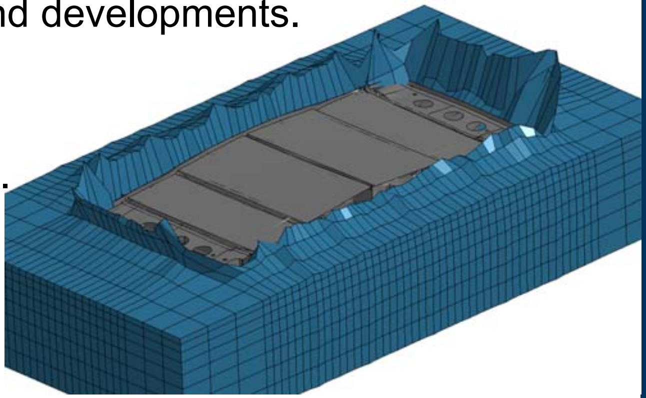
[1] Hughes K, Vignjevic R, Campbell J, “*Experimental observations of an 8 m/s drop test of a metallic helicopter underfloor structure onto a hard surface: Part 1*”, in Proc. IMechE Part G: J. Aerospace Engineering, 221/5 (2007), 661-678

[2] Hughes K, Vignjevic R, Campbell J, “*Experimental observations of an 8 m/s drop test of a metallic helicopter underfloor structure onto water: Part 2*”, in Proc. IMechE Part G: J. Aerospace Engineering, 221(5) (2007), 679-690

Water modelling

- Accurate prediction of structural response is not only limited by structural model itself, but also the ability of the model to accurately describe structural loads arising from fluid.

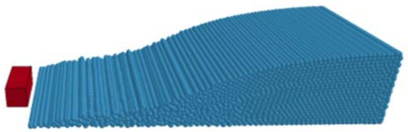
- Several approaches available:
  - Semi analytical fluid models: Von Karman/Wagner theory and developments.
    Low cost, does not allow non-linear structural response
  - Lagrangian FE: limited ability to treat large fluid deformation.
    (Timestep and stability issues)



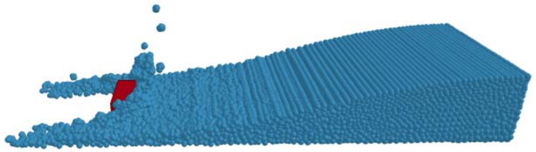
  - Meshless (SPH): Mathematical basis of method and treatment of boundary conditions conditions still requires development.
  - Meshed CFD: Known by various names – ALE, CEL, … Based on established CFD methods. Robust treatment of interaction between fluid and structural solver challenging, as structural model arbitrarily intersects fluid mesh.

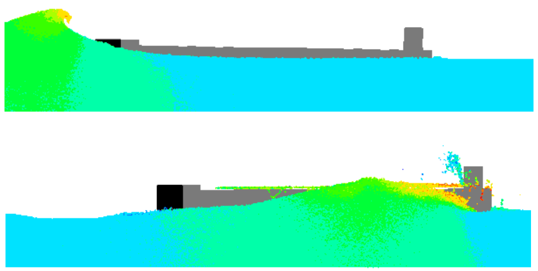
Hughes K, Vignjevic R, Campbell J, De Vuyst, T, Djordjevic N, Papagiannis L
"*From aerospace to offshore: Bridging the numerical simulation gaps – Simulation advancements for fluid structure interaction problems*", International Journal of Impact Engineering 61 (2013) 48- 63

