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OFFSHORE WIND ENERGY

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Water and electric power plants don’t mix well naturally, unless you add some wind

A wind turbine in the waters off Block Island, Rhode Island, U.S. *Photographer: Eric Thayer/Bloomberg*

Water tends to corrode and short out circuits. So what’s happening in the renewable energy industry, where developers are putting jumbo-jet sized wind turbines into stormy seas, is at very least an engineering miracle

Facts about Offshore Wind

- The installation away from residential areas eliminates the problem of noise and visual pollution.
- According to the Global Wind Energy Council, a total of 2,219 MW of new offshore wind power was installed across seven markets globally in 2016.
- Asset financing for wind power projects reached the record of €27.6bn in 2016.
- The reason for this remarkable growth lies in the decrease of the construction cost.
- Indeed, the construction and installation cost of offshore wind farms has fallen 46% in the last five years and 22% in 2016 alone; making the offshore wind sector competitive compared to land-based turbines, solar and nuclear power, even without subsidy.
- The installed offshore wind capacity is expected to increase to >120GW by 2030.

Facts about Offshore Wind

- New offshore wind investments in Europe reached ~€18bn in 2016 and ~€8bn in 2017 corresponding to new capacity financed ~18GW and ~8GW respectively
- The outlook for 2018 Renewables and Green Technologies Product, estimate a combined capacity of 3.9GW, while the financing needs could top up €9bn.
- According to International Energy Agency, wind electricity generation in the EU will reach 1,100TWh by 2040.
- Currently, OWTs achieve rated power of up to 8MW and they have been upgraded to 9.5MW.
- The aforementioned brief figures describe a boom in the years to come in the wind energy market.

Some Shortages

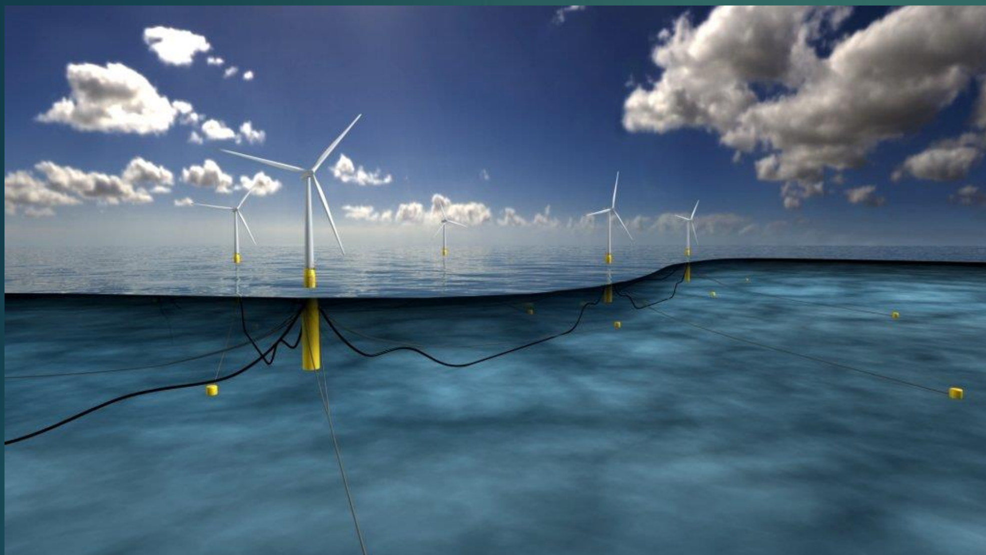
- OWTs have limitations in operation as the wind resource is variable and windfarms do not generate 100% of their potential electricity capacity 24/7.
- The capacity factor of bottom fixed wind farms is typically 40-50%.
- Wind speeds are higher in open ocean but deeper water requires the use of floating platforms.
- Bottom fixed OWTs are not always the most optimum solution in terms of installation, terrain and operation sites, due to specific peculiarities of the various ocean spaces.
- The Mediterranean basin for example is much deeper than the North Sea, a fact that imposes the necessity of a different way of thinking.
- To exploit the higher wind potential in the open ocean one should go deeper where, the advisable solution are floating platforms.
- Bottom fixed OWTs (monopiles, jackets, gravity based) are typically installed in <50m water depths, whilst floating OWTs can be located deeper and further from the shore so that they generally operate in a more extreme environment.

The flagship of Offshore Wind

MHI Vestas Offshore Wind will supply 90 of its flagship V164-9.5 MW turbines for the 860 MW project, its largest MW project to date.

Location: 860 MW Triton Knoll Offshore Wind Farm, confirming the largest MW project in the history.

Going deeper

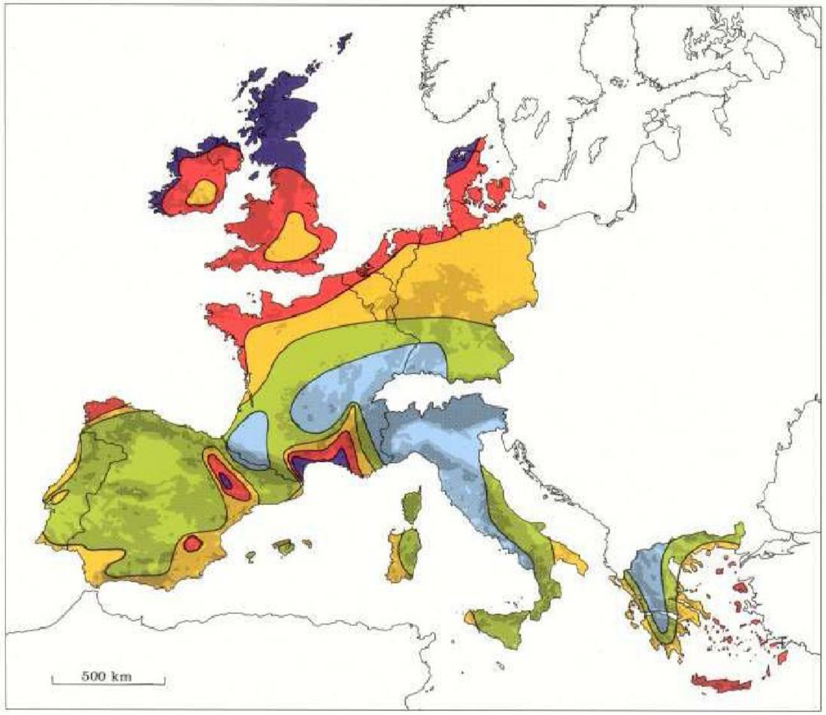


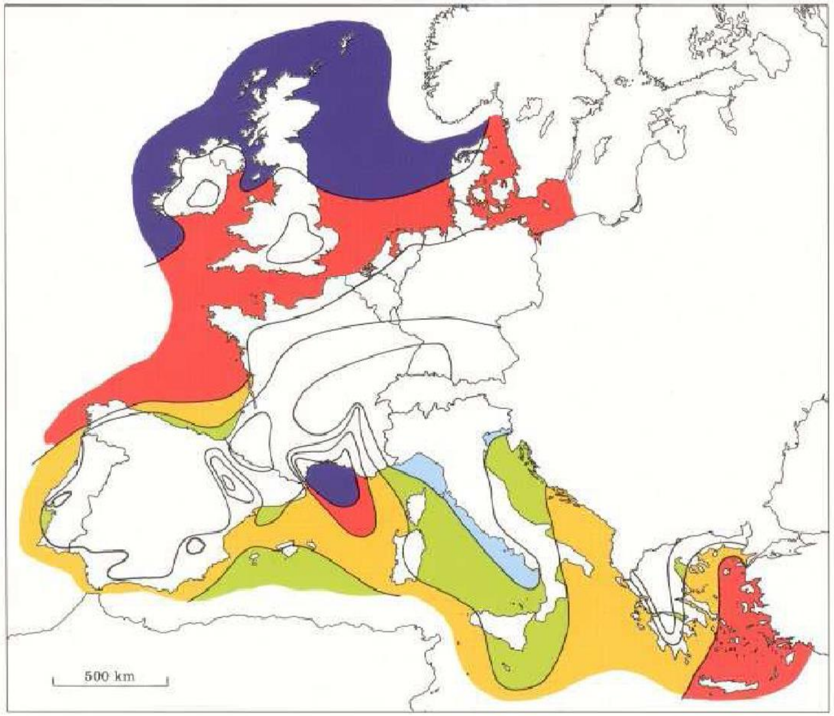
The world's first floating wind farm, the 3MW Hywind Scotland, is outperforming expectations and operating at levels consistently above that of its seabound offshore brethren.

