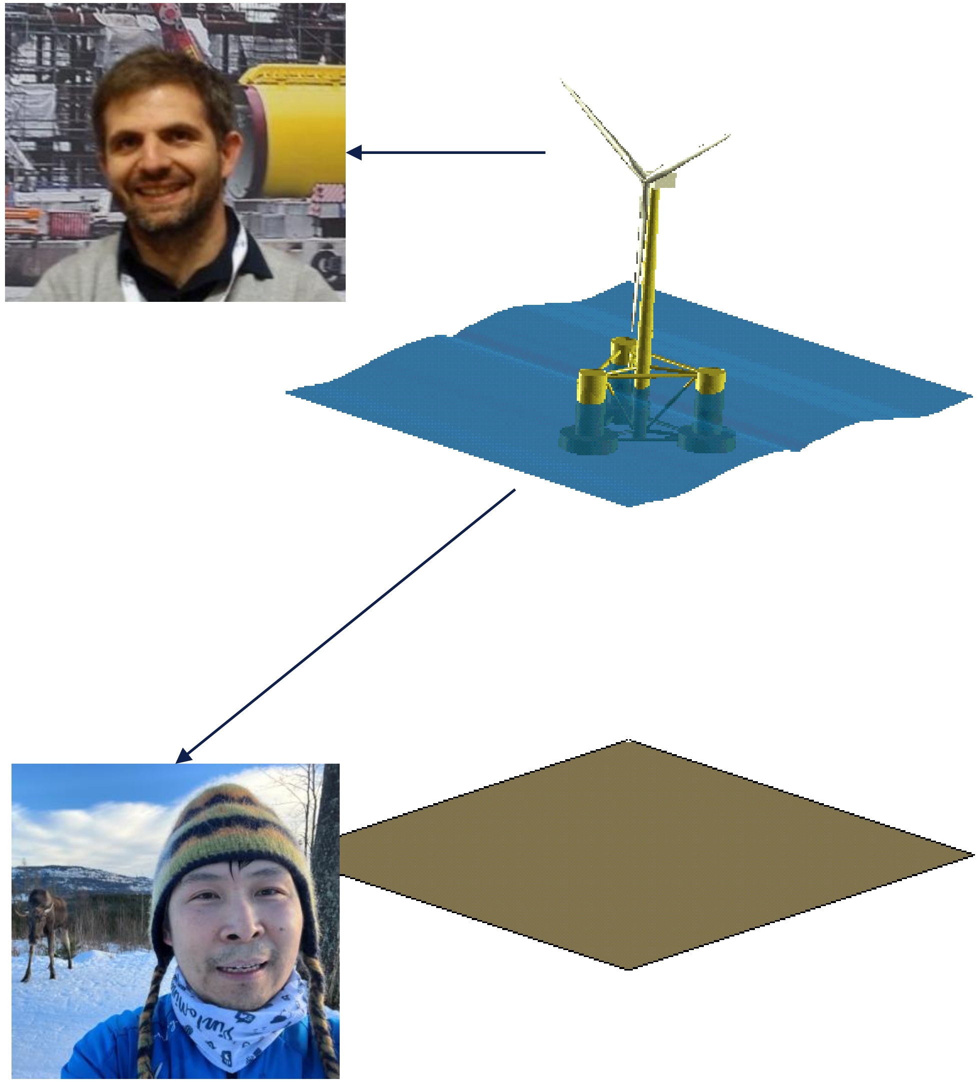
WHEN TRUST MATTERS

Frequency domain structural analysis for early design of floating wind systems using Sesam and Bladed

Armando Alexandre & Zhiyuan Pan

Floating offshore wind - The *theoretical* coupled analysis challenge



- Need to calculate internal **loads** and **response** for each component: wind turbine, tower, platform, moorings, …
- It's an active system and highly coupled!

- Workflow Time domain vs Frequency domain
- Responses -> load transfer
- Strength accessment of the floater in FLS/ULS
- Open sourse code vs. commercial software

FLOATING WIND SYSTEM DESIGN

Project phases and ‘typical’ analysis

Prospection – First Bid phase
- High-level estimates based on previous experience / databases etc

Concept + pre-FEED
- Design Basis
- Sizing
- Subset of load cases
- Large cost estimation error

Detail design / FEED
- Model validation
- Complete structural analysis
- Costing +/-10%

Fabrication / installation /deployment
- Quality and risk inspections.
- Last minute changes!

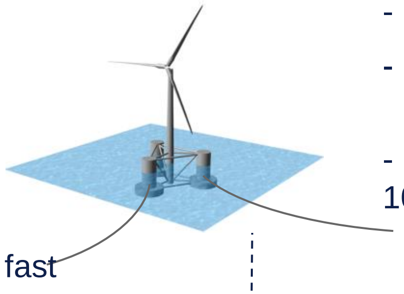
Operation
- Inspection and Maintenance scheduling
- Life extensions
- Performance monitoring

Coupled Model

Frequency Domain

Rotor and Platform Frequency domain

- Simple and fast



Time Domain Subset of runs

- Time domain analysis.
- Platform and simplified tower and rotor.
- Normally a reduced set of simulations 100s

Fully time Domain

- Time domain analysis.
- Models as detailed as possible
- Full set of load cases 20-30k

SIEMENS Gamesa RENEWABLE ENERGY
BHawC

Vestas
VTS/Flex5

Structural Analysis

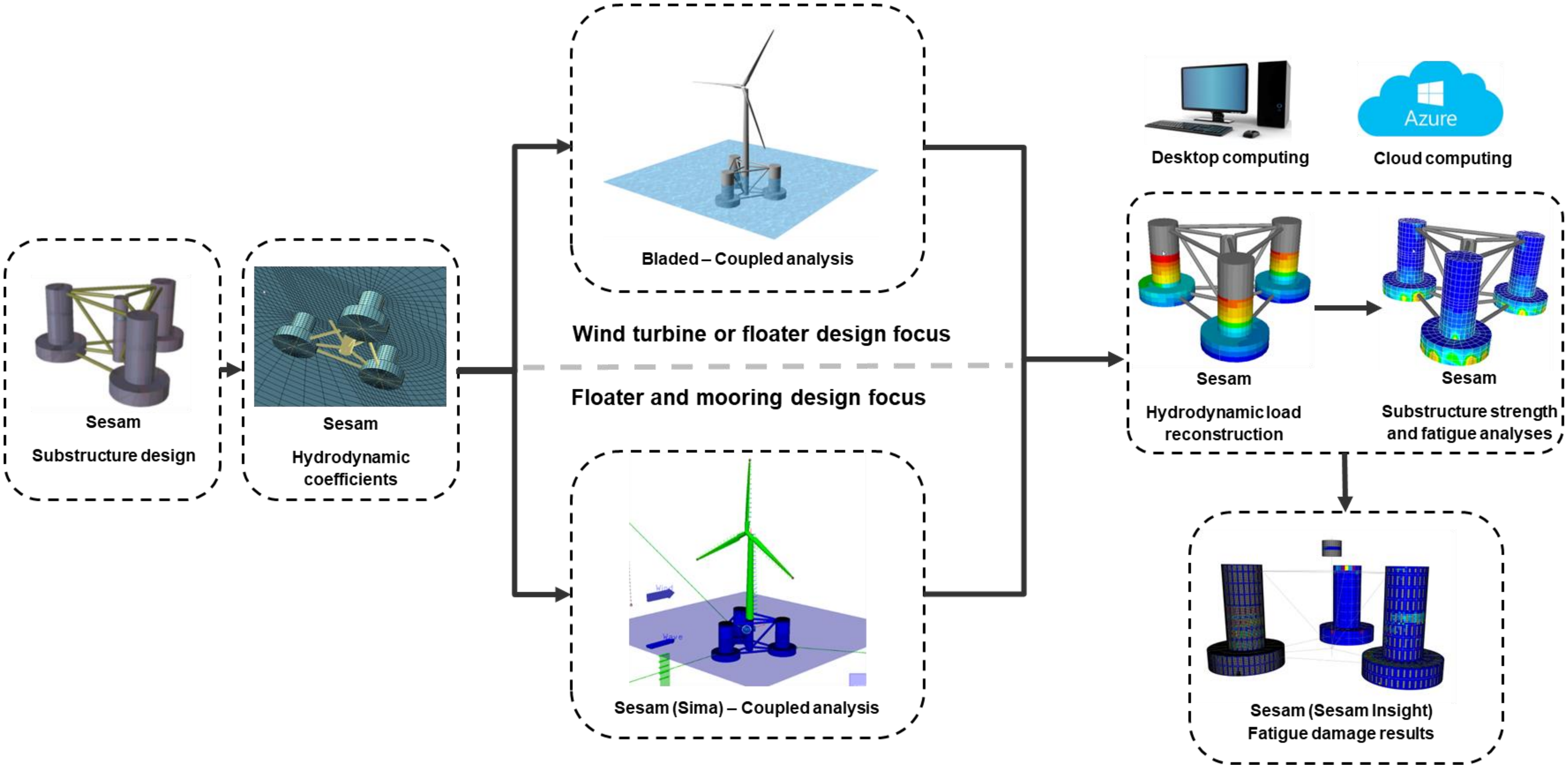
- ULS and FLS in the frequency domain.

