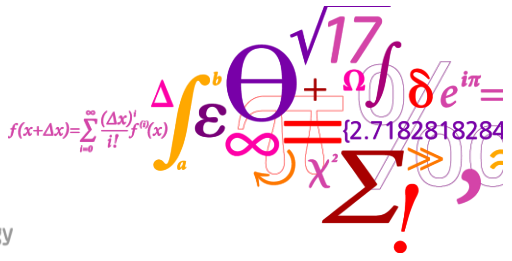
Floating turbines

Torben J. Larsen



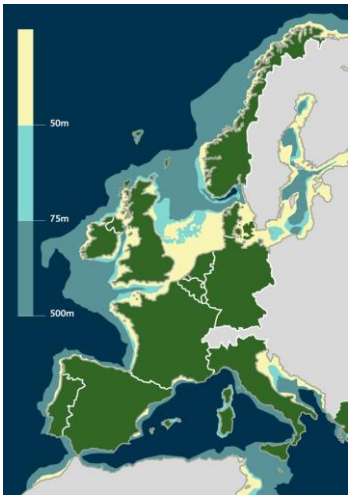
Risø DTU
National Laboratory for Sustainable Energy

Overview

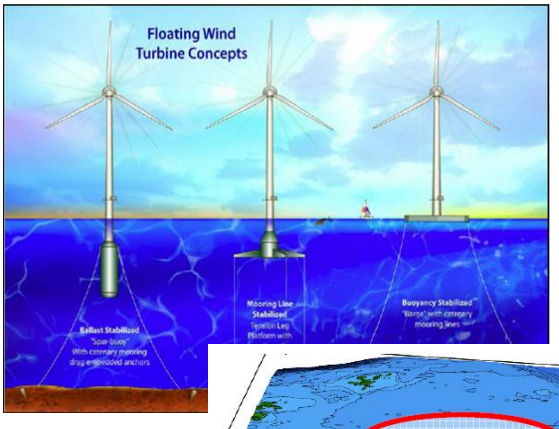
- Introduction
- Examples of floating turbine concepts
- Modeling floating turbines
- Modeling mooring lines
- Modeling combined wind and wave energy plant
- Code comparison project

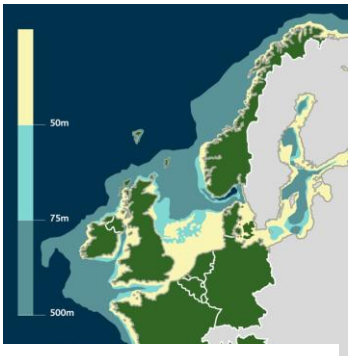
Why floating turbines?

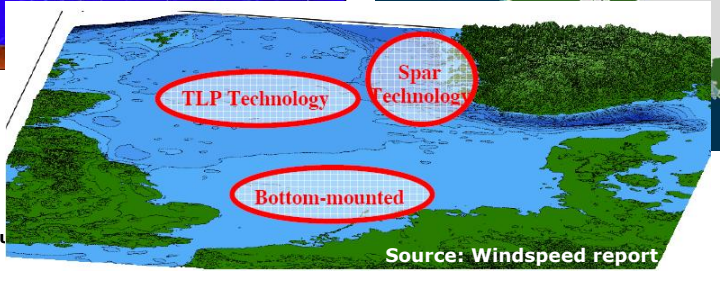
- Countries with deep water close to coast (USA, China, Japan, Norway, …)
- New areas for offshore wind
- Energy supply for offshore installations (oil rigs)
- At some water depth, floating foundations will be the economical best solution.
- Other conceptual ideas:
  - Mass production and assembly, and tow complete turbine to site
  - Combining wave energy conversion plants with wind energy



Conceptual floating foundations



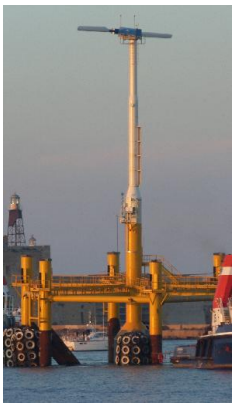




Blue H – the first floating turbine

World's First Floating Wind Turbine

- Demonstration project 10km from coast of Italy ongoing
- Submerged tension-leg platform
- Very sparse information available, but turbine is small and construction huge . . .



HYWIND concept by StatoilHydro

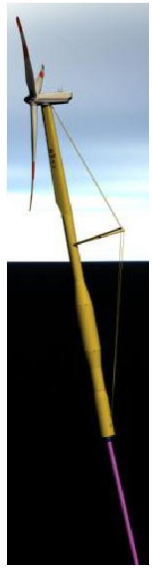
World's First Large Scale Floating Wind Turbine

- 2-5MW pitch controlled wind turbine
- Floating spar bouy attached to three mooring lines
- Intended for water depths between 120 – 700m.

- Demonstration project with Siemens 2.3MW 10km outside west coast of Norway.

SWAY concept

- Downwind rotor
- Wire construction to limit tower load
- Single tension leg (Stiff in torsion)
- Special joint bearing to avoid bending in tension leg
- Yaw bearing between tower bottom and tension leg
- Tower shape with non-circular shape
- Gravity anchor system

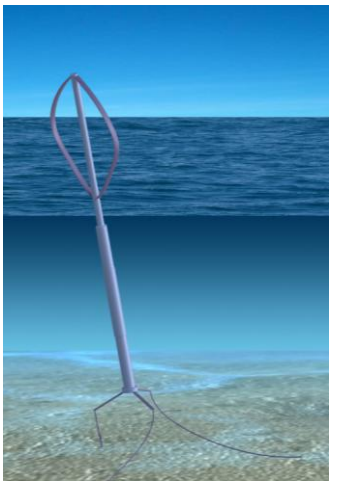


WindFloat concept by Principle Power

- Semi-submersible, pitch & roll restoring through waterplane area & fixed water ballast
- Tower mounted on one column
- Active ballast system maintains zero-mean pitch angle
- Heave plates improve natural response periods & damping