The wind farm is made up of five 6 MW wind turbines floating 25 kilometers off the coast of Peterhead, in Scotland.

A wind turbine doesn't generate 100% of its potential electricity capacity 24 hours, 7 days a week — to do that would require very disturbing wind conditions that pretty much don't exist anywhere on earth. Wind farms that are affixed to the seafloor generally generate at around 45 to 60% — in other words, they are generating 100% of their potential electricity capacity around 45 to 60% of the time.

WIND RESOURCE IN EUROPE





Wind resources[1] at 50 metres above ground level for five different topographic conditions										
	Sheltered terrain[2]		Open plain[3]		At a sea coast[4]		Open sea[5]		Hills and ridges[6]	
	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}
	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0- 8.5	400- 700
	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

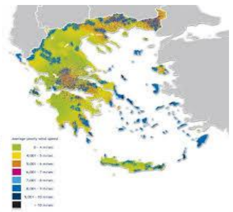
Wind resources over open sea (more than 10 km offshore) for five standard heights										
	10 m		25 m		50 m		100 m		200 m	
	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}
	> 8.0	> 600	> 8.5	> 700	> 9.0	> 800	> 10.0	> 1100	> 11.0	> 1500
	7.0-8.0	350-600	7.5-8.5	450-700	8.0-9.0	600-800	8.5-10.0	650-1100	9.5-11.0	900-1500
	6.0-7.0	250-300	6.5-7.5	300-450	7.0-8.0	400-600	7.5- 8.5	450- 650	8.0- 9.5	600- 900
	4.5-6.0	100-250	5.0-6.5	150-300	5.5-7.0	200-400	6.0- 7.5	250- 450	6.5- 8.0	300- 600
	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 6.0	< 250	< 6.5	< 300

OFFSHORE WIND ENERGY

EUROPEAN OFFSHORE WIND TARGET 2020

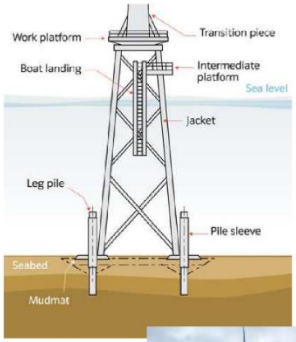
NREAP: National Renewable Energy Action Plan

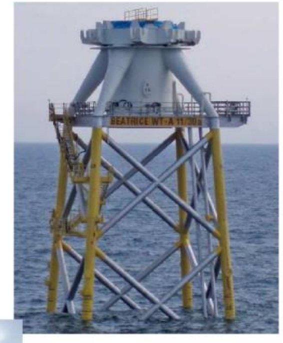
OFFSHORE WIND DEVELOPMENT - MAIN STEPS

	Origination	Development	Construction	Operation
				
Milestones	• Initial screening of potential sites • Preliminary evaluation of seabed and wind conditions • Securing of project and property rights • Application for permission	• Wind Assessment/ Ground Survey • Environmental Impact Assessment (EIA) • Technical planning • Securing of grid connection • Receiving of construction permit	• Component contracts signed • Installation of foundations and wind turbines • Connection to onshore grid • Commissioning and start of operation	• Hands-on and pro-active operation • Regular check and maintenance of technical equipment • Repairs, overhauls and upgrades • At end of lifetime: decommissioning or repowering

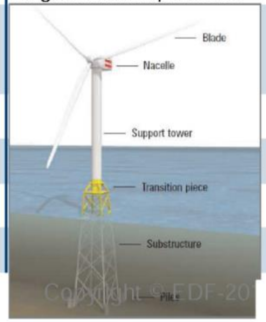
JACKET

- Jacket : steel lattice structure (welded pipes Ø 0.5 – 1.5m) from Oil & Gas industry. ~ 1000tons (> 1km welding!).
- Structure suitable for deep water (< 50-60 m) with heavy turbines (> 5 MW). Small leg monopiles are driven in the seabed (Ø 1 – 2.5m).
- 1st offshore wind installation: demonstration site Beatrice in Scotland in 2006 (2 x REpower 5 MW – 45 m water depth).





Advantages	Disadvantages
Lightweight and stiff structure	Complexity of fabrication
Better global load transmission compared to monopiles	Large number of joints required compared to other latticed structures
Large variations in water depth can be covered through cantilevering piles or modifying the geometry	Logistical issues due to the templates (pre-piling case)
No scour protection required	Complex connection to transition pieces
Structural redundancy	High manufacturing lead-times
Low soil dependency	No standardized design that leads to long certification processes
Good response to wave loads. Little sensitivity to large waves and limited dynamic amplifications of loads due to high stiffness	
Limited storage area compared to GBF	
Faster fabrication compared to GBFs (serial production)	
Better quality control	
Easy decommissioning	



TRIPOD INSTALLATION (ALPHA VENTUS)


Tripods being welded


Tripod up-ended for shipping


Tripods arriving at Wilhelmshaven port


Heavy-lift crane ship on site


Tripod foundation lowered to seabed

Installation complete

INSTALLATION – HEAVY OFFSHORE VESSELS

JAPANESE PROJECTS : SEA ANGEL (2015)

Fukushima
7 MW (MHI)

Items	Scopes
Turbine	• Verification of 7MW hydraulic turbine.
Floating	• Development of V-shape semi-sub floating. • Development of the reduction of floating motion by turbine control and O&M program.
Mooring	• 8 pieces catenary.

• Rotor diameter	164m
• Hub height	105m (ASL)
• Height of the floater	32m

Installed summer 2015

FUKUSHIMA-FORWARD Project

ADVANCED SPAR 5 MW (2016)

- **Last part of Fukushima forward project**
  - 5MW Turbine
    - Hitachi
    - Downwind type
  - Advanced-spar concept
    - Japan Marine United
    - Low draft solution (30m)
    - Large sections (50m)

➡ Japan is still working on prototypes

Full shape

Built in the dockyard of Hitz

Carried to Sumoto port on 2 May

The floater lost control and leaned on 9 May

The floater recovered stability again on 14 May

JAPANESE PROJECTS : SEMI-SUB AND SPAR (2013)

Fukushima
(Mitsui/Hitachi)

- Design for use with a 2MW turbine
- Width 58 m
- Total column length 32 m of which 16 mwill be submerged
- Hub height 60 m

GOTO OWT
(Toda/Hitachi)

Full Scale:

- 2MW downwind turbine with 80m rotor diameter
- Total spar length 172m
- Total weight incl. Turbine 3,400 t
- Steel with pre-stressed concrete
- Steel chain mooring, 3 points, catenary, attached to drag anchors

