Dynamic modelling of HiveWind floating wind substructure in OpenFAST

Roger Bergua[†], Iñaki Zabala[*], Alvaro Gomez[*], Lu Wang[†], Oier Peña[*], Jason Jonkman[†], Jorge Peña[*]

[†]National Renewable Energy Laboratory, Golden, CO, USA
[*]SENER Ingeniería y Sistemas, S.A., Getxo, Spain

NAWEA/WindTech 2024
RUTGERS–NEW BRUNSWICK

Dynamic modelling of HiveWind floating wind substructure in OpenFAST

SUMMARY

01
Rationale

02
Model description

03
Results

04
Summary

Funded by the European Union

Plan de Recuperación, Transformación y Resiliencia

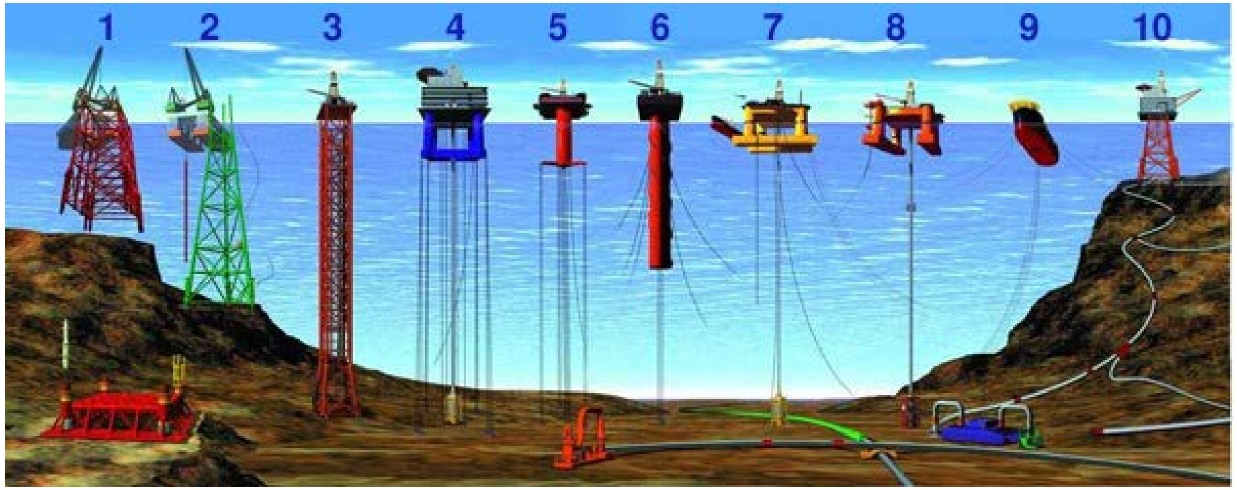
GOBIERNO DE ESPAÑA
MINISTERIO DE INDUSTRIA Y TURISMO

Development done within DECIMAP project

01 Rationale for this assessment

Speaker
The development of innovative designs for floating wind structures, although based on their previous experience, is moving beyond the conventional oil and gas substructures that initially shaped the floater designs.

From offshore oil & gas to floating wind.



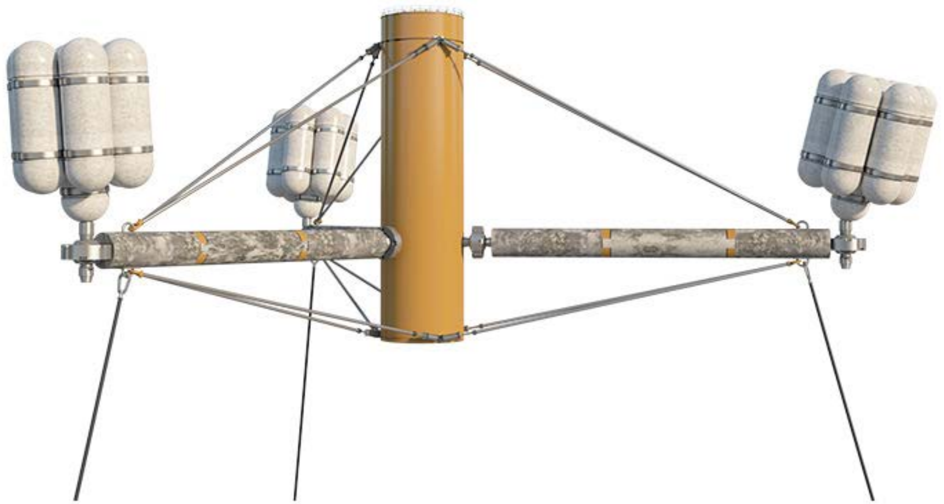
Speaker
The success in the first generation of floating substructures has demonstrated the technical feasibility of floating offshore wind.

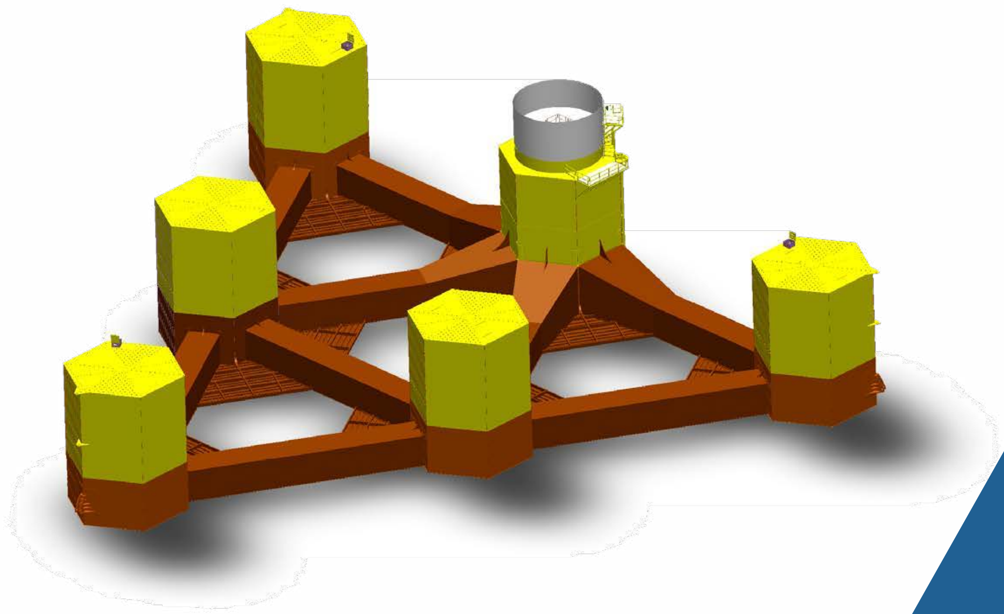
First generation floating wind.

01 Rationale for this assessment

Speaker
After floating offshore wind has demonstrated its technical feasibility, the second generation of new substructure designs is focused on achieving economic viability. This combines an increase in wind turbine capacity and dimensions with an optimization of materials and manufacturing costs. Both factors result in the inherent flexibility of the substructure becoming more and more pronounced.

The next generation.

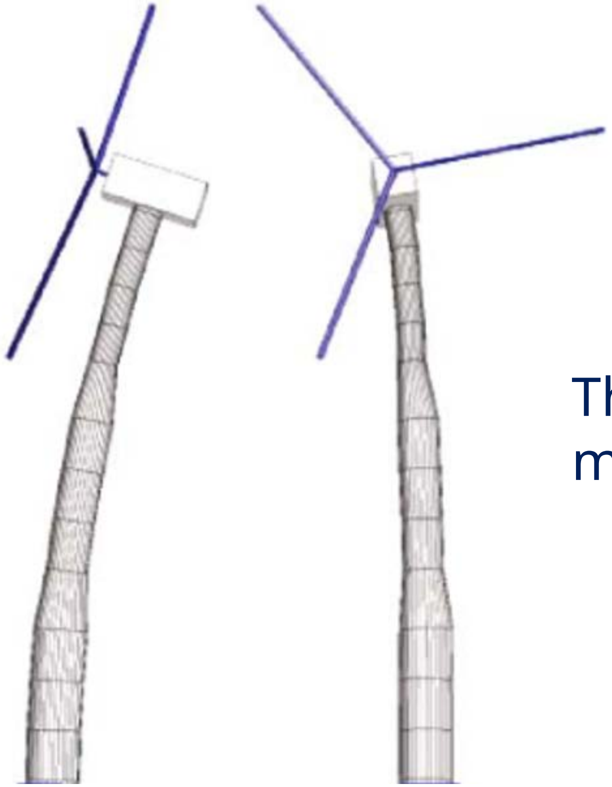




01 Rationale for this assessment

Load calculation: current situation.

Speaker
In order to make a proper design of these structures, it is essential to obtain their loads and dynamic results in multiple simulations. Up until recently, time domain-focused design load case (DLC) analysis using aero-hydro-servo-elastic simulations of floating wind turbines involved modelling of rotor blades, drive train, tower flexibility, and mooring dynamics, but the substructure is considered as a rigid body. Due to this limitation, it is not possible to analyze the loads within the substructure for a statistically reasonable number of cases, and additionally, it can lead to a distortion in the stresses obtained for elements coupled to the main substructure. The latter can be, for example, the transition piece with the tower, and the fairleads with the moorings. This situation, which may be tolerable for a wind turbine developer, is not suitable for a floater developer, as it does not allow the structural loads within a platform to be analyzed. (Image from https://www.researchgate.net/publication/274585664_Shake_Table_Testing_of_a_Utility-Scale_Wind_Turbine)

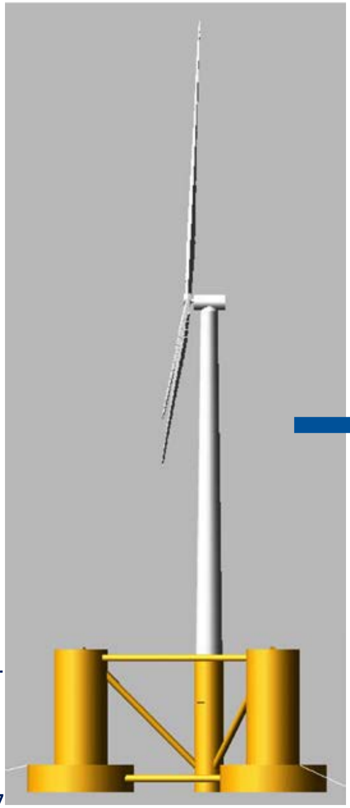


The turbine is modelled flexible

01 Rationale for this assessment

Load calculation: current situation.

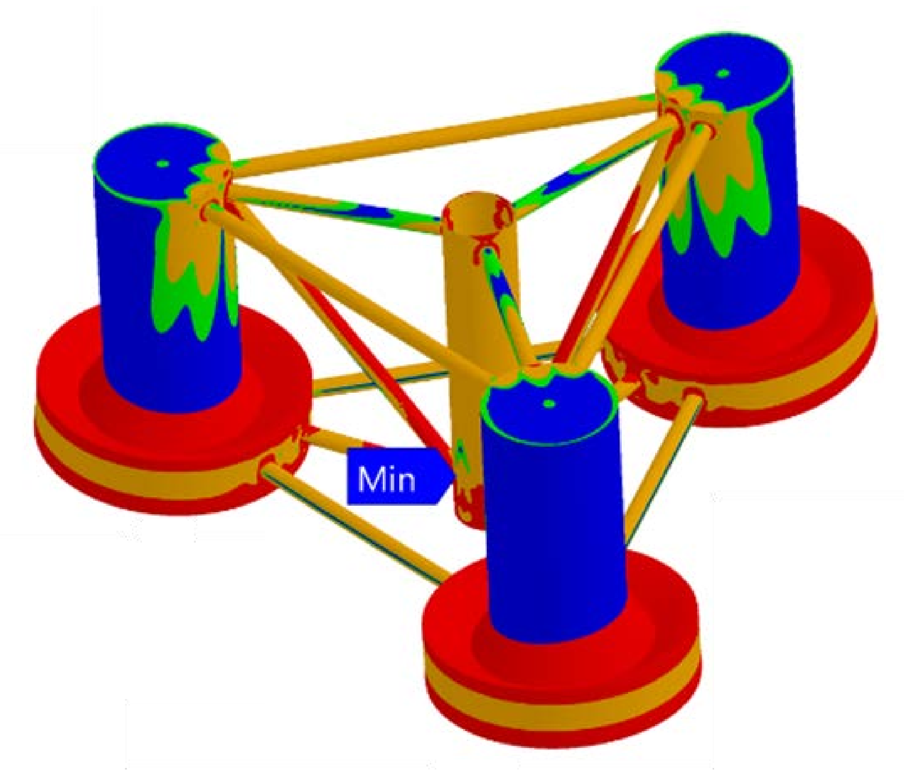
Speaker
In order to make a proper design of these structures, it is essential to obtain their loads and dynamic results in multiple simulations. Up until recently, time domain-focused design load case (DLC) analysis using aero-hydro-servo-elastic simulations of floating wind turbines involved modelling of rotor blades, drive train, tower flexibility, and mooring dynamics, but the substructure is considered as a rigid body. Due to this limitation, it is not possible to analyze the loads within the substructure for a statistically reasonable number of cases, and additionally, it can lead to a distortion in the stresses obtained for elements coupled to the main substructure. The latter can be, for example, the transition piece with the tower, and the fairleads with the moorings. This situation, which may be tolerable for a wind turbine developer, is not suitable for a floater developer, as it does not allow the structural loads within a platform to be analyzed.
(Image from https://www.researchgate.net/publication/274585664_Shake_Table_Testing_of_a_Utility-Scale_Wind_Turbine)

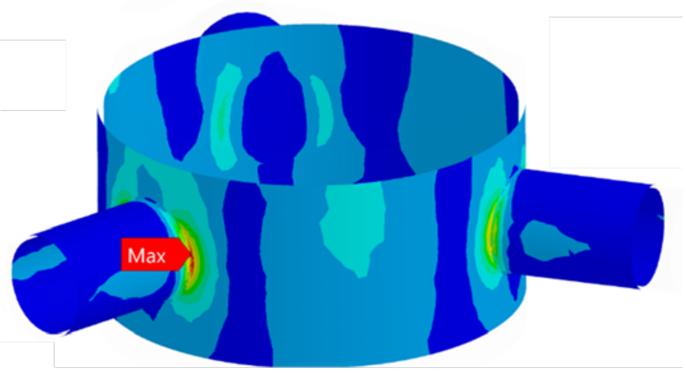


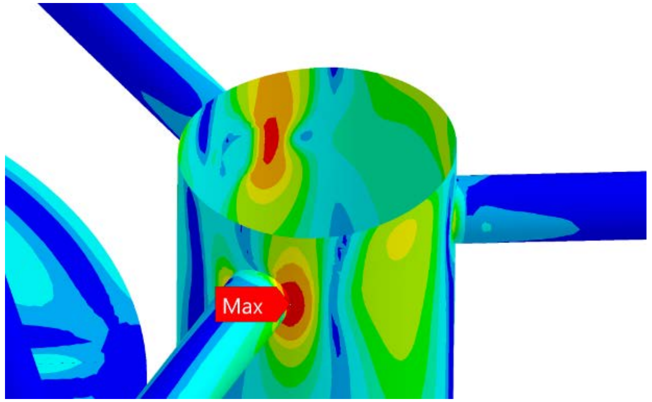
But the platform is modelled as a rigid body

Speaker
Software developers are making efforts to address this limitation. For example, there are more refined solvers available that couple advanced FEM and hydrodynamic analysis, in time domain simulations. Unfortunately, these solutions are expensive and computationally intensive, therefore can only be used in a limited set of cases. (Images from https://Fenix.tecnico.ulisboa.pt/downloadFile/1970719973966791/ExtendedAbstract_75925_DIASDiogo.pdf)

Load calculation: FEM.







