MARE-WINT
new MAterials and REliability
in offshore WINd Turbines technology

University of Glasgow

LABORATORY

MARIE CURIE ACTIONS

European Commission

A coupled floating offshore wind turbine analysis with high-fidelity methods

DeepWind 2016

Location: Trondheim, Norway
Date: 20.01.2016
Speaker's name: Vladimir Leble

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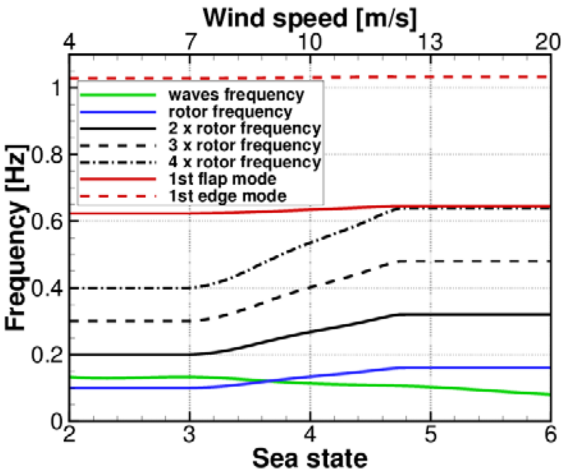
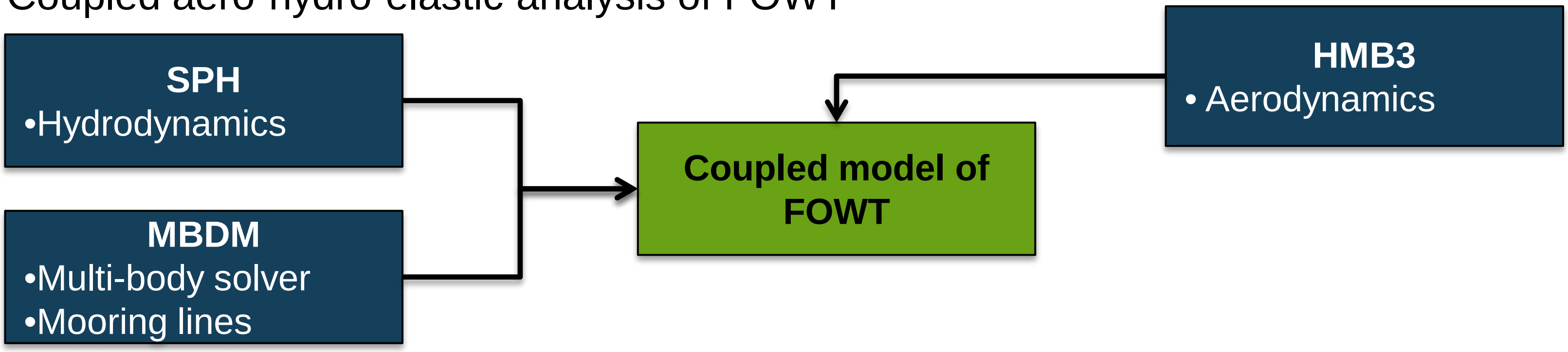
MARE-WINT PROJECT

- MARE-WINT project objectives:
  - Bring together specific partners capabilities:
    - Mechanical engineering
    - Material science
    - Fluid mechanics
    - Condition monitoring
    - Reliability analysis
  - Increase reliability of floating off-shore wind turbine (FOWT) designs
  - Contribute to operation and maintenance (O&M) cost reduction
  - Balanced industry-academia network consortium includes 6 Universities, 7 Research Institutes, 4 Small and Medium-sized Enterprises and 7 Large Industry Partners
- Current research objectives
  - Develop high-fidelity tools for FOWT analysis
  - Coupled aero-hydro-elastic analysis of FOWT





SPH
•Hydrodynamics

MBDM
•Multi-body solver
•Mooring lines

Coupled model of FOWT

HMB3
• Aerodynamics

FOWT PROTOTYPES

- Several prototypes built including:
  - Blue H prototype
    - 2008, Italy
    - 80kW
    - Tension leg platform
  - Hywind
    - 2009, Norway
    - 2.3MW
    - Spar buoy platform
  - WindFloat
    - 2011, Portugal
    - 2MW
    - Semi-submersible platform
  - Fukushima FORWARD
    - 2013, Japan
    - 2MW
    - Semi-submersible platform

Blue H prototype

Hywind

WindFloat

Fukushima FORWARD

LITERATURE REVIEW

- Most common approach is to combine simplified tools into a hybrid model of FOWT
  - Aerodynamics
    - Simple analytical expression[1,2]
    - Blade element momentum method[3,4,5]
  - Hydrodynamics
    - Morison's equation[6]
    - Airy wave theory (inviscid, incompressible and irrotational flow)[1,3,4]
  - FOWT dynamics
    - Components
      - Rigid
      - Flexible[4,5,6]
    - Mooring lines
      - springs and dampers[6]
      - multi-body chains[7]
      - catenary equation[5]
- Current development of coupled CFD models
- No experimental data available in open literature

[1] Roddier, D., Cermelli, C., Weinstein, A., 2009. WindFloat: A Floating Foundation for Offshore Wind Turbines–Part I: Design Basis and Qualification Process. In: ASME 2009 28th International Conference on Ocean, Offshore and Arctic Engineering. ASME, pp. 845–853

[2] Karimirad, M., Moan, T., 2012. A simplified method for coupled analysis of floating offshore wind turbines. Marine Structures 27 (1), 45 – 63.

[3] Jonkman, J., November 2007. Dynamics modeling and loads analysis of an offshore floating wind turbine. Technical Report NREL/TP-500-41958, NREL

[4] Karimirad, M., Moan, T., 2013. Modeling aspects of a floating wind turbine for coupled wavewind-induced dynamic analyses. Renewable Energy 53, pp. 299–305.

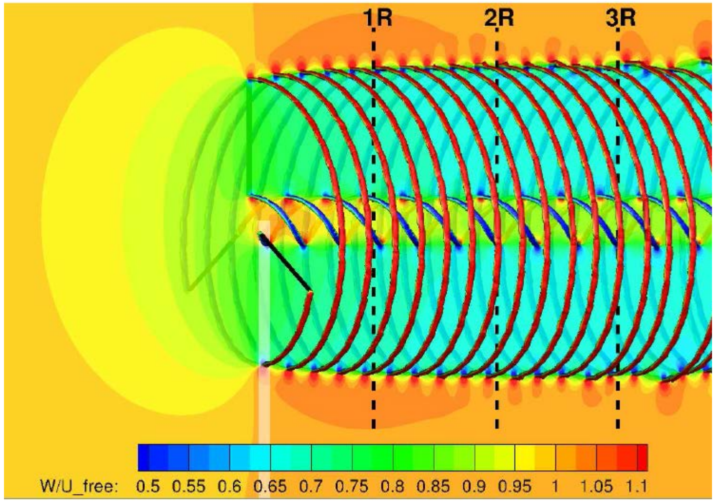
[5] Skaare, B., Hanson, T., Nielsen, F., Yttervik, R., Hansen, A., 2007. Integrated dynamic analysis of floating offshore wind turbines. In: Proceedings of 2007 European Wind Energy Conference and Exhibition.

[6] Savenije, L. B., Ashuri, T., Bussel, G. J. W., Staerdahl, J. W., 2010. Dynamic modeling of a spar-type floating offshore wind turbine. In: Scientific Proceedings European Wind Energy Conference & Exhibition.

[7] Matha, D., Schlipf, M., Cordle, A., Pereira, R., Jonkman, J., June 2011. Challenges in simulation of aerodynamics, hydrodynamics, and mooring-line dynamics of floating offshore wind turbines. In: 21st Offshore and Polar Engineering Conference.

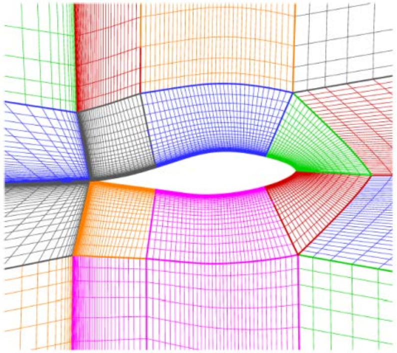
HELICOPTER MULTI-BLOCK (HMB3) SOLVER

- Control volume method
- Parallel - Shared and Distributed memory
- Multi-block (complex geometry) structured grids
- Unstructured mesh method
- Smoothed Particle Hydrodynamics method
- Unsteady RANS - Variety of turbulence models including LES/DES/SAS
- Implicit time marching and harmonic balance methods
- Osher's and Roe's schemes for convective fluxes
- All-Mach schemes based on AUSM/+UP and Roe
- MUSCL scheme for formally 3rd order accuracy
- Central differences for viscous fluxes
- Krylov subspace linear solver with pre-conditioning
- Moving grids, sliding planes, overset method
- Hover formulation, rotor trimming, blade actuation
- Documentation
- Validation database
- Range of utilities for processing data, structural models etc.
- Used by academics and engineers

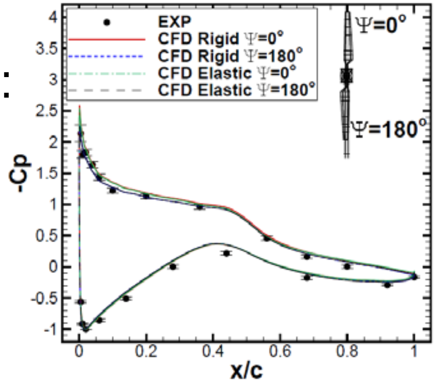


HELICOPTER MULTI-BLOCK (HMB3) SOLVER CONT.