- ULS (pressure distribution + first principles)
- Mostly No FLS run - Contingencies for FLS (changing now)

- ULS (time domain)
- FLS (time domain)

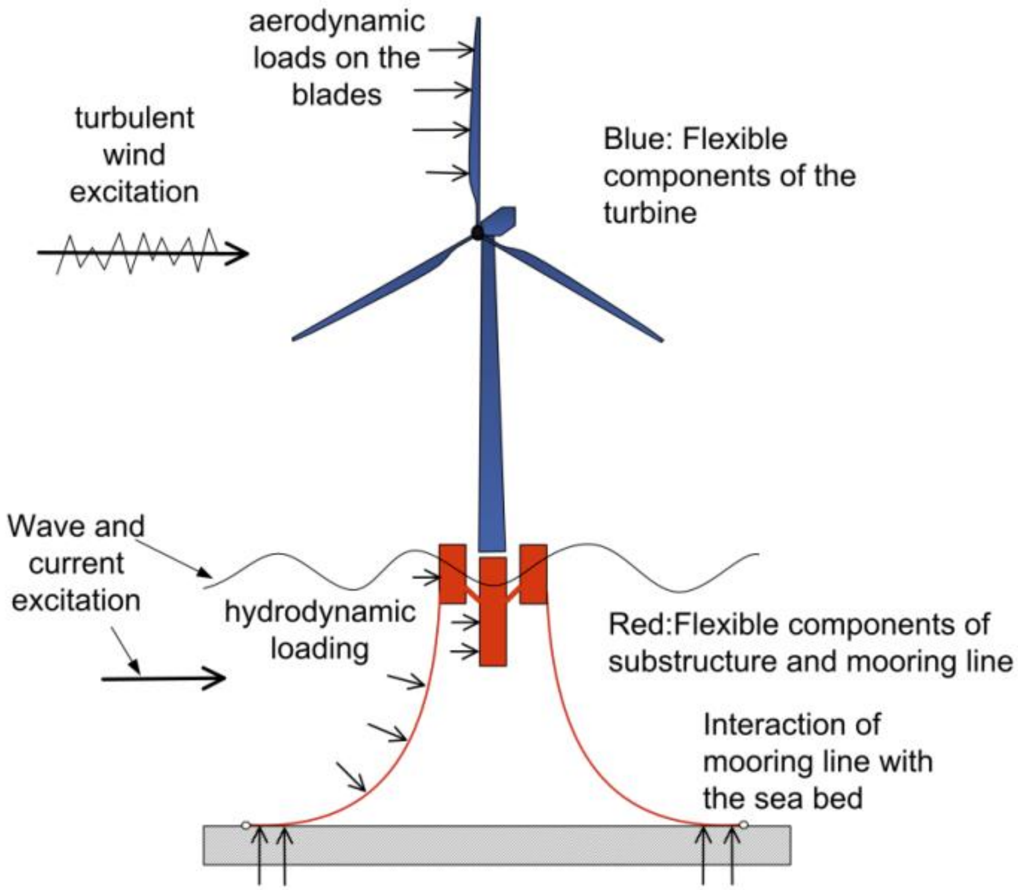
Note: With large projects volume, and turbine sizes some of this is still changing!

Time domain fatigue analysis of FOWT



Why we need TD models for FOWTs?

- Wind loads are similated in TD
- Nonlinear mooring
- Flexible structure
- Nonlinear FK wave load
- Morison load
- Blade control
- hydro-servo-aero-elastic multi-descipline



Can we still use FD models

- Wind loads and wave loads assumed to be uncorrelated
- Aerodynamic damping and excitation force can be obtained by numerical tests (forced motion, decay tests, FFT from time series, tabulated pre-evaluated data)
- Morison drag term can be linearized by iterative approach
- Nonlinear wave load could be insignificant, especially for FLS for base structure
- Linearized coefficients can be found by differentiation in (tangential value)
  - dF/dx as linear stiffness from mooring
  - df/dU linear damping from blade
- Elasticity ignored or taken as separated mode and superposed with rigid modes
- **If we use nonlinear model, we can solve it**
- **If we use linear model, then we can understand it.**

Frequency domain models for FOWT

Frequency domain models, earlier studies

- Souza et. al. (2019): «Freq. dependent aerodynamic damping and inertia in linearized dynamic analysis of FWTs» Wadam, SIMA, verified against SIMA TD
- Hall et. al. (2022): «An open-source FD model for FWT design optimization» RAFT(Open Source), verified against OpenFAST
- Pegalajar-Jurado, Borg, Bredmose (2018): «An efficient FD model for quick load analysis of FOWTs», QuLAF(in house), Wamit, FAST, MoorDyn
- Lemmer et. al. (2020): «Multibody modelling for concept-level FOWT design», SLOW(in house code), FAST(for aerodynamic coe.), TurbSim for wind realization.

Equation of Motion for FOWT

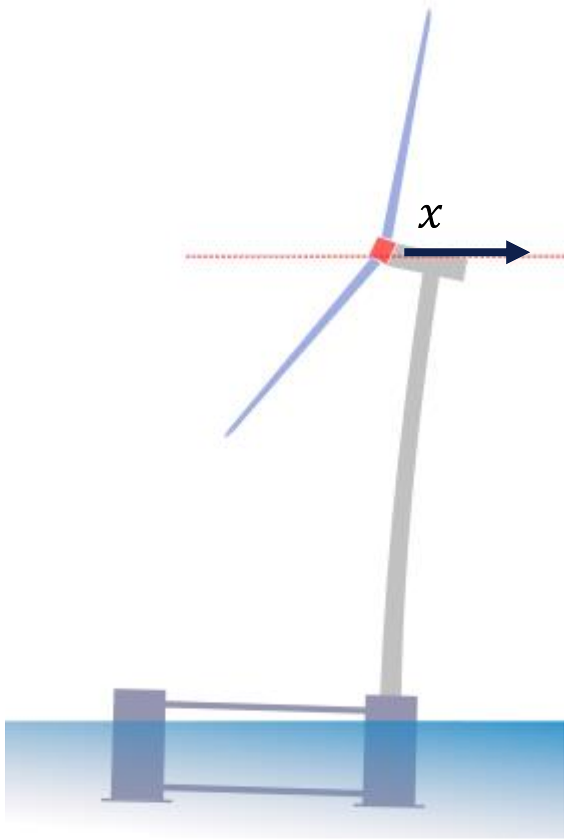
$$M\ddot{x}(t) + C\,\dot{x}(t) + K\,\boldsymbol{x}(t) = \boldsymbol{T}\,(t)$$

$$-(M + A_{total})\,\omega^2\boldsymbol{x} + i\,\omega\,C_{total}\boldsymbol{x} + K\,\boldsymbol{x} = \boldsymbol{F_{external}}(\omega)$$

$$A_{total} = A_{hydro}(\omega) + A_{aero}(\omega, U)$$

$$B_{total} = B_{hydro}(\omega) + B_{aero}(\omega, U)$$

$$F_{external} = F_{hydro}(\omega) + F_{aero}(\omega, U)$$



- The system added mass and damping will have two major contribution:
    - Aerodynamic and hydrodynamics.
    - These coefficients will now be function of:
        - frequency and Wind speeds , and static inclination

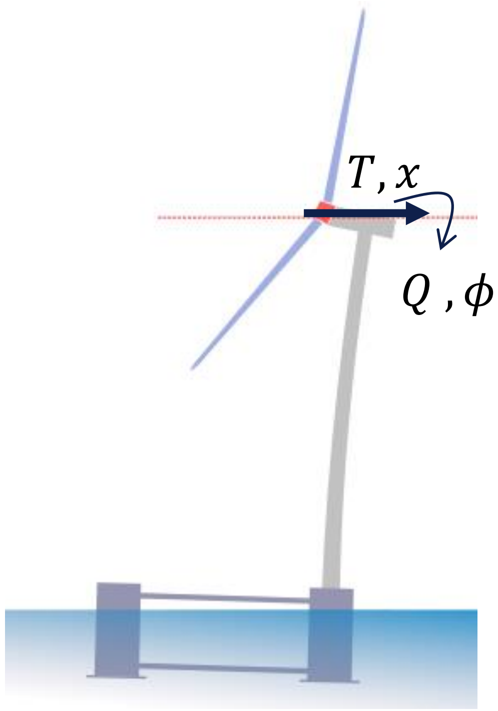
Rotor Frequency dependent contribution a, b and F_e

- From Hall (2022):

$$T(t) = T_0 + T_U\Delta(U-\dot{x}) + T_\Omega\Delta_\Omega + T_\beta\Delta_\beta$$

$$I_{rotor}\,\dot{\Omega}(t) = Q_0 + Q_U\Delta(U-\dot{x}) + Q_\Omega\Delta_\Omega + Q_\beta\Delta_\beta - N_g\Delta_{gen_{torque}}$$

