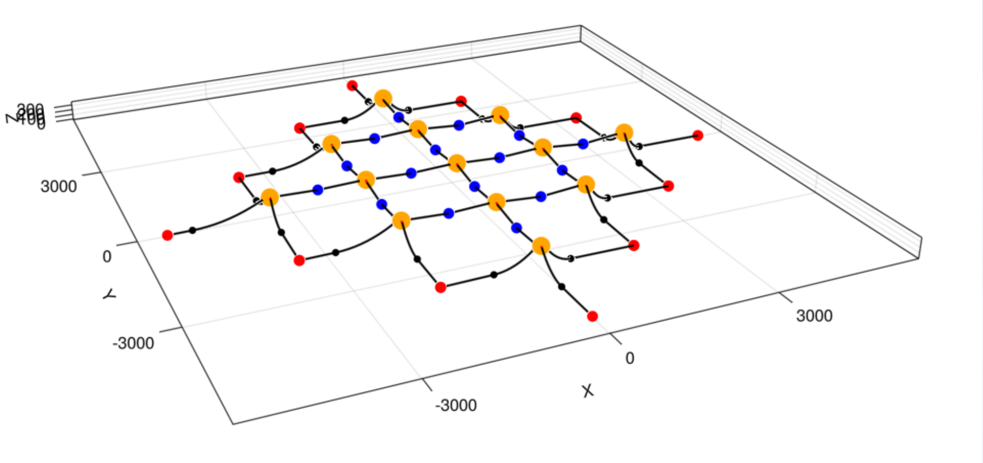
Second order wave-induced modal loads and responses on floating wind parks with shared mooring



Thomas Sauder

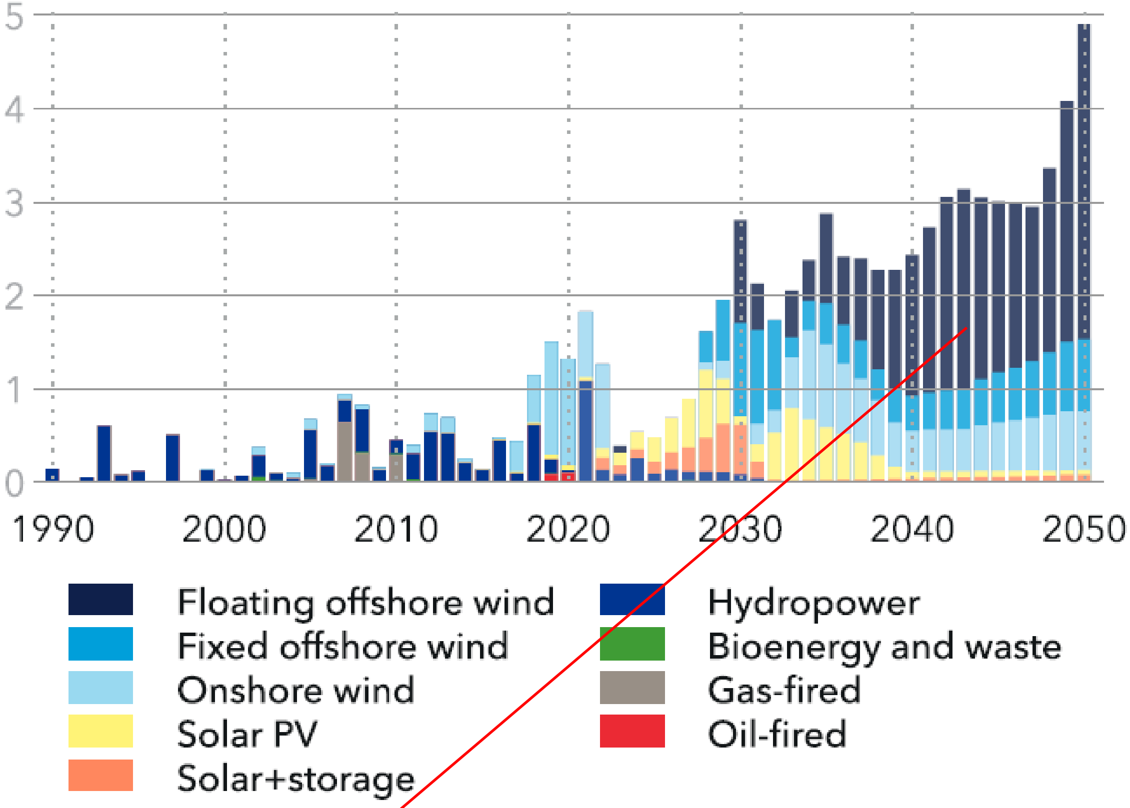
Senior researcher – SINTEF Ocean – Ships and Ocean Structures
Adjunct Professor – NTNU – Department of Marine Technology