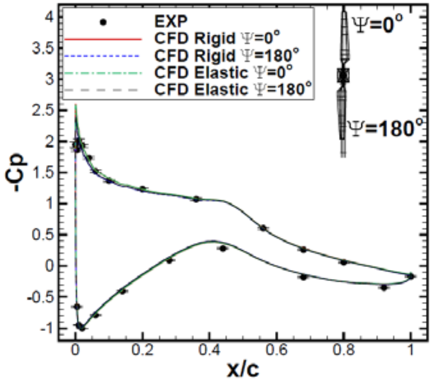
- HMB2 was validated for several wind turbine cases including:
  - NREL Annex XX[1][2] experiment
    - 2 bladed wind turbine
    - 18M cells for the rotor, nacelle and tower
    - k-ω SST turbulence model
    - Wind speed 7m/s
    - Rigid and elastic blades
    - Rotational speed 72RPM
    - Tip speed ratio 5.4



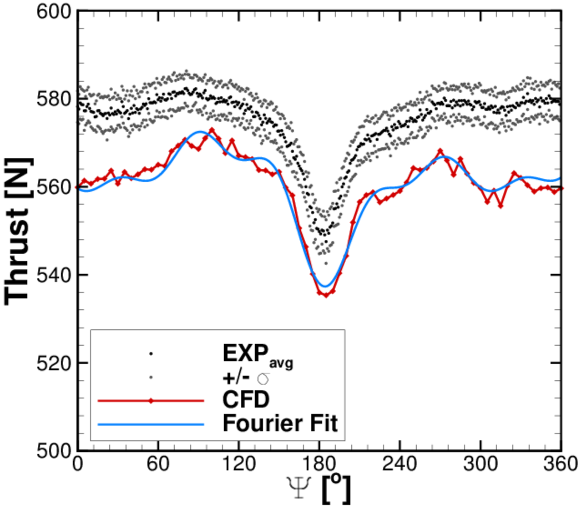
Multi-block grid around one NREL blade sections.

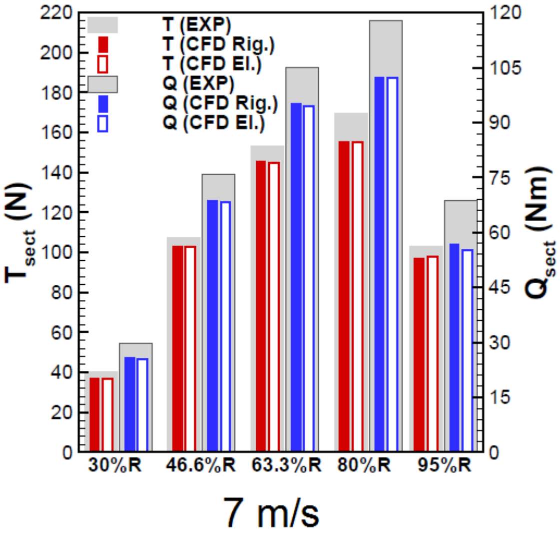


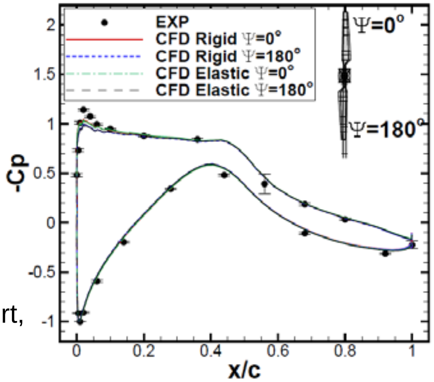
30% R (7m/s)



63.3% R (7m/s)







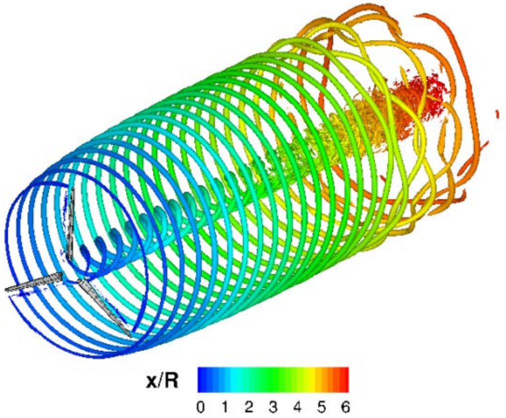
95% R (7m/s)

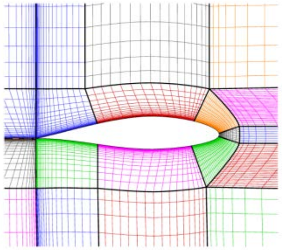
[1] M.M. Hand, D.A. Simms, L.J. Fingersh, D.W. Jager, J.R. Cotrell, S. Schreck, and S.M. Larwood. Unsteady Aerodynamics Experiment Phase VI: Wind Tunnel Test Configurations Available Data Campaigns. NREL Technical Report, December 2001.

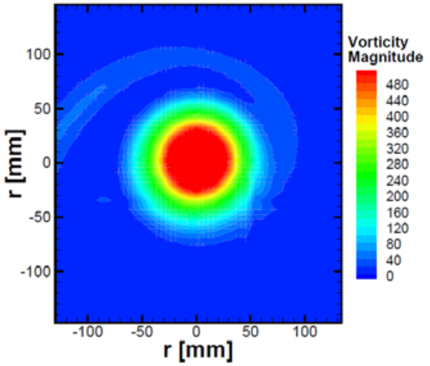
[2] Gomez-Iradi, S., Steijl, R., and Barakos, G. N., “Development and Validation of a CFD Technique for the Aerodynamic Analysis of HAWT,” Journal of Solar Energy Engineering, Vol. 131, (3), 2009, pp. 031009. doi: 10.1115/1.3139144

HELICOPTER MULTI-BLOCK (HMB3) SOLVER CONT.

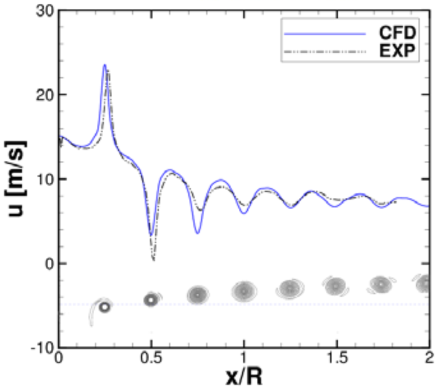
- HMB2 was validated for several wind turbine cases including
  - MEXICO[1][2][3] project experiments
    - 3 bladed wind turbine
    - 2000M cells for the full rotor and wake capture
    - Wind speed 15m/s
    - Rotational speed 424.5RPM
    - Tip speed ratio 6.67

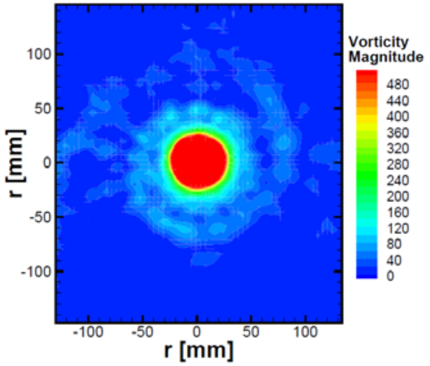



Multi-block grid around one MEXICO blade sections.

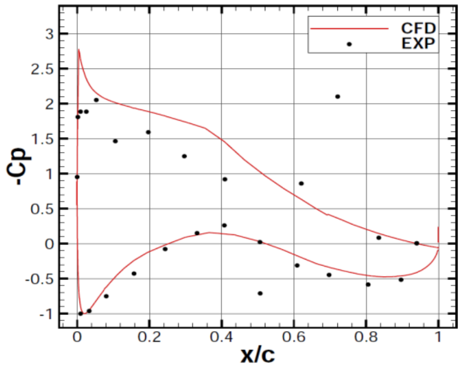


CFD: 15m/s ($\lambda = 6.67$).

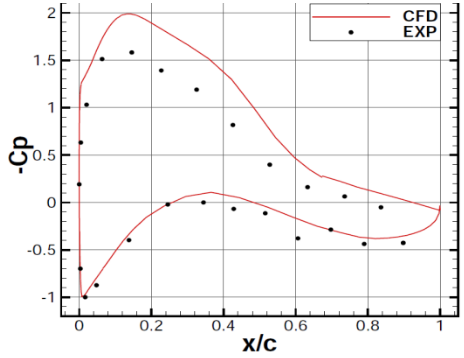




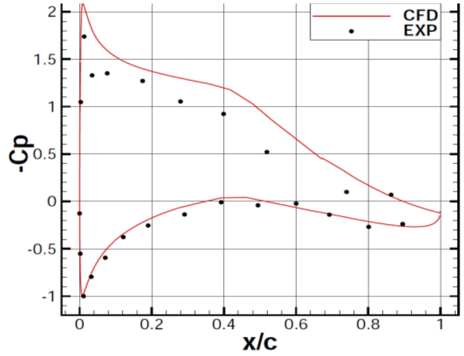
EXP: 15m/s ($\lambda = 6.67$).



