# Towards Reliable Nonlinear Simulations of WECs Using CFD

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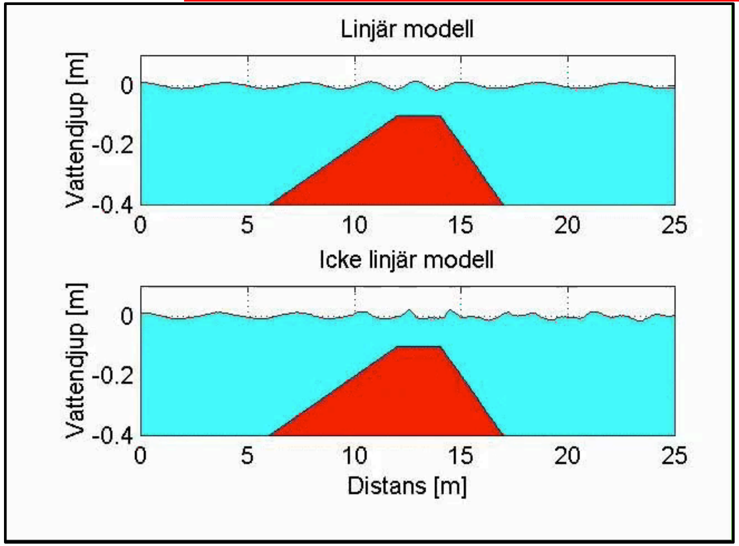
# Hydrodynamic nonlinearity?!

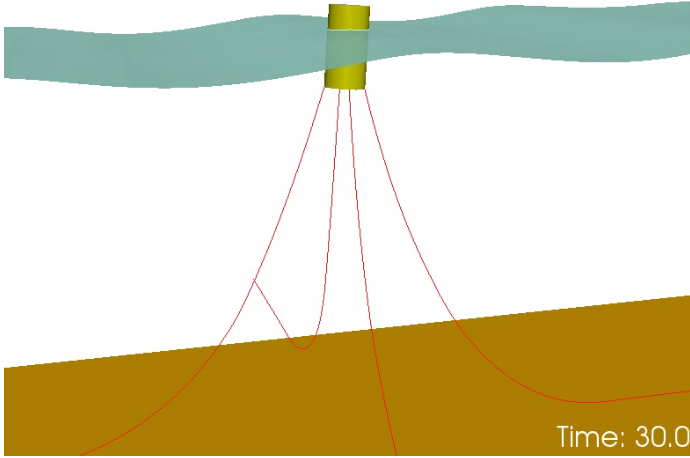
- “No longer a 1:1 mapping between incoming wave amplitude and response”
- Nonlinear terms are responsible for transfer of energy between different wave harmonics
- Important for wave run-up, shoaling, wave-to-wave interaction, side-band instabilities, etc

Shoaling transfer energy to bound higher harmonics causing peaking of the waves. On the top of the shoal the bound higher harmonics are released as free waves, giving a complicated interference pattern. This is missed by the linear wave theory.



# Coupled analysis of moored WEC using CFD

- OpenFOAM: CFD solver (incompressible Navier-Stokes + 6DoF solver)
- MooDy: in-house high-order DG mooring solver
- Swedish Energy Agency supports a project on:
  - Validation & Verification – what is the uncertainty of the simulations?
  - Applications to WEC existing technology - CorPower buoy
  - (Quantifying nonlinear and viscous parts)
  - (Numerical development – efficiency)

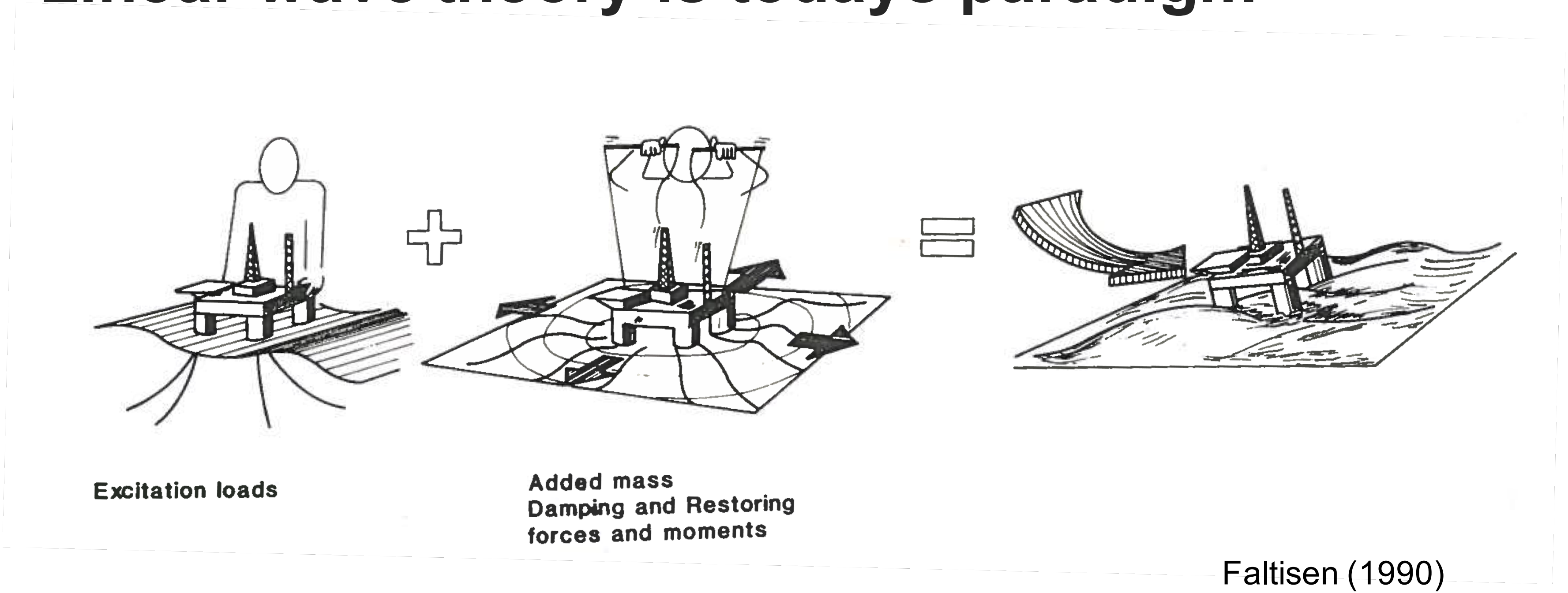



Palm et al (EWTEC 2013)

