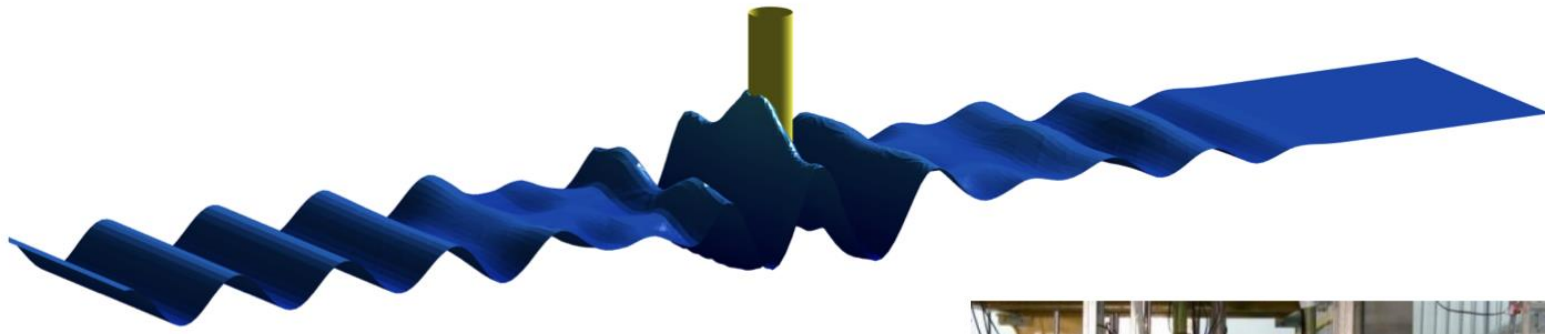
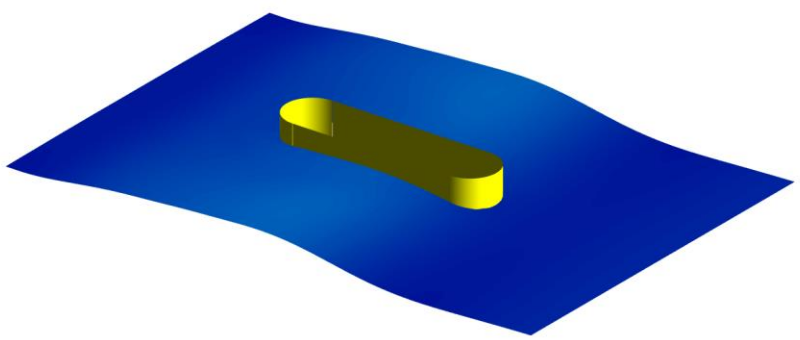
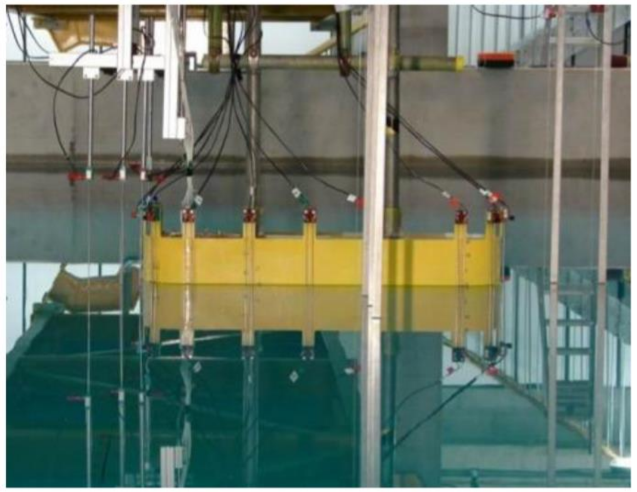
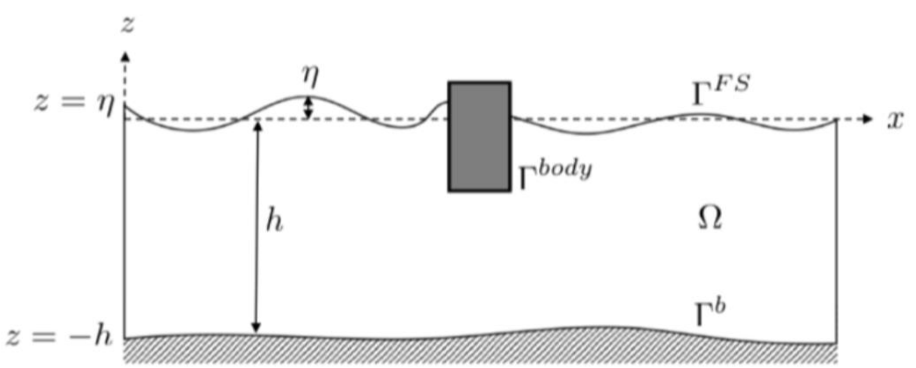
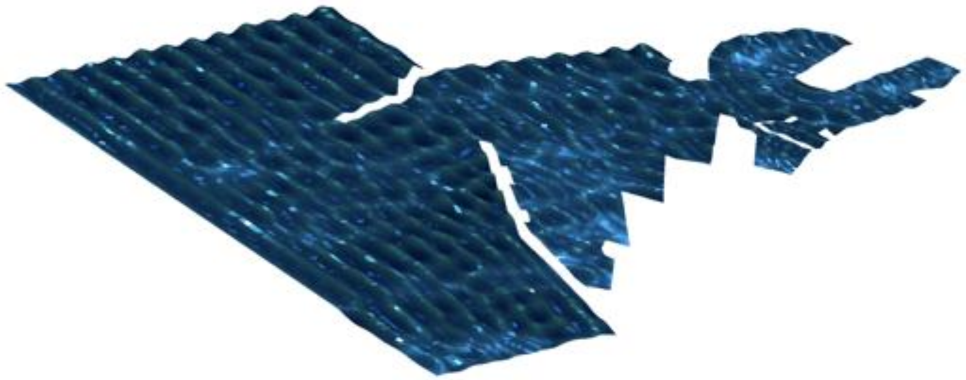
Advances and challenges in hydrodynamic simulation methods (Scientific computing perspective)











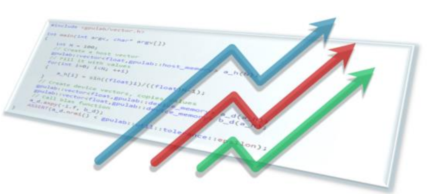
Wind Energy Denmark, October 2018, Hedensted.

Allan Peter Engsig-Karup (apek@dtu.dk)
Associate Professor, Scientific Computing
Department of Applied Mathematics and Computer Science
Center For Energy Resources Engineering (CERE)
Technical University of Denmark

DTU

DTU Compute
Department of Applied Mathematics and Computer Science

GPUlab
DTU Compute

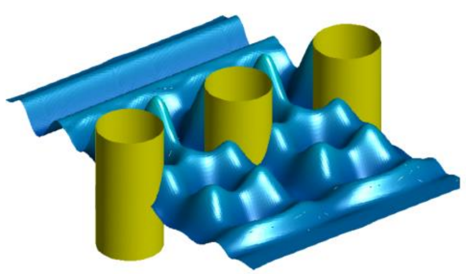


Scientific Computing Research

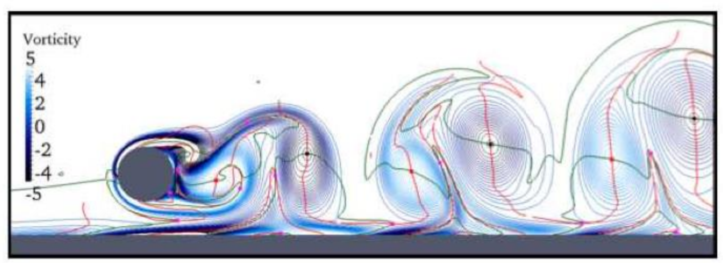
Research interest(s) and focus areas 2003-today: **novel tools!**

- ✦ Advanced (high-order) **numerical algorithms** and **analysis** of dynamical systems
- ✦ **High-performance computing**: massive parallelism and massive scalability
- ✦ **Simulation** techniques and modern **compute technologies** for acceleration
- ✦ **Mathematical analysis, theory** and **techniques**
- ✦ **Education** of large number of students in modern Scientific Computing

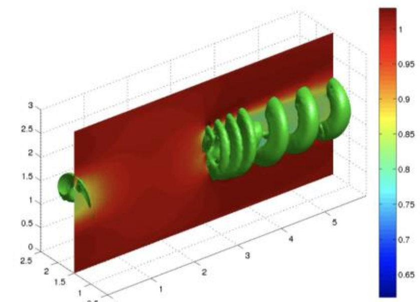
*Numerical **model-based simulation** increasingly important for cost-efficient engineering analysis and optimised design.*



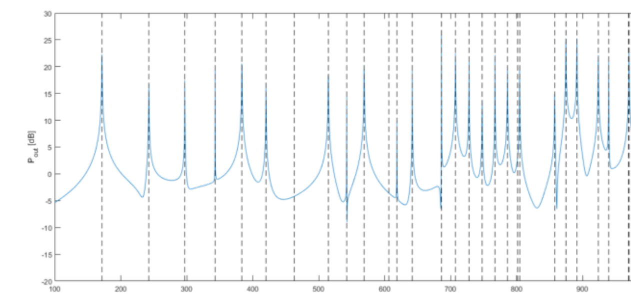
Wave scattering using Spectral Element Methods



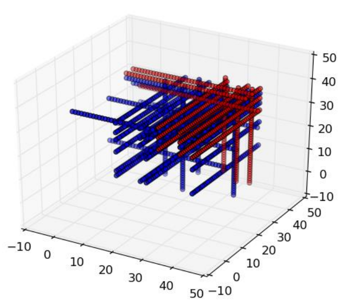
Vorticity generation using CFD based on Spectral Element Methods



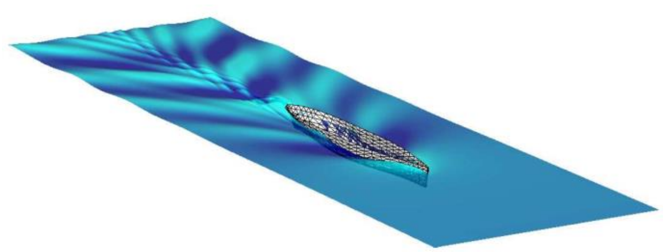
Wind turbine LES CFD simulation using Pseudospectral methods



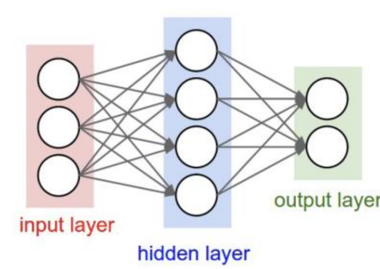
Room Acoustics using Spectral Element Methods



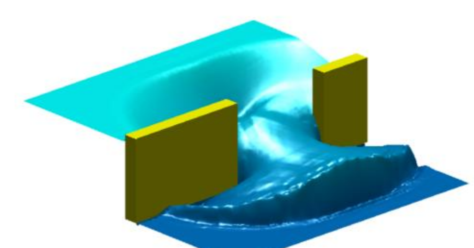
Scalable surrogate algorithms for Uncertainty Quantification



Seakeeping using high-order numerical methods



Machine Learning / Pattern Recognition



Nonlinear Hyperbolic PDEs using Spectral Element Methods

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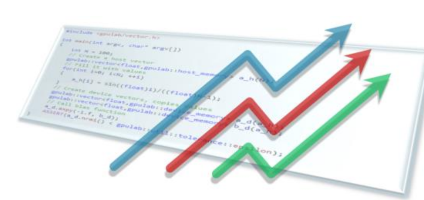
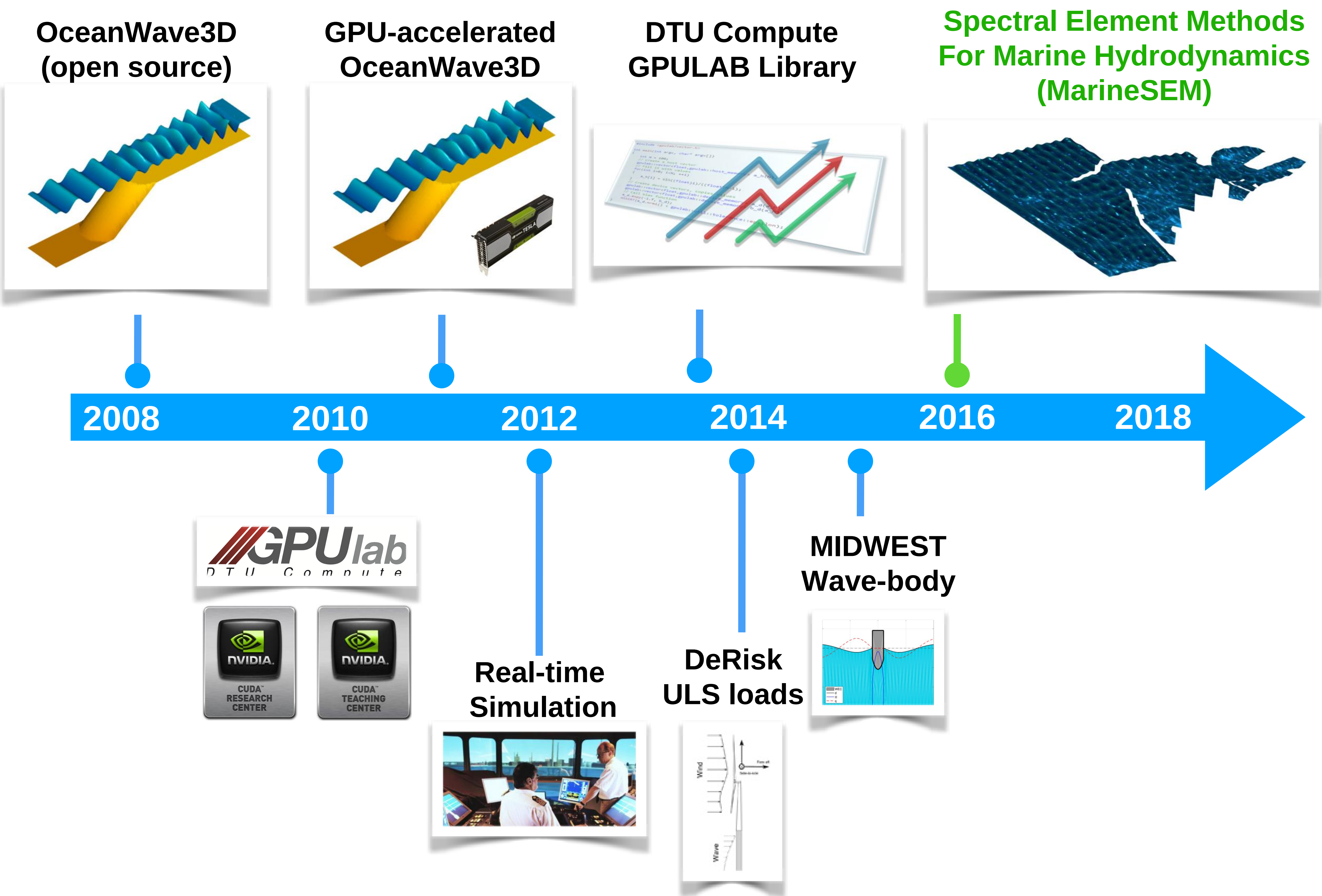


