2. An investigation of the Zefyros FOWT system based on in-situ and simulated data

Part II – Coupled eigen-frequency analysis of floating wind turbines

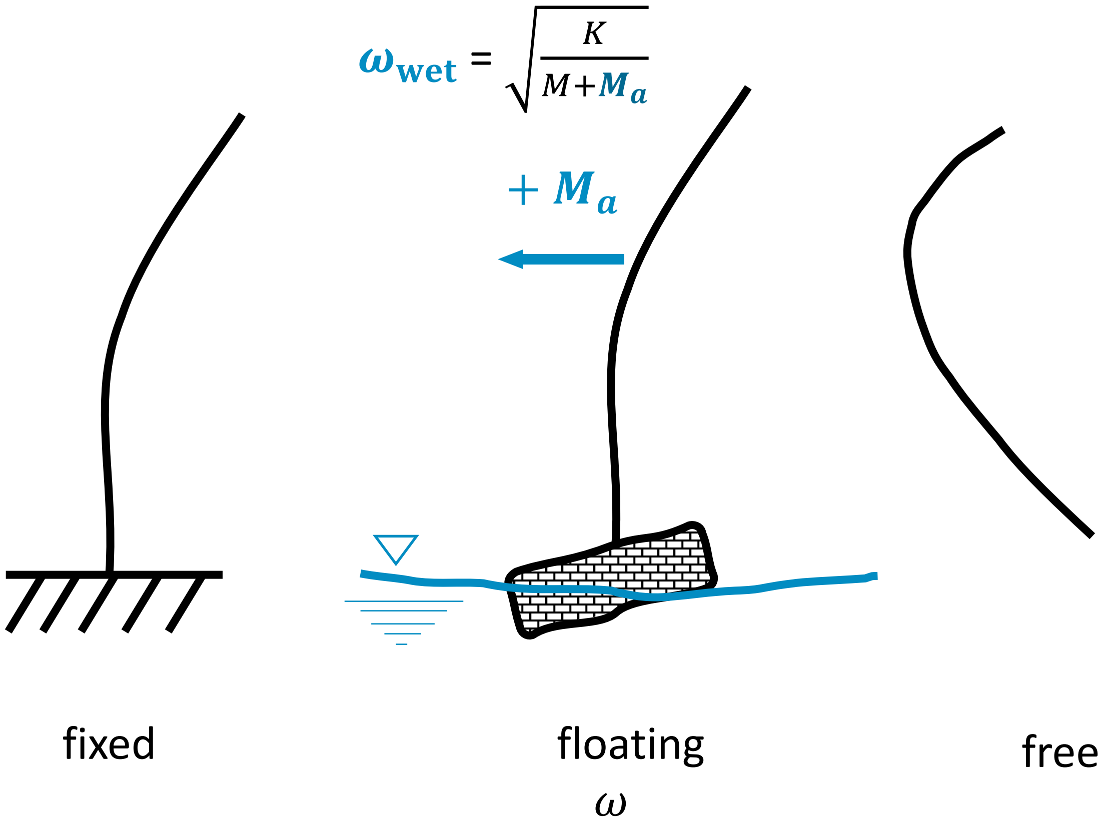
Jérôme de Lauzon, Bureau veritas

Introduction

- Vibration frequencies of the tower have to be checked
  - Should be far enough compared to 1P and 3P frequencies to avoid resonnant phenomenon
  - The eigen-frequencies of the model used for the integrated load analyses should be as precise as possible

- Effects to be included in the eigen-frequency analysis:
  - Hydrodynamic added mass
  - Flexibility of the floater
  - Orientation of the RNA
  - Flexibility of the blades
  - Mooring stiffness