Offshore Vertical Axis Wind Turbine With Floating and Rotating Foundation

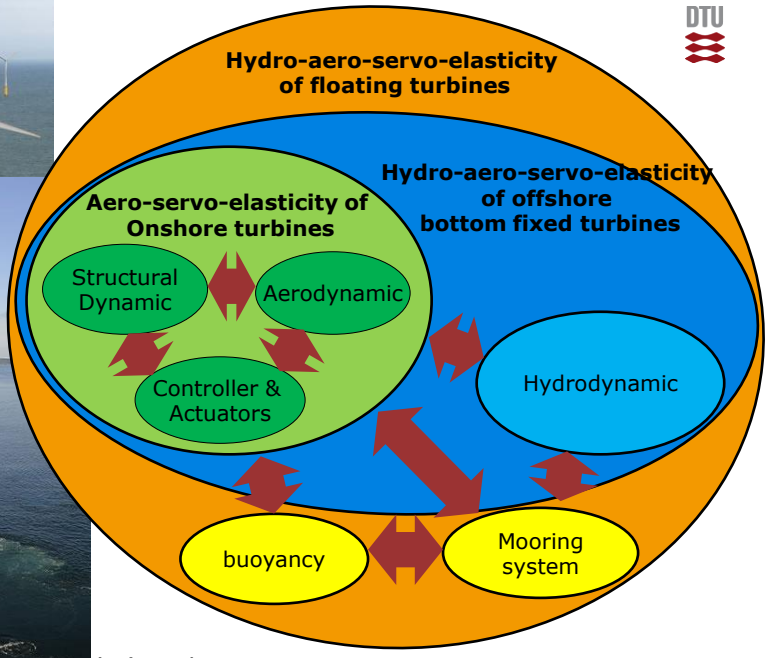
- Reduce issues with tower top mass
- Uses water column as main bearing
- New EU project to Risø DTU
- One PhD on model development
- Develop vertical axis aerodynamic module to HAWC2



Poseidon, combined wind and wave

World's first combined wind and wave plant

- Wave energy platform
- Dimensions are very large. Three turbines can produce extra power from wind – and contribute to the total damping of motion.



11 sity of Denmark

HAWC2-Risø's Hydro-aero-servo-elastic code

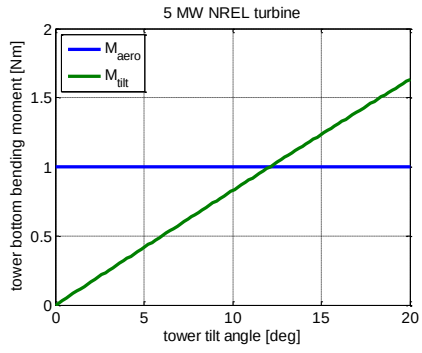
Continued collaboration between Statoil (StatoilHydro) and Risø DTU

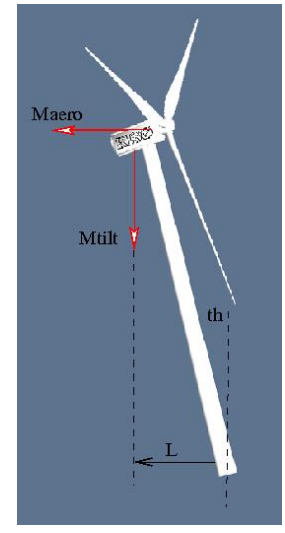
- Floating foundations
- Hydrodynamic forces only for slender bodies (HYWIND concept)
- Buoyancy forces based on pressure distribution
- Quasistatic mooring lines
- Resent developments
  - Dynamic mooring system
  - Full coupling to hydrodynamic module from DHI (WAMSIM)

12 Risø DTU, Technical University of Denmark

High tower bottom bending moments

- Tower tilt caused by foundation pitch or roll
- Mostly in same direction as the trust
- Extreme wind conditions
- Failure in float stabilizing mechanism (leak, slack mooring, etc.)





Focus on the HYWIND concept: Vibration modes.

New vibrations mode occurs for the floating concept

1. Horizontal translation (2 modes) 0.01Hz
2. Rigid body rotation, tilt (2modes) 0.035Hz
3. Vertical translation 0.037Hz

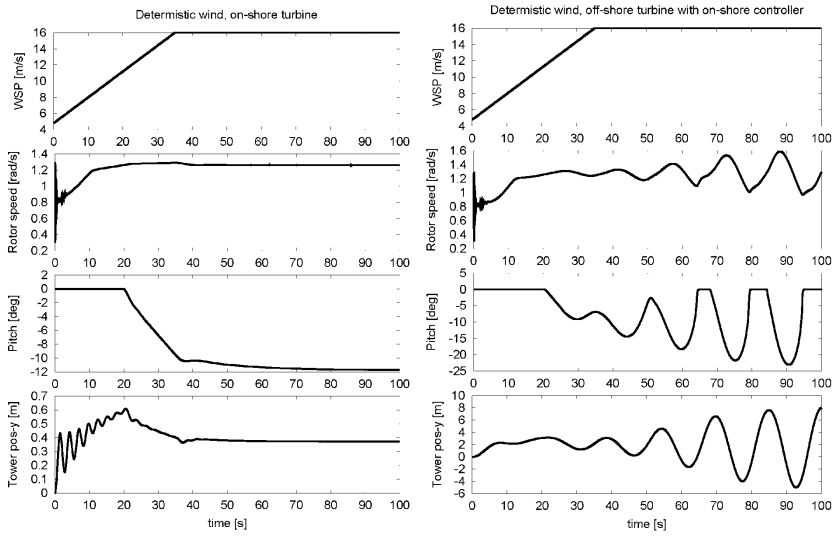
These modes are more low frequent than the dominating wave excitation.

For a similar on-shore turbine, the lowest natural frequency is

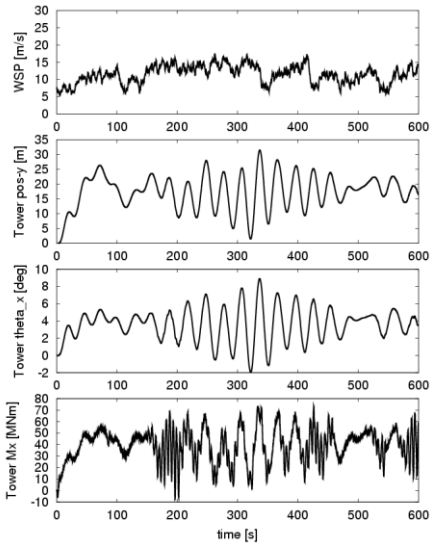
1st tower bending 0.4Hz

The stability problem – deterministic wind

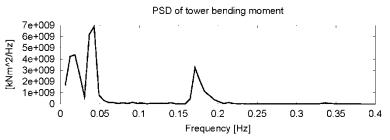
On-shore and floating turbine with normal on-shore controller



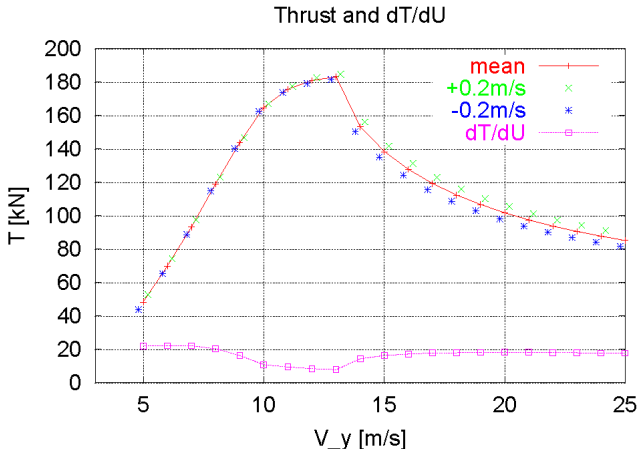
The stability problem – turbulent wind



- Main energy content at 0.035Hz (1st tilt rot.)
- Lateral and vertical modes damped by mooring lines.
- The tilt rotation mode is mainly damped by aerodynamics – but the aerodynamic damping can be negative!