Research-based Innovation at DTU Compute

- through focus on scientific challenges



On the need for general-purpose hydrodynamic simulators for offshore sectors



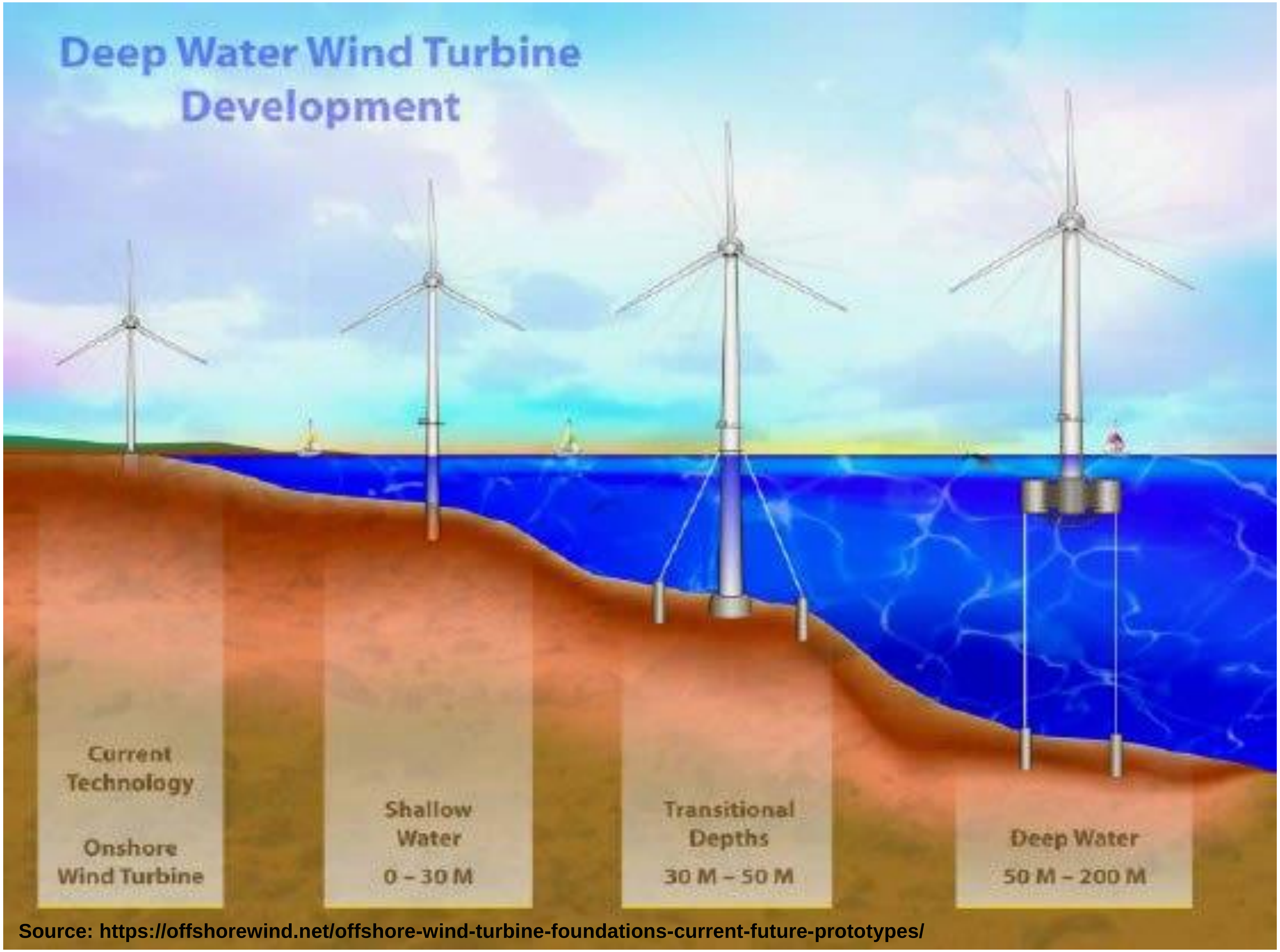



✦ Wave-impact loading on offshore marine structures and extreme/rare events.

✦ Influence on the bathymetry and marine structures of the sea state in near-coastal regions.

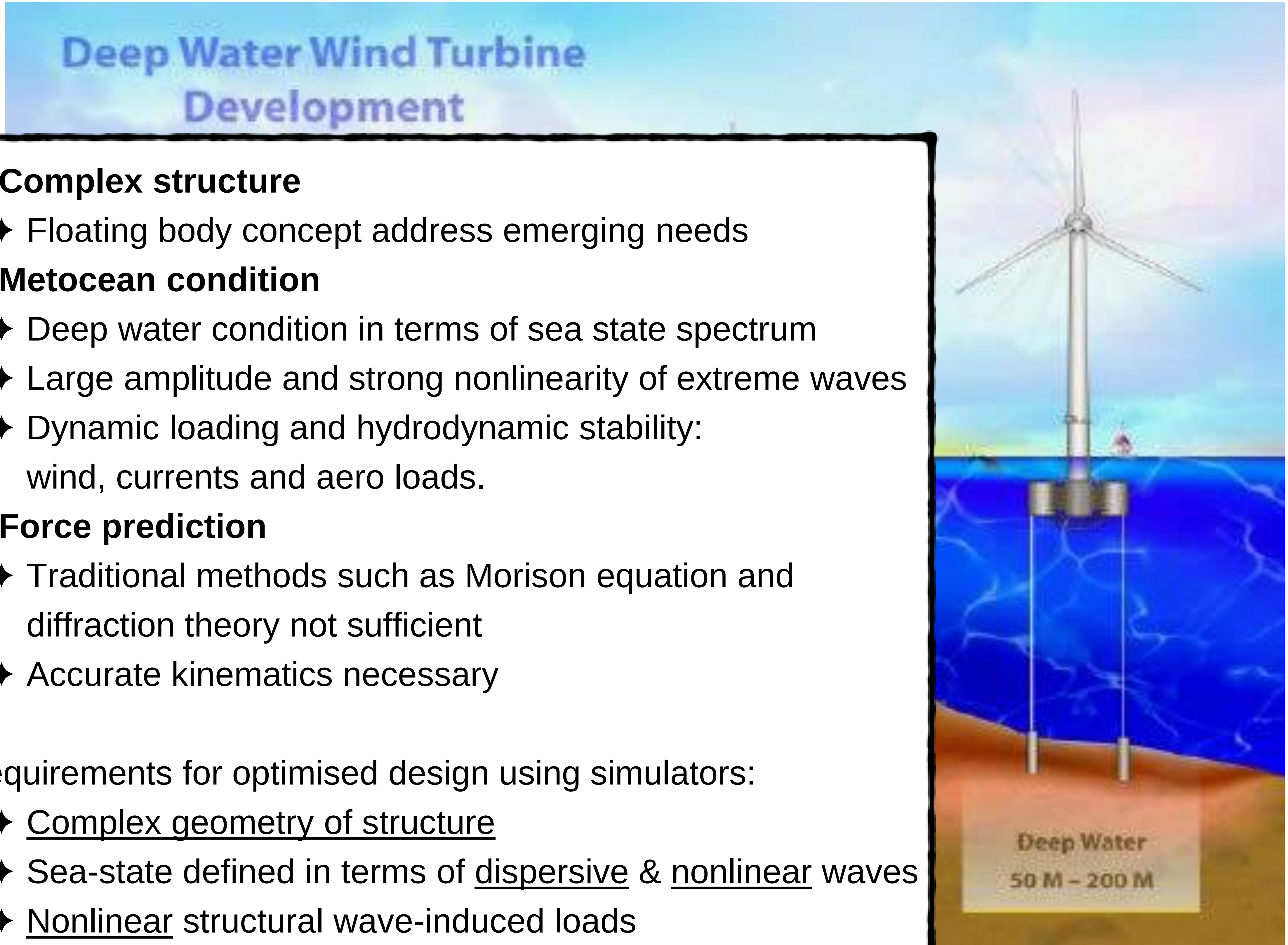
✦ Seakeeping performance, wave energy converters, floating production facilities, etc.

Deep Water Wind Turbine Development



✦ Wind turbines in production are moving from onshore to <u>offshore</u> for higher efficiency.

Deep Water Wind Turbine Development



- ✦ **Complex structure**
  - ✦ Floating body concept address emerging needs
- ✦ **Metocean condition**
  - ✦ Deep water condition in terms of sea state spectrum
  - ✦ Large amplitude and strong nonlinearity of extreme waves
  - ✦ Dynamic loading and hydrodynamic stability: wind, currents and aero loads.
- ✦ **Force prediction**
  - ✦ Traditional methods such as Morison equation and diffraction theory not sufficient
  - ✦ Accurate kinematics necessary

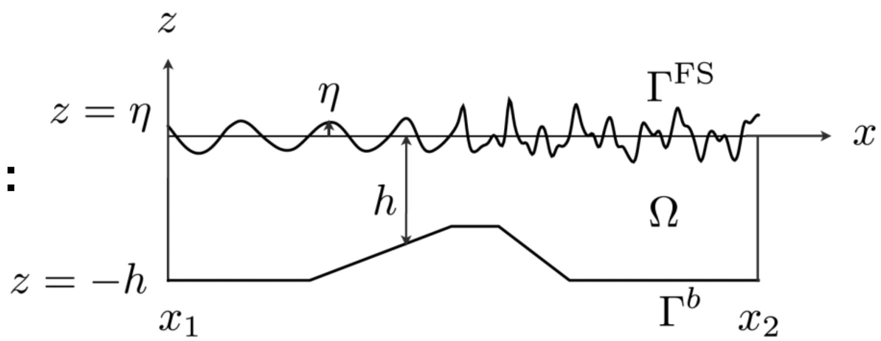
Requirements for optimised design using simulators:

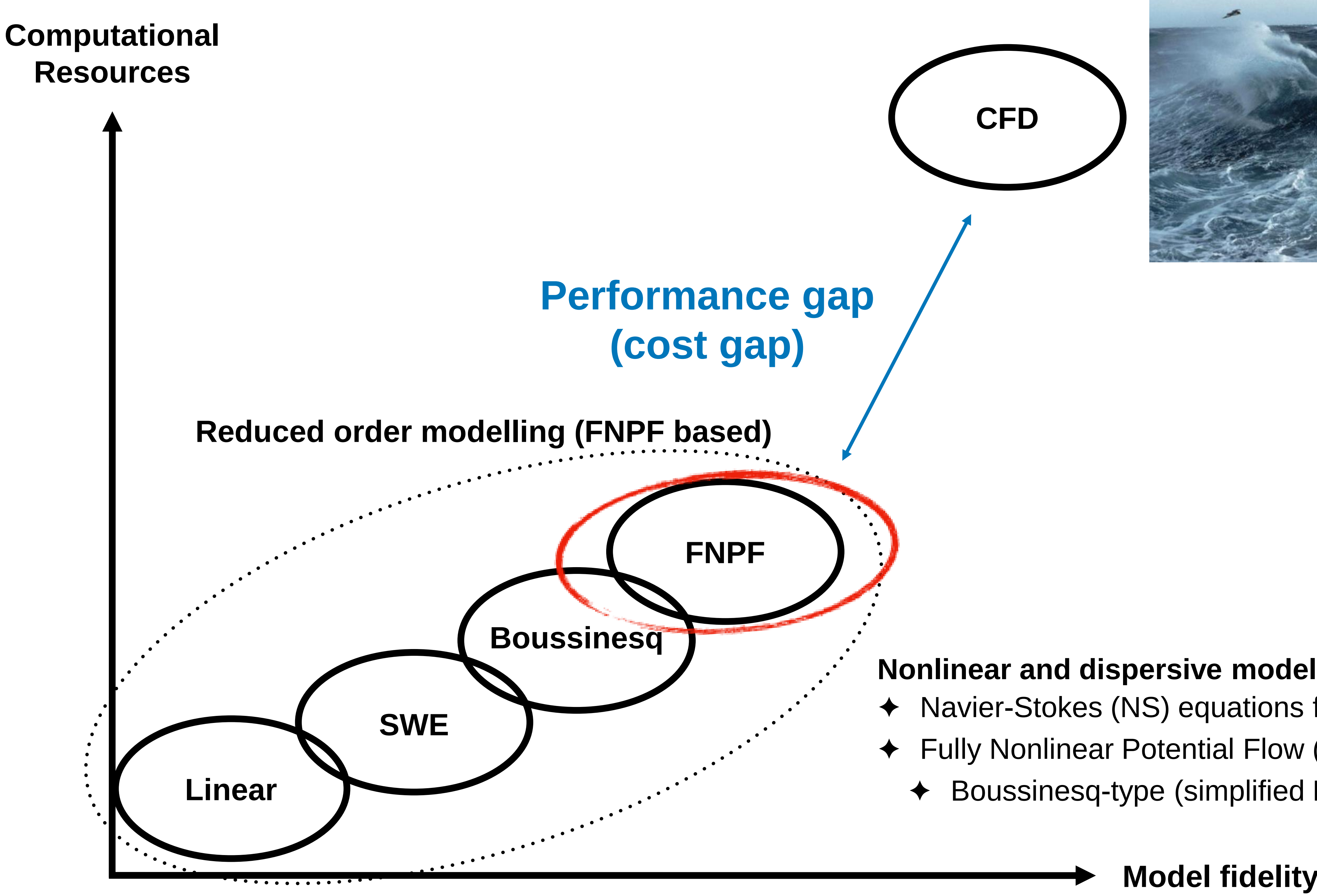
- ✦ <u>Complex geometry of structure</u>
- ✦ Sea-state defined in terms of <u>dispersive</u> & <u>nonlinear</u> waves
- ✦ <u>Nonlinear</u> structural wave-induced loads

✦ Wind turbines in production are moving from onshore to <u>offshore</u> for higher efficiency.