Image Source: Kyoto University

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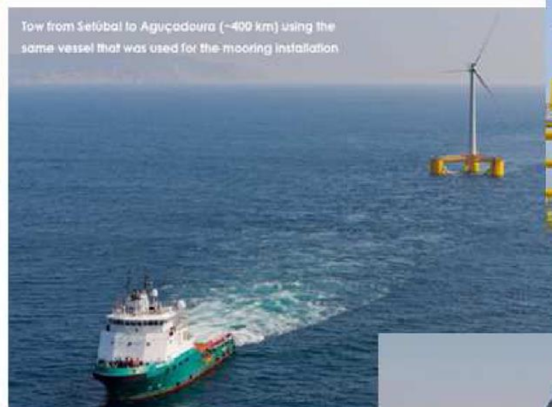
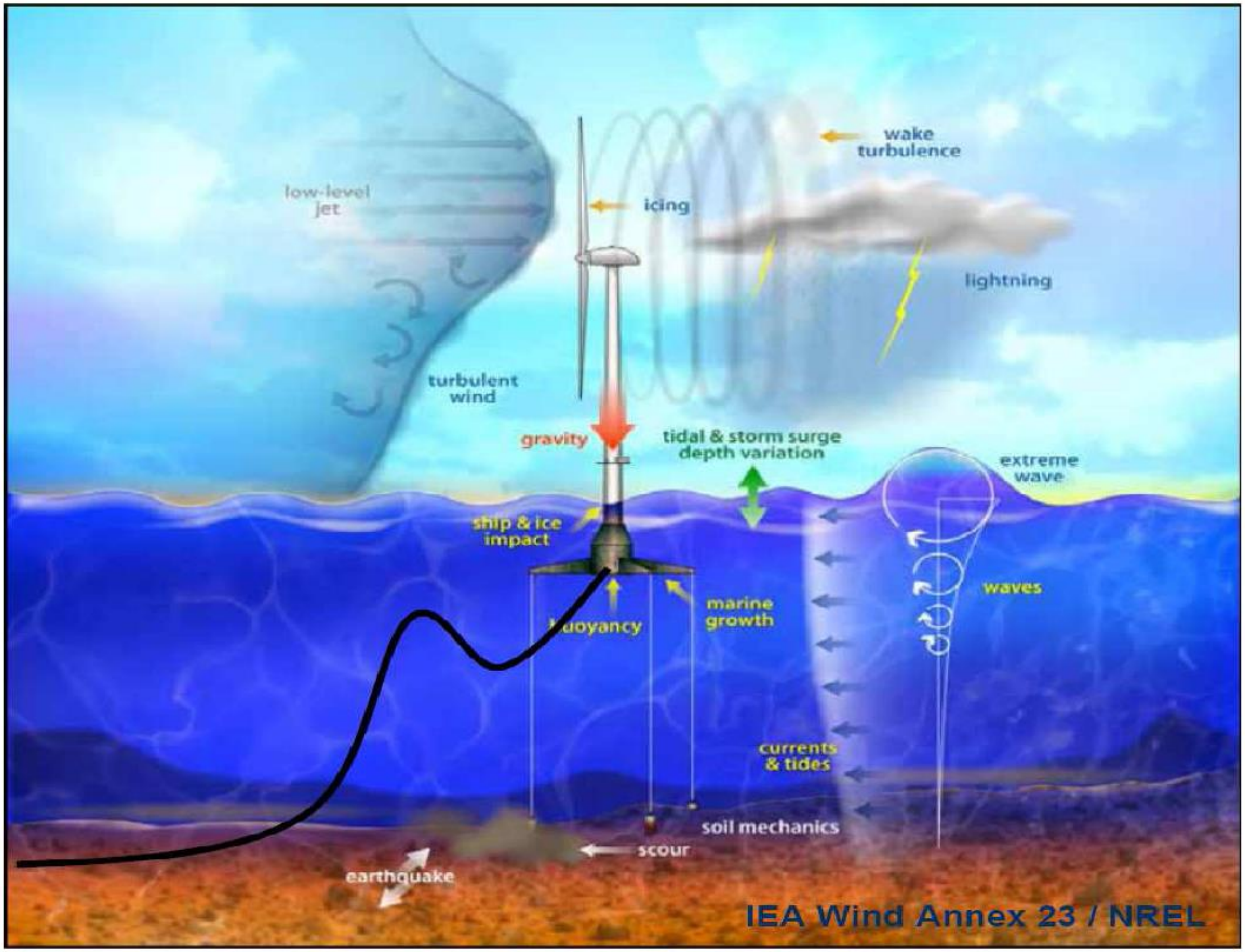
INSTALLATION - SEMISUBMERSIBLE



Challenges to be addressed



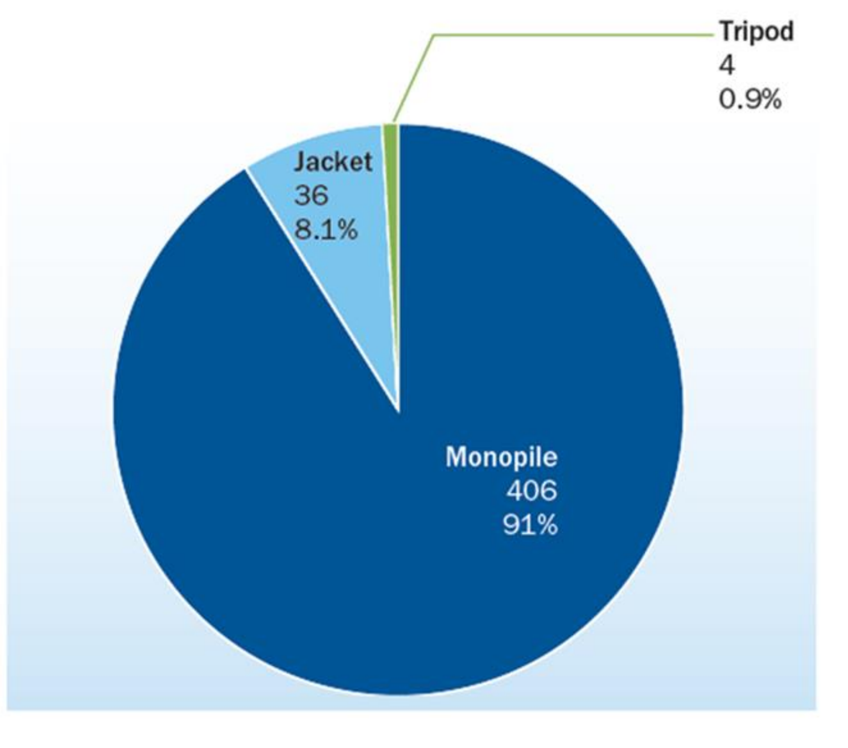
Short Overview: The framework

- Off shore Wind is "relatively" recent, challenging but promises a lot
- Most of current OWT are bottom mounted but in future a lot of Deep Water (Floating) installations are expected.
- The main challenge for FOWT at present is cost, therefore most of the current developments aim at reducing it
- Compared to LWTs, OWTs require additional data/modeling:
  - Wind & Sea combined environment
  - <u>Hydrodynamic Loading on the support structure (bottom mounted & floater)</u>
  - <u>Mooring line dynamics</u>
  - <u>Sea bed foundation</u>
  - Marinarization
- In this lecture we are going to discuss the underlined topics

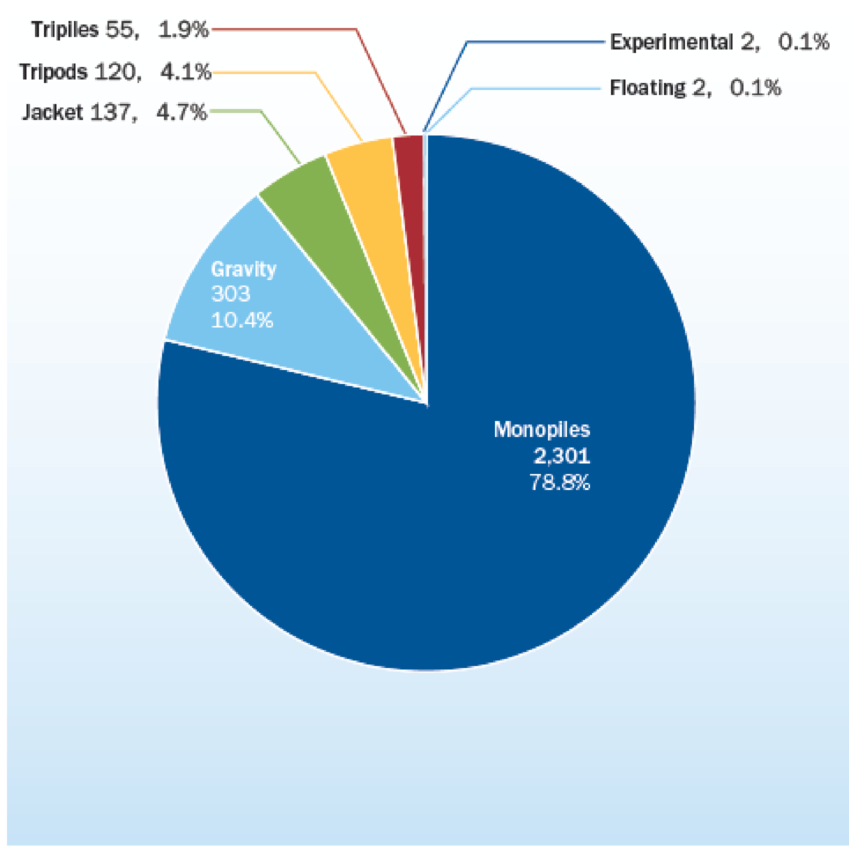
(B/F)(L/O)WT= (Bottom mounted / Floating) (Land /Off-Shore) Wind Turbine