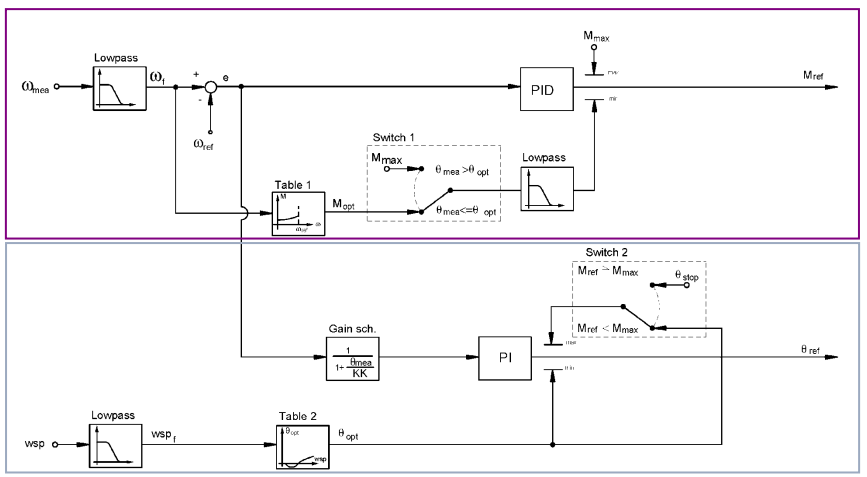
Aerodynamic damping on rotors



- A positive dT/dU gradient results in positive damping on tower motion
- When tower frequency is higher than pitch frequency the damping is positive

The Controller

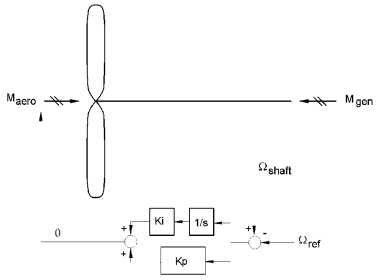
Generator control

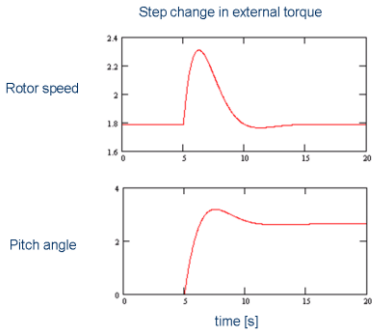


Pitch control

Controller gains for high wind operation

The natural frequency of the system depends on structure, aerodynamic and controller gain!

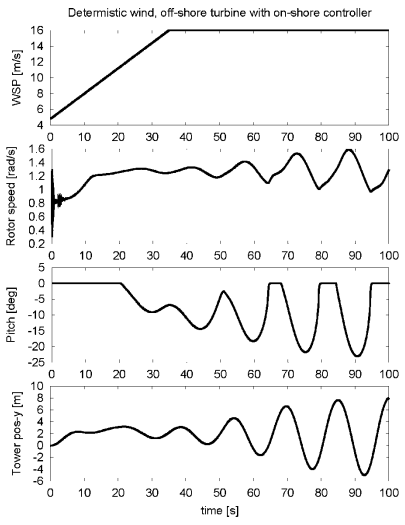


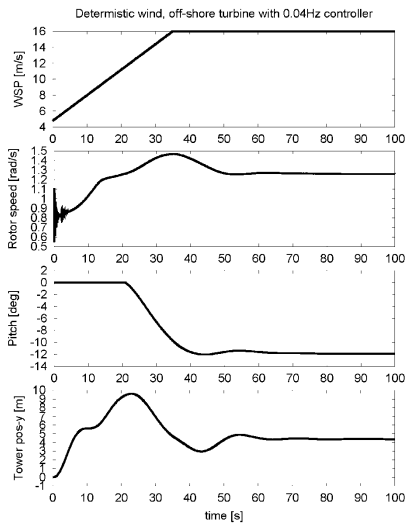


$$K_I = \frac{\Omega_0 I \omega_0^2}{\frac{\partial P}{\partial \theta}} \qquad K_p = \frac{2\zeta K_I}{\omega_0}$$

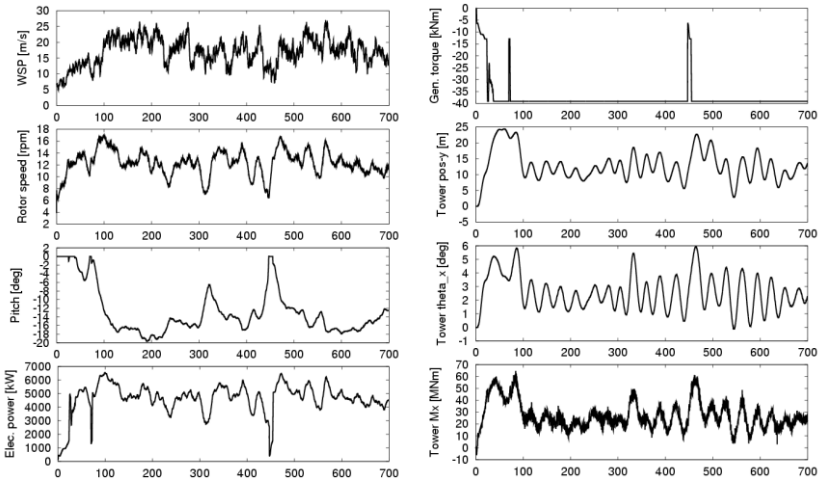
Rule of thumb: $\omega_0 = 0.1Hz \quad \zeta = 0.7$