Deepwind 2023

FIGURE 3.9

Norway capacity additions becoming operational by power station type

Units: GW/yr

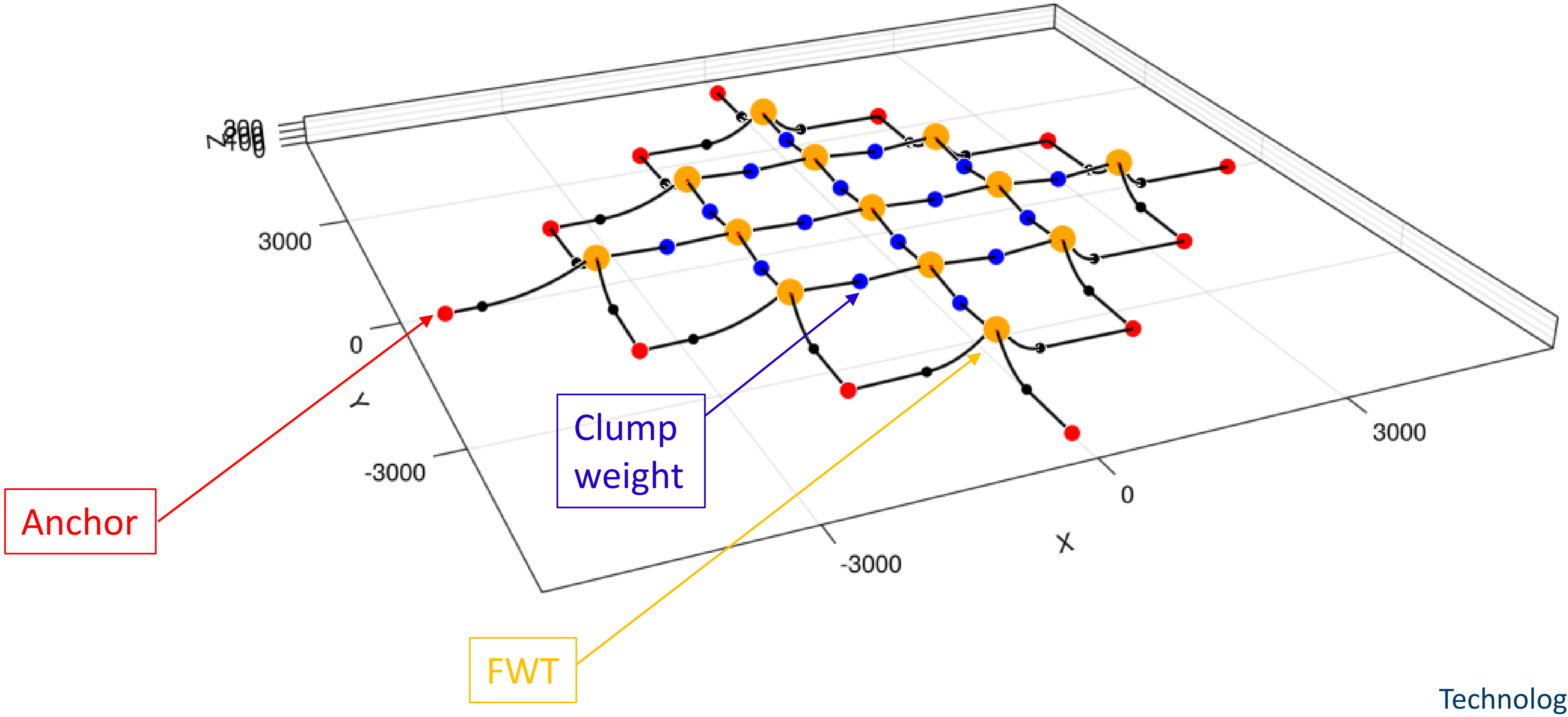


DNV Energy transition Norway 2022 – Commissioned by Norsk Industri

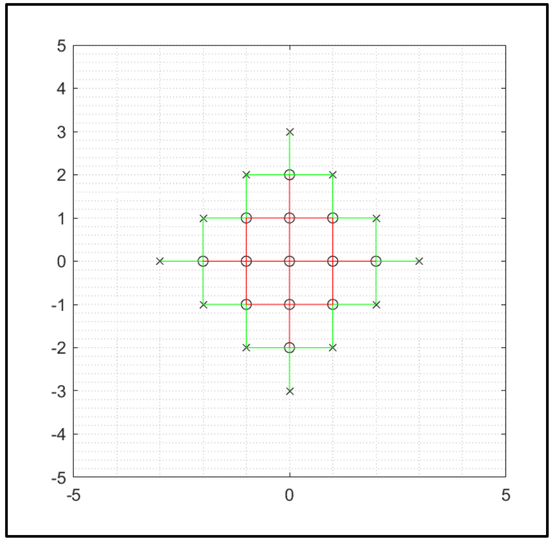
2x"Trollwind" / year!

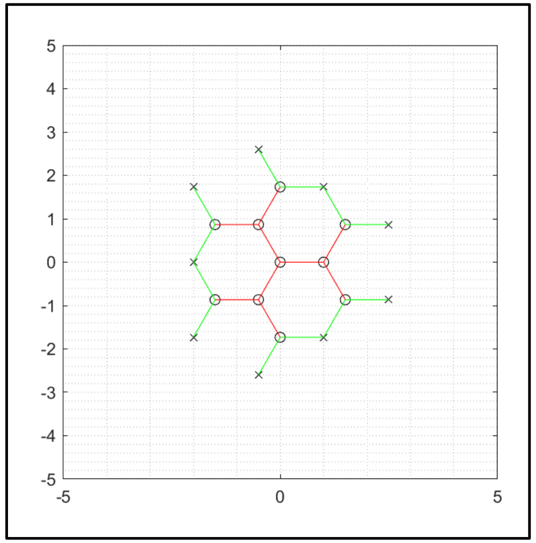
Positioning system for FWT has to be "optimal" (criteria yet to be defined) and standardized

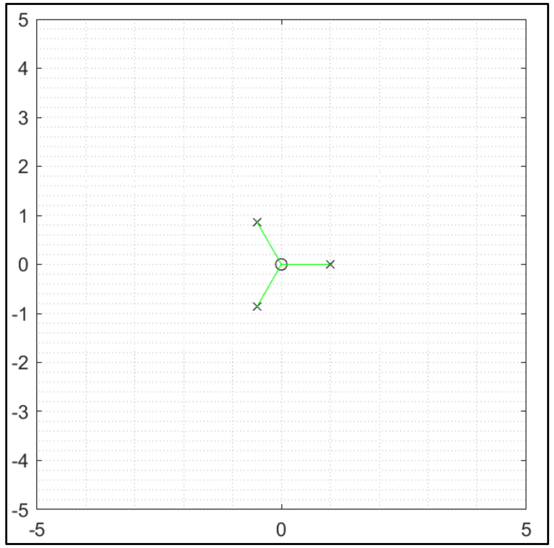
Shared mooring (shared anchors and lines)



Why are such "lattices" interesting?







Layout	Square (level 3)	Hexagonal (level 3)	Individually moored
Number of anchors/floater	**0.92**	**0.90**	**3**
Number of lines/floater	**2.77**	**2.10**	**3**

Literature review*

[1] **Yamamoto, S. and Colburn, W.** (**2006**). Power Generation Assemblies, and Apparatus for Use Therewith. Patent US7293960B2.

[2] **Goldschmidt, M. and Muskulus, M.** (**2015**). Coupled Mooring Systems for Floating Wind Farms. Energy Procedia, 80:255–262.

[3] **Connolly, P.** (**2018**). Resonance in Shared Mooring Floating Offshore Wind Turbine Farms. Master's thesis, University of Prince Edward Island

[4] **Hall, M. and Connolly, P.** (**2018**). Coupled Dynamics Modelling of a Floating Wind Farm With Shared Mooring Lines. In Volume 10: Ocean Renewable Energy, page V010T09A087, Madrid, Spain. American Society of Mechanical Engineers.

[5] **Connolly, P. and Hall, M.** (**2019**). Comparison of pilot-scale floating offshore wind farms with shared moorings. Ocean Engineering, 171:172–180.

[6] **Liang, G., Merz, K., and Jiang, Z.** (**2020**). Modeling of a Shared Mooring System for a Dual-Spar Configuration. In Volume 9: Ocean Renewable Energy, page V009T09A057, Virtual, Online. American Society of Mechanical Engineers

[7] **Wilson, S., Hall, M., Housner, S., and Sirnivas, S.** (**2021**). Linearized modeling and optimization of shared mooring systems. Ocean Engineering, 241:110009

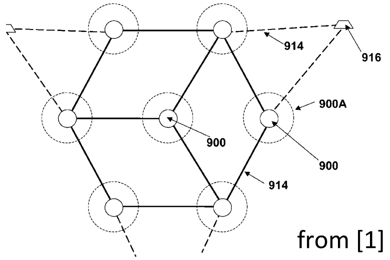
[8] **Hall et al** (**2022**) Design and analysis of a ten-turbine floating wind farm with shared mooring lines, J. Phys.: Conf. Ser. 2362 012016

[9] **Gözcü, O., Kontos, S., & Bredmose, H.** (**2022**). Dynamics of two floating wind turbines with shared anchor and mooring lines. Journal of Physics: Conference Series, 2265(4), 042026.