35% R (15m/s)



60% R (15m/s)



82% R (15m/s)

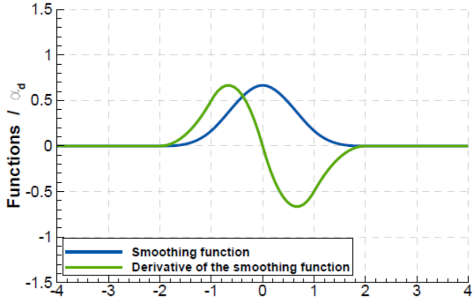
[1] J.G. Schepers and H. Snel. Final Report of IEA Task 29, MexNext (Phase I): Analysis of MEXICO Wind Tunnel Measurements. Technical report, ECN, February 2012.

[2] Carrion, M., Steijl, R., Woodgate, M., Barakos, G., Munduate, X., and Gomez-Iradi, S., “Computational fluid dynamics analysis of the wake behind the MEXICO rotor in axial flow conditions,” Wind Energy, 2014. doi: 10.1002/we.1745

[3] Carrion, M., Woodgate, M., Steijl, R., Barakos, G. N., Gomez-Iradi, S., and Munduate, X., “Understanding Wind-Turbine Wake Breakdown Using Computational Fluid Dynamics,”AIAA Journal, Vol. 53, (3), 2015, pp. 588 – 602. doi: 10.2514/1.J053196

SMOOTHED PARTICLES HYDRODYNAMICS (SPH)

- Particle method, where each particle represents the volume of the fluid
- Solves N/S equations in Lagrangian form
- Assumes weak compressibility of the fluid
- Moving boundaries and free surface resolved naturally
- Does not require floating structure-fluid coupling
- Employs weighted average approach limited by kernel function
- Derivatives of field functions are replaced by the derivative of kernel function
- Various kernel functions are implemented
  - Cubic spline
  - Quadratic spline
  - Gaussian



Cubic spline

- Various explicit time integration schemes are implemented
  - Symplectic
  - Verlet

SMOOTHED PARTICLES HYDRODYNAMICS (SPH) CONT.

- Lagrangian form of governing equations in SPH
  - Continuity equation

$$\frac{D\rho}{Dt} = -\rho\nabla\cdot\mathbf{U} \longrightarrow \frac{D\rho_i}{Dt} = \sum_{i=1}^{N} m_j \mathbf{U}_{ij} \nabla_i W_{ij} \qquad \mathbf{U}_{ij} = \mathbf{U}_i - \mathbf{U}_j$$

  - Momentum equation

$$\frac{D\mathbf{U}}{Dt} = -\frac{1}{\rho}\nabla p + \mathbf{g} + \Gamma \longrightarrow \frac{D\mathbf{U}_i}{Dt} = -\sum_{j=1}^{N} m_j \left[\frac{p_j}{\rho_j^2} + \frac{p_i}{\rho_i^2} + \Pi_{ij}\right] \nabla_i W_{ij} + \mathbf{g}$$

  - Equation of state

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

More details:

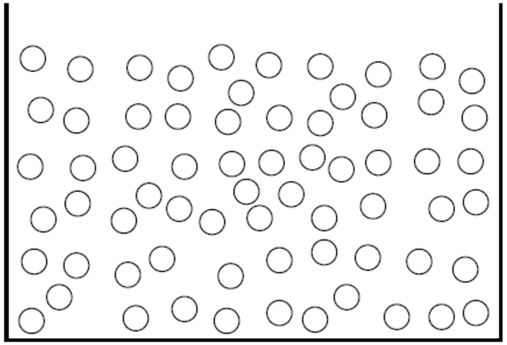
[1] Liu G.R. and Liu M.B. *Smoothed particle hydrodynamics - a meshfree method. World Scientific,* Singapore, 2003.

[2] Monaghan J.J. Smoothed particle hydrodynamics. *Annual review of astronomy and astrophysics,* 30:543–574, 1992.

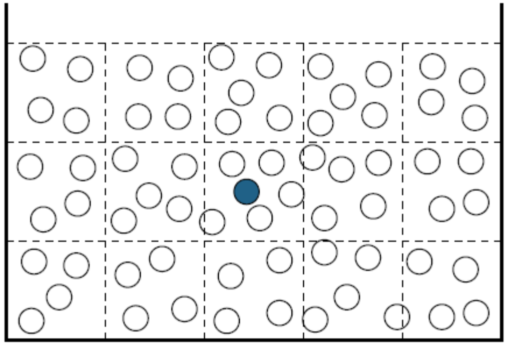
[3] Monaghan J.J. Simulating free surface flows with sph. *Journal of Computational Physics, 110(2):399* – 406, 1994.

SMOOTHED PARTICLES HYDRODYNAMICS (SPH) CONT.

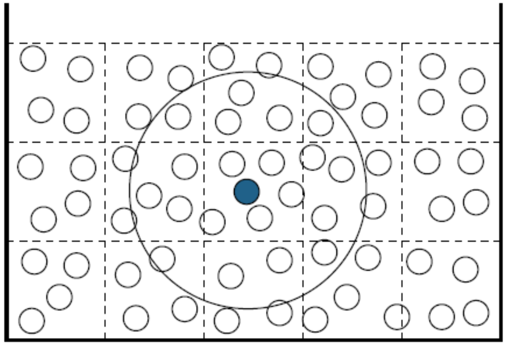
- SPH method key steps: **a)** represent the problem domain by a set of particles **b)** use particle approximation and iteratively choose particle **c)** find all the particles close to the current particle **d)** flag the interaction particles **e)** solve the NS equations using all the particles within the support domain **f)** update the particle to its new position.



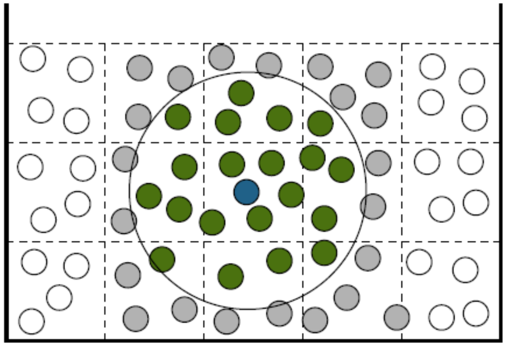
(a)



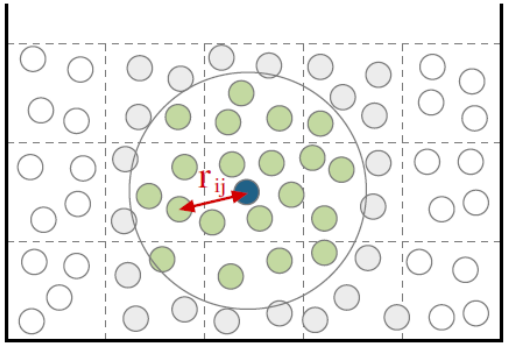
(b)



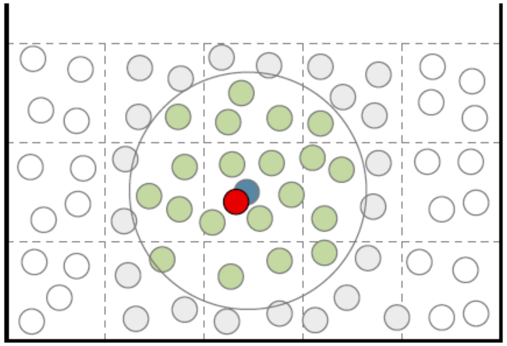
(c)



(d)



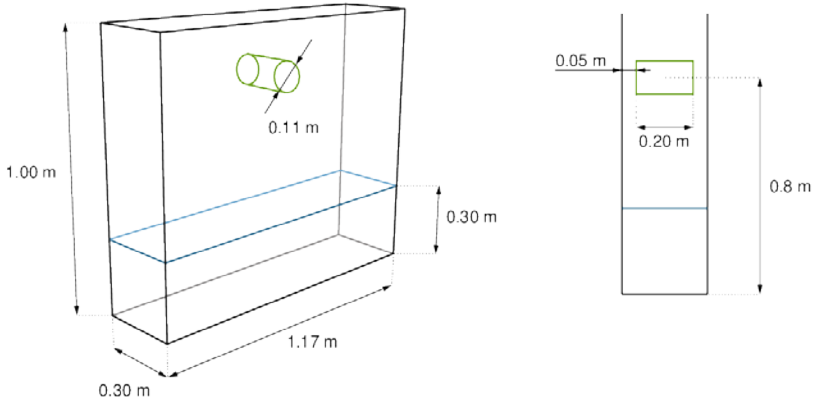
(e)