Controller with a lower frequency than the tower frequency





Results 18m/s

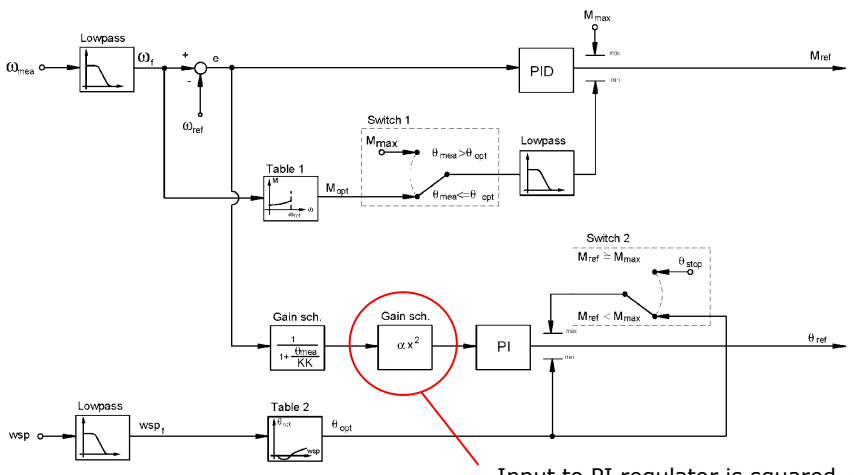


Tower response OK

Speed and power variation +/- 30% compared to nominal

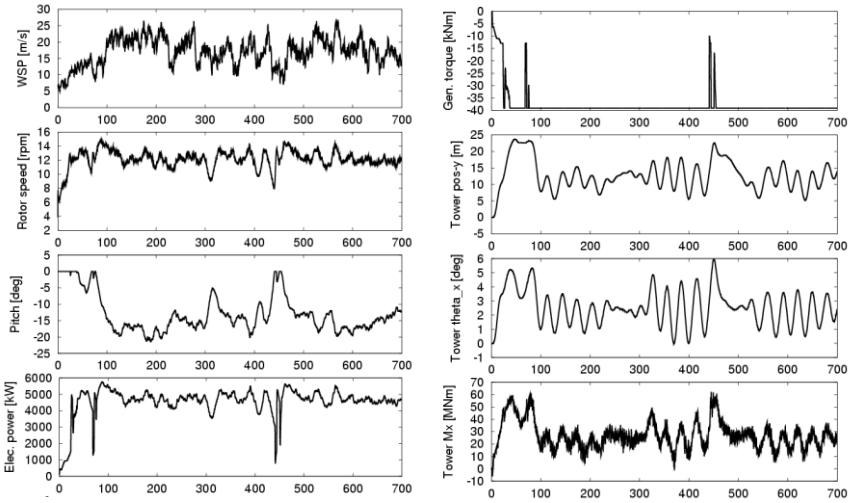
Improvements in the control

Non-linear gain on speed deviation



Input to PI regulator is squared. α is a gain constant.

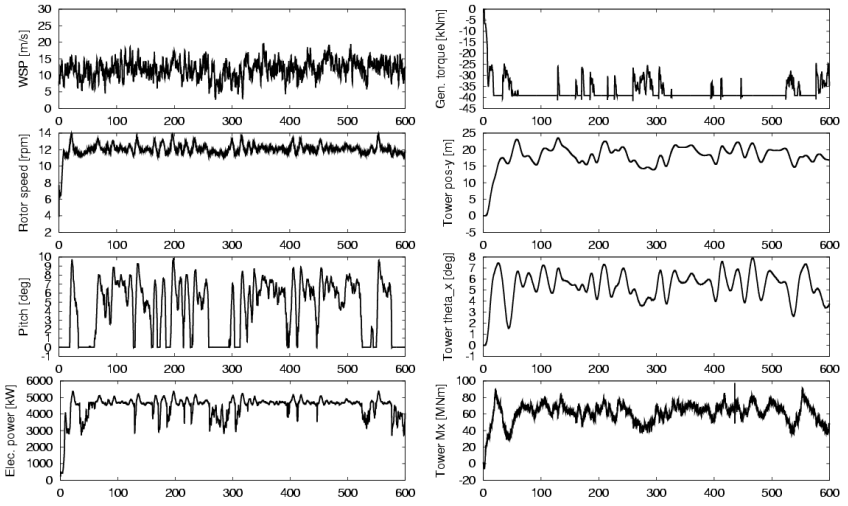
Results – controller with non linear gain



Tower response unchanged

Speed and power variation +/- 15% compared to nominal

What about active stall control?



Conclusions

- Floating turbines have a high risk for stability problems caused by a coupling between tower motion, aerodynamics and control.
- The system is stabilized if the pitch action is slow compared to the tower motion (the natural frequency of the controller must be lower than the critical vibration frequency), but performance is bad.
- Good performance of power and rotational speed can be compensated by a nonlinear gain on the pitch regulator.

- Active stall control seems to avoid this instability problem. Might be worth while investigating further.

Modelling a floating structure in HAWC2

- Do not use the fix0 constraint !
- Insert mooring line forces using Force DLL method
- Insert hydrodynamic forces including buoyancy
- Remember to use assymmetric solver option

```
begin Simulation;
  time_stop    520 ;
  solvertype   1 ;    (newmark)
;
  begin newmark;
    symmetry  2 ;   assymetric solver used
    deltat    0.1;
end newmark;

end simulation;
```

External Force DLL :: Commands

- The following lines should be included in htc-file:

```
;-----------------------------------------
begin force;
   begin dll;
     dll DemoForceDLL.dll;          ← Name of DLL
     update DemoForceDLL;           ← Name of subroutine
     mbdy floater;                  ←
     node 1;                        ← Node number (1 is body origin)
   end dll;
  end force;
;-----------------------------------------
```


External Force DLL :: DLL prototype

```
!
! Demonstration of force DLL
! Implementation of point mass
!
SUBROUTINE DemoForceDLL(time,x,xdot,xdot2,amat,omega,omegadot,F,M)
!DEC$ ATTRIBUTES DLLEXPORT::DemoForceDLL
!DEC$ ATTRIBUTES ALIAS:'demoforcedll' :: DemoForceDLL
! input
DOUBLE PRECISION                  :: time            ! time
DOUBLE PRECISION ,DIMENSION(3)    :: x               ! global position of reference node
DOUBLE PRECISION ,DIMENSION(3)    :: xdot            ! global velocity of reference node
DOUBLE PRECISION ,DIMENSION(3)    :: xdot2           ! global acceleration of reference node          !
DOUBLE PRECISION ,DIMENSION(3)    :: omega           ! angular velocity of reference node (global base)
DOUBLE PRECISION ,DIMENSION(3)    :: omegadot        ! angular acceleration of reference node (global base)
DOUBLE PRECISION ,DIMENSION(3,3)  :: amat            ! rotation matrix (body -> global)
! output
DOUBLE PRECISION ,DIMENSION(3)    :: F               ! External force in reference node (global base)
DOUBLE PRECISION ,DIMENSION(3)    :: M               ! External moment in reference node (global base)
! locals
LOGICAL, SAVE                     :: bInit = .FALSE. ! Initialisation flag
DOUBLE PRECISION                  :: mass  = 0.d0    ! Point mass
!
! Initialise on first call
IF ( .NOT.bInit) THEN
  bInit = .TRUE.
  ! Open file and read mass
  OPEN(10,FILE="DemoForceDLL_mass.dat")
  READ(10,*) mass
  CLOSE(10)
ENDIF
!
! Calc. force
F = mass*((/0.d0,0.d0,1.d0/) - xdot2)
M = 0.d0
!
END SUBROUTINE DemoForceDLL
```

