MAXIMUM LOADS ON A 1-DOF MODEL-SCALE OFFSHORE WIND TURBINE

Loup Suja-Thauvin (Industry PhD)

Jørgen Krokstad (prof II)

Joakim Fürst Frimann-Dahl (DNV-GL)

Statkraft

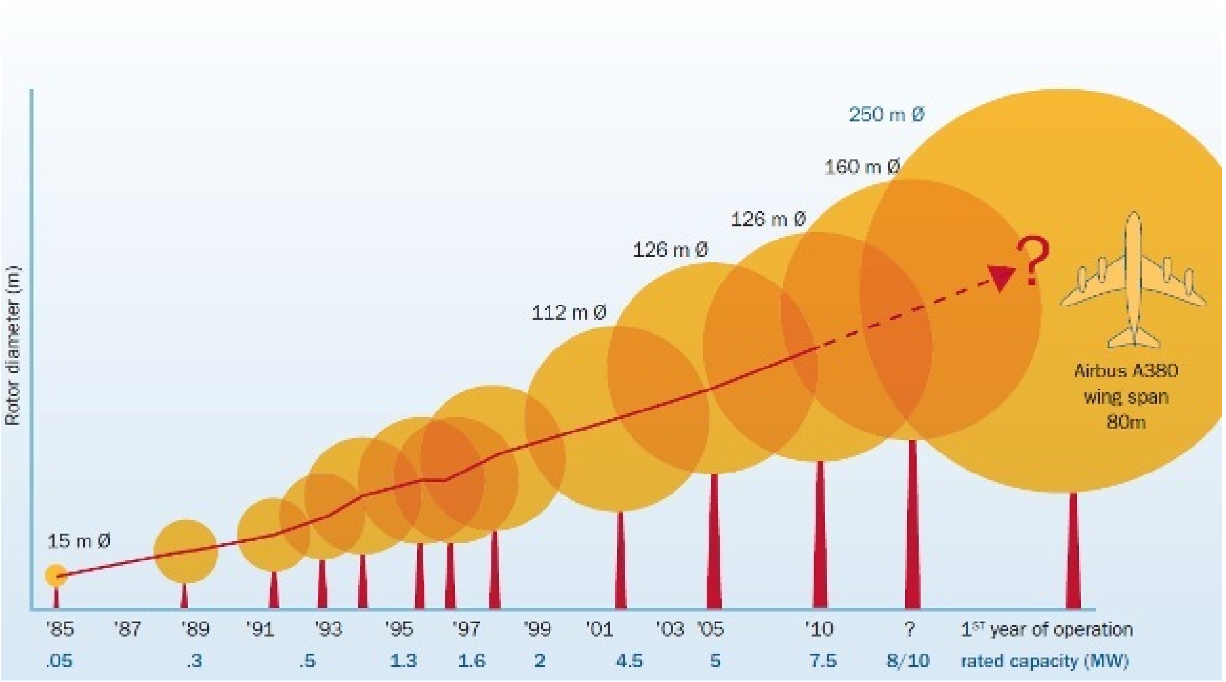
NTNU – Trondheim
Norwegian University of
Science and Technology

Table of contents

Table of contents

1. Motivation

- Increasing rotor diameter



1. Motivation

- Focus on
  - Large diameter monopiles
  - Shallow waters

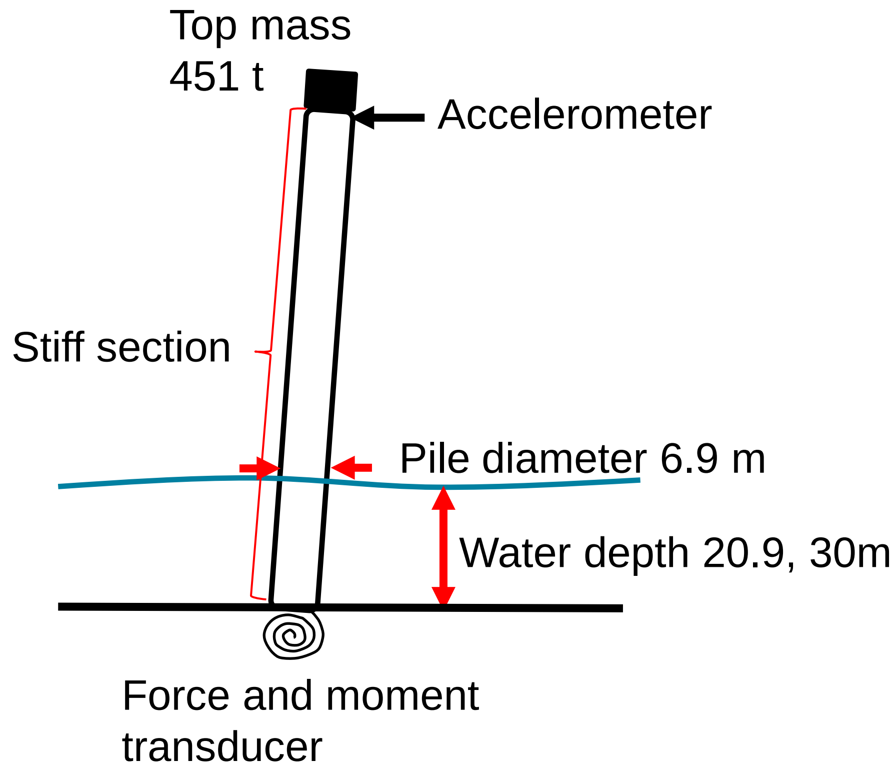
→ increase of non-linearities (frequent breaking)

ULS: what is the design driver?