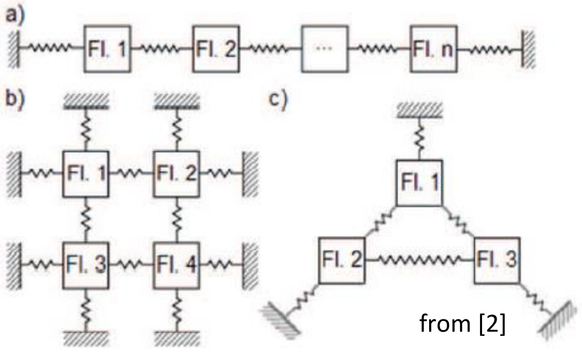
[10] **Lozon and Hall** (**2023**), Coupled loads analysis of a novel shared-mooring floating wind farm, Applied Energy, 332, 120513

Check also Honeymooring™ concept by Semar AS

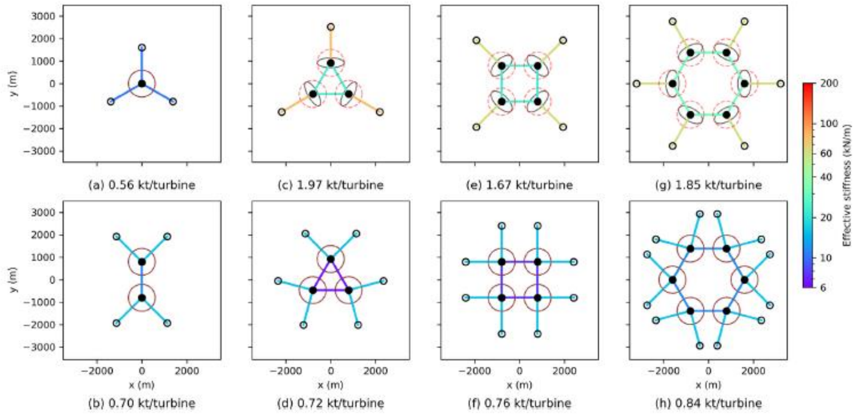
Fig. 10A



from [1]



from [2]

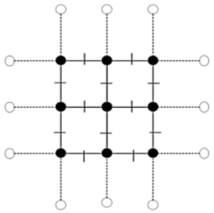


(a) 0.56 kt/turbine
(c) 1.97 kt/turbine
(e) 1.67 kt/turbine
(g) 1.85 kt/turbine
(b) 0.70 kt/turbine
(d) 0.72 kt/turbine
(f) 0.76 kt/turbine
(h) 0.84 kt/turbine

from [7]

*work on shared *anchors* not included

Challenges related to lattices

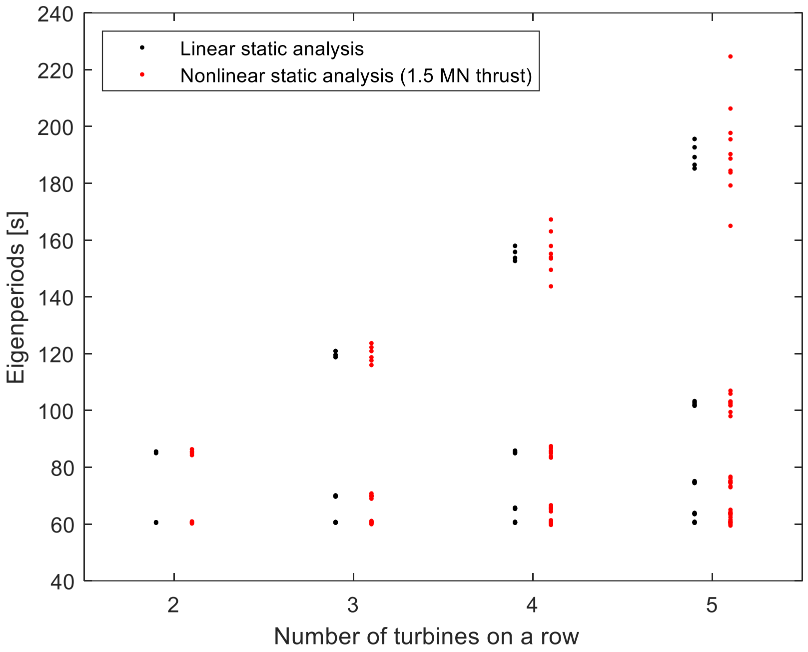


- Plenty! Resilience to line breakage, installation, maintenance, wind loading/coherence, design optimization, standards (load cases?, consequence classes?),…
- Focus today: *dynamic response to wave loads*
  - **#eigenmodes** increases with the size of the lattice
    - Associated eigenfrequencies are spread in the LF range →
  - **Resonances** might occur so:
    - Nonlinear (LF) wave loads need to be predicted correctly
    - LF damping also must be quantified.

"Connolly lattice"

Mass and added mass:	INO Windmoor 12MW	
Length/stiffness of anchored lines:	726 m	120 kN/m
Length/stiffness of shared lines:	1260 m	60 kN/m

Static loading along the horizontal axis (nonlinear static analysis)