Short Overview: Concepts & Trends

FOUNDATION TYPES' SHARE OF 2014 ANNUAL MARKET IN TERMS OF UNITS

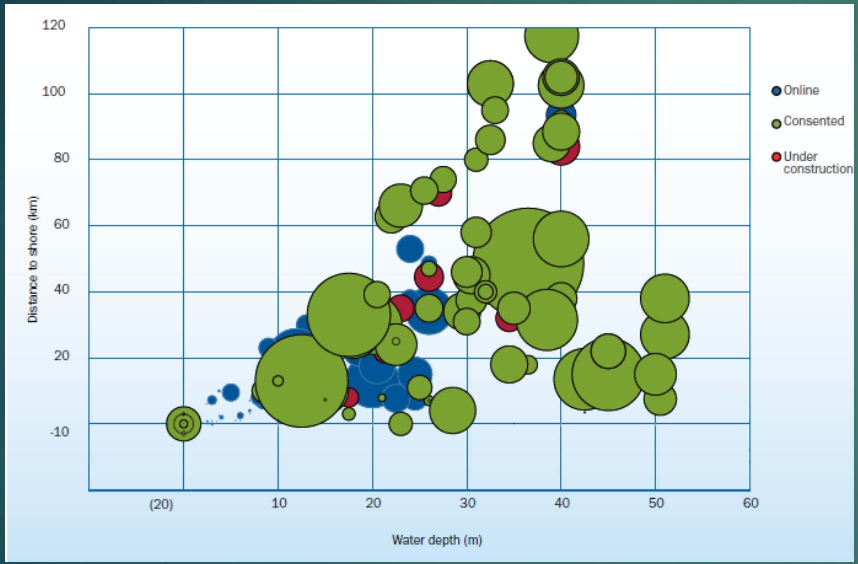


SHARE OF SUBSTRUCTURE TYPES FOR ONLINE WIND TURBINES END 2014 (MW)



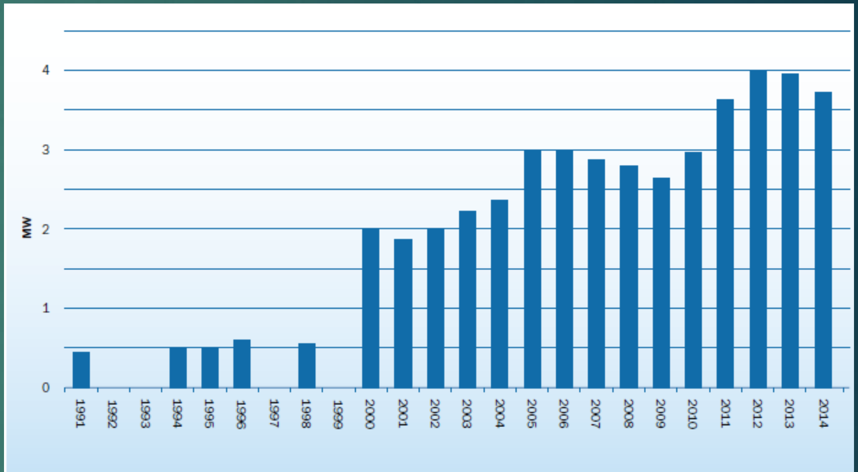
Short Overview: Concepts & Trends

AVERAGE WATER DEPTH AND DISTANCE TO SHORE



Depth & Distance from shore affect the sea-state and by that the wave loads

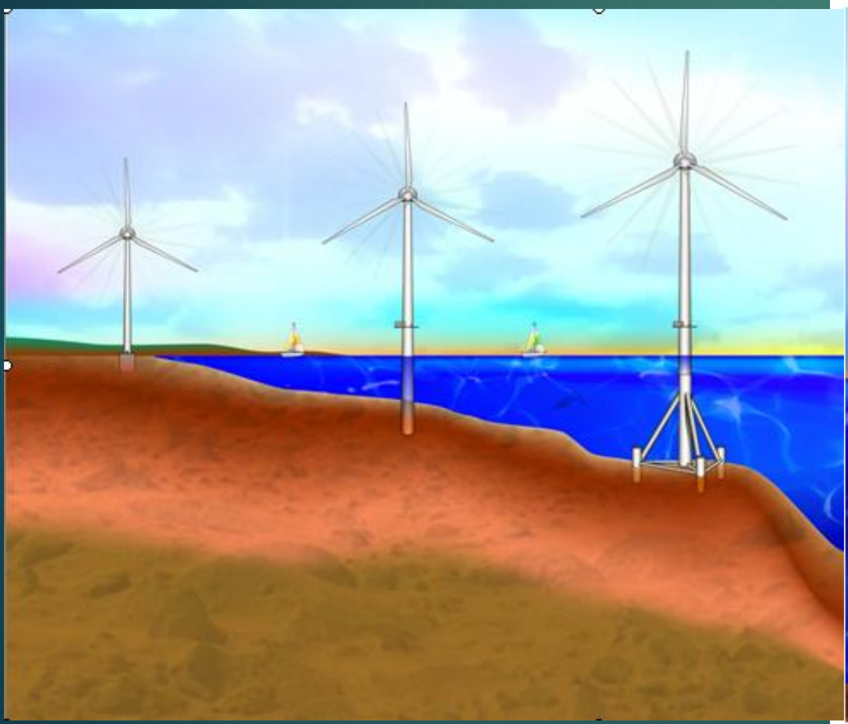
AVERAGE OFFSHORE WIND TURBINE RATED CAPACITY

