Vibrations of semi-submersible floating wind turbines
Consequences for experimental modelling

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Background and motivations

Tower vibrations play a key role for fatigue damage of the tower and reliability of the wind turbine generator. Model scale experiments typically consider a stiff tower and floater. The tower flexibility is represented through a flexible joint at the base. The joint's stiffness is selected to match the wet 1st bending natural frequency of the tower.

Questions

How does the common experimental approach (a rigid tower and rigid floater connected with a joint) compare with a fully flexible tower model in terms of

- Eigenmodes ?
- Damping ?
- Deflection at the nacelle ?

Joint at tower base and stiff tower

Model and assumptions

A simple model for design with a centered tower (figure 3.b) can be developed using two degrees of freedom: θ_f the rotation of the floater and θ_t the rotation of the tower both around the y-axis. Then, only 3 dimensionless ratios describe the model :

- κ, between the restoring coefficient (including gravitational effects) and the rotational stiffness of the joint
- ι, between the mass of the platform (including added mass) and the mass of the tower
- γ, between the radiation damping coefficient and the rotational damping of the joint

Equations

The dynamic equilibrium projected on the modal basis eq.(1) gives the natural frequencies $\omega_{+/-}$ and damping coefficients $\epsilon_{+/-}$ for each mode. The coupled system properties are compared with the corresponding limit cases :

- **Clamped tower on land** $\omega_t^2 = \frac{k}{I_t}$; $\epsilon_t = \frac{d}{2\sqrt{kI_t}}$
- **Rigid body pitch motion** $\omega_r^2 = \omega_t^2 \frac{\kappa}{1+\iota}$; $\epsilon_r = \epsilon_t \frac{\gamma}{\kappa(1+\iota)}$

$$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \ddot{\xi} + 2\epsilon_t\omega_t \begin{bmatrix} P_- & P_c \\ P_c & P_+ \end{bmatrix} \dot{\xi} + \begin{bmatrix} \omega_-^2 & 0 \\ 0 & \omega_+^2 \end{bmatrix} \xi = 0 \quad (1)$$