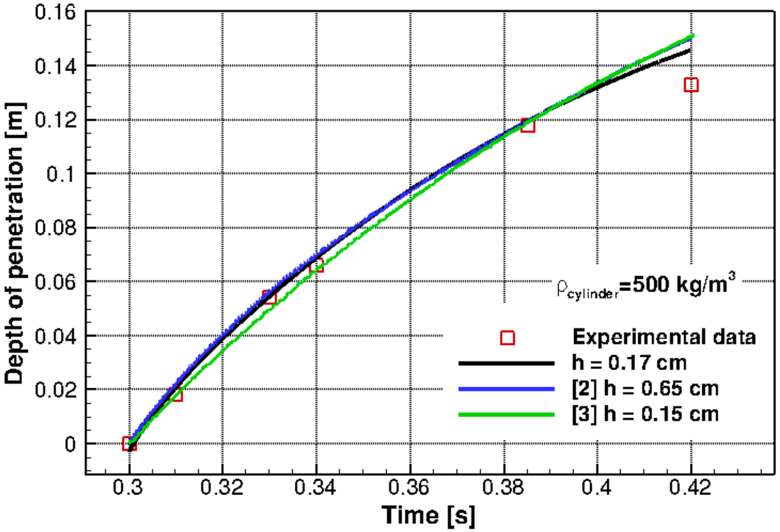
(f)

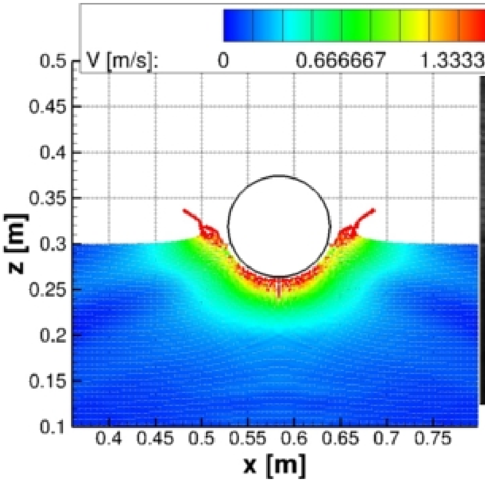
SMOOTHED PARTICLES HYDRODYNAMICS (SPH) CONT.

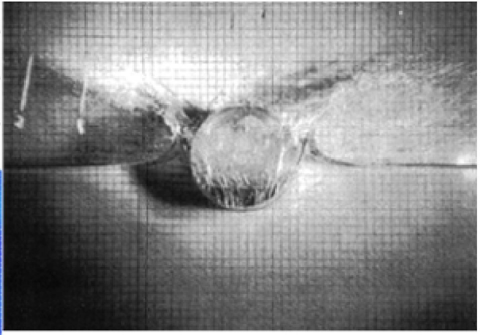
- High speed entry of a half-buoyant cylinder into calm water.

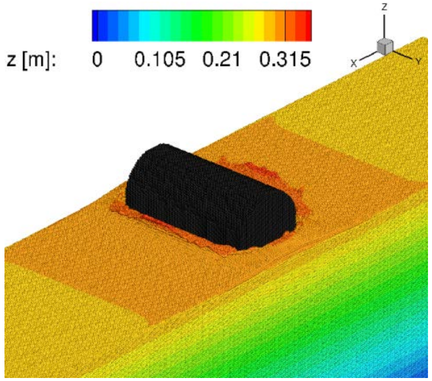


(a) isometric view (b) side view









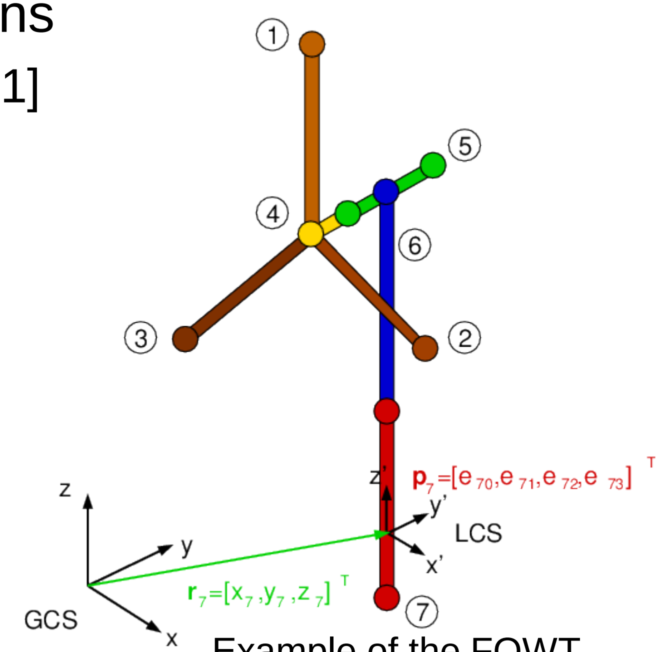
[1] Greenhow M. and Lin W.M. Nonlinear-free surface effects: Experiments and theory. Technical Report 83-19, MIT, September 1983.

[2] Vandamme J., Zou Q., and Reeve D.E. Modeling floating object entry and exit using smoothed particle hydrodynamics. *Journal of Waterway, Port, Coastal and Ocean Engineering, 137(5):213–224, 2011.*

[3] Skillen A., Lind S., Stansby P.K., and Rogers B.D. Incompressible Smoothed Particle Hydrodynamics (SPH) with reduced temporal noise and generalised Fickian smoothing applied to body-water slam and efficient wave-body interaction. *Computer Methods in Applied Mechanics and Engineering, (0):–,* 2013.

MULTI-BODY DYNAMIC MODULE (MBDM)

- Assumptions of the model:
  - Rigid bodies
  - Frictionless joints
- Unit quaternions are employed to orient bodies in space
- The non-linear constraint equations
  - Solved using Newton-Raphson method with exact analytical Jacobian
- System of mixed differential-algebraic equations
  - Solved with the coordinate partitioning method[1]
- Explicit integration schemes
  - Forward Euler
  - Symplectic
  - Runge-Kutta 4th order
- Additionally
  - Arbitrary number of springs and dampers
    - Between bodies
    - Between bodies and prescribed points



Example of the FOWT modelled with MBDM

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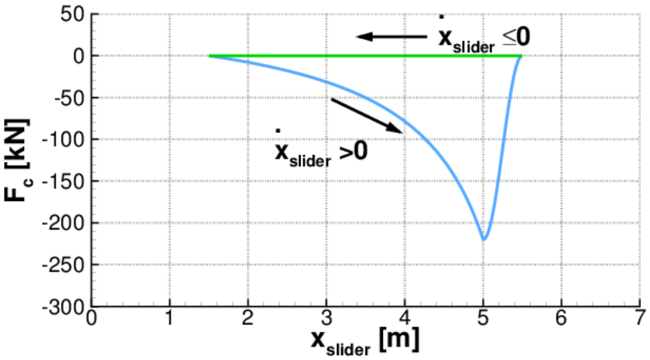
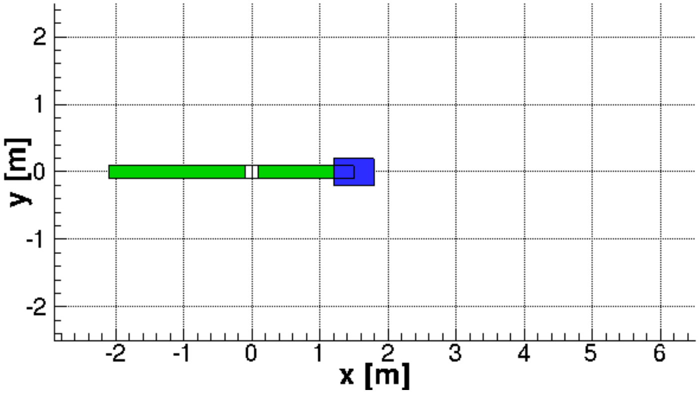
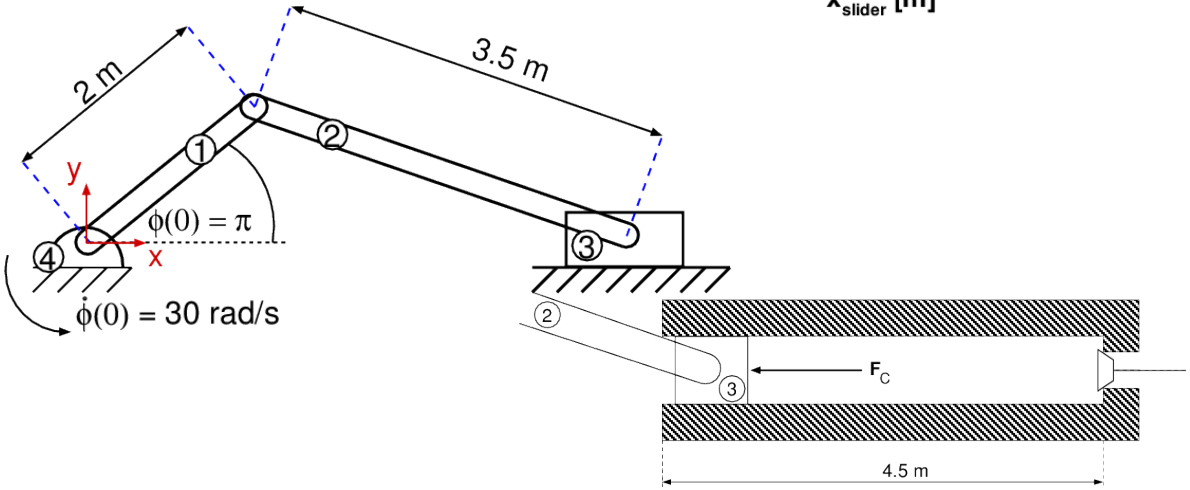
[1] Nikravesh, P. E., Computer-aided Analysis of Mechanical Systems, Prentice-Hall, Inc., Upper Saddle River, NJ, USA, 1988.