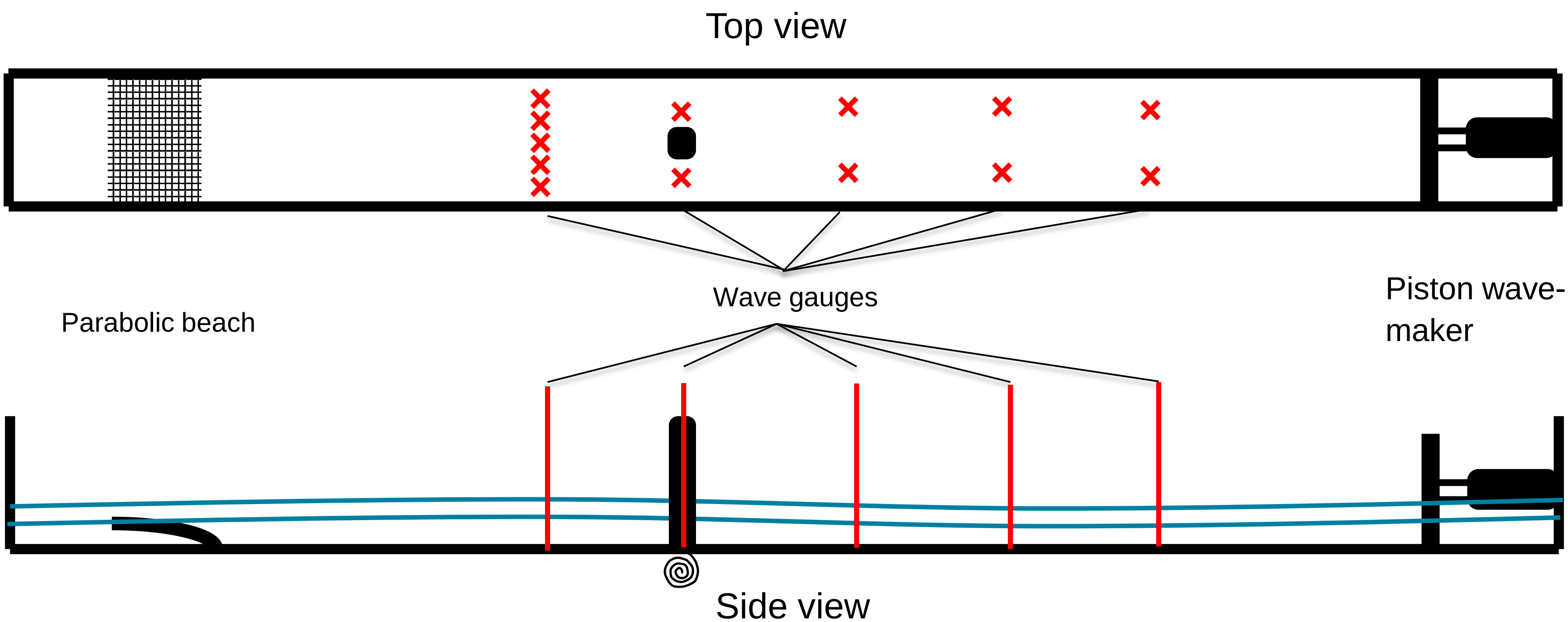
Table of contents

2. Experiments

Responding model



2. Experiments



2. Experiments

- Sea states:
  - JONSWAP spectra
  - Storms with different return periods
  - 20 seeds per sea state

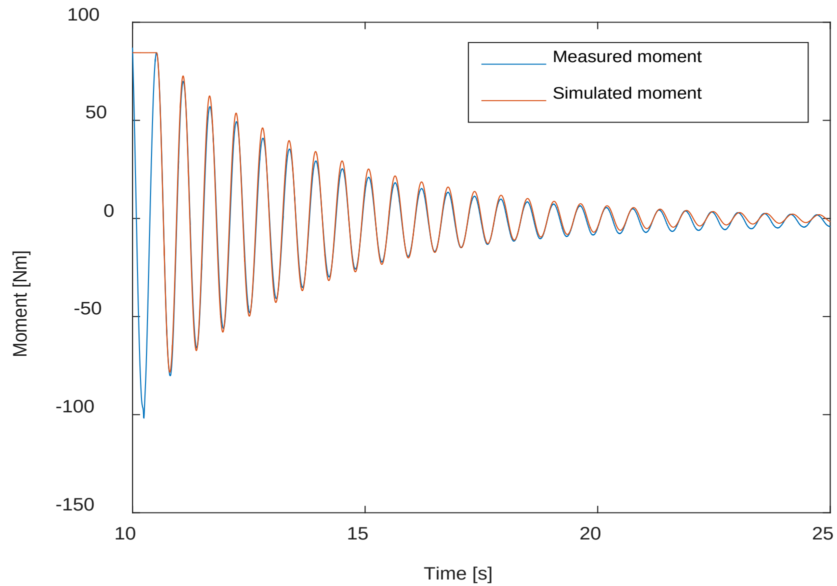
H_s (m)	T_p (s)	g
6.71	11.25	2.32
7.69	"	2.61
8.22	"	2.76
9.04	"	3
6.71	15	1.42
7.69	"	1.59
8.22	"	1.69
9.04	"	1.83

Table of contents

3. Numerical model

- Representation of the model: 1 degree of freedom equation

$$M_{hydro} = (I_P + I_A)\ddot{\theta} + C\dot{\theta} + K\theta$$



3. Numerical model

- Input hydrodynamic loads from FNV formulation

$$F_{FNV} = \quad 2\pi\rho R^2 \int_{-h}^{0} u_t(z)dz \qquad O(\epsilon)$$

$$+\, 2\pi\rho R^2\, u_t\Big|_{z=0} \zeta^{(1)} + \pi\rho R^2 \int_{-h}^{0} [2w(z)w_x(z) + u(z)u_x(z)]dz \qquad O(\epsilon^2)$$

$$+\pi\rho R^2 \left[\zeta^{(1)}\left(u_{tz}\zeta^{(1)} + 2ww_x + uu_x - \frac{2}{g}u_t w_t\right) - \left(\frac{u_t}{g}\right)(u^2 + v^2)\Big|_{z=0}\right] \qquad O(\epsilon^3)$$

$$+\pi\rho \frac{R^2}{g} u^2\, u_t\Big|_{z=0} \beta\left({}^{h}/_{R}\right) \qquad O(\epsilon^3)$$