Example FSI Case Studies

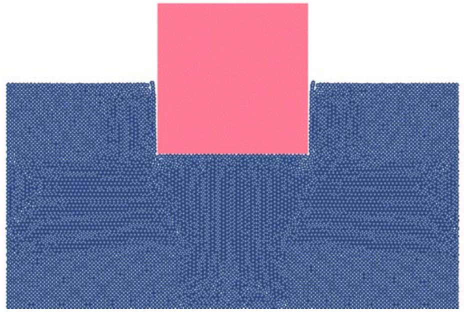


Dambreak

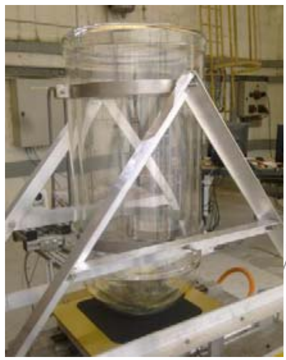


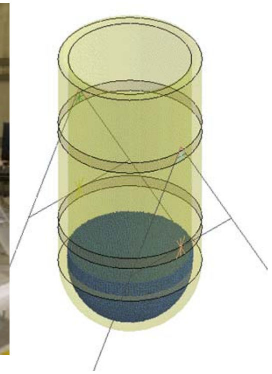


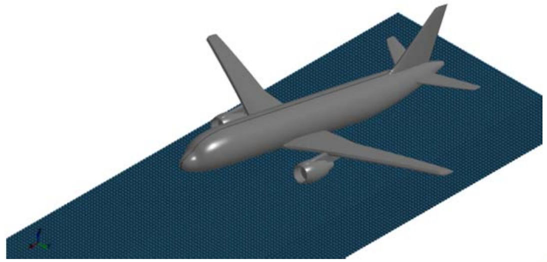
Floating bodies



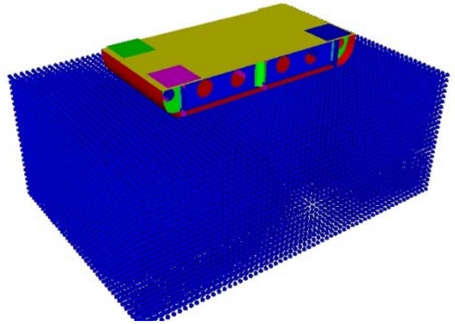
Sloshing



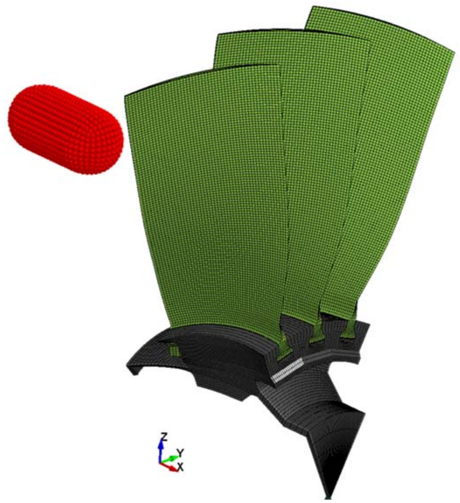




Impact on water / aircraft ditching



Birdstrike / Ingestion into aircraft engines



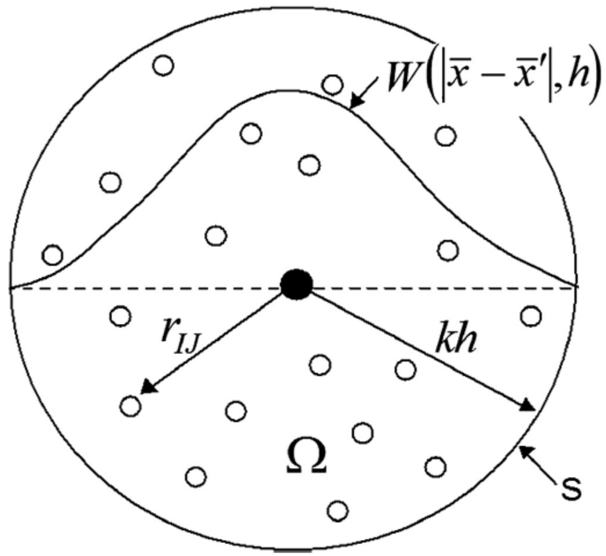
Smoothed Particle Hydrodynamics (SPH)

- SPH is a numerical technique for the approximate integration of the governing equations of continuum mechanics.
- It is a meshless Lagrangian method that uses pseudo-particle interpolation to compute smooth field variables.
- Solution variables are held at the nodes (particles), which move with the material.
  - SPH form of the velocity-gradient tensor calculation

$$\left.\frac{\partial \mathbf{v}}{\partial \mathbf{x}}\right|_i = \sum_j \frac{m_j}{\rho_j}\left(\mathbf{v}_j - \mathbf{v}_i\right)\nabla \mathbf{W}_{ij}$$

  - SPH form of momentum equation

$$\mathbf{a}_i = \sum_j m_j \left(\frac{\boldsymbol{\sigma}_i}{\rho_i^{\,2}} + \frac{\boldsymbol{\sigma}_j}{\rho_j^{\,2}}\right) \cdot \nabla \mathbf{W}_{ij}$$