NHMooringDLL input from MIMOSA

- Configuration of mooring lines written in file with the name: mooringsys.dat

Mooringsys.dat file example

```
NLINES
3
DIAMETER
10.4
ANCHORPOS
  426.935   739.47311  -320.0
-853.87      0.0  -320.0
  426.935  -739.47311  -320.0
LINETYPE_MIMOSA
annex23_mooring.res 1
LINETYPE_MAP
1
1
1
ADDED_MASS
0.
```

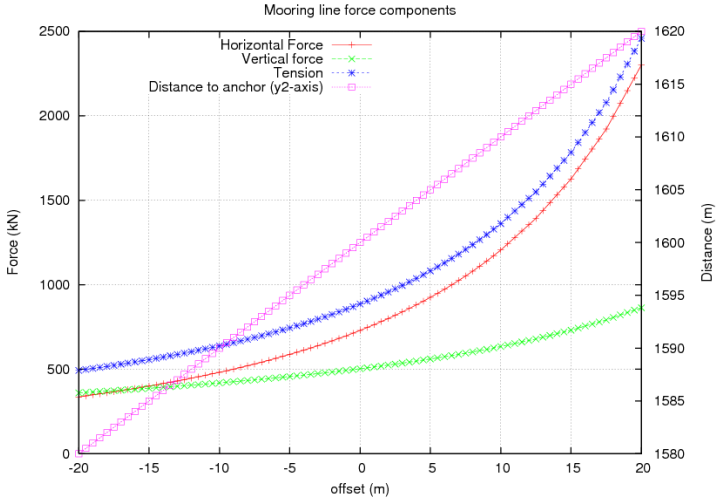

Mimosa file example

```
* LINE CHARACTERISTICS OF LINE NUMBER:   1 *
        ---------------------------------------------------
          Line characteristics number:  1
```

DISTANCE (m)	TENSION (kN)	H.TENSION (kN)	SUSPL (m)	TEN.ANCH (kN)
654.26	174.7	0.2	250.3	0.0
672.50	178.5	4.0	255.7	0.0
702.05	190.0	15.5	271.3	0.0
730.16	209.2	34.7	295.5	0.0
753.94	236.0	61.5	326.4	0.0
773.34	270.4	96.0	362.3	0.0
789.03	312.6	138.2	401.9	0.0
801.80	362.4	188.0	444.1	0.0
812.31	419.8	245.4	488.3	0.0
821.08	484.9	310.6	534.0	53.2
828.48	557.7	383.4	580.8	158.6
834.79	638.1	463.8	628.6	272.3
840.24	726.2	552.0	677.1	394.1
845.00	822.0	647.8	726.1	523.9
849.20	925.4	751.2	775.7	661.7
852.93	1036.4	862.3	825.6	807.5
856.28	1155.2	981.1	875.8	961.0
859.27	1281.5	1107.5	905.0	1107.6
861.67	1415.6	1240.6	905.3	1241.7
863.61	1557.3	1380.4	905.6	1383.4

External Force DLL :: Mooring Example (1)

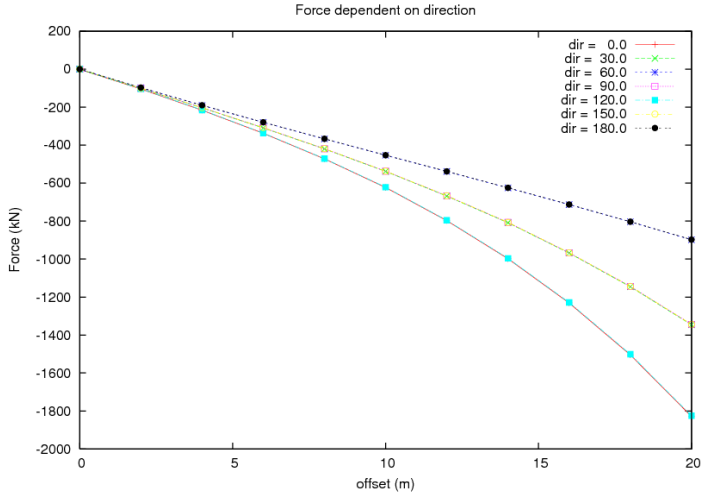
Static mooring line characteristics calculated from the solution of the chain equation :



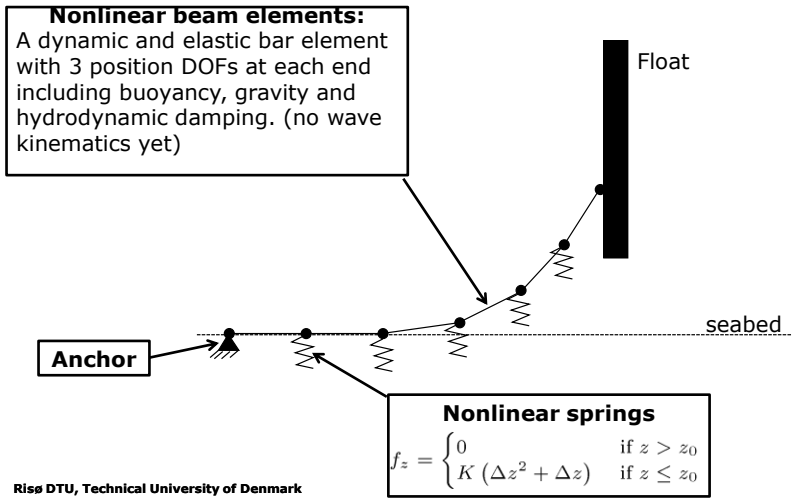
Risø DTU, Technical University of Denmark

External Force DLL :: Mooring Example (2)

Resulting force of mooring system with 3 mooring lines dependent on direction of displacement :



Dynamic mooring line modeling



Geometric non-linear beam element for HAWC2

- Each cable section with uniform properties are modeled as separate bodies
- In each body the cable is divided into a number of nonlinear beam elements
- Each body is connected by constraints

