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Hydro-Elastic Contributions to Fatigue Damage on a Large Monopile

Jan-Tore H. Horn[a,b], Jørgen R. Krokstad[b,c] and Jørgen Amdahl[a,b]

[a]Centre for Autonomous Marine Operations and Systems - AMOS
[b]Department of Marine Technology, NTNU
[c]Statkraft

January 21, 2016

Motivation

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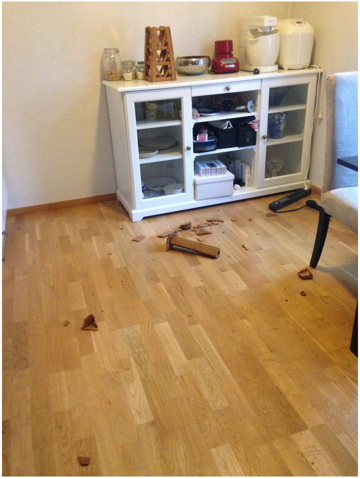

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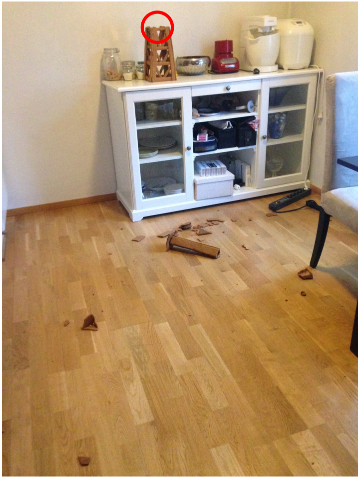

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Overview

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Hydrodynamic Modeling

Motivation:

— Need accurate and realistic load models to evaluate control strategies

— Upscaling of monopiles will give new response characteristics

— Load theory validation and relative impact on lifetime estimation

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Findings:

- Significant higher order contributions to fatigue damage in sea-states with $H_S > D/2$
- Necessary to include diffraction effects on second order inertia forces
- Higher order loads more prominent at low damping levels

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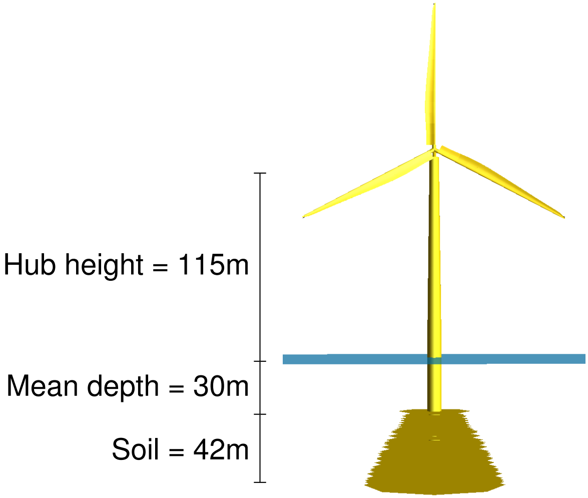

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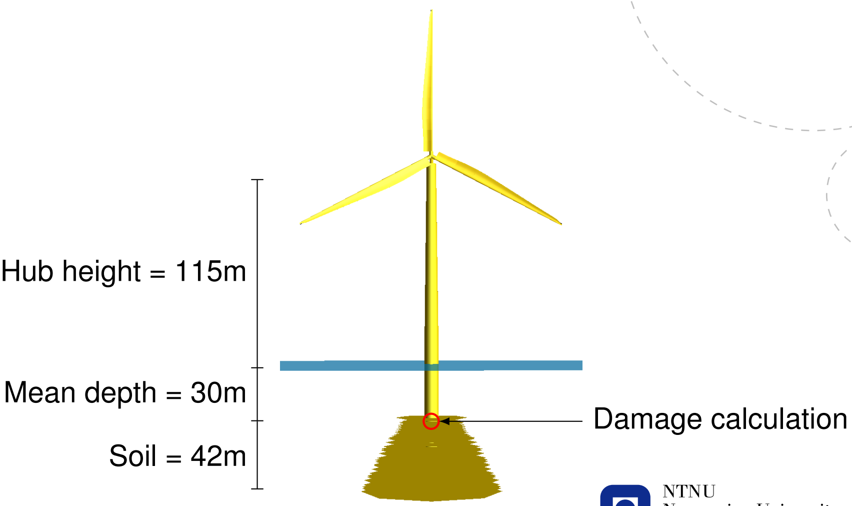