Modal analysis

$$M\ddot{r} + C\dot{r} + Kr = F$$

Dynamic equilibrium of the lattice

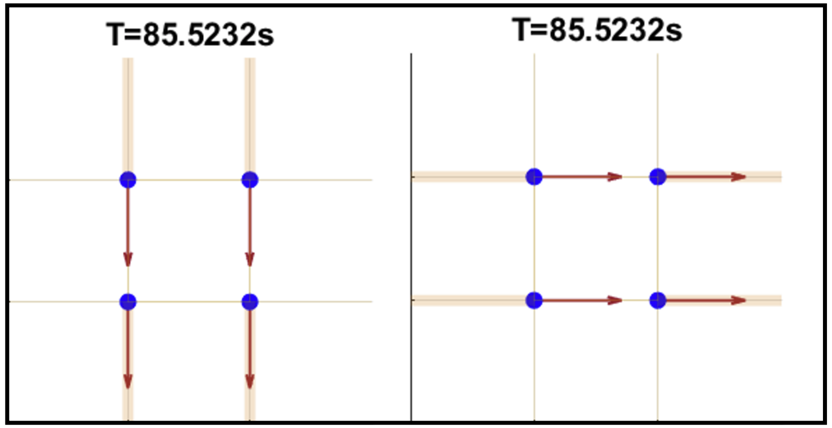
$$(-M\omega^2 + K)r = 0$$

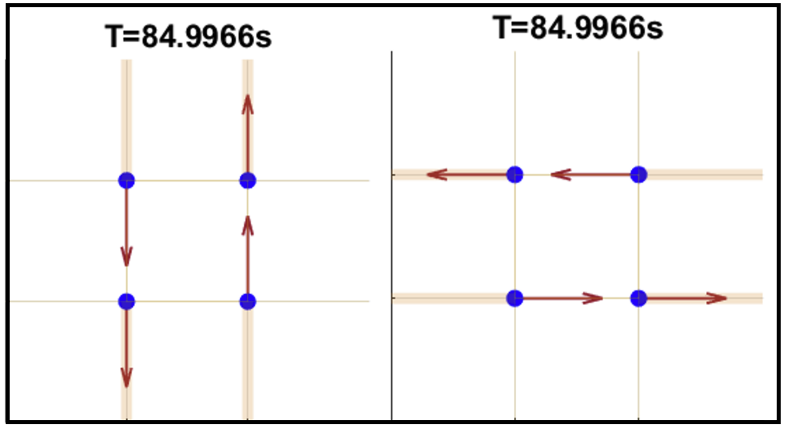
$$\Phi = [\phi_1, ..., \phi_n]$$ ← Eigenvectors

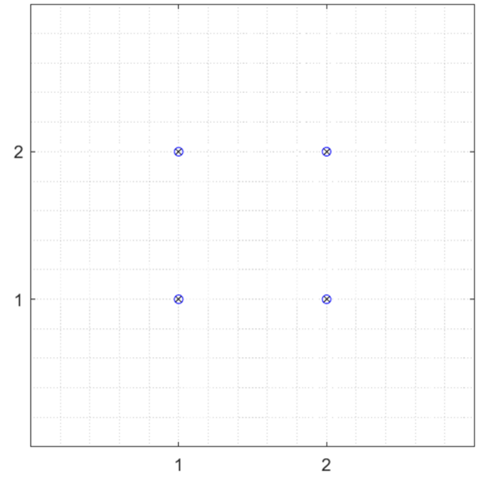
$$\Lambda = diag(\omega_1^2, ..., \omega_n^2)$$ ← Eigenvalues

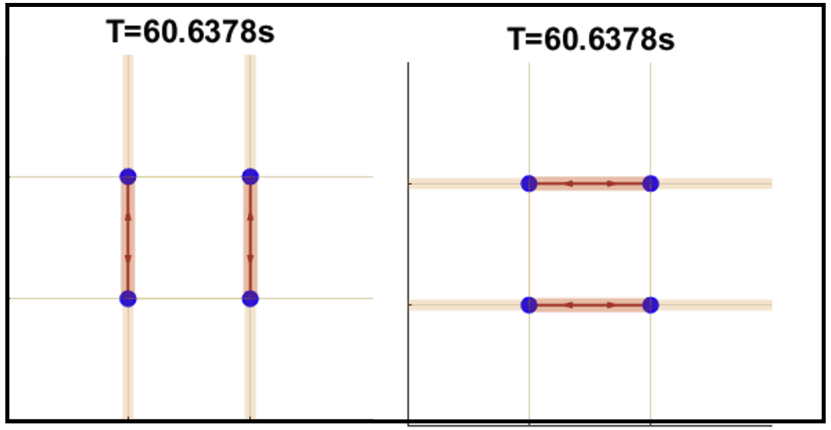
Free vibrations and eigenmodes

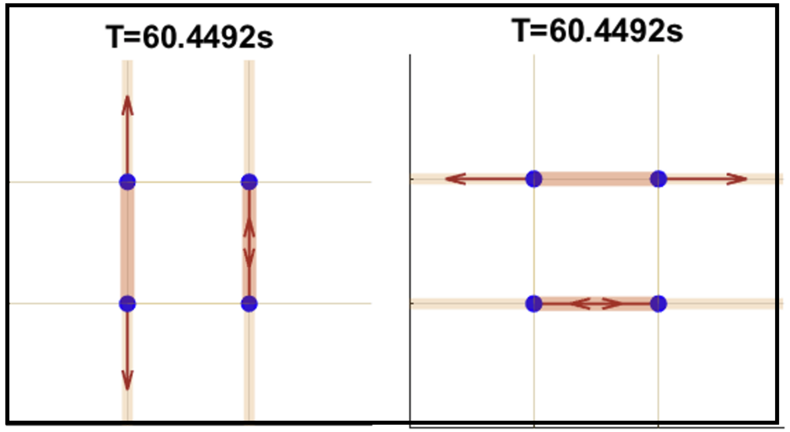
Eigenmodes (linear static analysis)