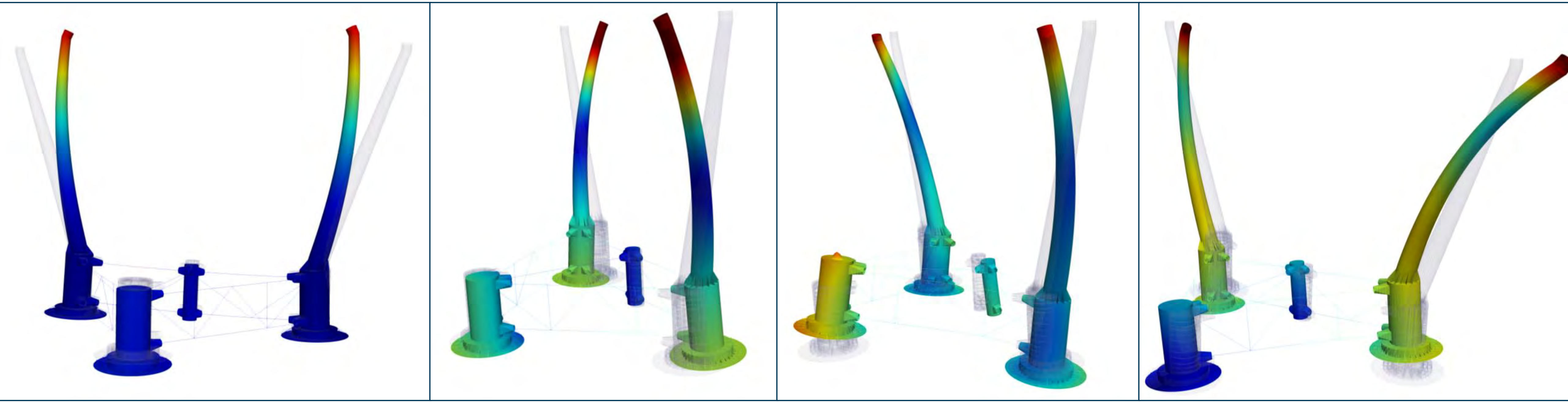
- 2 different tools to model the floating wind turbine
  - Opera: aero-hydro-elastic ILA tool (rigid floater)
  - Homer: full hydro-elastic coupled analysis



Generalized modes approach

- Displacement field decomposed on a basis of generalized modes
  - 6 rigid body degrees of freedom
  - N natural vibration modes (obtained from FE solver)