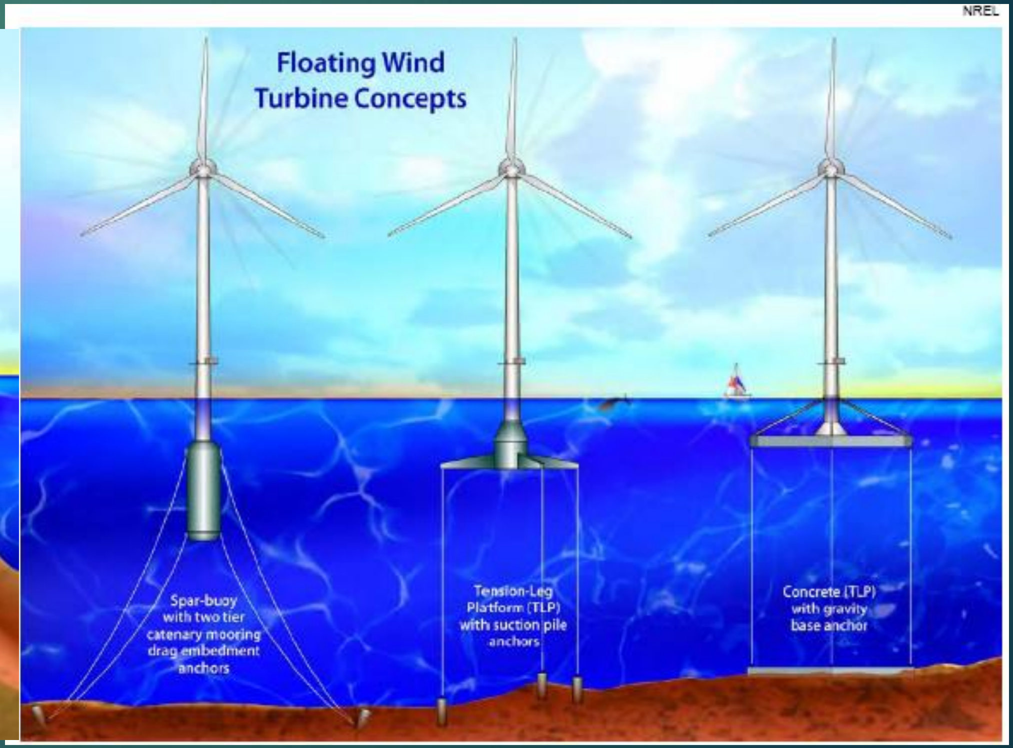


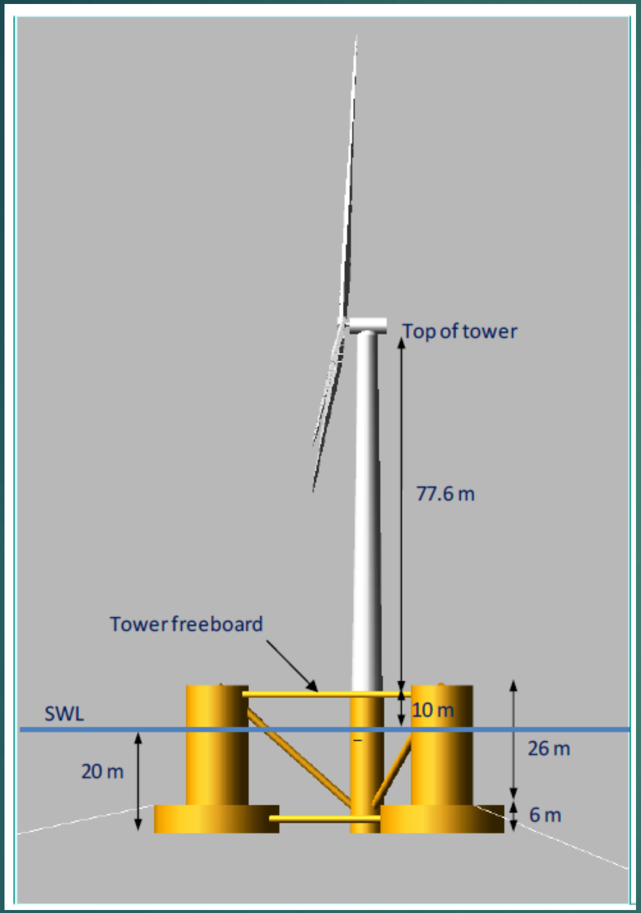
Size affects the installation procedure. The challenge of having larger wind turbines is important. At present the "market size" is installed

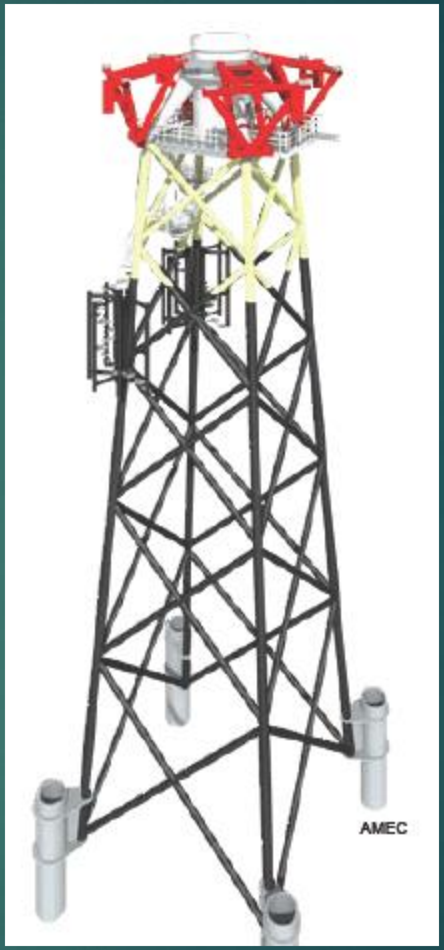
Short Overview: Concepts & Trends

Some OWT concepts



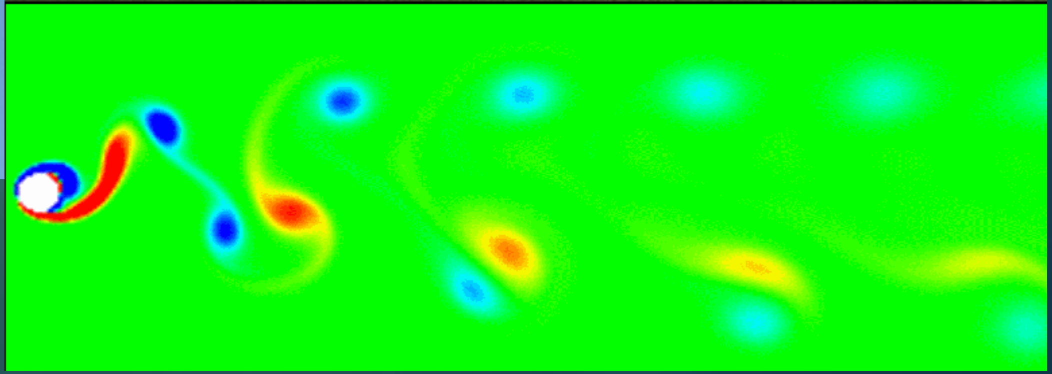



Top of tower
77.6 m
Tower freeboard
SWL
10 m
26 m
20 m
6 m


AMEC

Vertical axis WT

Vortex bladeless WT



The modeling aspect

The modeling approach remains more or less the same. In particular the multi-body modeling of the entire configuration is the basis. To this we add the aerodynamic excitation as in LWT case while the flexibility is still modeled using beam theory.

However for OWTs we have the following important differences:

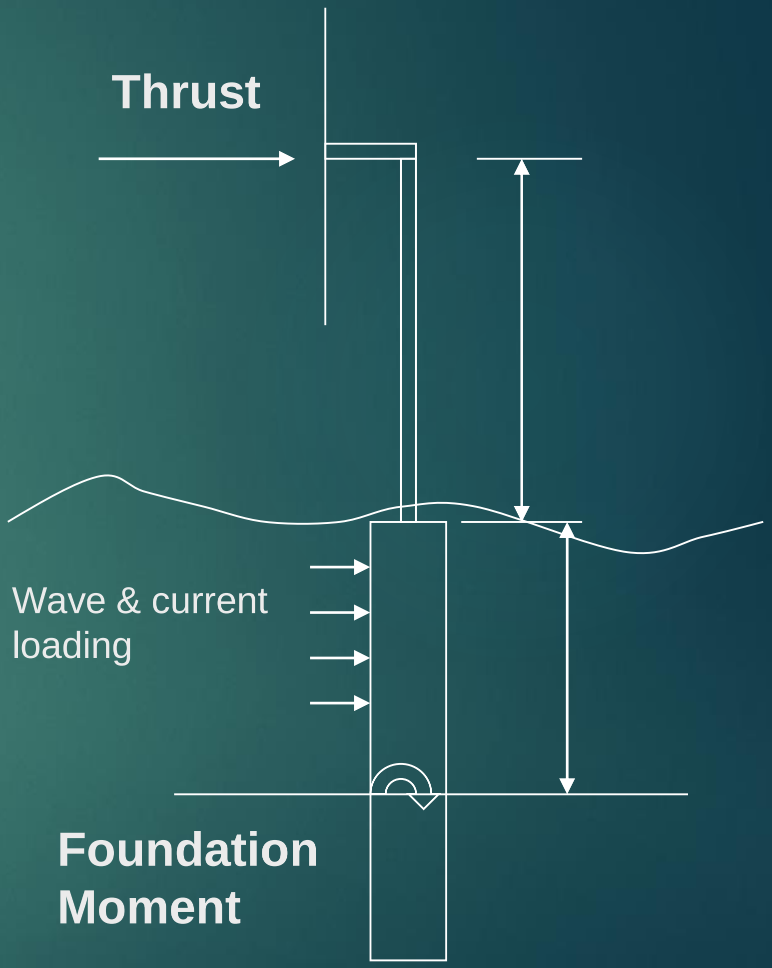
- The wind turbine does not “end” with the tower, there is a support structure on which the machine is placed
- The loading now also includes: wave loading & current loading
- The foundation design in the sea bed is different

The modeling aspect

This sketch shows the “flow of external loading” in the case of a bottom mounted.

In the Floating case the support structure is allowed to move in a rigid body mode which generates additional inertial loads, plus the moorings that hold the floater in place.

Wave & current loading will act on the submerged part of the support structure.



The modeling aspect

The “breakdown” of the full problem

The full description of the behavior of a Wind Turbine can be formulated in terms of appropriate dynamic equations:

$$\frac{dy}{dt} + \mathbf{A}(y, \dot{y}) = \mathbf{F}(y, \dot{y}), \quad \tilde{y} = (y, \dot{y})^T$$

Where

$\tilde{\mathbf{y}}$ denotes the vector of unknown DOFs. $\tilde{\mathbf{y}}$ must contain all the necessary information and describe the complete system. This means that any interaction or coupling (e.g. the fluid solid interactions) should be present. Usually the total number of equations is big!

F denotes the excitation

$\mathbf{A}(\tilde{\mathbf{y}})$ denotes an appropriate operator

If $\mathbf{A}(\tilde{\mathbf{y}}) \neq \mathbf{A}.\tilde{\mathbf{y}}$ and/or $\mathbf{F} = \mathbf{F}(\tilde{\mathbf{y}})$ then the problem is non-linear which is in fact the usual case.

