Dynamic Mooring Line Modeling in Hydro-Aero-Servo-Elastic Wind Turbine Simulations

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Background

Floating turbines

- The interest towards floating wind turbine concepts challenge the existing load prediction models.

Challenges

- Wind tradition =>10 min simulations.
- Offshore tradition =>3 hours of simulation time.
- Important wind turbine dynamic up to ~3 Hz, but to dissolve azimuth angle simulation frequency on up to ~40 Hz is necessary.
- Floating platform motion on frequencies down to 0.01 Hz.
- Highly nonlinear response, especially because of wind turbine controller.

Modeling philosophy

- Load simulations models **As Simple as Possible, as Complex as Necessary.**
- Need complex model to determine what is important for which loads.

This work

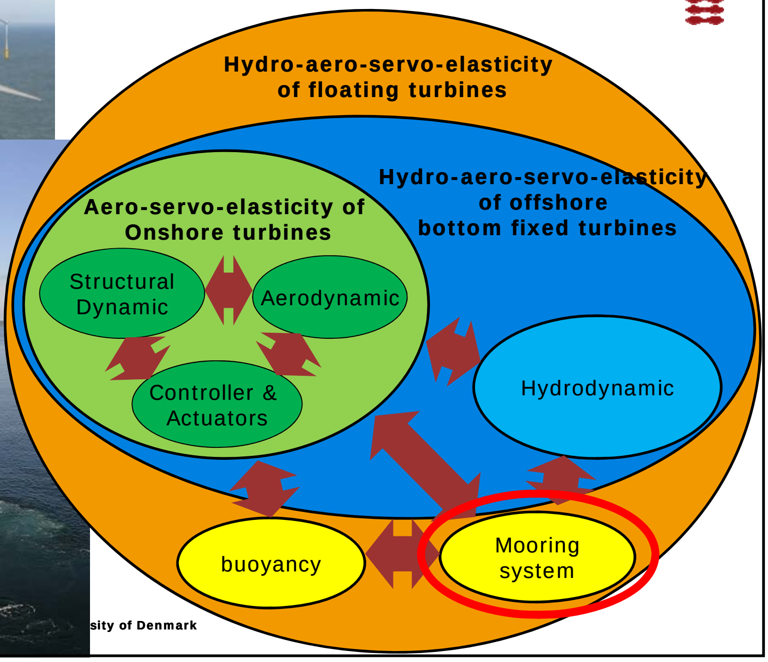
Why:

- To analyze the effect of an advanced mooring line model on the wind turbine loads.

How:

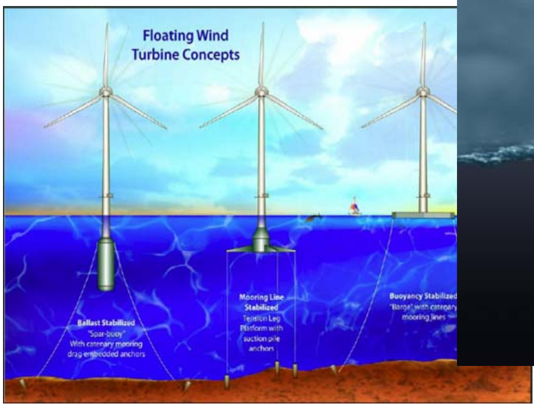
- Current mooring lines is modeled in a quasi-static framework.
- Add a new advanced dynamic mooring line model to the comprehensive hydro-aero-servo-elastic code HAWC2.
- Compare turbine loads from a selected number of load cases for the different mooring line model complexities.

The HAWC2 code

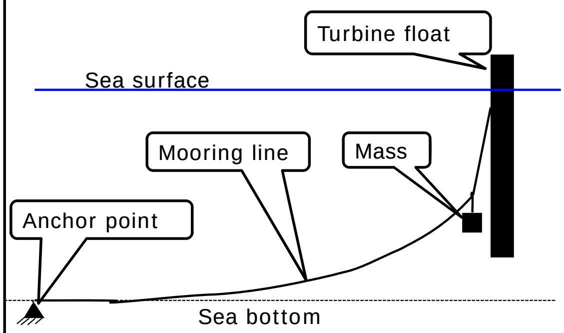


Mooring line modeling

HYWIND by STATOIL



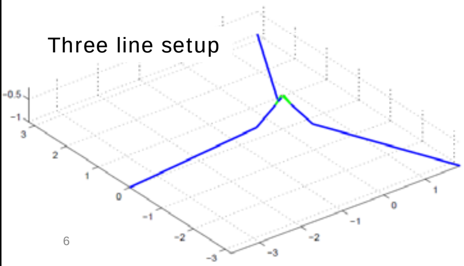
Catenary mooring system

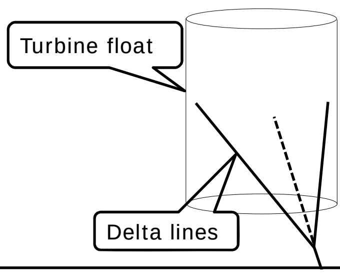


Mooring line properties.