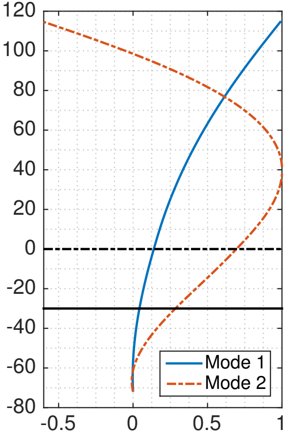
Model

Parameters:

Diameter	9m
Depth	30m
Structural damping	3% of critical damping (Rayleigh)
Aerodynamic damping	Constant Rayleigh included in structural
Soil	Non-linear springs for sand and clay
Natural periods	Mode 1: 4.2s, Mode 2: 1.0s
Sea-states	FLS

Modal analysis

Mode 1: 4.1 seconds
Mode 2: 1.0 seconds



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Wave load models

O1	Linear waves
O1D	Linear waves with diffraction (MacCamy and Fuchs)
O2	Second order contribution from kinematics stretching
O3	Third+fourth order contribution from kinematics stretching
FNV3	Third order FNV - direct implementation
O1P	First order distributed pressure from panel code
O2P	Second order total force from panel code

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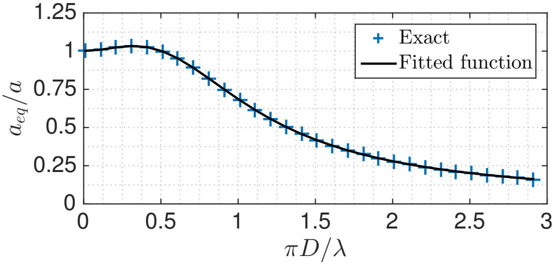
Diffraction - MacCamy and Fuchs

Correction of wave load due to interaction with large-volume structure. a_{eq} = equivalent water particle acceleration.



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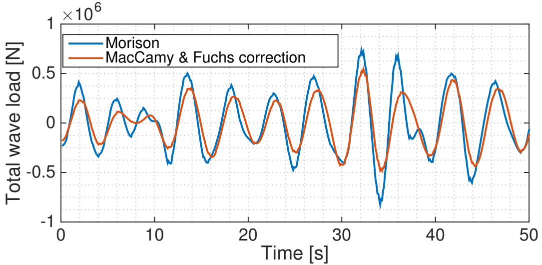

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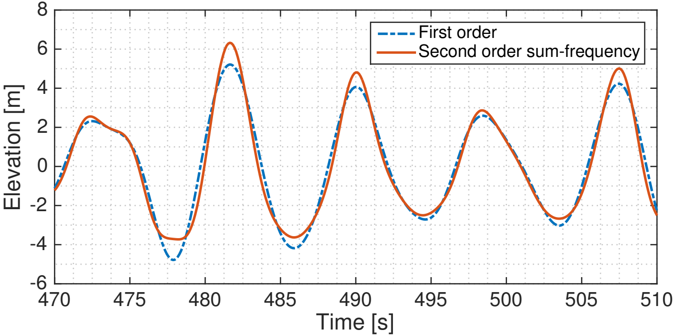
Second order wave elevation



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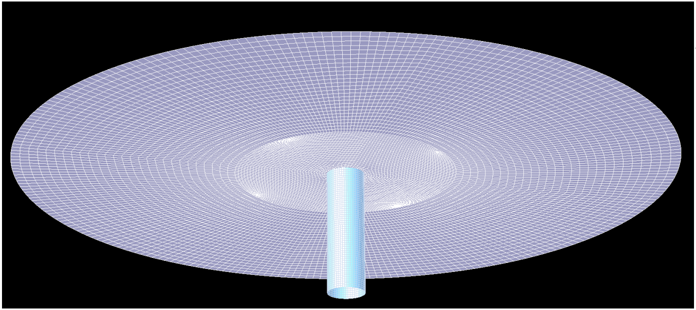
Second order sum-frequency from panel code