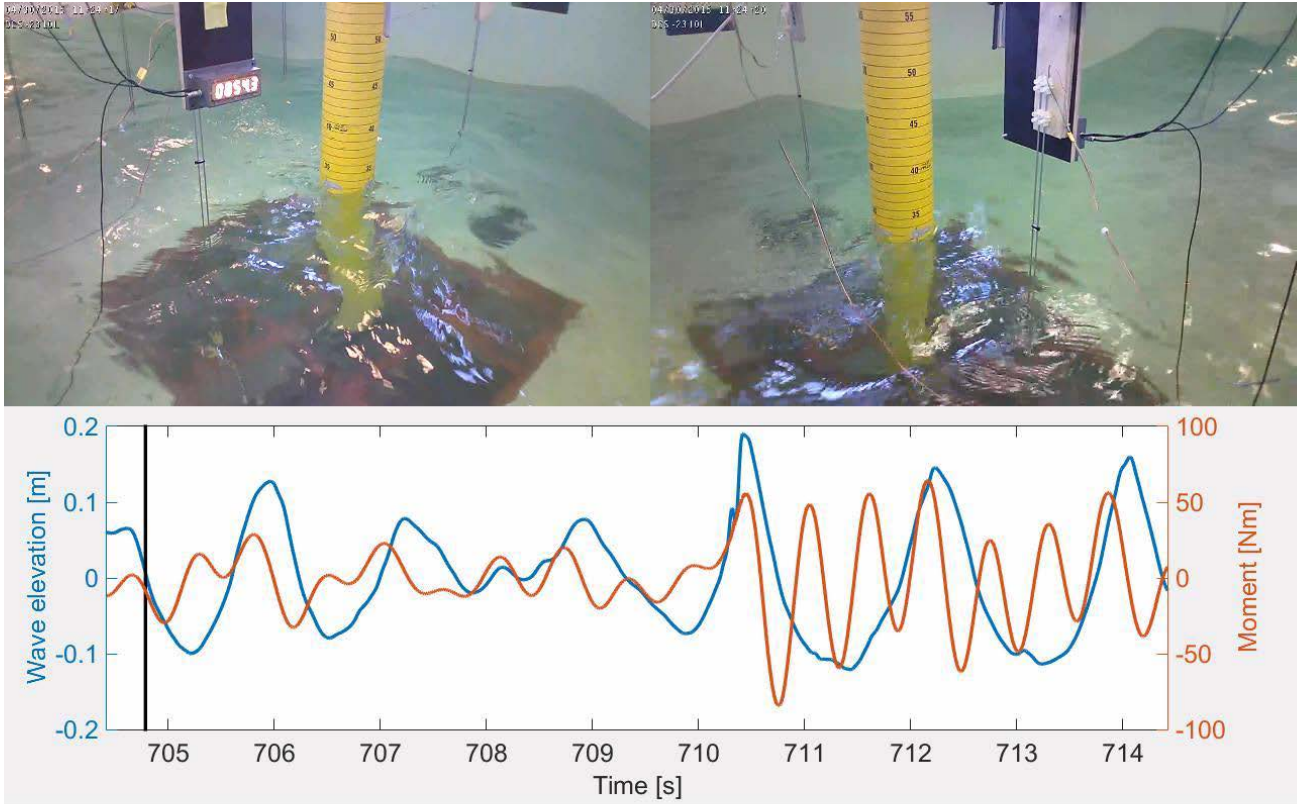
Finite water depth formulation

Table of contents

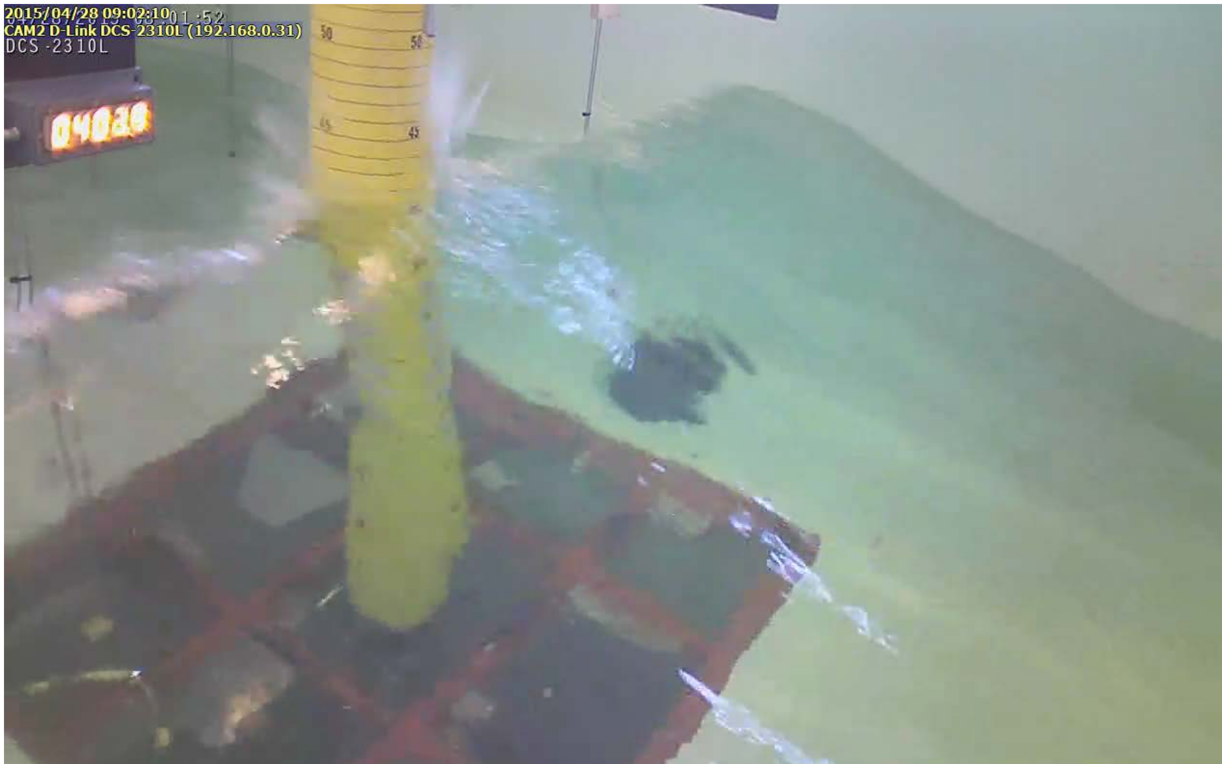
4. Analysis of the results

- Focus on maximum responses
  - Very long and steep waves hit the structure
  - Frequent breaking waves
  - 1st eigenperiod of the structure is excited