$$\vec{H}(x,y,z,t) = \sum_{i=1}^{6+N} \xi_i(t) \cdot \vec{h_i}(x,y,z)$$



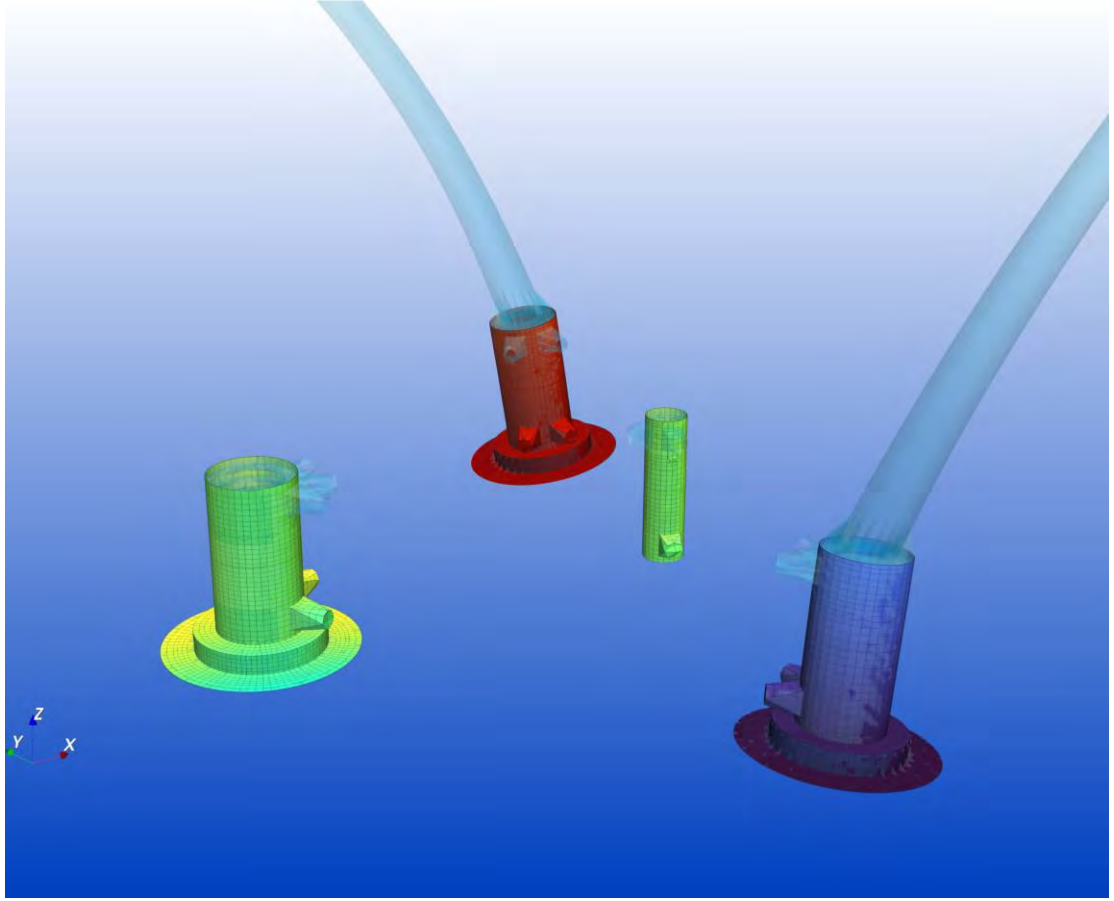
Hydrodynamics

- Flow around the floater solved with linear potential flow model
    - Frequency domain – harmonic wave excitation
    - 3D boundary element method
    - Diffraction & radiation boundary values problems

$$\varphi = \varphi^{Inc} + \varphi^{Diff} - i\omega \sum_{j=1}^{6+N} \xi_j {\varphi_j}^{Rad}$$

- Radiation problem solved for all 6+**N** generalized modes
    - Mapping procedure to get the eigen-modes shapes on the hydrodynamic mesh

$$\frac{\partial {\varphi_j}^{Rad}}{\partial n} = \overrightarrow{h_i} \cdot \vec{n}$$



Coupled eigen-value problem

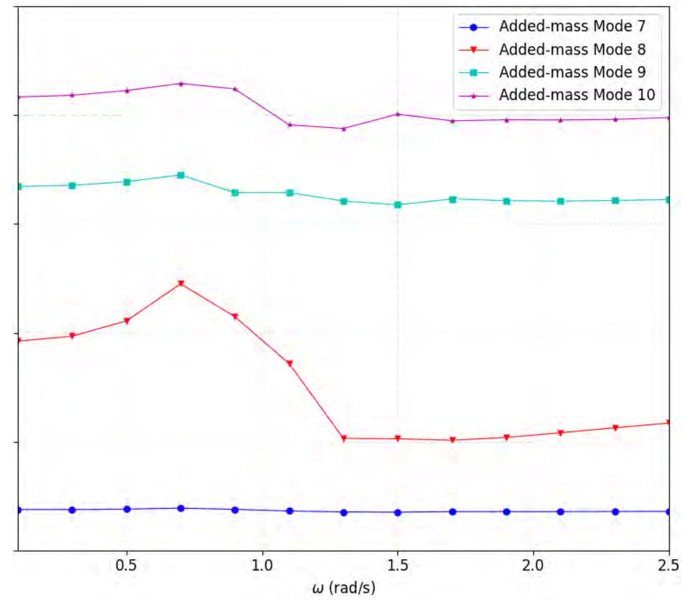
- Starting point: seakeeping motion equation in frequency domain
  - o The dimension of all matrices are now 6**+N**

