An efficient approach for inducing extreme second-order responses in slack-moored offshore wind substructures

David Lande-Sudall, email: dla@hvl.no
Peter Stansby

Høgskulen på Vestlandet

HYDROMORE
hydromore.no

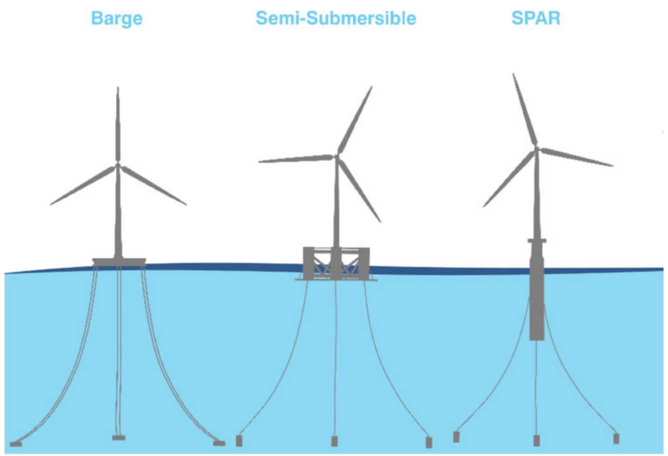
MANCHESTER 1824
The University of Manchester

contents

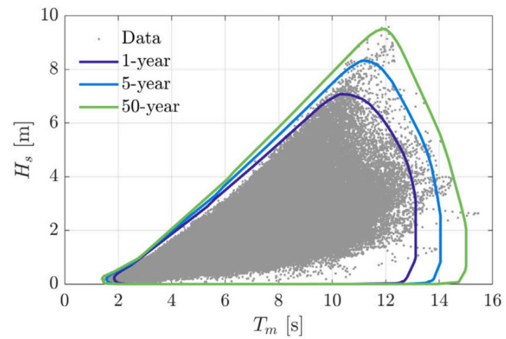
- Background & motivation
- Second-order theoretical considerations
- Simplified 1DOF response
- Numerical model validation
- Method - second-order design waves
- *Preliminary* results
- Conclusions

Background

- Catenary moored substructures have natural frequencies (surge, pitch, sway) below WF region.
  - Approx. 30 – 170 s period
- Resonance can occur in the LF region due to difference-frequencies.
- For IEC 61400-3-2, DLC 6.1 requires numerical modelling of multiple 3 hour sea-state seeds, around a 1/50 year return-period environmental contour.
- With full-QTF second-order diffraction models this is time-consuming, and infeasible with higher-fidelity methods.



