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

Part I – Effects of floater flexibility on the dynamic response of the wind turbine Zefyros

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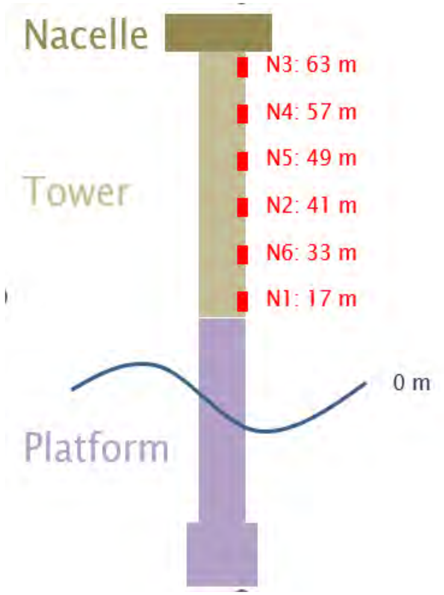
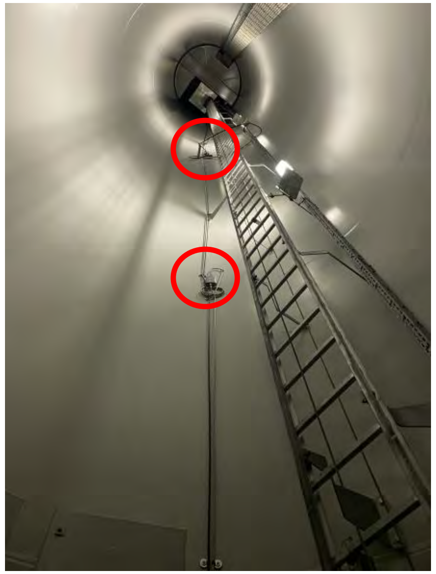
S-Morpho sensor installation

System configuration:

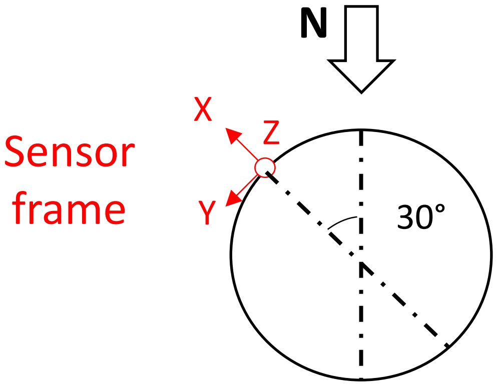
- Triaxial accelerations
- 6 nodes installed vertically along the tower
- Sampling frequency 40 Hz
- Data acquisition in *continuum from 10/2022*





System outputs :

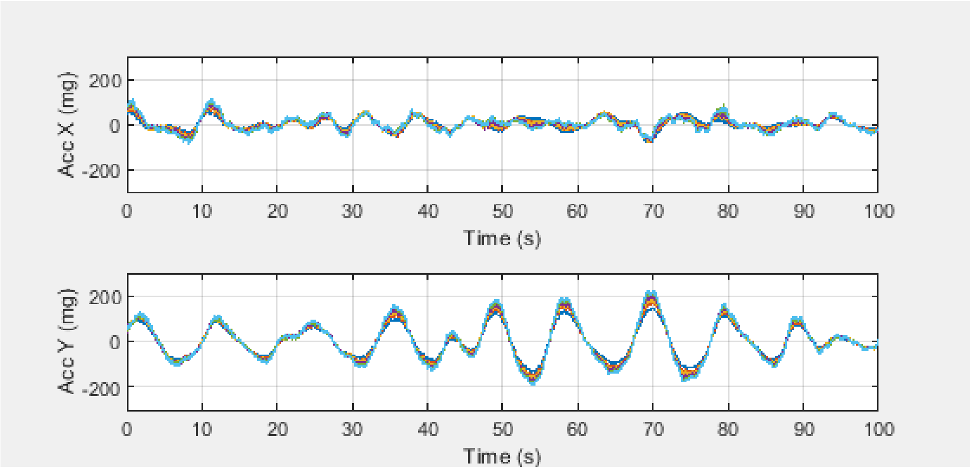
- Acceleration statistics
- Temperature
- Dynamic deformation
- Position of deformation max
- Modal frequencies and shapes