- Different section with uniform properties e.g. chain, synthetic rope, etc.
- Concentrated masses.
- Each line section modeled as one body
- Bodies connected by ball-joint constraints

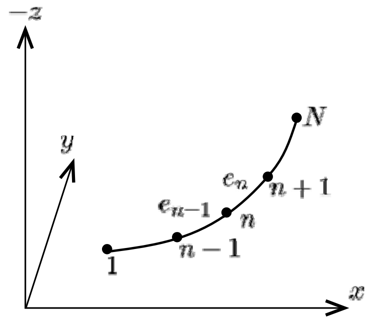
Three line setup





Nonlinear stiffness term

One line segment with uniform properties.



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:

$$f = EA\epsilon_G$$

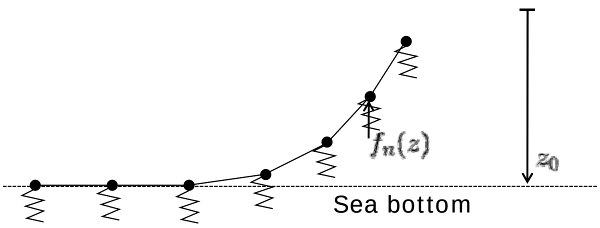
Element stiffness matrix:

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

Nodal elastic forces:

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

Bottom contact



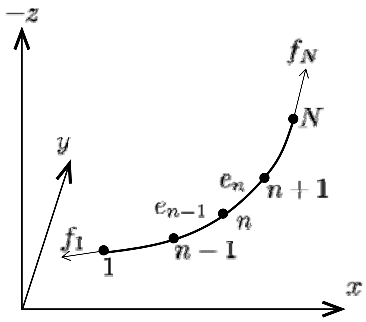
$$f_n(z) = \begin{cases} 0 & \text{if } z < z_0 \\ K\left((z-z_0)^2 + (z-z_0)\right) & \text{if } z \geq z_0 \end{cases}$$

Equations of motion

Unconstrained equation of motion:

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

One line segment with uniform properties.



Constrain forces from constrain conditions:

1) distance from first node on first line segment to mooring point = 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.

Mooring line modeling summary

- Dynamic mooring line model implemented.
- Concentrated masses and drag buoys.
- Quadratic drag on elements.
- Multi-body framework => flexible mooring line setup.

- Hydrodynamic forces need to be implemented.
- Check for compression forces.

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:

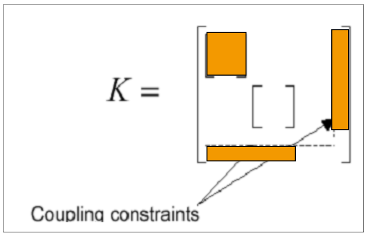
$$\delta W + \delta(\vec{\lambda} \cdot \vec{g}) = \delta W + \delta\vec{\lambda} \cdot \vec{g} + \delta\vec{g} \cdot \vec{\lambda} = 0 \quad for \quad \vec{g} = \vec{0}$$

Matrix EOMs:

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

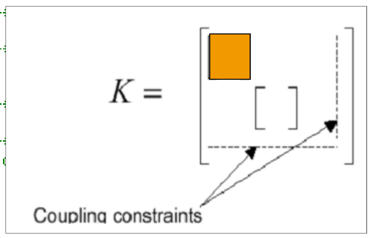
$$\delta\vec{\lambda} \cdot (\vec{g}) = 0$$

Implemented in DLL external systems !



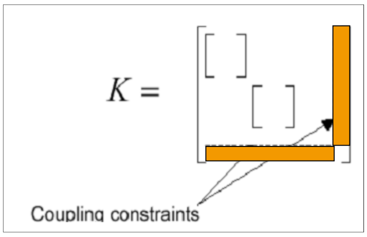
DLL Interface to external systems (2)

```
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
```



