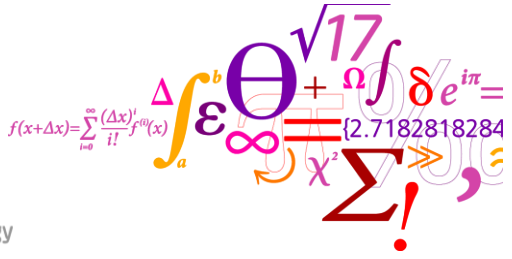
User-defined External Systems Applied to Floating structures and mooring lines

Anders M. Hansen (anmh@dtu.dk)



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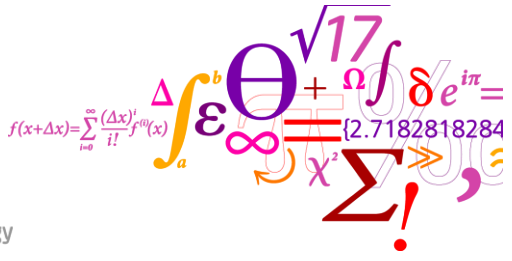

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DLL Interface to external systems

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:

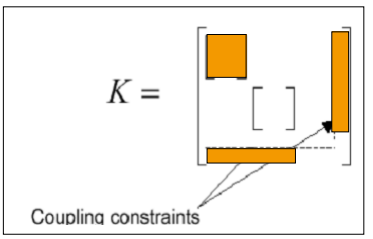
$$\delta W + \delta(\vec{\lambda} \cdot \vec{g}) = \delta W + \delta\vec{\lambda} \cdot \vec{g} + \delta\vec{g} \cdot \vec{\lambda} = 0 \quad for \quad \vec{g} = \vec{0}$$

Matrix EOMs:

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

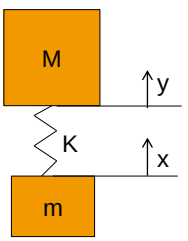
$$\delta \vec{\lambda} \cdot (\vec{g}) = 0$$

Implemented in DLL external systems !



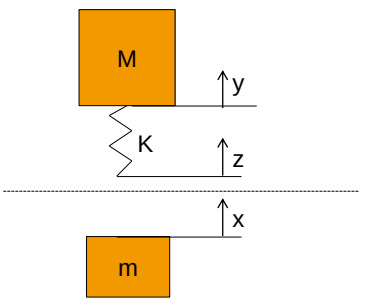
Simple example

General system



$$\begin{bmatrix} M & 0 \\ 0 & m \end{bmatrix} \begin{Bmatrix} \ddot{y} \\ \ddot{x} \end{Bmatrix} + \begin{bmatrix} k & -k \\ -k & k \end{bmatrix} \begin{Bmatrix} y \\ x \end{Bmatrix} - \begin{Bmatrix} f_y \\ f_x \end{Bmatrix} = 0$$

HAWC2 system using constraints

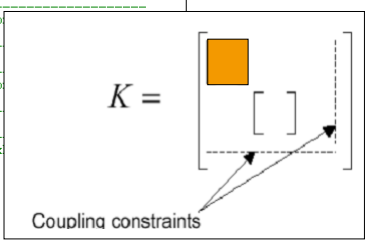


$$\left[\begin{array}{cc|c|c} M & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \hline 0 & 0 & m & 0 \\ \hline 0 & 0 & 0 & 0 \end{array}\right] \begin{Bmatrix} \ddot{y} \\ \ddot{z} \\ \ddot{x} \\ \ddot{\lambda} \end{Bmatrix} + \left[\begin{array}{cc|c|c} k & -k & 0 & 0 \\ -k & k & 0 & 1 \\ \hline 0 & 0 & 0 & -1 \\ \hline 0 & 1 & -1 & 0 \end{array}\right] \begin{Bmatrix} y \\ z \\ x \\ \lambda \end{Bmatrix} - \begin{Bmatrix} f_y \\ 0 \\ f_x \\ 0 \end{Bmatrix} = 0$$

DLL System (programmed by the user)