01 Rationale for this assessment

Speaker
If it would be possible, another approach would be to make available a solver that combines an optimized simplified modelling implementation of the structural response of the substructure, fed by a disaggregated analysis of the hydrodynamic loads. This allows the hundreds of thousands of simulation hours required by the regulations for substructure certification to be run in reasonable time with available computational resources. The result would be a global analysis of good statistical quality, which would allow a FEM solver to fine-tune the design through local analysis of the loads. (Image from https://www.mdpi.com/1996-1073/16/1/2#B71-energies-16-00002)

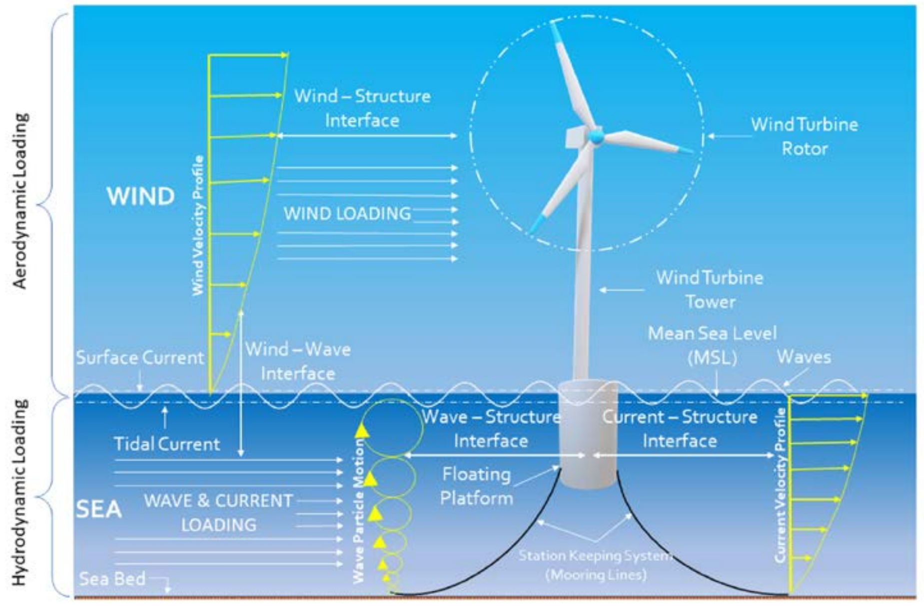
Load calculation: DLC.

Design situation	DLC	Wind condition	Waves	Wind and wave directionality	Sea currents	Water level	Other conditions	Type of analysis	Partial safety factor
1.x Power production	1.1	NTM $V_{in} < V_{hub} < V_{out}$ RNA	NSS $H_s = E[H_s \| V_{hub}]$	COD, UNI	NCM	MSL	For extrapolation of extreme loads on the RNA	U	N (1.25)
	1.2								
	1.3								
	1.4								
	1.5								
	1.6a								
	1.6b								

Design situation	DLC	Wind condition	Waves	Wind and wave directionality	Sea currents	Water level	Other conditions	Type of analysis	Partial safety factor
2.x Power production plus occurrence of fault	2.1	NTM $V_{in} < V_{hub} < V_{out}$	NSS $H_s = E[H_s \| V_{hub}]$	COD, UNI	NCM	MSL	Control system fault or loss of electrical network	U	N
	2.2								
	2.3								
	2.4								
3.x Start up	3.1								
	3.2								
	3.3								

Design situation	DLC	Wind condition	Waves	Wind and wave directionality	Sea currents	Water level	Other conditions	Type of analysis	Partial safety factor
4.x Normal shut down	4.1	NWP $V_{in} < V_{hub} < V_{out}$	NSS (or NWH) $H_s = E[H_s \| V_{hub}]$	COD, UNI	No currents	NWLR or ≥ MSL		F	*
	4.2								
5.x Emergency shut down	5.1								
6.x Parked (standing still or idling)	6.1a								
	6.1b								
	6.1c								
	6.2a								
	6.2b								
	6.3a								
	6.3b								
	6.4								

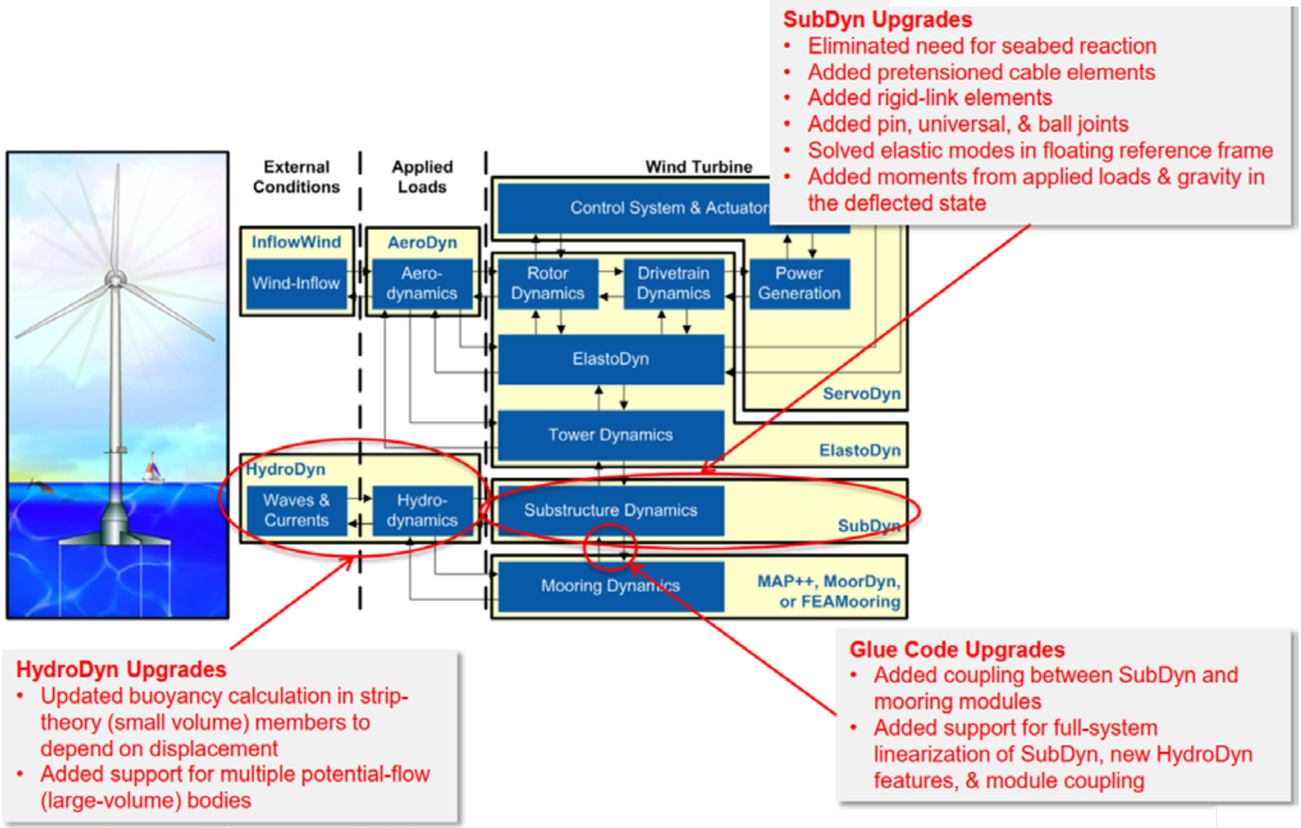
Design situation	DLC	Wind condition	Waves	Wind and wave directionality	Sea currents	Water level	Other conditions	Type of analysis	Partial safety factor
7.x Parked and fault conditions	7.1a	EWM Turb. wind model $V_{hub} = k_1 V_1$	ESS $H_s = k_2 H_{s1}$	MIS, MUL	ECM	NWLR		U	A
	7.1b	EWM Steady wind model $V(z_{hub}) = V_{e1}$	RWH $H = H_{red1}$	MIS, MUL	ECM	NWLR		U	A
	7.1c	RWM Steady wind model $V(z_{hub}) = V_{red1}$	EWH $H = H_1$	MIS, MUL	ECM	NWLR		U	A
	7.2	NTM $V_{hub} < 0.7\ V_1$	NSS Joint prob. distribution of H_s, T_p, V_{hub}	COD, MUL	No currents	NWLR or ≥ MSL		F	*
8.x Transport, assembly, maintenance and repair	8.1	To be stated by the manufacturer						U	T
	8.2a	EWM Turb. wind model $V_{hub} = k_1 V_1$	ESS $H_s = k_2 H_{s1}$	COD, UNI	ECM	NWLR		U	A
	8.2b	EWM Steady wind model $V_{hub} = V_{e1}$	RWH $H = H_{red1}$	COD, UNI	ECM	NWLR		U	A
	8.2c	RWM Steady wind model $V(z_{hub}) = V_{red1}$	EWH $H = H_1$	COD, UNI	ECM	NWLR		U	A
	8.3	NTM $V_{hub} < 0.7\ V_{ref}$	NSS Joint prob. distribution of H_s, T_p, V_{hub}	COD, MUL	No currents	NWLR or ≥ MSL	No grid during installation period	F	*



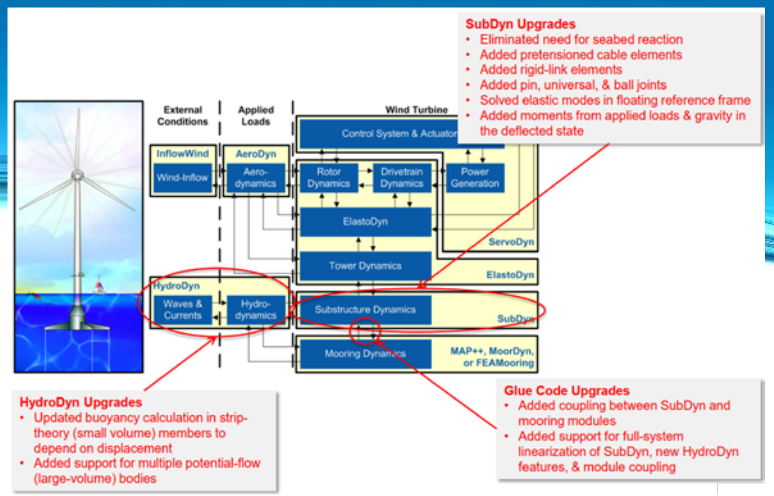
01 Rationale for this assessment

Speaker
Previous focus is possible: NREL has developed OpenFAST v4, which takes a leap forward by including a linear finite element model, a modal reduction of the dynamic system using the Craig-Bampton method, together with a static improvement method for the substructure. This allows to simplify the number of DOF of the FEM analysis of the platform, maintaining the fundamental response modes of the structure, with a proportionally low simulation time. In addition, OpenFAST includes a weakly non-linear hydrodynamic model, capable of assigning various hydrodynamic loads to each member of the structure separately.

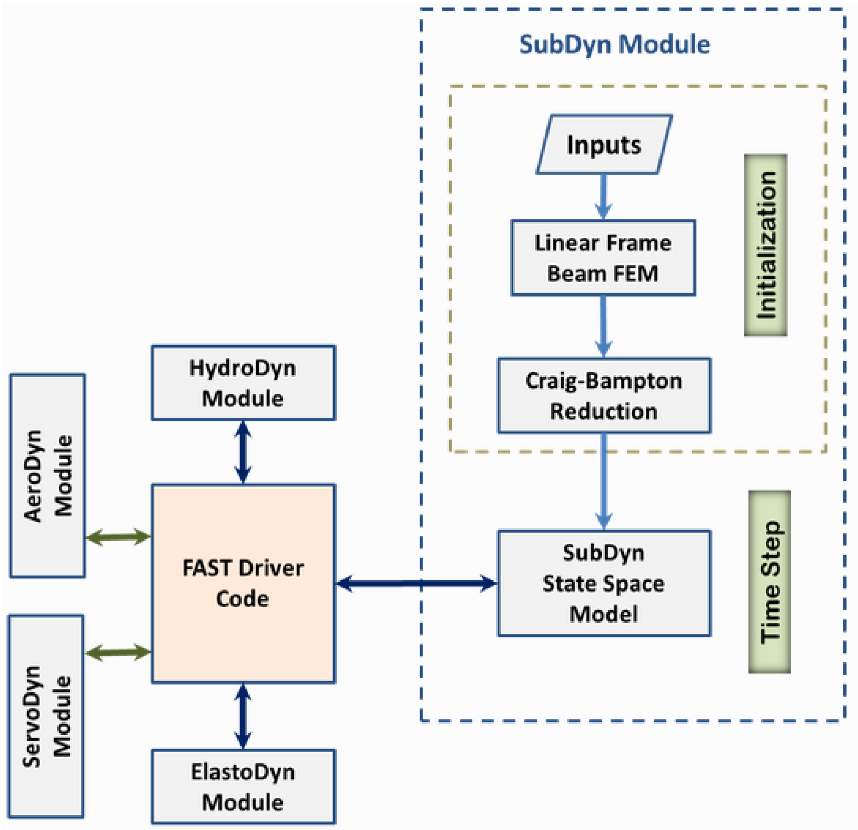
Load calculation: OpenFAST v4.



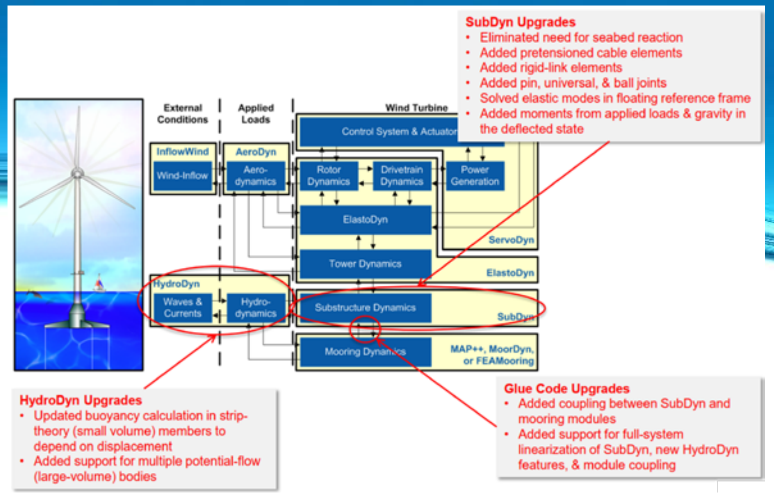
01 Rationale for this assessment



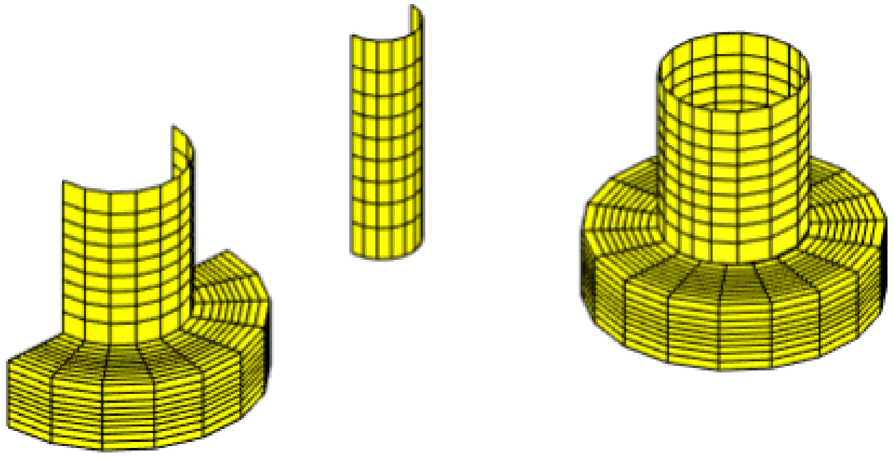
Load calculation: OpenFAST v4.