Results

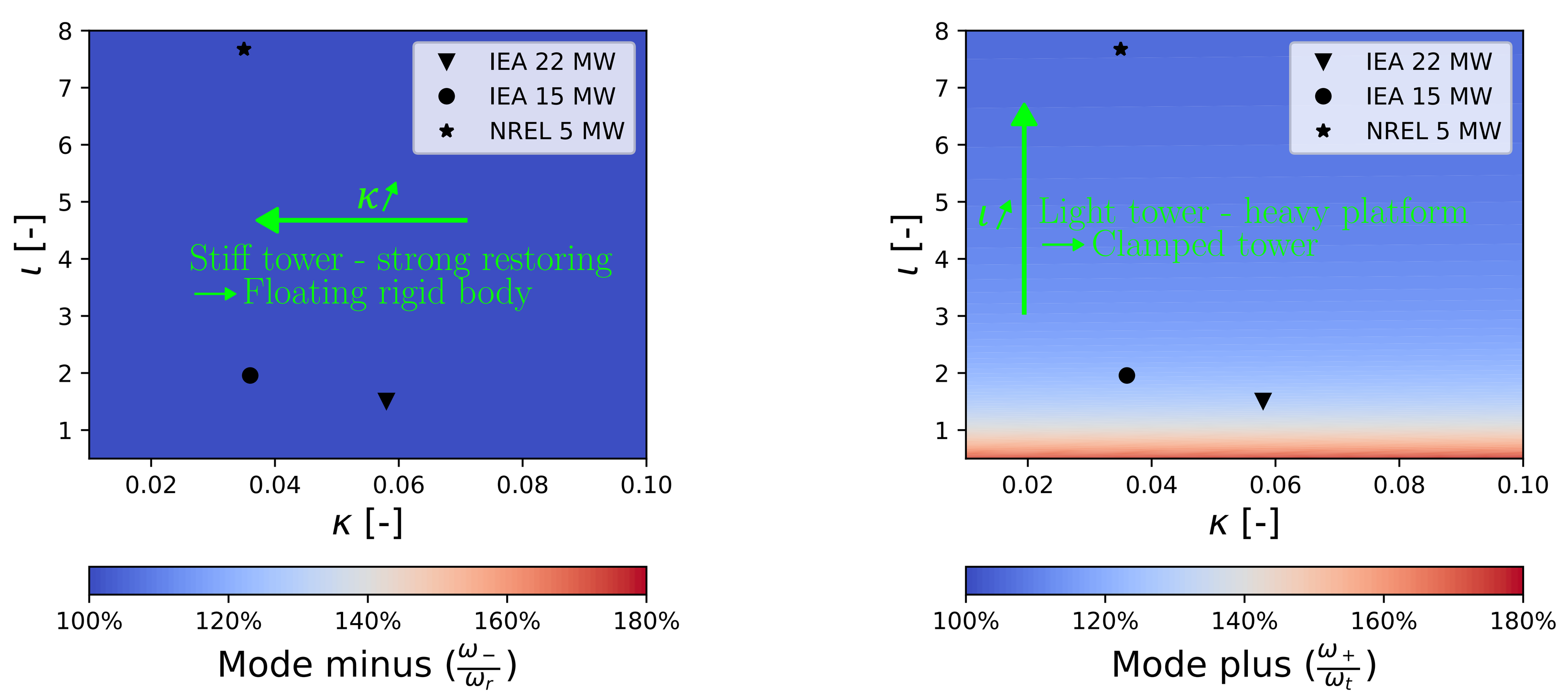


Figure 1 : Increase in frequency compare with limit cases

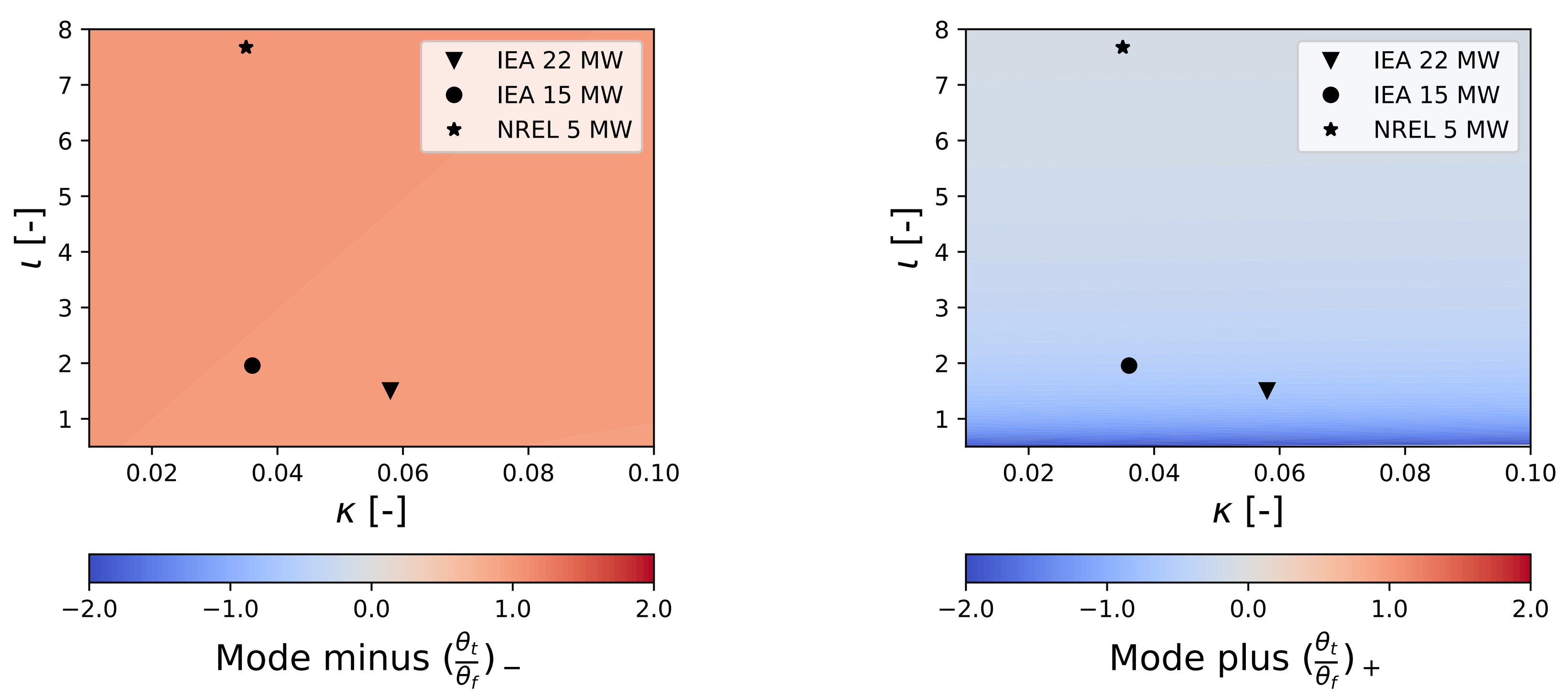


Figure 2 : Mode shape

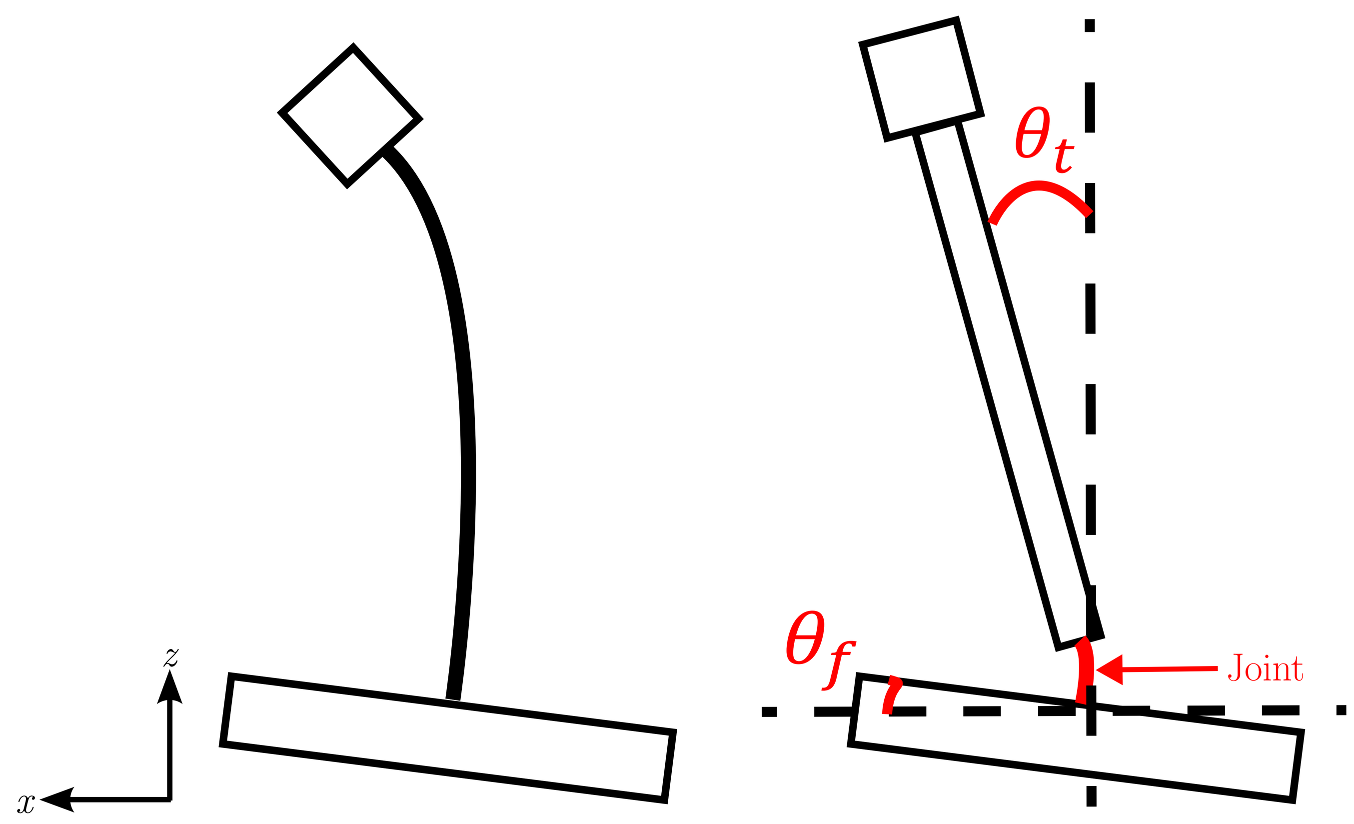
- Mode minus is a pitch rigid body motion where the turbine and its platform move together ($\theta_t = \theta_f$). κ and ι don't affect this low frequency mode.
- θ_t and θ_f have opposite signs in mode plus. The turbine and its platform vibrate out of phase. ι has a significant effect on mode plus. When small, it increases the frequency and the jack-knife effect on the mode shape.