Nonlinear stiffness term

Length of element:

$$L_n = \sqrt{(x_{n-1} - x_n)^2 + (y_{n-1} - y_n)^2 + (z_{n-1} - z_n)^2}$$

Green strain:

$$\epsilon_G = \frac{L_n^2 - L_{n,0}^2}{2L_{n,0}^2}$$

Axial force in element:

$$f = EA\epsilon_G$$

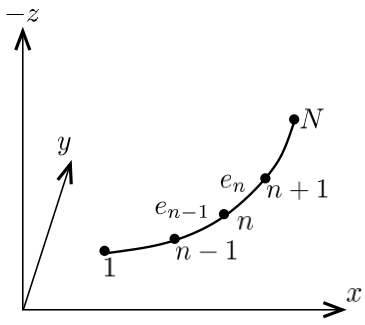
Element stiffness matrix:

$$K_e = f/L_n \begin{bmatrix} 1 & 0 & 0 & -1 & 0 & 0 \\ 0 & 1 & 0 & 0 & -1 & 0 \\ 0 & 0 & 1 & 0 & 0 & -1 \\ -1 & 0 & 0 & 1 & 0 & 0 \\ 0 & -1 & 0 & 0 & 1 & 0 \\ 0 & 0 & -1 & 0 & 0 & 1 \end{bmatrix}$$

Nodal elastic forces:

$$K_e \begin{bmatrix} \mathbf{x}_n \\ \mathbf{x}_{n+1} \end{bmatrix} = \begin{bmatrix} -f\delta \\ f\delta \end{bmatrix}, \quad \delta = \begin{bmatrix} \frac{x_{n+1}-x_n}{L_n} \\ \frac{y_{n+1}-y_n}{L_n} \\ \frac{z_{n+1}-z_n}{L_n} \end{bmatrix}$$

One line segment with uniform properties

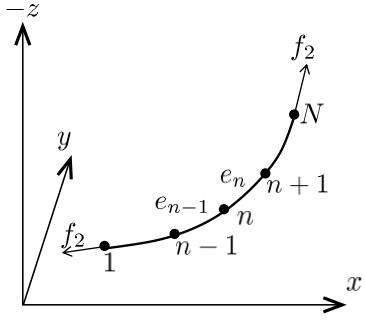


Equations of motion

Unconstrained equation of motion:

$$\mathbf{M}\ddot{\mathbf{x}}(t) + \mathbf{K}(\mathbf{x}, t)\mathbf{x}(t) - F_{gravity} - F_{buoyancy} - F_{drag}(\mathbf{x}, \dot{\mathbf{x}}, t) = \text{residual}$$

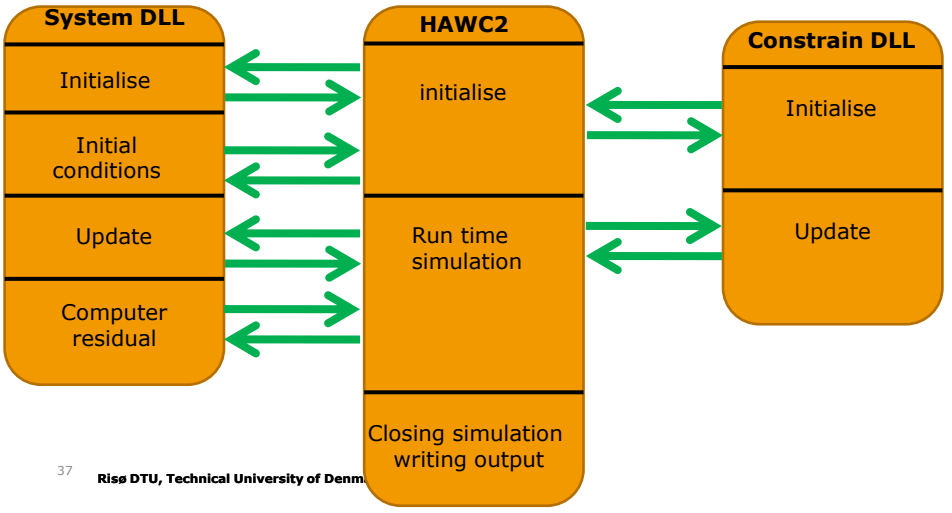
One line segment with uniform properties



Constrain forces from constrain conditions:
1) distance from end of 2D bottom contact section to node 1 of first line segment = 0
2) distance from node N of one line segment to node 1 of the next segment = 0
3) distance from node N of last line segment to node n on a HAWC2 body = 0

Implementation in HAWC2

- The mooring system model is implemented in HAWC2 by an external system DLL interface that couples external systems with its one degrees of freedom to the HAWC2 model in a tightly coupled manner.



DLL Interface to external systems (1)

Un-constrained EOMs:

$$\delta W = \sum_{i=1}^{N} \delta W_i = \sum_{i=1}^{N} \delta \vec{q}_i \cdot \vec{B}_i = 0$$

Constrained EOMs:

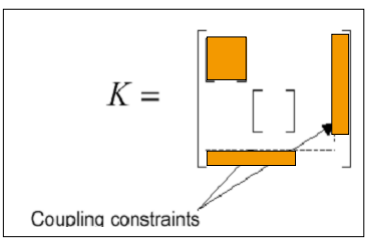
$$\delta W + \delta(\vec{\lambda} \cdot \vec{g}) = \delta W + \delta\vec{\lambda} \cdot \vec{g} + \delta\vec{g} \cdot \vec{\lambda} = 0 \quad for \quad \vec{g} = \vec{0}$$

Matrix EOMs:

$$\delta \vec{q}_i \cdot \left(\vec{B}_i + \nabla_{q_i}^T \vec{g} \cdot \vec{\lambda}\right) = 0 \quad for \ i = 1..N$$

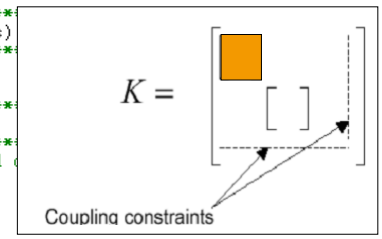
$$\delta \vec{\lambda} \cdot (\vec{g}) = 0$$

Implemented in DLL external systems !