01 Rationale for this assessment

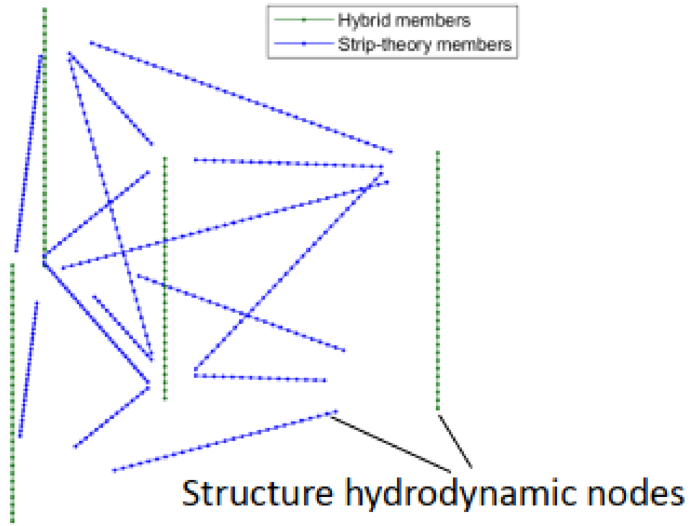


Load calculation: OpenFAST v4.



Potential-flow solution

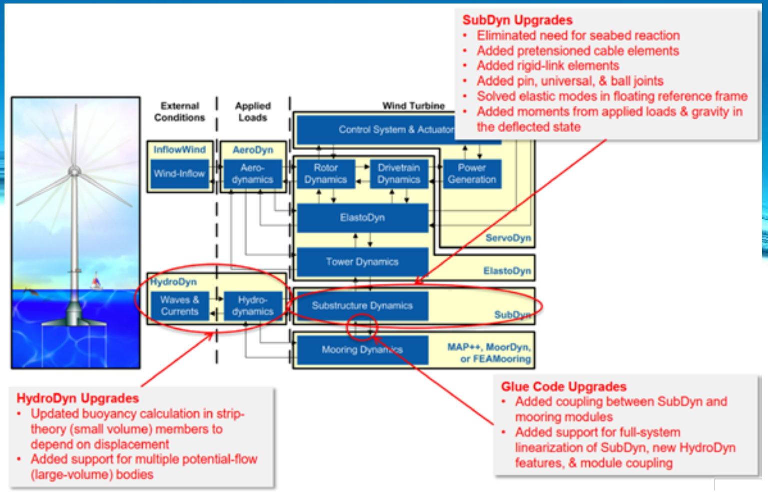
+

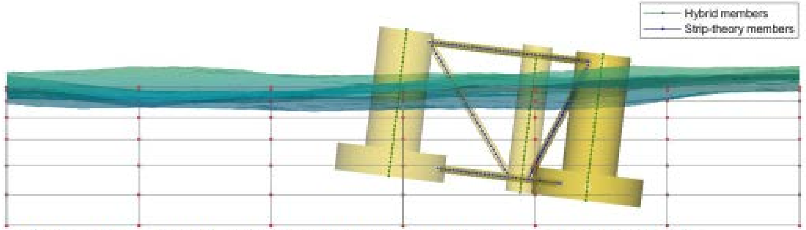


Strip-theory and hybrid members

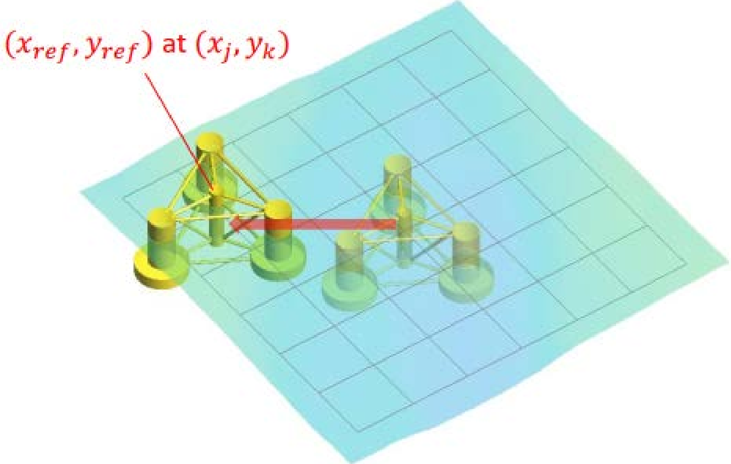
01 Rationale for this assessment

Load calculation: OpenFAST v4.



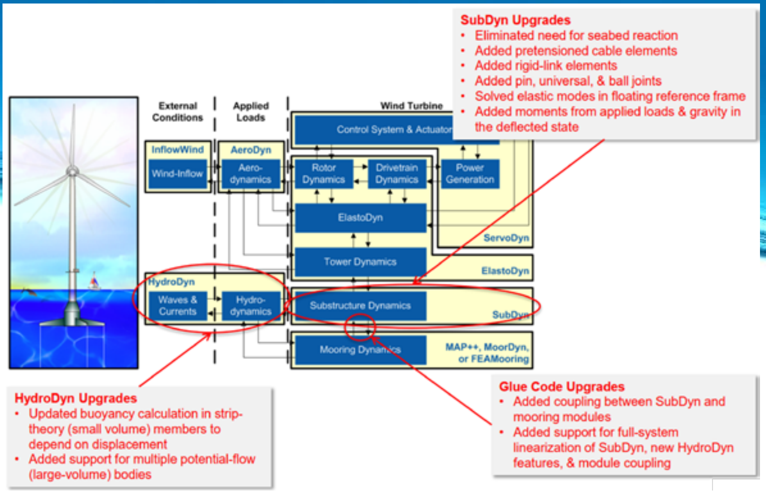


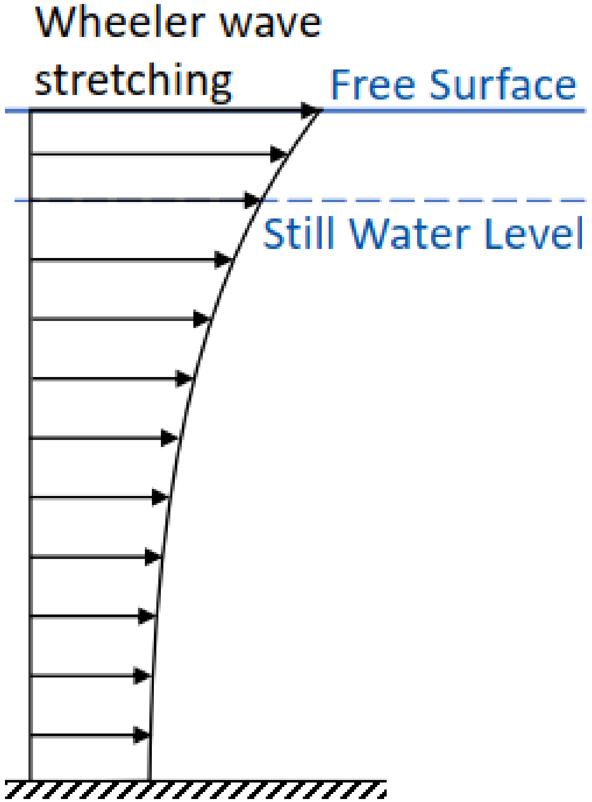
Strip theory: Perform interpolation to obtain wave kinematics at the displaced node positions.

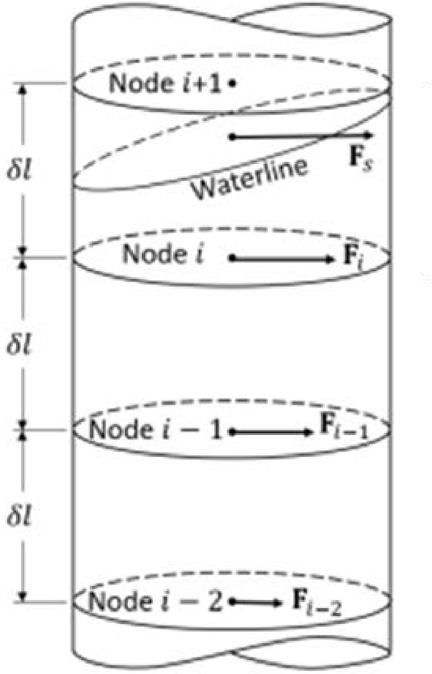


01 Rationale for this assessment

Load calculation: OpenFAST v4.



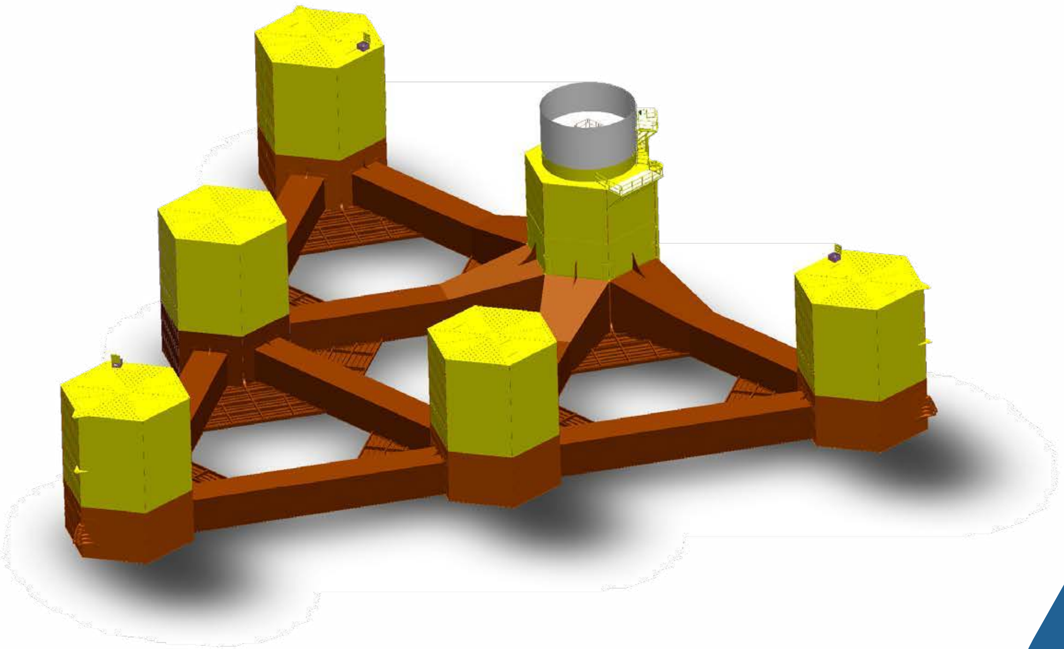




Elements of a surface-piercing member

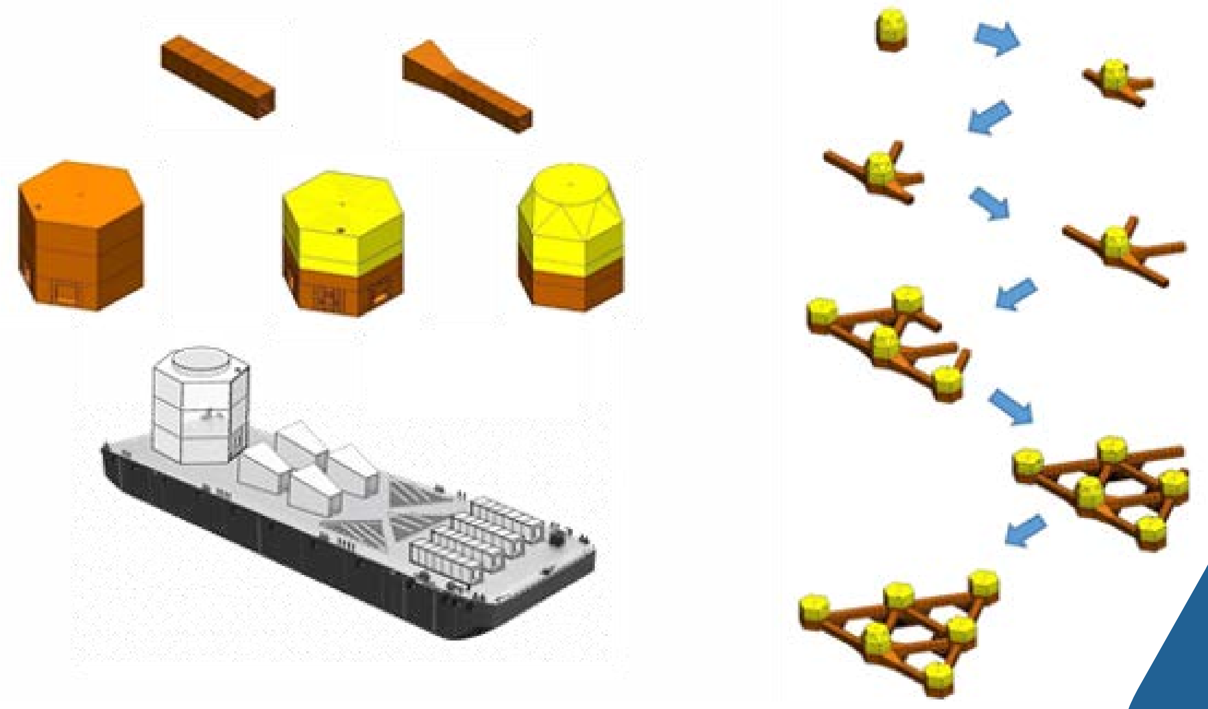
Speaker
With the support and collaboration of NREL, SENER has developed a distributed model, with local structural loads, of the HiveWind platform. This platform has an innovative design, with a reduced construction cost and manufacturing time, optimized to be a stable support for large turbines, and which will be tested at full scale.

NREL & SENER collaboration.



Speaker
With the support and collaboration of NREL, SENER has developed a distributed model, with local structural loads, of the HiveWind platform. This platform has an innovative design, with a reduced construction cost and manufacturing time, optimized to be a stable support for large turbines, and which will be tested at full scale.

NREL & SENER collaboration.