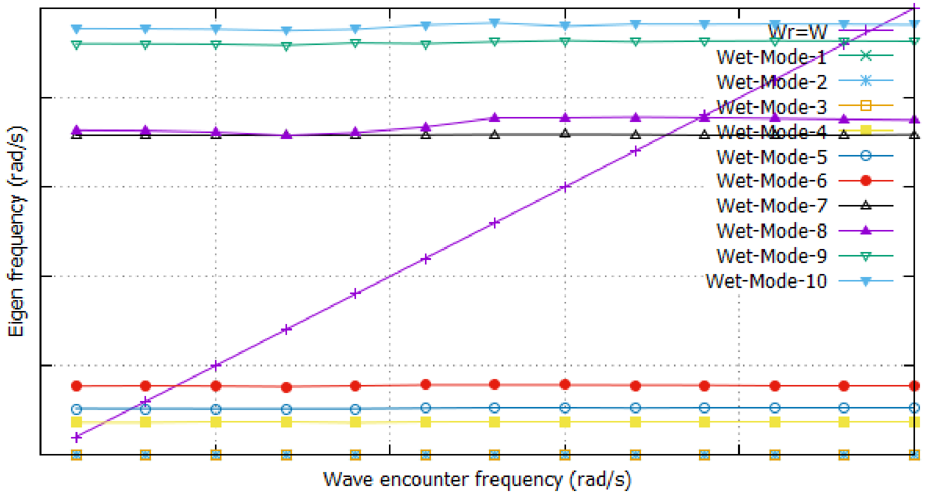
$$\left(-\omega^2\left(m + A(\omega)\right) - i\omega B(\omega) + C + k\right) \cdot \xi = F(\omega)$$

- Excitation and damping removed from the equation
- Diagonalization of the system for each frequency

$$\left(m + A(\omega)\right)^{-1} \times (C + k) \cdot \xi = \omega^2 \xi$$

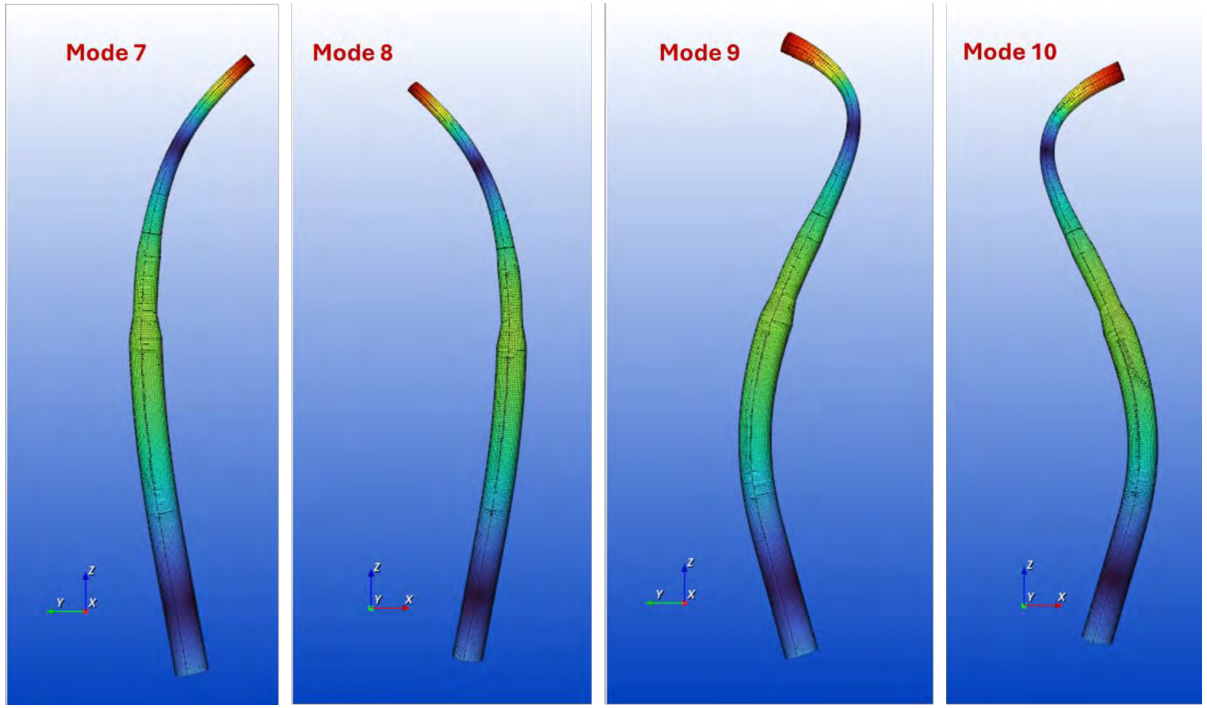
- The resonnant frequency is obtained when the frequency used for the added-mass matches the computed eigen-frequency