Wind speed | Rotor Speed | Pitch Angle | Generator Torque



Pitch and rotor speed PI controller:

- $\Delta\beta = k_{P,\beta}\Delta\Omega + k_{I,\beta}\int\Delta\Omega dt + k_{P,x}\,\dot{x}$
- $\Delta_{\tau g} = k_{P,\tau}\,\Delta\Omega + k_{I,\tau}\int\Delta\Omega dt$

- Re-writing equations above in the following format (eliminate Ω) :

$$-(M + A_{aero})\,\omega^2\boldsymbol{x} + i\,\omega\,b_{aero}\boldsymbol{x} + K\,\boldsymbol{x} = \boldsymbol{f}_{\boldsymbol{aero}}(\omega)$$

- We arrive at the following coefficients:

$$a_{\text{aero}}(\omega) = \Re\left\{\frac{1}{i\omega}\left[T_U - k_{Px}T_\beta - H_{QT}(\omega)\left(Q_U - k_{Px}Q_\beta\right)\right]\right\},$$

$$b_{\text{aero}}(\omega) = \Re\left[T_U - k_{Px}T_\beta - H_{QT}(\omega)\left(Q_U - k_{Px}Q_\beta\right)\right],$$

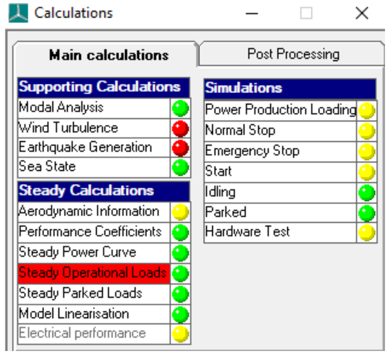
$$\hat{f}_{\text{aero}}(\omega) = \left(T_U - H_{QT}(\omega)Q_U\right)U(\omega) = H_{Uf}(\omega)U(\omega).$$

Note on Nomenclature:

$$T_U = \frac{\partial T}{\partial U}$$

DNV

Compute the rotor coefficients in Bladed

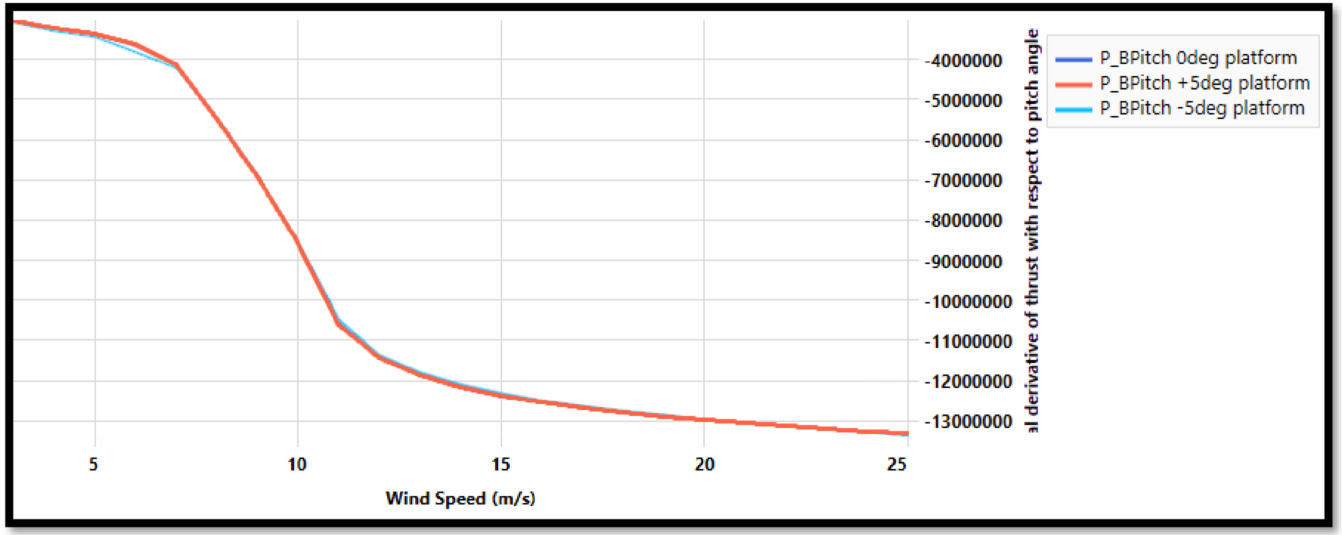


- Steady Operation Loads
  - Constant wind speed
  - Component flexibility included
  - Bladed prebend and sweep included
  - Possible to include static platform pitch with Tilt Angle

- Output :
  - Steady values for all variables
  - Partial derivatives required to compute a, b and f_e

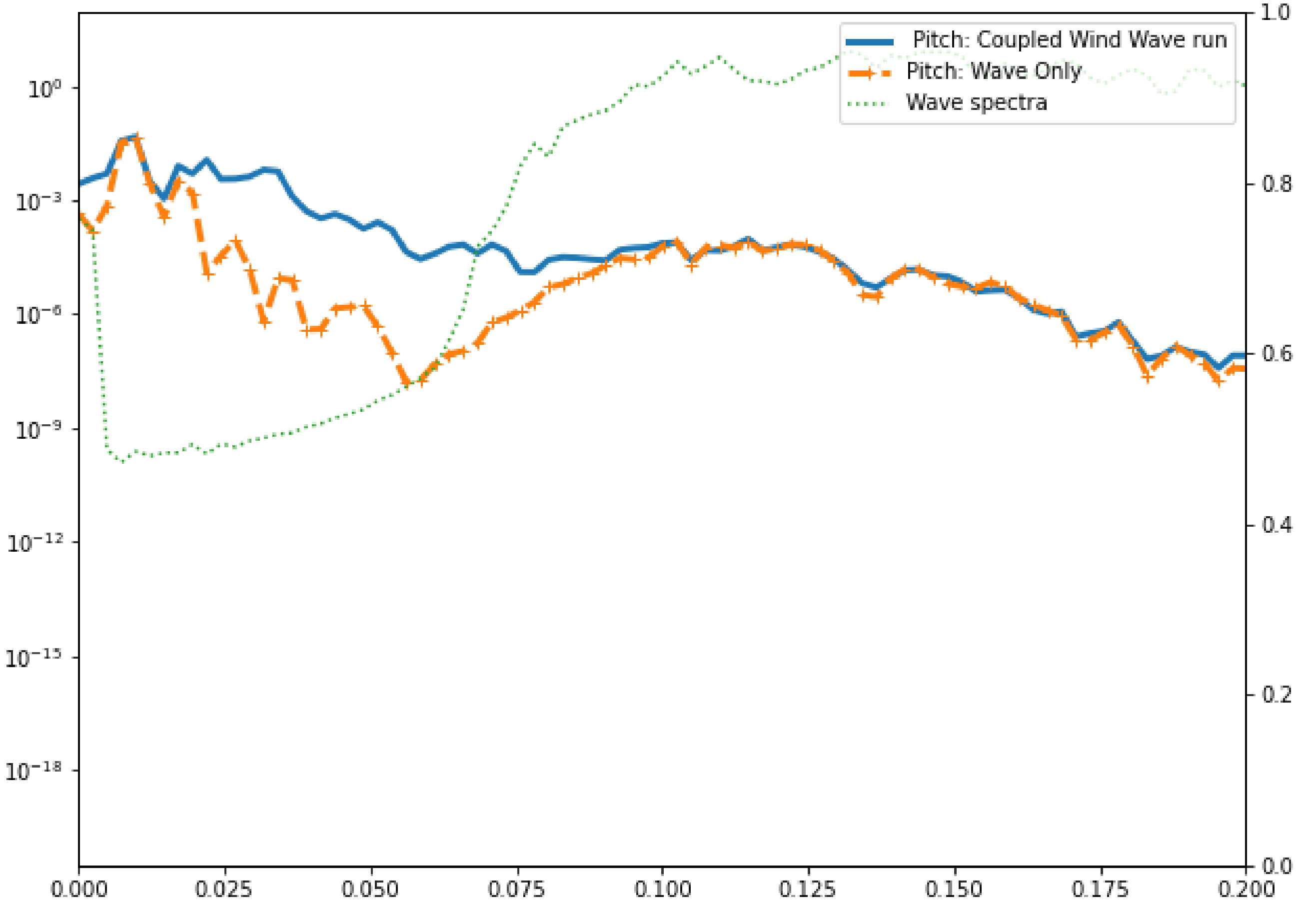
$$for\ example, \quad \frac{\partial T}{\partial U}, \frac{\partial T}{\partial \beta}, \frac{\partial Q}{\partial U} \ \dots$$

- Easily setup from existing turbine models.
- ASCII output possible



T_β for different platform inclinations (0, +/-5deg)