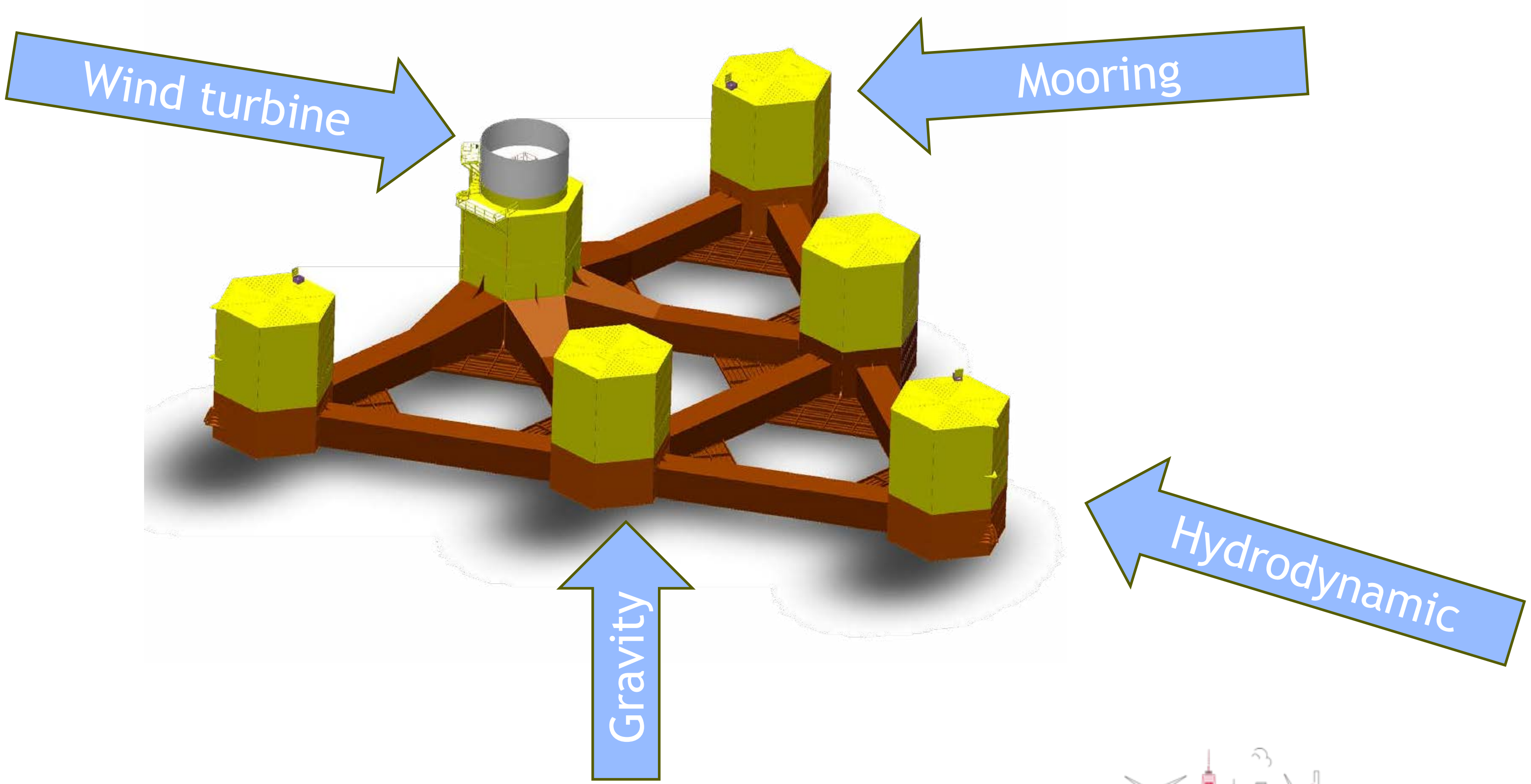
01 Rationale for this assessment

Speaker
With the support and collaboration of NREL, SENER has developed a distributed model, with local structural loads, of the HiveWind platform. This platform has an innovative design, with a reduced construction cost and manufacturing time, optimized to be a stable support for large turbines, and which will be tested at full scale.

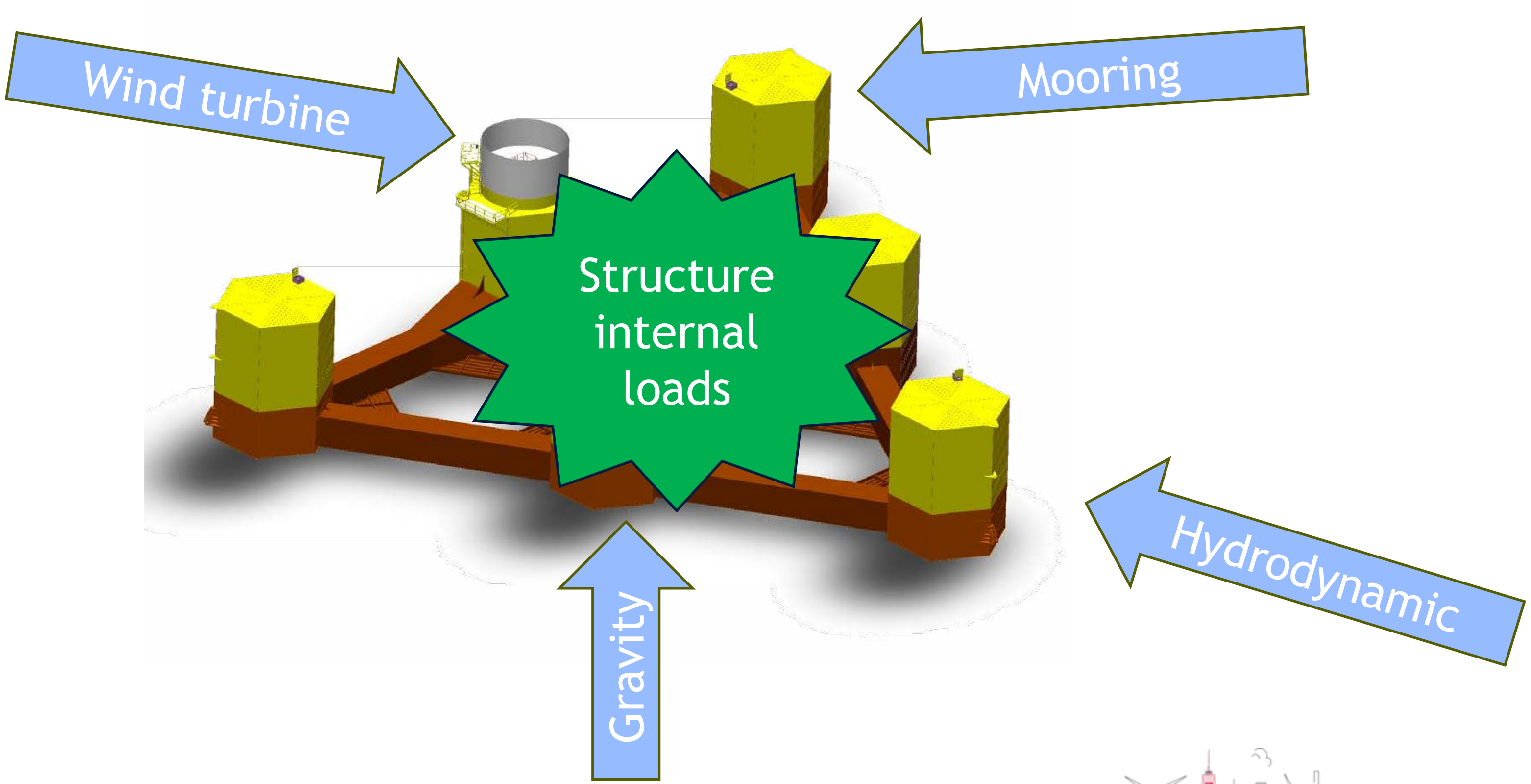
NREL & SENER collaboration.

02 Model description

Loads



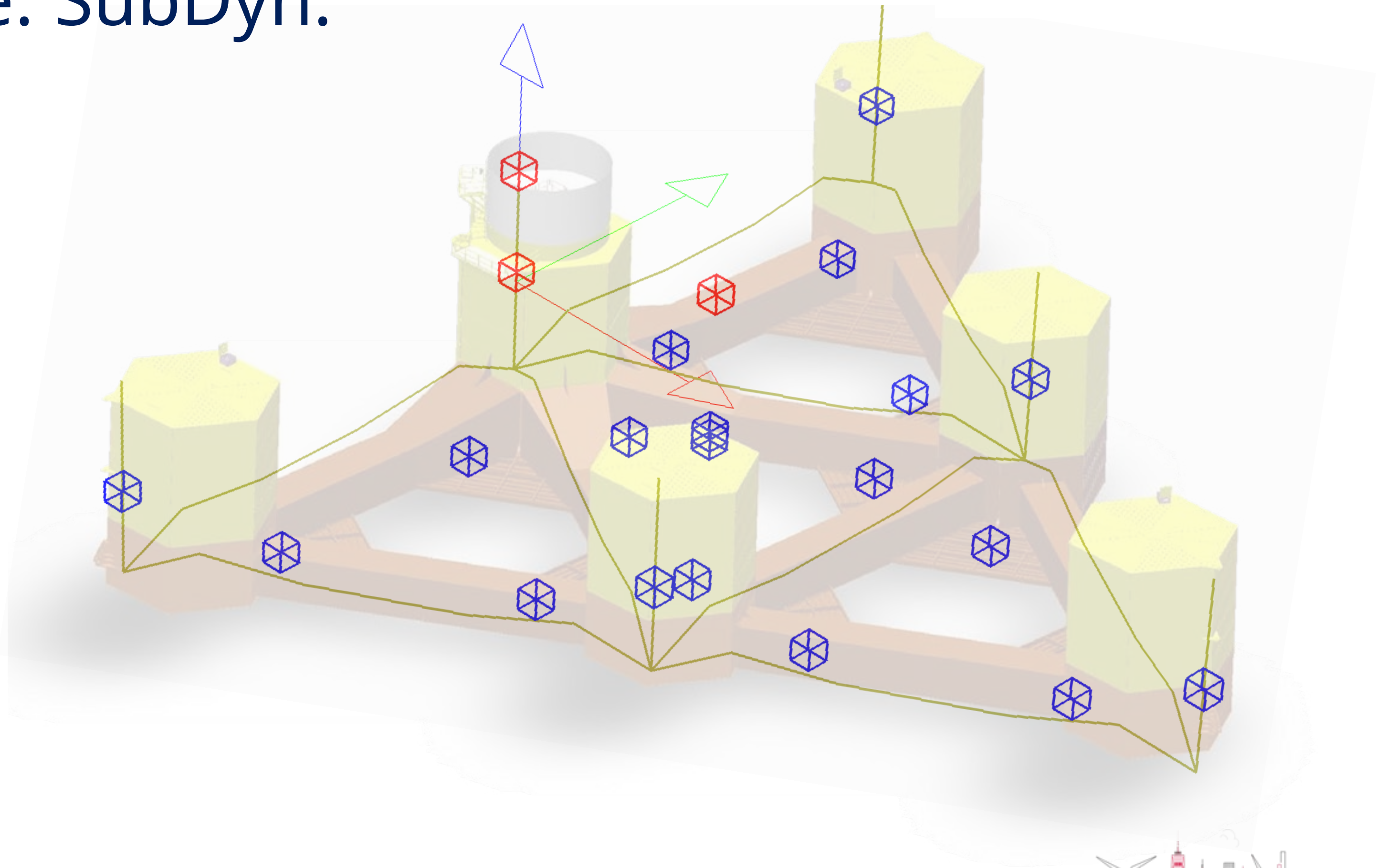
Loads


Wind turbine
Mooring
Structure internal loads
Hydrodynamic
Gravity

02 Model description

Speaker
The structural modelling of the floater is implemented in the OpenFAST SubDyn module, in the form of Timoshenko beams of circular section with a frustum shape. All the main structure parts are included, as columns, bracings, heave plates, ballast water and contingencies. To achieve the structural properties in each element that mimics the real properties of the HiveWind members, an adjustment has been made to the diameter, thickness, elasticity and density of the material used to define them.

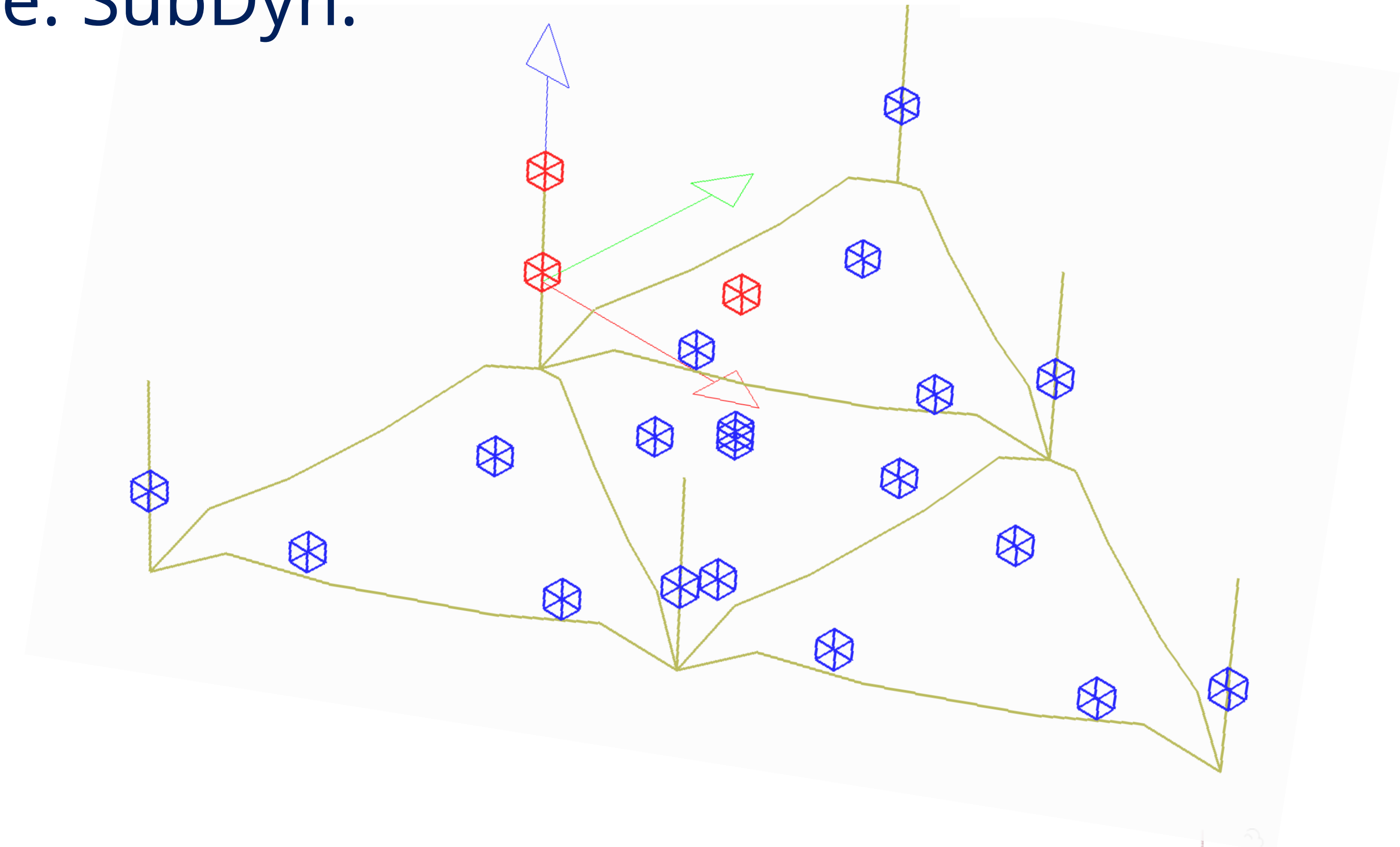
Structure: SubDyn.



02 Model description

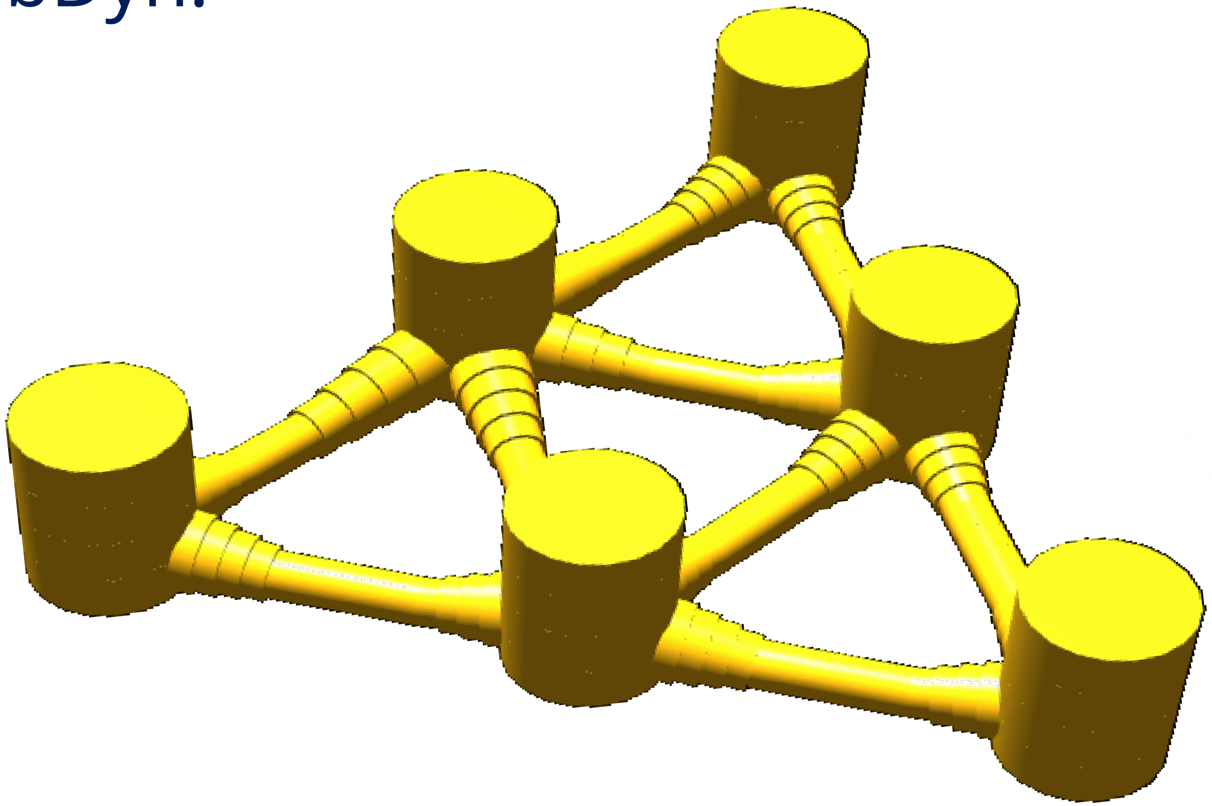
Speaker
The structural modelling of the floater is implemented in the OpenFAST SubDyn module, in the form of Timoshenko beams of circular section with a frustum shape. All the main structure parts are included, as columns, bracings, heave plates, ballast water and contingencies. To achieve the structural properties in each element that mimics the real properties of the HiveWind members, an adjustment has been made to the diameter, thickness, elasticity and density of the material used to define them.