Numerical Modelling of Water Waves

Wave propagation:



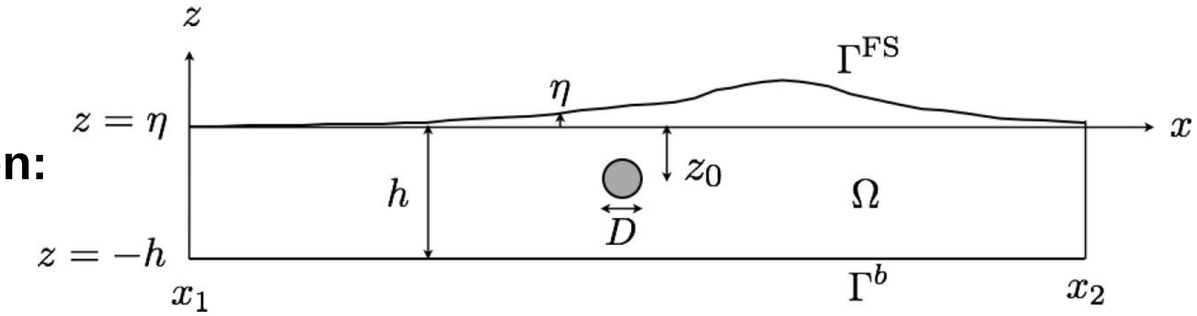


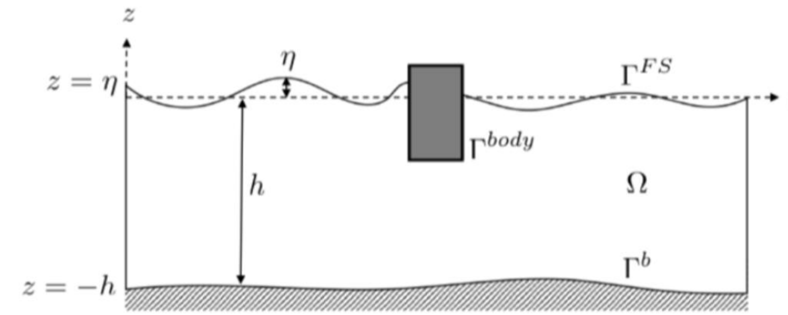
Nonlinear and dispersive models widely in use:

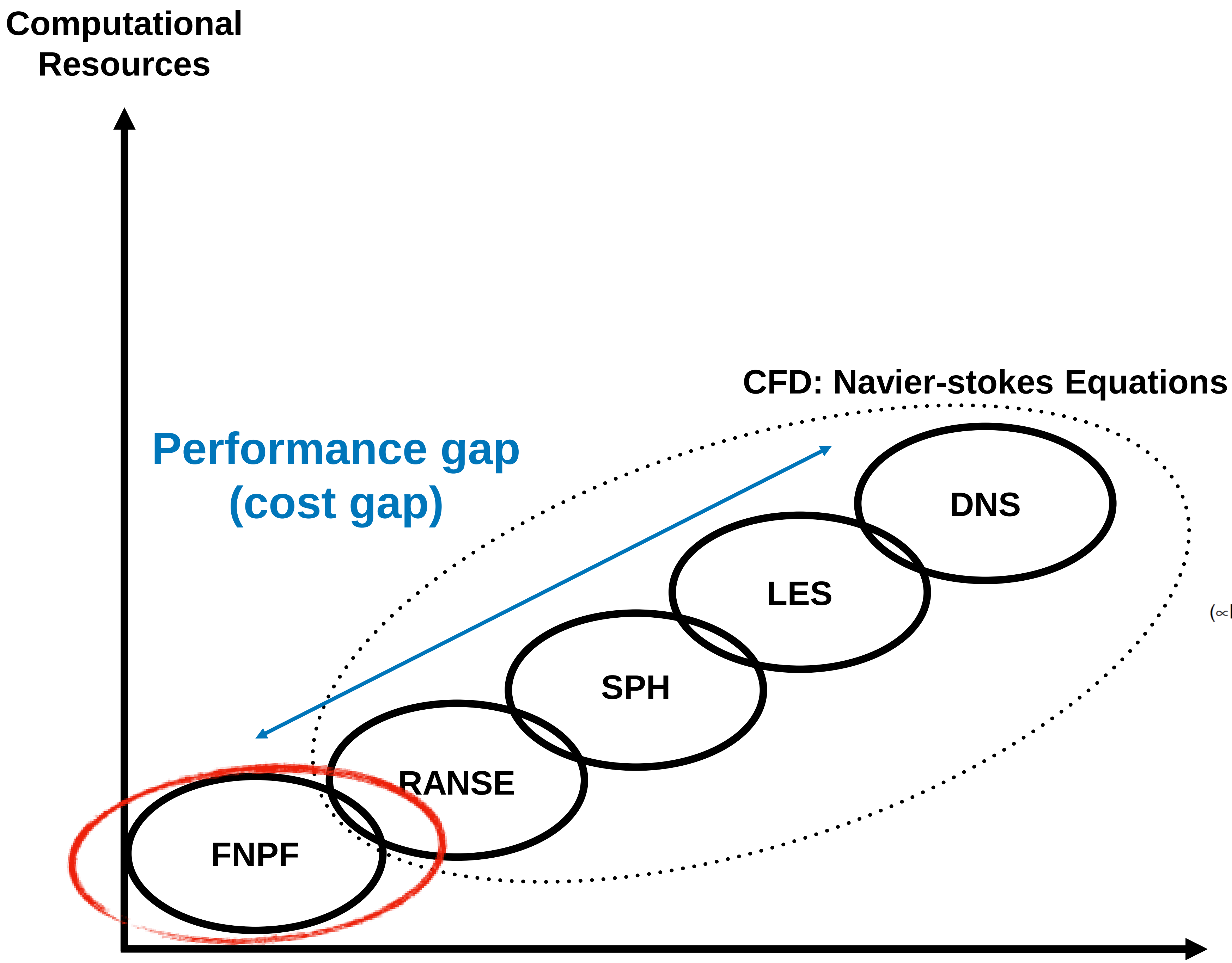
- ✦ Navier-Stokes (NS) equations for CFD, e.g. DNS, RANS, LES
- ✦ Fully Nonlinear Potential Flow (FNPF) equations
  - ✦ Boussinesq-type (simplified FNPF) equations

Numerical Modelling of Wave-Structure Forces

Wave-body interaction:







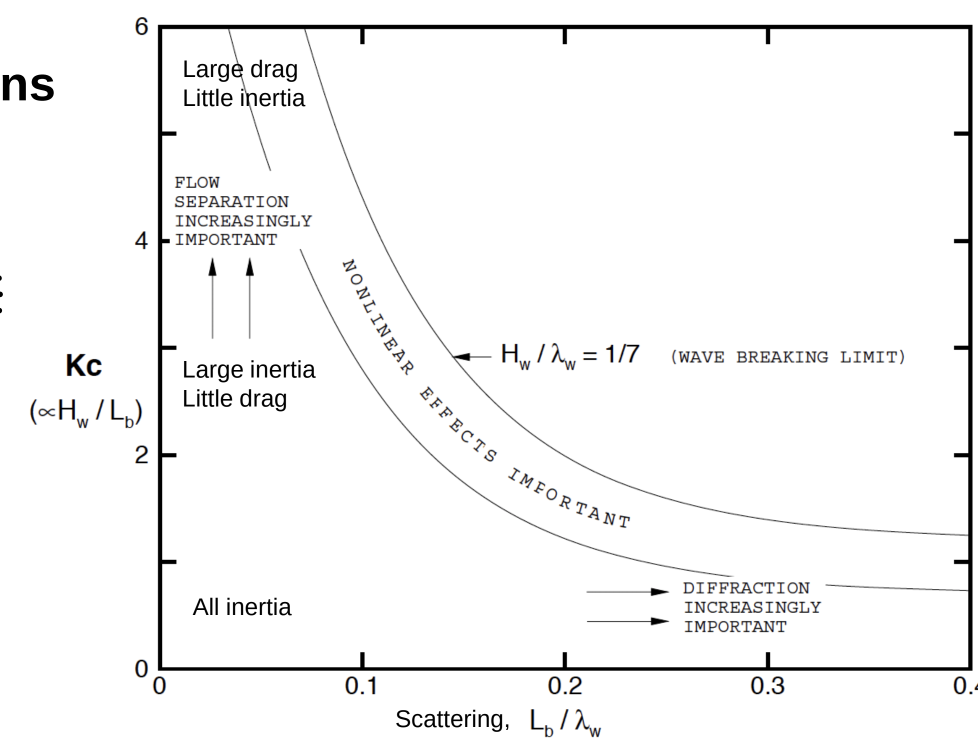
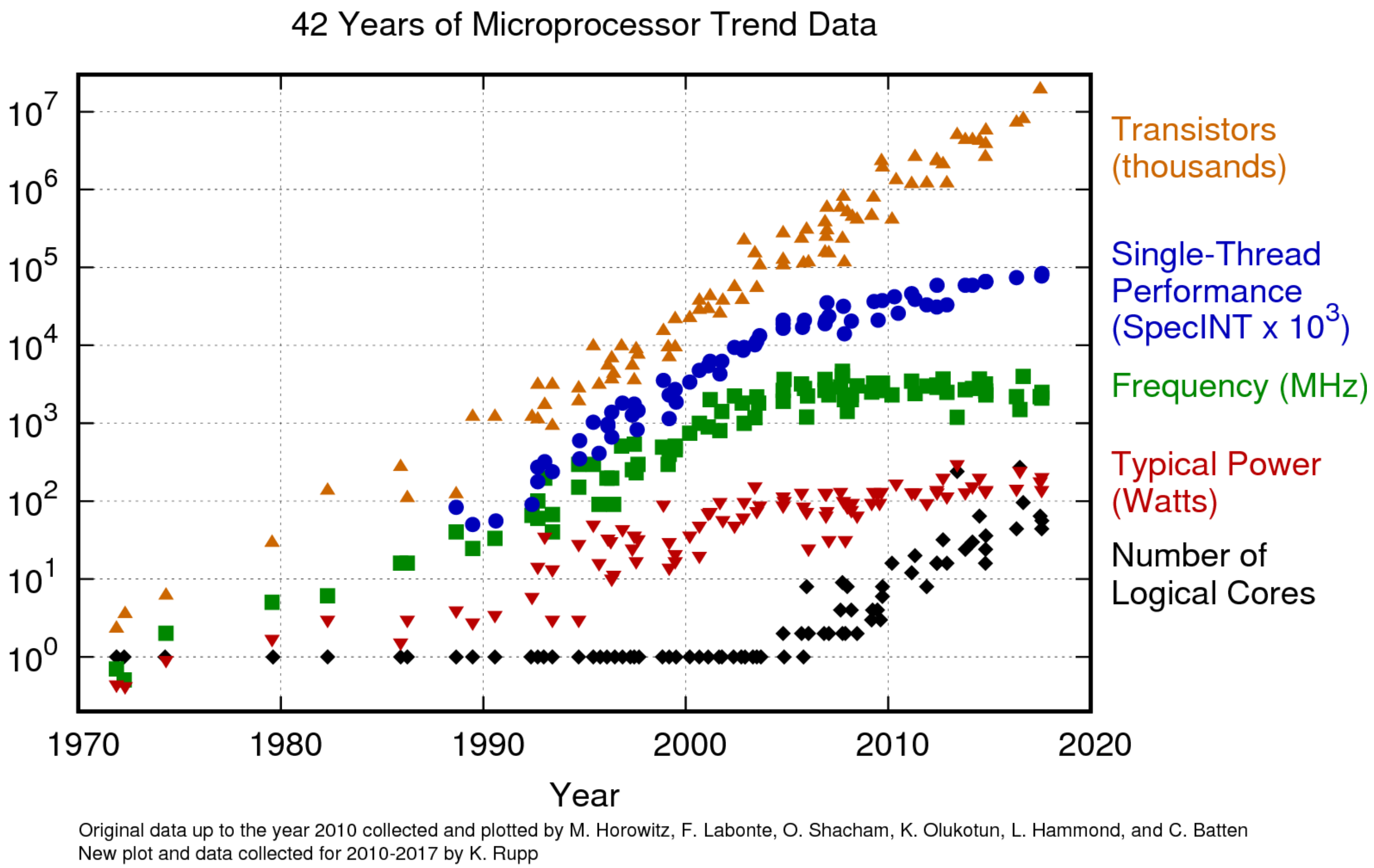
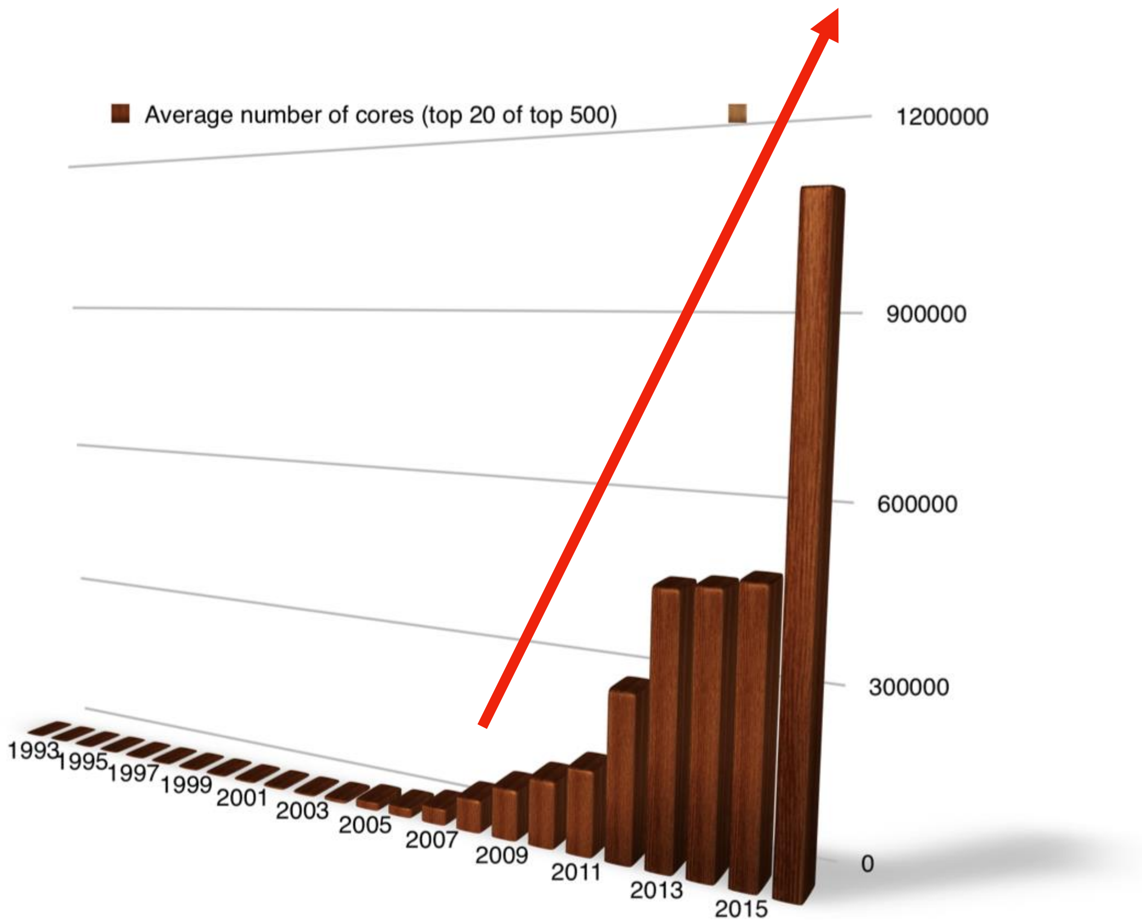