Total response: aerodynamic + hydrodynamic response



- *Total response:*

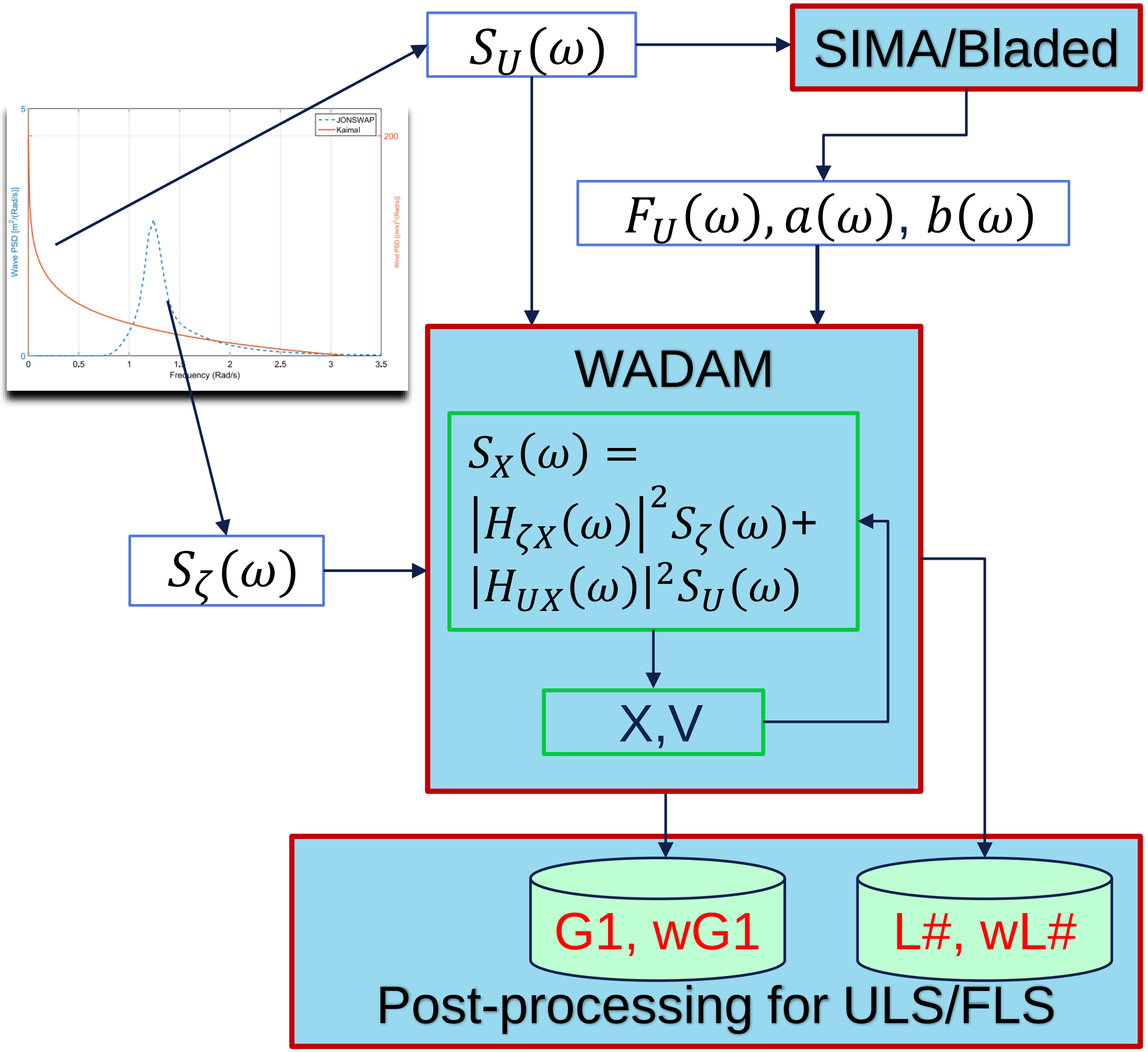
$$S_{R_{total}} = S_{R_{wave}} + S_{R_{wind}}$$

$$S_{R_{total}} = \frac{\left|f_{wind}\right|^2 S_{wind} + \left|f_{ex}\right|^2 S_{wave}}{\left(-\omega^2\left(m + A_{hydro} + A_{aero}\right) + j\omega\left(B_{hydro} + B_{aero}\right) + K\right)^2}$$

Coupled response

$$H_{\zeta X}(\omega) = \frac{F_\zeta(\omega)}{-\omega^2(M + A + a) + i\omega(V + B + b) + C}$$

$$H_{UX}(\omega) = \frac{F_U(\omega)}{-\omega^2(M + A + a) + i\omega(V + B + b) + C}$$

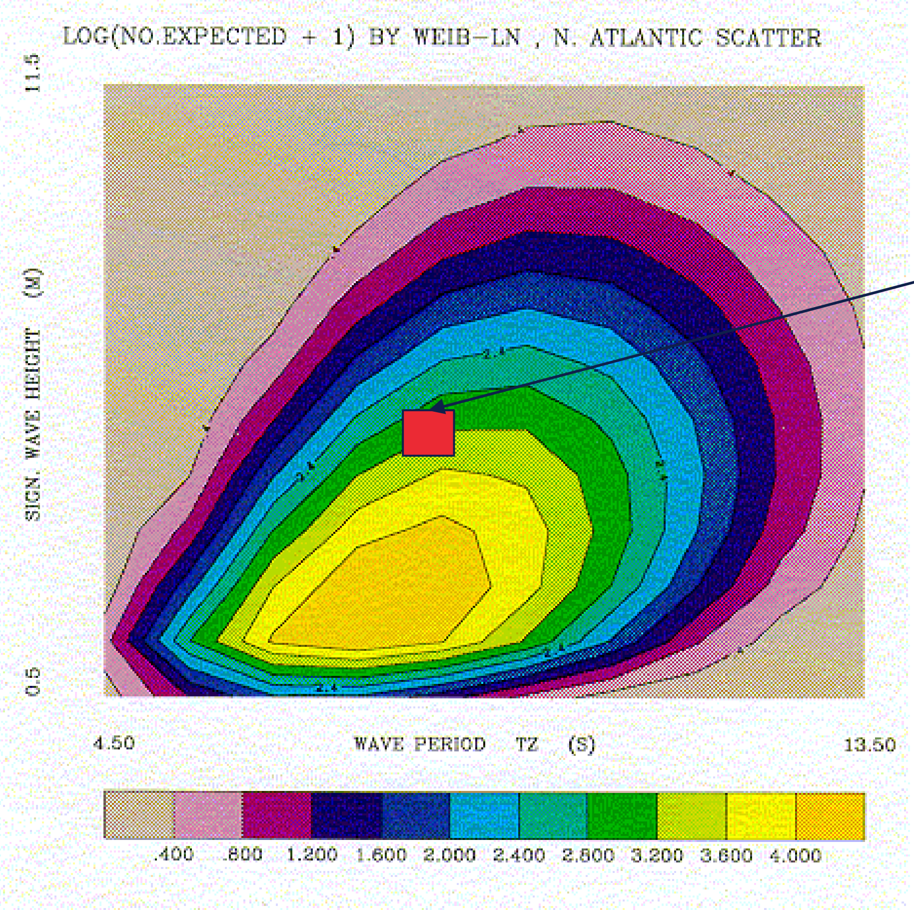


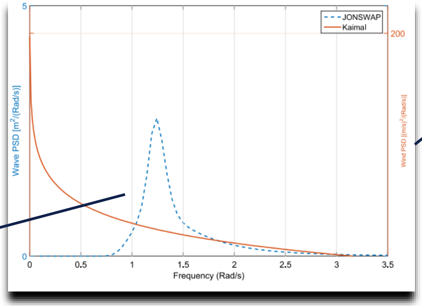
- *A, B* :Added mass, potentoal damping (per ω)
- a, b:Aerodynamic inertial & damping coef. (per ω)
- *V* :Linearized viscous fluid damping (per env. state)
- *C* :Total stiffness
- S_U S_ζ: Spectra for wind turbulent speed & wave, as PSD(ω)
- F_U F_ζ, :Excitation force due to wind and wave (unit amp./vel.)
- $H_{\zeta X}$ H_{UX} :Response (unit wave amp./unit turbulent wind vel.)
- S_X : Combined response spectrum, as PSD(ω)

Main assumption: Wave/wind uncorrelated, response considered separately and can be superposed!