# Why include nonlinear terms in the simulations?

- "Better"/"more accurate"/"…" simulation methodologies lead to:
  - Increased confidence in the results obtained by numerical models
  - Reduced risk in technology development
  - Improved device energy capture estimates
  - Improved loads estimates
  - Reducing uncertainty in LCOE models

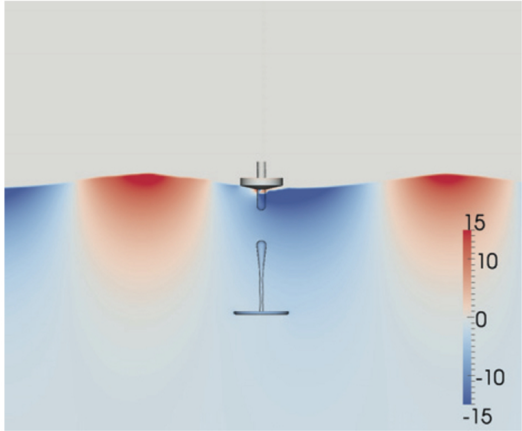
# Linear wave theory is todays paradigm

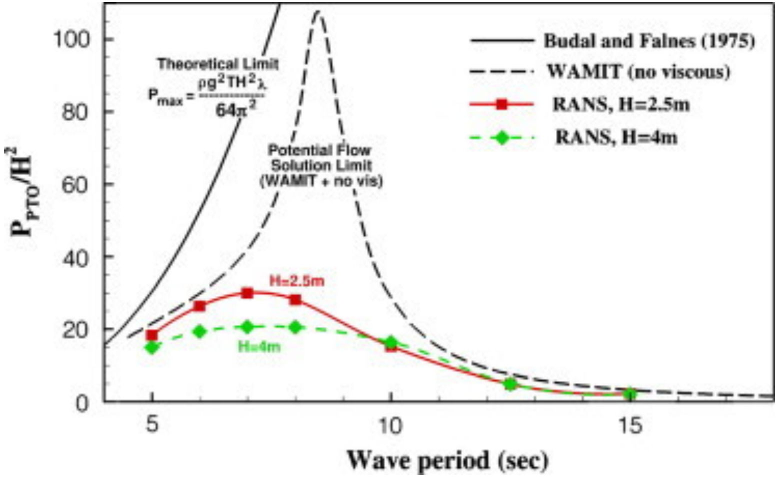



Faltisen (1990)

# Linear vs CFD simulations

Yu and Li simulated a heaving (1DoF) point absorber using CFD. The resulting power curve show not only a large difference compared to the linear potential (without drag) but also a difference due to wave steepness. There is not a 1:1 mapping




Yu & Li (CF 2013)

# Linear vs CFD simulations

## LINEAR

- **Small** amplitude assumption
- **Small** motion assumption (can be relaxed using nonlinear Froude-Krylov)
- Viscous terms not included but drag is parametrized
- Overtopping and green water can not be captured
- Some second-order effects are/can be include (e.g. drift, QTF, etc)
- Nonlinear source terms, e.g. mooring, be included
- **FAST** COMPUTATIONS

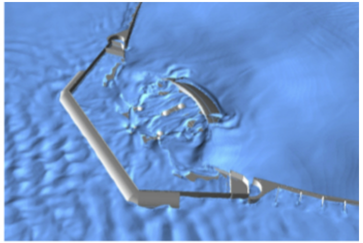
## CFD

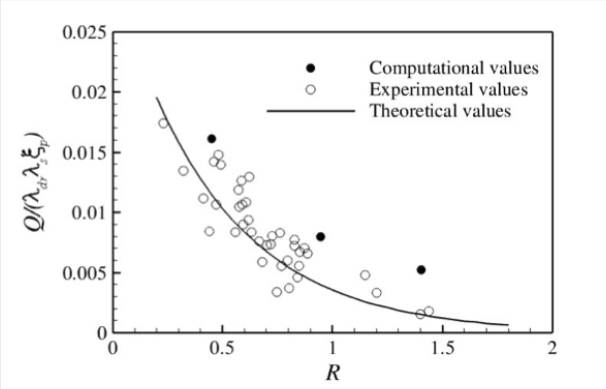
- **'All-inclusive'**
- Single fluid approximation
- Multiphase through (often) VOF
- Turbulence models
- **SLOW** COMPUTATIONS

Here FAST is in the order 10000-100000 times faster than SLOW...