HydroD - Wadam



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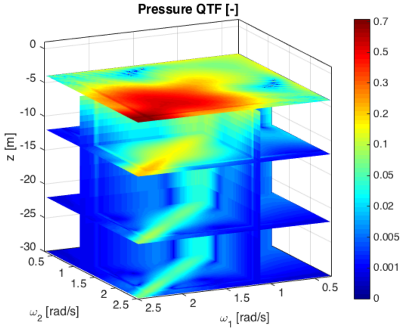
Second order sum-frequency from panel code

Non-dimensional resulting pressure in x-direction over the column as a function of ω_1, ω_2 and z.



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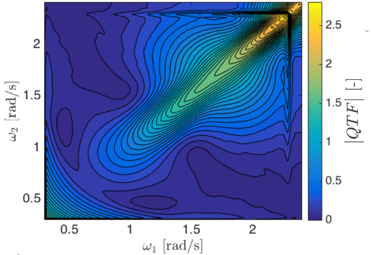
Second order sum-frequency from panel code

The second-order pressures are lumped to $z = 0$ and act as a point force.



$$\bar{F} = \Re\left\{\sum_{n=1}^{N}\sum_{m=1}^{M}\zeta_{a,n}\cdot\zeta_{a,m}\cdot QTF\cdot e^{-i(\phi_m+\phi_n)}\right\}$$

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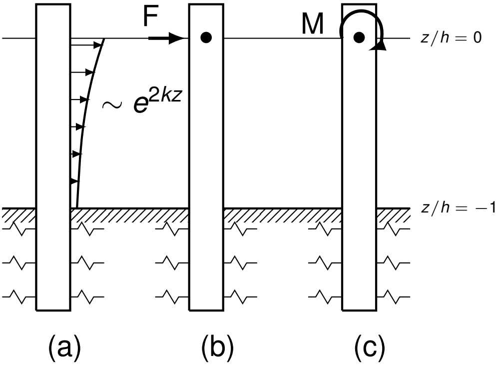
Load application

Distrubuted, point force or moment?



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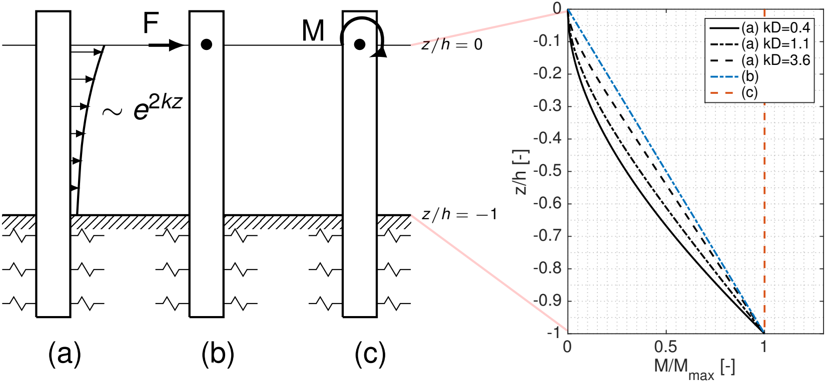

Third Order FNV

Third order horizontal force from linear elevation and diffraction potential assuming deep water:

$$F_x^{FNV(3)} = \rho\pi r^2 \left[\zeta_1 \left(\zeta_1 u_{tz} + 2ww_x + uu_x - \frac{2}{g} u_t w_t \right) - \left(\frac{u_t}{g} \right) (u^2 + w^2) + \frac{\beta}{g} u^2 u_t \right]_{z=0}$$