DNV-ST-0119: Floating wind turbine structures

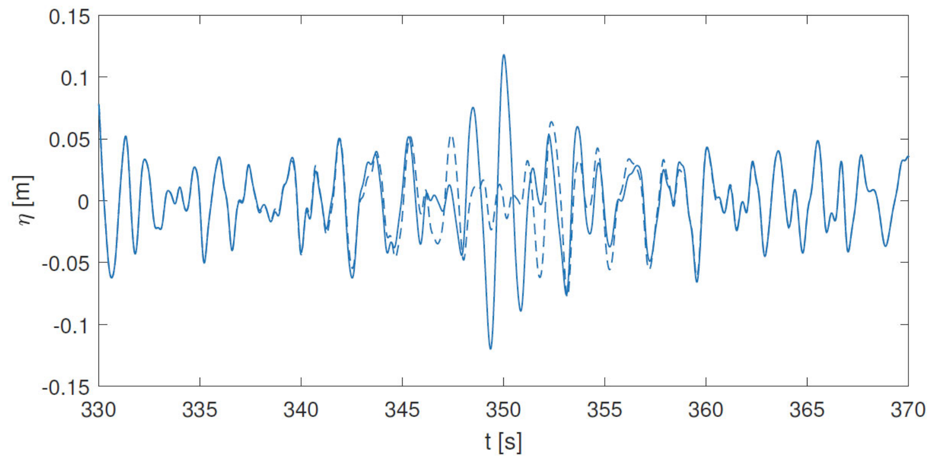


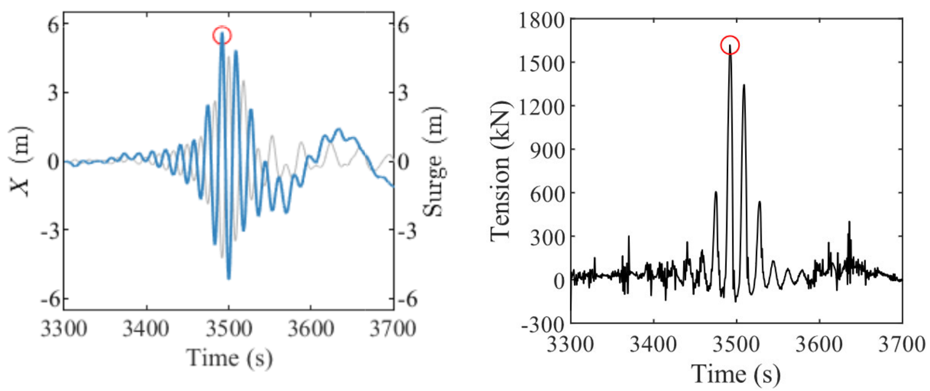
E. MacKay & G. Hauteclocque 2023

Høgskulen på Vestlandet

Background

- Fixed-bed: use constrained focus waves.
- Floating: greatest response is not directly related to maximum wave height.
- DeepWind 2023 - Experimental tests of Most-likely Extreme Response waves.
  - Using linear RAO of substructure, condition the wave group to excite greatest response.
  - Mixed-success.





Høgskulen på Vestlandet

motivation

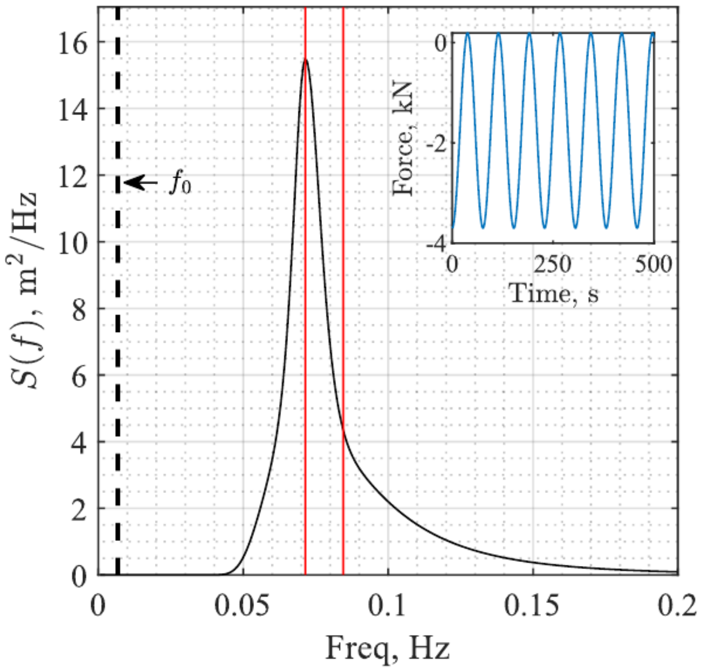
- How can we increase speed of the LF wave modelling process?
- Can we create a design wave group that can be run in O(100s), as opposed to O(1000 s) to enable wider use of high-fidelity modelling of catenary moored substructure?
- What is the maximum upper-bound to surge response?

Second-order difference forcing

- Total wave force: $g(t) = g^{(1)}(t) + g^{(2)}(t)$
- Difference forcing comes from linear-amplitudes:

$$g^{(2)}_{m,n}(t) = q_{m,n} A_m A_n e^{i\{(\omega_m - \omega_n)t + (\theta_m - \theta_n) + (\phi_m - \phi_n)\}}$$

- Pairs of frequencies with difference $f_m - f_n = f_0$ will produce forcing at f_0.
- Which pair of frequencies give greatest forcing from spectrum?
- For N components, can sweep across spectrum with $f_m - f_n = f_0$. Maximum when force-phases are aligned.
- What about maximum motion response?



Simplified 1DOF response

- The LF response can be represented as a 1DOF system, e.g. for surge, *X*:

$$g^{(2)}(t) = M\ddot{X}^{(2)}(t) + c\dot{X}^{(2)}(t) + kX^{(2)}(t)$$

$$\Rightarrow \sum_{m=1}^{N}\sum_{n=1}^{N} X_0(m,n)e^{i\phi_x} = \sum_{m=1}^{N}\sum_{n=1}^{N} \frac{q_{m,n}A_m A_n}{M} \frac{\omega_0^2 - \omega^2 - i\omega\left(\frac{c}{M}\right)}{(\omega_0^2-\omega^2)^2 + \omega^2\left(\frac{c}{M}\right)^2}$$

- This is maximised when:

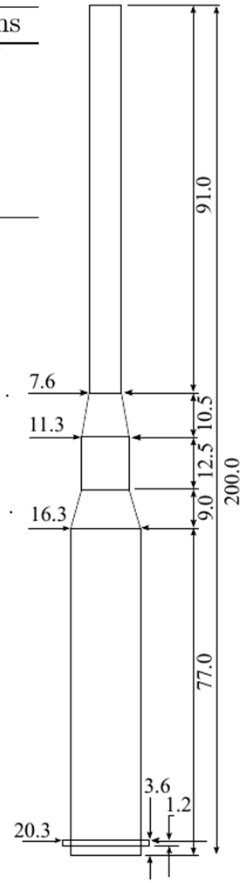
$$(\phi_m - \phi_n) + (\theta_m - \theta_n) + \phi_x = 0 \qquad \text{Eq.(1)}$$

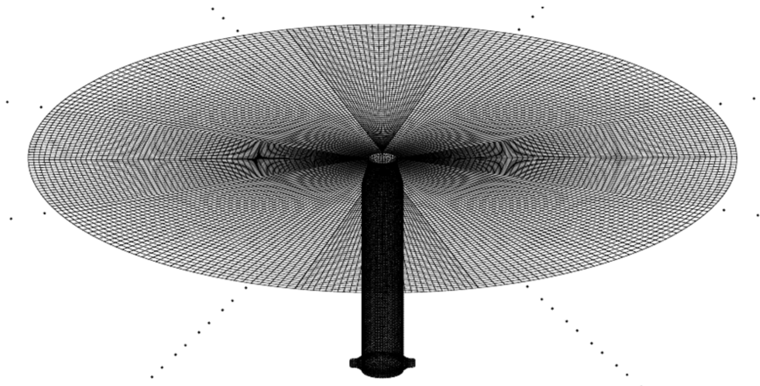
- 1DOF model is extremely quick to run and hence can approximately evaluate expected response from very long runs, e.g. 6hr, 12hrs.

Diffraction Model

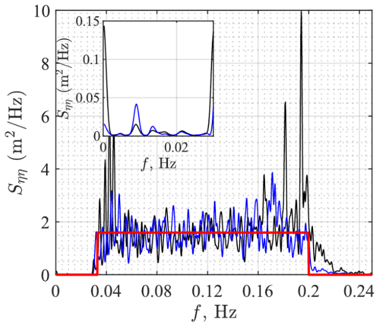
- Full QTFs from OrcaWave.
- Explicit time-domain model OrcaFlex (blue).
- Compared to Hs=2 m white-noise experiments in MarinLab (**black**)
- Reasonable agreement for moderate wave heights.

Particular	Dimensions
Total mass (dry), tonnes	18,123.7
RNA mass, tonnes	989.8
Draught, m	90
z_G, m	-56
Gyration radii, R_{xx},R_{yy} m	51.41

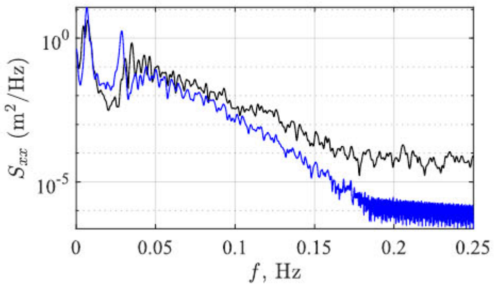


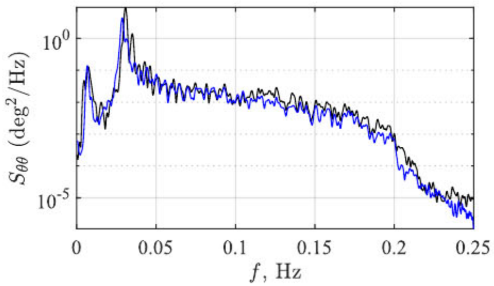


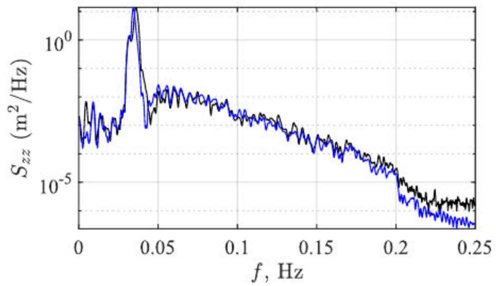
INPUT:



Response:

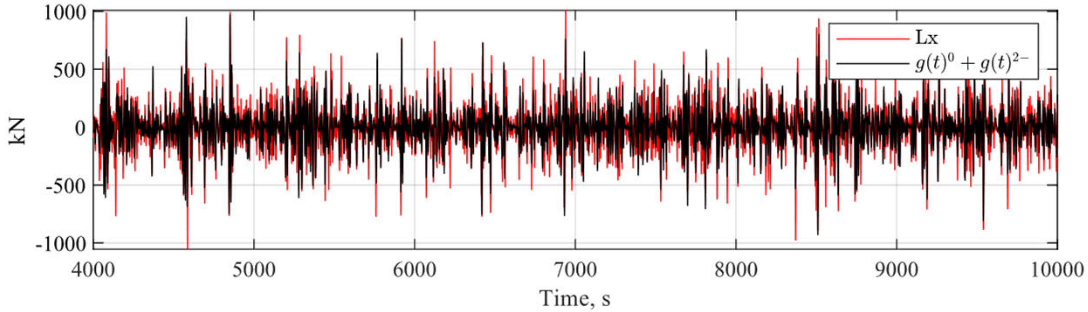


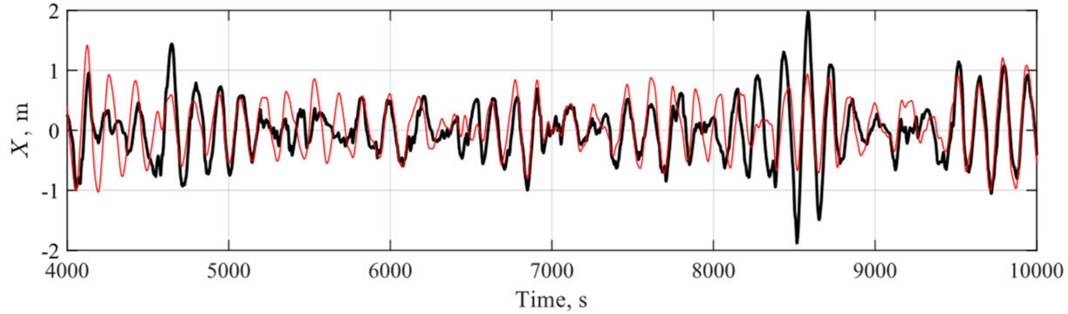




1DOF vs Diffraction model

- Only parameter to tune in 1DOF EoM is linear damping coefficient.
  - 7% critical damping from decay tests.
- Compared to 3hr random seed sea-state, Hs=4m, Tp=12 s.
- 1DOF model generally in good agreement.
  - Slightly under-predicts forcing.
  - Agreement on LF surge response varies.
- 3hr peak surge response is approx. 2 m
  - 1.97 m (1DOF)
  - 1.77 m (OrcaFlex)





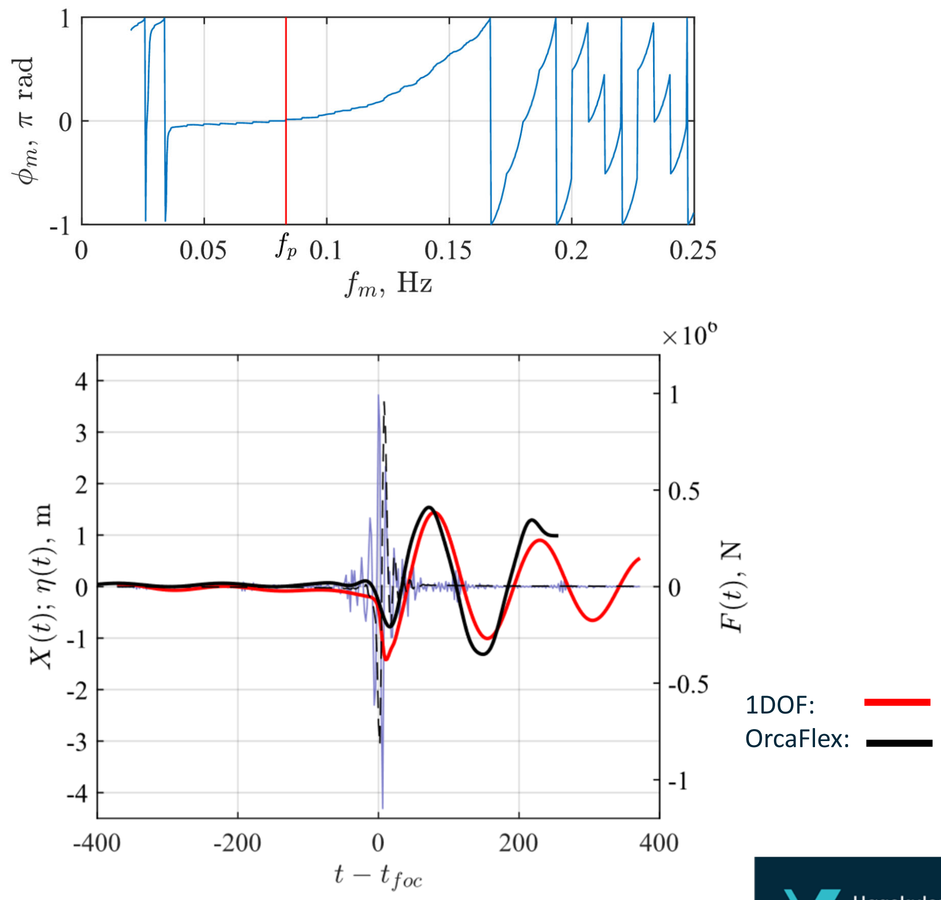
Second-order focused response wave

Aim – phase-match to get all difference frequencies with $f_m - f_n = f_0$ in phase at focus time, t_{foc} such that maximum response occurs at $t = t_{foc}$.