# On the computational effort of CFD simulations

- Wave Dragon overtopping discharge
- 14M cells (using a symmetry mesh)
- Complete 3 hour sea state simulation: JONSWAP Hs=2m, Tp=7s
- Simulated values of overtopping discharge in the same order as observed values (note one set of phase angles)
- Approximate **150 000 CPU** hours per simulation

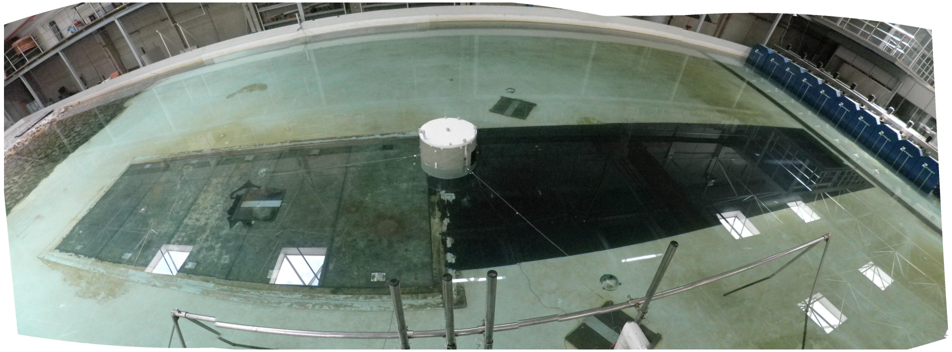


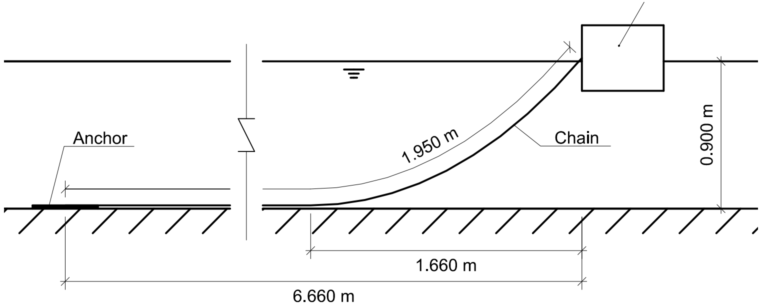



Eskilsson et al (RENEW 2015)

# Validation of the coupled CFD model

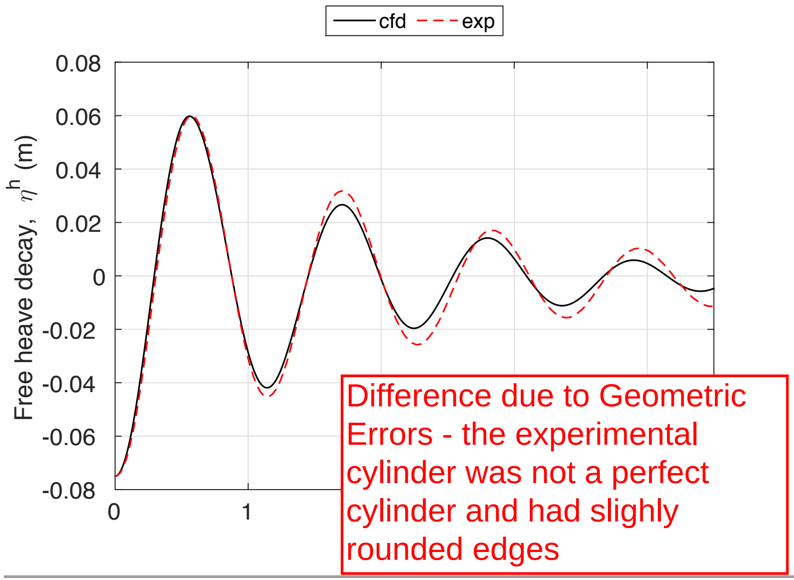
- Full study: Palm et al (IJOME 2016)
- Experimental data used: Paredes et al (IJOME 2016)
- Wave basin in Porto (d=0.9m)
- Moored generic cylinder (D=0.52m)
- No PTO
- Three catenary lines
- Part of a larger test suite