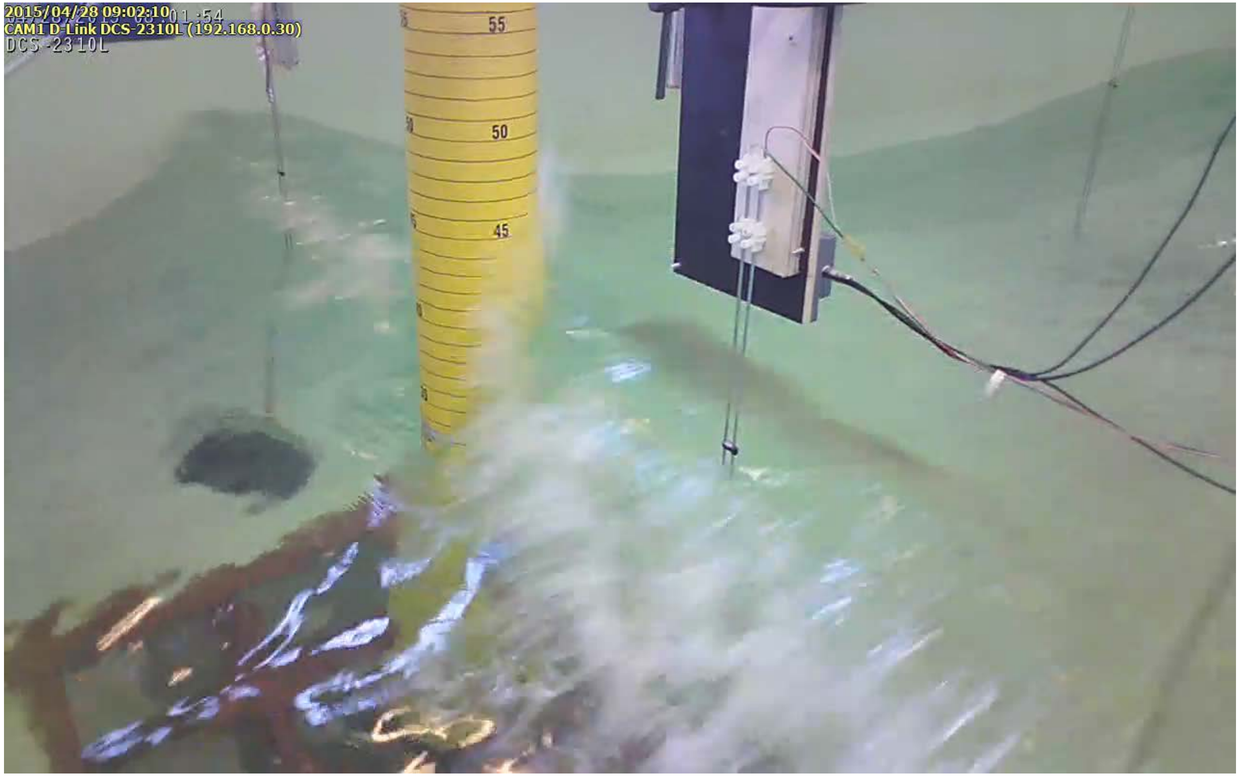
4. Analysis of the results



4. Analysis of the results



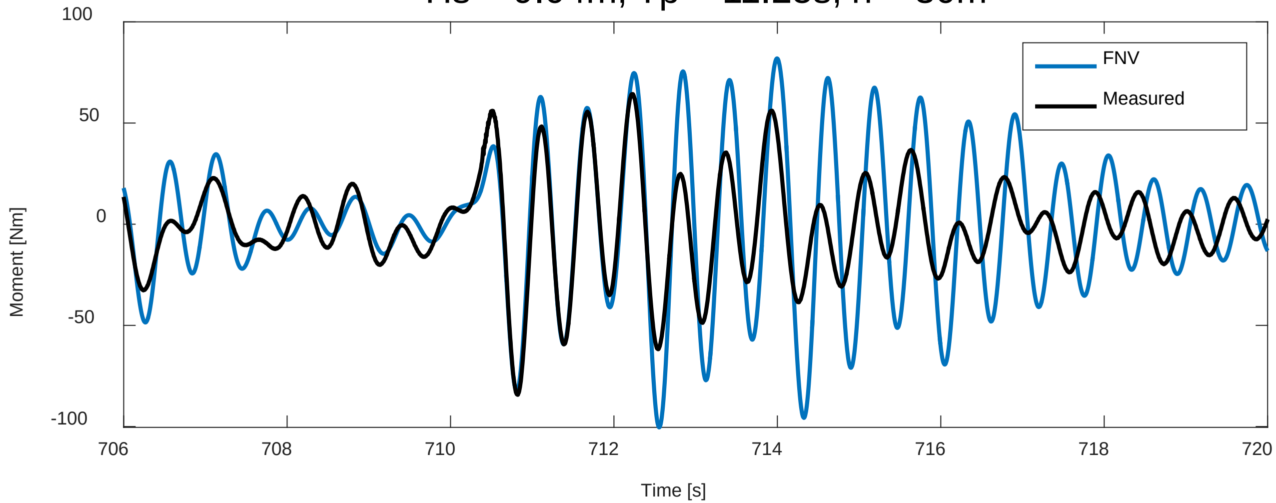
4. Analysis of the results



4. Analysis of the results

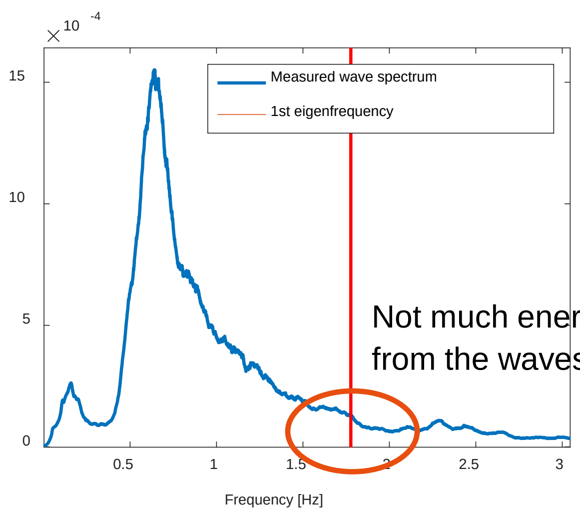
- FNV matches the maximum load

Hs = 9.04m, Tp = 11.25s, h = 30m

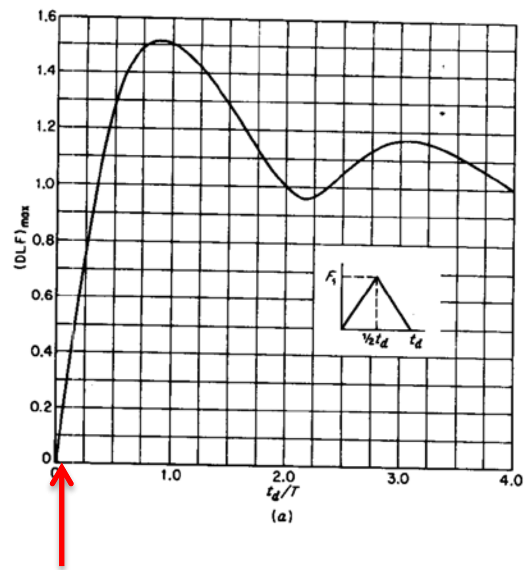


4. Analysis of the results

How does the 1st mode get triggered?