The modeling aspect

The equations include in "packages":

- The aerodynamic equations (e.g. the BEM equations + the dynamic inflow corrections – dynamic stall) related with **y_aero, F_aero**
- The dynamic equations per component. For the blades, the drive train and the tower remains and includes the structural (elastic) kinematics **y_str**. Excitation will come from wind flow, wave & current loads as well as gravity. So **F_str** will not only include "external-field" forcing but also "internal" forcing which would represent coupling-interaction with parts such as the aerodynamic and wave ones.
- The control equations of the system will involve the control variables (pitch & rotor speed) **y_cont** and relate that to input from the machine and our targets **F_cont**. The machine data in this case will give coupling with other parts.

The modeling aspect

- The support structure equations. They depend on the concept. For BOWTs, the support structure is modeled as a flexible component. The same can hold for FOWTs but one should then include in **y_float** also the rigid body motions of the floater. Concerning **F_float** will certainly include the wind and wave loads but also the loads contributed by the WT and by the moorings/foundation.
- The mooring line equations. There are different models available. In any case this part will include **y_moor** and **F_moor**

So putting all together one should have in mind a set-up which includes everything in one single package that contains all possible interactions/couplings.

In order to account for the couplings we distinguish between “external” and “internal” contributions. Contributions will concern both loading terms and kinematic terms.

The modeling aspect

In general: $\mathbf{A} = [\mathbf{A}_{m,n}]$ where m, n refer to one of the following: aero, str, cont, float, moor. So $\mathbf{A}_{m,m}$ represents the "self" operator while all other $\mathbf{A}_{m,n}$ correspond to couplings.

For example, in the "str" equations that concern the WT as a whole, there are internal kinematic connections (placed as a separate "q" column) that include the inter-component couplings: blade-hub, hub-tower connections. However we also have the tower-floater coupling In terms of loading we have gravity loads and aerodynamic loads.

The original form of certain equations are 2nd order (in particular the structural ones) but can be easily transformed into 1st order.

The modeling aspect

How equations are built

The “str” equation will contain the coupling with the “aero” equations and the coupling with the floater.

The “aero” coupling gives a loading term term: $\mathbf{F}_{\mathbf{aero2str}}$ which depends the blade deflections and provides additional stiffness and damping terms.

The coupling with the floater defines the kinematics at the bottom of the tower: i.e. the deflections and their velocities at that point.

The modeling aspect

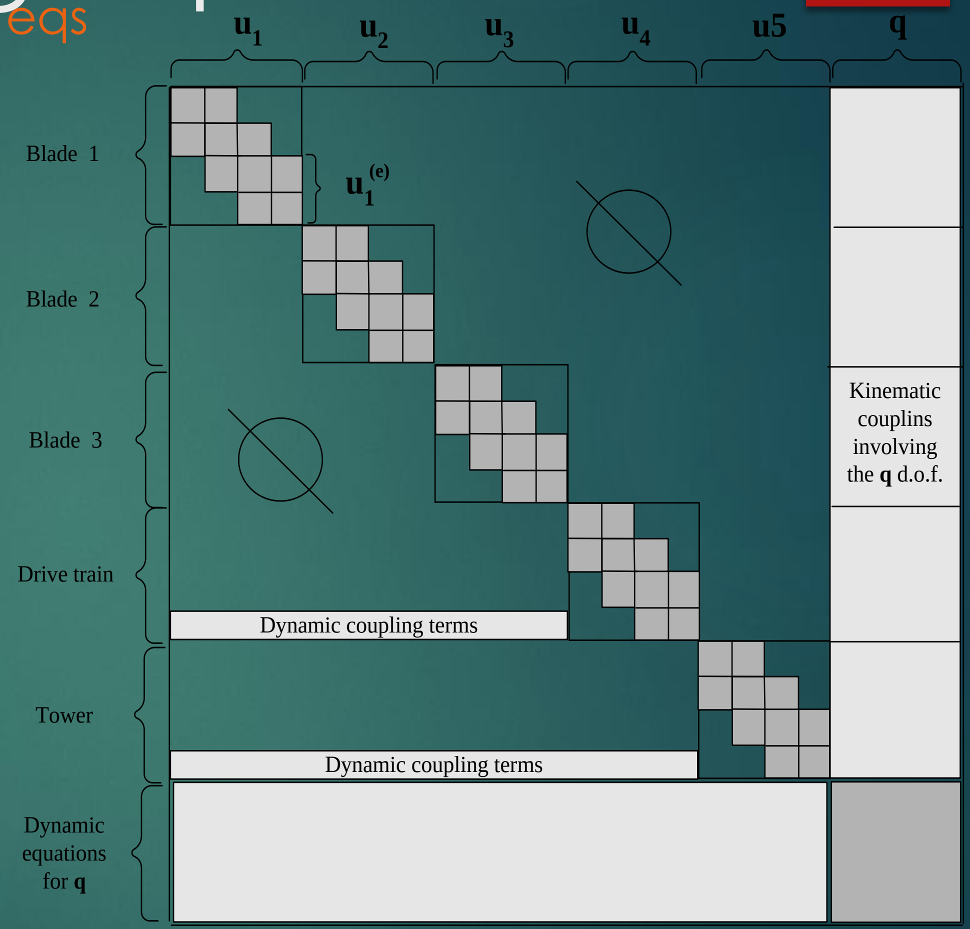
Reminder: The form of the "str" eqs

For the structural equations the kinematic d.o.f.. that refer to the internal connections are collected in **q.** They appear as the last column providing the kinematic coupling, and are involved in separate dynamic equations.

So the dynamic equations will depend on $\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}}$. The corresponding terms are **non-linear** and their **linearization** is done by Taylor's expansions:

$$\mathbf{F} = \mathbf{F_o} + \partial_{\mathbf{q}}\mathbf{F}.\,\delta\mathbf{q} + \partial_{\dot{\mathbf{q}}}\mathbf{F}.\,\delta\dot{\mathbf{q}}$$

Extra equations are needed for **q**'s. For example the eq's of the controller.



$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{D}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{Q} \qquad \mathbf{x} = \left(\hat{\mathbf{u}}^T, \mathbf{q}^T\right)^T$$

The modeling aspect

Reminder: Transformation of "str" eqs as a 1st order problem

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{D}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{Q} \qquad \mathbf{x} = \left(\hat{\mathbf{u}}^{T}, \mathbf{q}^{T}\right)^{T}$$

$$\mathbf{y} = \begin{Bmatrix} \dot{\mathbf{x}} \\ \mathbf{x} \end{Bmatrix}: \quad \tilde{\mathbf{M}}\frac{d\mathbf{y}}{dt} + \tilde{\mathbf{K}}\mathbf{y} = \tilde{\mathbf{Q}} \Rightarrow \frac{d\mathbf{y}}{dt} + \underbrace{\tilde{\mathbf{M}}^{-1}\tilde{\mathbf{K}}}_{\mathbf{A}}\,\mathbf{y} = \underbrace{\tilde{\mathbf{M}}^{-1}\tilde{\mathbf{Q}}}_{\mathbf{F}}$$

$$\tilde{\mathbf{M}} = \begin{bmatrix} \mathbf{M} & 0 \\ 0 & \mathbf{I} \end{bmatrix}, \quad \tilde{\mathbf{K}} = \begin{bmatrix} \mathbf{D} & \mathbf{K} \\ -\mathbf{I} & 0 \end{bmatrix}, \quad \tilde{\mathbf{Q}} = \begin{Bmatrix} \mathbf{Q} \\ 0 \end{Bmatrix}$$

- Because the mass matrix is invertible, the above equations can take exactly the form we have shown in the beginning.
- In fact the above form is the basis for investigating linear stability.