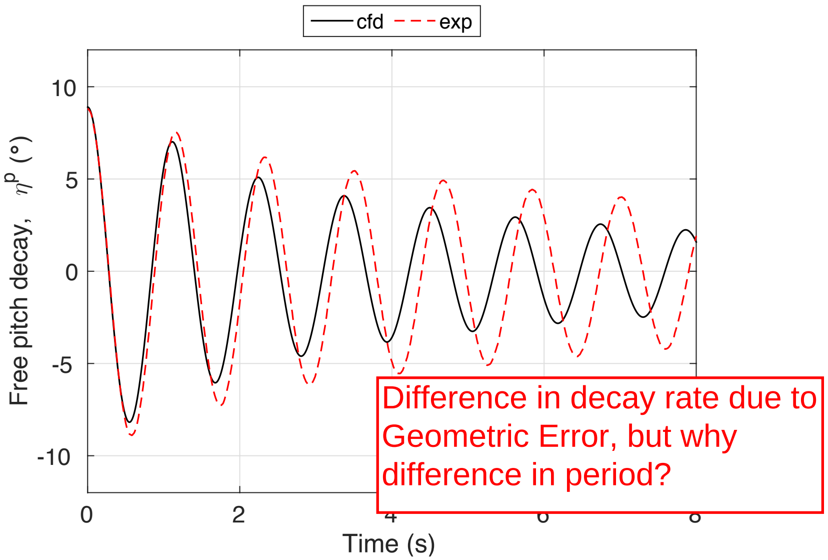


# Validation of the coupled model

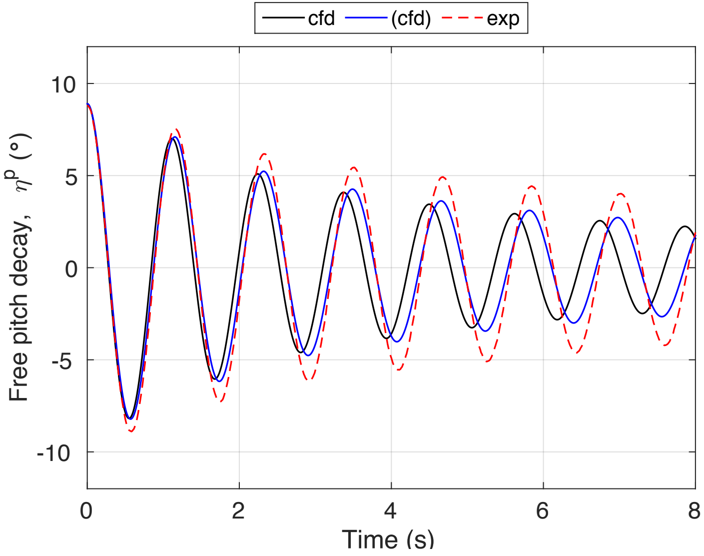
- Decay tests - Heave




- Decay tests – pitch: Problem!



# Validation of the coupled model



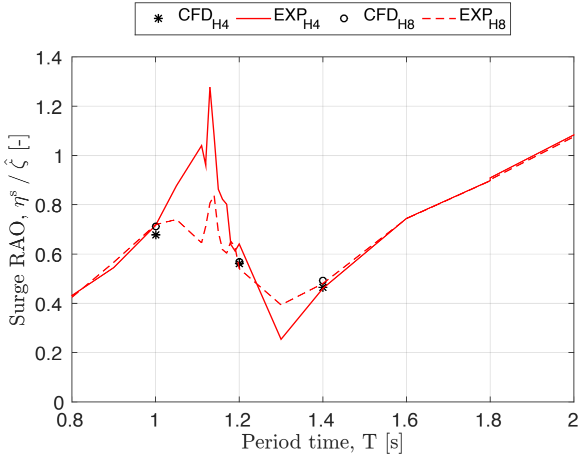

- Pitch very sensitive to input parameters
- Measurement uncertainty of draft, centre of gravity and inertial values.
- Sensitivity study:
  - Inertia + 0.03 kg m$^2$ (3%)
  - Centre of gravity +0.003 m (4%)

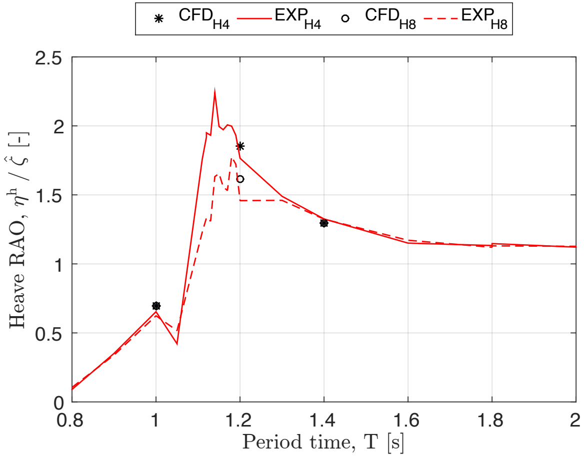
Varying  interia and CoG within the uncertainty limits of the measurements, we obtain a good fit with the  measured period. This highlights the need of high quality data for CFD validation

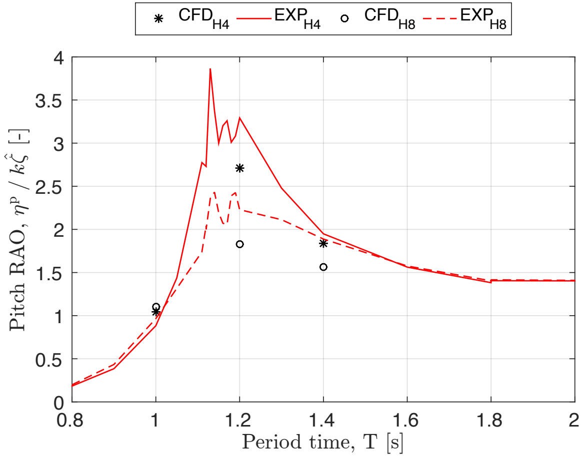
# Response amplitudes

- Good match in surge and heave
- Underestimated pitch response overall
- H4->H/L=0.02 and H8->H/L=0.04

Clear nonlinear effects in both experimental and computational results even for very weakly nonlinear waves!