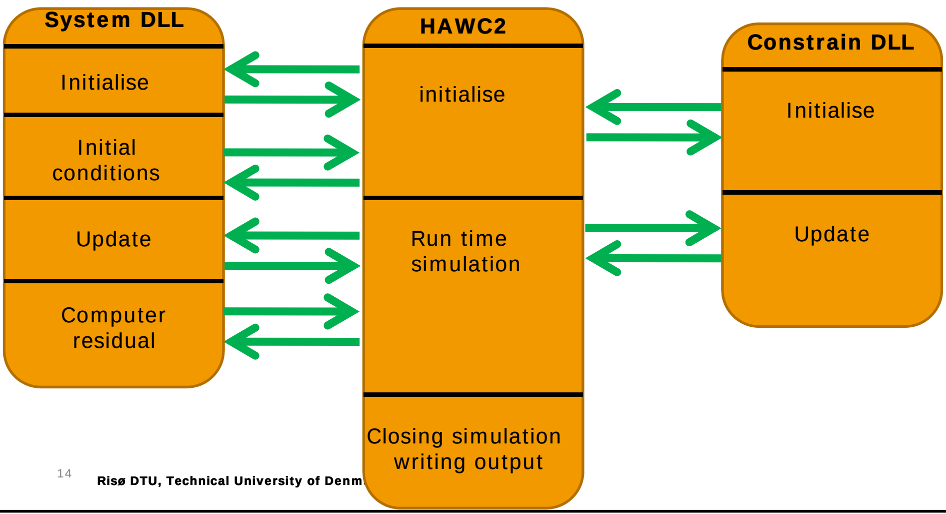
DLL Interface to external systems (3)

```
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
!
```



DLL Interface to external systems (2)

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



Implementation in *.htc file

External constrain 1

```
begin dll;
    ID 2 ;  id of fixed node
    dll .\Release\ESYSMooring.DLL ;
    init CSTRBarsFixedToBody_init;
    update CSTRBarsFixedToBody_update;
    neq 3;
    nbodies 1;
    nesys 1;
    mbdy_node floater 9;
    esys_node line_1_7 8 ; node is dummy for this
constraint
   end dll;
```

External body

```
begin   ext_sys          ;   2
   module  elasticbar          ;
   name    line_1_1            ;
   dll .\Release\ESYSMooring.DLL  ;
   ndata  10     ;
   data    20     ;   NELEM
   data    0       ;   L
   data    154  134.2   ;  ma, mw
   data    -810.6  0.0  220.0 ; x1(1:3)
   data    -611.3  0.0  203.4 ; x2(1:3)
   data    100.8  4.2 ; 0.5*rho*D*[Cd, Cd_axial]
   data    6.40E+10  ;   EA
   data    0  0  ;
   data    220 0.01 0.5  ; z0, Kbottom, Dbottom
   data    0.02  ; time step
end ext_sys          ;
```

External constrain 2

```
begin dll;
    ID ;
    dll .\Release\ESYSMooring.DLL ;
    init   cstrbarfixedtobar_init;
    update cstrbarfixedtobar_update;
    neq 3;
    nbodies 0;
    nesys 2;
    esys_node line_1_1 21 ;
    esys_node line_1_2 1  ;
   end dll;
```

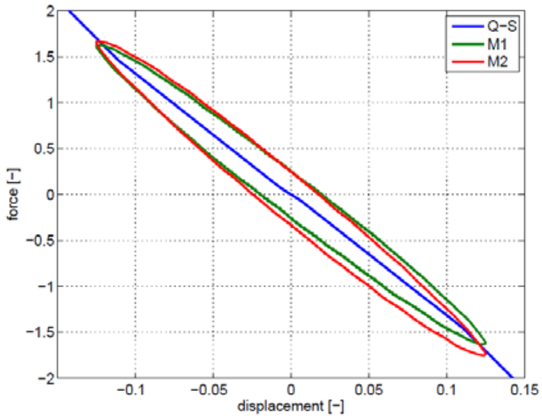

Data for preprocessor

- Anchor position
- Connection to main construction, global position, body name, node number
- Individual mooring lines, length and other data
- Concentrated masses and dampers

```
2    nlines
line1
COL1    6
ANCHOR1    1
-759.4312138    755.9312138    160    Anchor pos
-3.5    3.5    13.716    Fairlead pos
3  D [mm] L [m]  M_in_air [kg/m]  M_in_water [kg/m]  EA [MN]  Cd    Cd_axial  nelem
1  76        200    127.1              110.4                  586.45    2.4  0.1          20
2  76        800    24.2                19.55                  276.76    2.4  0.1          20
3  76        100    127.1              110.4                  586.45    2.4  0.1          20
line2
COL1    6
ANCHOR2    1
973.0465435    976.5465435    160    Anchor pos
3.5    3.5    13.716    Fairlead pos
3  D [mm] L [m]  M_in_air [kg/m]  M_in_water [kg/m]  EA [MN]  Cd    Cd_axial  nelem
1  76        200    127.1              110.4                  586.45    2.4  0.1          20
2  76        1100  24.2                19.55                  276.76    2.4  0.1          20
3  76        100    127.1              110.4                  586.45    2.4  0.1          20
```

Effect of dynamic mooring line model

Horizontal force for horizontal oscillations of the float (50 s period).



The mooring restoring force is normalized by the rated aerodynamic thrust for the particular turbine and the displacement by the rotor diameter.