Tower top view

Data analysis

- Temporal signals **dominated by the wave excitation** with a period about 10 s



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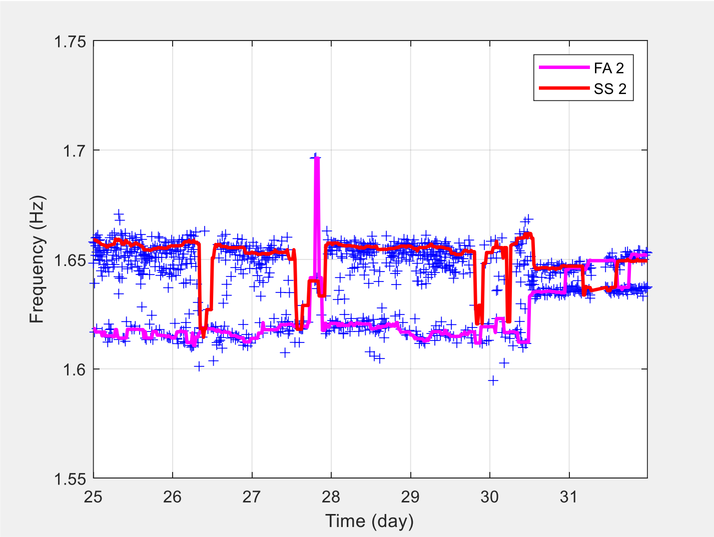
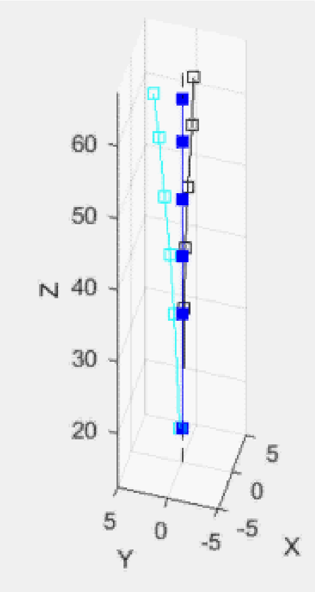
Wind speed: 20.7 m/s
Wind direction: 217.9°
Wave direction: 234.0°
Wave period: 10.0 s
Wave height: 5.9 m

- Correlation analysis

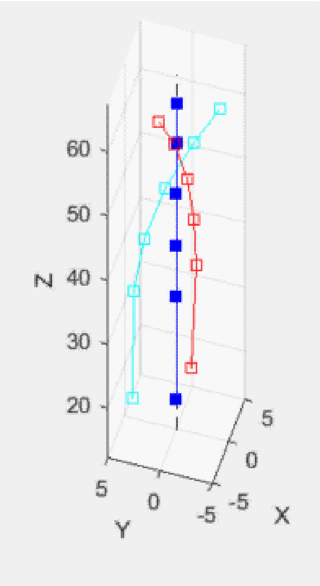
- Modal frequencies and shapes from Operational Modal Analysis techniques

- Mode tracking





$f_0 = 0.69$ / 0.69 Hz



$f_0 = 1.62$ / 1.65 Hz

Software and model description

OPENFAST NREL

Ansys

Fully coupled time domain analysis :

- Blades : Beam element theory
- RNA : rigid body
- Rosco controller tuned for floating wind
- Tower : beam element theory
- Floater & hydrodynamic : rigid body + LPT
- Mooring : lumped-mass (point-mass and rigid-body objects)

Modal analysis (Offshore ACT Extension):

- Blades : Equivalent beam element theory
- RNA : rigid body
- Tower : plate theory
- Floater & hydrodynamic : flexible body
- Mooring : lumped-mass

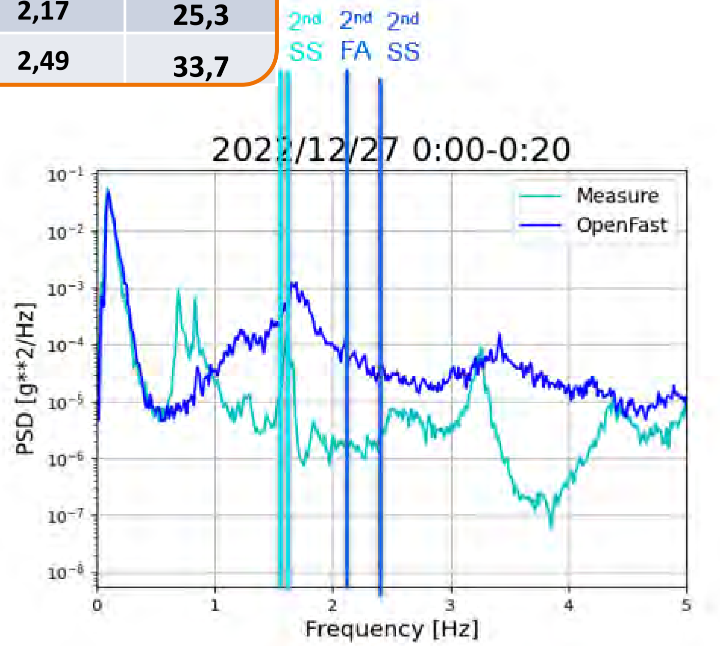
A common pitfall in fully coupled simulation of FOWT

To simplify the floater design, substructure may be modelled as a **rigid body**

Recommended practices as in DNVGL-RP-0286 **does not provide clear information** of the applicability of this hypothesis.