Not much energy from the waves



$$t_d = \frac{13R}{32c}$$

4. Analysis of the results

- Input hydrodynamic loads from FNV formulation

$$F_{FNV} = 2\pi\rho R^2 \int_{-h}^{0} u_t(z)dz \qquad O(\epsilon)$$

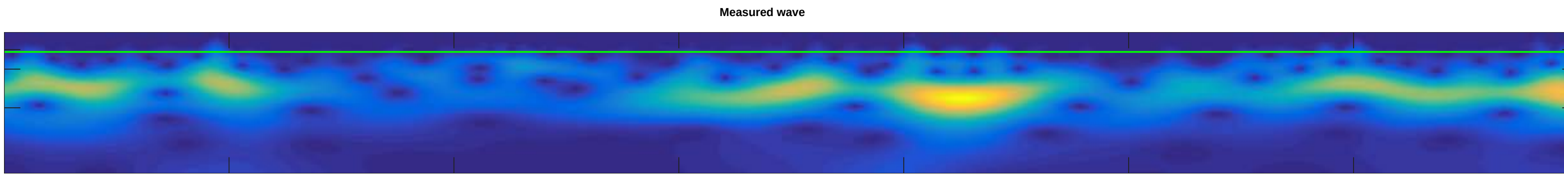
$$+ 2\pi\rho R^2 u_t\Big|_{z=0} \zeta^{(1)} + \pi\rho R^2 \int_{-h}^{0} [2w(z)w_x(z) + u(z)u_x(z)]dz \qquad O(\epsilon^2)$$

$$+\pi\rho R^2 \left[\zeta^{(1)} \left(u_{tz}\zeta^{(1)} + 2ww_x + uu_x - \frac{2}{g}u_t w_t \right) - \left(\frac{u_t}{g} \right) (u^2 + v^2) \Big|_{z=0} \right] \qquad O(\epsilon^3)$$

$$+\pi\rho \frac{R^2}{g} u^2 u_t\Big|_{z=0} \beta \left({}^{h}/_{R} \right) \qquad O(\epsilon^3)$$

Contribution of linear potential at the free surface

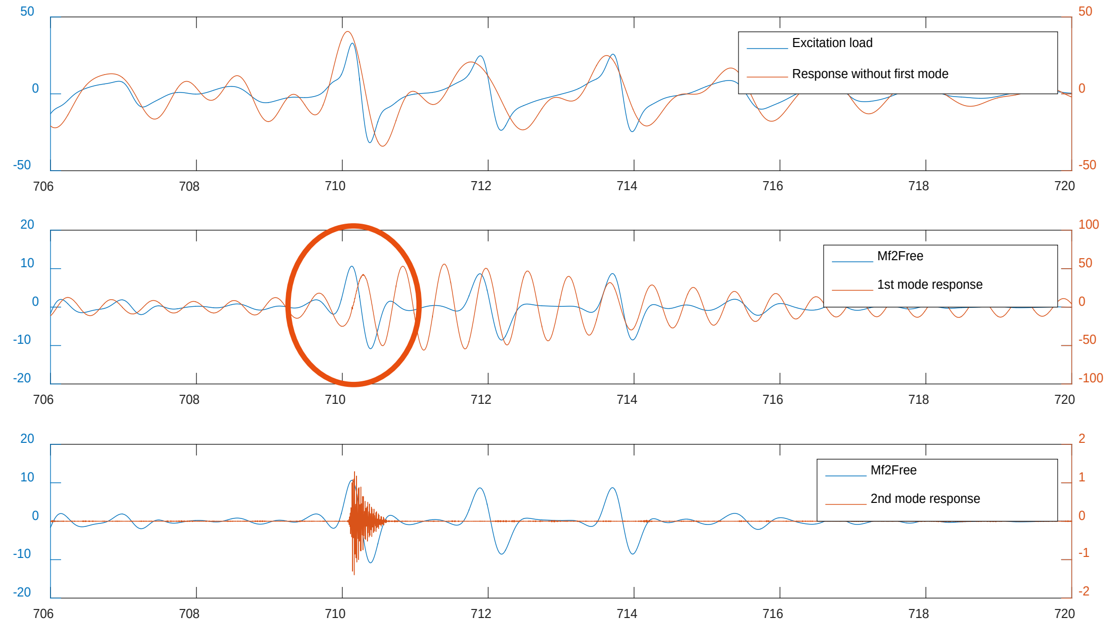
4. Analysis of the results



4. Analysis of the results

- Decomposition of the response into different modes

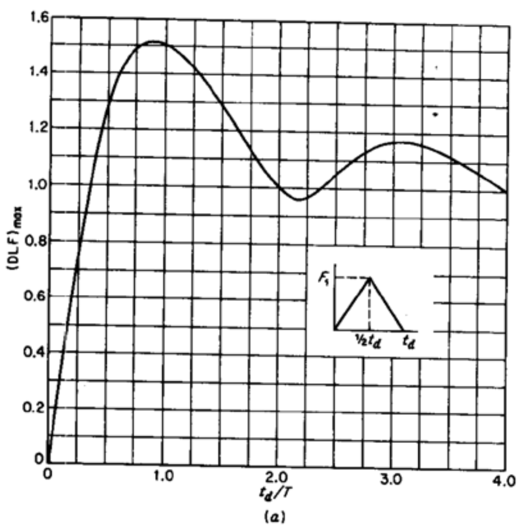
For all cases, there is a hump in the 2nd order excitation load

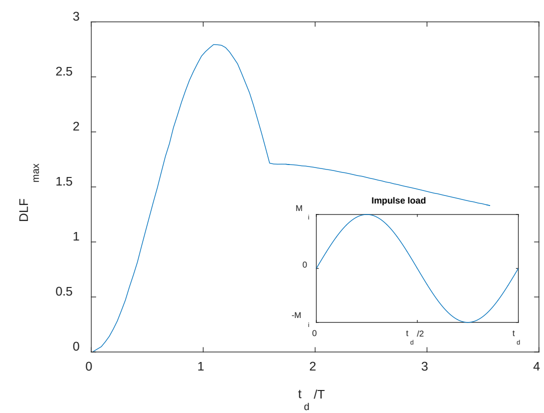


(artificial second mode is triggered by slamming)

4. Analysis of the results

- Simple approximation: trying to match the 2nd order load with an impulse load of sinusoidal shape