Structure: SubDyn.



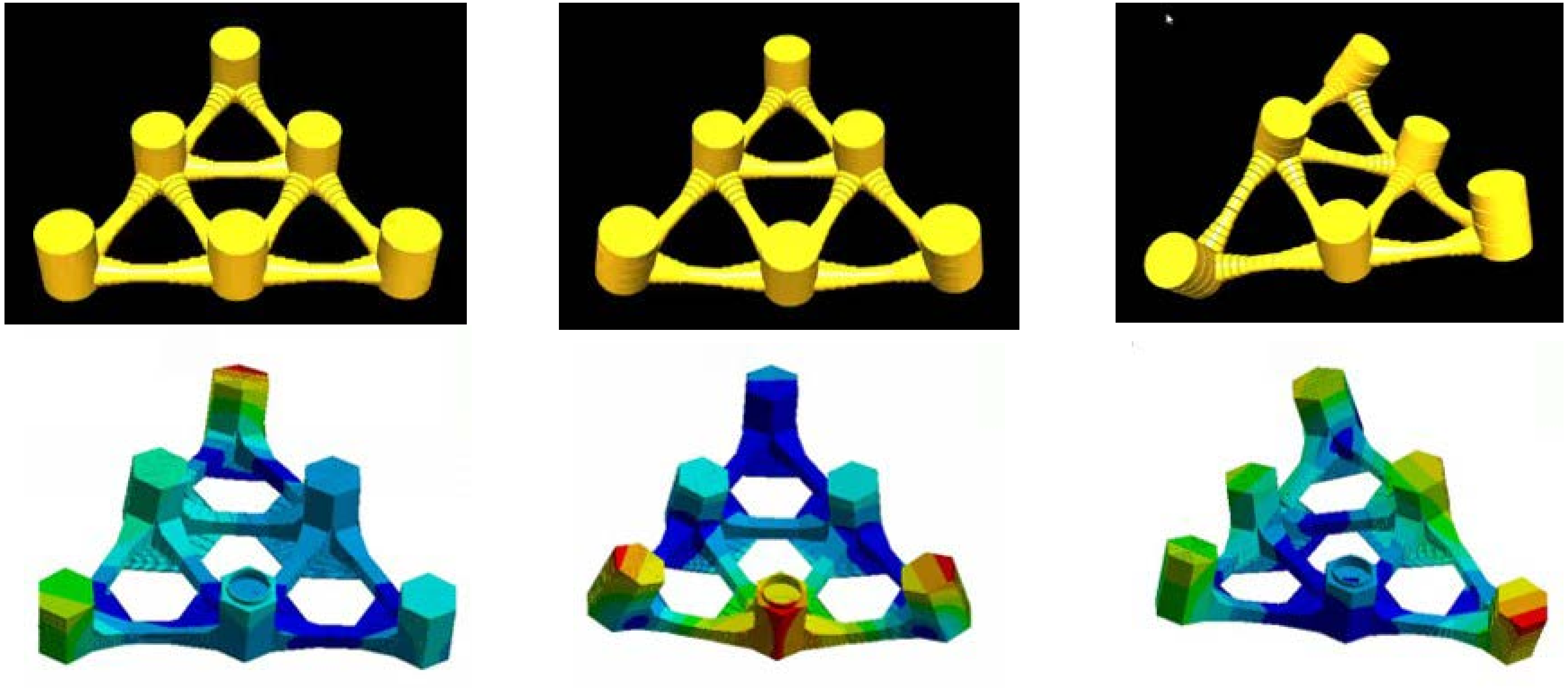
Speaker
The structural modelling of the floater is implemented in the OpenFAST SubDyn module, in the form of Timoshenko beams of circular section with a frustum shape. All the main structure parts are included, as columns, bracings, heave plates, ballast water and contingencies. To achieve the structural properties in each element that mimics the real properties of the HiveWind members, an adjustment has been made to the diameter, thickness, elasticity and density of the material used to define them.

Structure: SubDyn.



Speaker
With this definition, analyses of the platform’s first natural frequencies have been carried out on the dry platform. Here are shown the modes comparing OpenFAST and ANSYS.

Structure: SubDyn. Dry modes vs FEM.



Speaker
Comparing the results, SubDyn optimised model gets an error of 4 % or less in the bending modes with respect to the calculations carried out in ANSYS Mechanical.

Structure free-free boundary condition: SubDyn vs FEM. Verification.

			Model Error
Total mass		t	0.0%
CDG	X	m	-0.1%
	Y	m	0.0%
	Z	m	-0.2%
Ixx		t·m2	-0.1%
Iyy		t·m2	0.5%
Izz		t·m2	0.0%

Flexible Modes	Model Error
1	2.0%
2	3.8%
3	-4.4%
4	0.4%
5	1.9%

Speaker
The hydrodynamic modelling set by HydroDyn adopts a hybrid strip-theory model with a distributed potential flow model at each of the bracings and columns of the substructure. This is achieved because OpenFAST can handle multiple potential flow bodies. In this model, the strip theory elements circular frustum properties have been adjusted so that the hydrodynamic properties like buoyancy, hydrostatic stiffness, centre of gravity, and inertia matrix, are similar to those of the real device. On the other hand, the drag coefficients of the Morison elements have been calibrated on the basis of experimental tests carried out in the IHCantabria laboratory. Wave stretching is used to capture the kinematics of the wave up to the instantaneous free surface. MacCamy-Fuchs inertial load correction has been applied to the vertical elements (the columns). Another factor that increases the accuracy of OpenFAST is that it calculates all the hydrodynamics considering the instantaneous position of the body.
To apply the rest of the hydrodynamic coefficients to the platform, the incident, radiation and diffraction potentials have been analysed in each of the thousands of panels of the submerged mesh, obtaining the contribution of each of them for the added mass, radiation and diffraction. To obtain this information with this level of breakdown by potential and by grid cell, the Capytaine solver has been used. This information has been transferred to each component of the structure from each grid cell using a simple to use automated process, obtaining a potential-flow body for each independent substructure component.

Hydrodynamics: HydroDyn Rigid vs distributed.

Physics		Potential flow theory (linear)	Strip theory
Damping	Viscous	None	Morison
	Linear radiation	Frequency dependant radiation (x1)	None
Wave excitation and inertia	Second order	Frequency dependant (x1)	None
	Froude-Krylov	Frequency dependant (x1)	Wheeler wave stretching
	Diffraction scattering	Frequency dependant (x1)	None
	Added mass	Frequency dependant (x1)	Constant added mass coefficient
Hydrostatic restoring		Linear (x1)	Distributed
Buoyancy		Submerged volume	Distributed
Inertia		Centre of gravity, mass and inertia (x1)	Distributed

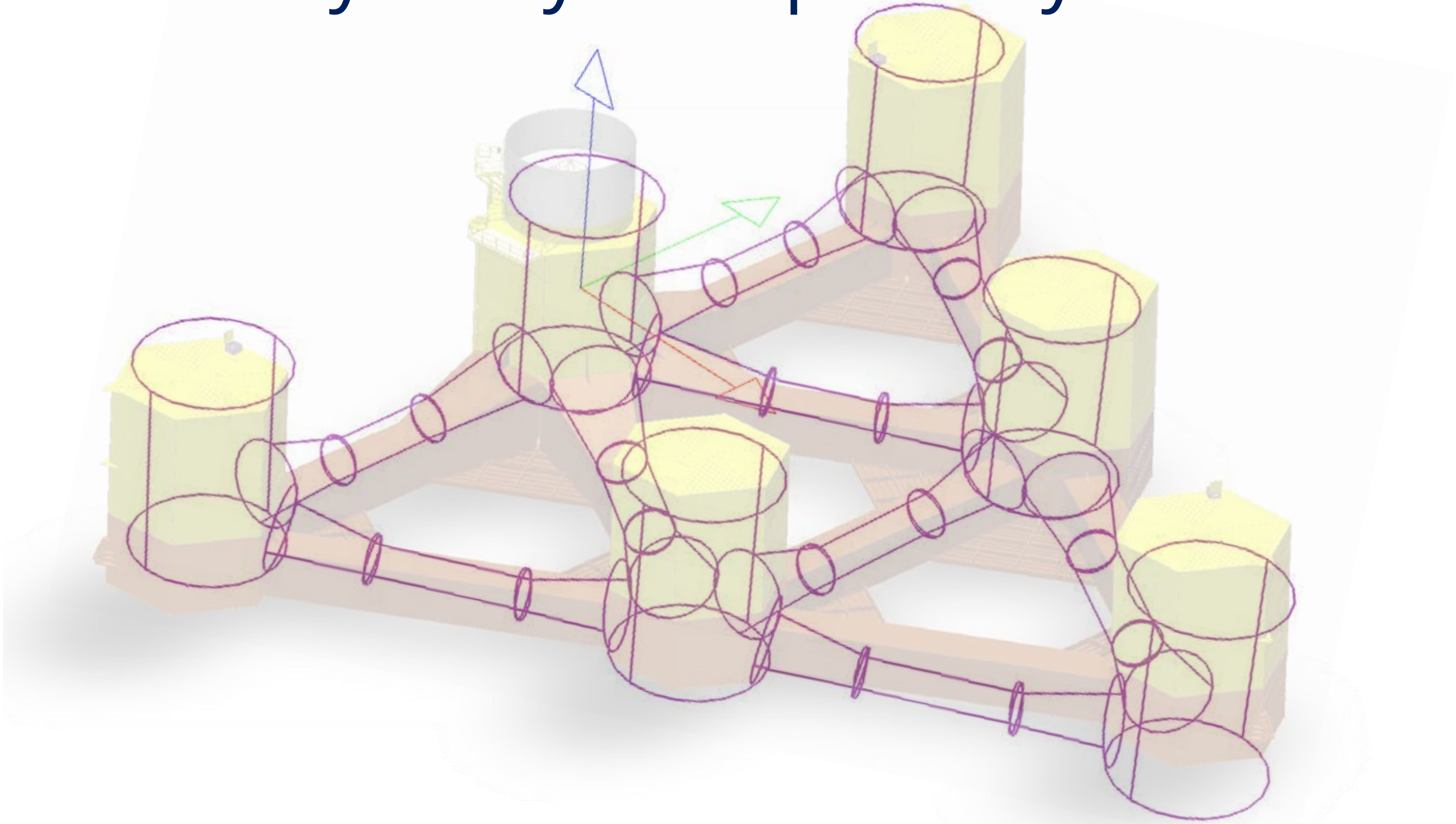
Rigid

Physics		Potential flow theory (linear)	Strip theory
Damping	Viscous	None	Morison
	Linear radiation	Frequency dependant radiation (x6)	None
Wave excitation and inertia	Second order	Frequency dependant (x6)	None
	Froude-Krylov	Frequency dependant	Wheeler wave stretching
	Diffraction scattering	Frequency dependant (x6)	None
	Added mass	Frequency dependant (x6)	Constant added mass coefficient
Hydrostatic restoring		Linear	Distributed
Buoyancy		Submerged volume	Distributed
Inertia		Centre of gravity, mass and inertia	Distributed