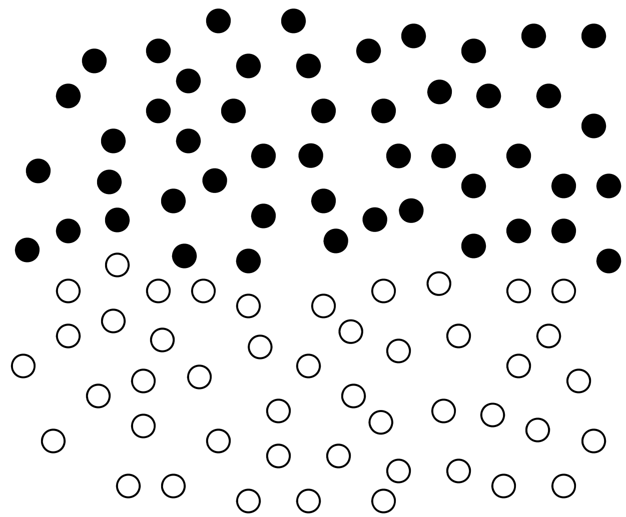


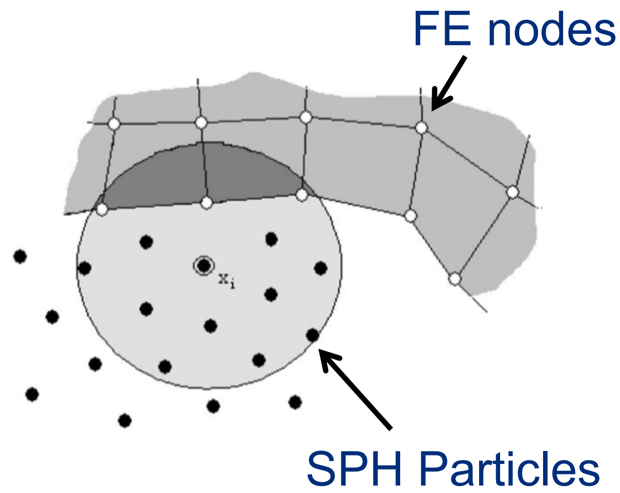
Coupled FE-SPH Contact

- The boundary of the SPH domain is not well defined.
- A contact potential based on the kernel function is used, with FE nodes interacting with SPH particles. Provides a simple contact treatment allowing large deformations, including material failure.

$$f_c = \frac{m_i}{\rho_i}\frac{m_j}{\rho_j} K n \frac{W(\mathbf{x}_i - \mathbf{x}_j)^{n-1}}{W(\Delta p_{avg})^n} \nabla W(\mathbf{x}_i - \mathbf{x}_j, h)$$

- A commonly used alternative to this approach is based on mesh node-to-surface contact algorithms.

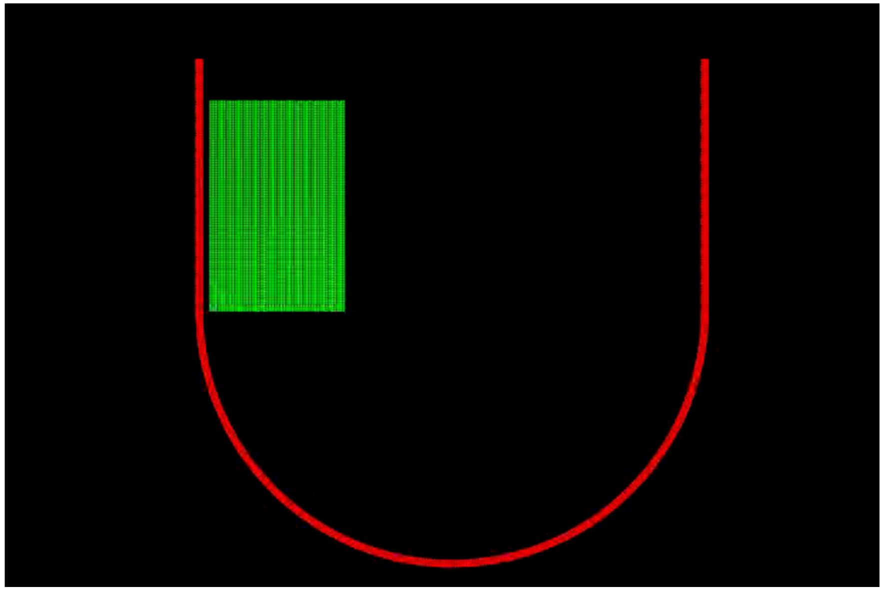




De Vuyst, T, Vignjevic R, Campbell J, "*Coupling between Meshless and Finite Element Methods*", International Journal of Impact Engineering 31(8):1054-1064, September 2005

Coupled FE-SPH Contact

- Structure represented with FE mesh
- Fluid represented as SPH domain
- Use of different 'best' solvers for different domains within a single problem
- The advantage of this approach is that contact between the fluid and structure can be simply and robustly treated.
- (Potential for allowing the simulation of fluid ingress following structural failure).



Fluid Sloshing in 2D
De Vuyst, "*Hydrocode Modelling of Water Impact", PhD Thesis, Cranfield University, 2003*

De Vuyst T, Vignjevic R, Campbell J, "*Coupling between Meshless and Finite Element Methods*", International Journal of Impact Engineering 31(8):1054-1064, 2005

De Vuyst T, Campbell J, Vignjevic R, "*A Frictionless Contact Algorithm for Meshless Methods*" Computer Methods in Engineering and Science 13(1): 35-48, 2006.

Water modelling in SPH

- Under low velocity (< ≈ 10^2 m/s) loading conditions the water can be considered incompressible. However the SPH solver assumes the fluid is compressible, therefore an equation of state (EOS) is required.
- The Murnaghan EOS is used:

$$P = B\left[\left(\frac{\rho}{\rho_0}\right)^{\gamma} - 1\right]$$

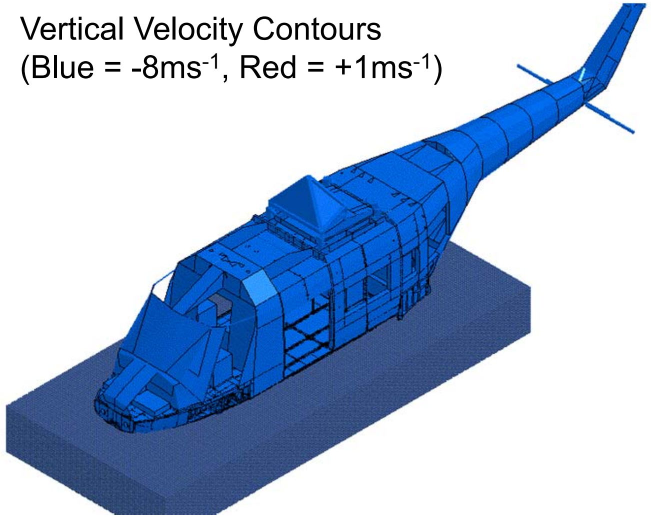
- The parameters are chosen to give the fluid an artificially low speed of sound, but keep density changes small. Potential of significant computational cost reduction via CFL condition.
- This is valid provided the flow velocities are small compared with the speed of sound.