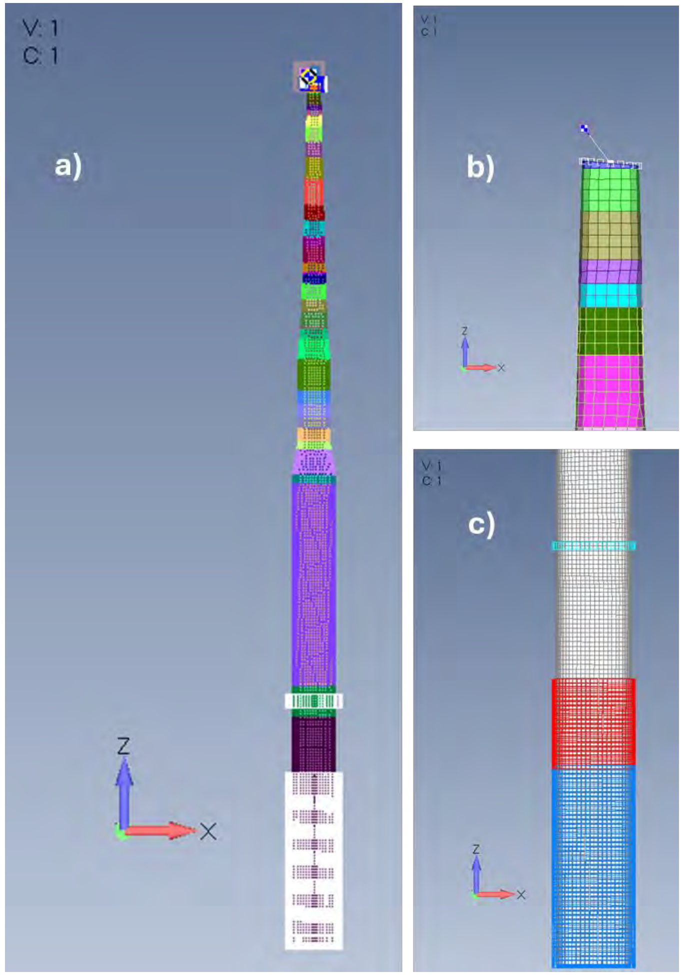




Example: Zephyros floating wind turbine

- ANSYS model translated to Nastran
  - RNA and blades modeled by a mass element
  - Water ballasts modeled as mass + rigid elements
- Eigen-modes analysis in Nastran