Figure 1.1: Wave force regimes. Traced from Issacson (1979)

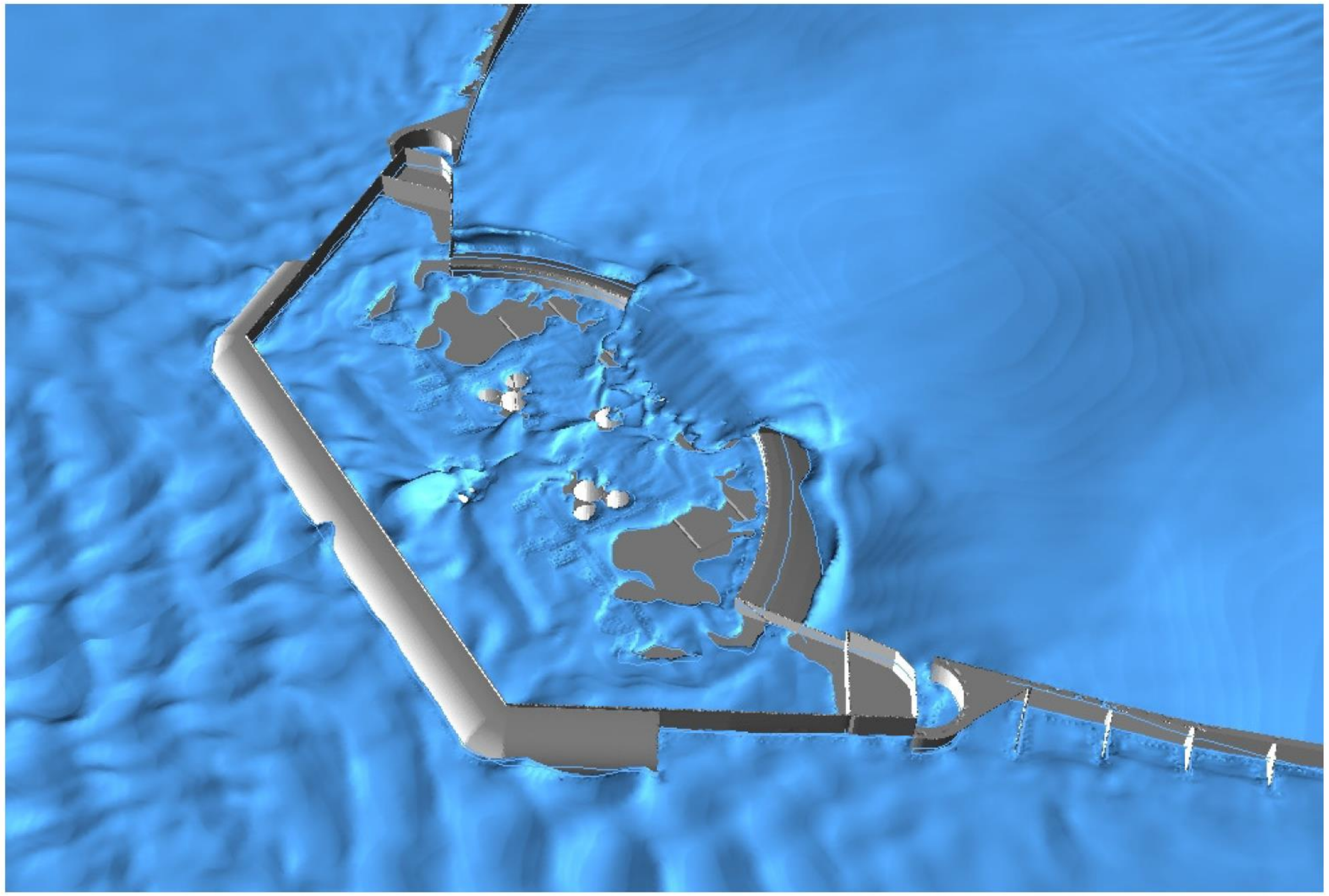
Trend I : Multiprocessor Evolution and Trends

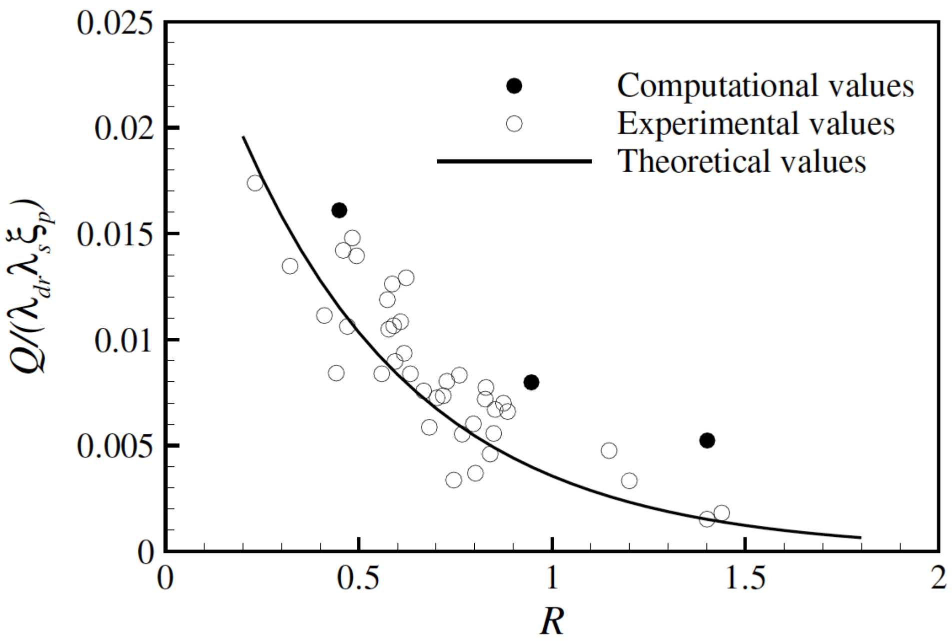




- ✦ In **many-core era** : Performance scales with number of cores (= software problem)
- ✦ High-performance computing an important driver in improving both **numerical efficiency** and **fidelity** of simulators.

What model fidelity is required?



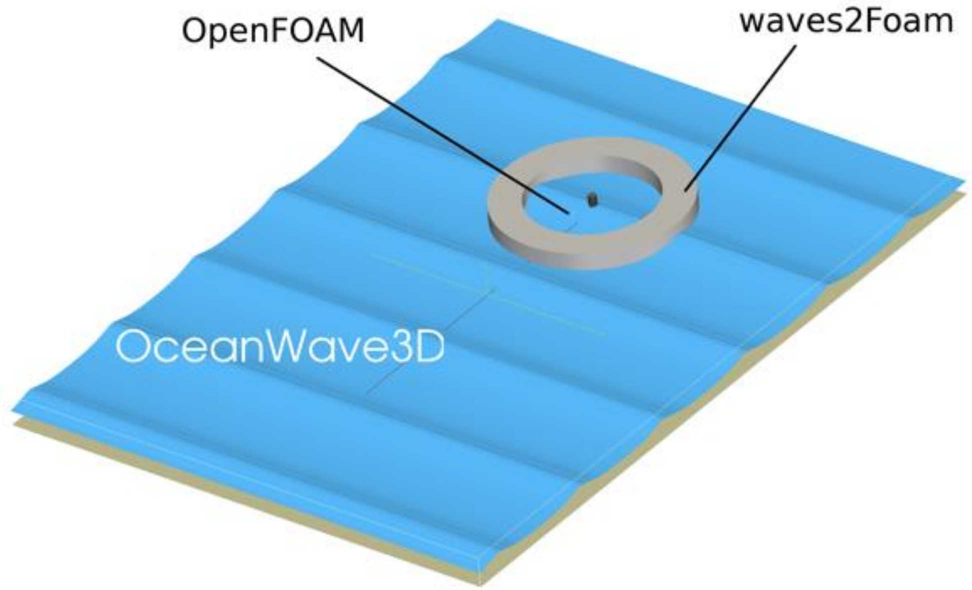


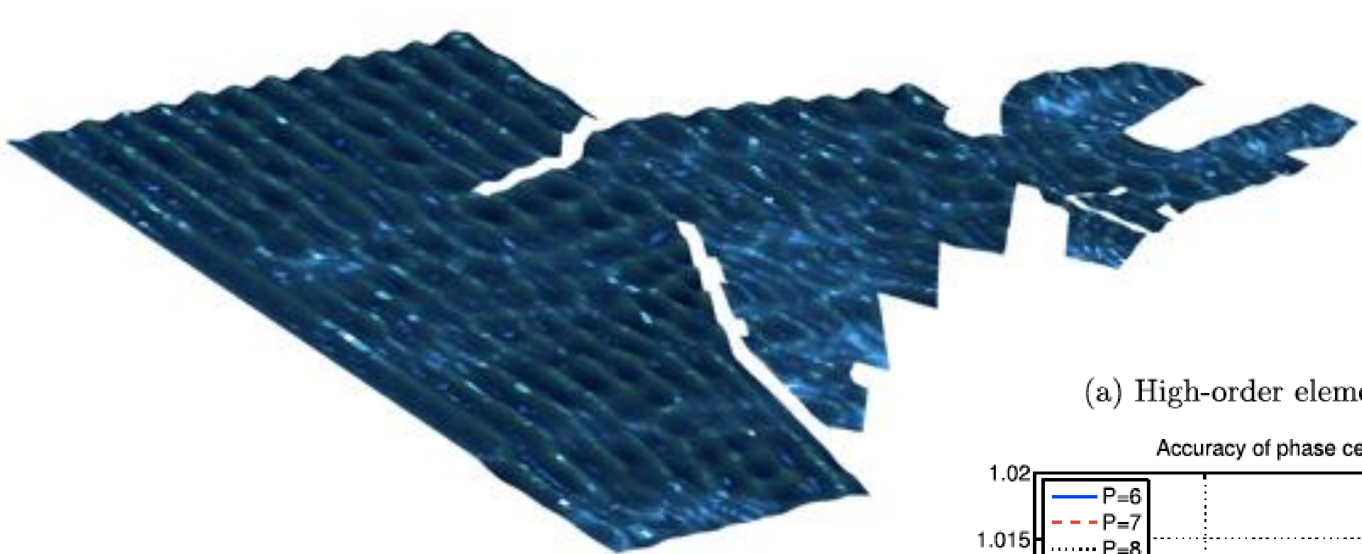
Source: Eskilsson et al, RENEW 2014.

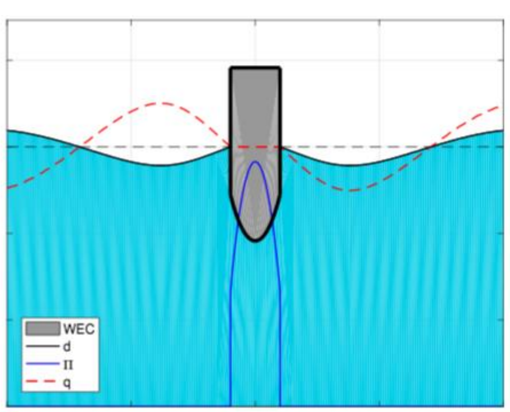
- ✦ VOF-EULER CFD Study of the Wave Dragon (wave-energy device)
- ✦ Overtopping discharge requires two-phase (air/water) studies
- ✦ Full 3h sea state simulation: JONSWAP with Hs=2m, Tp=7s (same phase angles)
- ✦ Simulated values on the order of the largest observed experimental values.
- ✦ Approximately 150 000 CPU hours(!) per simulation
  (128 cores, 14M cells, insufficient resolution in overtopping basin)
- ✦ CFD excessively expensive for irregular sea states.

Why increased interest in FNPF solvers?

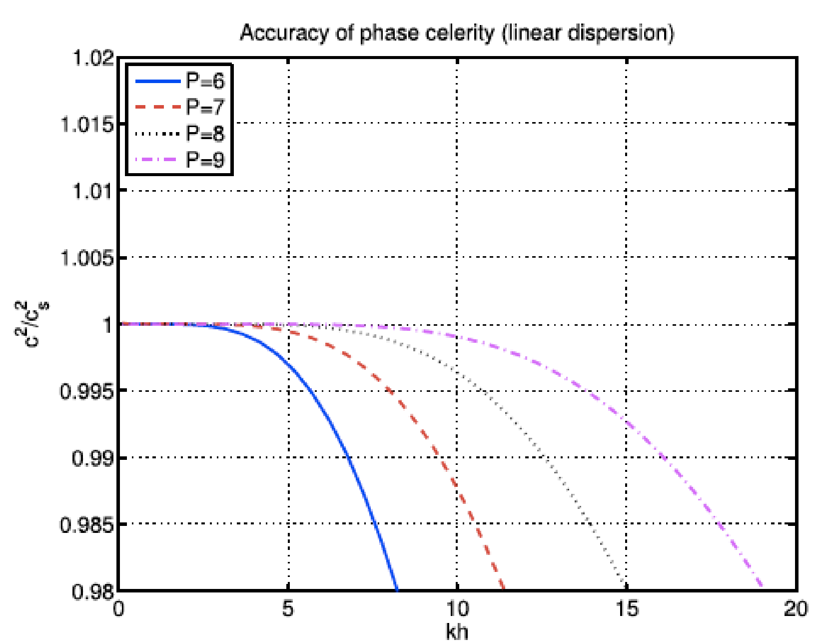
- ✦ Progress in HPC facilitates sea-state simulations including variable bathymetry
- ✦ Dispersive FNPF needed for wave propagation in offshore engineering
- ✦ FNPF as far-field solver coupled with NS for fluid-structure problems
  - ✦ Fx. OceanWave3D + OpenFOAM / Refresco / SPHysics
- ✦ As a medium fidelity method for marine renewables
- ✦ Accurate representation of internal kinematics
- ✦ Wave breaking modelling ongoing research.