Kinematics models

Assuming

$k\zeta_a = O(\epsilon)$

$kD = O(\delta)$

where $\epsilon \ll 1$ and $\epsilon \approx \delta$

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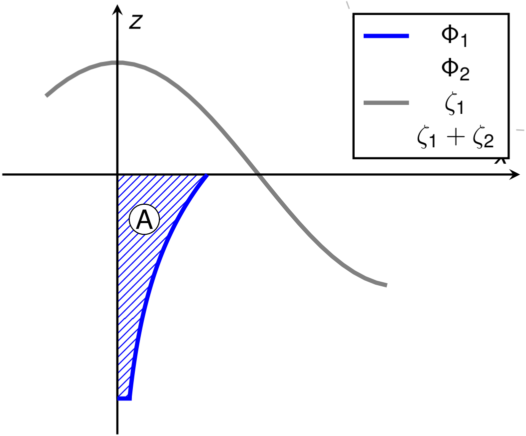
Kinematics models

Assuming
$k\zeta_a = O(\epsilon)$
$kD = O(\delta)$

Order of horizontal inertia forces:

— A: $\epsilon^1\delta^2$



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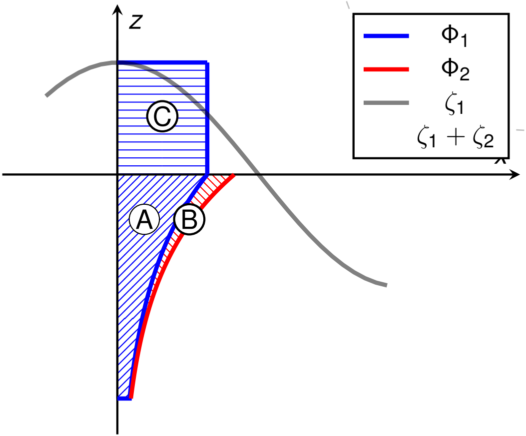
Kinematics models

Assuming
$k\zeta_a = O(\epsilon)$
$kD = O(\delta)$

Order of horizontal inertia forces:

- A: $\epsilon^1\delta^2$
- B+C: $\epsilon^2\delta^2$



Kinematics models

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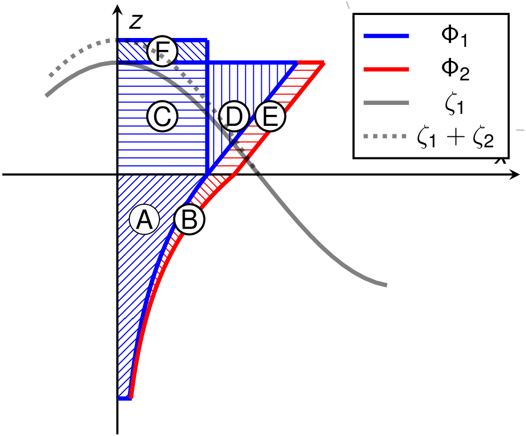
$kD = O(\delta)$

Order of horizontal inertia forces:

- A: $\epsilon^1\delta^2$
- B+C: $\epsilon^2\delta^2$
- D+E+F: $\epsilon^3\delta^2$



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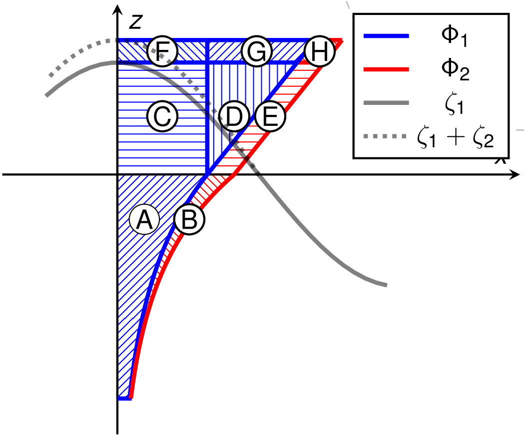
Kinematics models

Assuming
$k\zeta_a = O(\epsilon)$
$kD = O(\delta)$

Order of horizontal inertia forces:

- A: $\epsilon^1\delta^2$
- B+C: $\epsilon^2\delta^2$
- D+E+F: $\epsilon^3\delta^2$
- G+H: $\epsilon^4\delta^2$