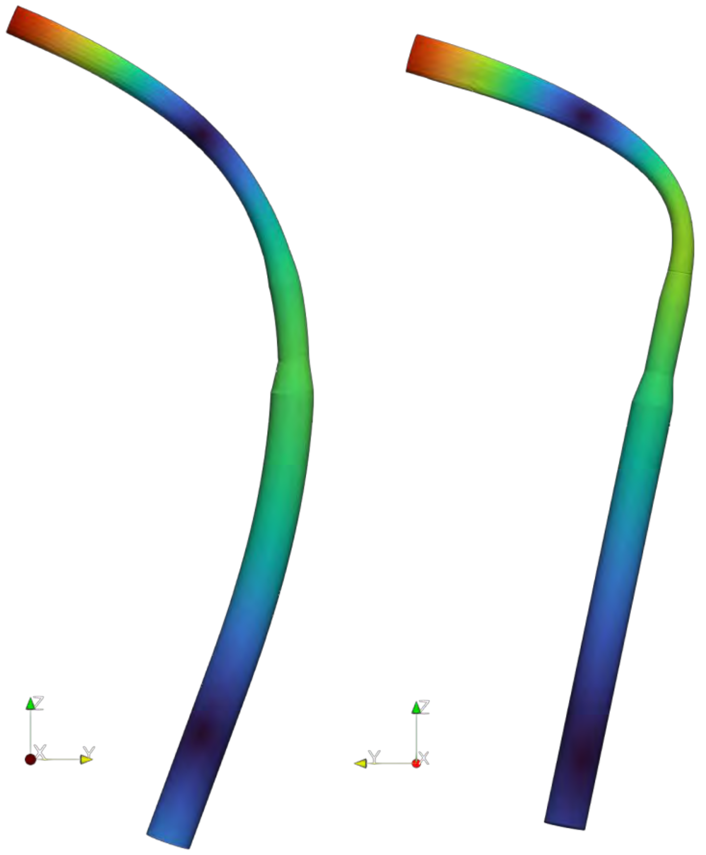


Example: Zephyros floating wind turbine

- Coupled eigen-value analysis
  - Added mass effect included
  - No mooring stiffness considered

- 2 assumptions tested for the floater
  - Flexible floater
  - Rigid body (to match the assumption in ILA software)

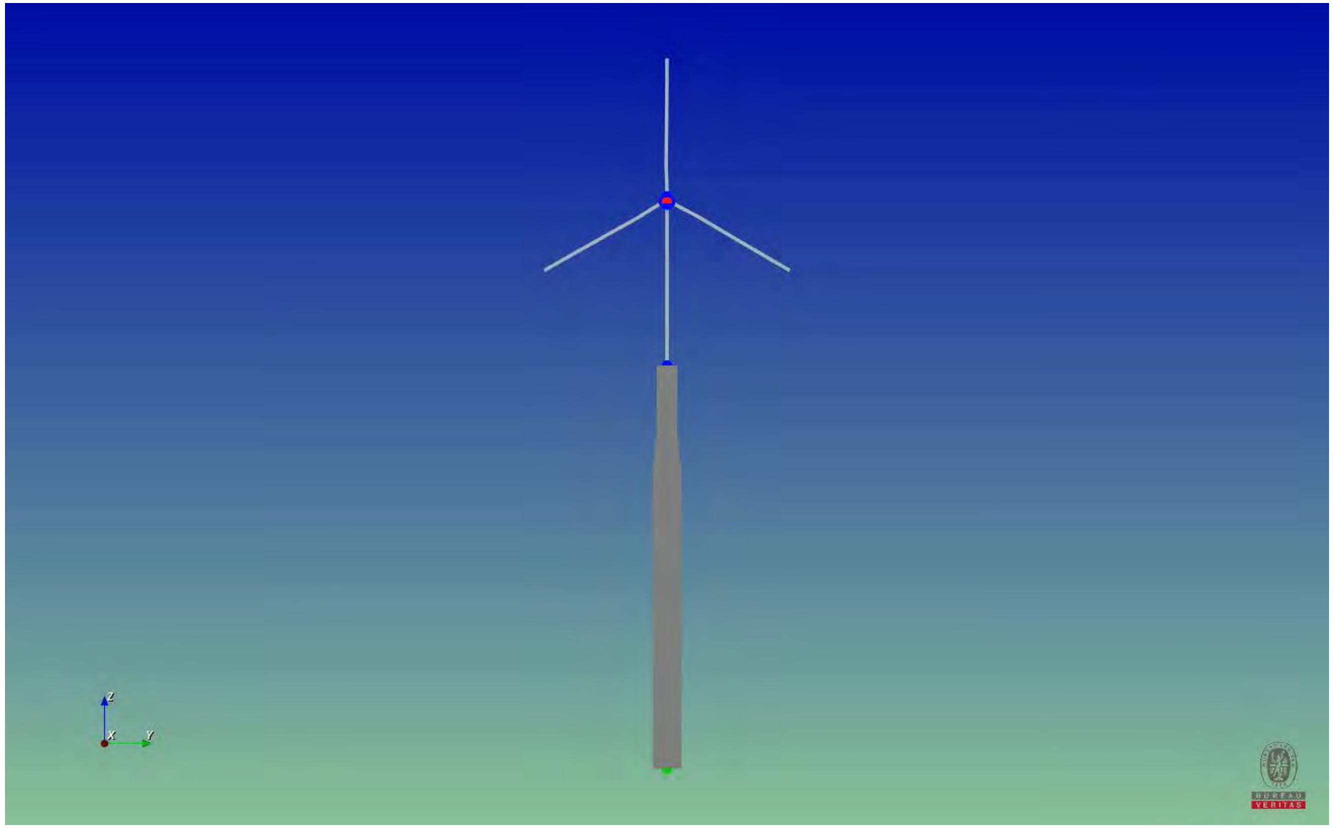
Description	Dry	Wet	Measured
Fore-aft (flexible floater)	*0.84*	***0.65***	*0.69*
Side-side (flexible floater)	*0.86*	***0.66***	*0.69*
Fore-aft (rigid floater)	*1.10*	***0.96***	*0.69*
Side-side(rigid floater)	*1.14*	***0.98***	*0.69*