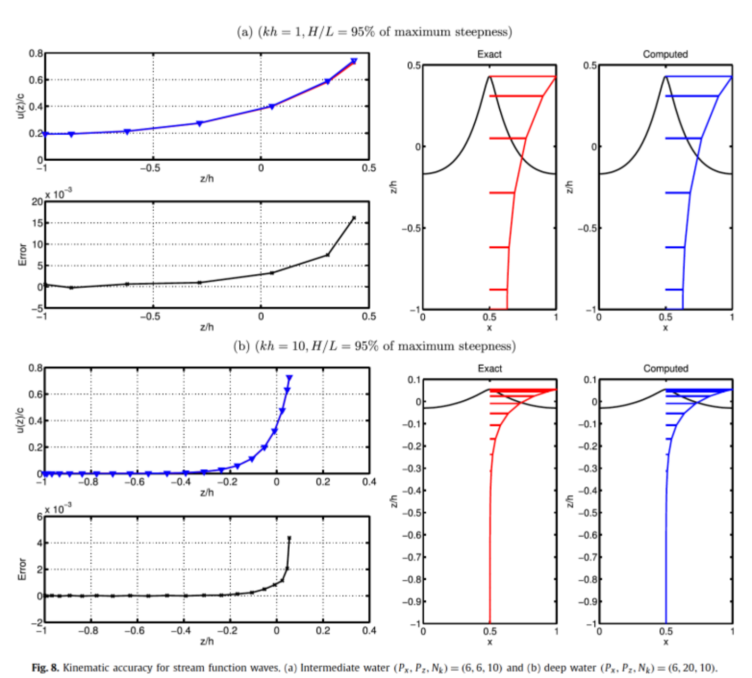






(a) High-order elements (x and σ)

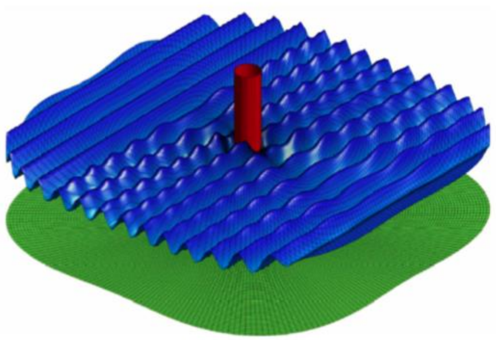


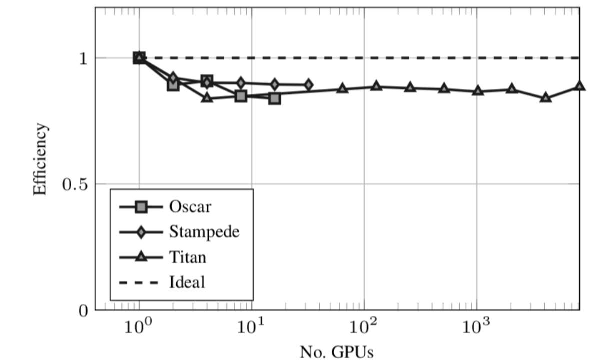


OceanWave3D (Open Source) Software

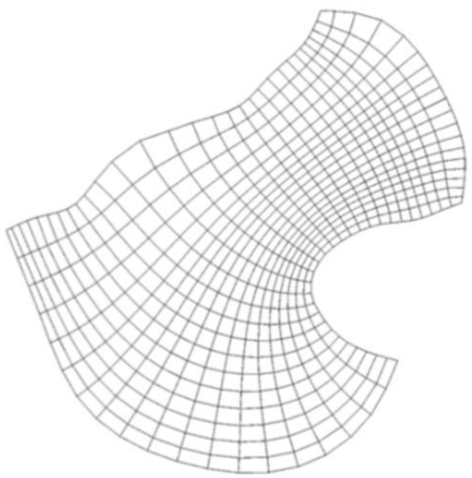
DTU Compute GPULAB C/C++ Library & OceanWave3D-GPU

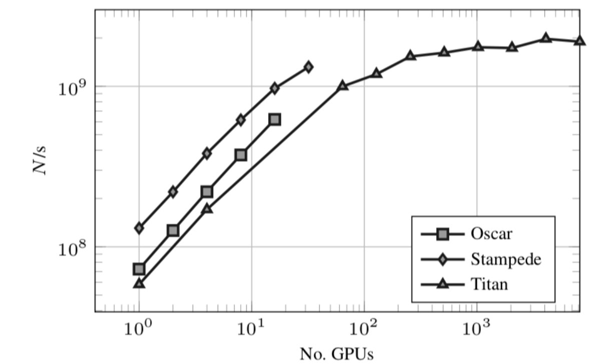
- ✦ FNPF solver developed since 2009 at DTU Compute.
- ✦ Massively parallel multigrid solver.
- ✦ CUDA/OpenCL + MPI implementation.
- ✦ Curvilinear Multi-block implementation.
- ✦ Benchmarked on desktops and super clusters **>1.000.000.000 DOFs** in linear solver.
- ✦ Fast large-scale simulations in marine regions with variable bathymetry using FNPF.
- ✦ Massively scalable simulations on heterogeneous clusters using **DTU Compute GPULAB Library**



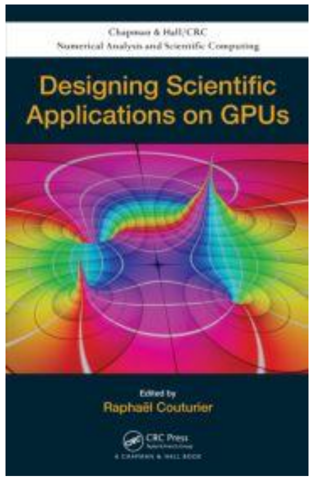


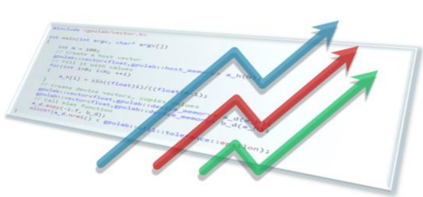
(a) Weak scaling, using $N \approx 3.8 \cdot 10^7$ per GPU.

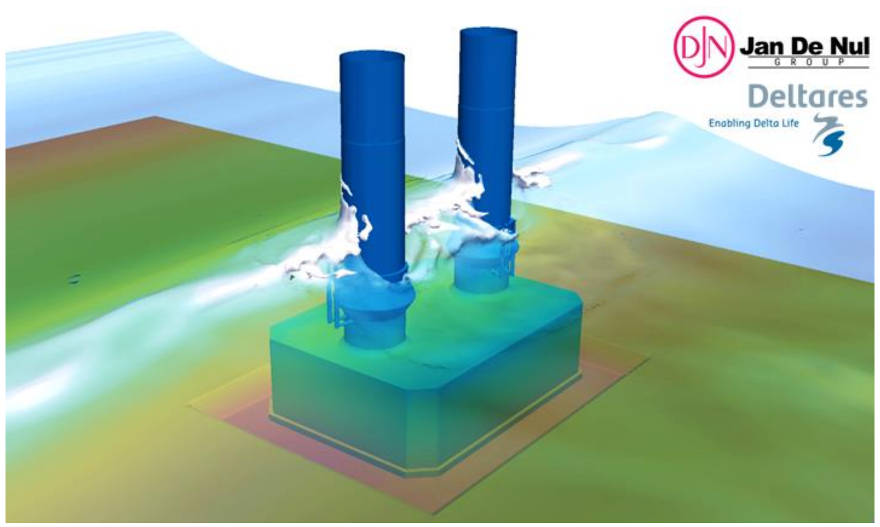


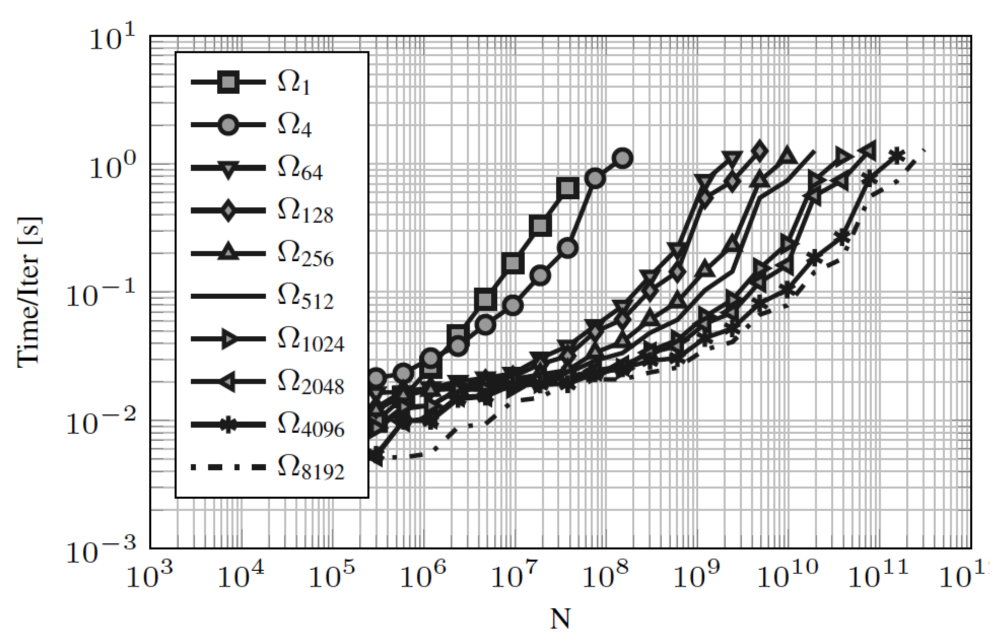


(b) Strong scaling in terms of number of grid points per second. At a constant problem size of $N \approx 3.8 \cdot 10^7$.