Typical values of κ and ι

IEA 22MW ($\kappa = 0.058, \iota = 1.510$) and 15MW ($\kappa = 0.036, \iota = 1.957$)
NREL 5MW ($\kappa = 0.035, \iota = 7.674$)

Modeling a FWT : 2 approaches

A finite element model representing a full scale flexible tower is compared with the 2-DoFs model close to common testing strategy. All were validated with dedicated experiments (figure 4). Even if the joint is chosen to match the wet 1st bending natural frequency of the tower, the corresponding mode shape is different between the two approaches. For a given rotation of the floater, nacelle's deflection is underestimated during model test (rigid tower) compared to a fully flexible tower.



3a. Fully flexible tower 3b. Model testing strategy

Figure 3 : Sketch of the two approaches

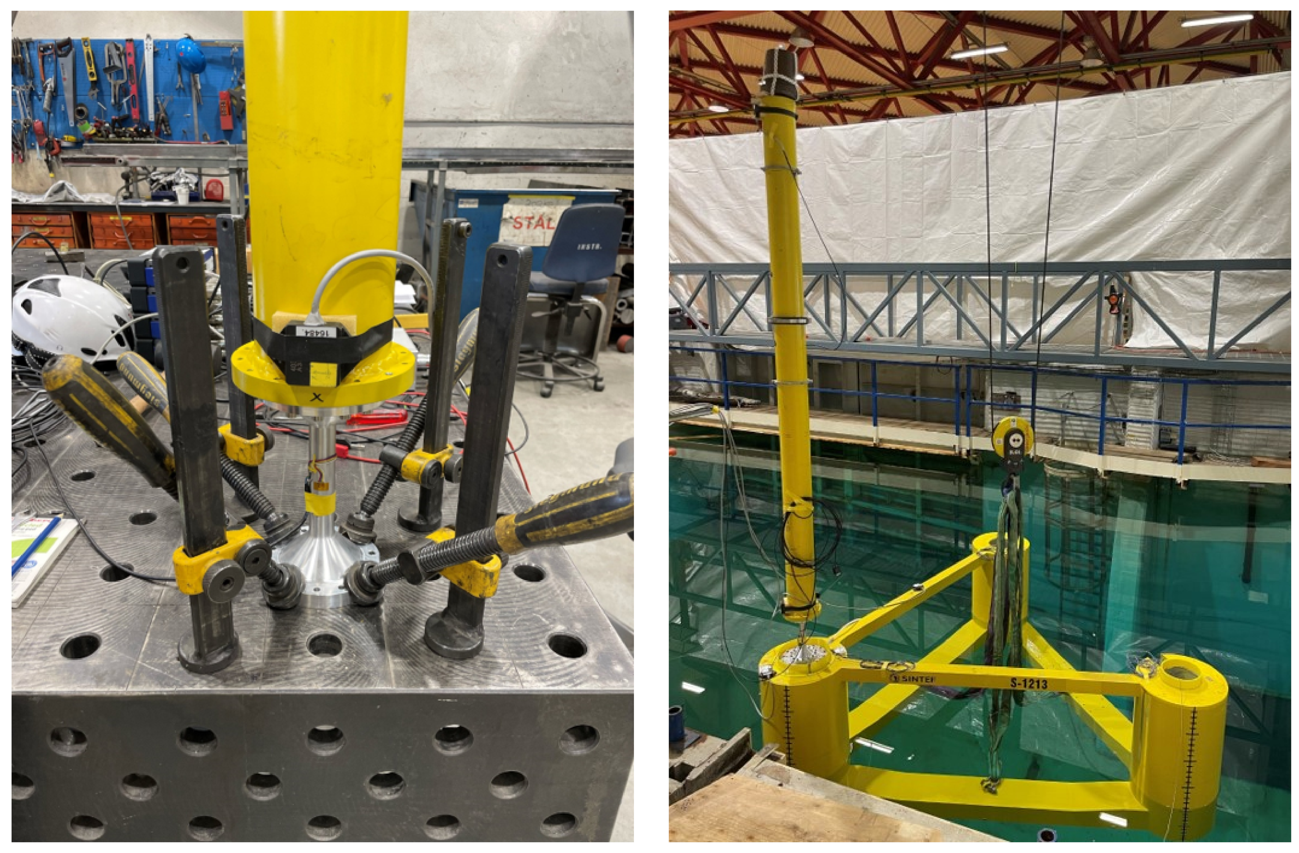


Figure 4 : Common model testing strategy of a semi-submersible FWT

Damping

The system of equilibrium eq.(1) dissipates power according to eq.(2). The coupling coefficient P_c is proportional to the exchanged energy between modes. For both limit cases $P_c \to 0$. A large coupling coefficient leads to strong coupling effects. Energy is transferred from the tower vibration mode to the near-rigid-body mode, and dissipated by hydrodynamic damping. Damping of tower vibrations can be significantly increased for heavy turbines on light platform through $Pc(\kappa, \iota, \gamma)$.