Way ahead for stochastic postprocessing

- FLS
  - Stress being proportional to the loading
  - Wind/Wave stress response spectrum can be superpositioned





$$S_X(\omega) = \left|H_{\zeta X}(\omega)\right|^2 S_\zeta(\omega) + \left|H_{UX}(\omega)\right|^2 S_U(\omega)$$

Weibull fit of the sum of Rayleigh distributions

- ULS
  - Long term sectional forces
  - Long term stress level for selected locations

➢ Postresp / Stofat for well designed/used for wave conditions
➢ to be incoporate with wind condition

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FD model application

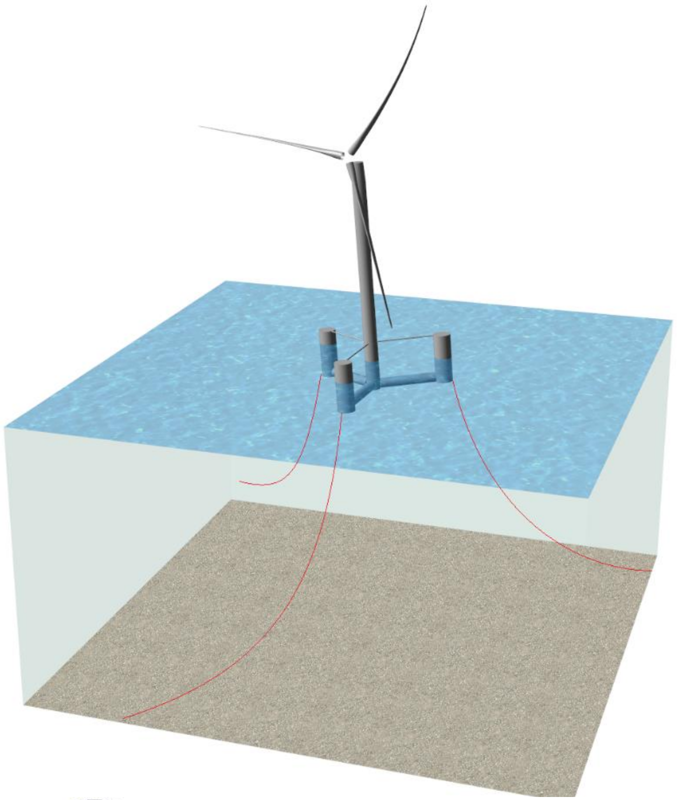
- Complement to TD model in early stages of design
- Quick overview of response
- Give indication of the how design response to the changes in parameters
- Identify critical load cases

Verification

VolturnUS-S + 15 MW

- IEA 15MW + VolturnUS-S
  - ROSCO controller adapter to Bladed
  - 2D look-up mooring lines
  - No 2nd Order Loads . No quadratic viscous.

- Focused on power production cases
  - Design Load Case 1.1 – Power production



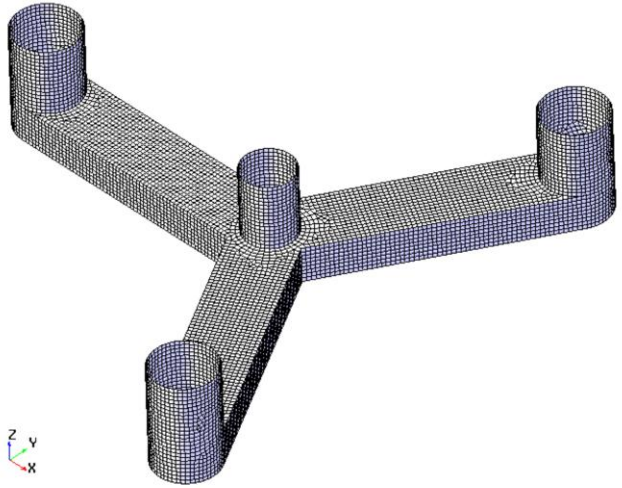


Table 12. IEC Design Load Case Matrix

DLC	Wind Condi-tion	Hub Height Wind Speed (m/s)	Wind Headings (°)	Significant Wave Height (m)	Peak Period (s)	Gamma Shape Factor (-)	Wave Headings (°)	Settings	# of Seeds	Total # of Sims.
1.1	NTM	4.00	0.00	1.10	8.52	1.00	0.00	-	6	6
		6.00	0.00	1.18	8.31	1.00	0.00	-	6	6
		8.00	0.00	1.32	8.01	1.00	0.00	-	6	6
		10.00	0.00	1.54	7.65	1.00	0.00	-	6	6
		12.00	0.00	1.84	7.44	1.00	0.00	-	6	6
		14.00	0.00	2.19	7.46	1.00	0.00	-	6	6
		16.00	0.00	2.60	7.64	1.35	0.00	-	6	6
		18.00	0.00	3.06	8.05	1.59	0.00	-	6	6
		20.00	0.00	3.62	8.52	1.82	0.00	-	6	6
		22.00	0.00	4.03	8.99	1.82	0.00	-	6	6
		24.00	0.00	4.52	9.45	1.89	0.00	-	6	6

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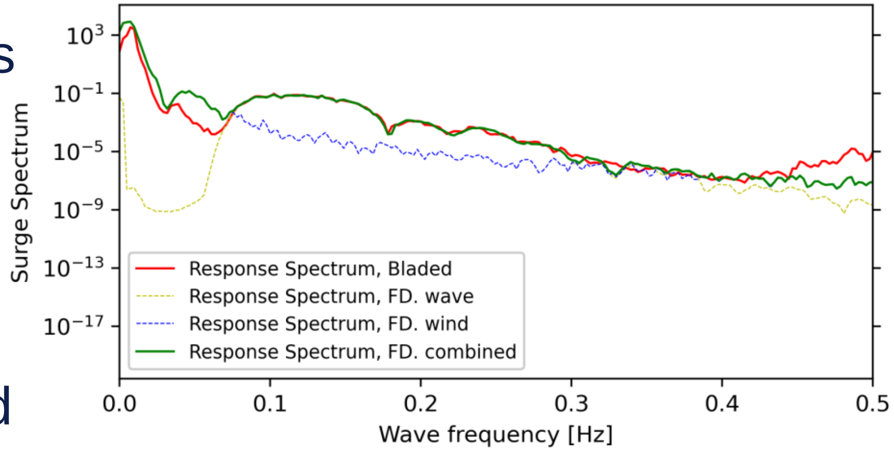
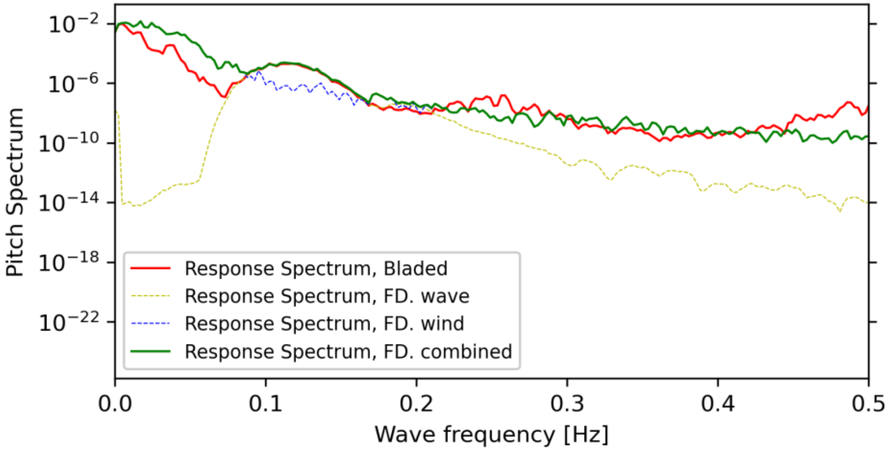
Frequency vs coupled run (U = 6m/s , 12m/s)

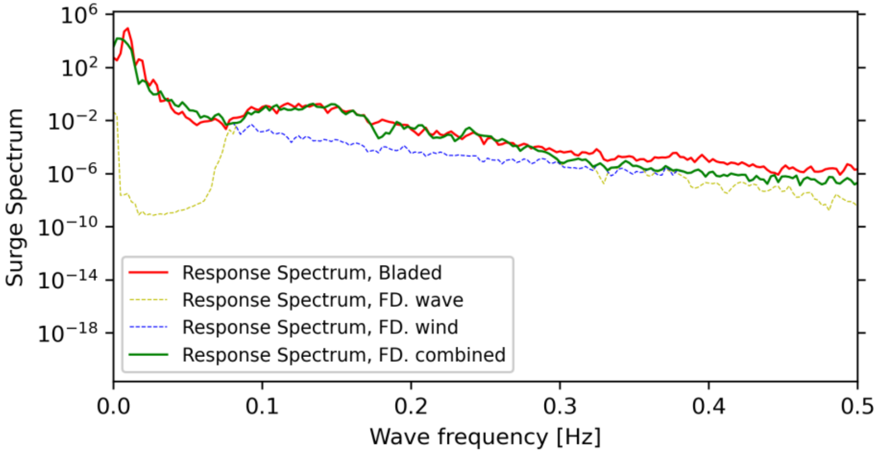
- The wind components is can be easily seen in Pitch and Surge response. (f< 0.05Hz)
- Good representation of the peak wave and wind contributions in frequency domain.
- Important to consider both.