Kinematics models

	$F_x/(0.5\pi\rho D^2)$	$O(F_x)$	$F_x \propto$	Frequency
A	$\int_{-h}^{0} u_{1,t}(z)dz$	$\epsilon\delta^2$	ζ_a	1ω
B	$\int_{-h}^{0} u_{2,t}(z)dz$	$\epsilon^2\delta^2$	ζ_a^2	2ω
C	$\int_{0}^{\max(0,\zeta_1)} u_{1,t}(0)dz$	$\epsilon^2\delta^2$	ζ_a^2	2ω
D	$\int_{0}^{\max(0,\zeta_1)} zu_{1,tz}dz$	$\epsilon^3\delta^2$	ζ_a^3	$1\omega + 3\omega$
E	$\int_{0}^{\max(0,\zeta_1)} u_{2,t}(0)dz$	$\epsilon^3\delta^2$	ζ_a^3	$1\omega + 3\omega$
F	$\int_{\max(0,\zeta_1)}^{\max(0,\zeta_1+\zeta_2)} u_{1,t}(0)dz$	$\epsilon^3\delta^2$	ζ_a^3	$1\omega + 3\omega$
G	$\int_{\max(0,\zeta_1)}^{\max(0,\zeta_1+\zeta_2)} zu_{1,tz}(0)dz$	$\epsilon^4\delta^2$	ζ_a^4	4ω
H	$\int_{\max(0,\zeta_1)}^{\max(0,\zeta_1+\zeta_2)} u_{2,t}(0)dz$	$\epsilon^4\delta^2$	ζ_a^4	4ω

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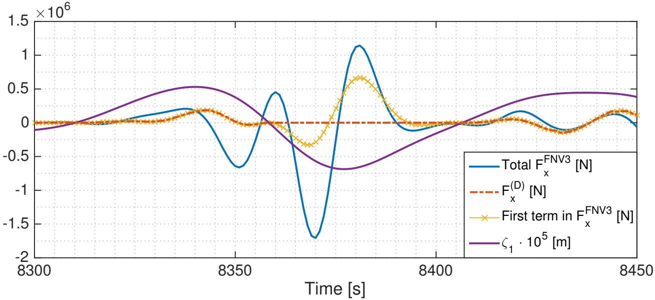
Third order forces



$$F_x^{FNV(3)} = \rho \pi r^2 \left[\zeta_1^2 u_{tz} + 2\zeta_1 w w_x + \zeta_1 u u_x - \frac{2}{g}\zeta_1 u_t w_t - \left(\frac{u_t}{g}\right)(u^2 + w^2) + \frac{\beta}{g} u^2 u_t \right]_{z=0}$$

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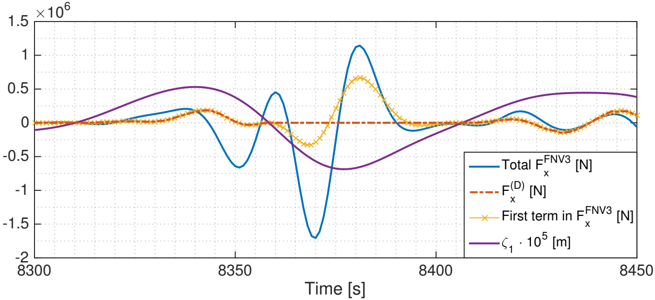

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Kinematics models

Notation	Fields	Description
O1	A	First order incident wave potential
O1D	A	First order incident wave potential w/diffraction
O2	B+C	Second order incident wave potential and stretched first order potential
O3	D+E+F+G+H	Third and fourth order force from stretched first and second order potential
O1P	A	First order diffraction pressure from panel code modeled as acceleration
O2P	B+C	Total second order diffraction force from panel code
FNV3	N/A	Third order FNV ringing force based on first order incident potential