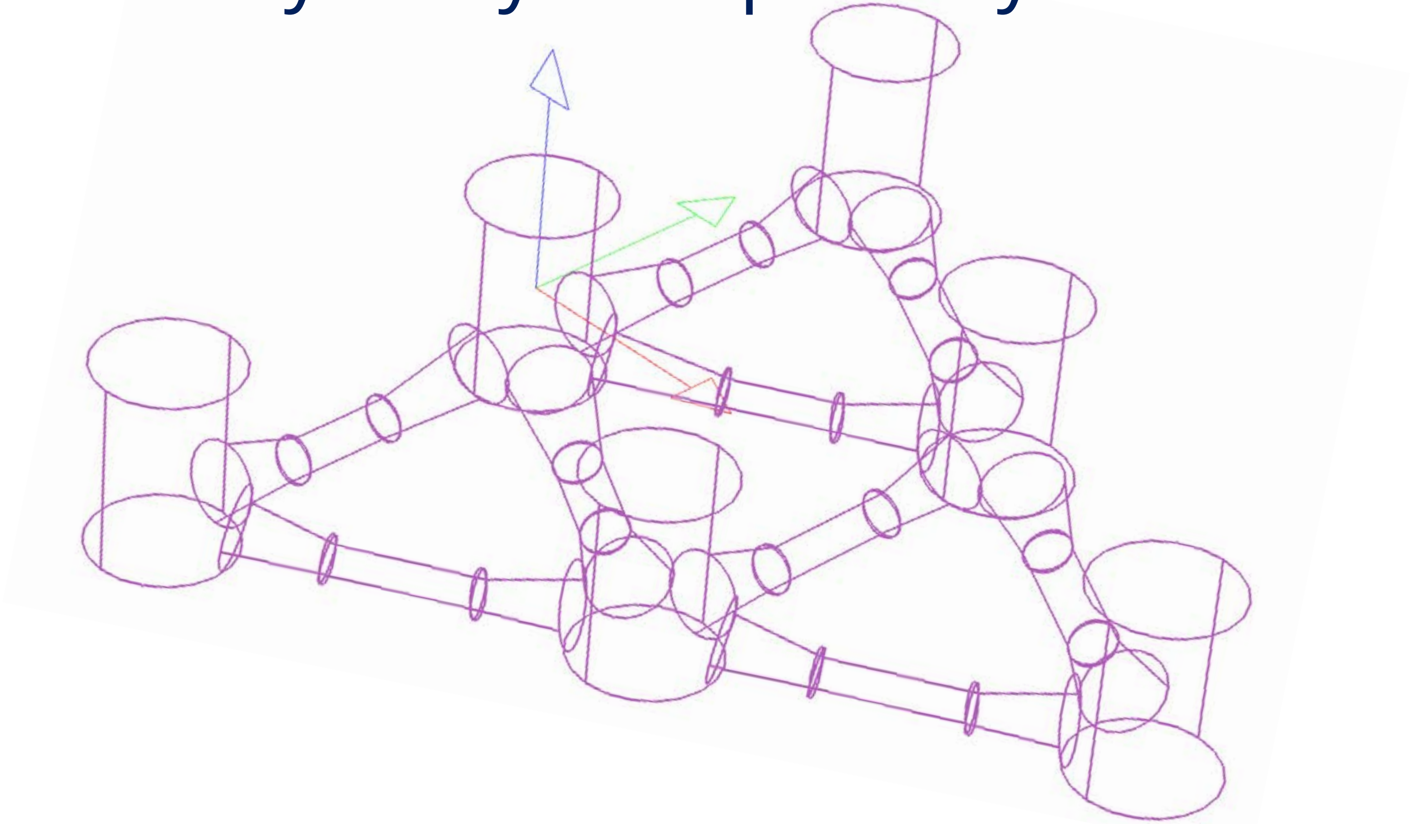
Flexible

02 Model description

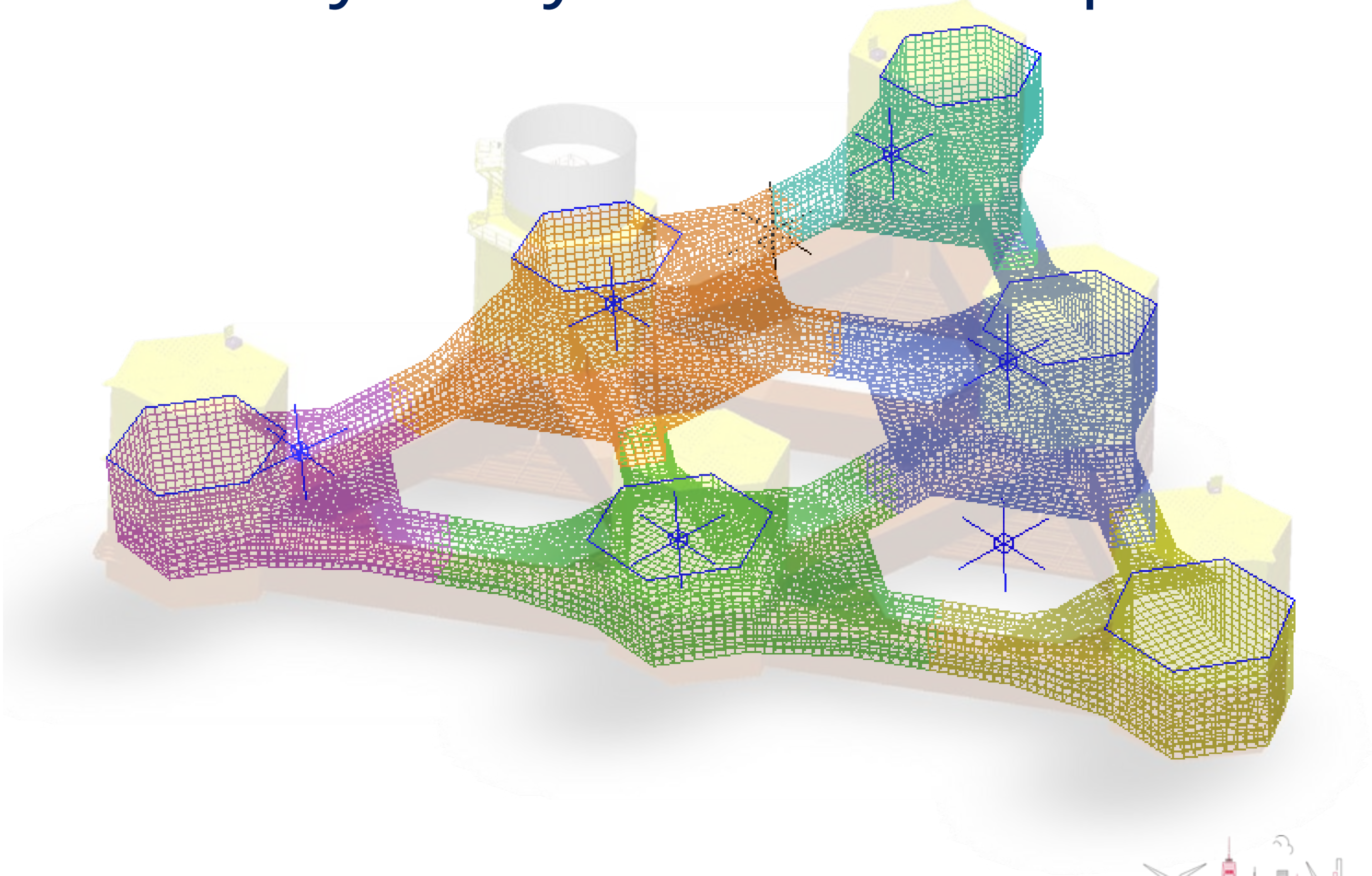
Hydrodynamics: HydroDyn. Strip theory.



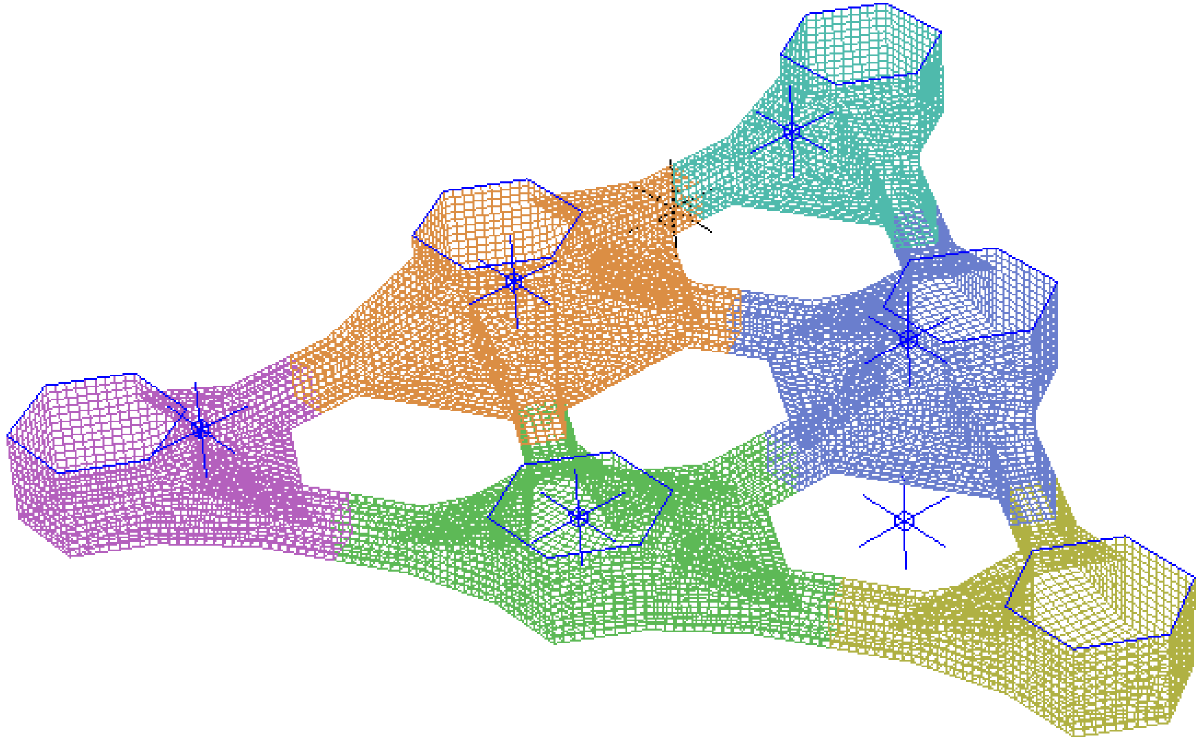
Hydrodynamics: HydroDyn. Strip theory.



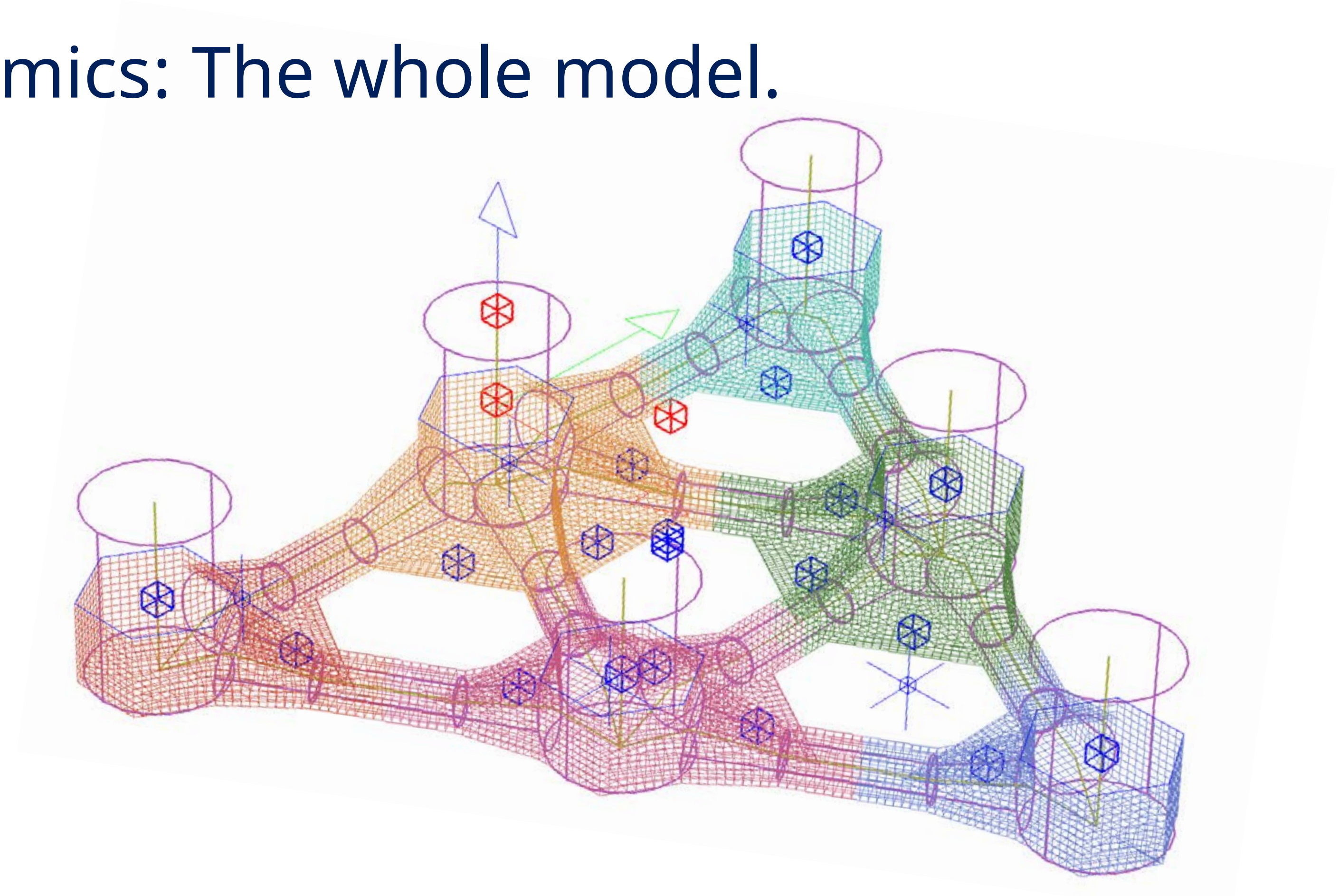
Hydrodynamics: HydroDyn. Distributed potential flow.



Hydrodynamics: HydroDyn. Distributed potential flow.

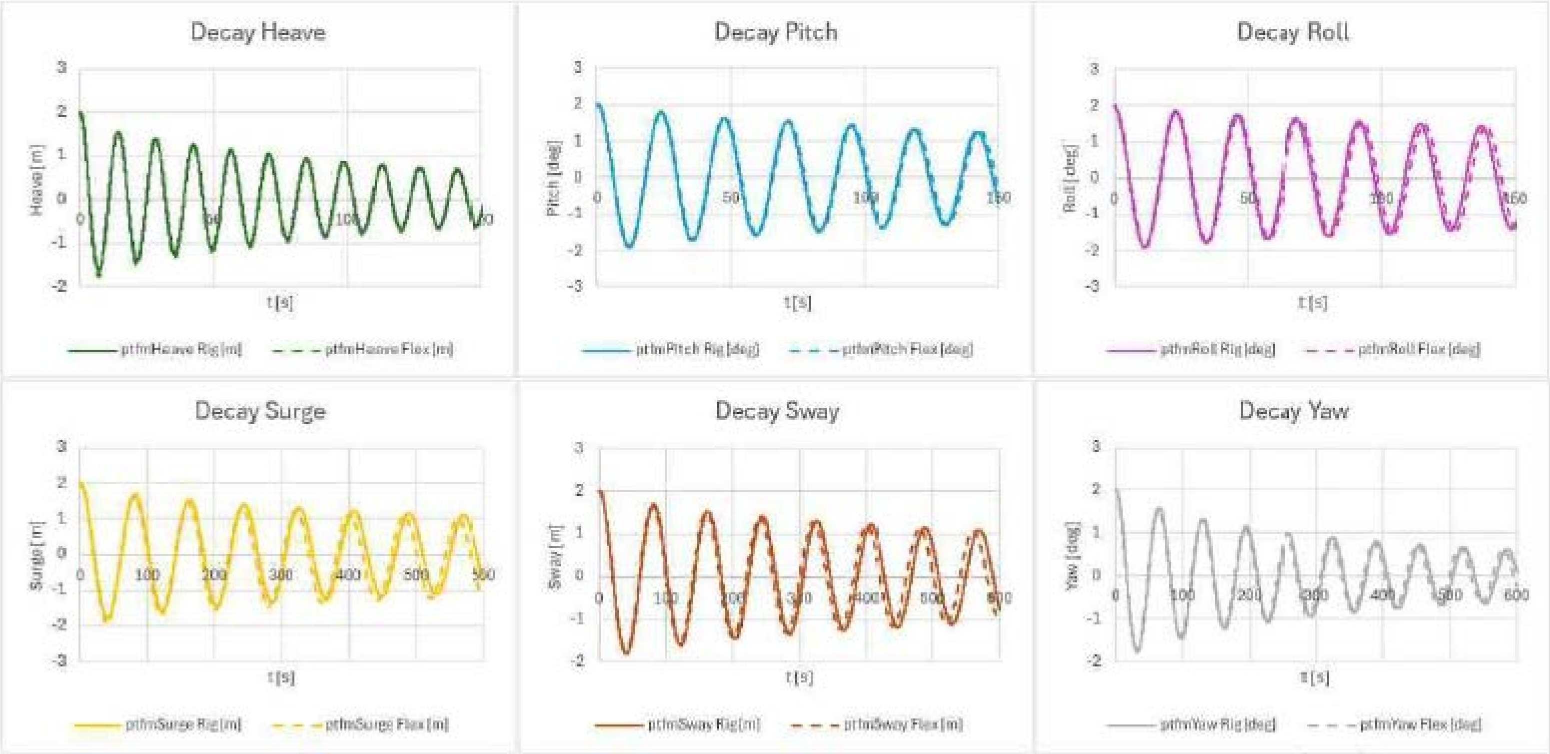


Hydrodynamics: The whole model.