Eigen-frequency analysis in ILA software (BV Opera)

- Tower modeled with lumped mass (finite elements possible too)
- Same modeling for time-domain analyses and for eigen-frequency analysis

- Eigen-frequency analysis
  - Hydrodynamic added mass
  - ~~Flexibility of the floater~~ (in general case)
  - Orientation of the RNA
  - Flexibility of the blades
  - Mooring stiffness

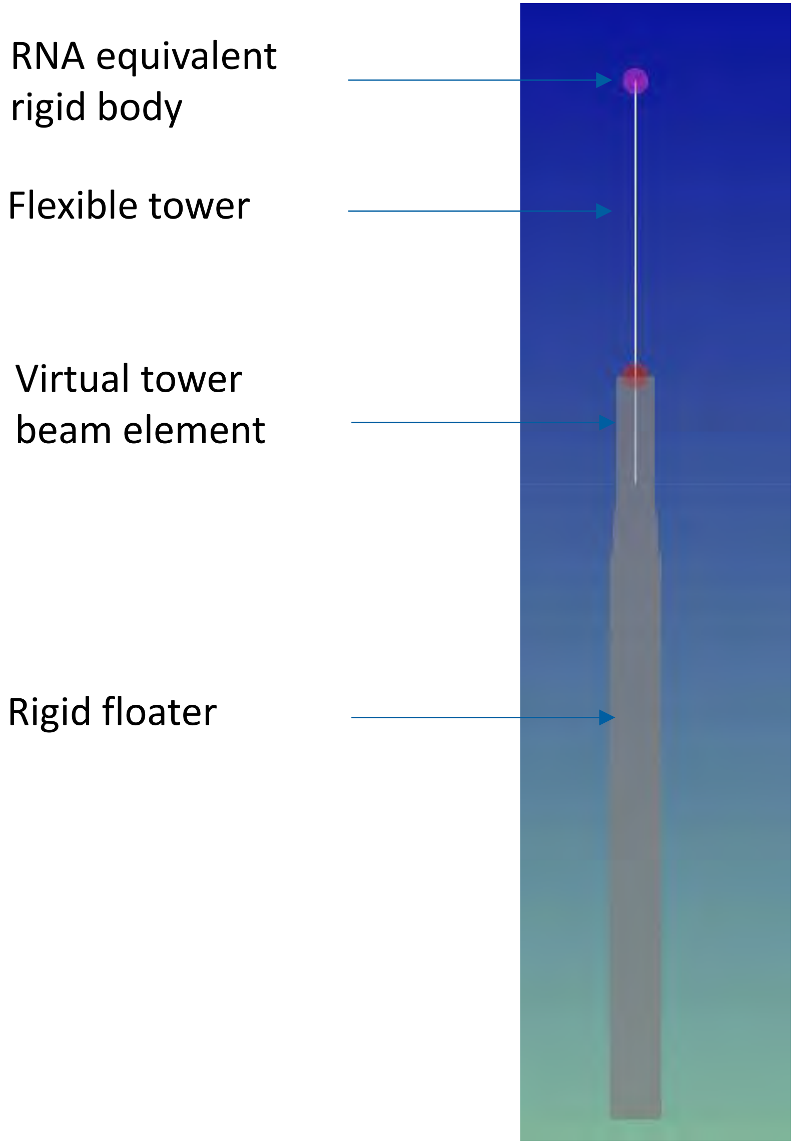


Calibration of the model for the ILA

- Flexible floater not possible in ILA software, only the tower can be flexible
  - Will give wrong results for the strength assessment
  - (especially at the connection with the floater)

- Calibration of the model
  - Use of a « virtual tower » element to connect the floater with the tower (different approach compared to OpenFAST)
  - Calibration of the massless beam properties to match the reference eigen-frequency

Description	Dry	Wet	Measured
Fore-aft – no virtual tower	*1.22*	***1.12***	*0.69*