Aero-hydro-servo-elastic **simulation tools are not adapted** yet to consider the hydro-elastic coupling

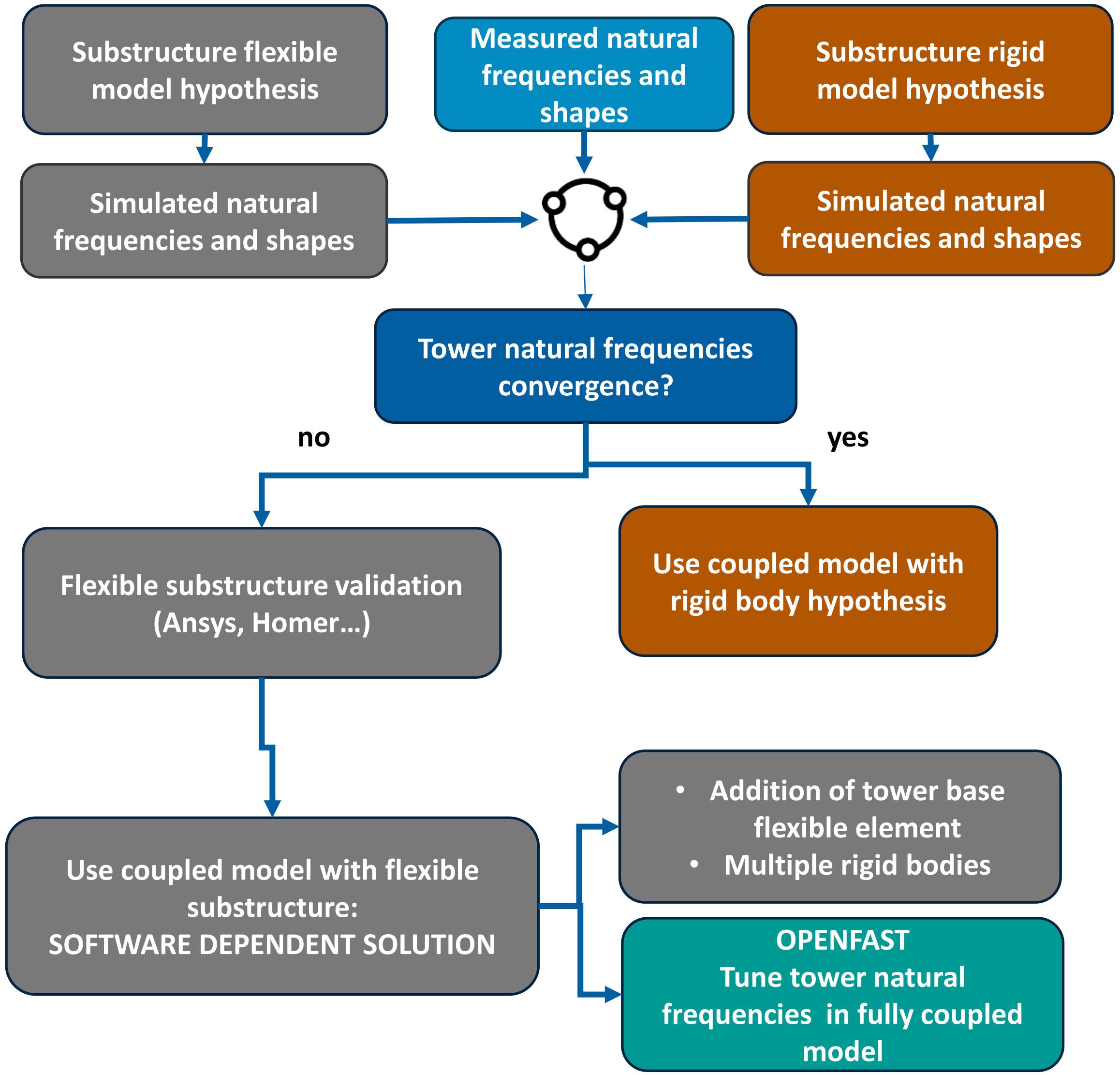
NUM	MODE	MEASURE (Hz)	OPENFAST (Hz)	ε (%)
1	Surge	0,008	0,0083	3,6
2	Sway	0,008	0,0083	3,6
3	Heave	0,036	0,037	2,7
4	Roll	0,042	0,0411	2,2
5	Pitch	0,042	0,0411	2,1
6	Yaw	0,161	0,15	7,3
1	Tower FA	0,69	0,8	13,75
2	Tower SS	0,69	0,93	25,8
3	Tower FA	1,62	2,17	25,3
4	Tower SS	1,65	2,49	33,7



Proposed methodology

Due to the fuzziness of the guidelines to cover this topic, we proposed the following **engineering method** based on:

- A specialized offshore structural modal analysis tool (Ansys, Homer)
- An aero-hydro-servo-elastic simulation tool
- An optimization routine
- Verification of simulated tower frequencies (OpenFast linearization)