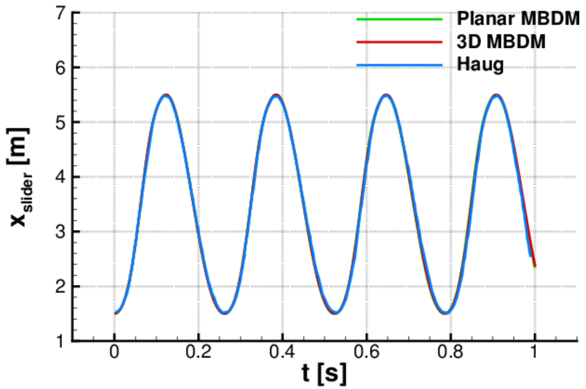
MBDM VALIDATION

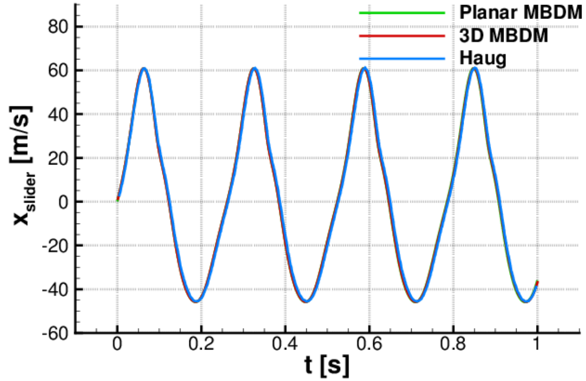
- Slider-crank dynamic model results
  - Constant torque applied to the crank: $41.450\cdot10^3$ Nm
  - Gravity force acting in positive *x* direction
  - Slider acts as a compressor with reaction force F_c
  - Runge-Kutta 4th order scheme with $\Delta t=0.001$s

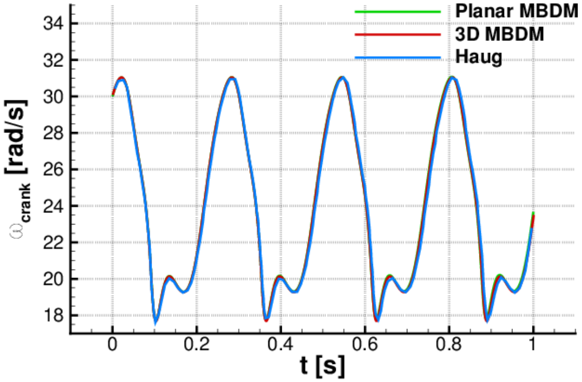










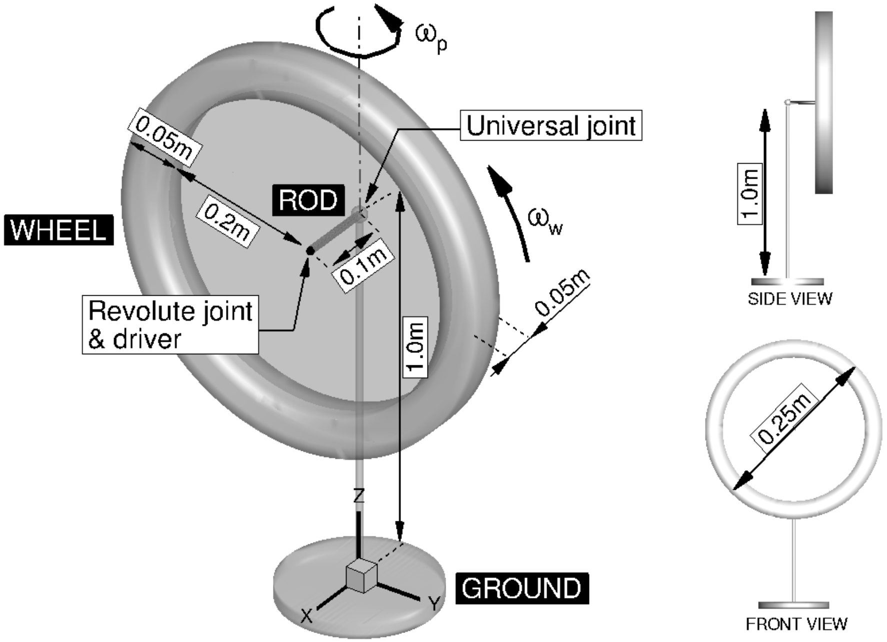


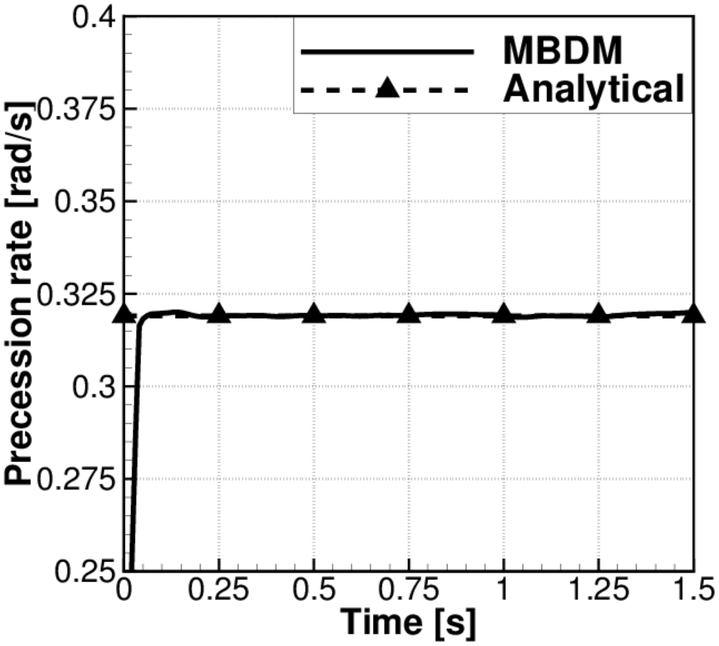
[1] E. J. Haug, Computer aided kinematics and dynamics of mechanical systems. Allyn and Bacon, Boston, 1989.

MBDM VALIDATION CONT.

- Gyroscopic wheel results
  - Constant rotational speed of the wheel:
    $$\omega_w = 60 rad/s$$
  - Gravitational force applied to all bodies
  - Analytical precession obtained from the gyroscopic approximation:
    $$\omega_p = \tau / L = m_w g l / I_{xx} \omega_w$$

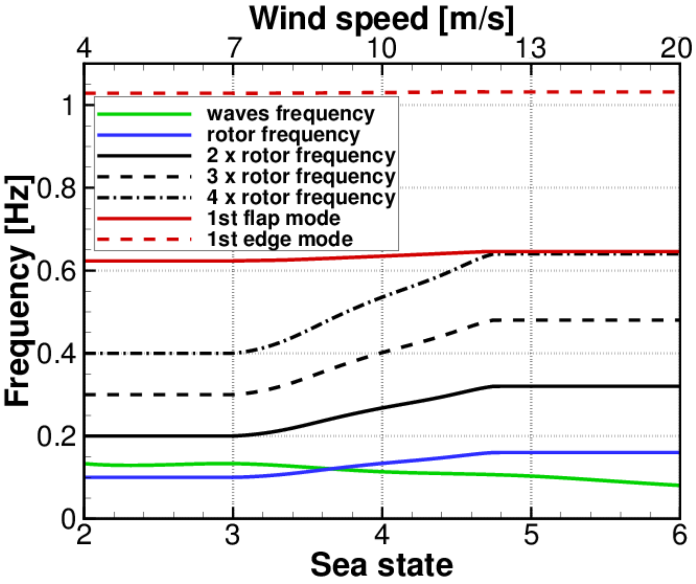
Name	Mass $[kg]$	Inertia tensor $[kg \cdot m^2]$
Wheel	28.3	$\begin{bmatrix} 1.45 & 0 & 0 \\ 0 & 0.73 & 0 \\ 0 & 0 & 0.73 \end{bmatrix}$
Rod	0.1	$\begin{bmatrix} 10^{-6} & 0 & 0 \\ 0 & 8.3 \cdot 10^{-5} & 0 \\ 0 & 0 & 8.3 \cdot 10^{-5} \end{bmatrix}$





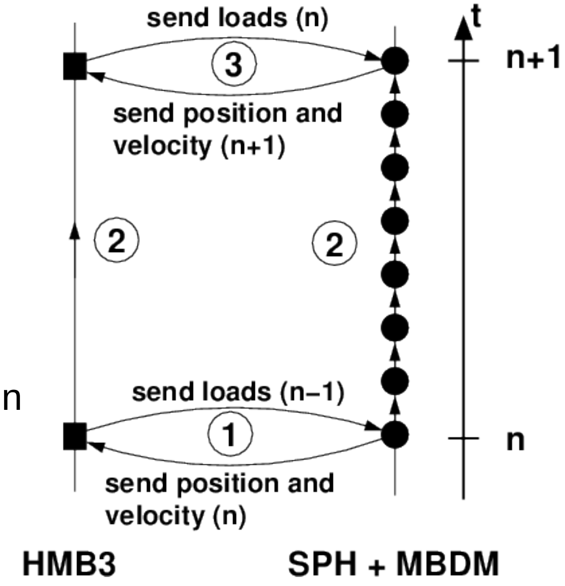
COUPLING

- Coupling problems have been extensively studied
  - Fluid-Structure Interaction
  - Thermal-Structure Interaction
  - Structure-Soil Interaction
- Coupling methods
  - Weak (loose)
    - explicit schemes
    - each solver evaluated only once per time step
    - simple to implement and computationally inexpensive
  - Strong (tight)
    - implicit schemes
    - require multiple evaluation of solution with each step
    - slow convergence with simple relaxation methods
      - Adaptive Aitken relaxation, fixed under-relaxation, steepest descent relaxation
    - fast convergence if Jacobians are employed, most likely requires approximation of Jacobian-vector product
      - Interface Quasi-Newton algorithm with an approximation for the inverse of the Jacobian from a Least-Squares model
      - Interface Block Quasi-Newton with an approximation for the Jacobian from a Least-Squares model
      - Interface Generalised Minimal Residual method
    - difficult to implement and computationally expensive