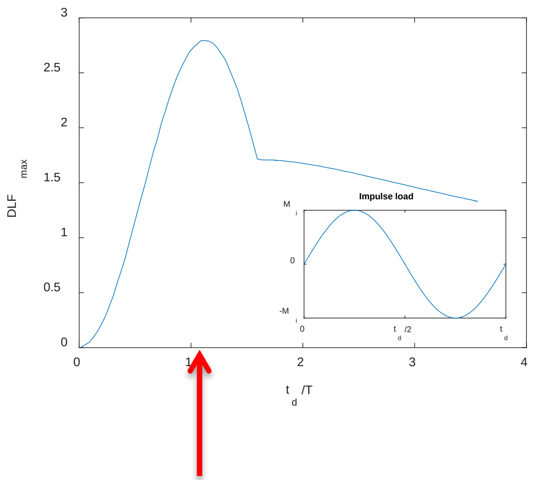


Statkraft

4. Analysis of the results

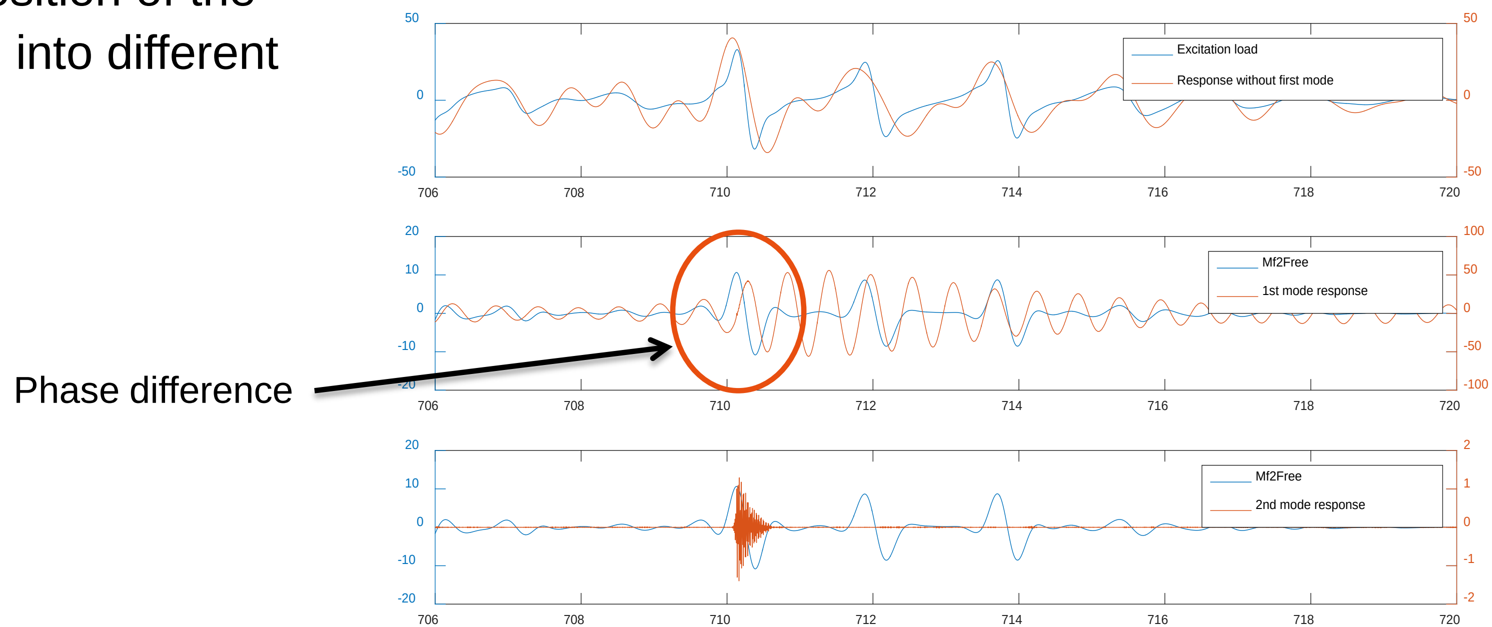
- Simple approximation: trying to match the 2nd order load with an impulse load of sinusoidal shape

The free surface 2nd order load has a high energy content around the eigenfrequency of the structure



4. Analysis of the results

- Decomposition of the response into different modes



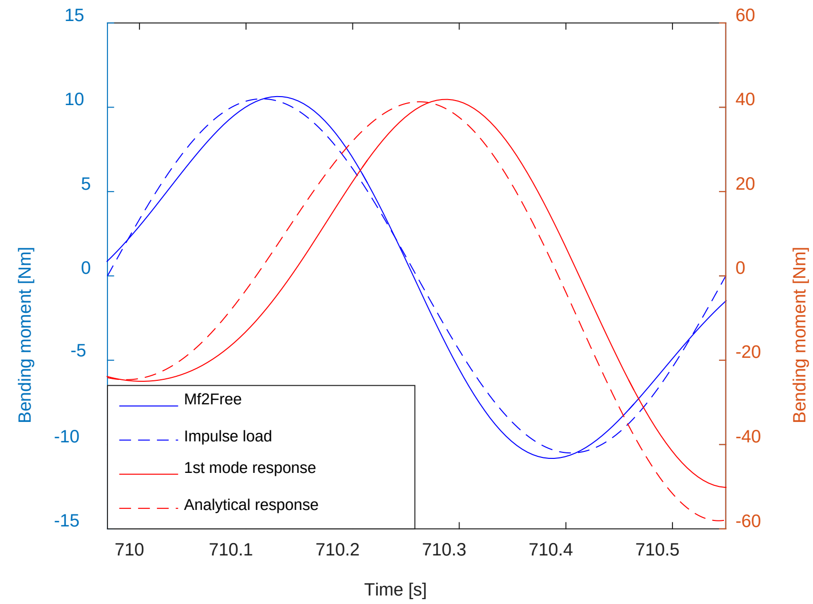
4. Analysis of the results

- Analytical formula for the response

$$M(t) = M_0 \cos(\omega t) + \frac{\dot{M}_0}{\omega} \sin(\omega t) + \omega M_a \int_0^t f(\tau) \sin[\omega(t-\tau)] d\tau$$

with

	M	the response moment of the structure
	M_0	moment at initial state
	M_a	load amplitude
	f	load shape function
	ω	eigenperiod of the system

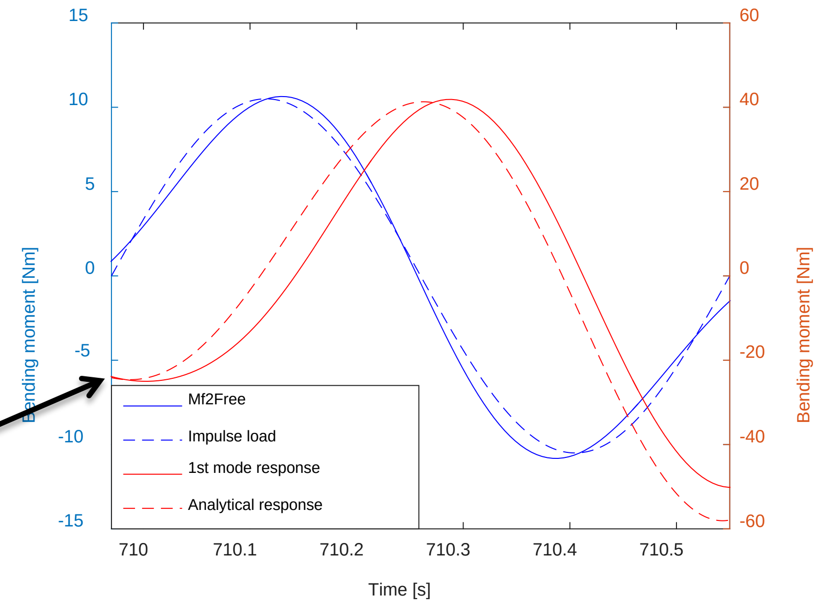


4. Analysis of the results

- Analytical formula for the response

$$M(t) = M_0 \cos(\omega t) + \frac{\dot{M}_0}{\omega}\sin(\omega t) + \omega M_a \int_0^t f(\tau)\sin[\omega(t-\tau)]d\tau$$