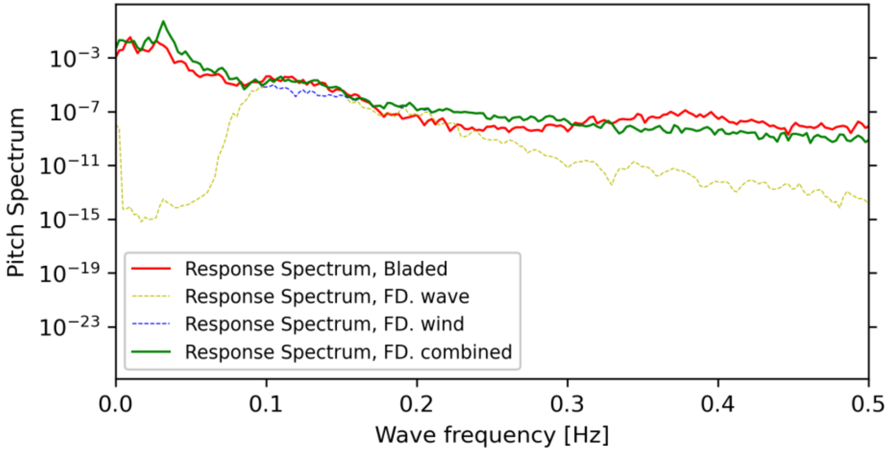
6 m/s





12 m/s



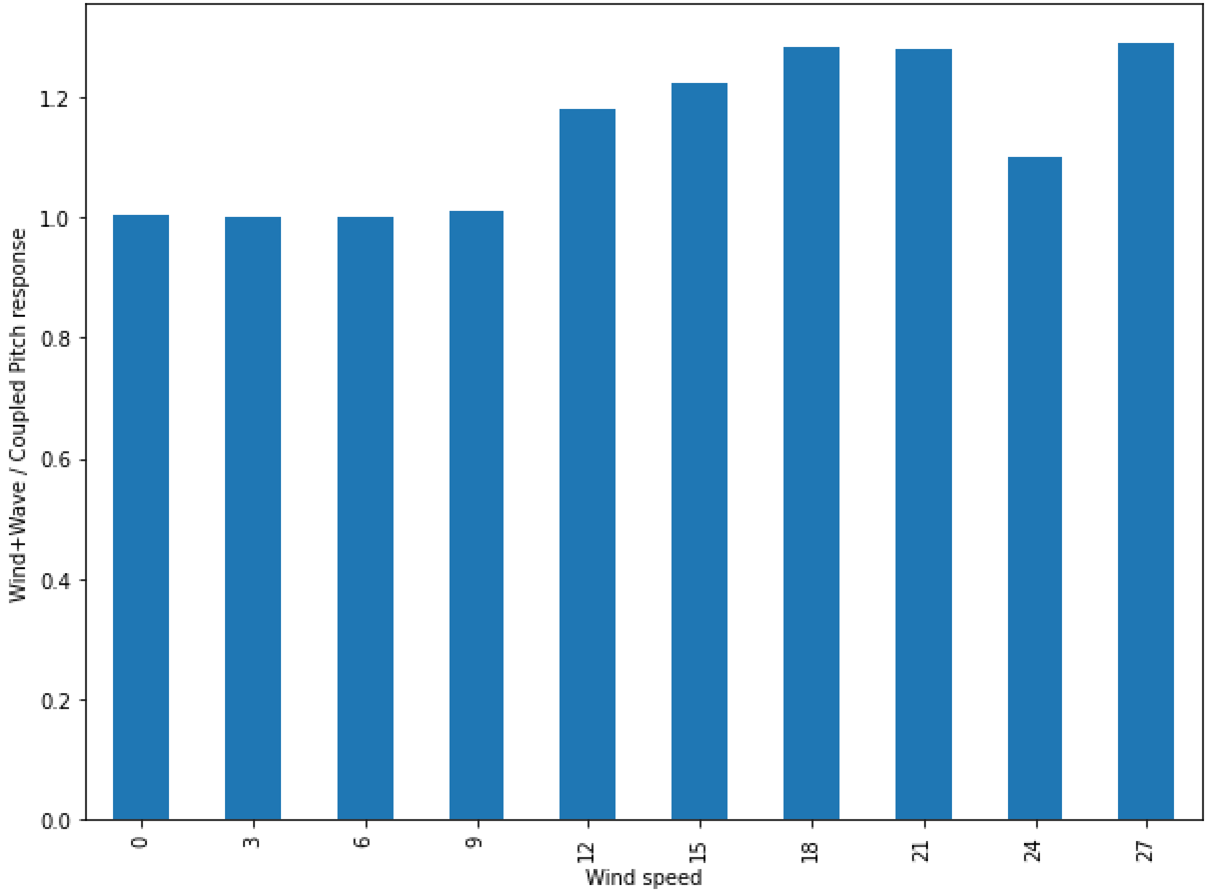


- Low frequency load component is well noticed

Coupled response and wind and wave

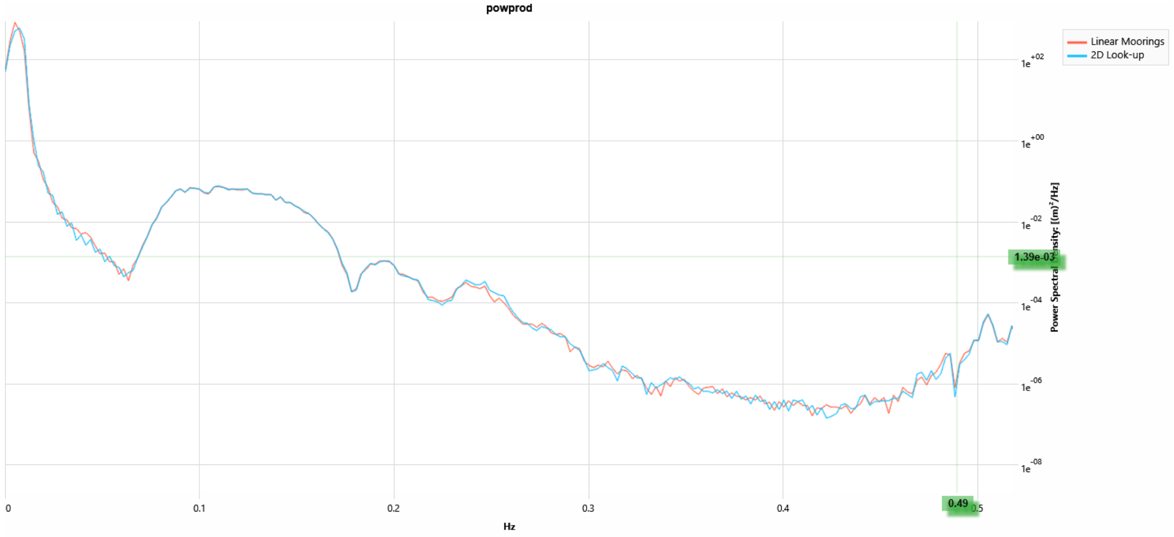
$$S_{R_{total}} = S_{R_{wave}} + S_{R_{wind}}$$

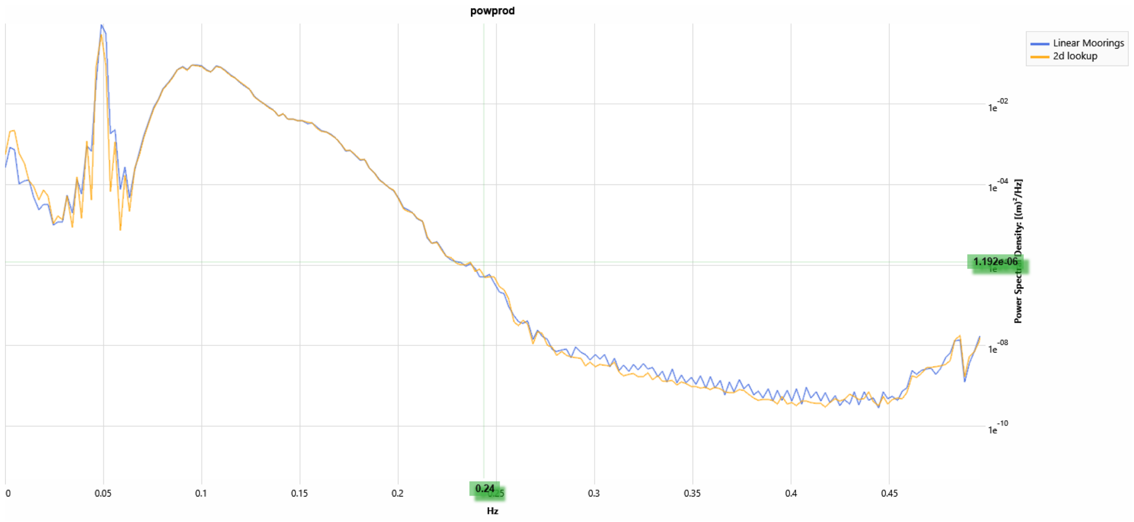
	Wind	Wave
Wind Only	Turbulent Wind	No Wave
Wave Only	Steady wind	Irregular Wave
Coupled	Turbulent Wind	Irregular Wave