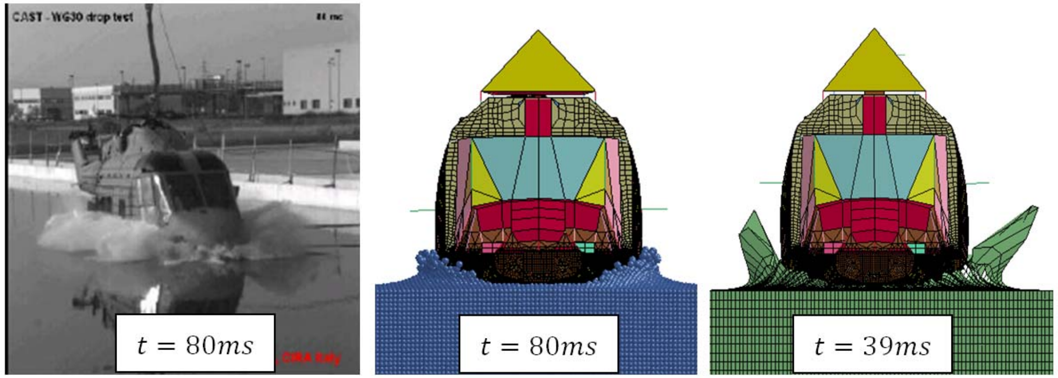
Helicopter impact on water

- A full scale drop test of WG30 fuselage on water was performed within the FP5 CAST programme at CIRA in October 2001.

Full scale helicopter simulation

Vertical Velocity Contours
(Blue = $-8ms^{-1}$, Red = $+1ms^{-1}$)





Structural Model:

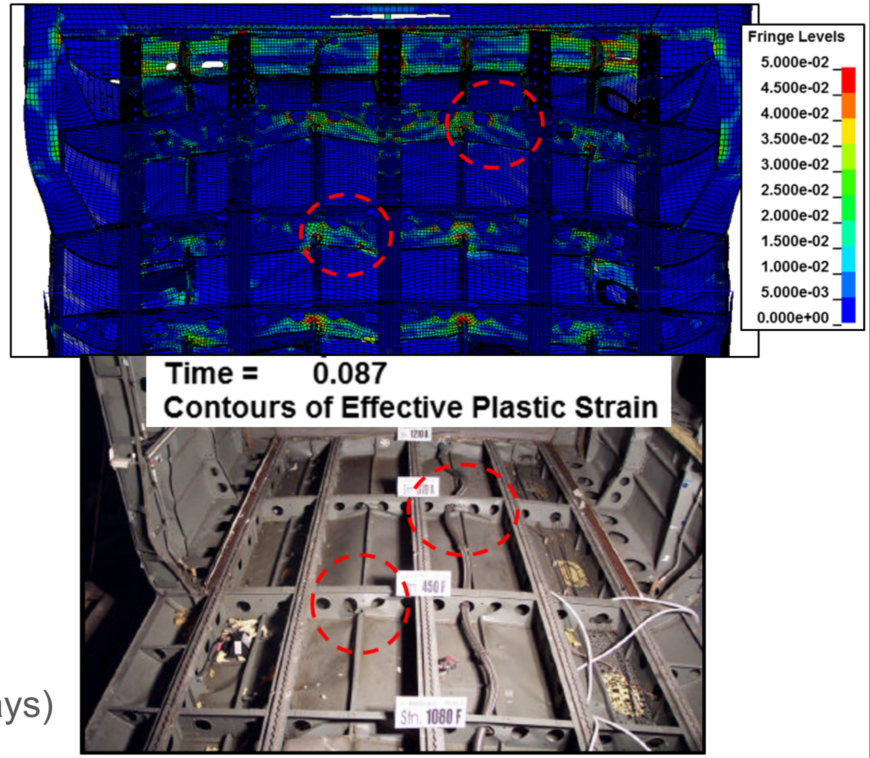
- 366,194 shell elements
- 5,206 beam elements