Initial conditions are necessary to match the maximum value and phase



4. Analysis of the results

- Input hydrodynamic loads from FNV formulation

$$F_{FNV} = 2\pi\rho R^2 \int_{-h}^{0} u_t(z)dz \qquad O(\epsilon)$$

$$+ 2\pi\rho R^2 u_t\Big|_{z=0} \zeta^{(1)} + \pi\rho R^2 \int_{-h}^{0} [2w(z)w_x(z) + u(z)u_x(z)]dz \qquad O(\epsilon^2)$$

$$+\pi\rho R^2 \left[\zeta^{(1)}\left(u_{tz}\zeta^{(1)} + 2ww_x + uu_x - \frac{2}{g}u_t w_t\right) - \left(\frac{u_t}{g}\right)(u^2 + v^2)\Big|_{z=0}\right] \qquad O(\epsilon^3)$$

$$+\pi\rho \frac{R^2}{g} u^2 u_t\Big|_{z=0} \beta\left({}^{h}/_{R}\right) \qquad O(\epsilon^3)$$

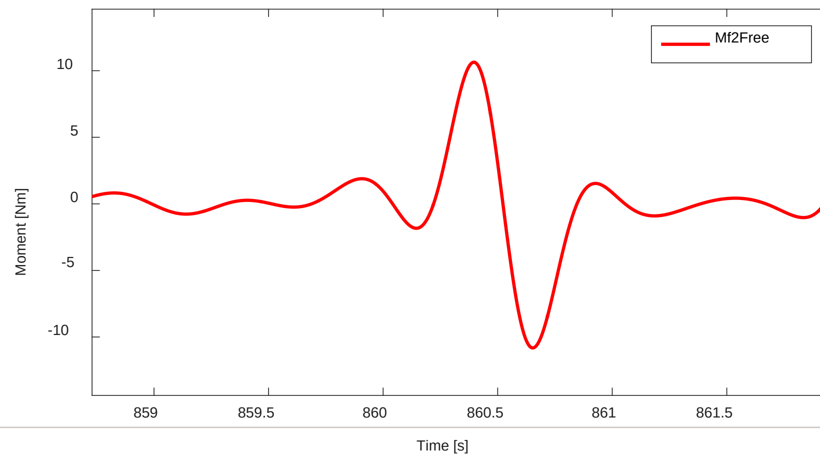
4. Analysis of the results

$$F_{FNV} = 2\pi\rho R^2 \int_{-h}^{0} u_t(z)\,dz \qquad O(\epsilon)$$

$$+\,2\pi\rho R^2\, u_t\Big|_{z=0} \zeta^{(1)} + \pi\rho R^2 \int_{-h}^{0} [2w(z)w_x(z) + u(z)u_x(z)]\,dz \qquad O(\epsilon^2)$$

$$+\pi\rho R^2 \left[\zeta^{(1)} \left(u_{tz}\zeta^{(1)} + 2ww_x + uu_x - \frac{2}{g} u_t w_t \right) - \left(\frac{u_t}{g} \right) (u^2 + v^2) \Big|_{z=0} \right] \qquad O(\epsilon^3)$$

$$+\pi\rho \frac{R^2}{g} u^2\, u_t\Big|_{z=0} \beta \left({}^{h}/_{R} \right) \qquad O(\epsilon^3)$$



Statkraft

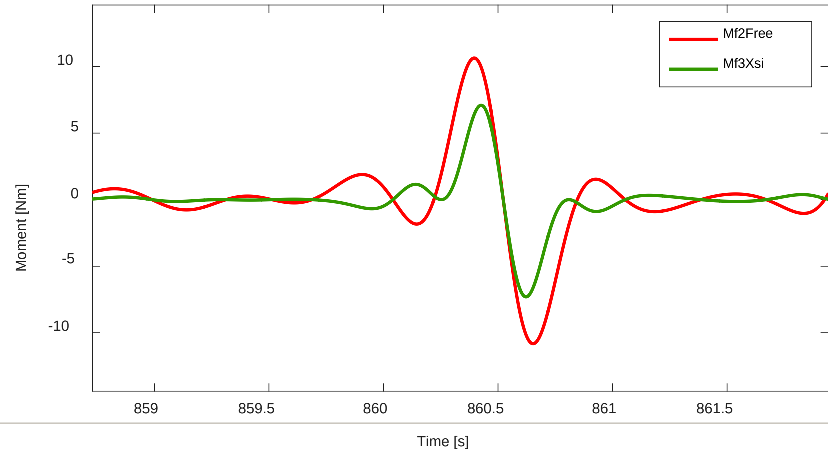
4. Analysis of the results

$$F_{FNV} = 2\pi\rho R^2 \int_{-h}^{0} u_t(z)dz \qquad O(\epsilon)$$

$$+ 2\pi\rho R^2 u_t\Big|_{z=0} \zeta^{(1)} + \pi\rho R^2 \int_{-h}^{0} [2w(z)w_x(z) + u(z)u_x(z)]dz \qquad O(\epsilon^2)$$

$$+\pi\rho R^2 \left[\zeta^{(1)} \left(u_{tz}\zeta^{(1)} + 2ww_x + uu_x - \frac{2}{g}u_t w_t\right) - \left(\frac{u_t}{g}\right)(u^2 + v^2)\Big|_{z=0}\right] \qquad O(\epsilon^3)$$

$$+\pi\rho \frac{R^2}{g} u^2 u_t\Big|_{z=0} \beta\left(h/_R\right) \qquad O(\epsilon^3)$$