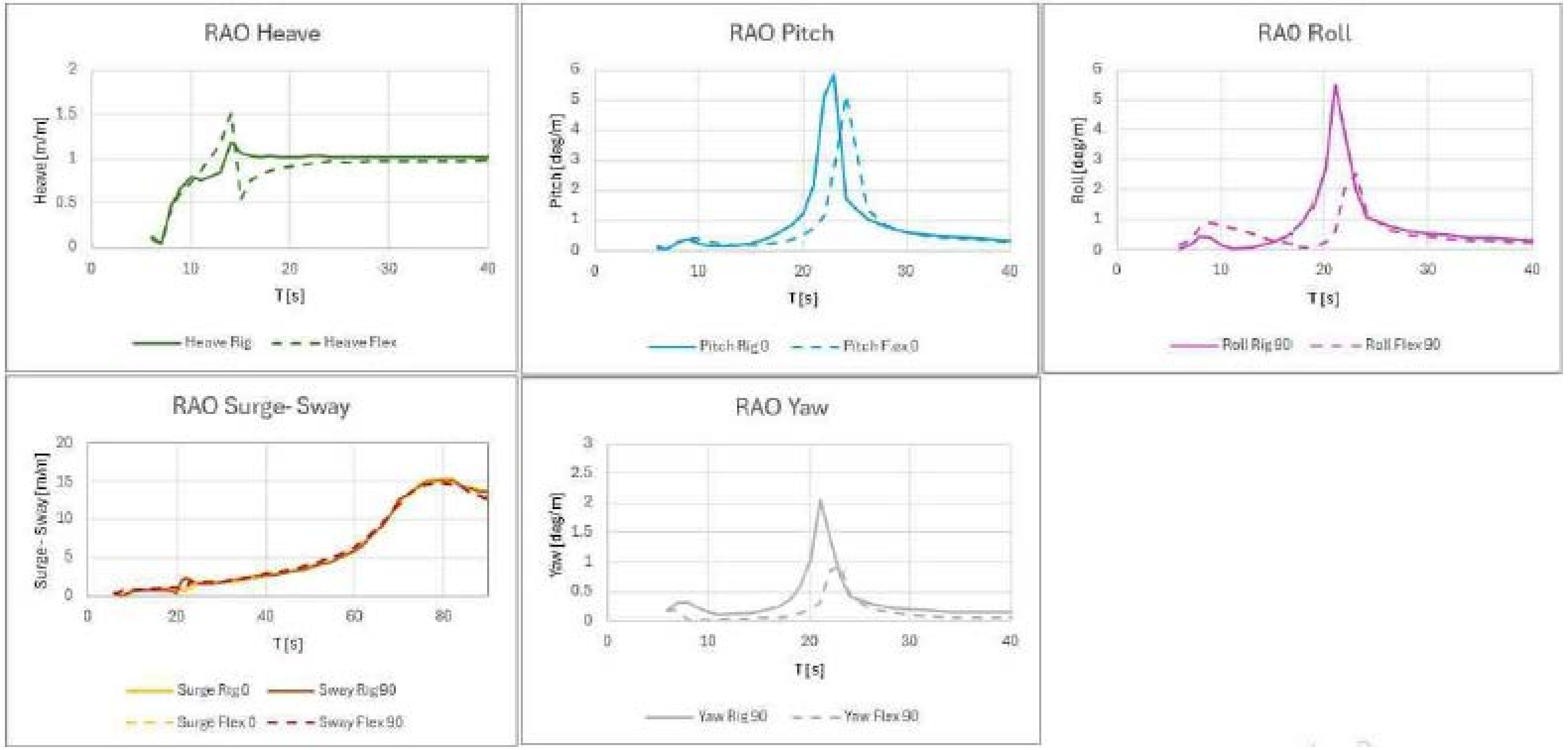


Speaker
Once the flexible model has been defined, its general behaviour has been found to be similar to that of the rigid structure under reduced loads.

Rigid vs Flexible: Free decays.

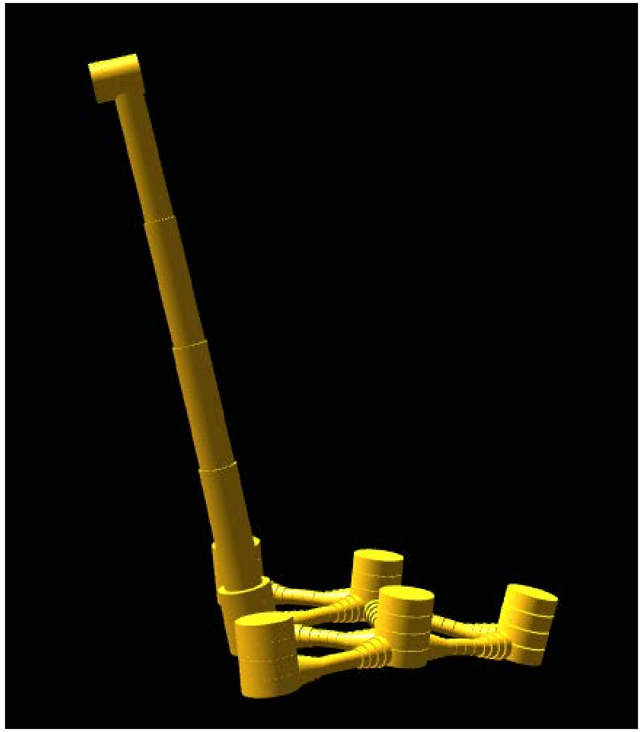


Rigid vs Flexible: RAO.



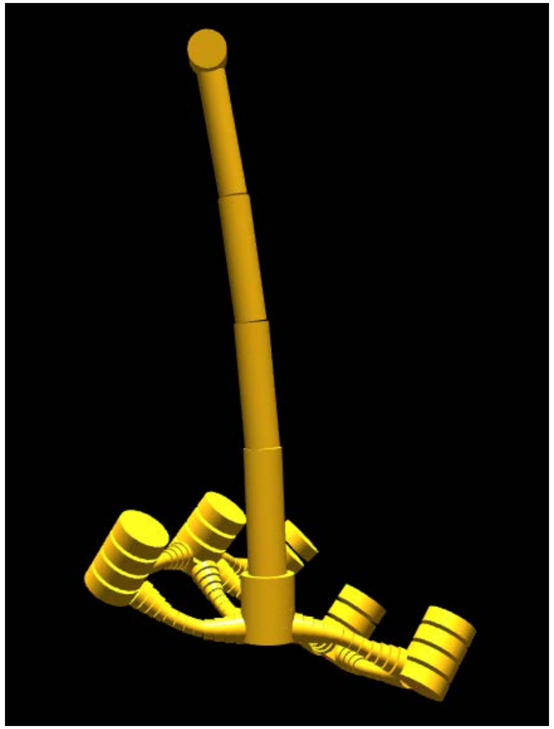
Speaker
With the structural and hydrodynamic model validated, it is possible to obtain the vibration modes of the wind turbine-substructure system, both dry (with SubDyn) and wet (with the linearized HydroDyn model).

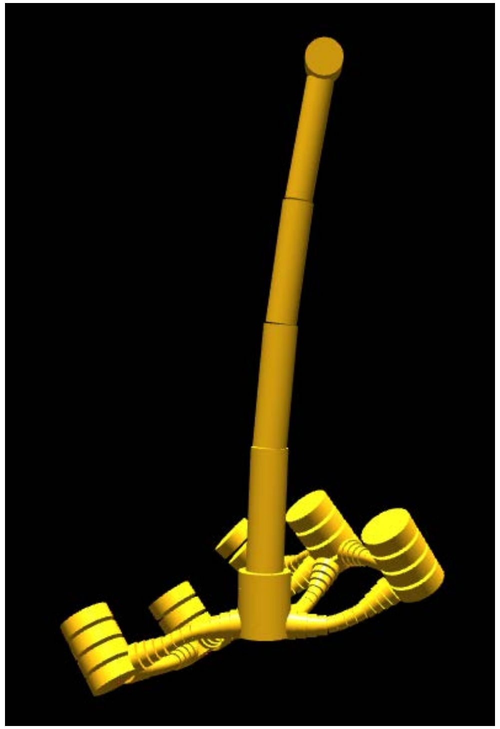
SubDyn: Dry modes platform and tower



Speaker
With the structural and hydrodynamic model validated, it is possible to obtain the vibration modes of the wind turbine-substructure system, both dry (with SubDyn) and wet (with the linearized HydroDyn model).

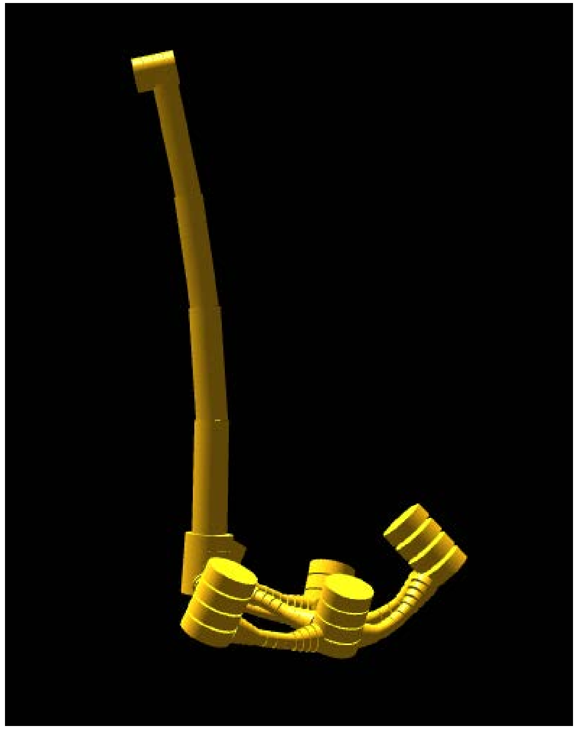
SubDyn: Dry modes platform and tower

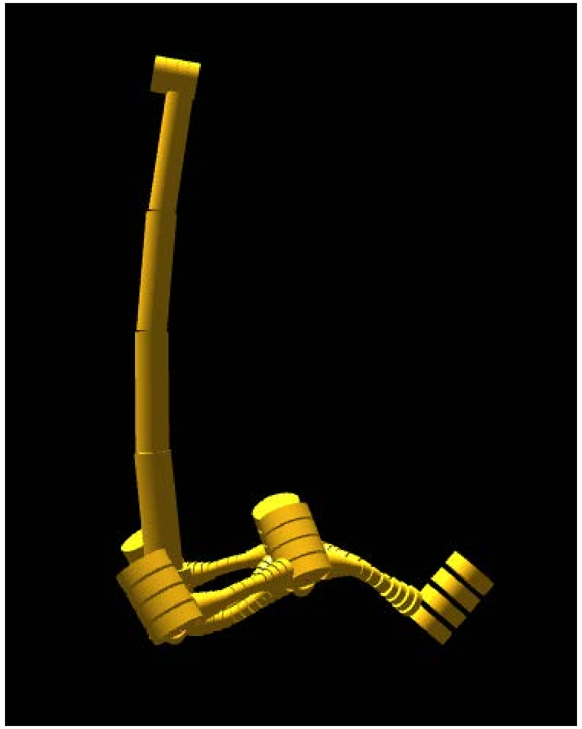




Speaker
With the structural and hydrodynamic model validated, it is possible to obtain the vibration modes of the wind turbine-substructure system, both dry (with SubDyn) and wet (with the linearized HydroDyn model).

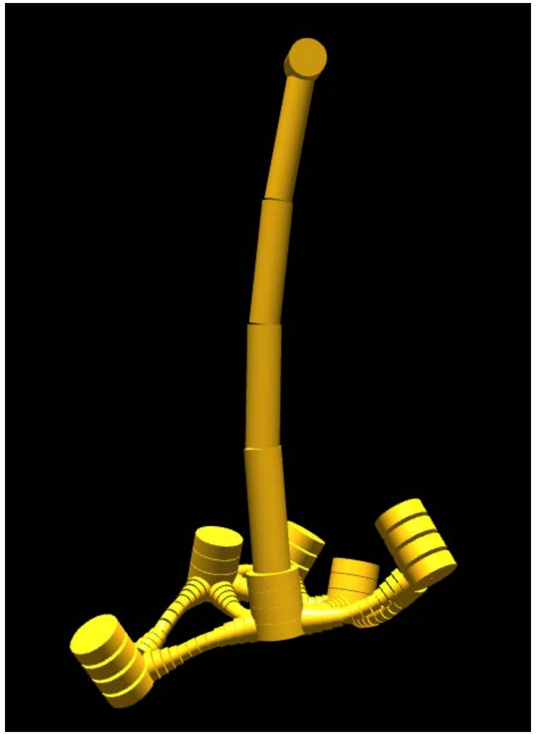
SubDyn: Dry modes platform and tower

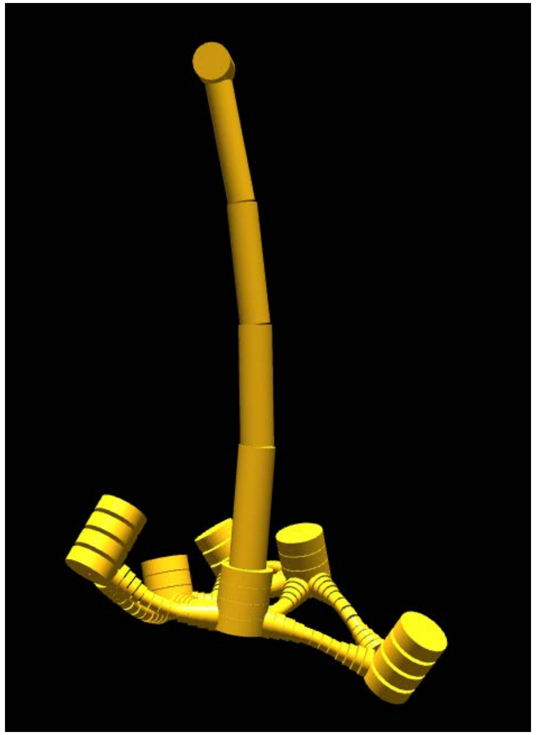




Speaker
With the structural and hydrodynamic model validated, it is possible to obtain the vibration modes of the wind turbine-substructure system, both dry (with SubDyn) and wet (with the linearized HydroDyn model).

SubDyn: Dry modes platform and tower





Speaker
In order to compare the results of the classical with the advanced model, a list of representative ULS and FLS cases has been defined for the location of Tramuntana (Spain). The models include the IEA 15 MW turbine.

Rigid vs flexible: Set of comparison DLC.

- ULS (Ultimate Limit State)
  12 worst cases.

- FLS (Fatigue Limit State)
  88 worst cases causing
  45% of tower base damage.

IEA 15 MW turbine.

03 Results

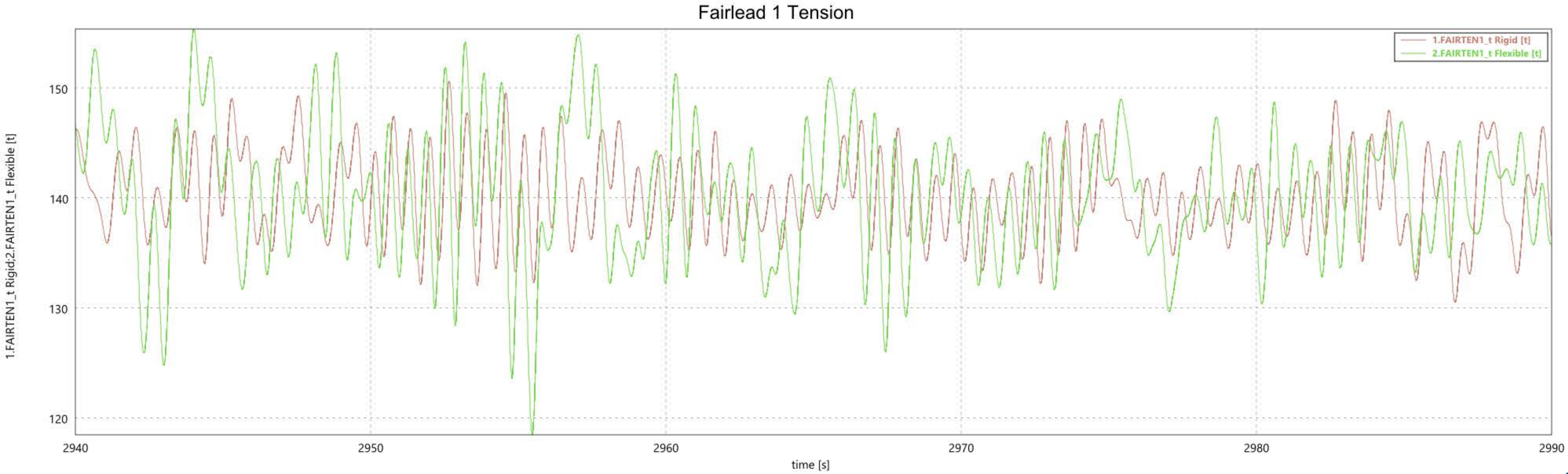
Speaker
The results of the one-hour simulations show a slight reduction in the loads on the moorings, and a significant increase in the average and especially the maximum values of the tower base loads and the platform inclination.