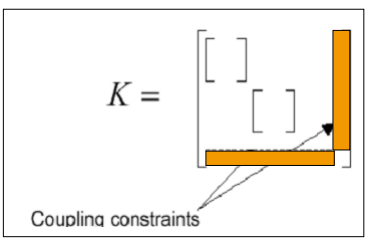
```
MODULE GearBoxDLL
!
CONTAINS
!
!+ ---------------------------------------------------------------------
subroutine GearBoxDLL_init(pwrk,nnr, nnq, nout, nvis, nheader, sdata)
!+ ---------------------------------------------------------------------
!DEC$ ATTRIBUTES ALIAS:"gearboxdll_init", DLLEXPORT::GearBoxDLL_init
!
!+ ---------------------------------------------------------------------
subroutine GearBoxDLL_initcond(pwrk,x, xdot, xdot2)
!+ ---------------------------------------------------------------------
!DEC$ ATTRIBUTES ALIAS:"gearboxdll_initcond", DLLEXPORT::GearBoxDLL_initcond
!
!+ ---------------------------------------------------------------------
subroutine GearBoxDLL_update(pwrk, time, x, xdot, xdot2, MEFF, CEFF, KEFF)
!+ ---------------------------------------------------------------------
!DEC$ ATTRIBUTES ALIAS:"gearboxdll_update", DLLEXPORT::GearBoxDLL_update
!
!+ ---------------------------------------------------------------------
SUBROUTINE GearBoxDLL_visual(pwrk, flag, iodata)
!+ ---------------------------------------------------------------------
!DEC$ ATTRIBUTES ALIAS:"gearboxdll_visual", DLLEXPORT::GearBo
!
!+ ---------------------------------------------------------------
SUBROUTINE GearBoxDLL_output(pwrk, time, output)
!+ ---------------------------------------------------------------
!DEC$ ATTRIBUTES ALIAS:"gearboxdll_output", DLLEXPORT::GearBo
!
!+ ---------------------------------------------------------------
SUBROUTINE GearBoxDLL_input(pwrk, time, nin, input)
!+ ---------------------------------------------------------------
!DEC$ ATTRIBUTES ALIAS:"gearboxdll_input", DLLEXPORT::GearBox
!
END MODULE GearBoxDLL
```

Mandatory



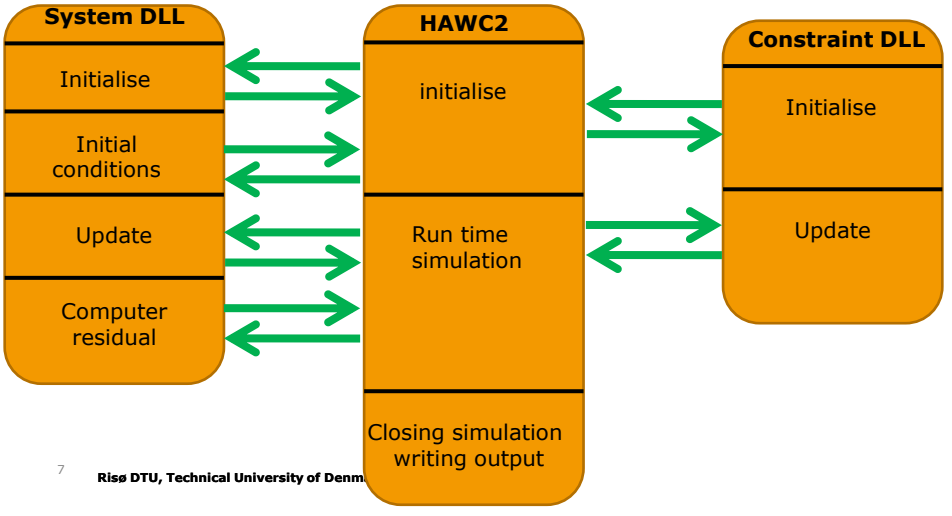
DLL Constraints (programmed by the user)

```
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
!
```

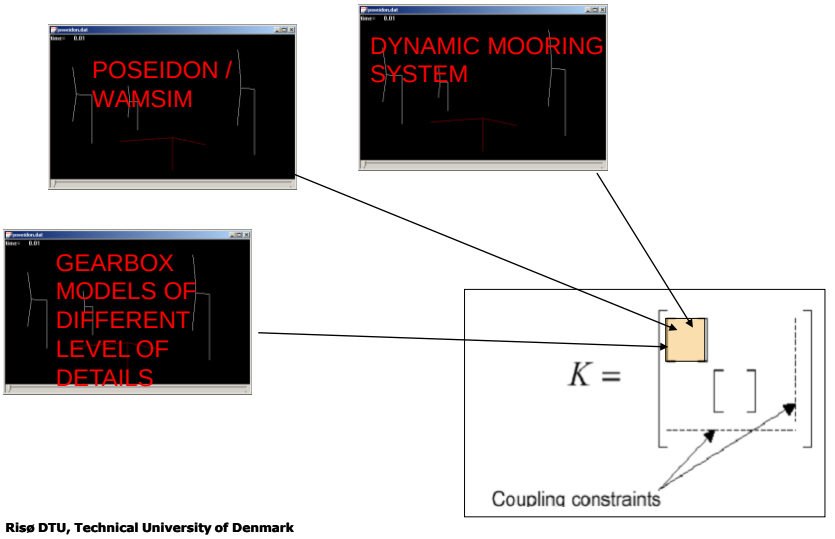


DLL Interface to external systems (2)

- The external system 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.