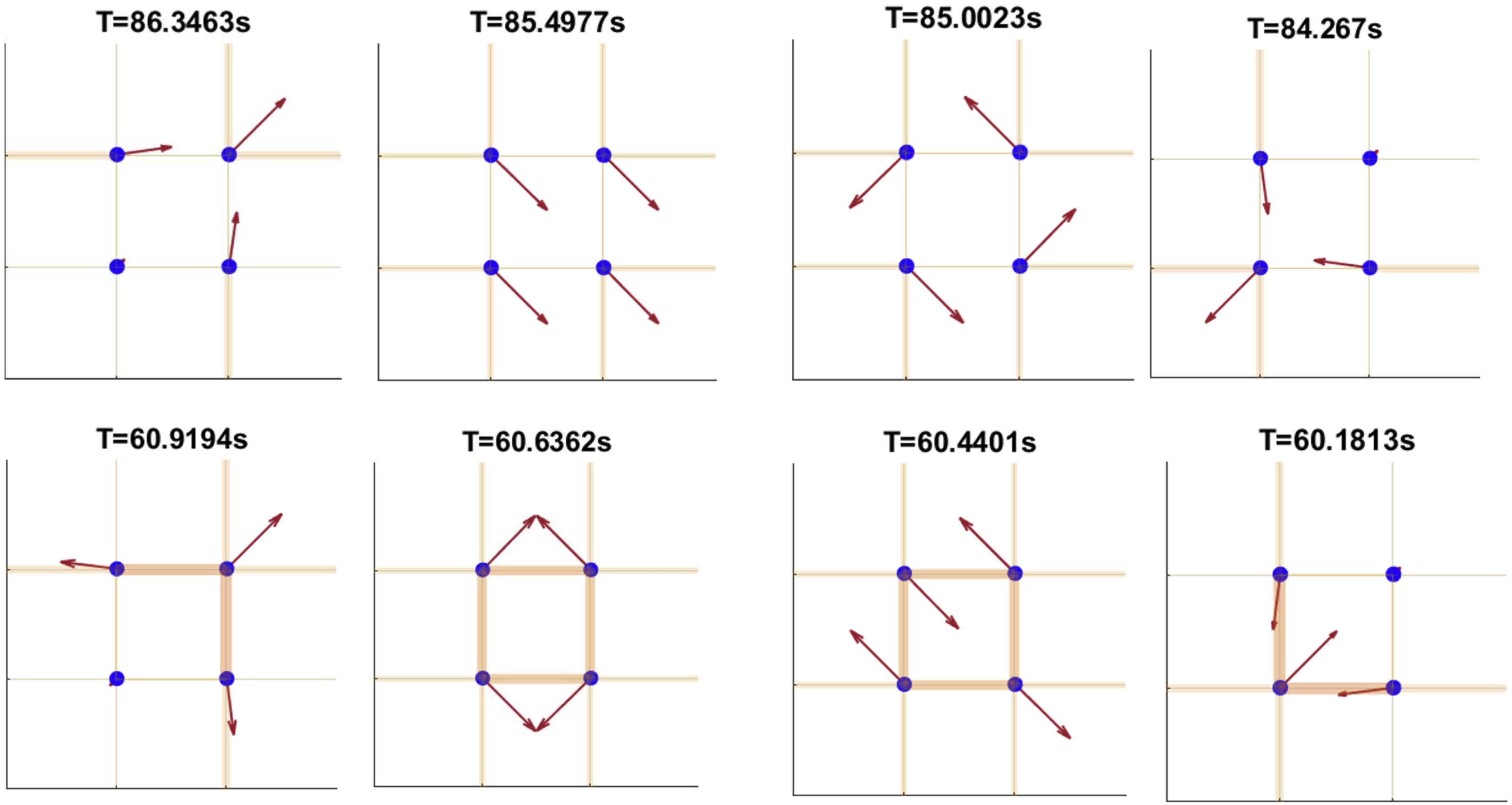


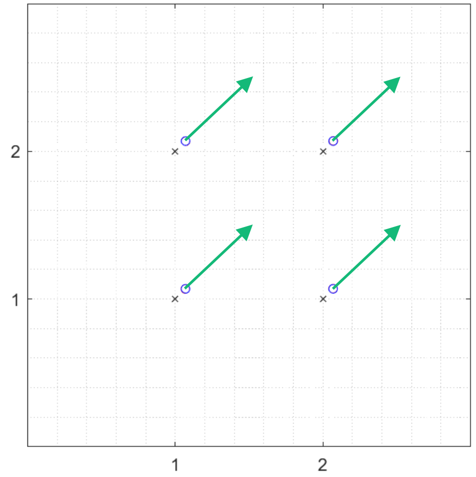




NB: degenerate modes (same eigenfrequency for different modeshapes)

Eigenmodes (nonlinear static analysis)





Loading:
1.5 MN
45 deg

NB: note that modes are nondegenerate (symmetry has been broken due to mean load)

Modal analysis

$$M\ddot{r} + C\dot{r} + Kr = F$$

Dynamic equilibrium of the lattice

$$(-M\omega^2 + K)r = 0$$

$$\Phi = [\phi_1, ..., \phi_n]$$ ← Eigenvectors

$$\Lambda = diag(\omega_1^2, ..., \omega_n^2)$$ ← Eigenvalues

Free vibrations and eigenmodes

$$\ddot{\xi} + \Phi^* L^{-1} C (L^{-1})^* \Phi \dot{\xi} + \Lambda \xi = \mu$$

where $M = LL^*$

Modal version of the dyn. equilibrium

Assumption: Rayleigh damping

- Let us assume that $C = \gamma_1 M + \gamma_2 K$
- **NB: absolutely no indication that this assumption is fulfilled**
- Uncoupled system of linear oscillators:

Modal response $\xi = \Phi^* L^* r$

Modal load $\mu = \Phi^* L^{-1} F$

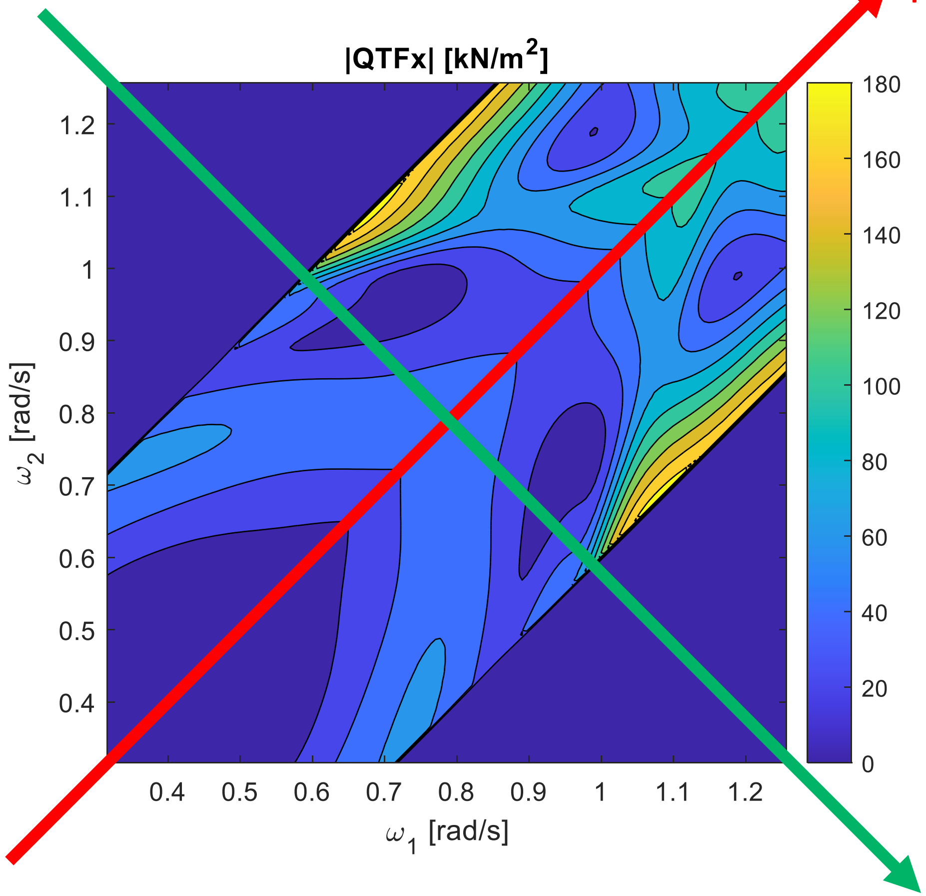
?

$$\forall i \in \{1, \ldots, n\}, \ddot{\xi}_i + (\gamma_1 + \gamma_2 \omega_i^2)\dot{\xi}_i + \omega_i^2 \xi_i = \mu_i$$

$$\forall i \in \{1, \ldots, n\}, \bar{\xi}_i = \frac{\bar{\mu}_i}{\omega_i^2 - \Omega^2 + i\Omega(\gamma_1 + \gamma_2 \omega_i^2)}$$