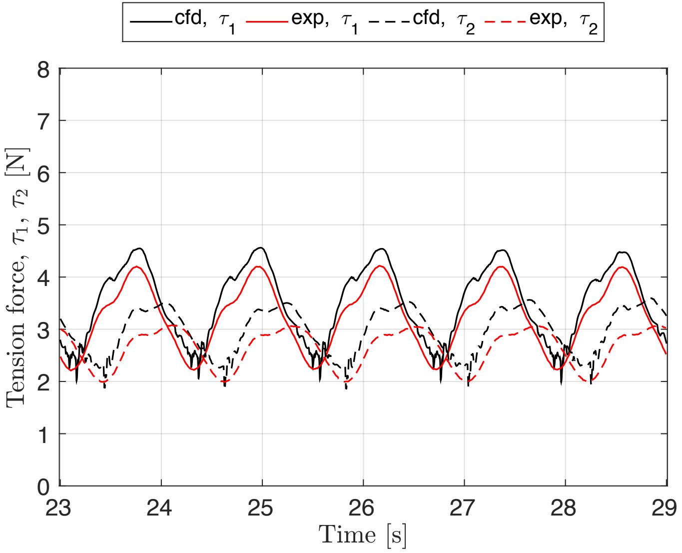



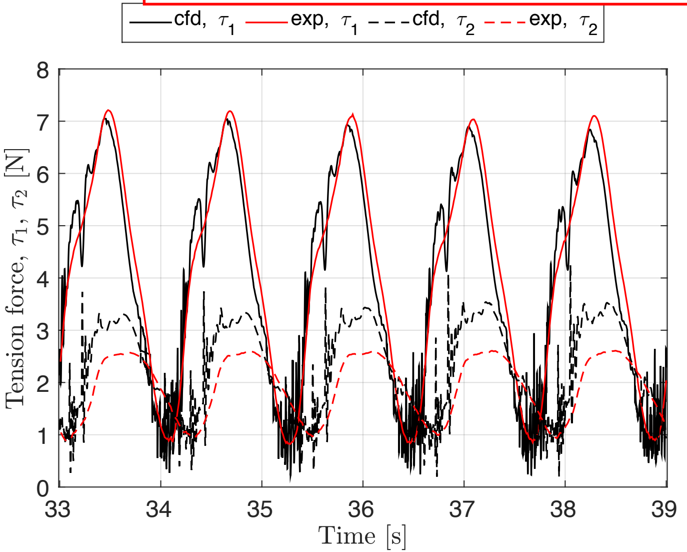



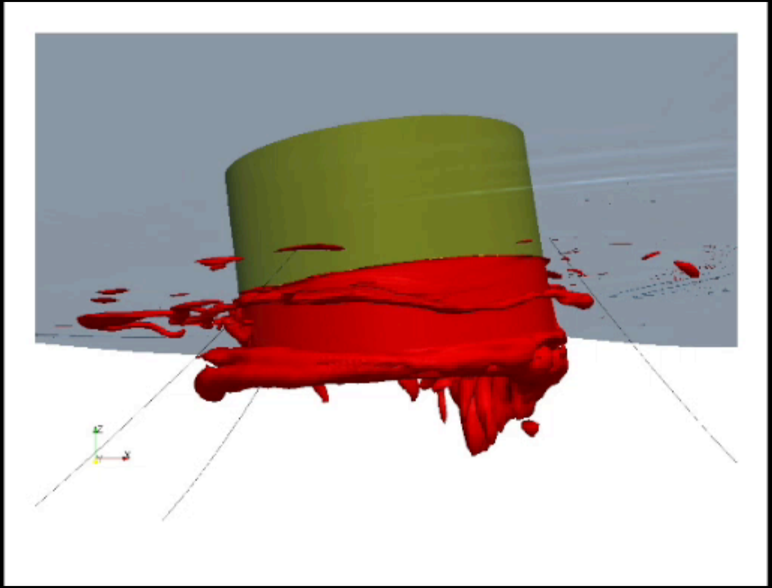
# Validation of the coupled model

The noice in the mooring force is due to the cable going slack and then the governing equation is ill-posed (as MooDy presently does not support bending). Please note that there is no filtering of these results

- Mooring forces in resonance (T=1.2s)



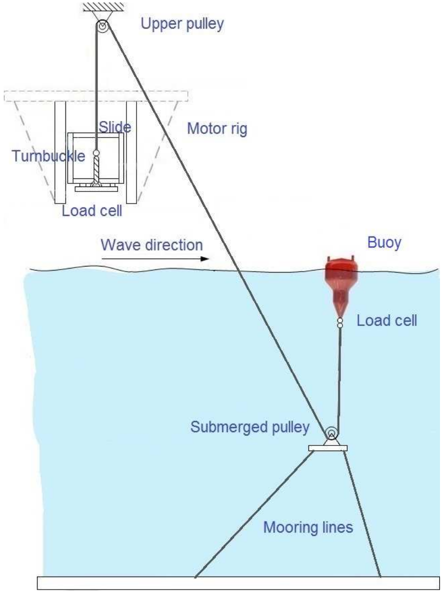



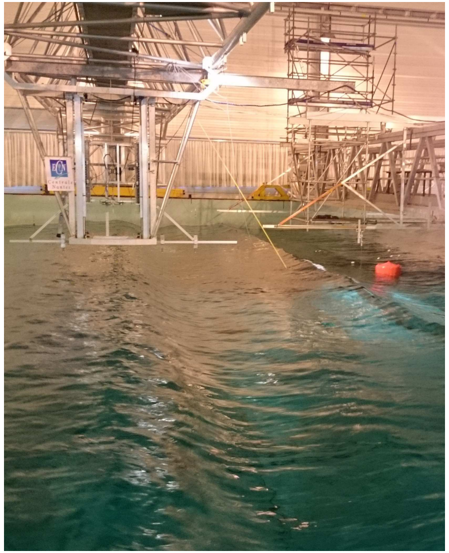


CFD offer so much more information of the fluid motion! Right now we only use CFD to extract motion/ forces on the body. We need to start utilizing all available data