Other Examples?



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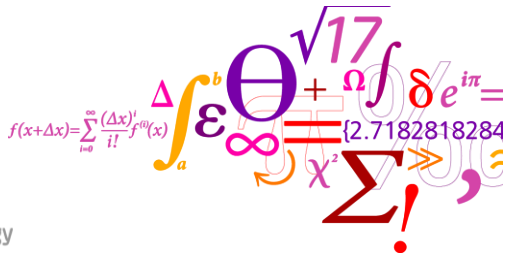

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Dynamic Mooring Line Modeling in Hydro-Aero-Servo-Elastic Wind Turbine Simulations

Bjarne S. Kallesøe
Anders M. Hansen

ACKNOWLEDGMENTS
The work has been funded by the Danish Energistyrelsen under contract EUDP 63011-0190.

A special acknowledgment goes to STATOIL for helpful discussion of mooring systems and providing the mooring setup and MIMOSA results.

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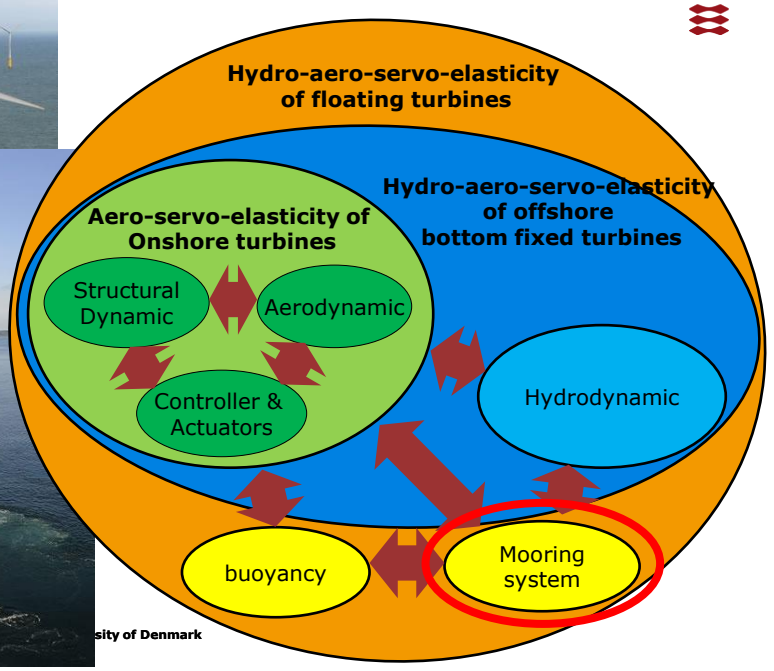
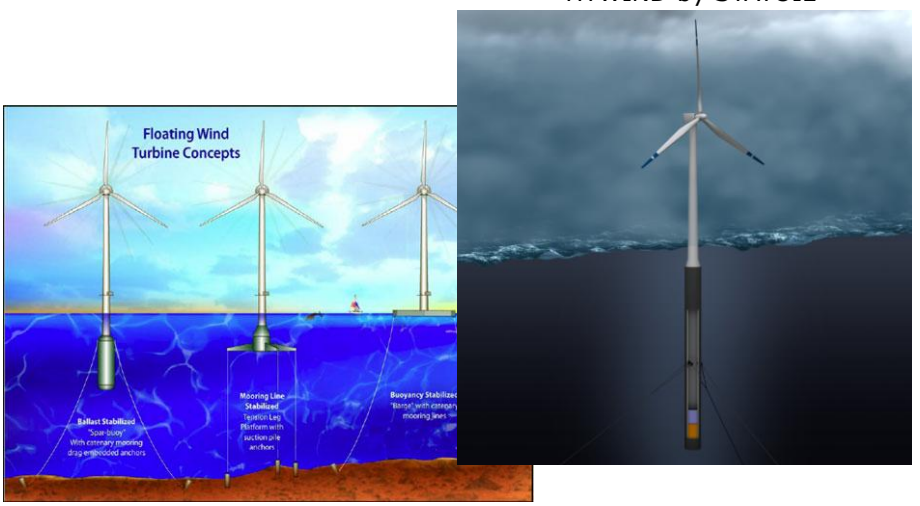
The HAWC2 code