Load cases

- Normal operation.
- 5 to 23 m/s in 2 m/s steps.

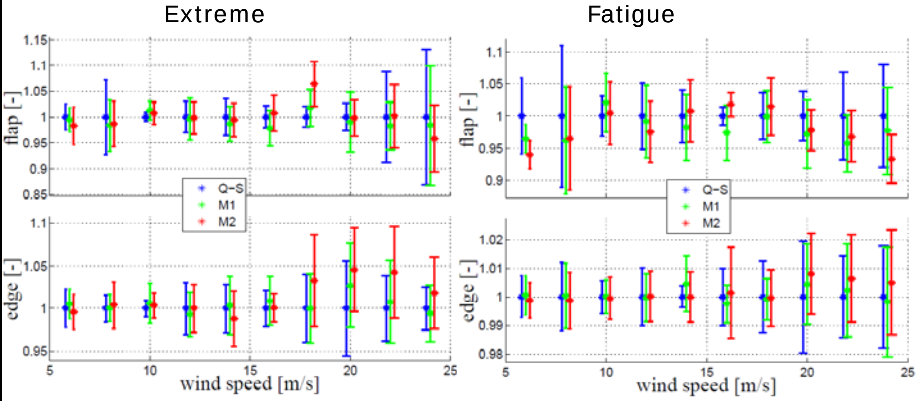
Ws	[m/s]	5	7	9	11	13	15	17	19	21	23
Ti	[-]	0.224	0.186	0.165	0.151	0.142	0.135	0.130	0.125	0.122	0.119
H_s	[m]	1.94	2.26	2.65	3.11	3.61	4.14	4.70	5.25	5.79	6.31
T_p	[s]	3.82	3.98	4.20	4.49	4.85	5.26	5.73	6.24	6.77	7.30
time	[h]	22460	26068	25102	23340	18958	14123	9708	6182	3657	2014

- 1200 seconds simulations, skip first 300 seconds for transients
- 6 different seeds for wind and waves for each wind speed.

- Compare extreme and fatigue loads for 3 different model complexities:
  - Q-S: Quasi-static model.
  - M1: Dynamic without delta lines.
  - M2: Dynamic with delta lines.

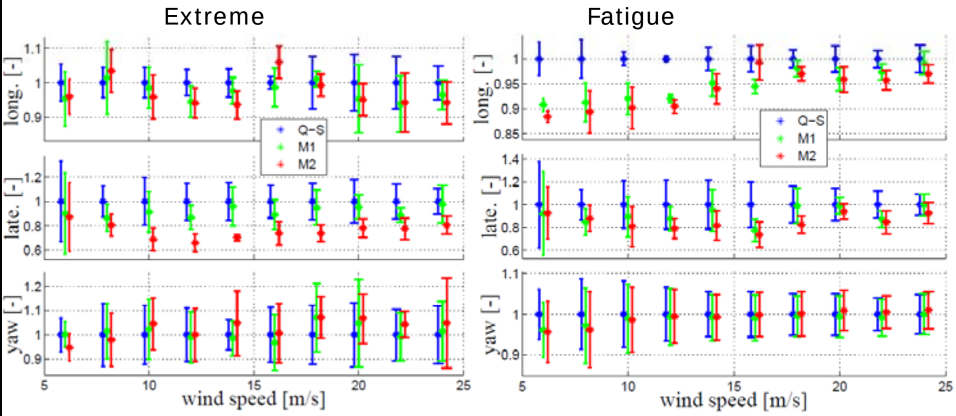
- Added mass not included, since no added mass coefficient available.

Blade Loads



All loads are normalized with respect to the quasi-static result.

Tower Loads



All loads are normalized with respect to the quasi-static result.

Lifetime fatigue loads

Lifetime fatigue loads for normal operation.

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

Normal operation cases.

Ws	[m/s]	5	7	9	11	13	15	17	19	21	23
Ti	[-]	0.224	0.186	0.165	0.151	0.142	0.135	0.130	0.125	0.122	0.119
H_s	[m]	1.94	2.26	2.65	3.11	3.61	4.14	4.70	5.25	5.79	6.31
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time	[h]	22460	26068	25102	23340	18958	14123	9708	6182	3657	2014

Conclusion and further work

- A dynamic mooring line model has been implemented in a comprehensive aeroelastic code.
- The lateral tower extreme load is reduced by the most comprehensive mooring models, but the extreme lateral tower load is not design driven.
- The fatigue of both the lateral and longitudinal tower modes are reduced, and these reductions can lead to tower cost reductions.
- The results in this work indicates that the mooring system has an effect on the tower loads, but it is conservative to used the quasi-static modeling approach.

Further work

- Need to analyze more load cases, especially yaw errors.
- Turbine modeling complexities effect on mooring line loads.

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