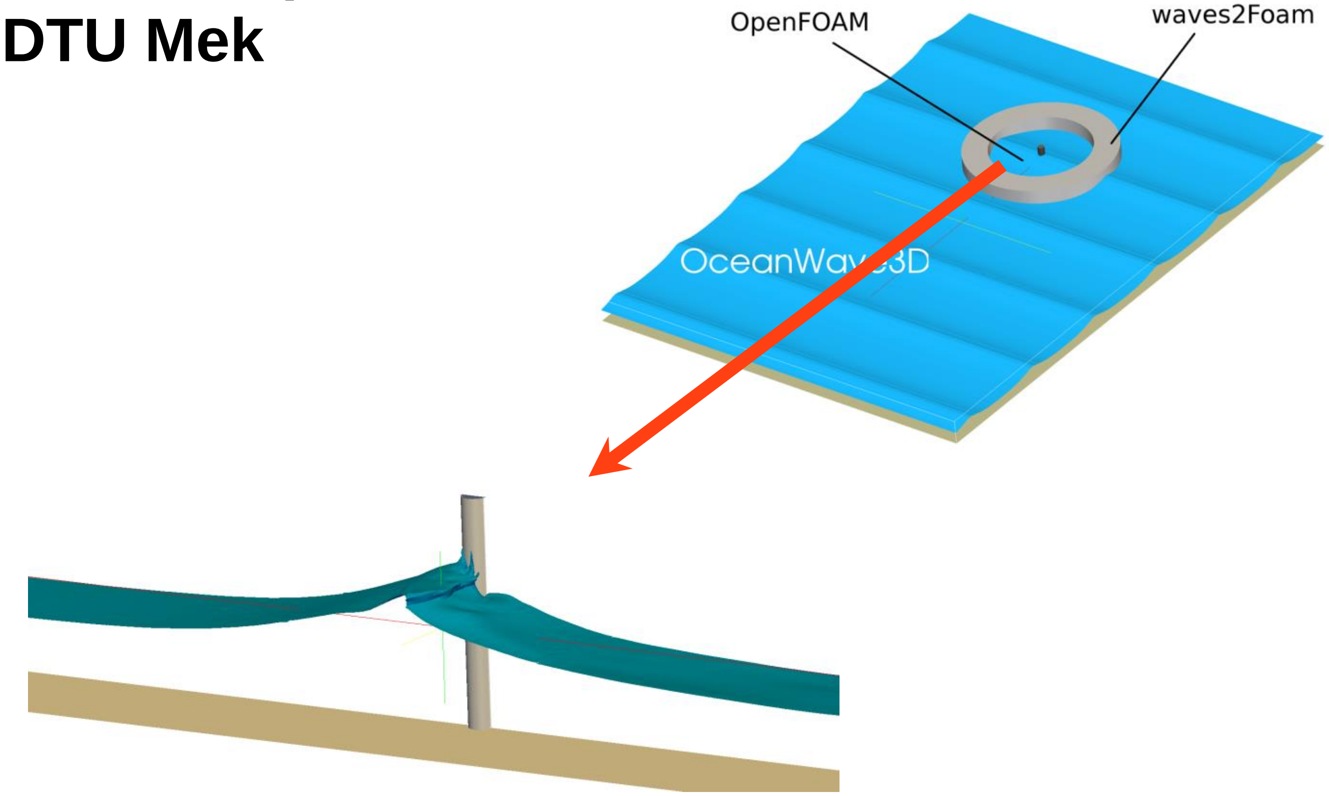


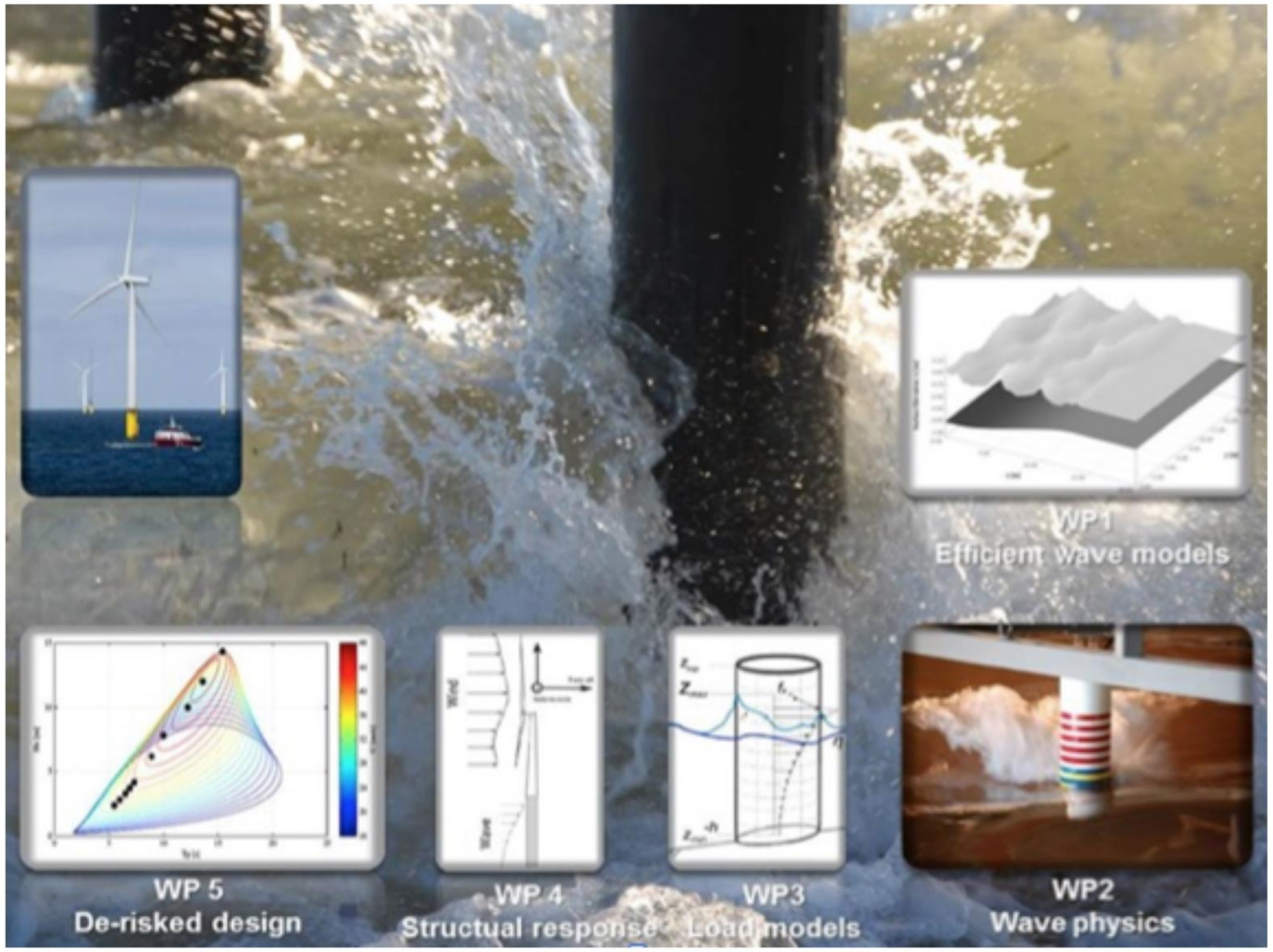
Website: http://www2.compute.dtu.dk/~apek/OceanWave3D/

DeRisk 2014-2018

www.derisk.dk

DTU Wind
DTU Compute
DTU Mek



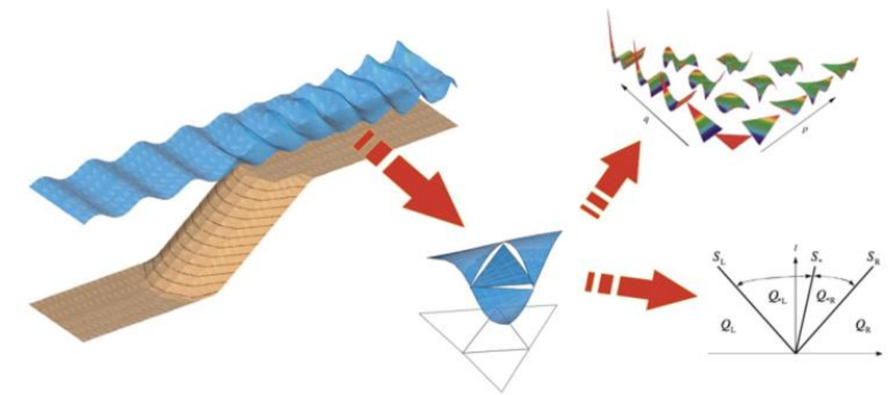


- ✦ De-Risking of ULS nonlinear wave loads on wind turbine offshore structures (DeRisk).
- ✦ Hybrid modelling: Far-field (FNPF) coupled to Near-field (CFD) solver.
  - ✦ OceanWave3D-GPU solver used for sea state calculations in regional marine areas with varying bathymetry.
  - ✦ OpenFoam Volume of Fluid (VOF) based CFD solver.
  - ✦ OpenFoam coupling module, Waves2Foam used for violent wave-structure interactions using a one-way coupling concept.

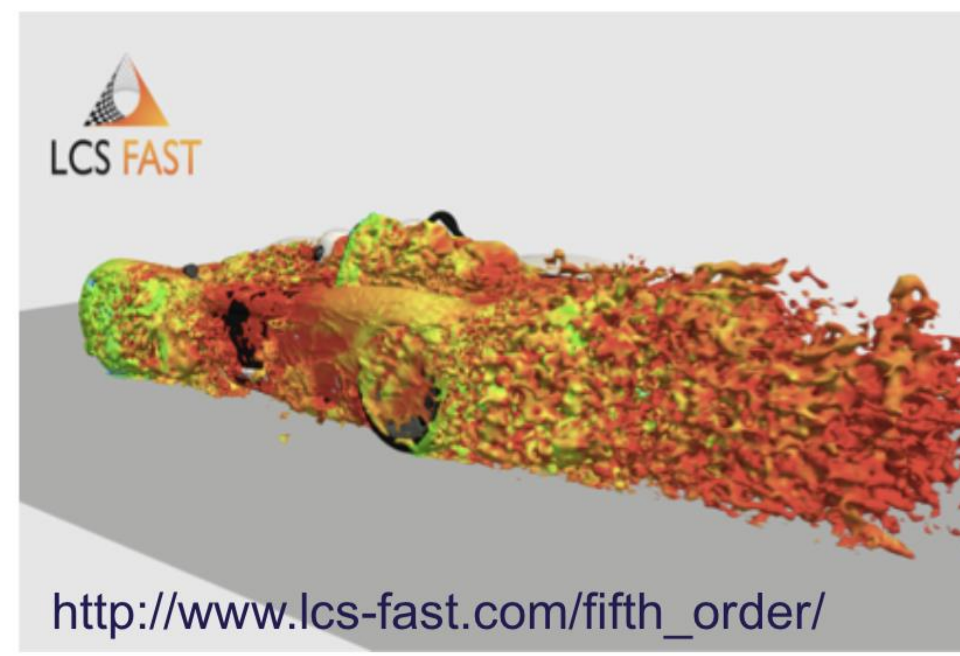
Trend II : Increased modelling fidelity using high-order numerical methods

SPECTRAL/*hp* ELEMENT METHODS

- *p*-type finite elements due to Babuska et al (1981)
- Spectral element method (SEM) due to Patera (1984)
- Spectral/*hp* Element Methods for CFD (Karniadakis and Sherwin, 1999)
- Nodal high-order DG methods (Hesthaven and Warburton, 2008)
- Today – frameworks (nektar++, nek5000, fenics, deal.II, etc)
- Often used for DNS (uDNS/ILES) simulations of bluff bodies
- Next generation NWP models are high-order DG
- Industrial engineering applications emerging now



NEKTAR++
SPECTRAL/HP ELEMENT FRAMEWORK



✦ High-order methods can be significantly more **cost-efficient** than low-order methods

✦ High-order methods maps to modern **many-core hardware** for improved performance

Trend II : Increased modelling fidelity using high-order numerical methods

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2018,30(1):1-22
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JHD

Spectral/*hp* element methods: Recent developments, applications, and perspectives*

Hui Xu[1], Chris D. Cantwell[1], Carlos Monteserin[2], Claes Eskilsson[4, 5], Allan P. Engsig-Karup[2, 3], Spencer J. Sherwin[1]

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(Received December 22, 2017, Accepted December 28, 2017)

Abstract: The spectral/*hp* element method combines the geometric flexibility of the classical *h*-type finite element technique with the desirable numerical properties of spectral methods, employing high-degree piecewise polynomial basis functions on coarse finite element-type meshes. The spatial approximation is based upon orthogonal polynomials, such as Legendre or Chebychev polynomials, modified to accommodate a C^0- continuous expansion. Computationally and theoretically, by increasing the polynomial order p, high-precision solutions and fast convergence can be obtained and, in particular, under certain regularity assumptions an exponential reduction in approximation error between numerical and exact solutions can be achieved. This method has now been applied in many simulation studies of both fundamental and practical engineering flows. This paper briefly describes the formulation of the spectral/*hp* element method and provides an overview of its application to computational fluid dynamics. In particular, it focuses on the use of the spectral/*hp* element method in transitional flows and ocean engineering. Finally, some of the major challenges to be overcome in order to use the spectral/*hp* element method in more complex science and engineering applications are discussed.

Key words: High-precision spectral/*hp* elements, continuous Galerkin method, discontinuous Galerkin method, implicit large eddy simulation

Project Leader

Spencer Sherwin is Professor of Computational Fluid Mechanics and the Head of Aerodynamics Section in the Department of Aeronautics at Imperial College London. He received his MSE and Ph. D. from the Department of Mechanical and Aerospace Engineering Department at Princeton University in 1995. Prior to this he received his BEng from the Department of Aeronautics at Imperial College London in 1990. In 1995, he joined the Department of Aeronautics at Imperial College as a lecturer and subsequently became a full professor in 2005. Over the past 27 years he has specialised in the development and application of advanced parallel spectral/*hp* element methods for flow around complex geometries with a particular emphasis on vortical and bluff body flows, biomedical modelling of the cardiovascular system and more recently in industrial practice through the partnerships with McLaren Racing and Rolls Royce. Professor Sherwin's research group also develops and distributes the open-source spectral/*hp* element package *Nektar++* (www.nektar.info) which has been applied to direct numerical simulation, large eddy simulation and stability analysis to a range of applications including vortex flows of relevance to offshore engineering and vehicle aerodynamics as well as biomedical flows associated with arterial atherosclerosis. He has published numerous peer-reviewed papers in international journals covering topics from numerical analysis to applied and fundamental fluid mechanics and co-authored a highly cited book on the spectral/*hp* element method. Since 2014 Prof. Sherwin has served as an associate editor of the

* **Biography:** Hui Xu (1981-), Male, Ph. D.
Corresponding author: Hui Xu,
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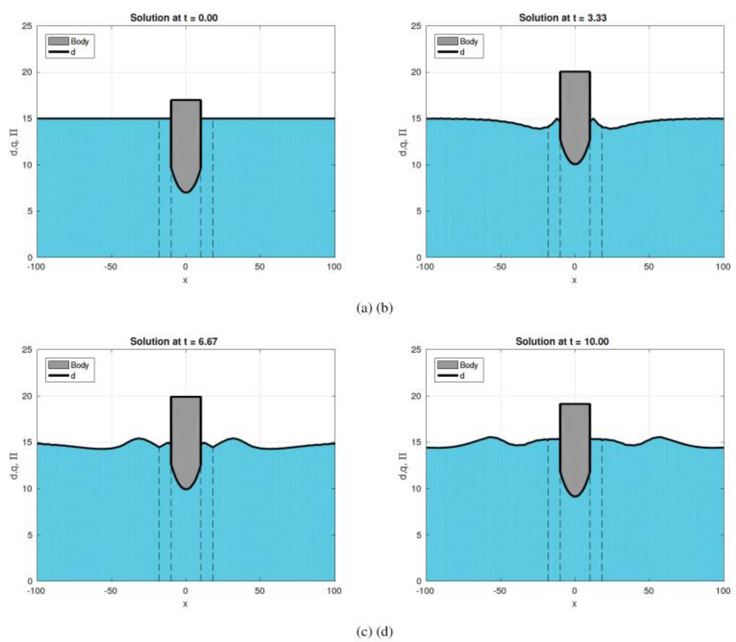
✦ High-order methods maps to modern **many-core hardware** for improved performance

MIDWEST 2014-2018 (EU-OceaneraNET program)

Multi-fIdelity Decision making tools for Wave Energy Systems

https://project.inria.fr/midwest/

RISE (SWEDEN)
INRIA (FRANCE)
DTU COMPUTE (DENMARK)
CENTEC, Instituto Superior Técnico Lisboa (PORTUGAL)



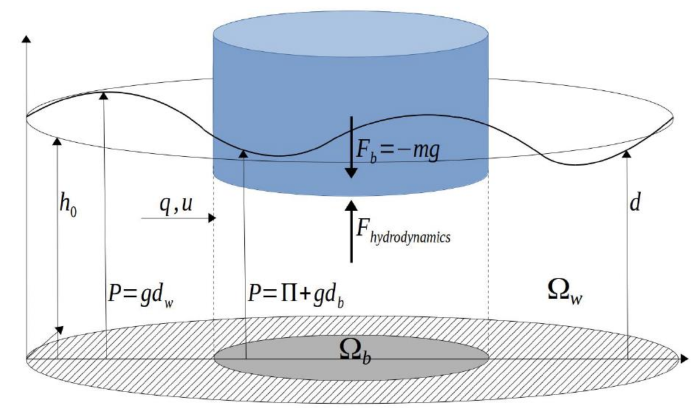
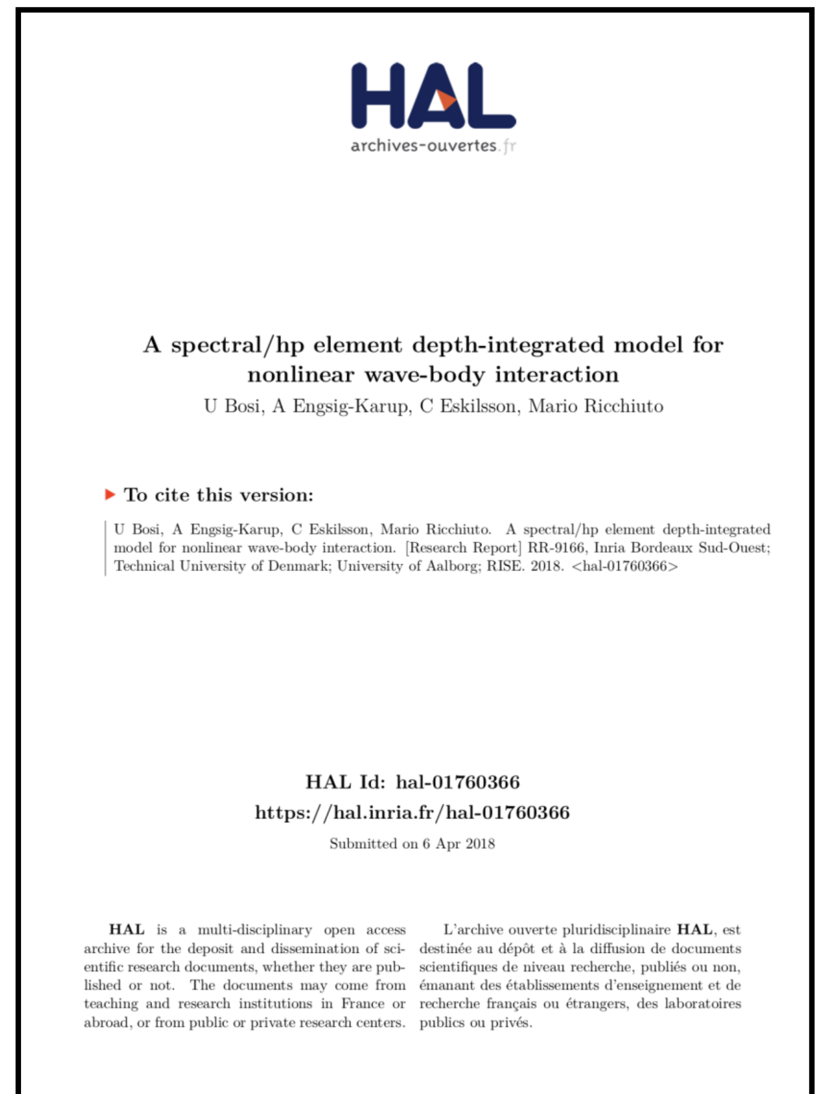


Figure 1: Layout of the problem describing the nonlinear wave-body interaction in a domain decomposition framework.