Tower modes sensitivity

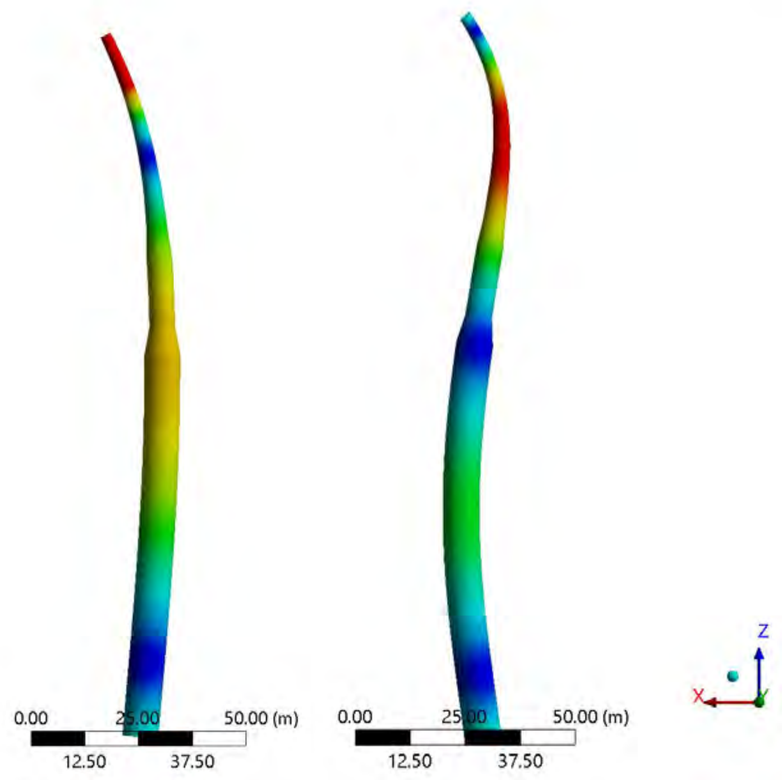
FOWT's are sensible to specific **physical phenomena,** which have effects on the dynamic simulations:

Added mass : YES

Floater : RIGID

Blades : POINT MASS

	Measured [Hz]	ANSYS [Hz]	HOMER [Hz]	difference Ansys-measure [%]
Tower mode (ss)	0.690	0.937	0.960	26%
Tower mode (fa)	0.690	1.001	0.984	31%



COUPLED MODE 1 **COUPLED MODE 2**

Tower modes sensitivity

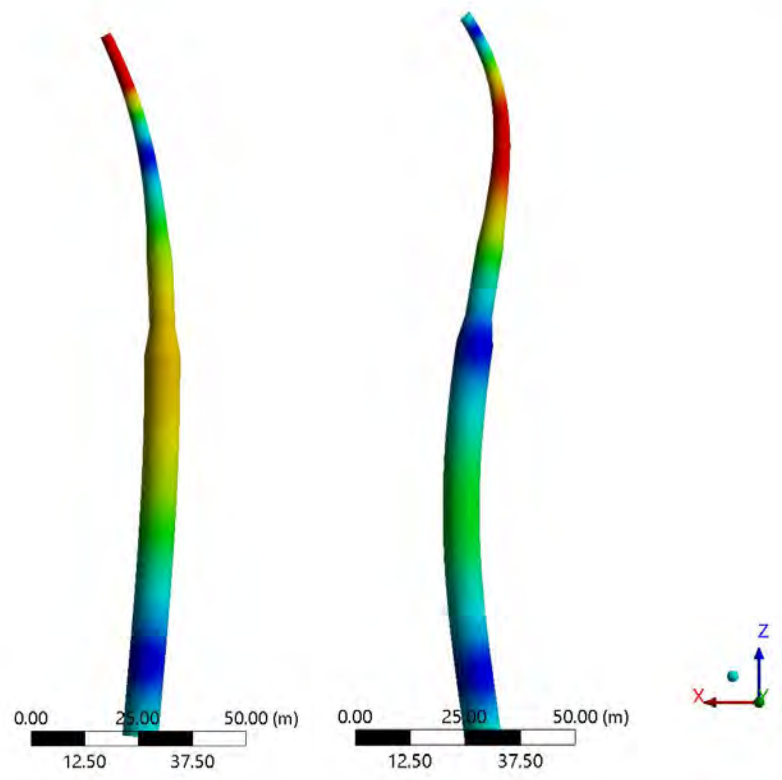
FOWT's are sensible to specific **physical phenomena,** which have effects on the dynamic simulations:

Added mass : **YES**

Floater : **FLEXIBLE**

Blades : **POINT MASS**

	Measured [Hz]	ANSYS [Hz]	HOMER [Hz]	difference Ansys-measure [%]
Tower mode (ss)	0.690	0.657	0.659	5%
Tower mode (fa)	0.690	0.665	0.663	3.7%



COUPLED MODE 1

COUPLED MODE 2

Tower modes sensitivity

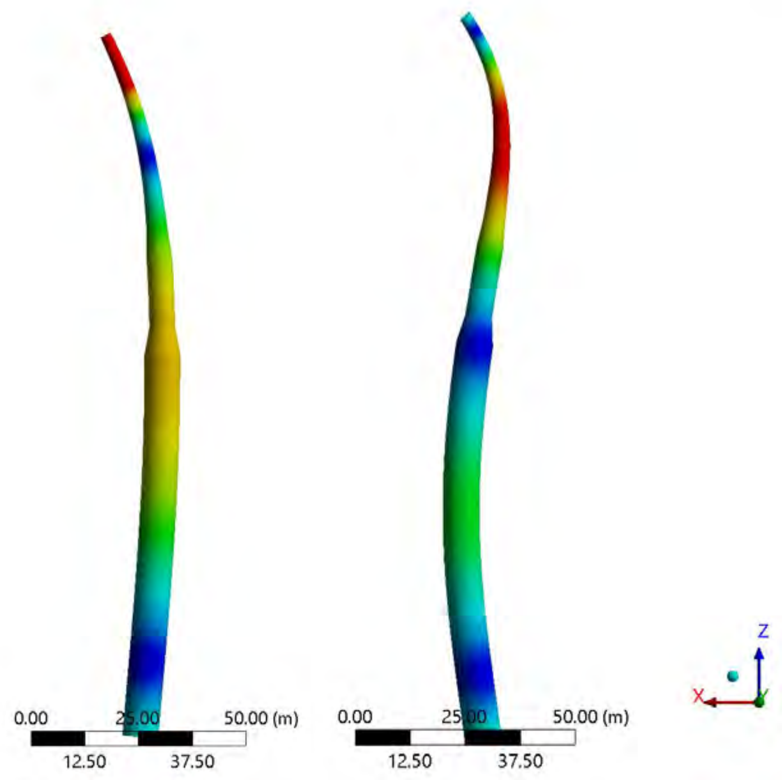
FOWT's are sensible to specific **physical phenomena,** which have effects on the dynamic simulations:

Added mass : **YES**

Floater : **FLEXIBLE**

Blades : **FLEXIBLE**

	Measured [Hz]	ANSYS [Hz]	HOMER [Hz]	difference Ansys-measure [%]
Tower mode (ss)	0.690	0.726	0.706	4.9%
Tower mode (fa)	0.690	0.726	0.721	4.9%



COUPLED MODE 1 **COUPLED MODE 2**

Parametric optimization : SimuOptuna

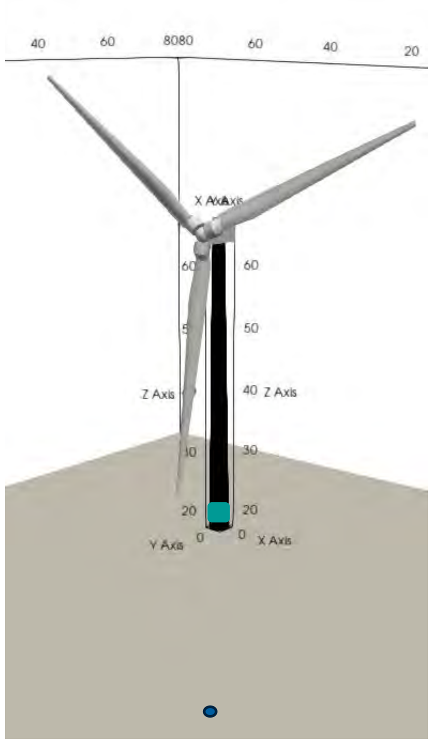
The use of optimization routines for **modal frequencies tunning**.

SimuOptuna is an optimization package developed by FEM during the project and designed to perform parametric optimizations of model inside a simulator software tool.

Two approaches were tested:

1. **Tower base modification:**

- Modification of the first element of the tower (connection with transition piece)
- Optimization of the **length and stiffness** of this element
- **Nonphysical coherence** of the tuned length and stiffness



2. **Tower Adjustment Factors :**

- FAStTunr1 and 2 : Tuning of the global tower stiffness for fore-aft modes
- SSStTunr1 and 2 : Tuning of the global tower stiffness for side-to-side modes

Parametric optimization : Tower Adjustment Factors

<u>Optimization configuration:</u>

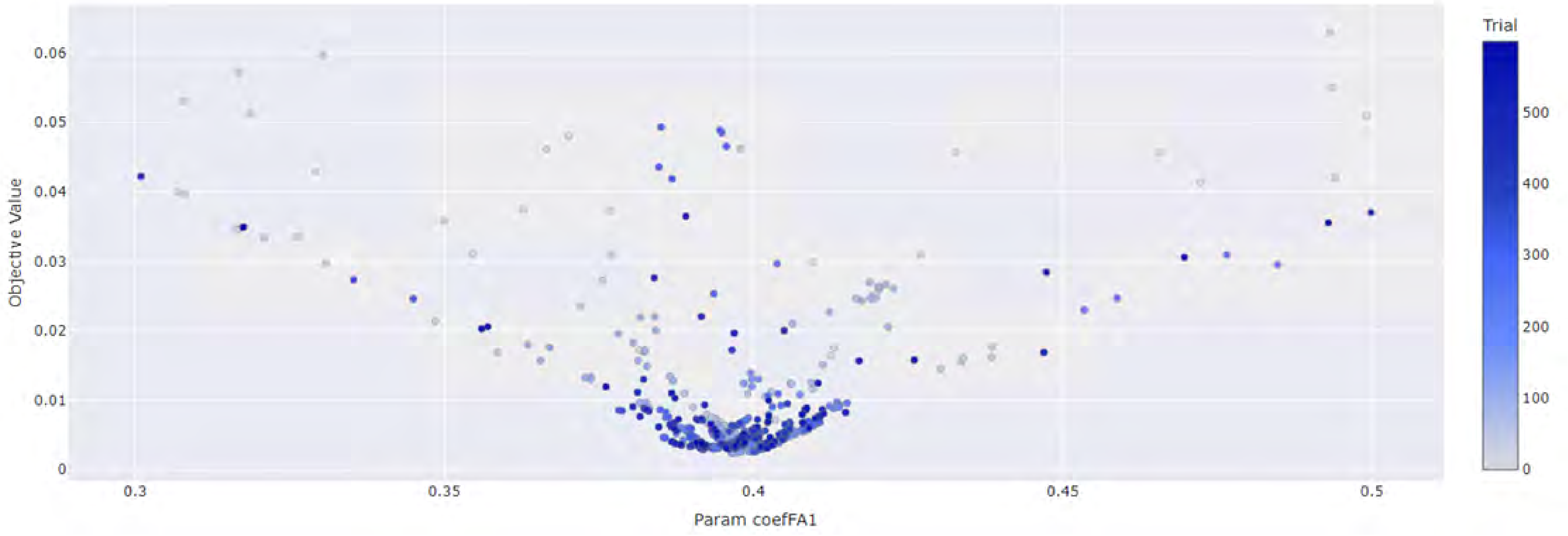
- Sampler : TPE
- Number of trials : 600
- Loss function : mean squared error