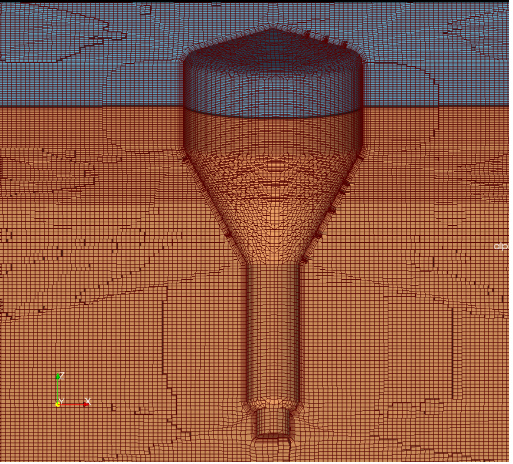
# Real-life application: CorPower buoy

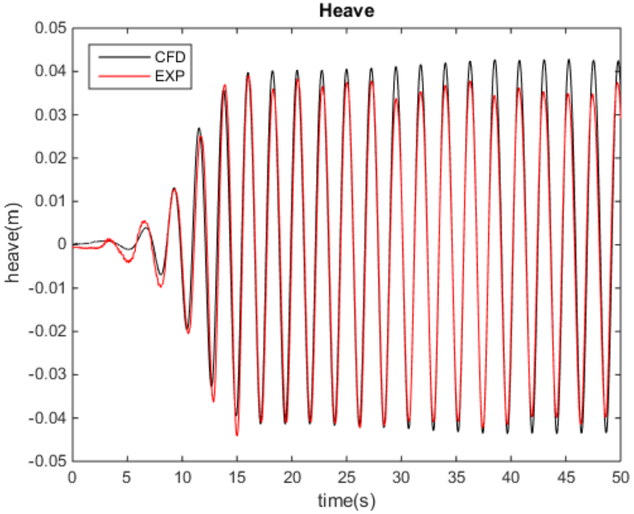
- Wu & Wang (MSc thesis, 2016)
- Experimental data: Hals et al (EWTEC 2015)
- Wave basin in Nantes
- 1:16 scale buoy
- PTO Linear damper
- No mooring – linear spring
- No WaveSpring yet…

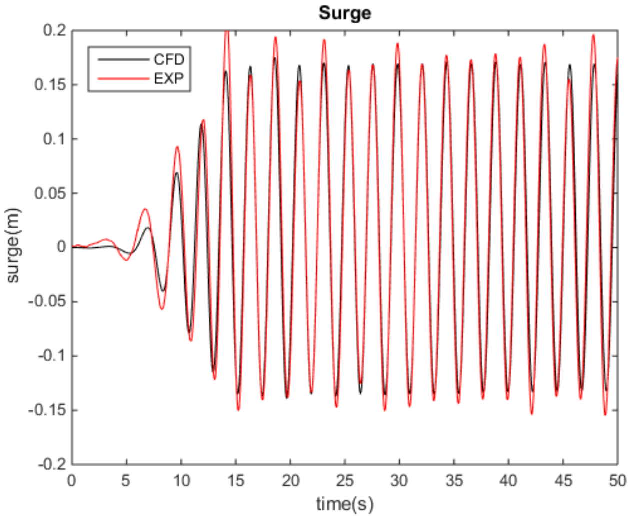


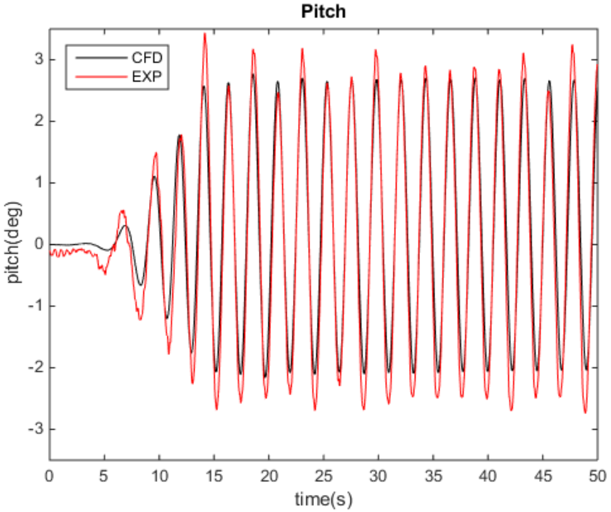
Hals et al (EWTEC 2015)

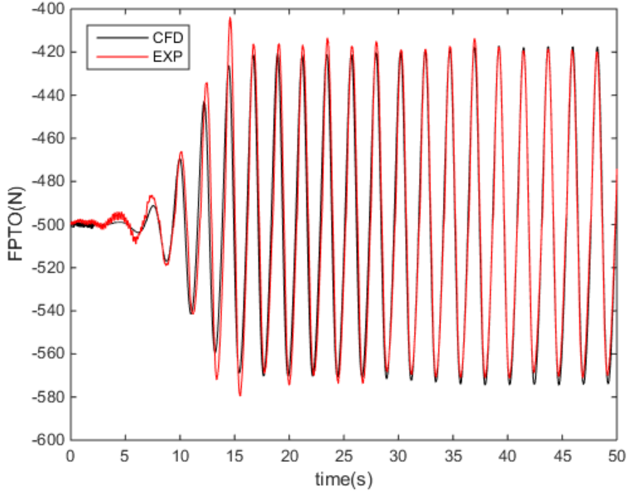





- 10M cells
- Regular waves
  T=2.25s
  H=15.6cm
  H/L=0.02
- Sensitive to pre-tension (3%)



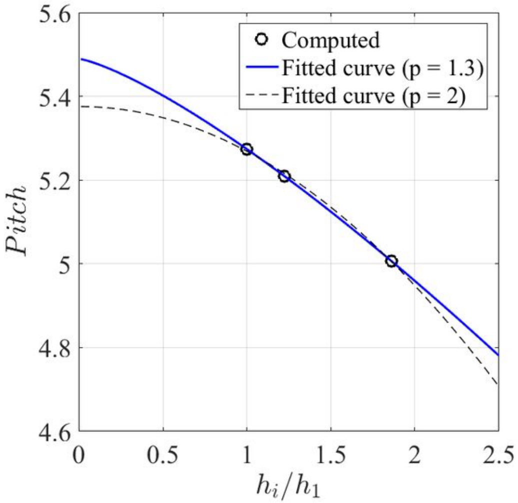



# Verification & Validation procedure

- Numerical uncertainty (Eça & Hoekstra, JCP 2014)
  - **Discretization error**
  - Iteration error (under evaluation)
- Modelling error (turbulence - ongoing)
- Geometry error (not performed)
- Domain error (done - no influence of width)

# Discretization error

| Number of cells | Surge response (-) | Heave responce (-) | Pitch responce (-) |
|---|---|---|---|
| 20M | 2.047436 | 0.525000 | 1.484474 |
| 10M | 2.025641 | 0.519231 | 1.466318 |
| 3M | 1.956410 | 0.503846 | 1.409064 |
| p (convergence) | 1.32 | 0.78 | 1.30 |
| h2/h1 | 1.223 | 1.223 | 1.223 |
| Error | -0.093 | -0.039 | -0.078 |
| Uncertainty | 11.6% | 5.0% | 9.9% |




- Uncertainty results for the 10M cell mesh in approximately 10%
- 10M results typically differ from 20M results by <2%

# Concluding remarks

# On validation data

"Many of the experimental comparisons made at this early stage are compromised, to some degree, by the fact that the objective of the experiments is something other than providing good data for CFD validation."