SPH Model

- 292,800 SPH particles
- Ran to 87ms in 5 days on 8CPUs

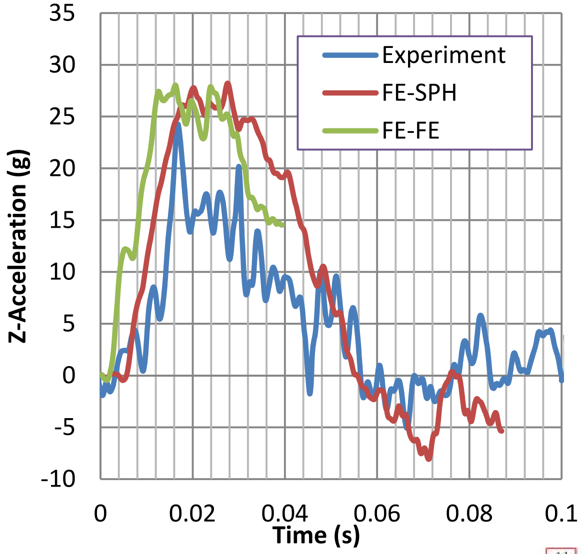
FE Model

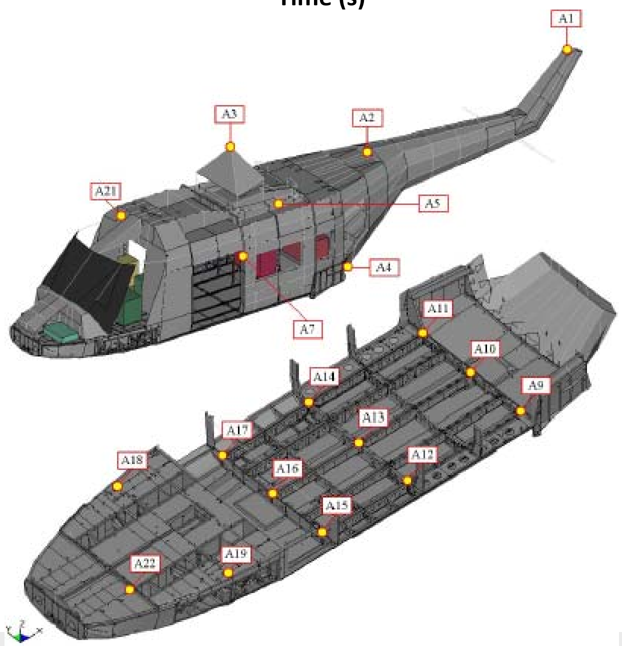
- 234,845 solid elements
- Ran to ~40ms (negative volume) in 16 CPUs (3.5 days)