<u>After xx iterations</u>:

FAStTunr1 = 0.3968

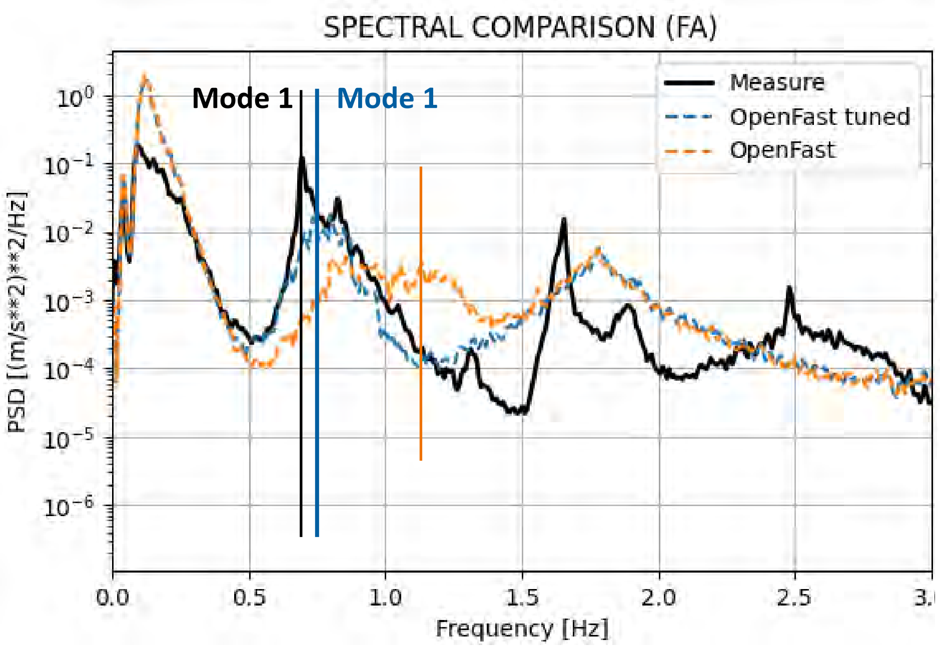
SSStTunr1 = 0.4219

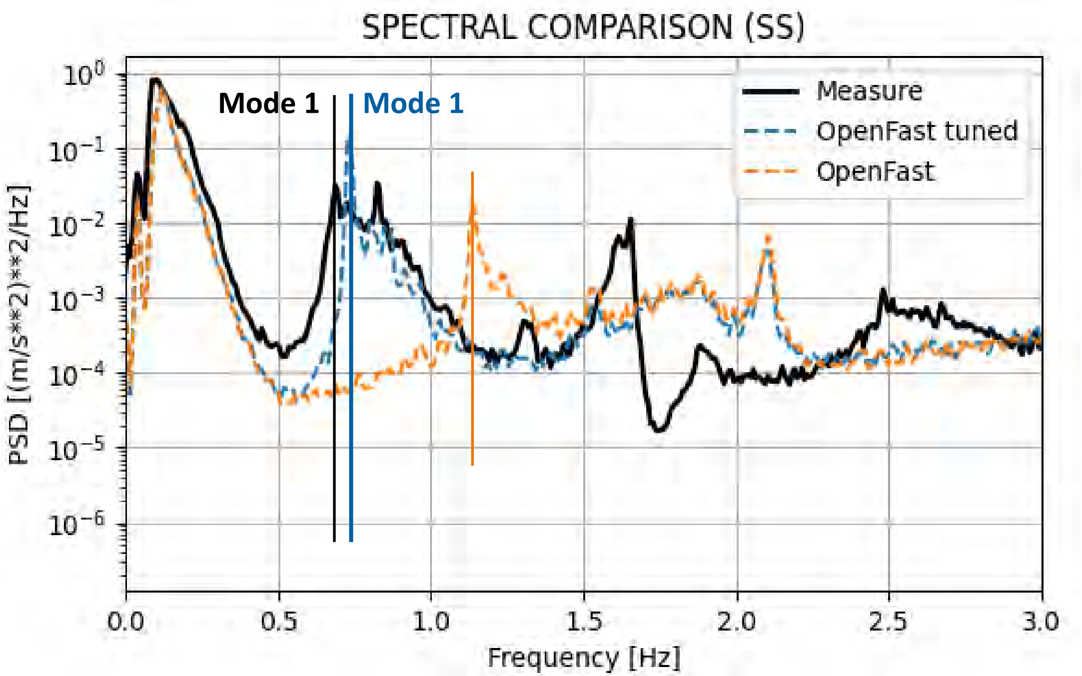
Very small coefficients (significant tower stiffness reduction)