<u>First approach:</u>

- Amplitudes defined by spectrum and scaled to match A_{max}=H_{max}/2 = 3.7 m
- Runtime=1/df; *df=n_f/df_0*.
- Sweep across *n* frequencies, $f_n = f_p : f_p - f_0$, and phase-match corresponding diff. freq. to satisfy Eq.(1).
- Continue working outwards away from f_p to phase-match across rest of spectrum.

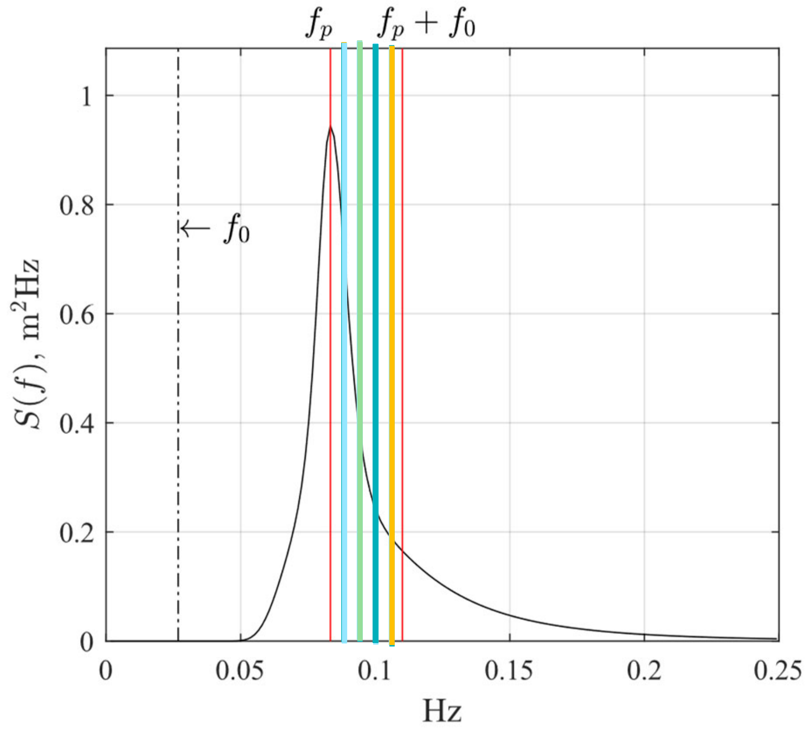
Doesn't generate an equivalent maximum response!



spreading Energy across multiple peaks

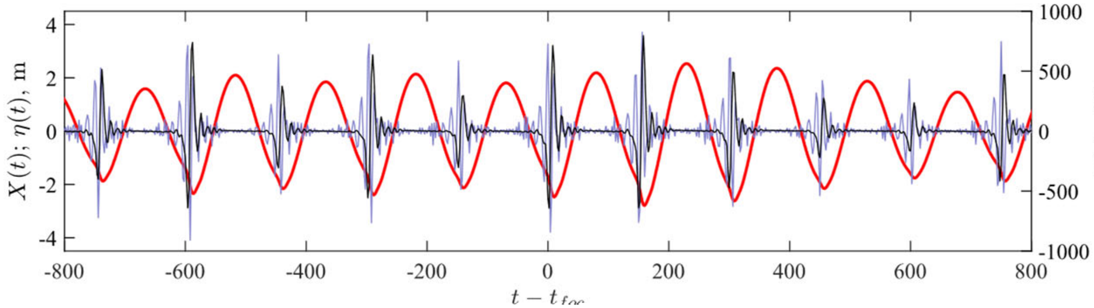
- Underlying force was periodic at f_0, but insignificant magnitude.
- If we can spread the peak energy over several wave groups, the difference excitation becomes more regular and less impulsive.
- Shift phases of adjacent frequencies, f_m and $f_m + df$ by using different *focal times*.
- Optimal algorithm needs consideration, but consider three:

1. Move *phases* of frequencies $f_p \pm \alpha df$ to
   $t_{foc} + \frac{2}{f_0}$; for α is even
   $t_{foc} + \frac{1}{f_0}$; for α is odd
2. Redistribute *phases* so that highest amplitude components move to maximum $\frac{2}{f_0}$ out of phase relative to phase of f_p.
3. Redistribute *phases* so that amplitude components are equally distributed about the mean amplitude of each difference frequency band, $f_p \pm m f_0 : f_p \pm (m+1) f_0$.