Excitation frequency

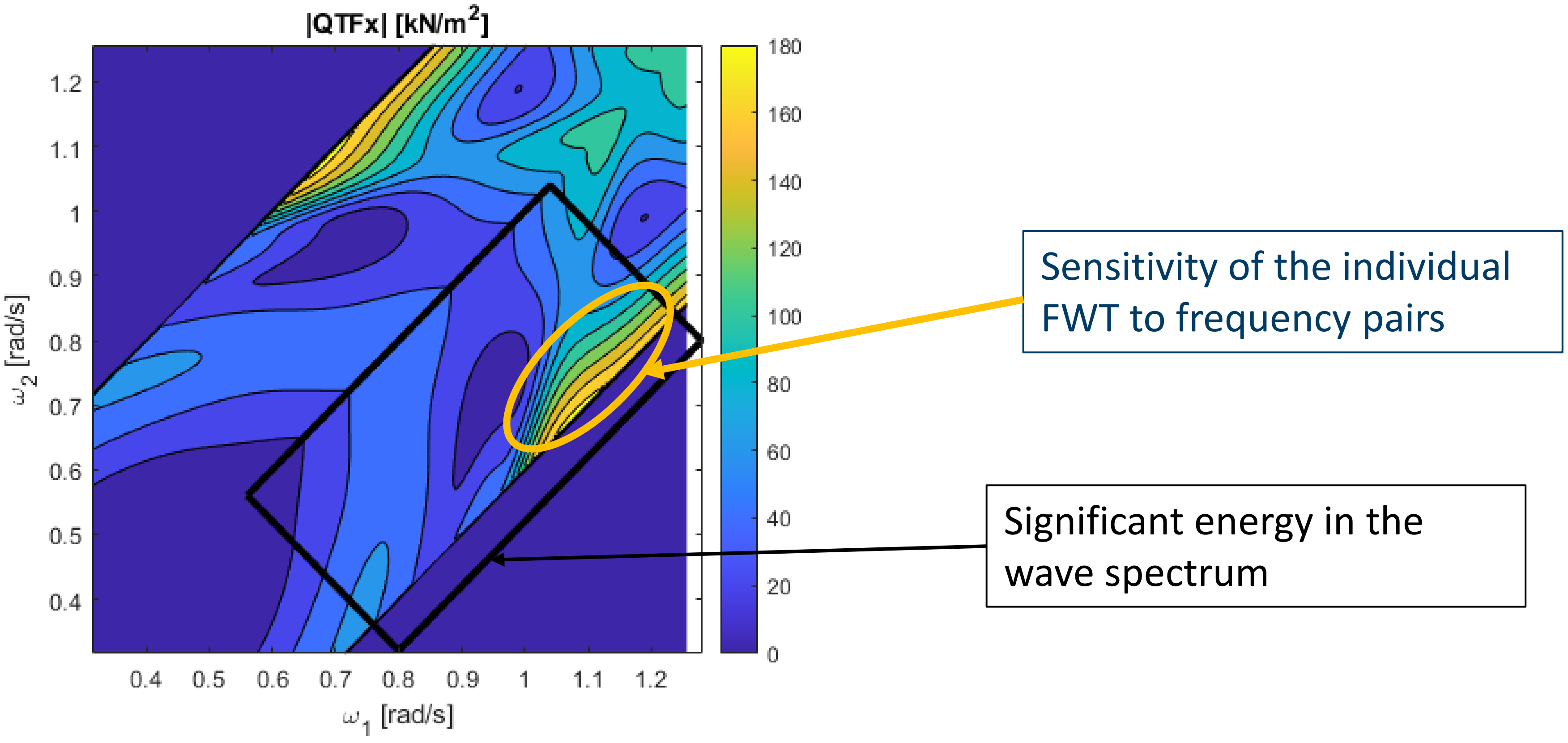
Difference-frequency QTF
INO WINDMOOR 12MW floater



Mean frequency: $\frac{\omega_1+\omega_2}{2}$

Difference frequency: $\omega_1 - \omega_2$
(which is also the loading frequency)

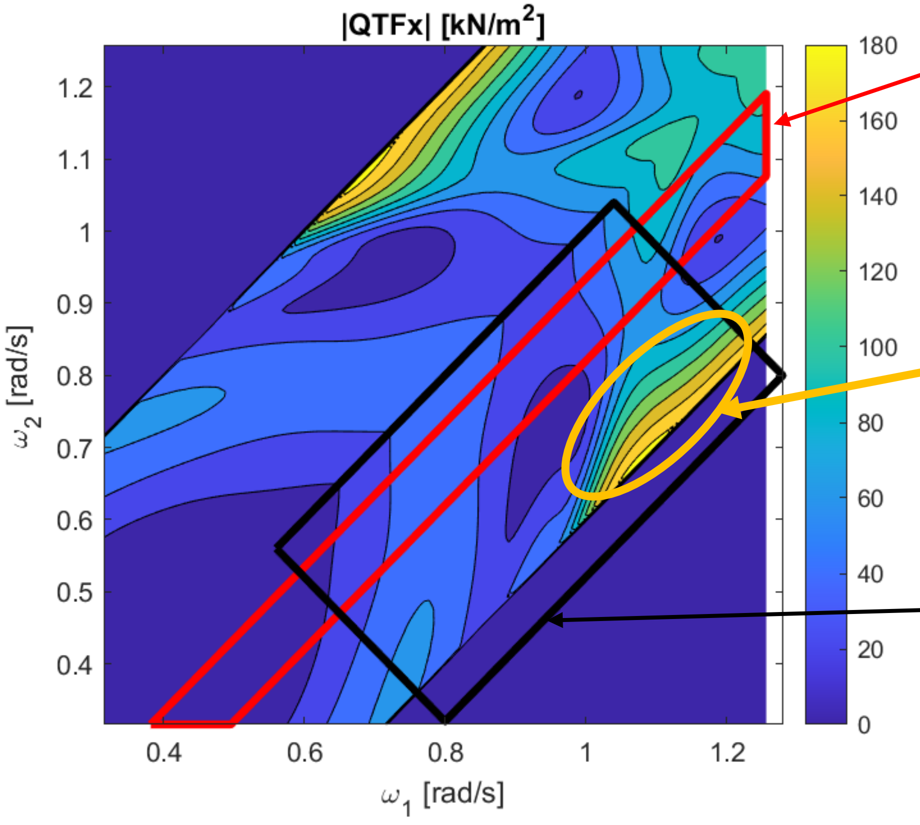
What drives the modal response of a lattice