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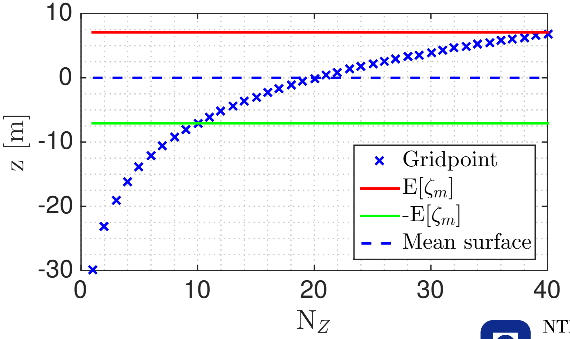
Wave kinematics grid

- Logarithmically distributed in z-direction to increase accuracy in wave-zone
- 4.3 million points for 30 minute simulation with $dt = 0.1$ and $N_Z = 40$, $\rightarrow$ large files!



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Sea-states

Chosen sea-states for Dogger Bank conditions. JONSWAP spectrum with peak parameter 3.3 is used.

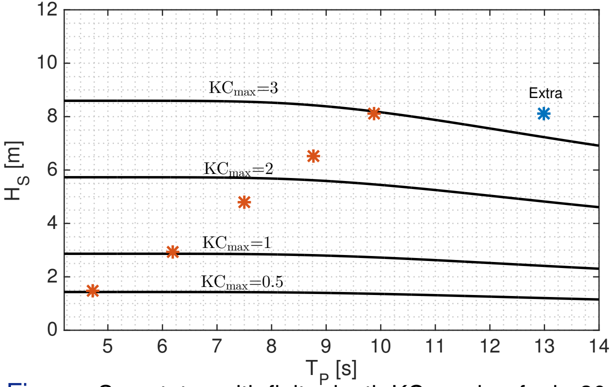

Figure: Sea-states with finite depth KC number for h=30m.

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Sea-states

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Chosen sea-states for Dogger Bank conditions. JONSWAP spectrum with peak parameter 3.3 is used.

No.	H_S [m]	T_P [s]	f_{H_S,T_P}[-]	KC_{max}[-]	$\pi D/\lambda$ [-]
1	1.46	4.72	0.1002	0.5	1.28
2	2.95	6.18	0.0314	1.0	0.75
3	4.79	7.50	0.0092	1.7	0.50
4	6.54	8.76	0.0016	2.3	0.37
5	8.13	9.88	0.0002	3.0	0.29
6*	8.13	13.00	0.0000	3.5	0.17

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Results

- For each sea-state and hydrodynamic model, 3$\times$30 minute simulations have been run without wind
- Average findings presented
- Small variances between the seeds

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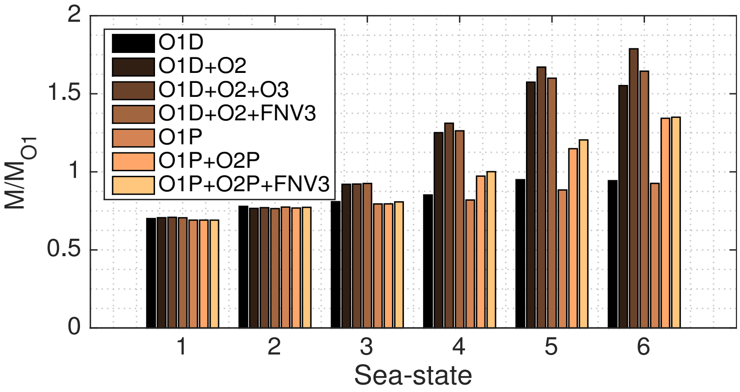
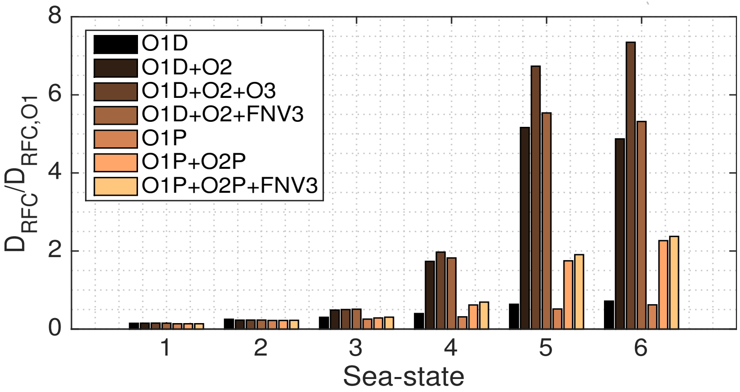
Results