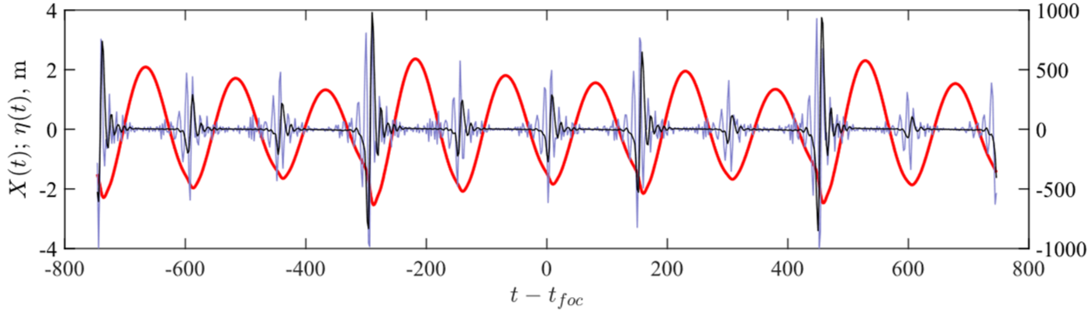


Second-Order spread-focus waves

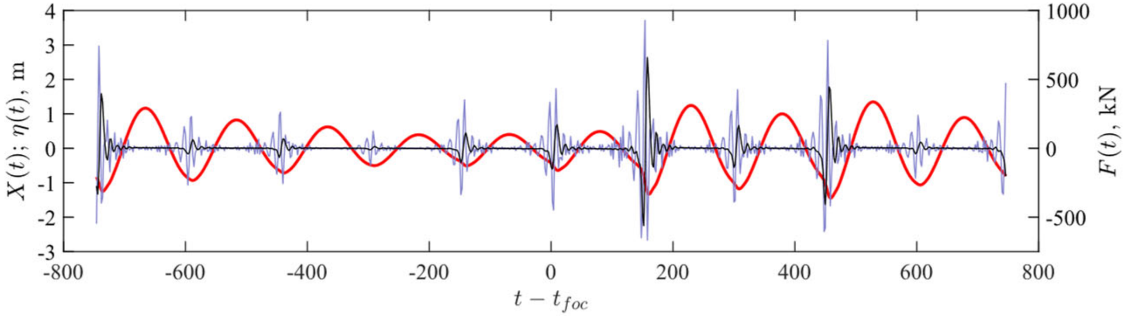
Spread odd/even
|X| **$_{max}$= 2.8 m**



Spread for max. phase difference,
|X| **$_{max}$= 2.5 m**



Spread amplitudes about mean,
|X| **$_{max}$= 1.5 m**

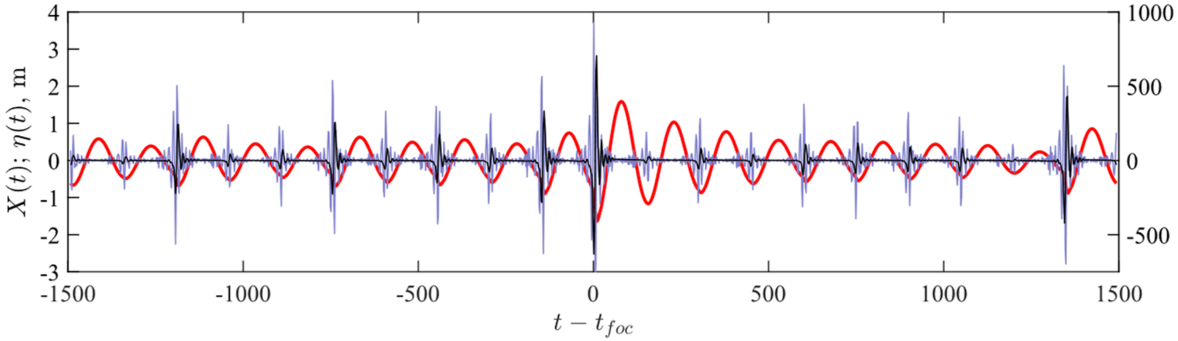


- $df = f_0/10$
- Greatest response when only spread over 2-3 '*focus*' times.