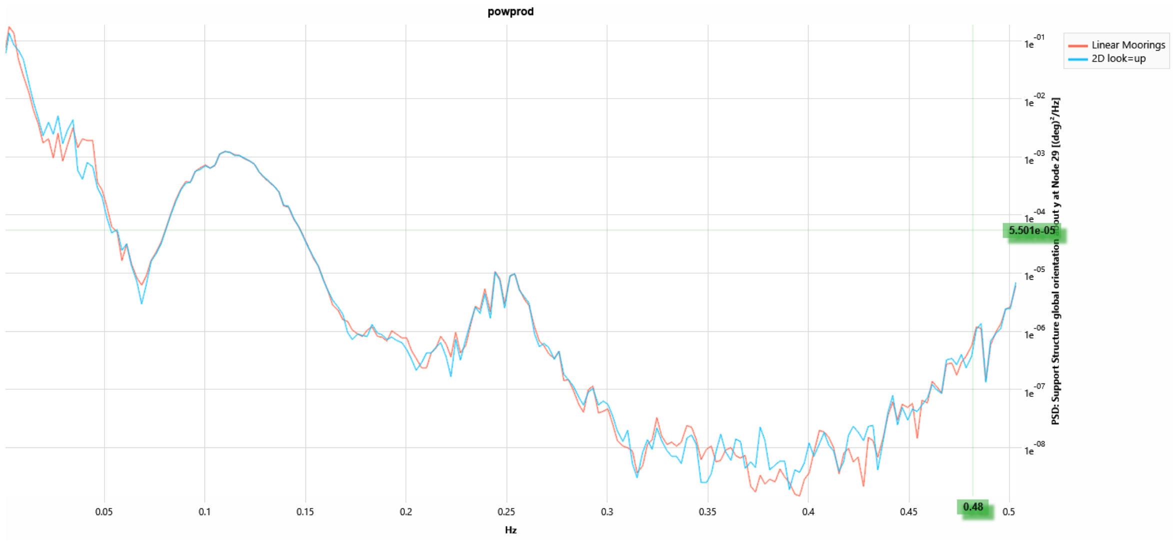


Linear vs 2D lookup Moorings

• Very little different is observed.







EMULF II FOWT

EMULF I&II

- "Efficient numerical methods for ultra large floating wind turbines"
- Joint industry project
- Funding from COWIfonden
- Balancing accuracy and time

Accuracy

Time

EMULF I

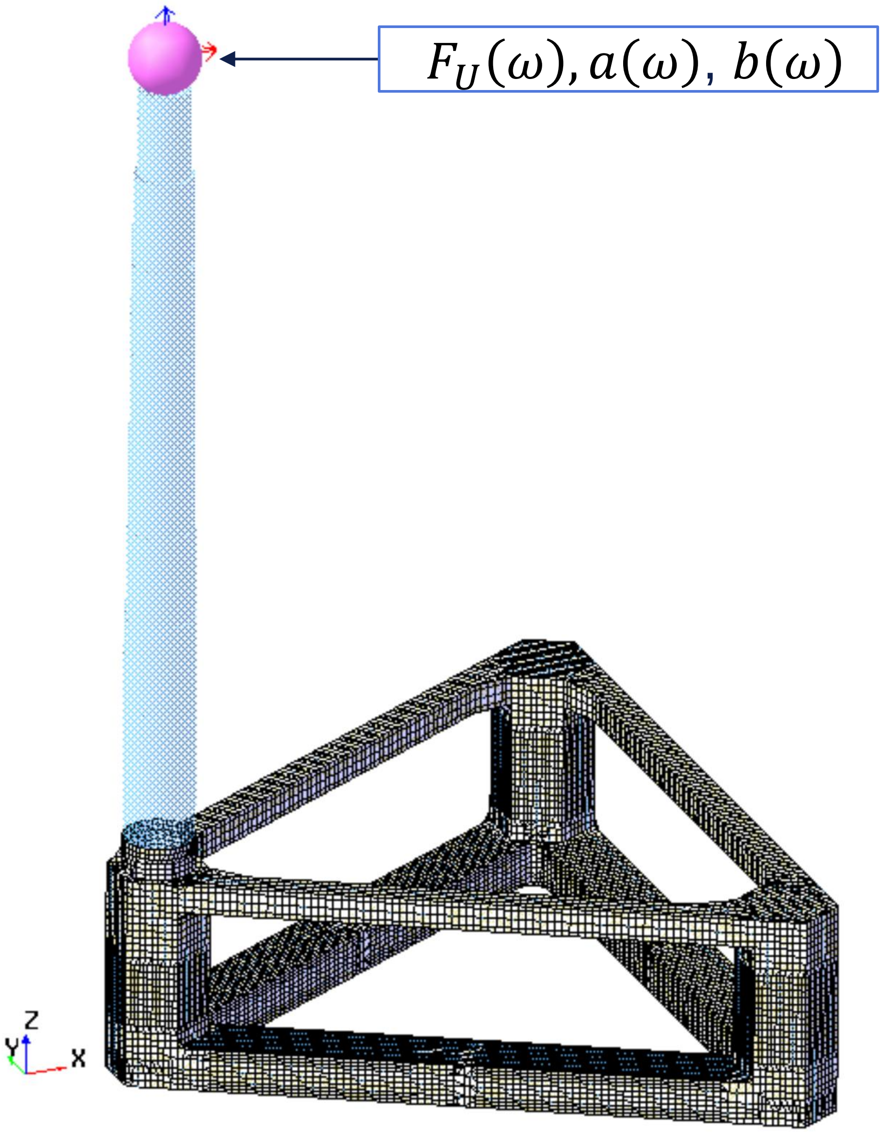
- Focus area 1:
  The influence of floater flexibility on the structural response
- Focus area 2:
  Simplified analysis methods for motion response
- Focus area 3:
  Simplified methods for structural analysis

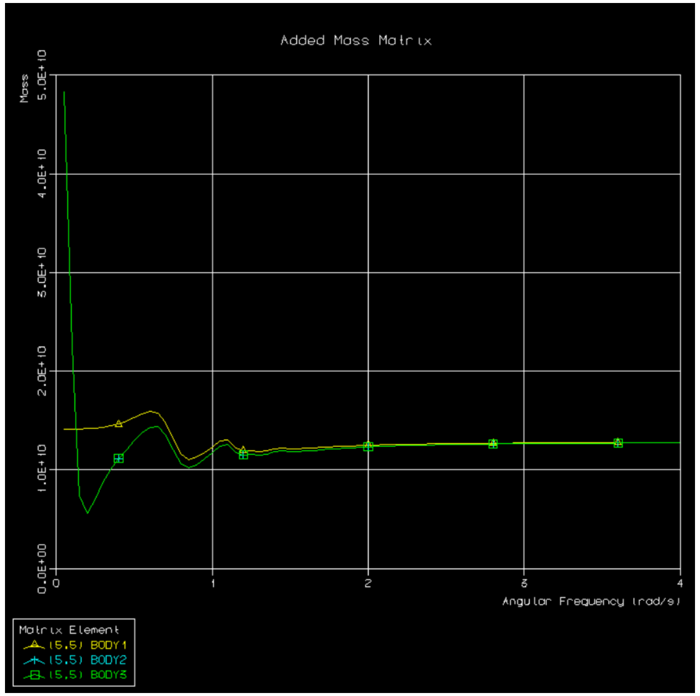
EMULF II

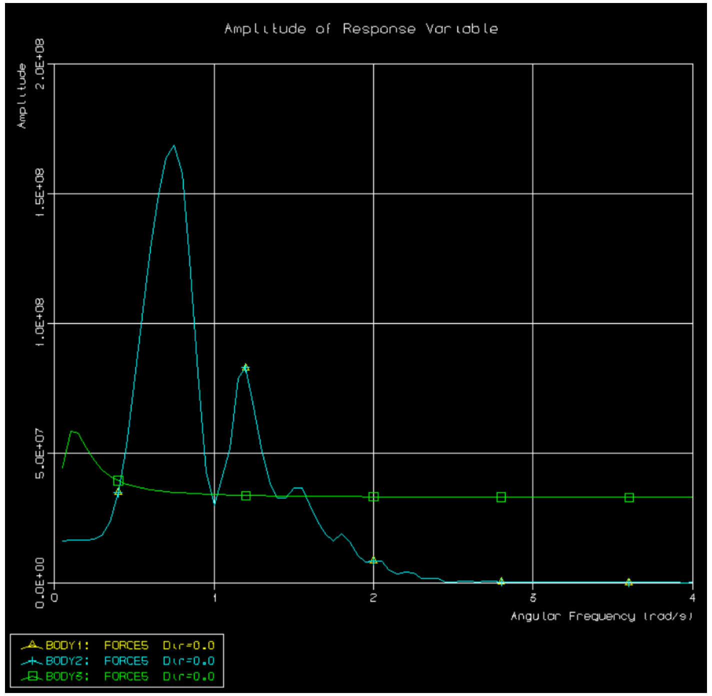
- Focus area 1:
  Broaden the findings on floater flexibility to other architypes
- Focus area 2:
  Effects from extreme waves
- Focus area 3:
  Super element modelling – similar approach to bottom fixed