Sensitivity of the individual FWT to frequency pairs

Significant energy in the wave spectrum

What drives the modal response of a lattice

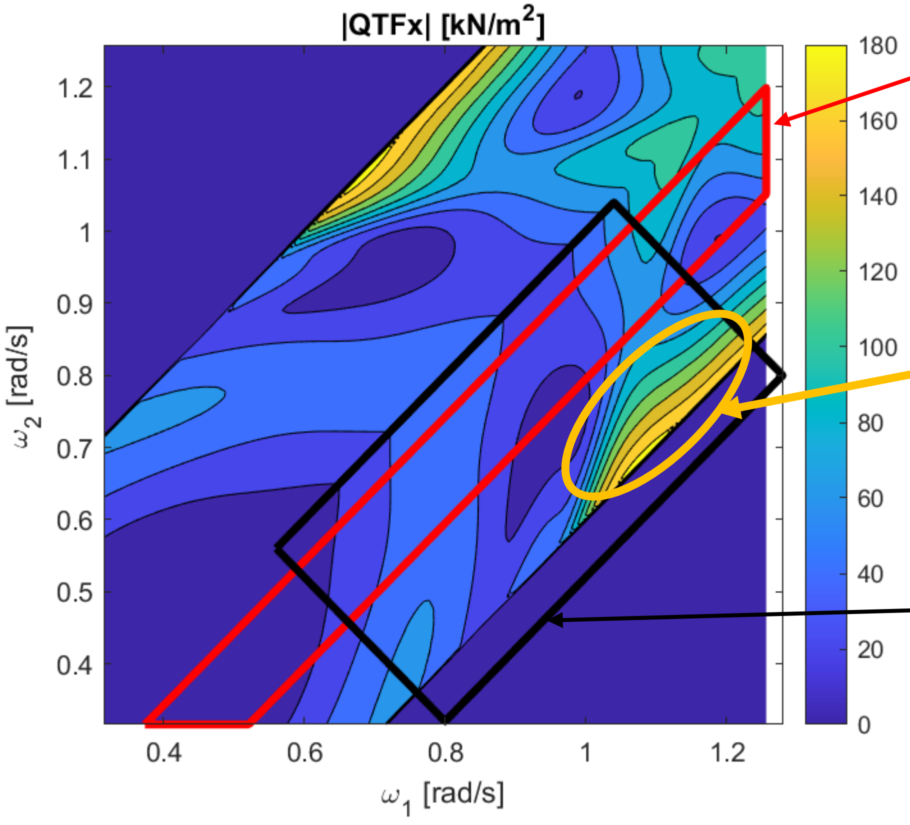


Difference-frequency matching an eigenfrequency of the lattice (N=3)

Sensitivity of the individual FWT to frequency pairs

Significant energy in the wave spectrum

What drives the modal response of a lattice

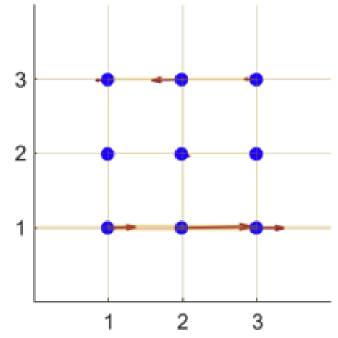


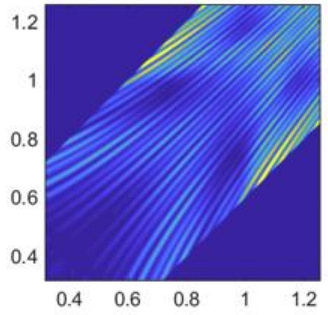
Difference-frequency matching an eigenfrequency of the lattice (N=4)

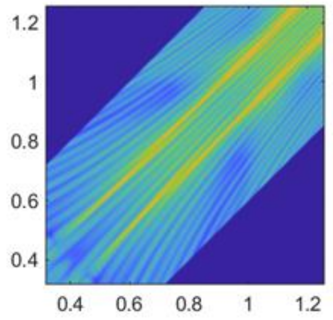
Sensitivity of the individual FWT to frequency pairs

Significant energy in the wave spectrum

Modal second-order wave load







2nd order load at a frequency $\Delta\omega$ on **one floater** located at x

$$\sum_{|\omega_i-\omega_j|=\Delta\omega}(\zeta_i e^{-ik_i u\cdot x})^*(\zeta_j e^{-ik_j u\cdot x})Q^-(\omega_i,\omega_j,\beta)$$

Use dispersion relation for deep water

$$f_d(\Delta\omega,x)=\sum_{|\omega_i-\omega_j|=\Delta\omega}\zeta_i^*\zeta_j e^{i\frac{\omega_i^2-\omega_j^2}{g}u\cdot x}Q_d^-(\omega_i,\omega_j,\beta)$$

Nodal loads (example, for a 3 cells x 2 dofs system)

$$F(\Delta\omega)=[f_1(\Delta\omega,x_1),f_2(\Delta\omega,x_1),f_1(\Delta\omega,x_2),f_2(\Delta\omega,x_2),f_1(\Delta\omega,x_3),f_2(\Delta\omega,x_3)]^\top$$