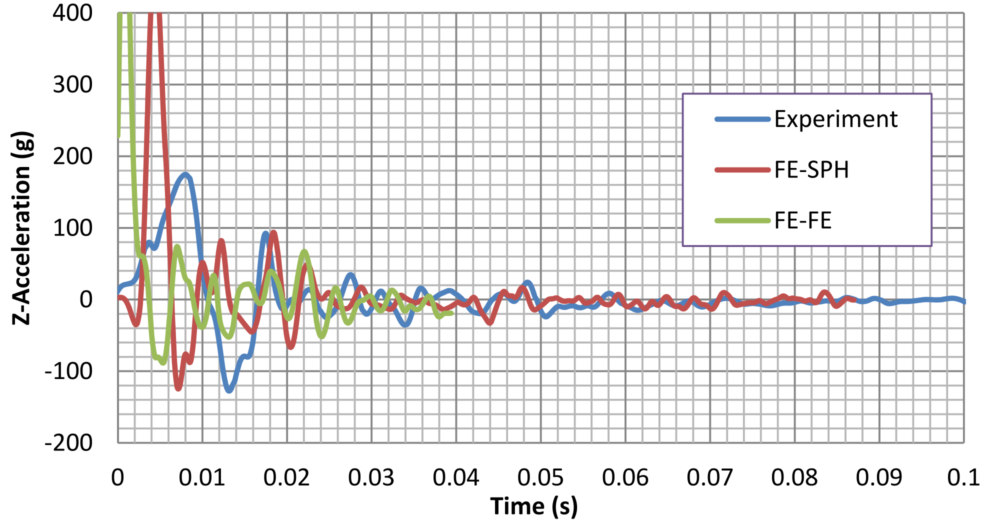
Accelerometers

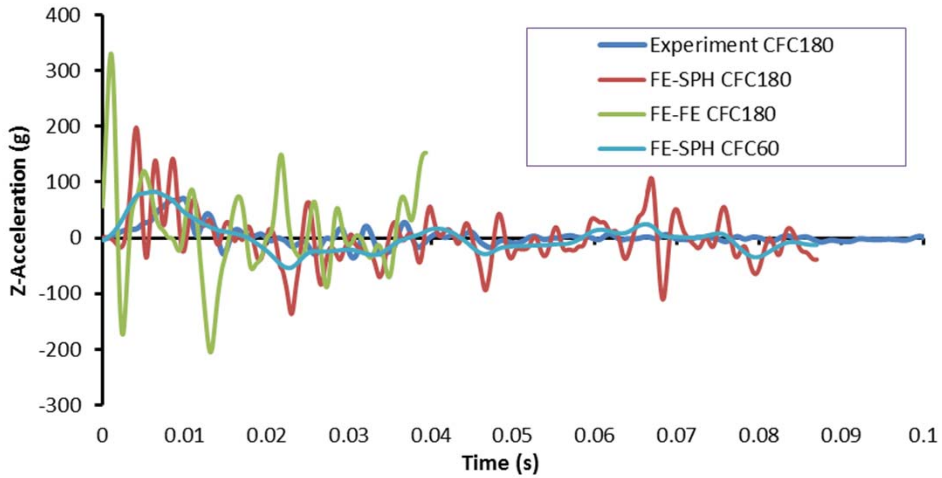
A3





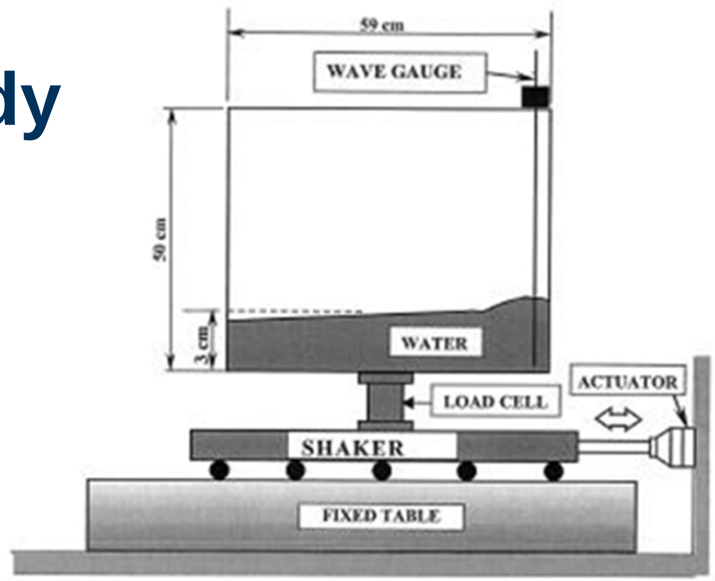
A13- centre seat rail





A17 – starboard seat rail

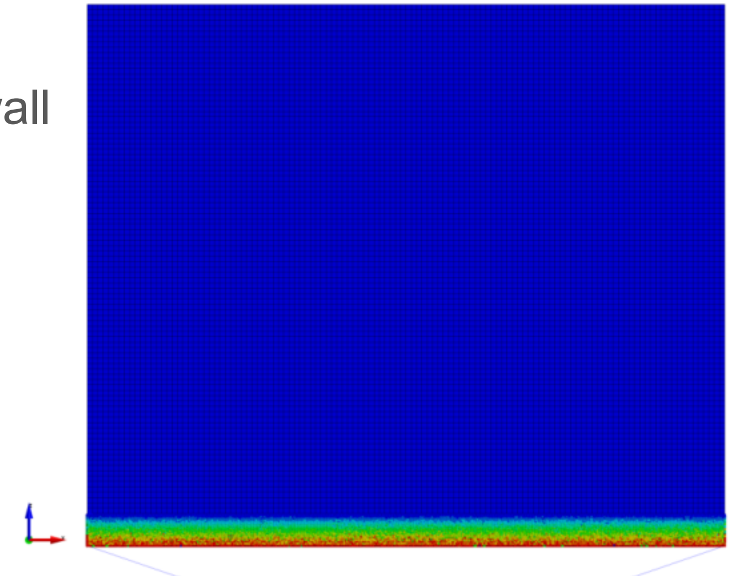
Sloshing Validation Case Study



Undeformable tank

- Excitation amplitude = 0.02m
- Excitation Frequency = 0.458 Hz
- Water depth = 0.03m
- Test duration = 12s

- Normalised wave height at centre and tank wall
- Reaction force at load cell
- Dynamic Relaxation -> Pressure distribution



H. Yeh, J. Yu, S. Gardarsson D. Reed, "*Tuned Liquid Dampers Under Large Amplitude Excitation*," Journal of Engineering Mechanics, vol. 124, 1998.

Sloshing Validation Case Study

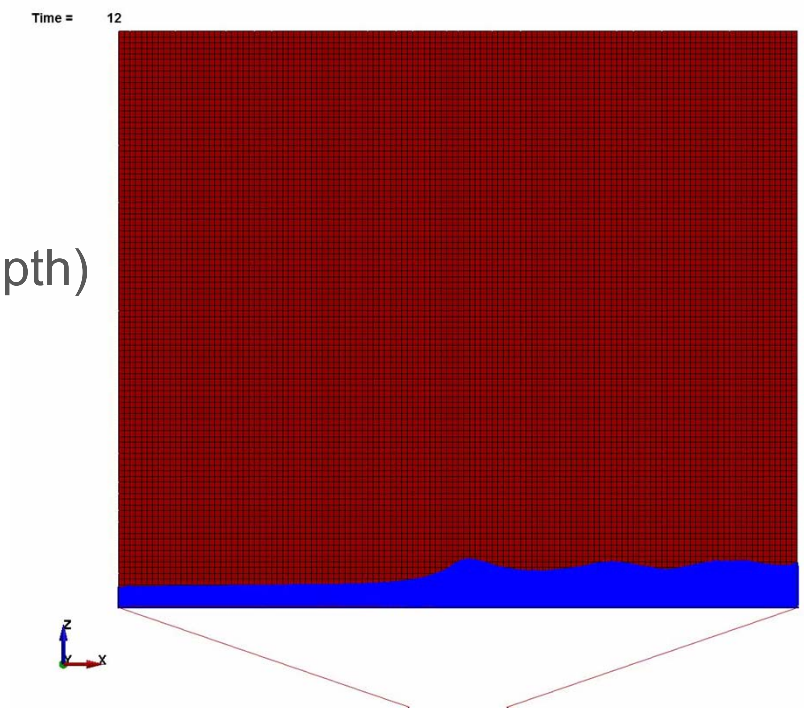
2D SPH model:

- SPH for tank and fluid (~13K particles)
- Quasi-incompressible viscous fluid
- Particle-to-particle contact
- Pressure initialisation (dynamic relaxation)
- 5 SPH particles in tank thickness

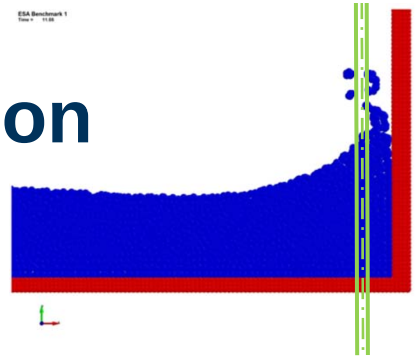
- Parametric Studies performed:
  - Spatial Resolution (20-50 particles depth)
  - Artificial Viscosity
  - Density Calculation (MLS)
  - Contact Stiffness
  - Wave Height Sensor location

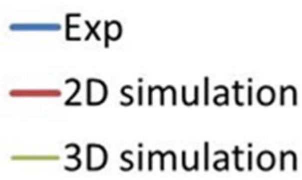
3D FE-SPH model:

- Box modelled with FE
- Particle-to-surface contact
- 12 days on standard pc

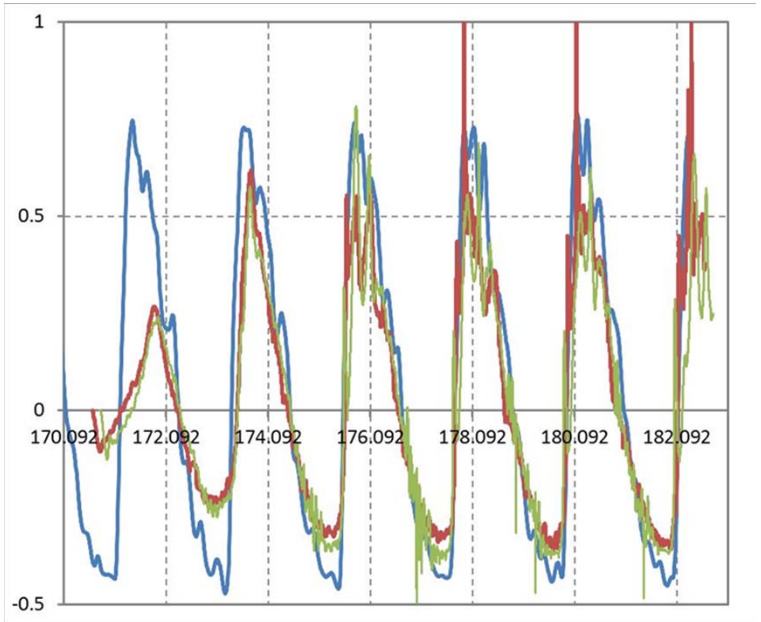


Test – Analysis comparison
- Wave Height

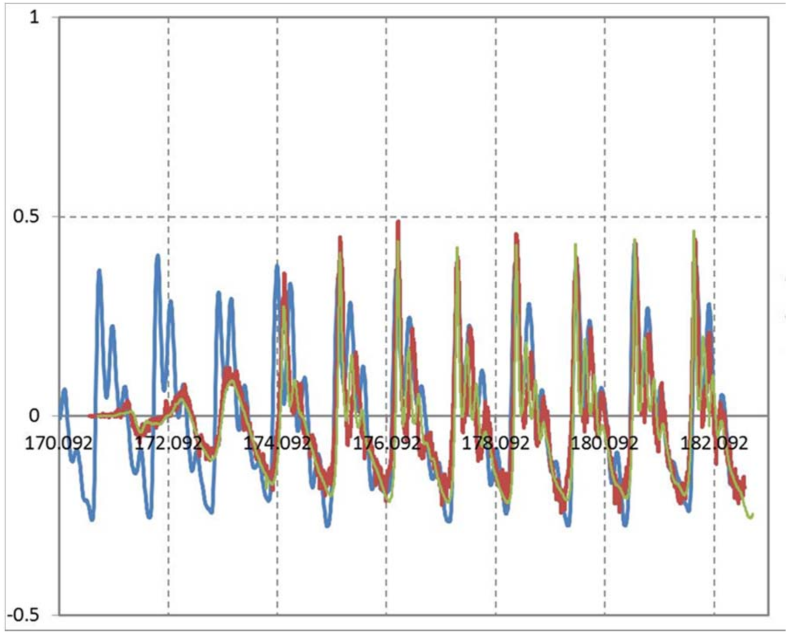




a) tank wall

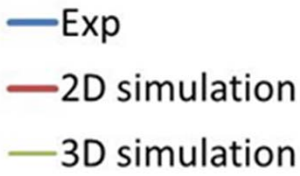


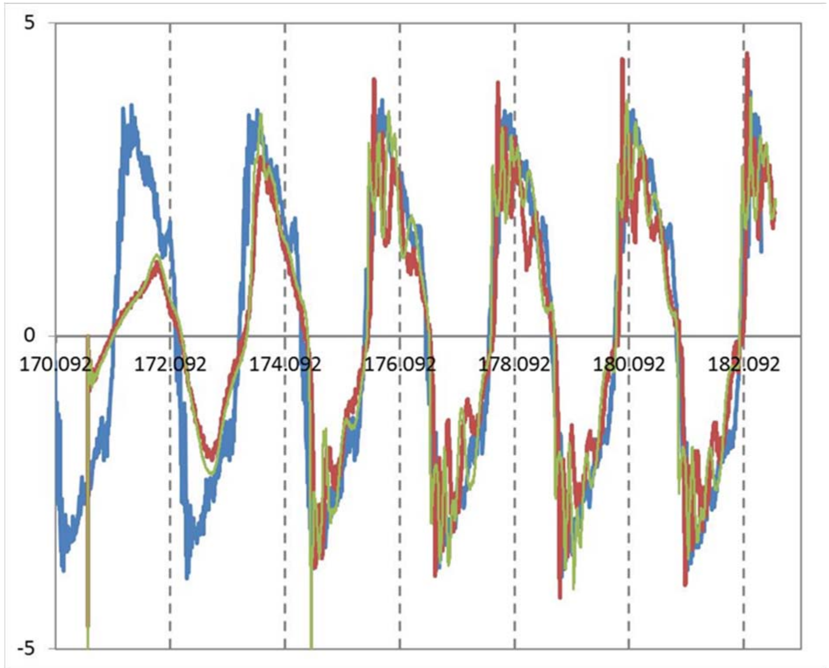
b) tank centre

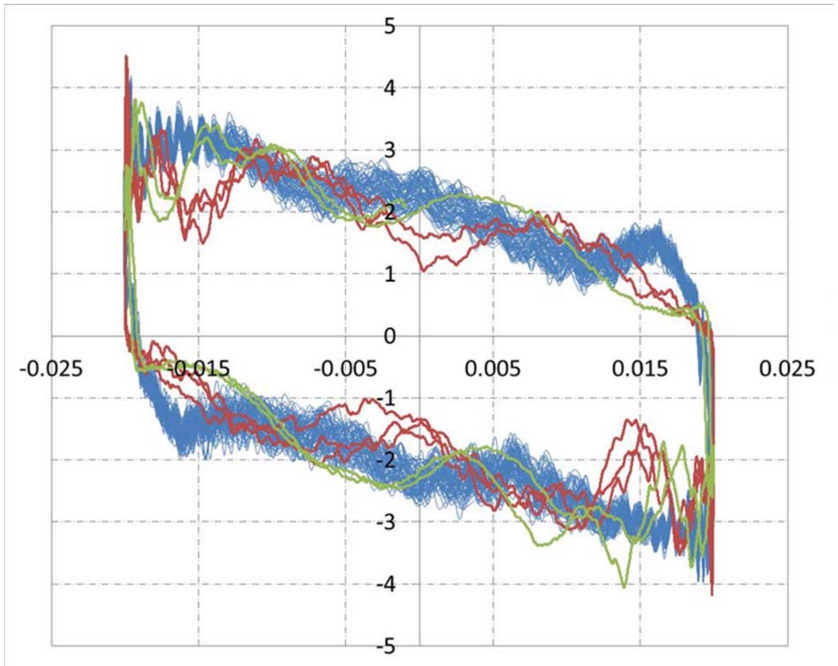


- (CAVEAT: No information on filtering applied in test, or positioning of wave sensor location).
- Wave heights near tank wall are far less pronounced for 3D results (fewer isolated particles “flying off”), and attributed to differences in contact algorithm and end constraints.

Test – Analysis comparison
- Sloshing force







The magnitude, frequency of the waves (and forces) against time and tank displacement is captured accurately

Summary

- Coupling a meshless fluid model to a finite element structural model provides a powerful approach in simulating complex fluid-structure interaction problems.

- Permits investigations into predicting free surface motion and removes issues of (mesh) instabilities, but models are computationally expensive

- For sloshing, coupled approach is capable of accurately predicting fluid motion / time histories

- Further work required for impact cases, as divergence between test could be due to:
  - Limitations in structural model (->need for non-linear behaviour under dynamic fluid loads)
  - Limitations in fluid modelling (is Physics represented correctly?)
  - (Or a combination of both effects!)
  - Reliability / repeatability issues in capturing high, amplitude pressures
    - Van Nuffel et al, “Study on the Parameters Influencing the Accuracy and Reproducibility of Dynamic Pressure Measurements at the Surface of a Rigid Body During Water Impact”, Experimental Mechanics 53(12), 2012