The modeling aspect

So after transforming the equations into 1st order we obtain:

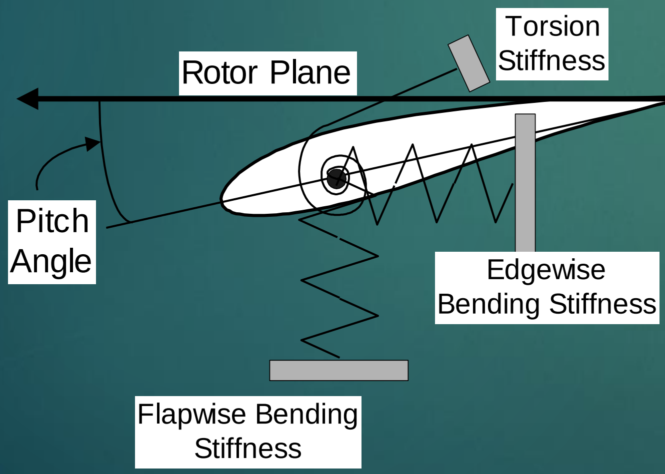
$$\frac{\mathrm{d}\,\mathbf{y}_{\mathrm{str}}}{\mathrm{dt}} + \mathbf{A}_{\mathrm{str,str}} \cdot \mathbf{y}_{\mathrm{str}} + \mathbf{A}_{\mathrm{str,aero}} \cdot \mathbf{y}_{\mathrm{aero}} + \mathbf{A}_{\mathrm{str,contr}} \cdot \mathbf{y}_{\mathrm{contr}} + \mathbf{A}_{\mathrm{str,float}} \cdot \mathbf{y}_{\mathrm{float}} = \mathbf{F}_{\mathrm{str}}$$

Which can be generalized as follows:

$$\frac{\mathrm{d}}{\mathrm{dt}}\begin{Bmatrix}\text{structural}\\ \text{aerodyna}\\ \text{control}\\ \text{floater}\\ \text{mooring}\end{Bmatrix} + \begin{bmatrix}\otimes & \times & \times & \times & 0\\ .. & \otimes & .. & & \\ & & \otimes & & \\ & & & \otimes & \\ & & & & \otimes\end{bmatrix}\begin{Bmatrix}\text{structural}\\ \text{aerodyna}\\ \text{control}\\ \text{floater}\\ \text{mooring}\end{Bmatrix} = \begin{Bmatrix}\text{gravity}\\ \text{inflow data}\\ \text{target curve / values}\\ \text{boyancy} + \text{wave} + \text{current}\\ \text{boyancy} + \text{wave} + \text{current}\end{Bmatrix}$$

Reminder: Aeroelastic coupling

- One difficulty in rotor aerodynamics is lift and drag are defined with respect to the **relative** to the blade flow
- So when the blade is deforming then the velocity of deformation as well as the deformation of its orientation must be included
- Deformation will be vibratory and therefore we will have unsteady aerodynamics
- The time dependence is however indirect. Aerodynamic loads will depend on deformations and deformation velocities which are not known before hand.



Bending will give horizontal and vertical motion/velocity

Torsion will give change in the angle of attack and angular (pitching) velocity

Mooring line modeling: Introduction

Note At sea bed it is important to "prevent" the truss element to cross the limiting line. This is done by means of "non-linear springs"

The mooring line is split into truss (straight) elements that only transmit axial loads.

Every element is defined by its two end points.

The deformation derives from the different repositioning of the ends as a change in length

The mooring line equations are "dynamic equilibrium relations" subjected to boundary conditions.

At the sea bed the position is fixed while at the connection point the mooring line follows the floater motions

Wave & Current loading

The main objective is to determine the loads contributed by the water flow on the support structure.

Basically there exist two types of models: A “simple” one based on Morison’s equation and a more complicated one based on hydrodynamic theory.

For BOWTs the Morison’s equations is exclusively used.

For FOWTs both options are currently applied but wave theory is clearly more accurate and should be preferred.

In all cases the basic idea is to integrate the pressure on the submerged surface while pressure itself is determined through a flow solver.

Wave & Current loading

Morison's equation

The idea is simple: wave loading should depend on acceleration, velocity and position.

The loading because of the "position" will contain static buoyancy which is due to the pressure distribution over the mean wetted floater surface. According to Archimedes law this is equal to the volume times water density times g.

The loading due to velocity "u" has the form of drag and is ~velocity^2

The loading due to acceleration "a" has the form of a "volume" load.

Notes:

- If the floater is "moving" then one should refer to relative velocity $\dot{q}$ and acceleration $\ddot{q}$.
- C_a, C_d are constants that depend on the shape of the body.

$$dF = C_m \rho \, dV \, a_n - C_a \, \rho \, dV \, \ddot{q}_n + 0.5 \, C_d \, \rho \, dA \, |u - \dot{q}|_n \, (u - \dot{q})_n , \qquad C_m = 1 + C_a$$

Wave & Current loading

Hydro-dynamic theory

Wave loading is usually formulated in the context of potential theory.

$\nabla^2 \varphi = 0$

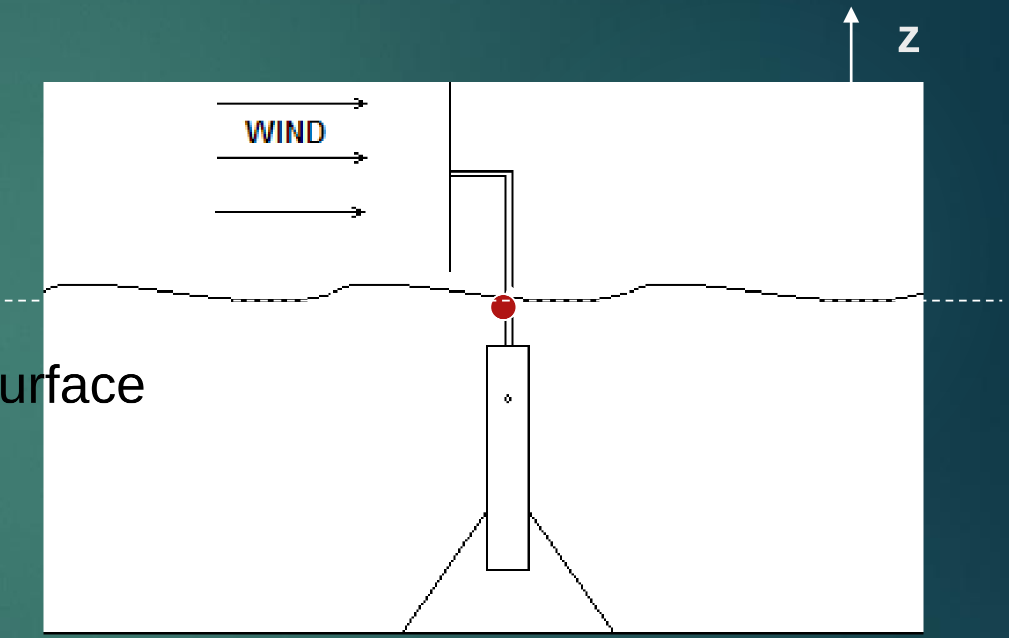
$\partial_z \varphi = 0$ at the sea bottom

$\partial_z \varphi = \partial_t \zeta$ at the free surface

$\partial_t \varphi + \frac{1}{2} |\nabla \varphi|^2 + g\zeta = 0$ at the free surface

$\partial_n \varphi = U_{B,n}$ at the body surface

$\hat{\varphi} \to O(r^{-1/2} e^{-ikr})$ in the far field



One particular difficulty of water waves is that water waves are non-local and dispersive.

Wave & Current loading

In off-shore hydrodynamics we can define two problems:

- The diffraction problem which corresponds to the effect an incident wave has. There will be pressure acting on the solid surface because of the wave but there will also be a back disturbance from the submerged body on to the wave.
- The radiation problem which assumes that the sea is originally still but the body is moving. Then waves will be formed near the body and propagating outwards. They will generate a pressure field on the body surface.

  Note that once a radiating wave is formed it will affect the body dynamics until it gets far enough. This provides the non-locality of water waves

Let v_i denote the velocities of the submerged structure and R_{ij} the hydrodynamic response then the wave loading due to radiation is obtained:

$$F_i(t) = \int_{-\infty}^{t} R_{ij}(t-\tau)v_j(\tau)d\tau$$

Linear theory

The field equation for the diffraction as well as the radiation problems is the Laplace. Only the boundary conditions change and again not all. The basic wave character remains the same.

Consider the <u>linear case</u> (Airy wave theory):

$$\text{at the free surface: } \partial_t\varphi + \cancel{\tfrac{1}{2}|\nabla\varphi|^2} + g\zeta = 0,\ \partial_z\varphi = \partial_t\zeta$$

$$\text{if } \zeta = \zeta_0 \cos(kx - \omega t) \Rightarrow$$

$$\varphi = \frac{\omega}{k}\zeta_0 \underbrace{\frac{\cosh(k(z+h))}{\sinh(kh)}}_{\text{the basic term}} \sin(kx - \omega t)$$

In order to get non trivial wave amplitudes, the rotational frequency and the wave number, i.e. the time and space “scales” must satisfy the dispersion relation:

$$\omega^2 = gk\tanh(kh)$$

Linear Theory

In the linear case (small free surface elevations) and for an axi-symmetric body, the diffraction and radiation problems in the frequency domain admit closed form expressions.