Baseline maximum moment



Results

Fatigue damage relative to first order incident wave



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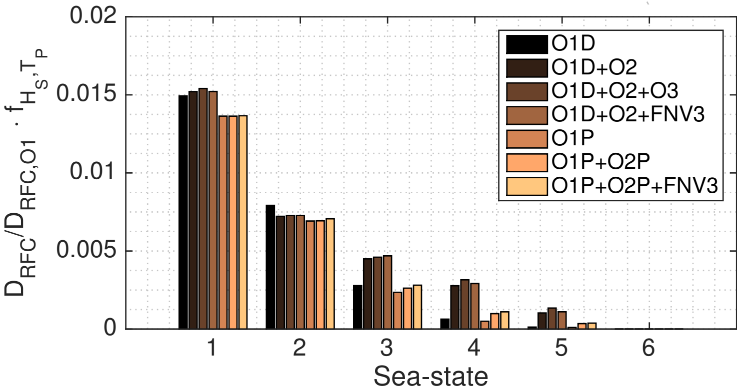
Results

Relative fatigue damage accounting for probability of occurrence



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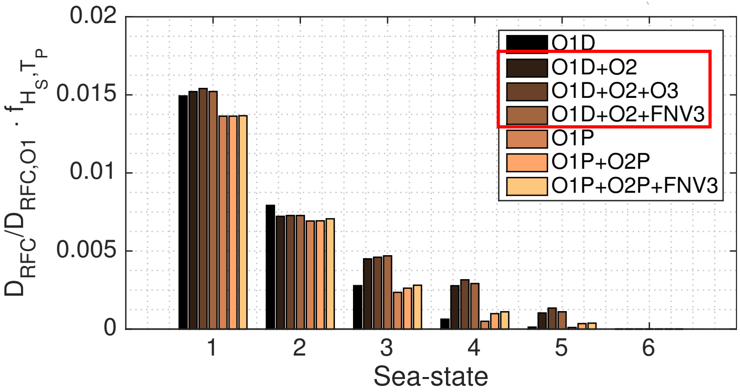

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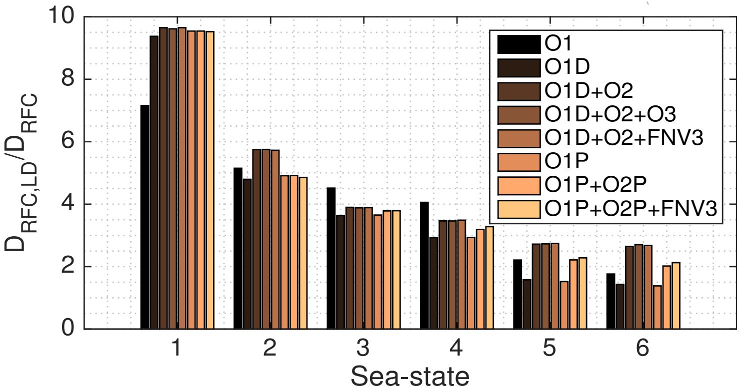
Results

Increased fatigue damage for lightly damped system: 3% → 1%



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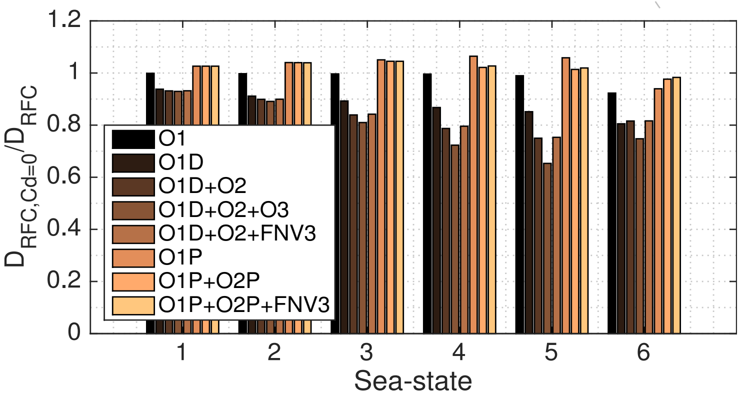
Results