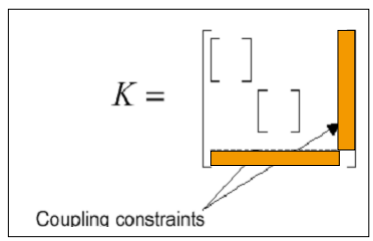
DLL Interface to external systems (2)

```
MODULE GearBoxDLL
CONTAINS
!*************************************************************************
subroutine initialise(pwrk,nnr, nnq, nout, nvis, nheader, sdata)
!*************************************************************************
! Tasks: Return dimension of the system.
!
!*************************************************************************
subroutine initcond(pwrk,x, xdot, xdot2)
!*************************************************************************
! Tasks: Set initial conditions and post initialisation
!*************************************************************************
subroutine update(pwrk, time, x, xdot, xdot2,&
                  KEFFRR, KEFFRQ, KEFFQR, KEFFQQ)
!*************************************************************************
! Tasks: Update time dependent parameters
!
!*********************************************
SUBROUTINE residual(pwrk, x, xdot, xdot2, qres)
!*********************************************
! Tasks: Calc. residual of unconstrained EOMs
!
!*********************************************
SUBROUTINE visual(pwrk, flag, iodata)
!*********************************************
! Tasks: Write/read visual headers, output and
!
END MODULE GearBoxDLL
```



DLL Interface to external systems (3)

```
MODULE constraint96
CONTAINS
!
!*************************************************************************
SUBROUTINE constraint96_init(pwrk, itask, var1, var2, var3, var4, var5, strID)
!*************************************************************************
! Tasks: Initialisation, pointer setting and reading of input
!
!*************************************************************************
SUBROUTINE constraint96_update(pwrk, time)
!*************************************************************************
! Tasks: Calc. constraint vector and gradients
END MODULE
!
```



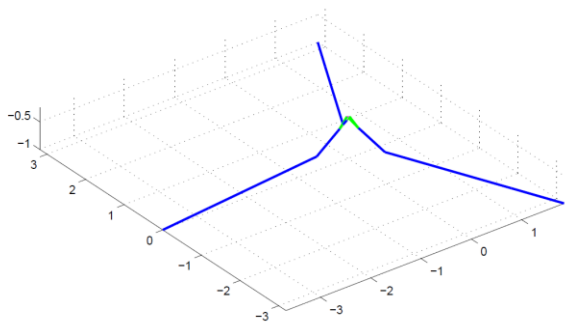
External system DLL interface

- Newly developed interface
- Solves external set of equations by HAWC2 solver
- External system is setup exactly as internal HAWC2 bodies by DLL interface
- Coupled to HAWC2 by constrain DLL
- Applications:
  - Coupled WAMSIM model of float to HAWC2
  - Mooring line modeling
  - Gear box modeling

- Extremely flexible interface
- Can do everything which can be done in the HAWC2 frame work
- Complicated to use
- Plan to develop simpler but less flexible intermediate interface on top of this

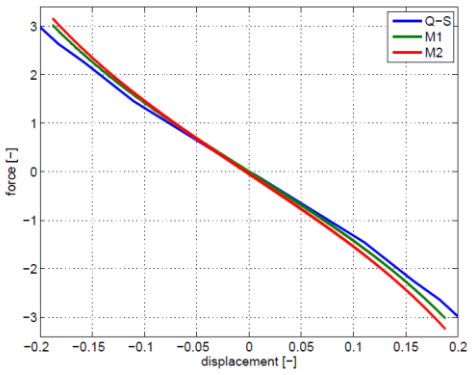
Test case: Three line mooring system

- Mooring system as the one used in the OC3 project
- Three mooring lines, each with a concentrate mass to increase stiffness



Quasi-static results (three lines)

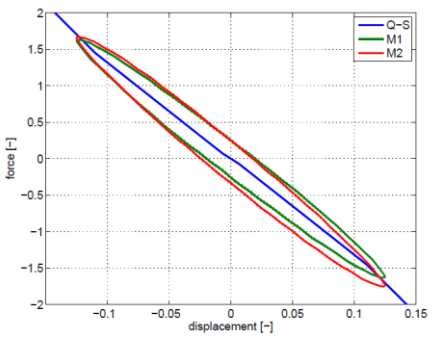
- Results fits well with MIMOSA quasi-static results



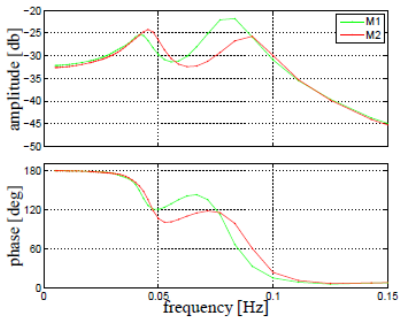
Result normalized by:
•Aerodynamic trust at rated power
•Rotor diameter and
•Systems natural surge period

Dynamic results (three lines)

Increasing oscillation frequency opens the loop



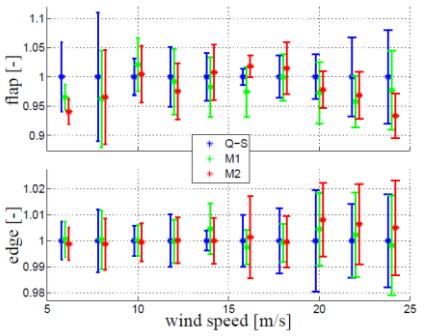
Power spectrum of mooring system



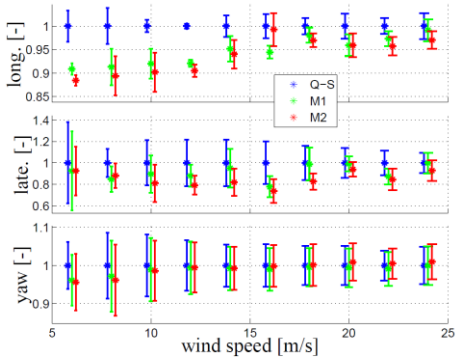
Result normalized by:
•Aerodynamic trust at rated power
•Rotor diameter and
•Natural surge period

Effects of dynamic mooring system on fatigue

Blade root bending



Tower bottom



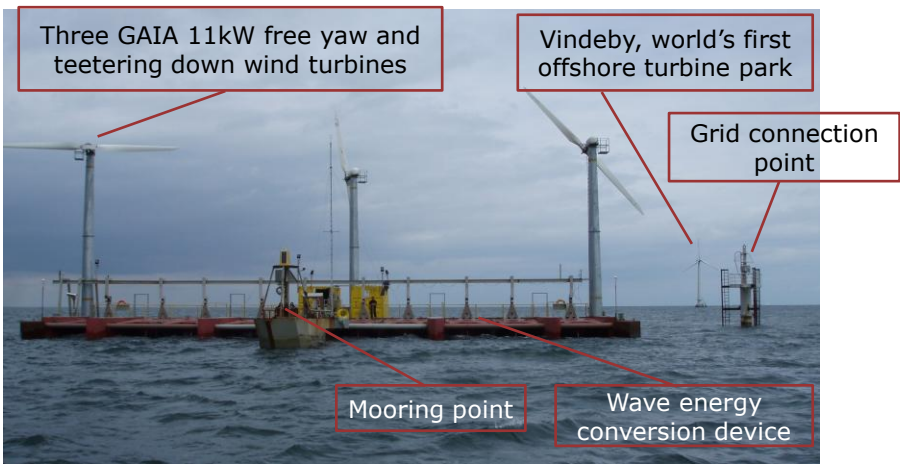
Lifetime equivalent load relative to the quasi-static results.