Fore-aft – virtual tower	*0.85*	***0.70***	*0.69*

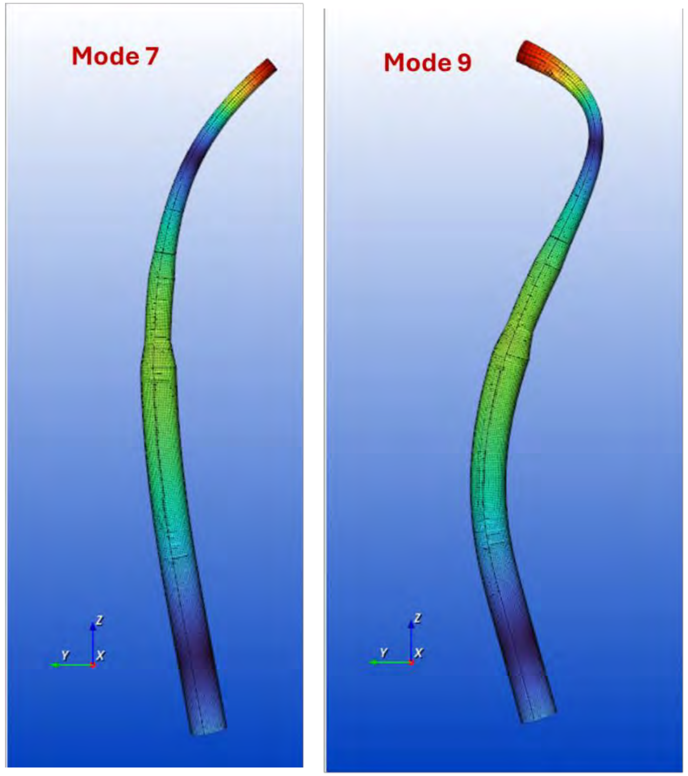


Conclusion

- Robust and accurate hydro-elastic coupling method
  - Use of generalized modes approach – modal decomposition
  - Full flexiblity of the floating wind turbine is considered, including floater
  - Added mass consistently computed for all modes, and all frequencies
  - Possible to take into account mooring stiffness if relevant (TLP for example)
  - Simple and consistent method: no trick

Conclusion

- Calibration of the ILA model
  - Use of a « virtual tower » element to connect the floater with the tower
  - Full flexible solution used as reference
  - Not fully consistent is the floater is very flexible: hard to match higher-frequencies eigen-modes



- For the future
  - Possible to implement the same generalized mode approach in ILA software
  - Especially useful for very large & flexible floaters