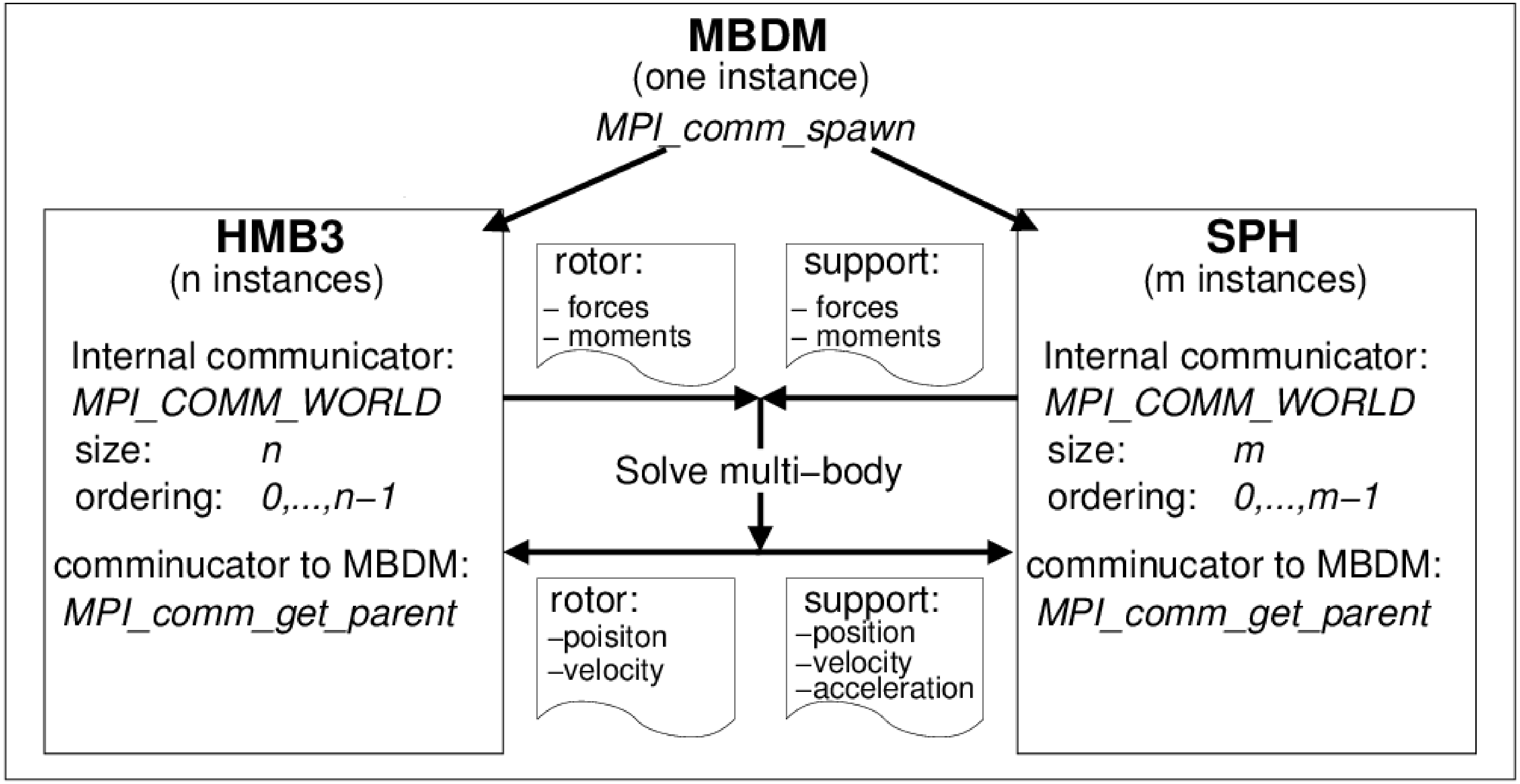
WEAK COUPLING

- Communication through the Message Passing Interface (MPI)
- MBDM substitutes the body motion routines of the SPH solver:
  - – reduces the number of coupled solvers to two - SPH and HMB3
- SPH time step of $\Delta t_{SPH} = 2 \cdot 10^{-4}\ s$ – required by explicit scheme
- HMB3 time step of $\Delta t_{HMB3} = 2 \cdot 10^{-2} s = 100\ \Delta t_{SPH}$ – dual-time implicit method
- Synchronisation of the solvers at the end of each HMB3 step
- Parallel conventional staggered method
  - – At each synchronisation time step
    - position and velocities of the rotor are transferred to the HMB3
    - forces and moments on the rotor are passed to the SPH
  - – Advance both solvers in parallel to a new time level
    - SPH performs 100 symplectic steps keeping forces constant
    - HMB2 performs 250 implicit pseudo-time steps keeping position and velocities constant
  - – Once the synchronisation point is reached, repeat



MPI IMPLEMENTATION

- MBDM is in charge of starting both solvers
- MBDM replaces SPH’s body motion routines
- MBDM gathers all the information about forces and moment and returns positions and velocities



MBDM
(one instance)
MPI_comm_spawn

HMB3
(n instances)
Internal communicator:
MPI_COMM_WORLD
size: *n*
ordering: *0,...,n–1*
comminucator to MBDM:
MPI_comm_get_parent

rotor:
– forces
– moments

support:
– forces
– moments

Solve multi–body

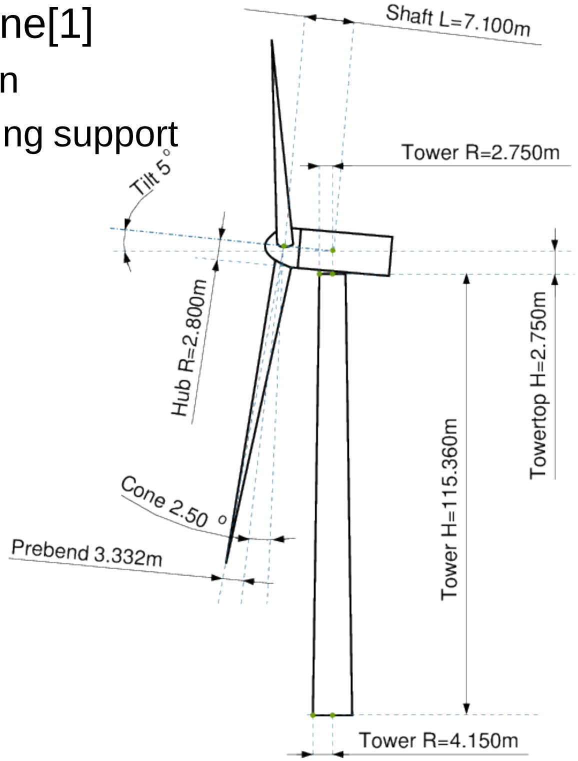
rotor:
–poisiton
–velocity

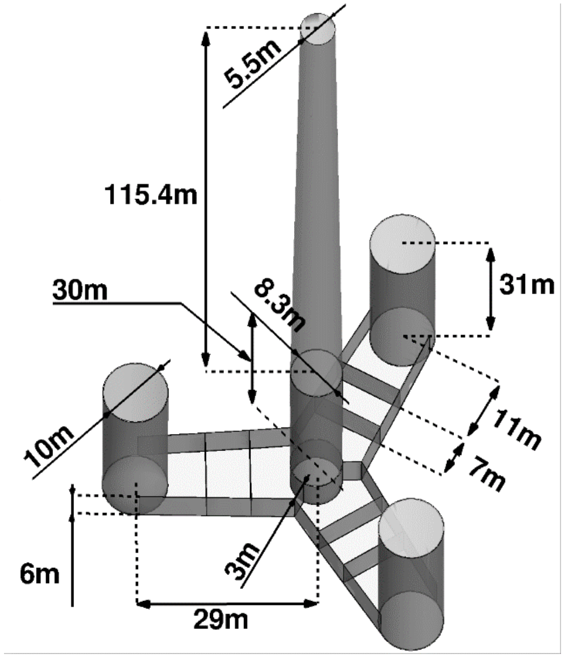
support:
–position
–velocity
–acceleration

SPH
(m instances)
Internal communicator:
MPI_COMM_WORLD
size: *m*
ordering: *0,...,m–1*
comminucator to MBDM:
MPI_comm_get_parent