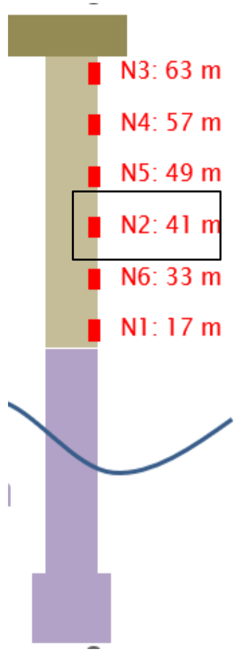


Validation

Acceleration spectra of node 2 FA and SS directions.

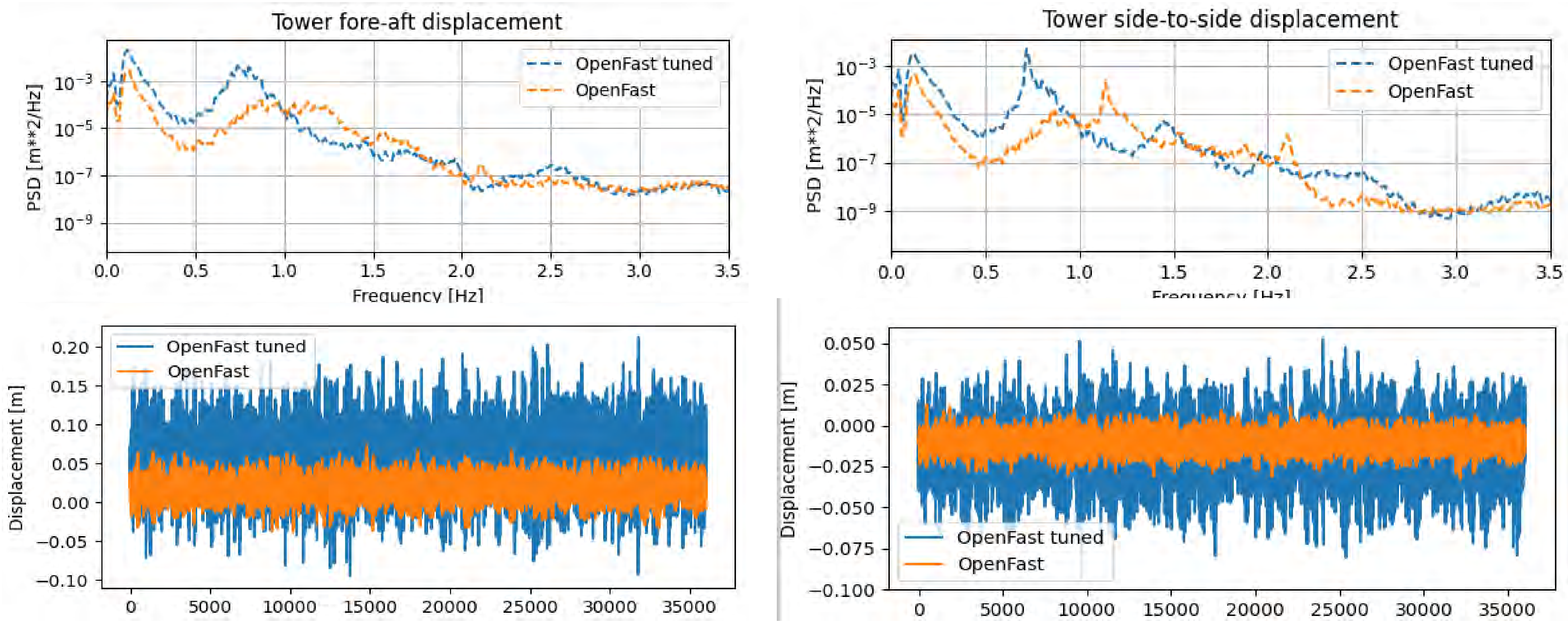






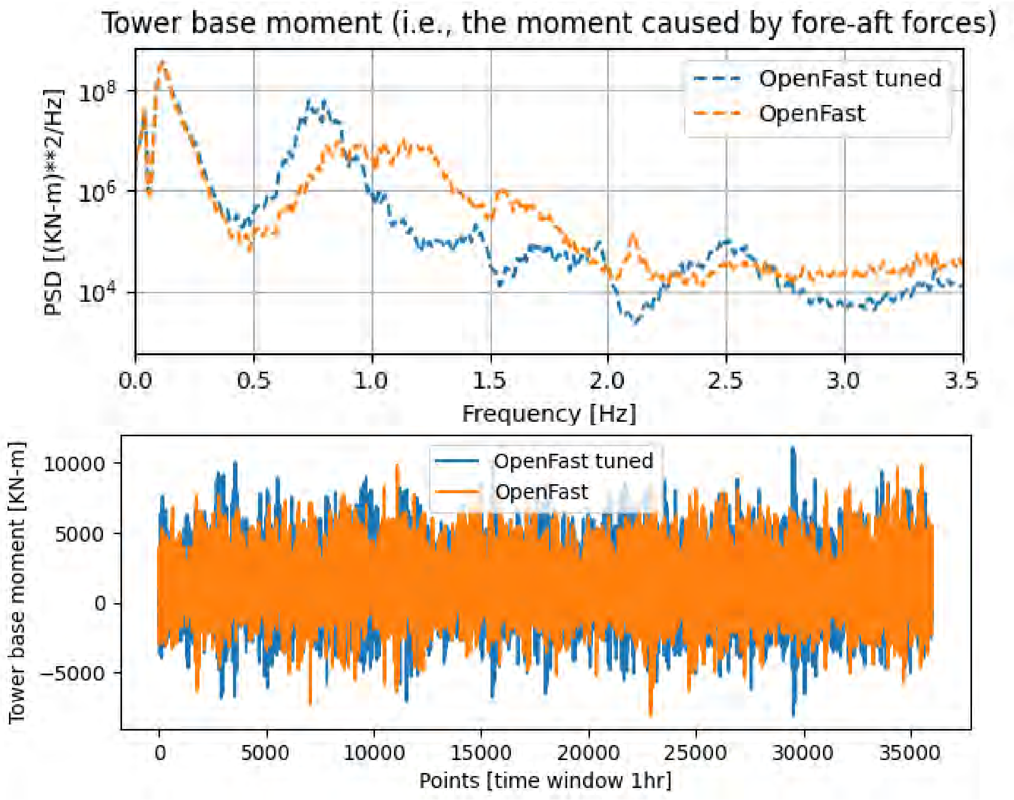
Results

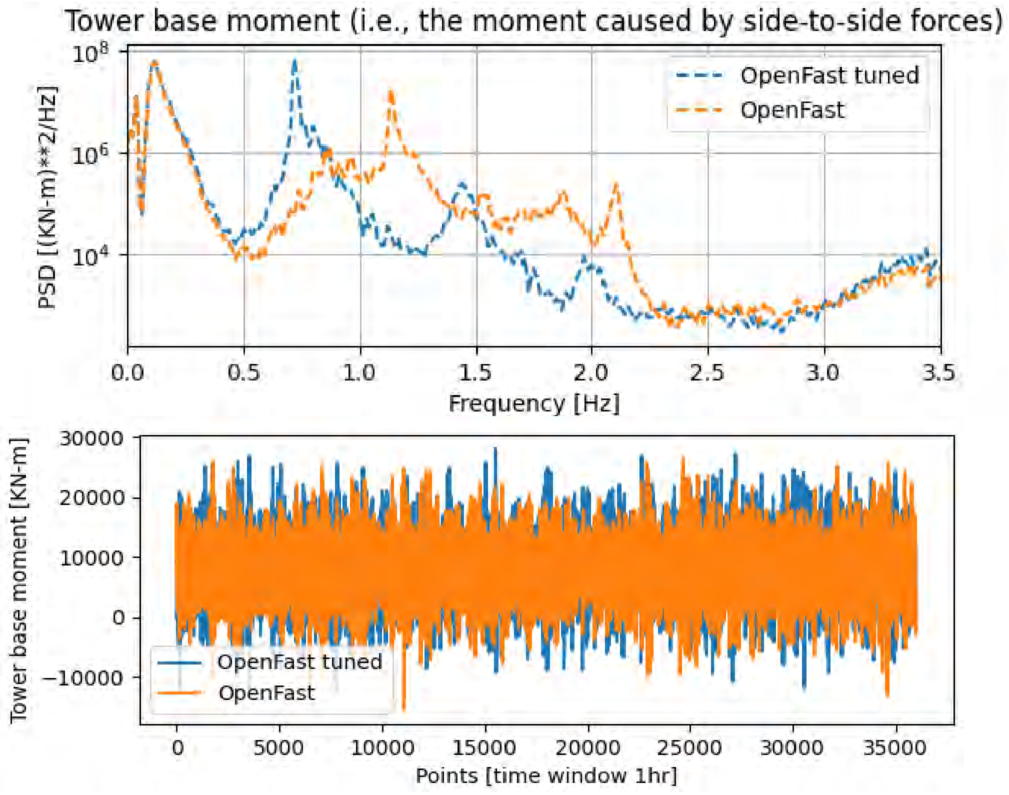
Tower top displacements in FA and SS directions.



Results

Tower base bending moments in the FA and SS directions.





For this type of structure, beam stiffness does not impact on the tower base bending moment)

Conclusions

- There is a consensus of the substructure rigid body hypothesis limitations in recommended practices, but no clear information of how to address it.
- The aero-hydro-servo-elastic simulation tool are not adapted yet to consider the hydro-elastic coupling
- Different approaches are proposed in literature to overcome this problem (software dependent)
- This proposed methodology may help during the design phase to determine the hypothesis viability and using state of the art of optimization routines, to overcome the measure-model discrepancies.