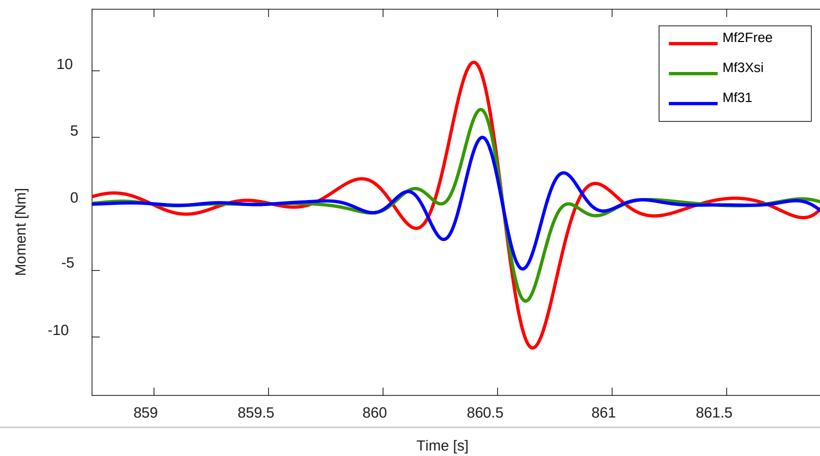
4. Analysis of the results

$$F_{FNV} = 2\pi\rho R^2 \int_{-h}^{0} u_t(z)\,dz \qquad O(\epsilon)$$

$$+\, 2\pi\rho R^2\, u_t\Big|_{z=0} \zeta^{(1)} + \pi\rho R^2 \int_{-h}^{0} [2w(z)w_x(z) + u(z)u_x(z)]\,dz \qquad O(\epsilon^2)$$

$$+\pi\rho R^2 \left[\zeta^{(1)} \left(u_{tz}\zeta^{(1)} + 2ww_x + uu_x - \frac{2}{g} u_t w_t\right) - \left(\frac{u_t}{g}\right)(u^2 + v^2)\Big|_{z=0}\right] \qquad O(\epsilon^3)$$

$$+\pi\rho \frac{R^2}{g} u^2\, u_t\Big|_{z=0} \beta\left(h/_R\right) \qquad O(\epsilon^3)$$



Statkraft

4. Analysis of the results

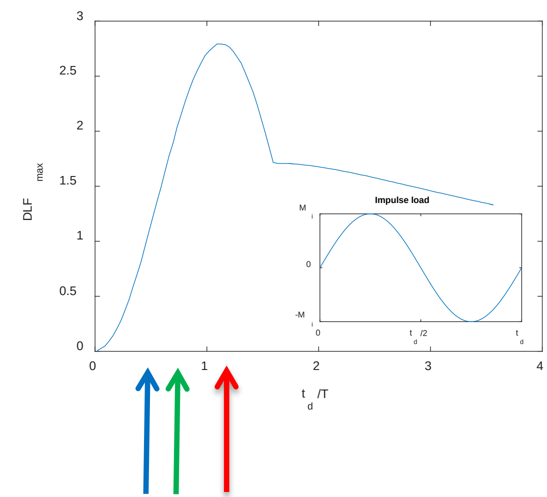
- Input hydrodynamic loads from FNV formulation

$$F_{FNV} = 2\pi\rho R^2 \int_{-h}^{0} u_t(z)\,dz \qquad O(\epsilon)$$

$$+\, 2\pi\rho R^2\, u_t\big|_{z=0}\, \zeta^{(1)} + \pi\rho R^2 \int_{-h}^{0} [2w(z)w_x(z) + u(z)u_x(z)]\,dz \qquad O(\epsilon^2)$$

$$+\pi\rho R^2 \left[\zeta^{(1)}\left(u_{tz}\zeta^{(1)} + 2ww_x + uu_x - \frac{2}{g}u_t w_t\right) - \left(\frac{u_t}{g}\right)(u^2+v^2)\Big|_{z=0}\right] \qquad O(\epsilon^3)$$

$$+\pi\rho \frac{R^2}{g} u^2\, u_t\big|_{z=0}\, \beta\left(h/R\right) \qquad O(\epsilon^3)$$



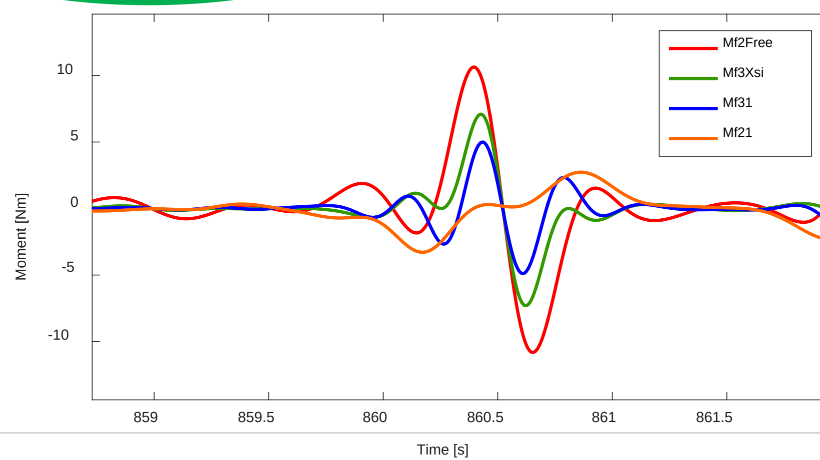
4. Analysis of the results

$$F_{FNV} = 2\pi\rho R^2 \int_{-h}^{0} u_t(z)dz \qquad O(\epsilon)$$

$$+ 2\pi\rho R^2 u_t\Big|_{z=0} \zeta^{(1)} + \pi\rho R^2 \int_{-h}^{0} [2w(z)w_x(z) + u(z)u_x(z)]dz \qquad O(\epsilon^2)$$

$$+\pi\rho R^2 \left[\zeta^{(1)} \left(u_{tz}\zeta^{(1)} + 2ww_x + uu_x - \frac{2}{g}u_t w_t\right) - \left(\frac{u_t}{g}\right)(u^2 + v^2)\Big|_{z=0}\right] \qquad O(\epsilon^3)$$

$$+\pi\rho \frac{R^2}{g} u^2 u_t\Big|_{z=0} \beta\left(h/_R\right) \qquad O(\epsilon^3)$$



Statkraft

4. Analysis of the results

- Damping considerations:
  - Low damping due to idling turbine (here 2.4%)
  - If the turbine is already oscillating, maximum load can be amplified or decreased depending on initial conditions

Table of contents

5. Conclusion

- Simple model to explain qualitatively maximum loads observed during experiments with high frequency of breaking waves
- Impulsive slamming has shown not to induce 1st mode shape response
- The maximum load can be explained as the transient response to an impulse load caused by higher order hydrodynamic loads components
- Low damping can potentially increase the maximum load by changing the initial conditions
- 2nd mode of the structure is triggered by breaking and should be taken into consideration when assessing maximum loads

Acknowledgments

The experiments were done using the set-up developed by Statoil for the Dudgeon project

TAKK

NTNU – Trondheim
Norwegian University of
Science and Technology

Statkraft
REN ENERGI

www.statkraft.no