TEST CASE DESCRIPTION

- DTU 10MW reference wind turbine[1]
  - Designed for offshore application
  - Only tower is designed, no floating support
  - Number of blades 3
  - Rotor diameter 178.3m
  - Hub height 119 m
  - Rated power 10-MW
  - Rated wind speed 11.4 m/s
  - Rotor pre-cone angle -2.5°
  - Blade pre-bend 3.3m
  - Nacelle tilt 5°
  - Upwind configuration





- Floating support design
  - mass properties

Component	Mass [kg]
Support	$2{,}351{,}188\cdot10^3$
Tower	$628{,}442\cdot10^3$
Nacelle	$446{,}036\cdot10^3$
Rotor	$227{,}962\cdot10^3$
Total	$3{,}653{,}628\cdot10^3$
Total with balast	$4{,}451{,}900\cdot10^3$

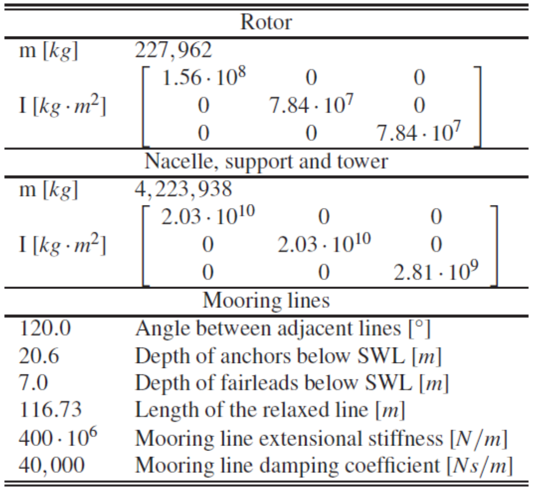
– estimated mechanical properties

Draft	7.25 m
CoG below SWL	0.0 m
Roll inertia about centre of mass (Ixx)	$2.030\cdot10^{10}$ kg·m^2
Pitch inertia about centre of mass (Iyy)	$2.030\cdot10^{10}$ kg·m^2
Yaw inertia about centre of mass (Izz)	$2.809\cdot10^{9}$ kg·m^2

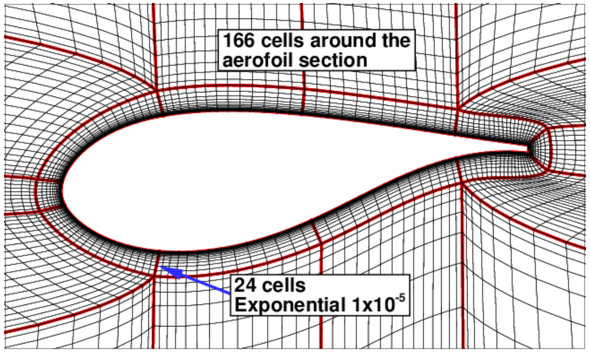
[1] Bak C., Zhale F., Bitsche R., Kim T., Yde A., Henriksen L.C., Andersen P.B., Natarajan A., and Hansen M.H. Description of the DTU 10 MW Reference Wind Turbine. DTU Wind Energy Report-I-0092, Technical University of Denmark, June 2013.

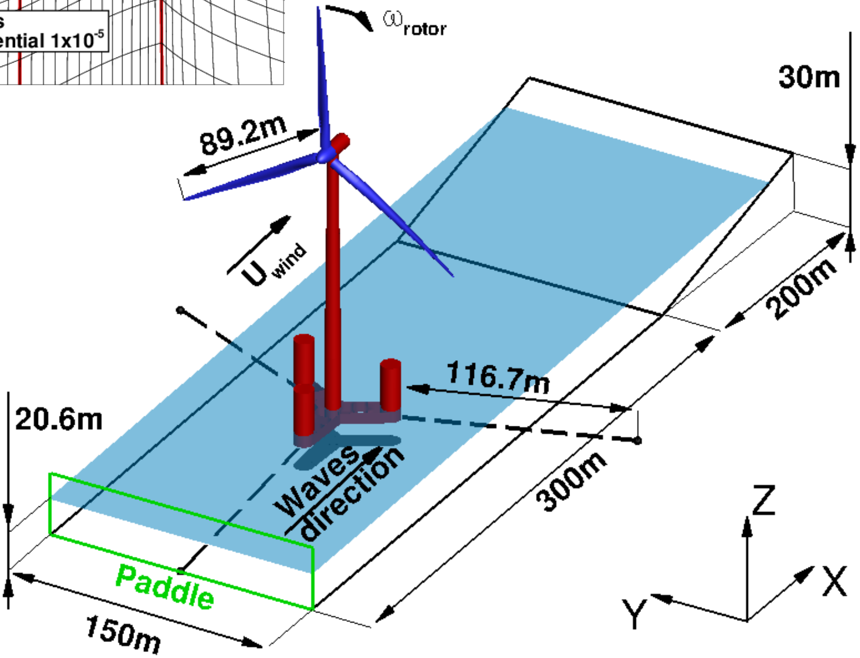
TEST CASE DESCRIPTION CONT.

- HMB2 aerodynamic domain
  - 8M cells mesh for the full rotor and nacelle
  - k-ω SST turbulence model
- SPH hydrodynamic domain
  - 5M particles
  - Artificial viscosity model
  - Cubic spline kernel
- MBDM configuration
  - 2 rigid bodies
  - 3 mooring lines as springs and dampe
  - 1 revolute driver of constant speed
- Waves imposed by sinusoidal paddle motion and dissipated by a beach-like slope
- Initial conditions obtained separately before coupling



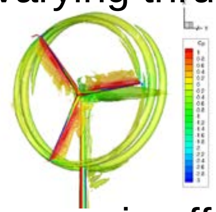
Rotor	
m $[kg]$	227,962
I $[kg \cdot m^2]$	$\begin{bmatrix} 1.56\cdot10^8 & 0 & 0 \\ 0 & 7.84\cdot10^7 & 0 \\ 0 & 0 & 7.84\cdot10^7 \end{bmatrix}$
Nacelle, support and tower	
m $[kg]$	4,223,938
I $[kg \cdot m^2]$	$\begin{bmatrix} 2.03\cdot10^{10} & 0 & 0 \\ 0 & 2.03\cdot10^{10} & 0 \\ 0 & 0 & 2.81\cdot10^9 \end{bmatrix}$
Mooring lines	
120.0	Angle between adjacent lines [°]
20.6	Depth of anchors below SWL $[m]$
7.0	Depth of fairleads below SWL $[m]$
116.73	Length of the relaxed line $[m]$
$400\cdot10^6$	Mooring line extensional stiffness $[N/m]$
40,000	Mooring line damping coefficient $[Ns/m]$