model	blade		tower		
	flap	edge	long.	late.	yaw
Q-S	1	1	1	1	1
M1	0.97	1.0	0.95	0.89	0.99
M2	0.97	1.0	0.94	0.83	0.99

Combined wind and wave energy – Poseidon

World's first floating combined wind and wave energy plant

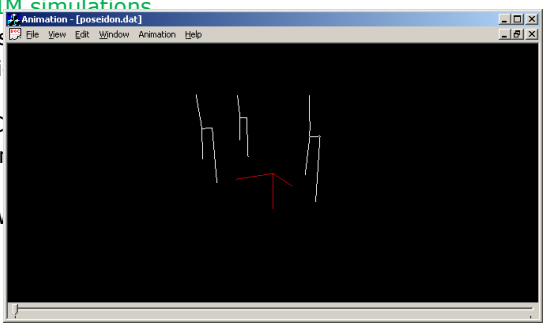
PSO project on measurements and modeling of this platform; DONG,FPP,DHI and Risø DTU



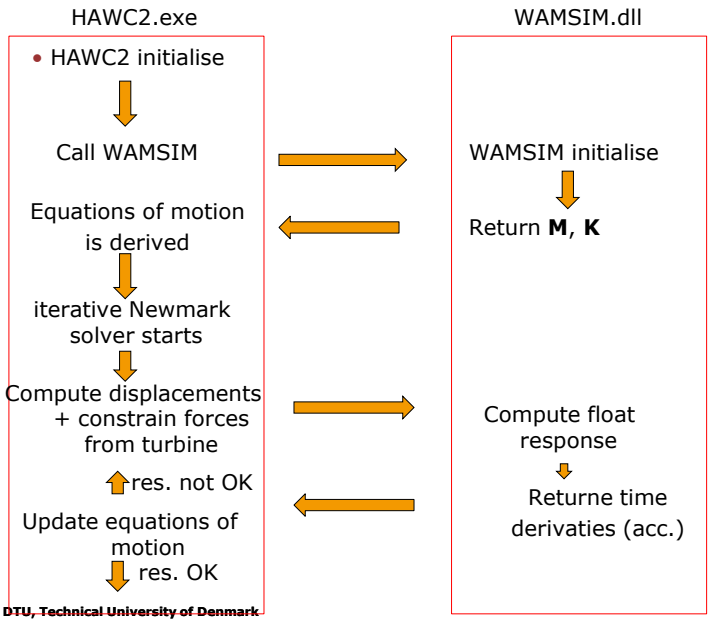
New challenges

- Wake from upwind rotors
  - Already possible with the dynamic wake meandering model in HAWC2
- Three rotors in one simulation
  - Structural modeling already possible in the multi-body formulation
  - Aerodynamic model updated to handle this
- Large water surface area
  - full coupled HAWC2-WAMSIM simulations
    - HAWC2 validated aeroelas
    - WAMSIM validated radiati structures from DHI
    - WAMSIM recode to HAWC
    - Ordinary HAWC2 turbine r
    - Ordinary WAMSIM model
    - Full system solved by HAV

Three GAIA turbines in one HAWC2 model

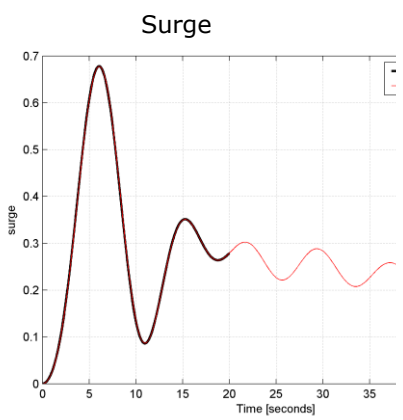


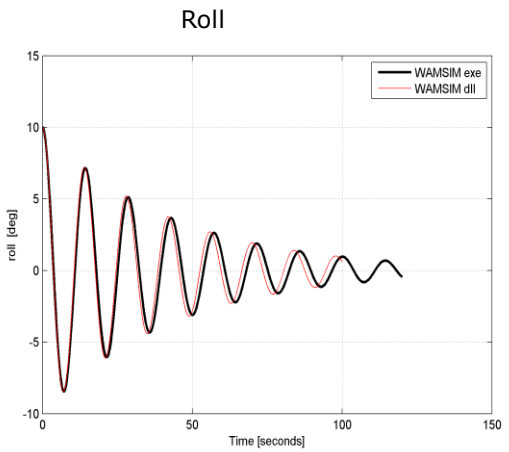
HAWC2-WAMSIM coupled simulation platform



HAWC2-WAMSIM coupled simulation platform

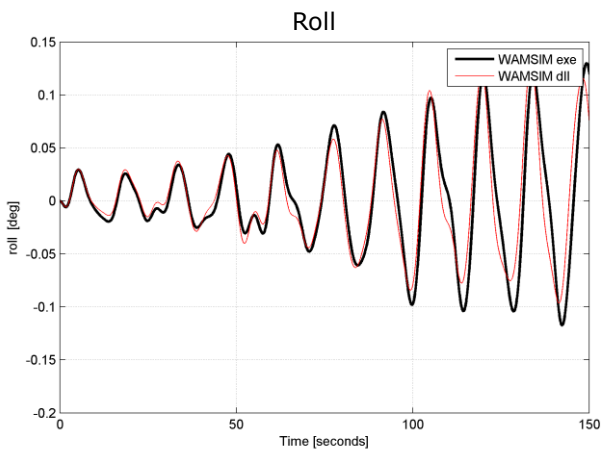
Decay test still water, Poseidon platform, first comparison





HAWC2-WAMSIM coupled simulation platform

Wave loading, Poseidon platform, first comparison



OC4 project on code to code comparison WP2 (Phase VI): Semisubmersible

- Title: Verification of simulation codes for a WT on a floating semi-submersible
- Principle Power Inc. (PPI) has kindly agreed to design a semi-submersible, based on the WindFloat, for use in OC4:
  - Floater supports the NREL 5-MW turbine
  - Pitch & roll restoring through waterplane area & fixed water ballast
  - Tower mounted on one column
  - Active ballast system maintains zero-mean pitch angle (not considered in OC4)
  - Heave plates improve natural response periods & damping
- Results will be published in a conference paper

WindFloat (Image: D. Roddier, PPI)