ULS. Average values

		Ratio to the maximum				Maximum: Increment from rigid to flexible			
Case	Type	FAIRTEN1	PtfmTilt	TwrBsBend	NacAccel	FAIRTEN1	PtfmTilt	TwrBsBend	NacAccel
0	Rigid	0.88	0.56	0.56	0.58	13.1%	40.4%	50.6%	27.1%
	Flexible	1.00	0.79	0.84	0.74				
1	Rigid	0.79	0.58	0.55	0.50	-4.6%	13.7%	30.0%	50.3%
	Flexible	0.75	0.66	0.72	0.75				
2	Rigid	0.76	0.43	0.49	0.46	4.1%	31.7%	42.0%	44.5%
	Flexible	0.79	0.57	0.69	0.66				
3	Rigid	0.75	0.50	0.61	0.61	1.4%	36.5%	33.8%	37.5%
	Flexible	0.76	0.68	0.81	0.84				
4	Rigid	0.78	0.52	0.45	0.45	-2.1%	27.4%	101.0%	98.2%
	Flexible	0.76	0.66	0.90	0.89				
5	Rigid	0.82	0.62	0.51	0.49	4.2%	40.8%	54.2%	66.3%
	Flexible	0.85	0.87	0.79	0.82				
6	Rigid	0.68	0.74	0.55	0.49	6.4%	21.5%	27.5%	52.4%
	Flexible	0.72	0.90	0.70	0.75				
7	Rigid	0.72	0.61	0.52	0.48	-0.5%	33.6%	40.9%	41.5%
	Flexible	0.71	0.82	0.74	0.68				
8	Rigid	0.72	0.64	0.61	0.52	1.7%	48.8%	50.8%	62.3%
	Flexible	0.73	0.95	0.91	0.85				
9	Rigid	0.64	0.66	0.61	0.49	7.3%	30.3%	46.9%	50.3%
	Flexible	0.68	0.86	0.90	0.74				
10	Rigid	0.65	0.72	0.76	0.62	0.5%	38.1%	32.2%	61.0%
	Flexible	0.66	1.00	1.00	1.00				
11	Rigid	0.73	0.73	0.72	0.55	2.0%	33.8%	21.0%	80.9%
	Flexible	0.74	0.98	0.88	[illegible]				
					Average	2.8%	33%	44%	56%

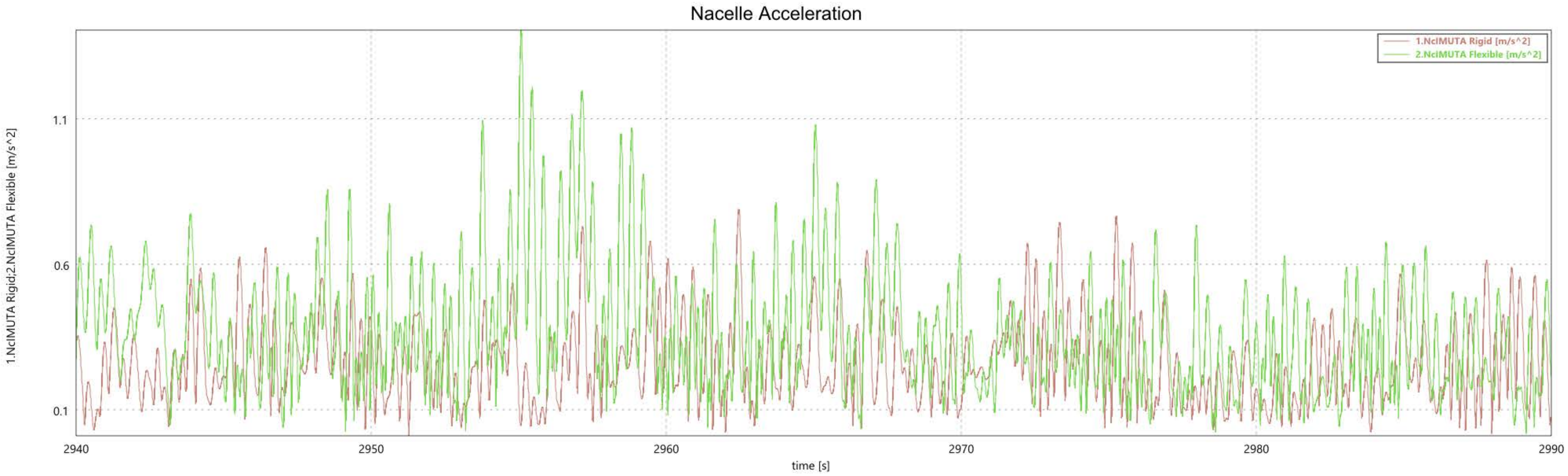
Speaker
To see the detail of this increase, some graphs are shown. While for some parameters flexibility may amplify the movements, thus increasing loads and displacements, for moorings flexibility can absorb part of the energy, damping the loads.

ULS. Some plots.



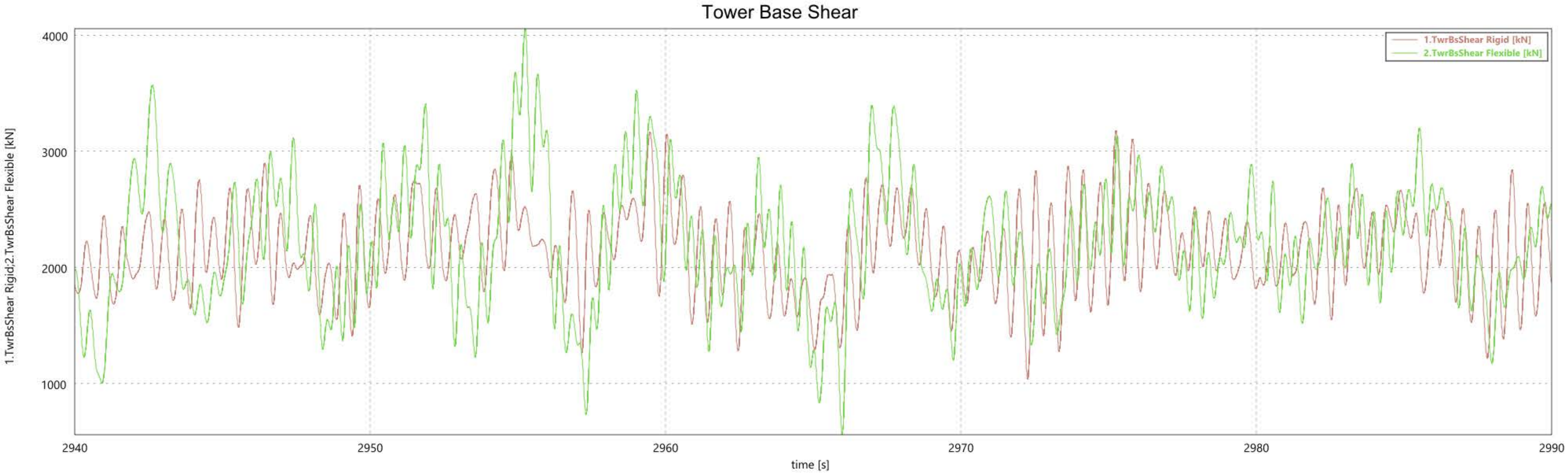
Speaker
To see the detail of this increase, some graphs are shown. While for some parameters flexibility may amplify the movements, thus increasing loads and displacements, for moorings flexibility can absorb part of the energy, damping the loads.

ULS. Some plots.



Speaker
To see the detail of this increase, some graphs are shown. While for some parameters flexibility may amplify the movements, thus increasing loads and displacements, for moorings flexibility can absorb part of the energy, damping the loads.

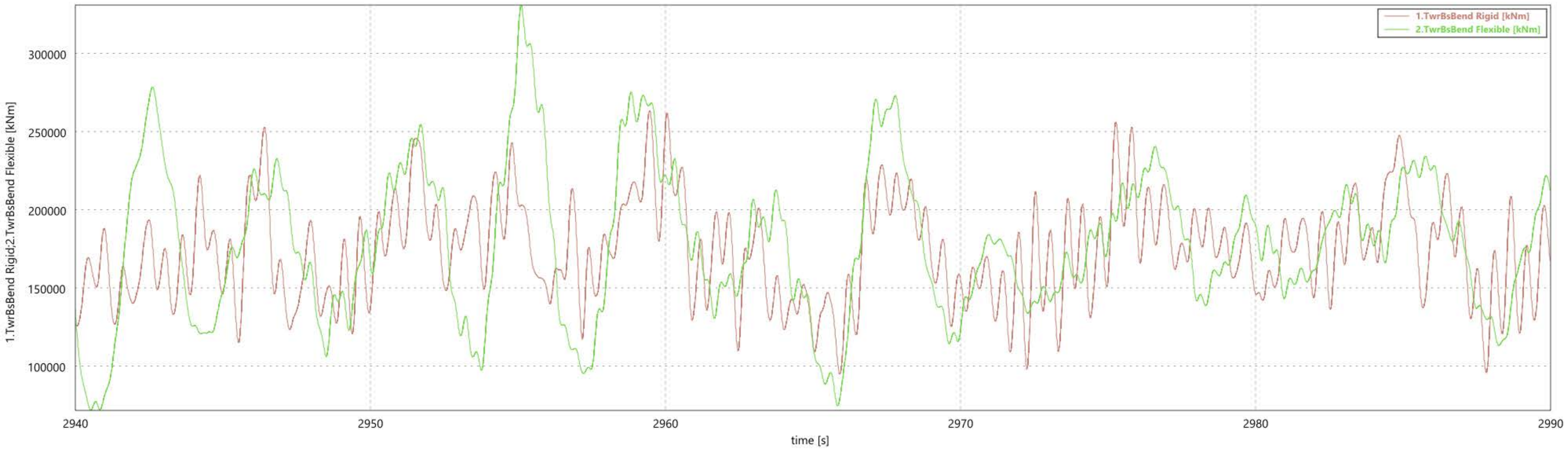
ULS. Some plots.



Speaker
To see the detail of this increase, some graphs are shown. While for some parameters flexibility may amplify the movements, thus increasing loads and displacements, for moorings flexibility can absorb part of the energy, damping the loads.

ULS. Some plots.

Tower Base Bending Moment



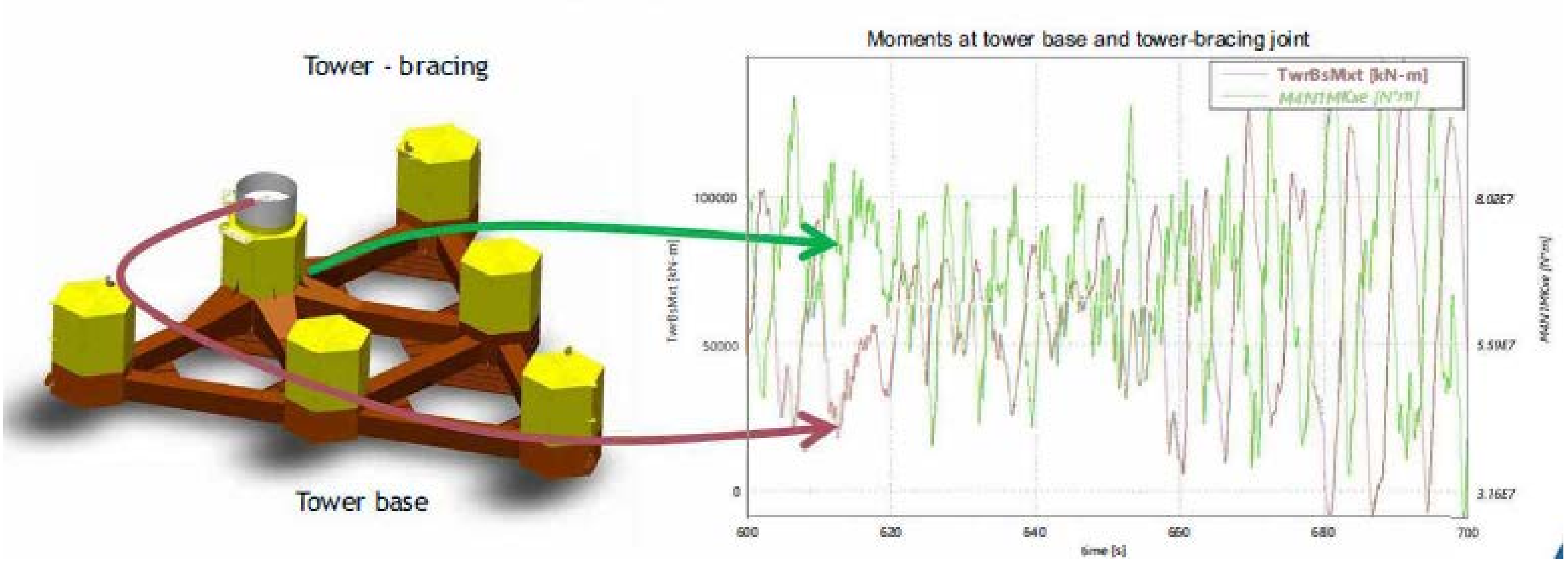
Speaker
Fatigue calculations procedure: Firstly, for the tower base bending moment, the ranges and means associated are obtained using a Rainflow counting algorithm. Next, those are represented in a Markov Matrix, where the table columns are the range interval and the rows the mean interval. Each cycle obtained with the Rainflow counting is introduced in the corresponding cell of the matrix, applying the case occurrence probability and the design life duration (25 years). With the defined Markov Matrix, the DEL value is obtained, with a Wöhler coefficient of 4. The cases analyzed for fatigue are the ones included in DLC 1.2 and 6.4, being a sum of 88 simulations, summing the 45% of the damage.

FLS

Considering a series of cases that add up to 45% of the total fatigue, the damage produced by the flexible model in the tower base is 8.3% higher than that obtained with the rigid model.

Speaker
This model allows to study the loads on the internal elements of the structure, thus performing the necessary FLS and ULS analyses. This makes it possible to check the relationships between different loads at any given moment. In this way, the designer is provided with critical information on the internal behaviour of the structure.

Loads at internal substructure locations.



04 Summary

Speaker
The simulation of the load cases is usually done by considering the substructure to be rigid. This approach may be too simplified for the latest generation of offshore wind platforms. Nowadays, solvers such as OpenFAST allow, in an efficient way, to analyse these cases considering the flexibility of the structure. The results indicate non-negligible differences in critical parameters. In addition, information is obtained on the critical areas at internal joints of the structure, allowing to calculate ULS and FLS in any point of the structure accounting for concomitant aero-hydro-elasto-servo loads. Thus, thanks to this improved information, the flexibility modelling will allow for tighter and more economical designs.

- Current modelling considers floating substructures as rigid.
- Latest offshore wind platforms are leaner, less rigid.
- OpenFAST now considers the flexibility of the floating substructure.
- Flexible model has non-negligible differences in KPI.
- It allows to calculate ULS and FLS inside the substructure accounting for concomitant aero-hydro-elasto-servo loads.
- This will allow for tighter and more economical designs.

Roger Bergua
roger.bergua@nrel.gov
www.nrel.gov

OffshoreWind@sener.es
https://www.group.sener/markets/energy/offshorewind-marineenergies

www.nrel.gov

www.group.sener

www.linkedin.com/company/sener

NREL/PR-5000-91769

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Wind Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.