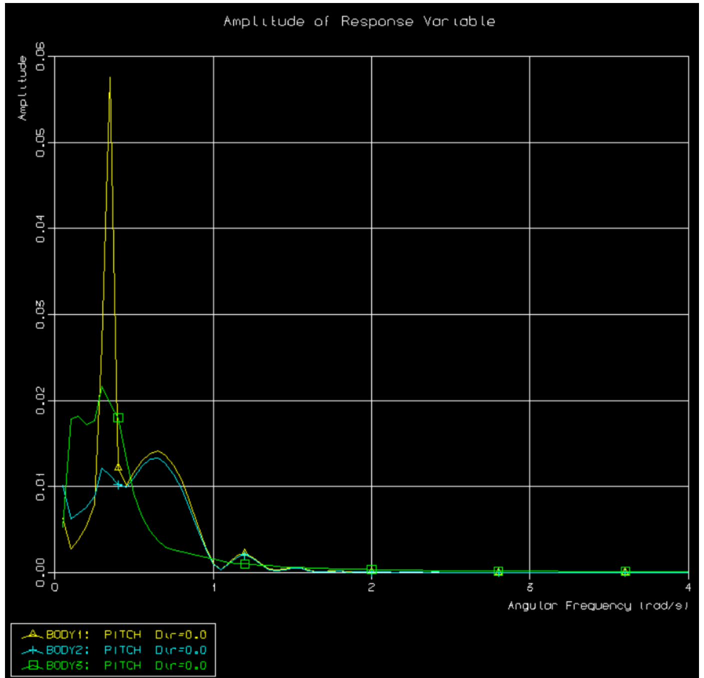
COWI COWIfonden NTNU DTU DNV

Aerodynamic coef. & responses



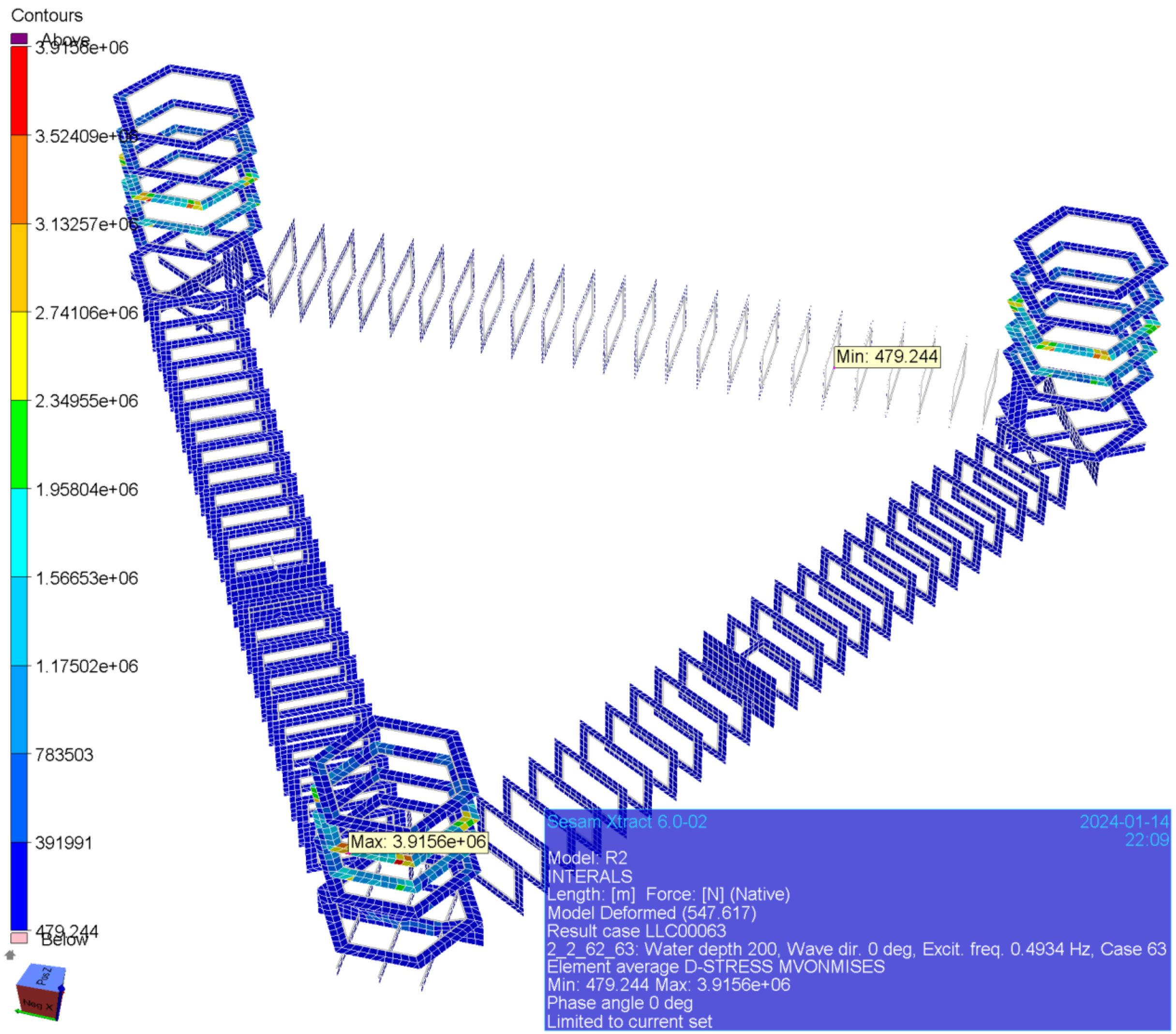


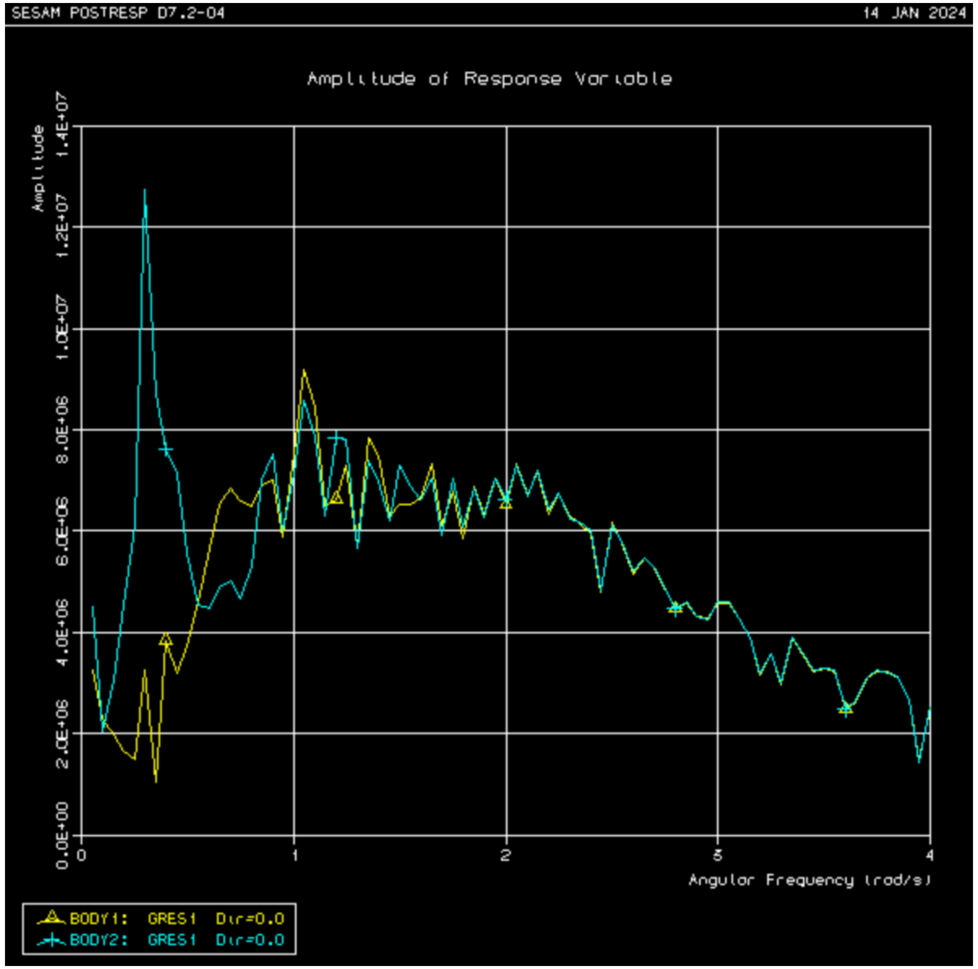




- BODY1: a=0, b=0, Wave excited
- BODY2: a, b, Wave excited
- BODY3: a, b, Wind excited

Principal stress response





BODY1: a, b, Wave excited

BODY2: a, b, Wind excited

Summary

Summary

- Frequency domain workflow for structural analysis of FOWTs proposed.
- Linearized areodynamic forces
  - ✓ added mass & damping, excitation force
  - ✓ obtained from Bladed
  - ✓ inserted into WADAM
- Short term responses & loads due to wave and wind proved to be
  - ✓ uncorrelated
  - ✓ response spectra can be superposed for stochastic postprocessing
- Long term responses & stresses can be used for FLS/ULS check
- Q&A

leftovers slides

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