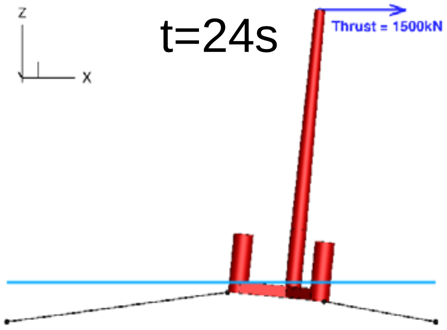


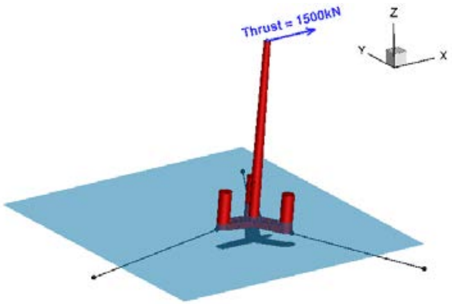


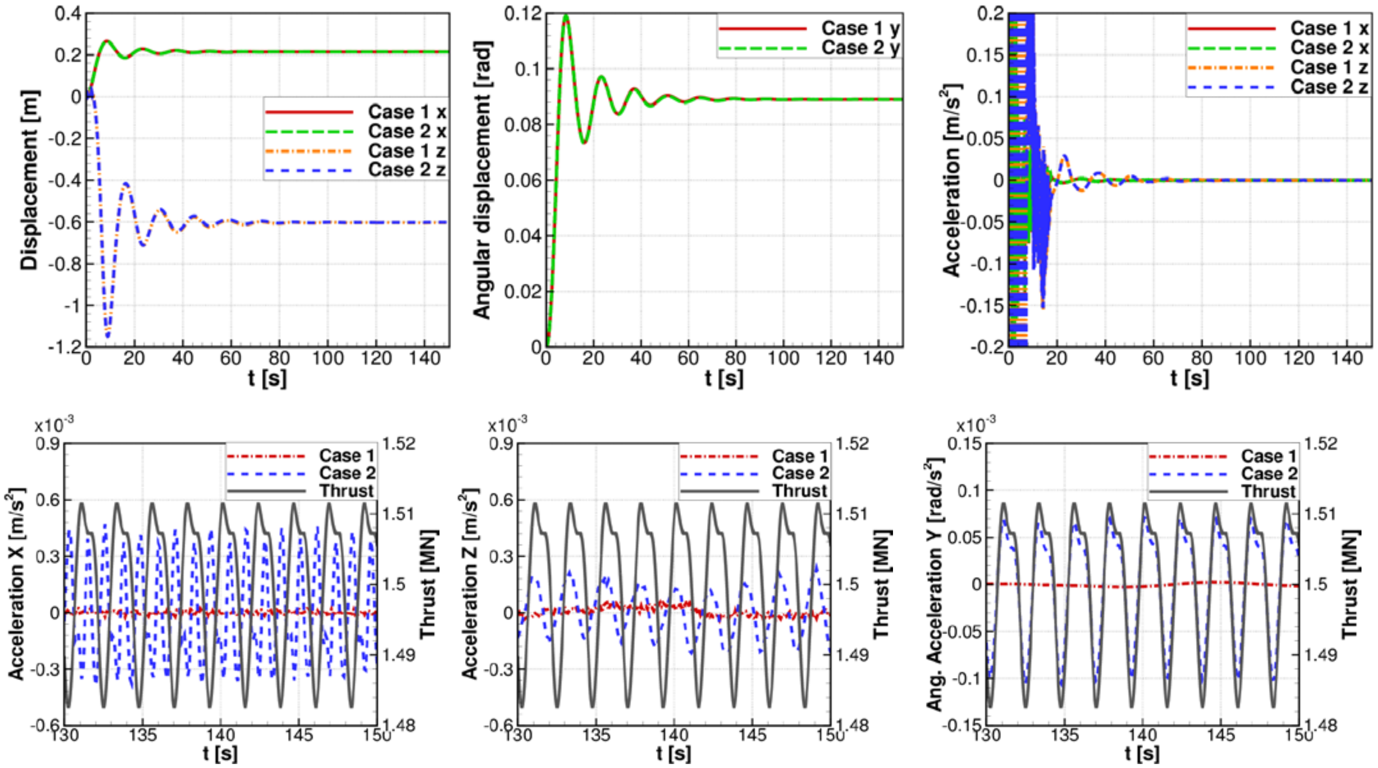
DECOUPLED COMPUTATIONS

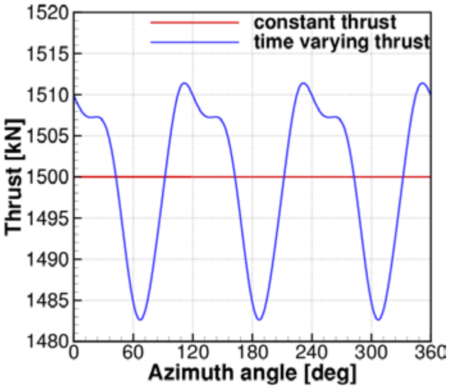
- Aerodynamic forcing is prescribed: constant or time varying thrust applied at the location of nacelle
- Variation of thrust estimated form CFD computation
- Calm water
- Inertia properties of the rotor not considered – no gyroscopic effect
- Centre of mass offset due to rotor overhung not included







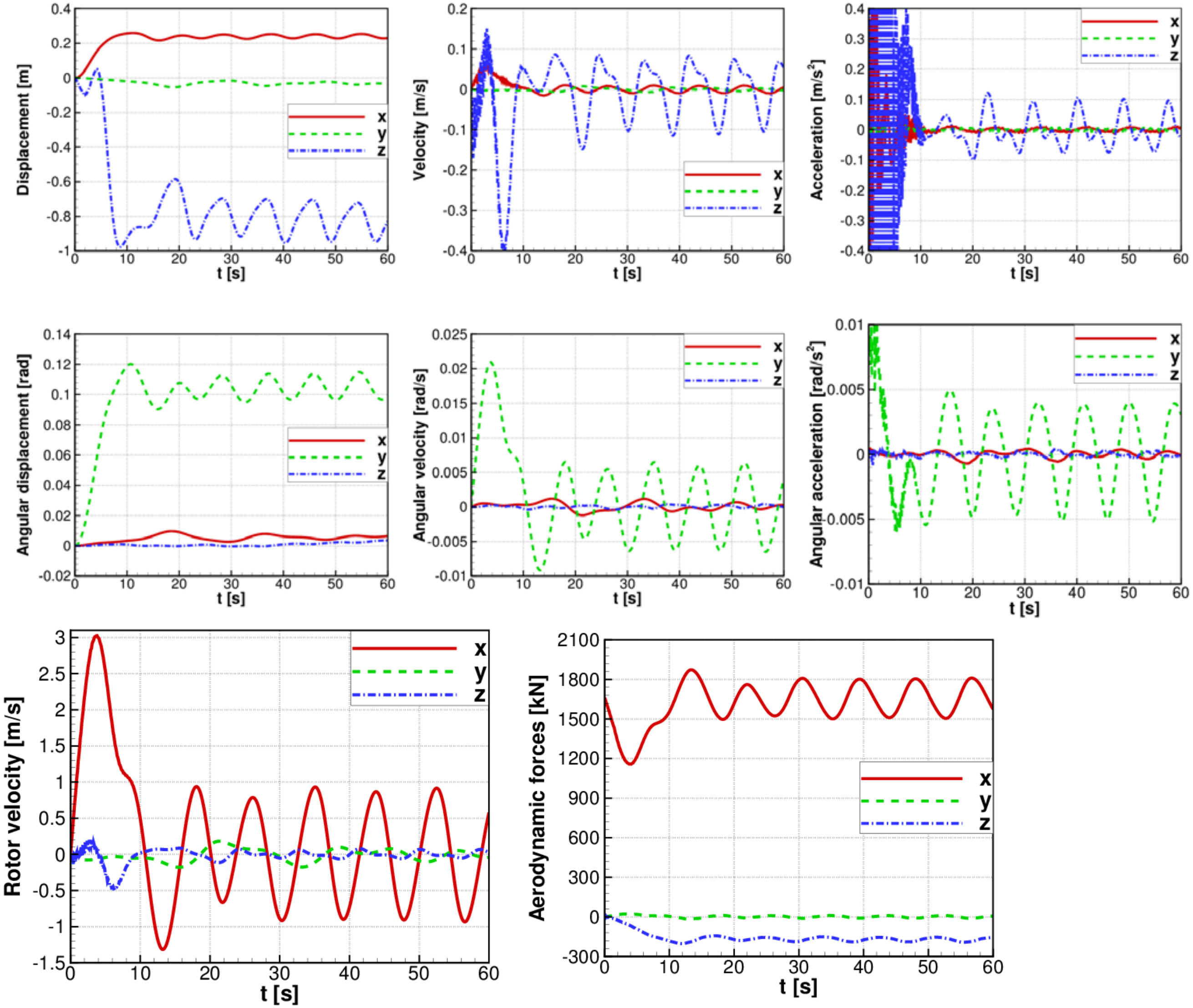


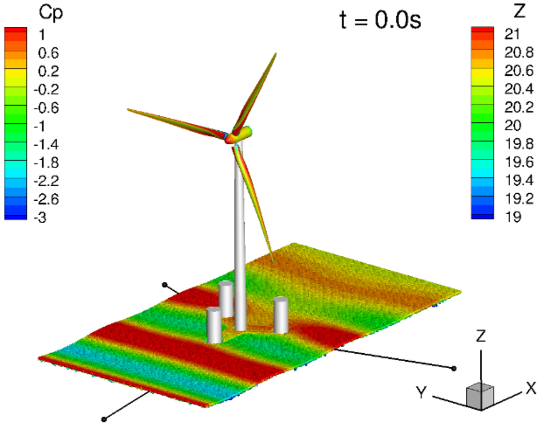


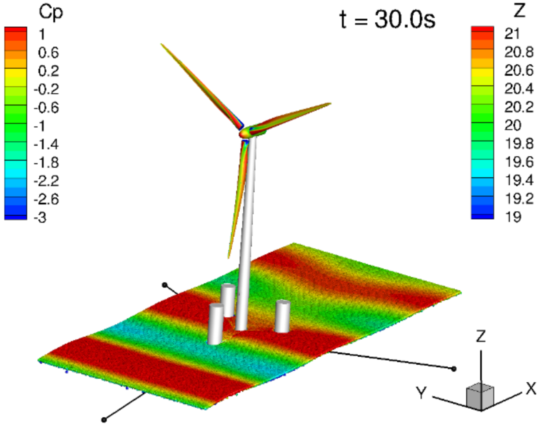
Comparison of the dynamics of the support for two test cases: constant thrust (Case 1) and time varying thrust (Case 2)

RESULTS OF WEAKLY COUPLED COMPUTATION

- Parallel conventional staggered method







RESULTS OF WEAKLY COUPLED COMPUTATION CONT.

- Displacement in the direction of wind and waves by ~0.25m
- Sinking by ~0.9m
- Maximum dynamic pitch ~0.12rad (~6.9deg)
- Initial settling dominates over the first wave passage
- The effect of consecutive wave passages clearly visible
- Initial high frequency response due to the sudden release of the floating body

SUMMARY AND FUTURE WORK

- The work has so far developed the weakly coupled method necessary for realistic simulation of dynamic FOWTs
- Strongly coupled model is being developed
- There is a clear need for validation data from scaled or full-size FOWTS
- There is also a clear need for time-resolved aerodynamic data alongside the usual forces, accelerations and moments measured in water-basins
- Future work includes
  - Implementation of other coupling algorithms – weak and strong
  - Implementation of mooring lines as set of rigid bodies linked by springs and dampers, or alternatively with the catenary line equation
  - FOWT model with tower, elastic blades and actuated flaps
  - Attempt to couple a load control algorithm with the flap actuation
  - Analysis of the WT undergoing prescribed yawing and pitching motion

THANK YOU FOR YOUR ATTENTION