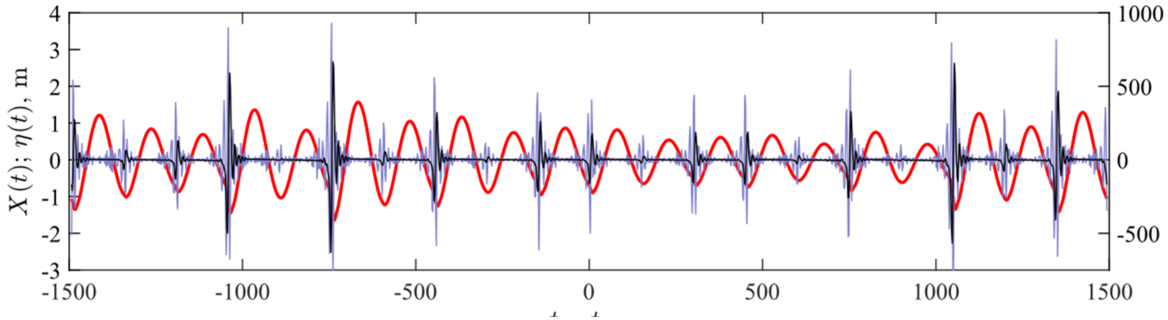
Høgskulen på Vestlandet

Second-Order spread-focus waves

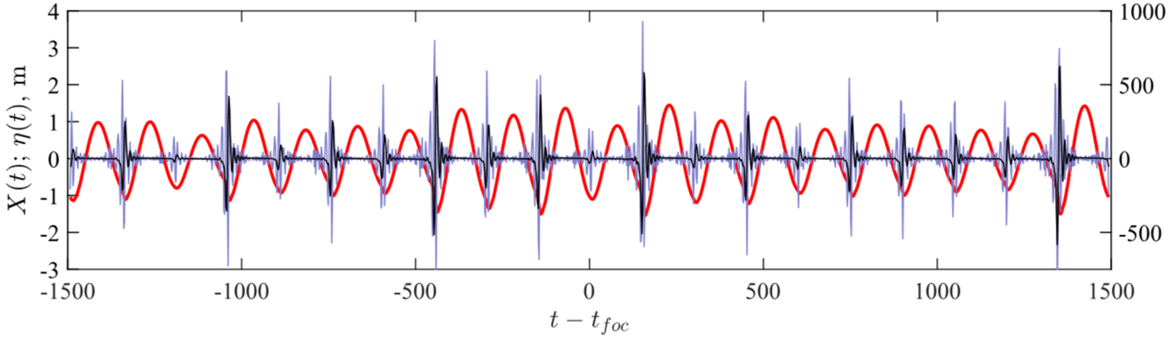
Spread odd/even
***|X|**$_{max}$* **= 1.7 m**