Mooring line modeling

HYWIND by STATOIL



This work

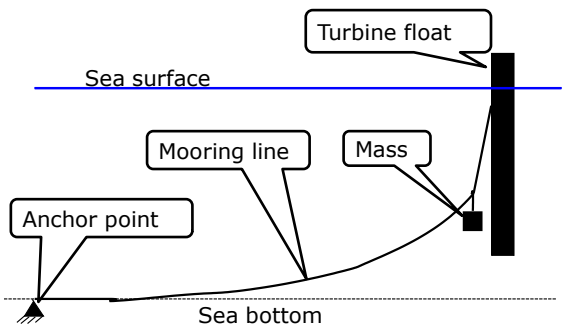
Why:

- 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 dynamic mooring line model to the hydro-aero-servo-elastic code HAWC2.
- Compare turbine loads from a selected number of load cases for the different mooring line model complexities.

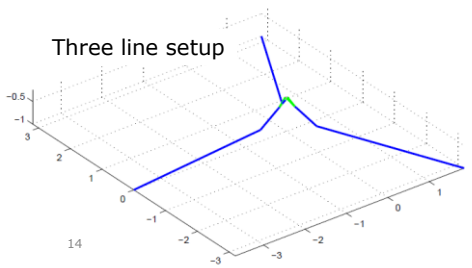
Catenary mooring system

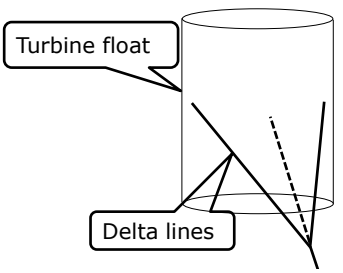


Mooring line properties.

- 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

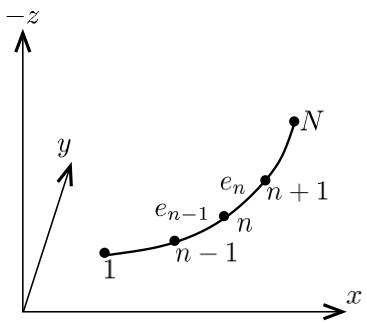
Three line setup





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:

$$f = EA\epsilon_G$$

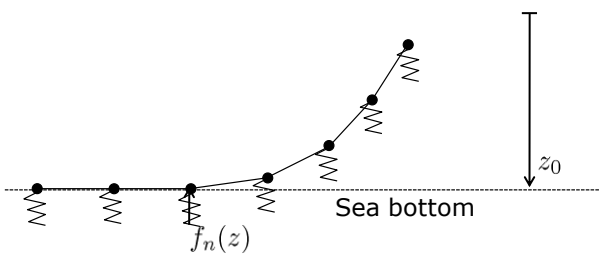
Element stiffness matrix:

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

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



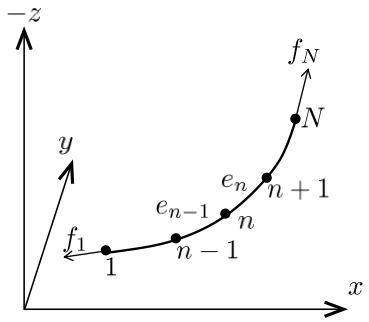
$$f_n(z) = \begin{cases} 0 & \text{if } z < z_0 \\ K\left((z-z_0)^2 + (z-z_0)\right) & \text{if } z \geq z_0 \end{cases}$$

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.



Constraint forces from constraint 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.

Implementation in *.htc file

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    1.0  0.9   ;  ma, mw
  data    -80.6  0.0  100.0 ; x1(1:3)
  data    -61.3  0.0   80.0  ; x2(1:3)
  data    10.8  4.2 ; 0.5*rho*D*[Cd, Cd_axial]
  data    6.0E+09  ;   EA
  data    0  0  ;
  data    100 0.01 0.5  ; z0, Kbottom, Dbottom
  data    0.02  ; time step
end ext_sys        ;
```

External constraint 1

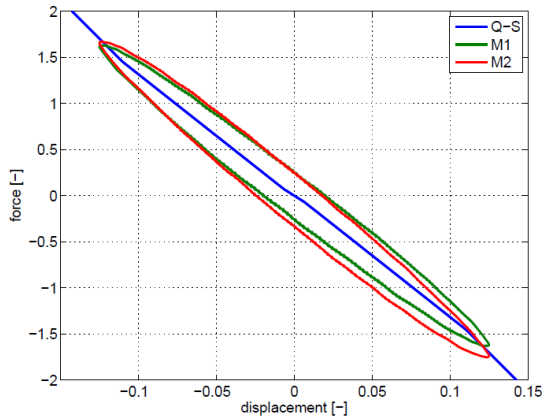
```
begin dll;
    ID 2 ;
    dll .\Release\ESYSMooring.DLL ;
    init CSTRBarsFixedToBody_init;
    update CSTRBarsFixedToBody_update;
    neq 3;
    nbodies 1;
    nesys 1;
    mbdy_node floater 9;
    esys_node line_1_7 8 ;
  end dll;
```

External constraint 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;
```