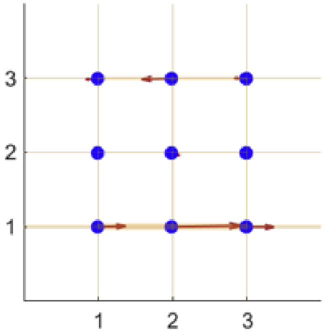
Modal load for mode Φ

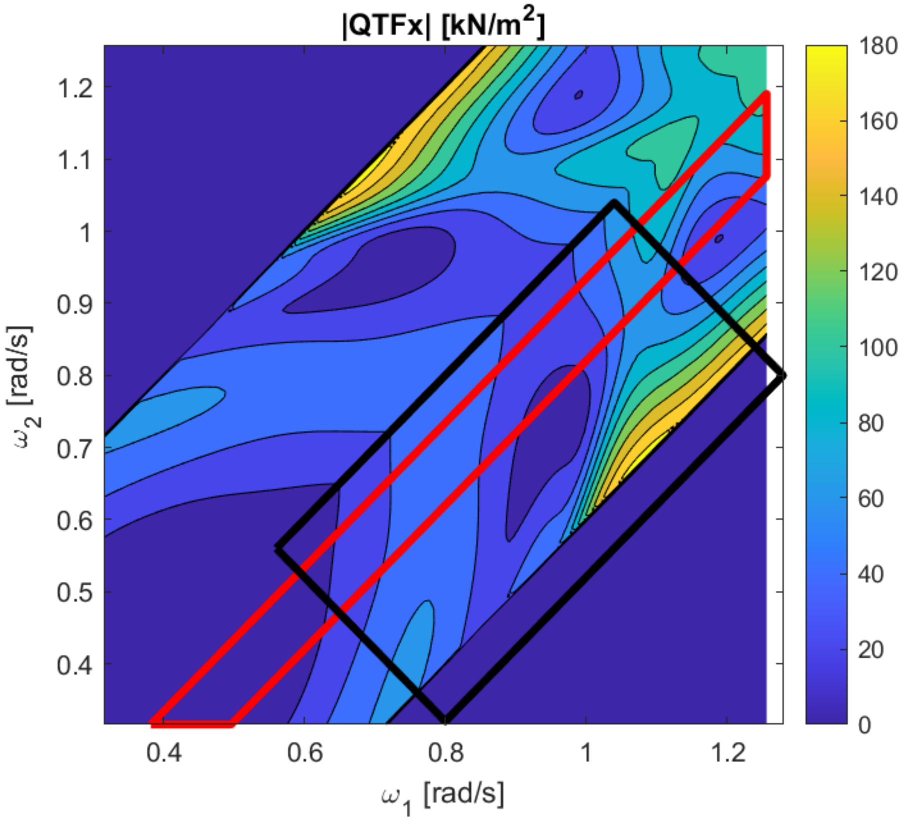
$$\mu=\Phi^*L^{-1}F$$

Modal response for mode Φ

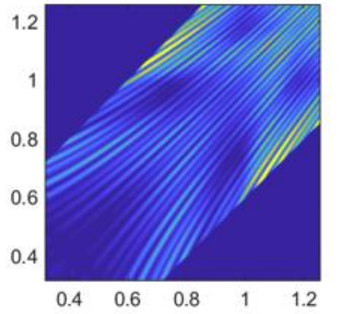
$$\bar{\xi}_i=\frac{\bar{\mu}_i}{\omega_i^2-\Omega^2+i\Omega(\gamma_1+\gamma_2\omega_i^2)}$$

Modal excitation of a given mode →



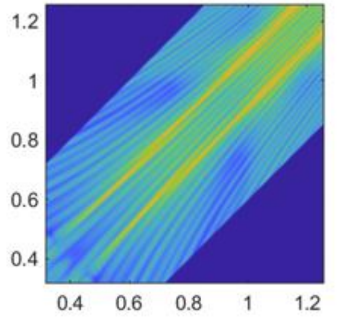


Modal excitation →
"Modulation" of the background excitation (QTF)



Modal response →

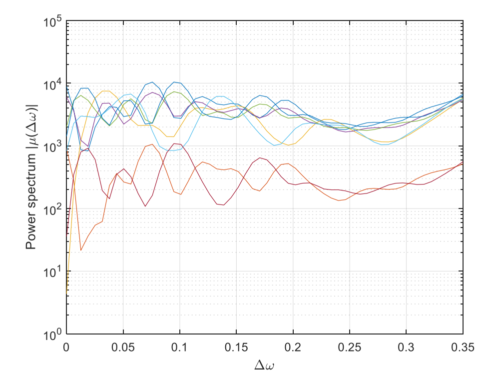
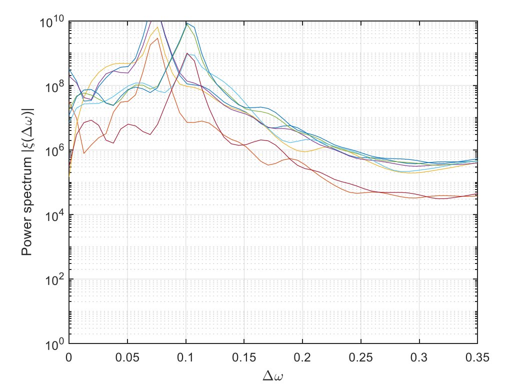
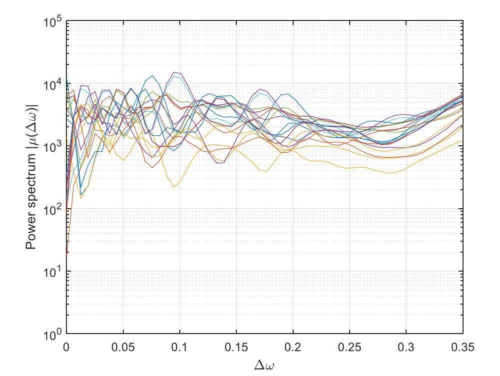
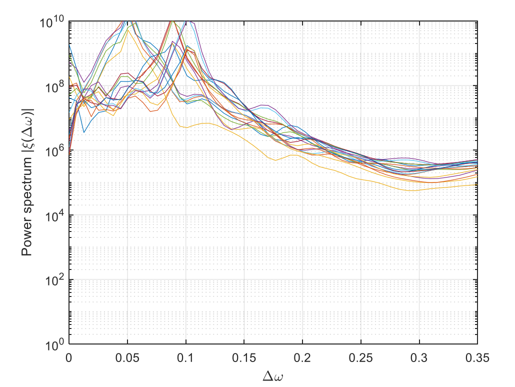
Amplification at the corresponding eigenfrequency



SINTEF

Example of modal excitation and response

JONSWAP, Hs=7m, Tp=10s, wave propagation direction: 30deg

	Modal excitation	Modal response
2x2 lattice (8 modes)		
3x3 lattice (18 modes)		

Conclusion

- Nonlinear wave loads will excite lattices of FWT near resonance
- Modelling approach:
  - Non-linear static analysis
  - Modal analysis
  - Classical second-order hydrodynamics
  - Extend the concept of QTF to modal QTFs for the lattice
- Important
  - Phase of the excitation is important (between dofs also)
  - Resonance frequencies cover a large frequency range, including relatively "high" frequencies (>10mHz)
  - So steer away from Newman approximation!!
- Further work (regarding wave loads)
  - Next: Line damping model
  - Ultimate goal: compute QoI's (e.g. line tension) and obtain their statistical properties from modal response
- For lattices: work needed on many more fronts (design optimization, standards/RP, among other)

Thomas Sauder
Project/WP5 leader

Øyvind Rogne
WP1 leader

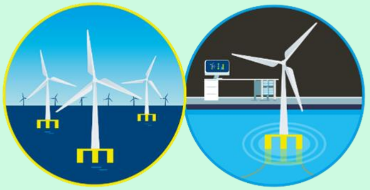
Erin Bachynski-Polić
WP2 leader

Giuseppe Abbiati
WP3 leader

Yngve Jenssen
WP4 leader

Maxime Thys
Project quality assuror
Project owner

Philippe Maincon
Scientific advisor



CYBERLAB KPN
NFR project 326654

Vishnu R.N. Rajasree
PhD candidate

David Stamenov
PhD candidate

Kjell Larsen
Advisor - Marine Structures and Hydrodynamics

Øivind Paulshus
Senior Engineer

Geir Olav Hovde
Principal Engineer, New Concepts

Einar Bernt Glomnes
Lead, Marine Analysis

Kai Roger Nilsen
Director of Engineering