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A spectral/hp element depth-integrated model for nonlinear wave-body interaction

U Bosi, A Engsig-Karup, C Eskilsson, Mario Ricchiuto

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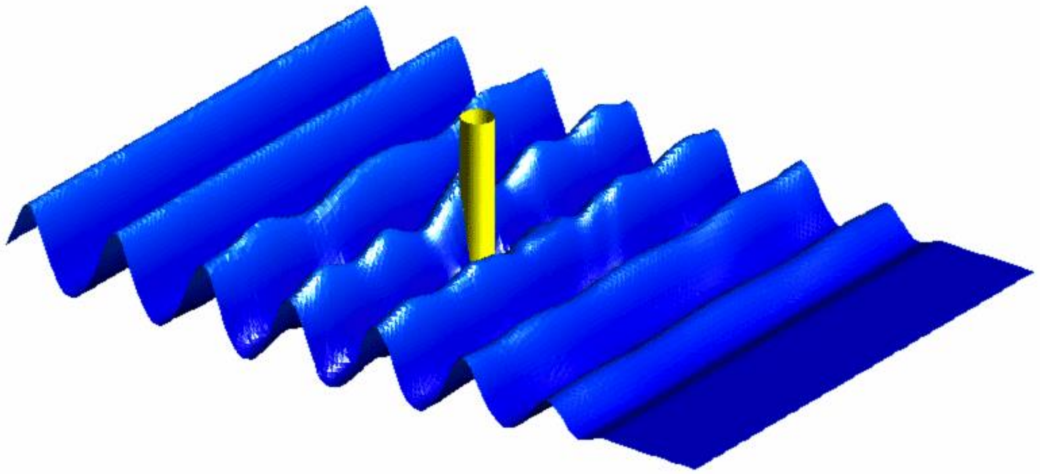
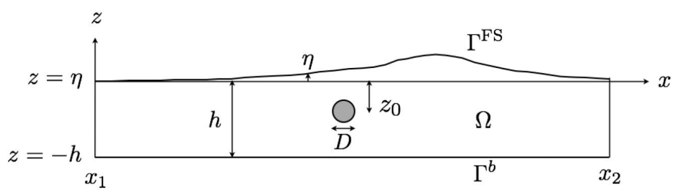
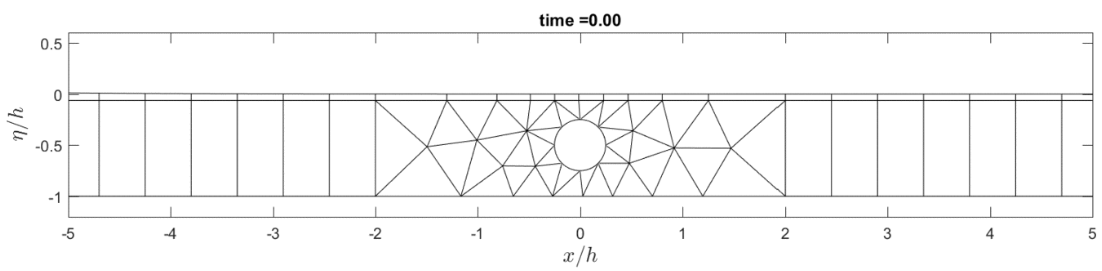
- ✦ Proposing new efficient tools of medium fidelity for the wave energy industry based on the Spectral Element Method.
- ✦ Development of decision making framework for the design of the next generation WECs.
- ✦ Assessment of model fidelity needed to capture nonlinear effects.

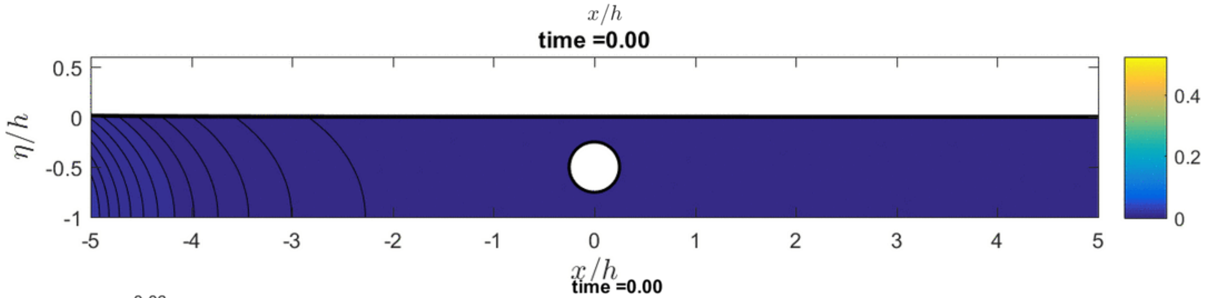
MarineSEM 2014-Today
Spectral Element Methods for Marine Hydrodynamics
https://www.researchgate.net/project/Spectral-Element-Methods-for-Nonlinear-Waves-Wave-Structure-and-Wave-Body-modelling

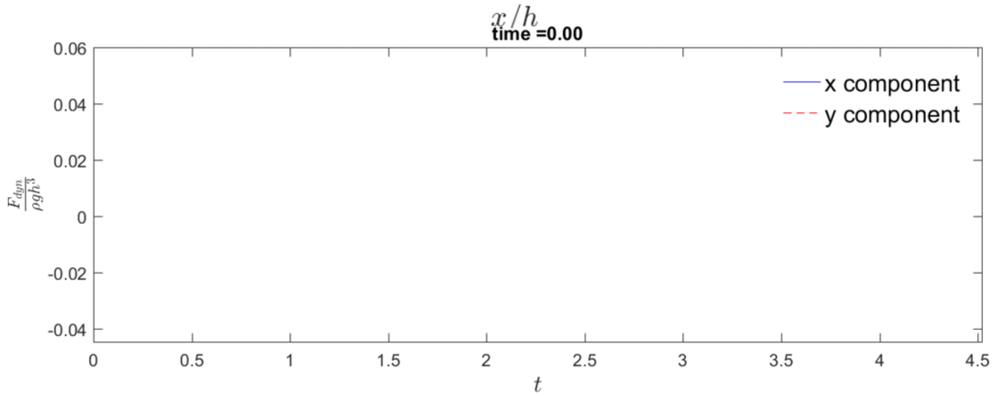


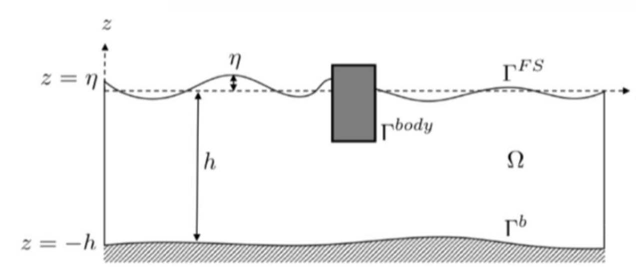
Allan P. Engsig-Karup & Claes Eskilsson
DTU COMPUTE and AALBORG UNIVERSITY

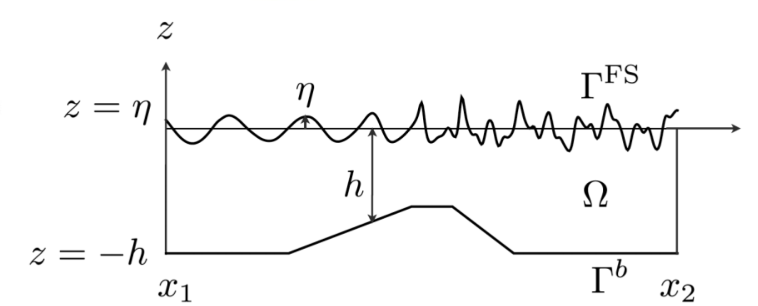













Journal of Computational Physics

A stabilised nodal spectral element method for fully nonlinear water waves

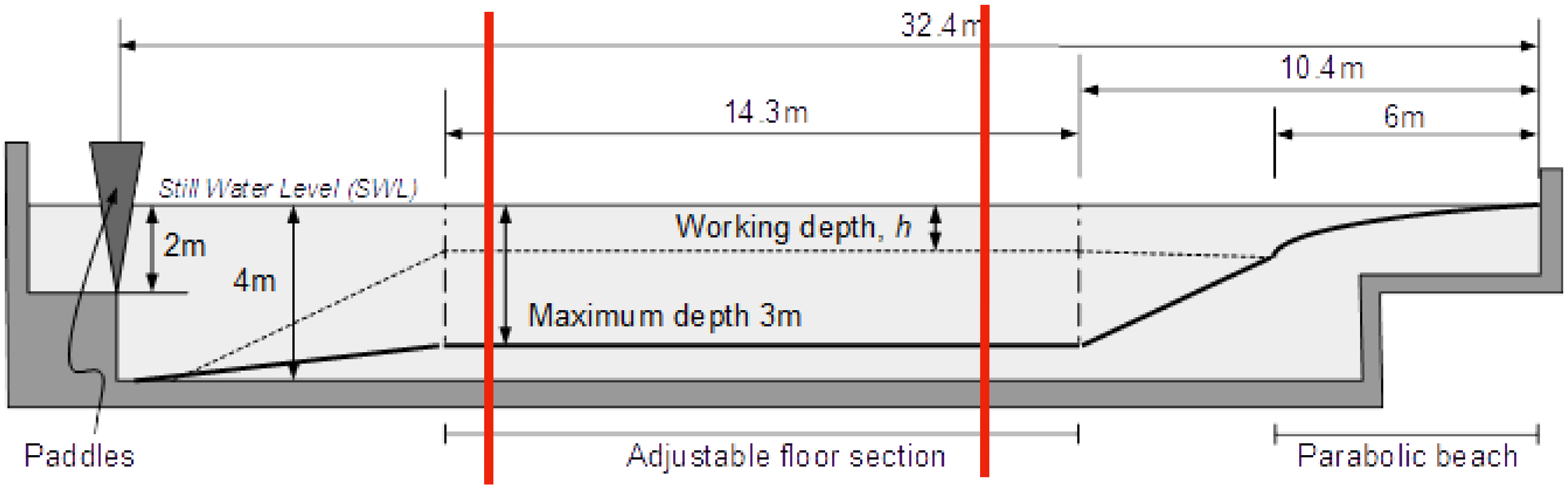
A.P. Engsig-Karup, C. Eskilsson, D. Bigoni

1. Introduction

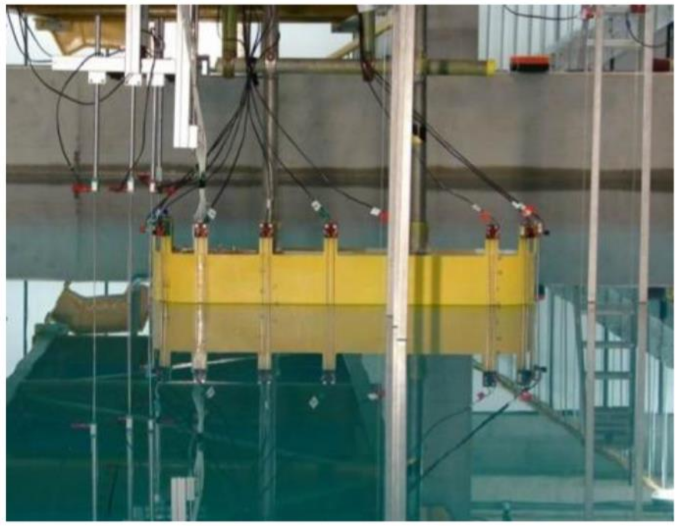
- ✦ Proposing world-wide new efficient and flexible tools for marine hydrodynamics based on the Spectral Element Method.
- ✦ Nonlinear wave propagation, wave-structure and wave-body applications.