Spread for max. phase difference,
***|X|**$_{max}$* **= 1.7 m**

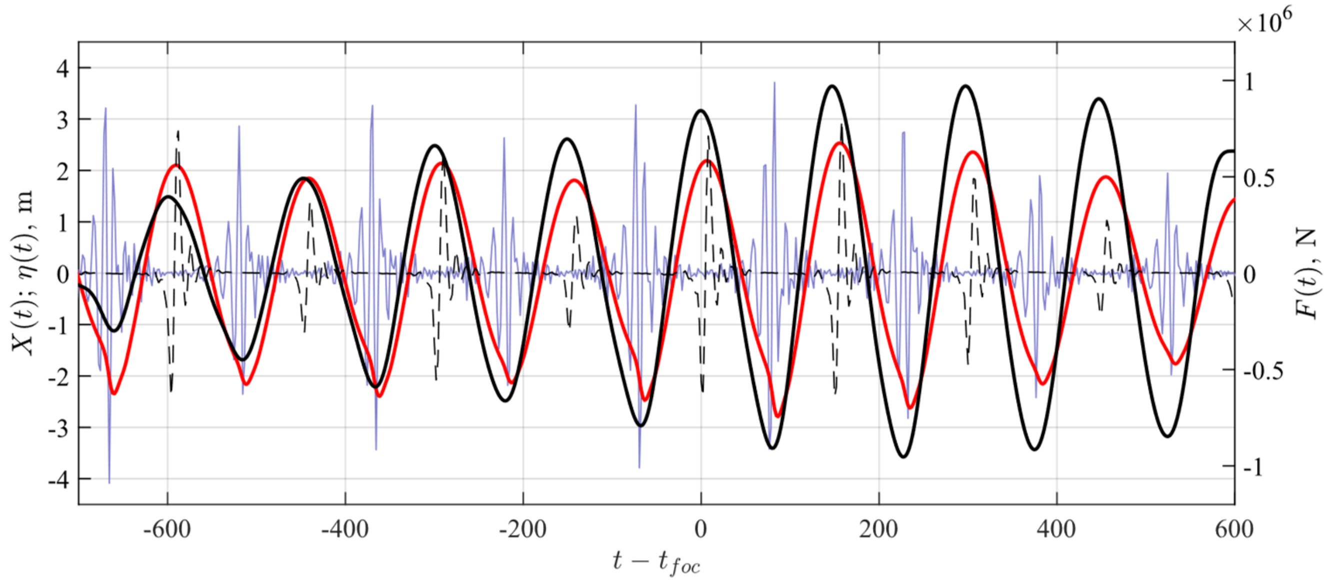


Spread amplitudes about mean,
***|X|**$_{max}$* **= 1.6 m**



- $df = f_0/20$
- Response smaller than for $df = f_0/10$.
- Spreading energy over more peaks, fewer components in-phase less often.
  - I.e. More random

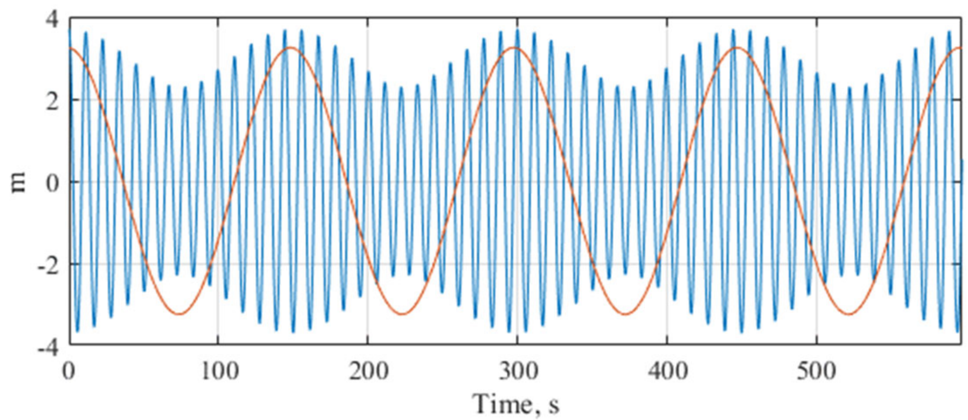
Time-Domain diffraction model



- $df = f_0 / 10$; Even/Odd energy spread
- Xmax for OrcaFlex, 3.6 m
- OrcaFlex shows steady build-up of response (resonance) before maximum occurs – not captured by simple 1DOF model.
- Build-up is due to wave damping/drag damping coefficients – higher damping (e.g. other substructures) reduce the build-up time.
- Hence a minimum total runtime is required – approx. 6-15 oscillations (depending on damping)

Maximum upper bound?

- Achieve same difference force using two wave components from spectrum:
  - $A_n = \sqrt{2S(f_p)\Delta f}$
  - $A_m = \sqrt{A_{\{max\}}^2 - A_n^2}$
- (wave is impossible to generate)

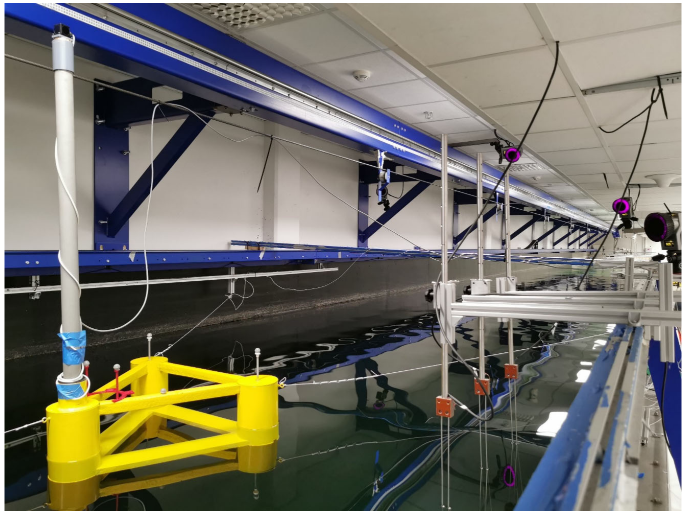


Høgskulen på Vestlandet

Conclusions & future work

- 1DOF model is quick to run, allowing rapid evaluation of long time-series (small df), but does not capture damping fully.
- Single focus time, targeting surge response at f_0, is impulsive and so cannot generate max. response.
- Spreading peak of wave group over several *focal times* increases response, in-line with that expected from 3hr sea-state.
- Runtime reduced from 3,6, 10 hrs to <1000 s (damping dependent)

- Energy spreading algorithm to be optimised especially for small df.
- Effect of randomness?
- Method needs demonstrating in more extreme wave climate.
- Conditional second-order response wave
- Experiments planned – WINDMOOR 1:100 scale



Thanks for listening!

Høgskulen på Vestlandet