$$P_d^{(coupled)} = 2\epsilon_t\omega_t(P_-\xi_-^2 + P_+\xi_+^2 - 2P_c\xi_-\xi_+) \quad (2)$$

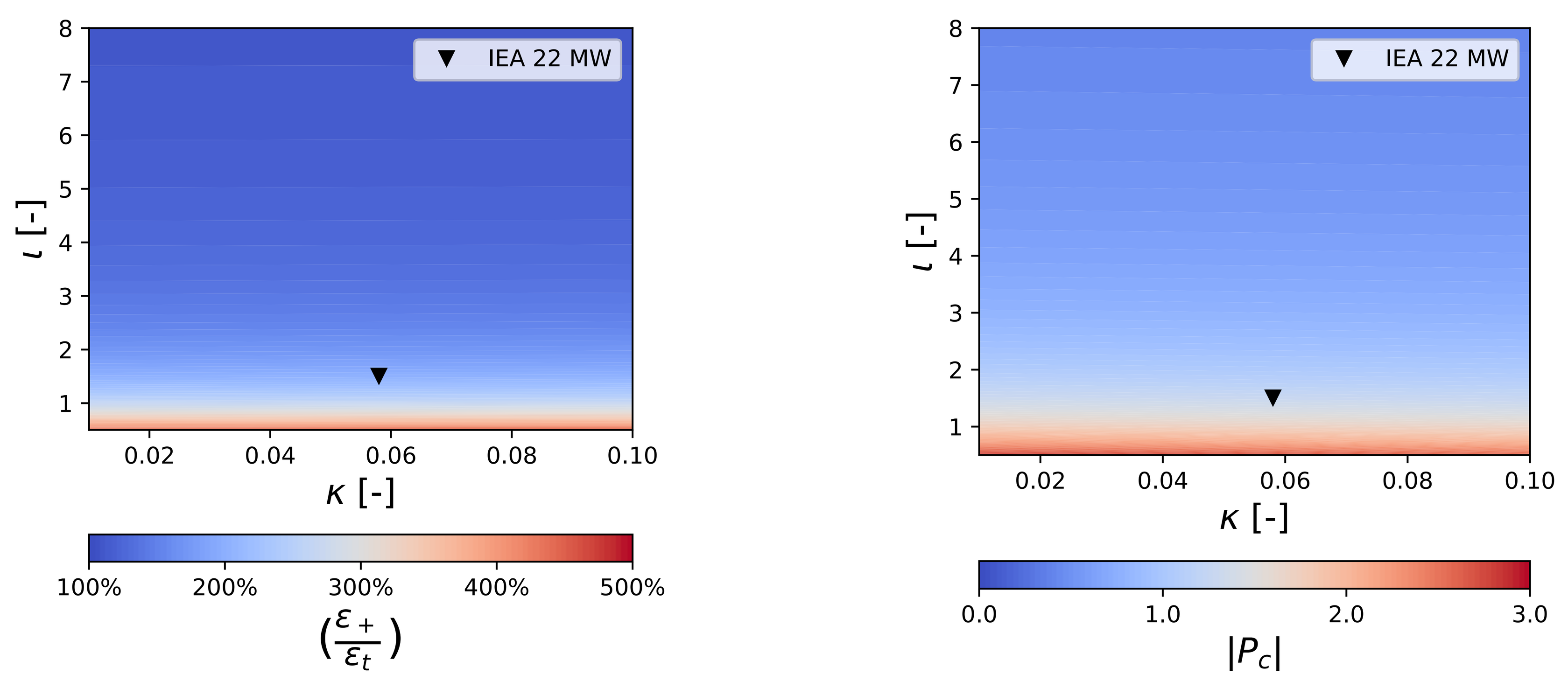


Figure 5 : Mode plus increase in damping (left) and coupling coefficients (right)

Conclusions

- Coupling effects are strong between tower vibrations and floater motions. For large turbines mounted on optimized floaters it becomes significant on tower vibrations.
- Although a lumped stiffness approach can match the first eigenfrequency of the tower, it leads to different eigenmodes and damping compared to a fully flexible tower model. The impacts are especially significant for lighter platforms.
- Modelling FWTs with a flexible tower could be a wiser approach when vibrations are important.