Wolgamot & Fitzgerald (IME, 2015)

- CFD sensitive to small variations in input data (CoG, pre-tension, etc) – need better information of indata
- Load cells especially problematic
- Needs uncertainty estimates also from experimental data

# On reliability of CFD results

- No tuning, no semi-empirical factors!
- **Clear nonlinear responses even for weakly nonlinear waves**
- "Decent" results compared to experimental data for several cases
- **CFD is not an easy fix!**
- Numerical uncertainties shown to be unacceptable large for our test case (~10%)
- **Need to get estimates of computational uncertainty in order to judge simulation results**
- Sensitive to input data: Need to start looking into how random inputs propagate through the nonlinear system -> **uncertainty quantification**

An example of uncertainty quantification of wave propagation. The tools are today fast enough to support propagating random inputs through the complete nonlinear system

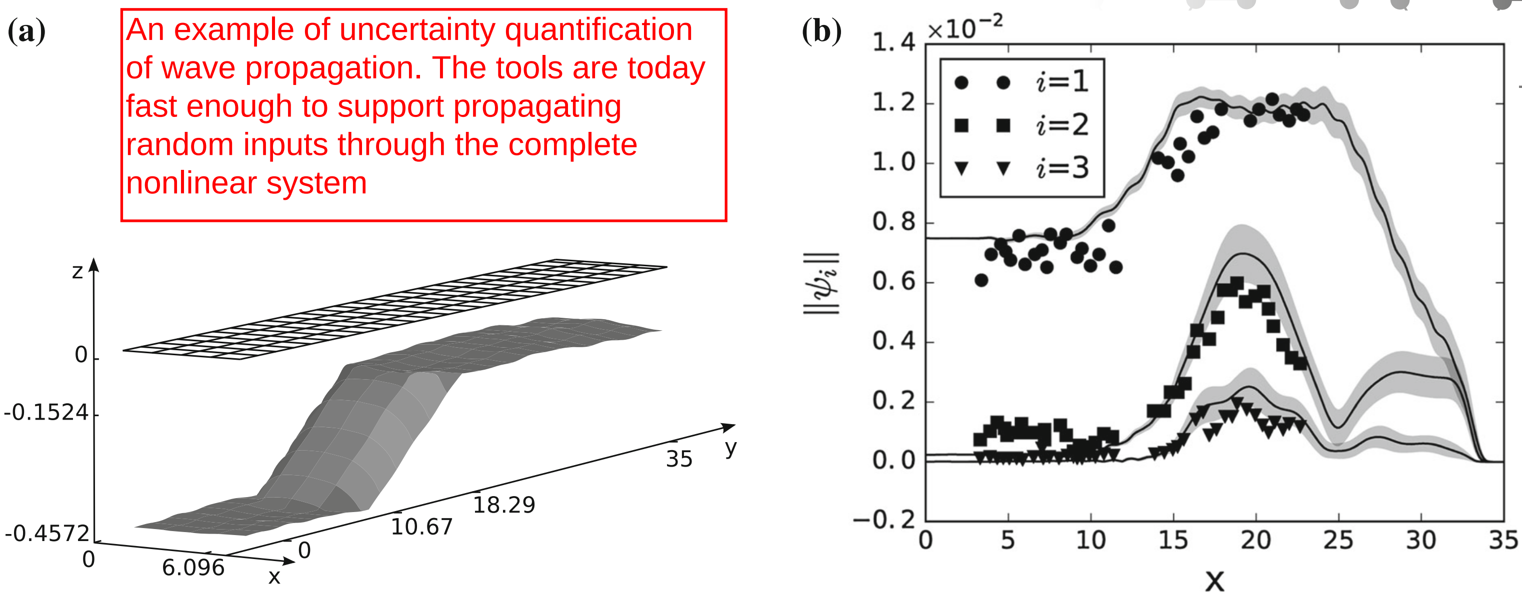



**Fig. 15** Experimental setting accounting for uncertainty on the bottom topography and solution of the wave propagation in three dimensions over a semicircular shoal. **a** Realization from the Gaussian random field with correlation length $a = 10.0$ describing the uncertain bottom topography. **b** Mean and 95 % tolerance interval of first three harmonics of numerical solution (*full lines*), compared with the corresponding experimental measurements at different longitudinal locations in the basin (*dots*)

Bigoni et al (JEM, 2016)

# On efficiency of nonlinear computations

- Heavy computations, but doable!
- AMR will be very useful in cutting down CPU time
- Hybrid nonlinear models appearing (FNPF-farfield/VOF-nearfield)
- Medium-fidelity nonlinear models (FNPF/asymptotic)
- Higher-order methods offering efficient methods for wave propagation problems

CFD is not for operational or fatigue computations - but for survival cases CFD can be used

For operational/fatigue/ optimization new models including nonlinearity are under development

Important if larger areas are to be investigated. This is why high-order methods are frequently used in numerical weather prediction.