CCP-WSI
A Collaborative Computational Project in Wave Structure Interaction

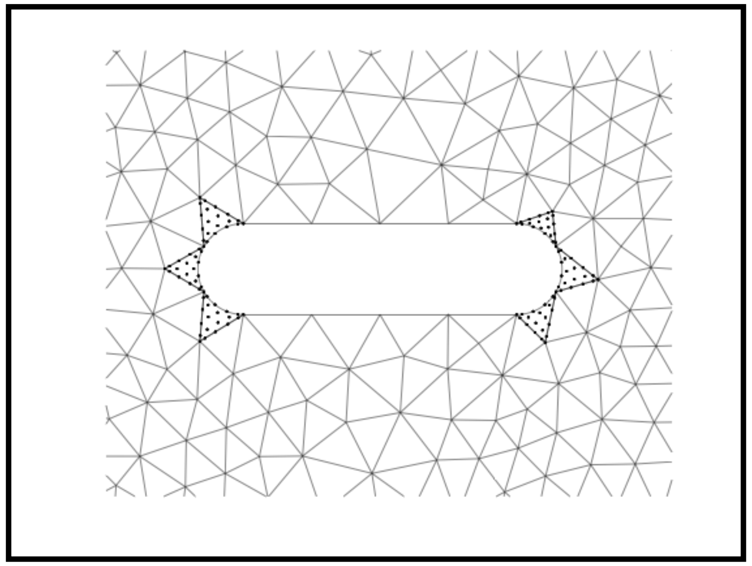
ISOPE 2018 Blindtest Experiment, NWT Setup



Numerical wave tank domain

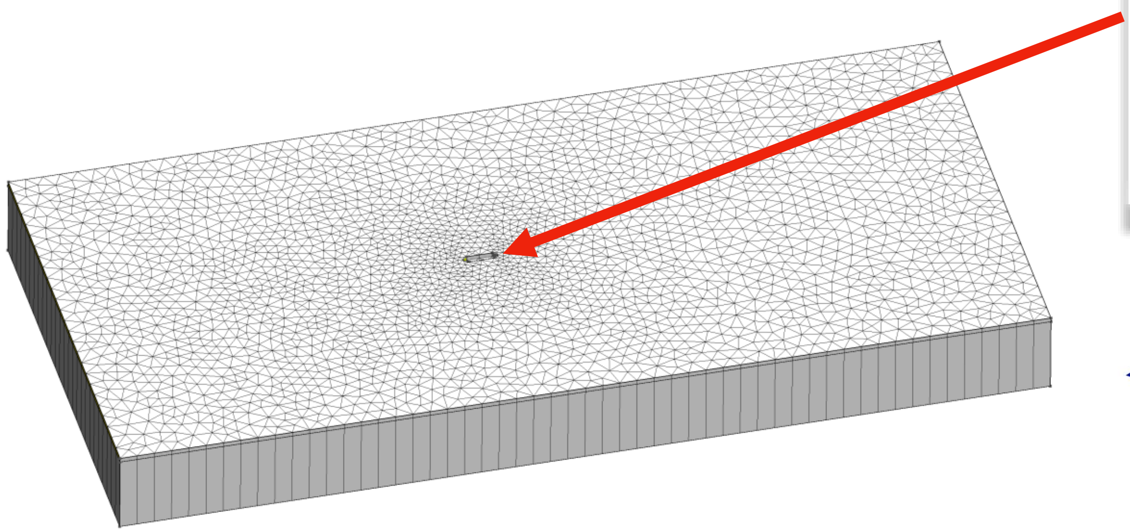


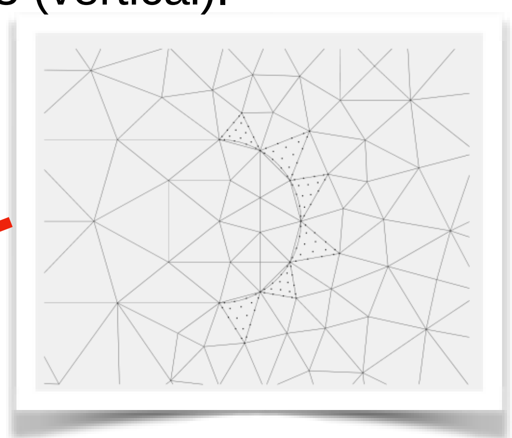
FPSO 2D body structure

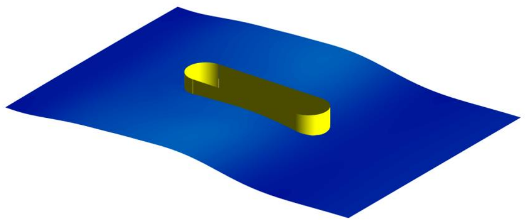


FPSO Setup in 3D

- Domain size:
  - FPSO 2D body structure is resolved with just 14 higher order elements.
  - Length = 12 m, Width = 8 m , h = 2.93 m
- High-order polynomial basis, P = 5 (horizontal), P = 3 (vertical).
- Total number of prism elements are 12440.
- Total number of degrees of freedom are 555945.







Computational ressources

- MarineSEM library v0.8 (beta)
- Matlab R2017a
- Sequential execution.
- Code well structured but not optimised extensively.
- 1 Core, <4.5 days of execution for one simulation.

CCP-WSI
A Collaborative Computational Project in Wave Structure Interaction

Experimental id 13BT1

Free Surface Elevation Wave Gauges, Case 1.3 (Fixed FPSO)

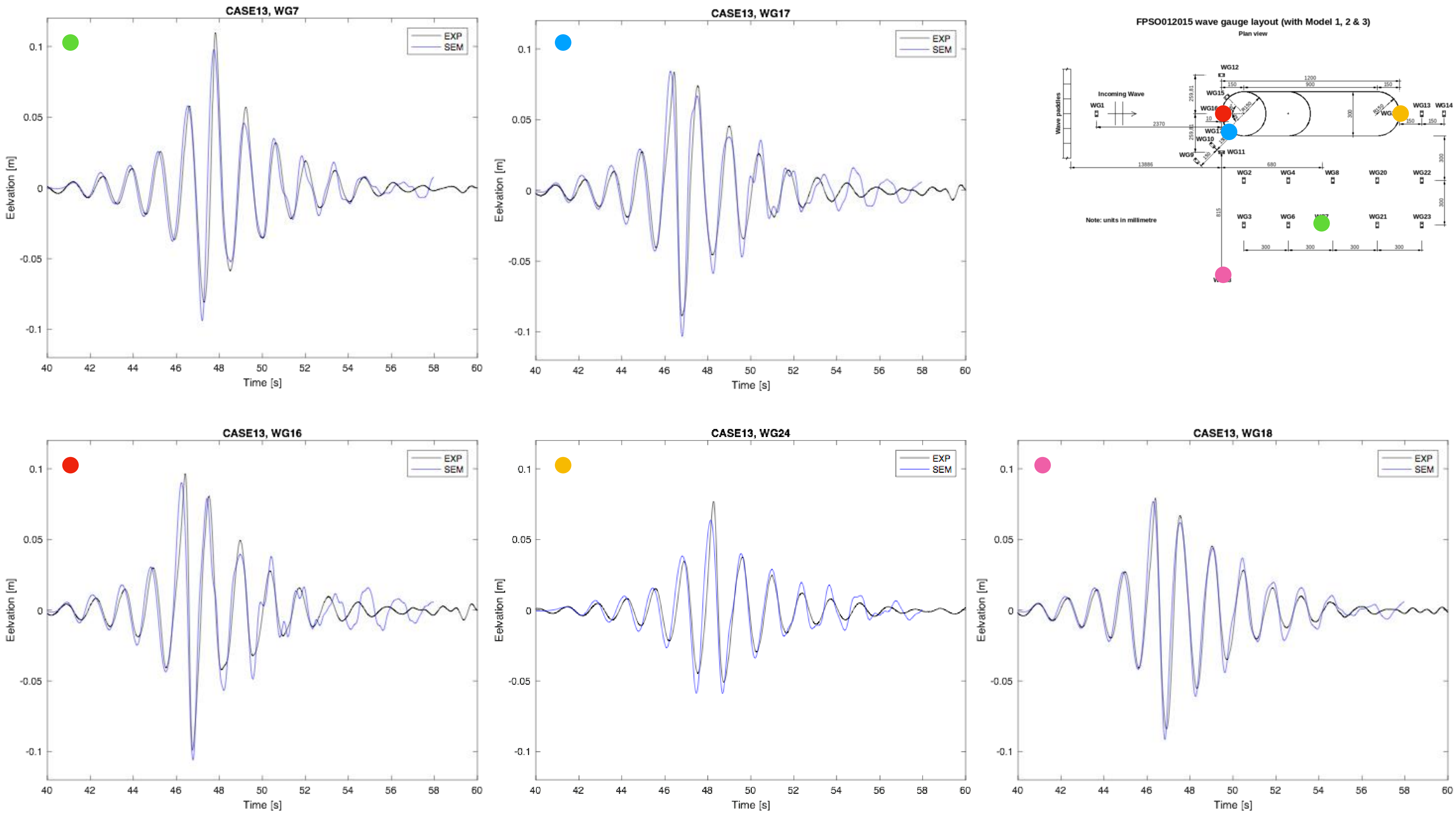
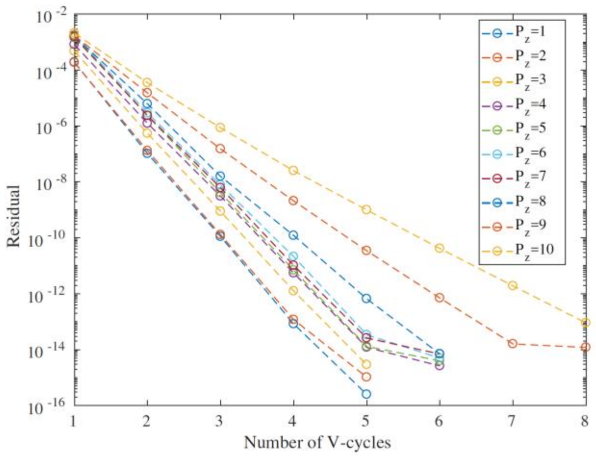
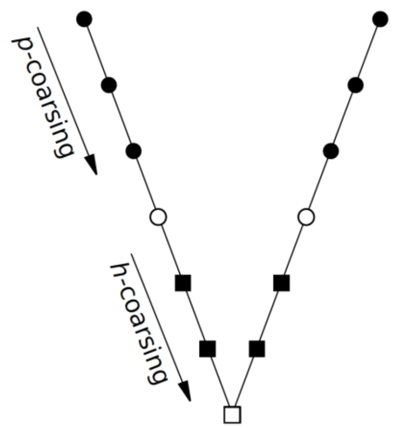


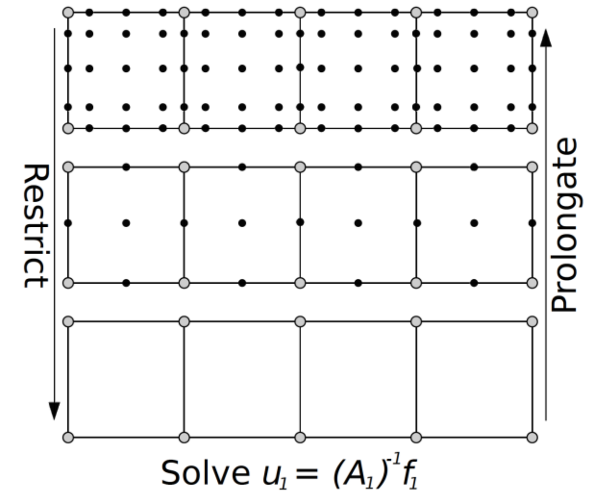
Figure 8. Compute Wave Gauge measurements for NWT with FPSO. The time is started at t=38s of the measurement signal and corresponds to t=0s in the figures.

Trend III : Open source codes, fast algorithms and parallel implementations

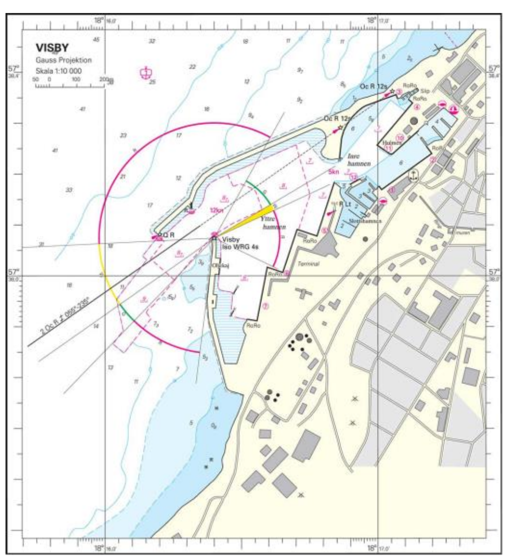
Scientific Computing Research: Multigrid methods and HPC for acceleration:

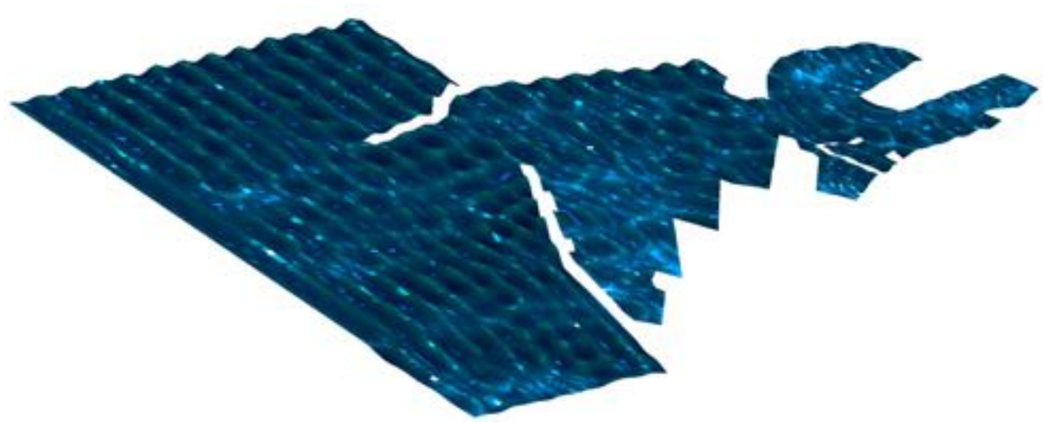


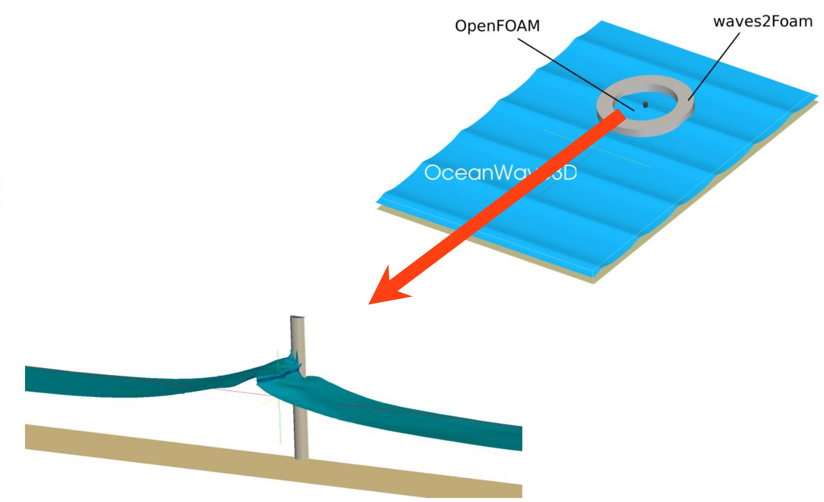




Open source Software, improved fidelity and large-scale simulation sees increasing adoption:







NEKTAR++
SPECTRAL/HP ELEMENT FRAMEWORK

DTU

DTU Compute
Department of Applied Mathematics and Computer Science

GPUlab
DTU Compute

AALBORG UNIVERSITY

Questions?

Allan Peter Engsig-Karup (apek@dtu.dk)

See also: http://www2.compute.dtu.dk/~apek/

Website(s):
High-order parallel numerical solvers for Marine Hydrodynamics Simulations

MarineSEM (2004-):
https://www.researchgate.net/project/Spectral-Element-Methods-for-Nonlinear-Waves-Wave-Structure-and-Wave-Body-modelling

OceanWave3D (2008-):
http://www2.compute.dtu.dk/~apek/OceanWave3D/

DTU Compute
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