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.

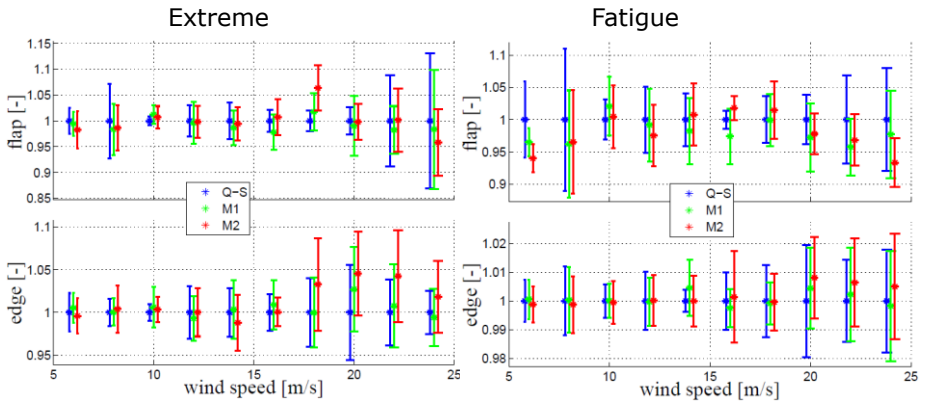
Ws	[m/s]	5	7	9	11	13	15	17	19	21	23
Ti	[-]	0.224	0.186	0.165	0.151	0.142	0.135	0.130	0.125	0.122	0.119
H_s	[m]	1.94	2.26	2.65	3.11	3.61	4.14	4.70	5.25	5.79	6.31
T_p	[s]	3.82	3.98	4.20	4.49	4.85	5.26	5.73	6.24	6.77	7.30
time	[h]	22460	26068	25102	23340	18958	14123	9708	6182	3657	2014

- 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.

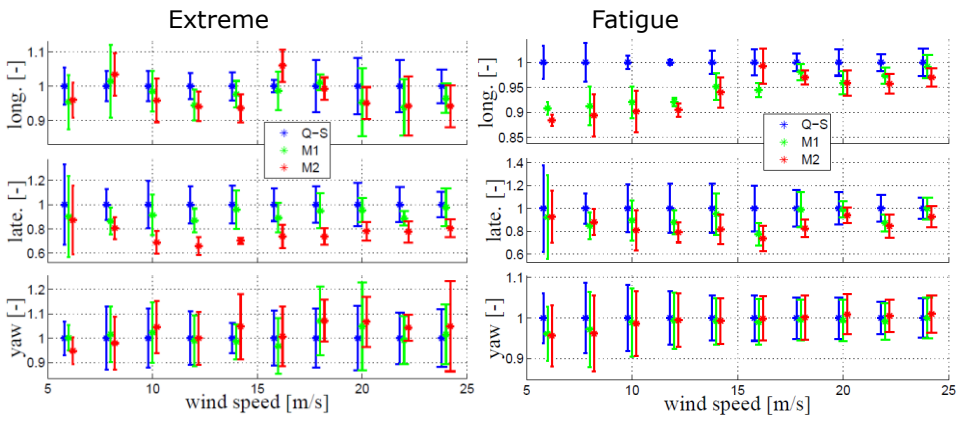
- Added mass not included, since no added mass coefficient available.

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
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

Conclusion

- 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, however, 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 of this work indicate that the mooring system has an effect on the tower loads, but it is conservative to use the quasi-static modeling approach.

Eigenvalue analysis including External Systems (preliminary results)

Future Systems

- Plan is to make external systems publically available from the HAWC2 web page (keep an eye on www.hawc2.dk) – for some systems including source code.

- Future systems might include:
  - Super element import from commercial FEM programmes
  - Large floating (flexible) foundations based on WAMIT like hydrodynamics
  - Drive-train models of various kinds