Drag force contribution due to wave elevation and increasing KC-number



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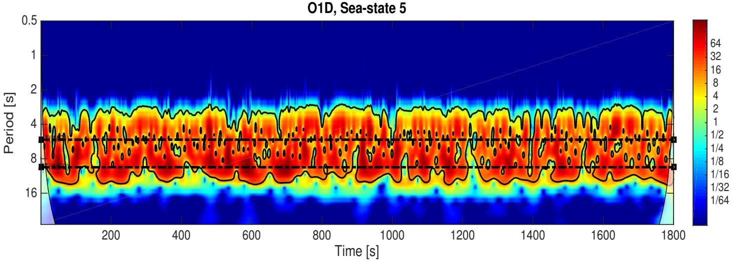
Time-frequency analysis

Wavelet analysis revealing most dominating oscillation periods.



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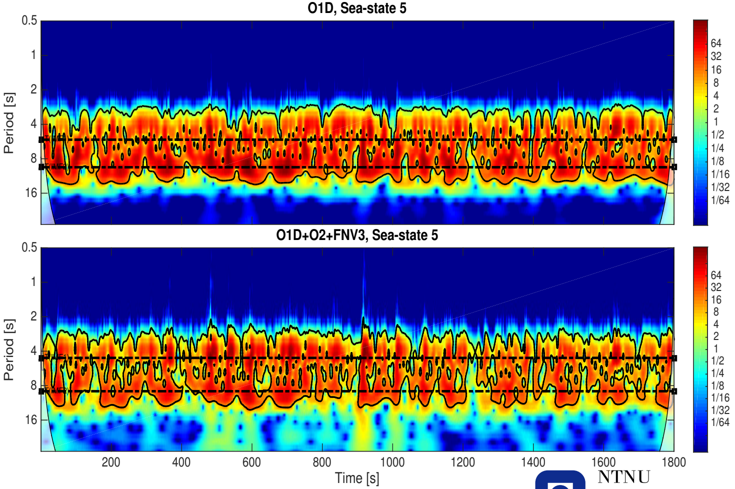

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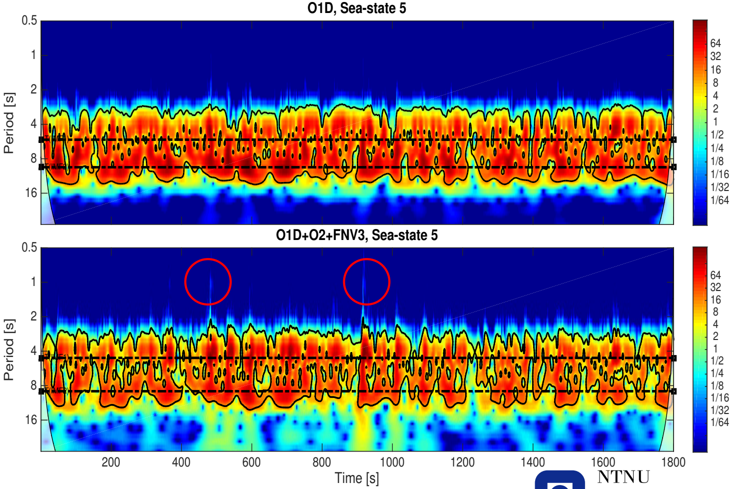

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- When $H_S > D/2$, significant contributions to fatigue damage from higher order loads are observed
- Higher order effects not important for smaller sea-states - overall small contributions when frequency of occurrence is accounted for
- Lower damping level results in more prominent contributions from higher order forces
- Drag forces still important when wave elevation is accounted for - need sensitivity study of C_D
- A Morison type loading for second order load seems to be predicting very large responses and fatigue damage for large sea-states - elevation important
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Thank you for your attention.
- Questions?

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