# An unstructured spectral element method for fully nonlinear potential flow

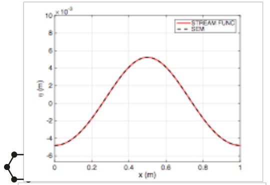



Table 1. Error and convergence rate in the $L_2$ norm for the free surface elevation. $H/L = 0.1\ (H/L)_{max}$.

| | $h$=1/4 | $h$=1/8 | | $h$=1/16 | |
|---|---|---|---|---|---|
| $p$ | Error | Error | Order | Error | Order |
| 4 | 2.42E-06 | 1.90E-07 | 3.67 | 1.58E-08 | 3.59 |
| 5 | 2.22E-07 | 1.29E-08 | 4.11 | 5.36E-10 | 4.59 |

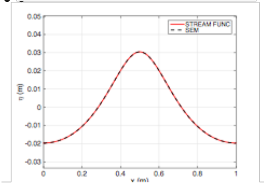



Table 2. Error and convergence rate in the $L_2$ norm for the free surface elevation. $H/L = 0.5\ (H/L)_{max}$.

| | $h$=1/8 | $h$=1/16 | | $h$=1/32 | |
|---|---|---|---|---|---|
| $p$ | Error | Error | Order | Error | Order |
| 4 | 3.82E-05 | 3.57E-06 | 3.42 | 2.17E-07 | 4.04 |
| 5 | 2.86E-06 | 1.76E-07 | 4.02 | 4.48E-09 | 5.30 |

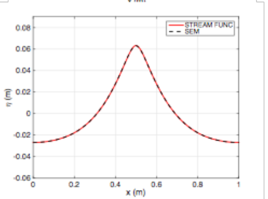
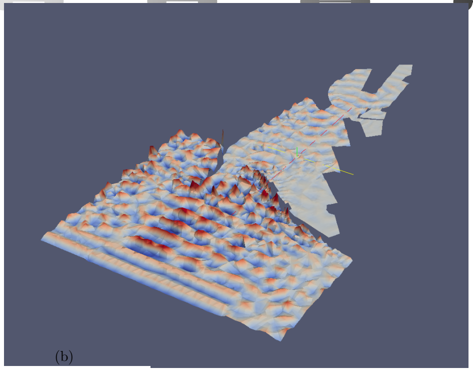
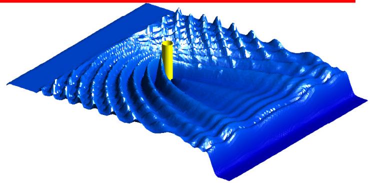


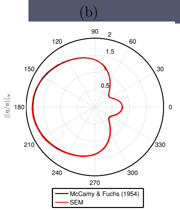

Table 3. Error and convergence rate in the $L_2$ norm for the free surface elevation. $H/L = 0.9\ (H/L)_{max}$.

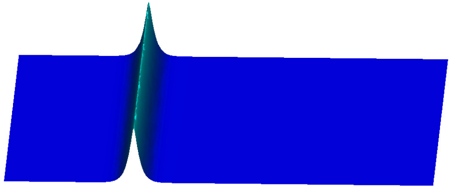
| | $h$=1/16 | $h$=1/32 | | $h$=1/64 | |
|---|---|---|---|---|---|
| $p$ | Error | Error | Order | Error | Order |
| 4 | 8.68E-04 | 1.80E-04 | 2.27 | 7.19E-06 | 4.65 |
| 5 | 5.14E-04 | 2.51E-05 | 4.36 | 2.06E-06 | 3.61 |

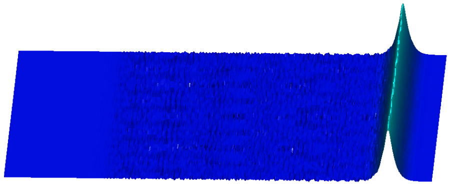
Example of on-going development of high-order finite element methods for computing wave propagation (including very steep waves)







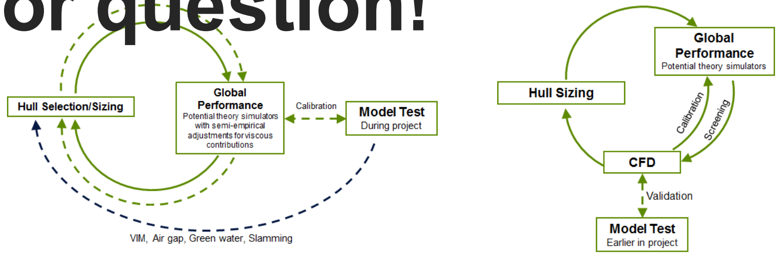


Engsig-Karup et al (JCP, 2016)

Engsig-Karup et al (ISOPE, 2016)

# This is not an either/or question!

- Integrate CFD in the design loop to replace experimental tests
- Drag coefficients from CFD
- Survival cases
- Hybrid simulations
- Overtopping
- Multi-fidelity optimization
- Nonlinear black-boxes




(a) Existing Design Spiral (b) New Design Spiral with CFD

**Figure 1 Design Spirals of Offshore Floater Design**

Kim et al (OS, 2014)

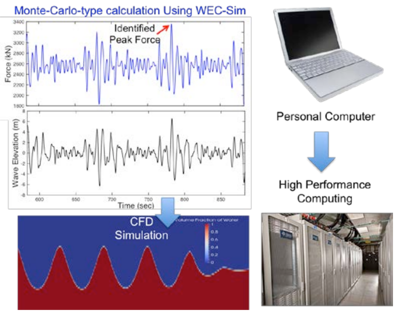



Figure 3. PROCESS CONCEPT FOR PREDICTING THE DESIGN LOAD.

Yu et al (OMAE, 2015)