Then the diffraction loading is obtained by integrating the pressure distribution on the surface and then back transforming in time.

In the non-linear case and for “slim” bodies, an acceptable approximation is that there is no interaction, or else that the wave is not modified by the presence of the body.

In this case (Froude Krylov wave loads) the incident wave is given together with its associated potential from which we can calculate the pressure distribution.

The final equation takes the form:

Linear theory

$$(\mathbf{M}+\mathbf{a}_\infty)\ddot{\mathbf{x}}+\int_0^t \mathbf{R}(t-\tau)\dot{\mathbf{x}}(\tau)d\tau+(\mathbf{K}_\mathrm{H}+\mathbf{K}_\mathrm{G}+\mathbf{K}_\mathrm{EXT})\,\mathbf{x}=$$

$= \mathbf{F}_{exc}^{(1)}$ (1st order hydrodynamic loads)

$+\mathbf{F}_{exc}^{(2)}$ (2nd order hydrodynamic loads)

$+\mathbf{F}_{Moor}$ (from the mooring lines - one or more)

$+\mathbf{F}_{WT}$ (from the WT at the tower-floater connection)

$+\mathbf{F}_{visc}$ (surface viscous loads)

$+\delta_{\iota 3}(B\text{-}W)$ buoyancy/weight

Where M is the mass matrix, $\boldsymbol{a}_\infty$ is the added mass, and

$\mathbf{K}_\mathrm{H}$ hydrostatic stiffness, $\mathbf{K}_\mathrm{G}$ restoring stiffness

$\mathbf{K}_\mathrm{EXT}$ any other stiffness

Future work

Technical aspects:

- Linear wave theory is in general sufficient but not for non-linear waves. Currently there is research activity towards the consideration of non-linear waves. A reliable extreme loads estimation is missing.
- Validation of design tools is still missing at least for the FOWTs.
- Conclude a systematic certification procedure.
- Design low cost wind turbines (increase the size to 10MW and more)

Linear Solution

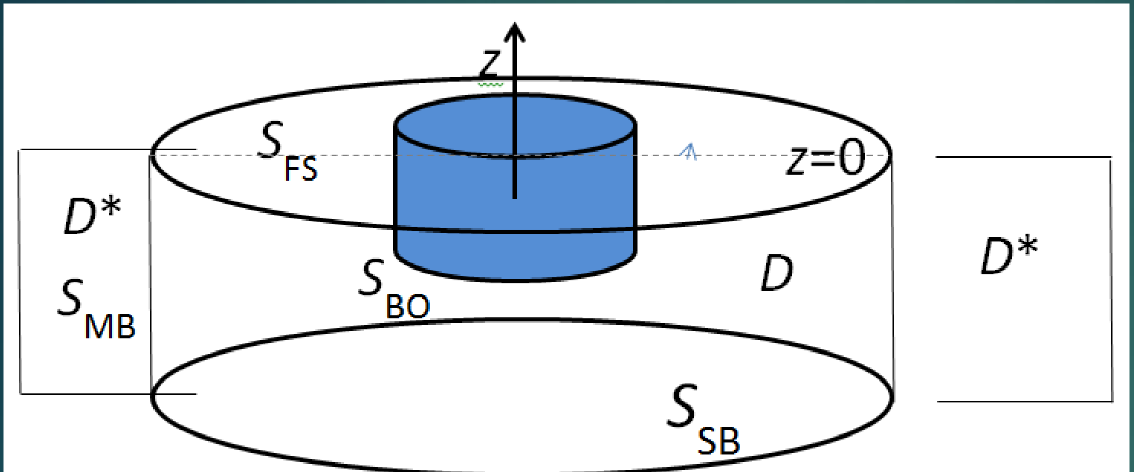


Figure 4-1: Definition of the inner domain *D*, the boundary surfaces and the outer domain *D**

$$\Phi(x,y,z;t)=\mathrm{Re}[\varphi(x,y,z)\,\mathrm{e}^{-i\omega t}]$$

$$\varphi=\varphi_I+\varphi_0+\varphi_R=\varphi_I+\varphi_0-i\omega\sum_{j=1}^{6nb}\tilde{x}_j\ \varphi_j=\varphi_D+\sum_{j=1}^{6nb}\dot{\tilde{x}}_j\ \varphi_j$$

$$\varphi_I=-\frac{igA}{\omega}\frac{\cosh[k(z+d)]}{\cosh[kd]}e^{ik(x\cos\theta+y\sin\theta)}\qquad \varphi_I=-\frac{igA}{\omega}e^{kz}e^{ik(x\cos\theta+y\sin\theta)}\ \text{[deep water]}$$

Linear solution

General expression: $p=-\rho\dfrac{\partial\varphi}{\partial t}=i\omega\rho\varphi \Rightarrow F=-\int_S pndS=-i\omega\rho\int_S \varphi ndS$

Excitation force: $F_{EXC_k}/A=-i\omega\rho\int_S(\varphi_I+\varphi_0)\hat{n}_k dS$,k=1:6

Reaction force:

$$F_{REACT_k}=-i\omega\rho\int_S \varphi_R\hat{n}_k dS=-\omega^2\rho\int_S x_j\varphi_j\hat{n}_k dS=\omega^2\left(a_{kj}+\frac{i}{\omega}b_{kj}\right)x_j\ ,\ \ k=1:6,\ j=1:6*nb$$

$$\left(a_{kj}+\frac{i}{\omega}b_{kj}\right)=-\rho\int_S \varphi_j\hat{n}_k dS\ ,\ \ k=1:6,\ j=1:6*nb$$

Linear theory

$$F_{H_i}(t) = -\sum_{j=1}^{6}\left\{\bar{a}_{ij}\cdot\ddot{\xi}_j(t)+\int_{-\infty}^{t} R_{ij}(t\text{-}\tau)\cdot\dot{\xi}_j(\tau)\cdot d\tau\right\}+F_{wav_i}(t)+F_{D_i}(t)+\rho\cdot g\cdot V_0\cdot\delta_{i3}\text{-}K_{hyd_{ij}}\cdot\xi_j(t)$$

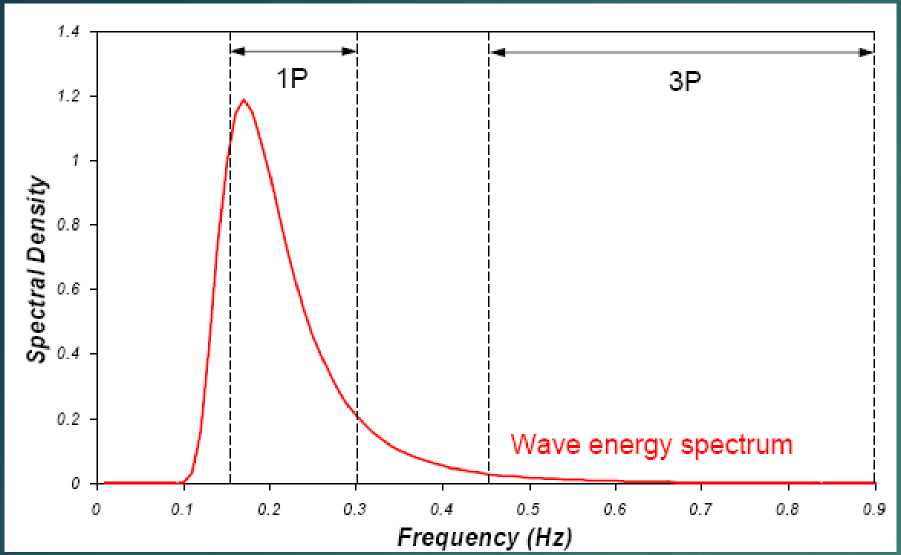
$$\bar{a}_{ij} = \lim_{\omega\to\infty} a_{ij}(\omega)$$

$$R_{ij}(t) = \frac{2}{\pi}\int_{0}^{\infty} b_{ij}(\omega)\cdot\cos(\omega t)\cdot d\omega$$

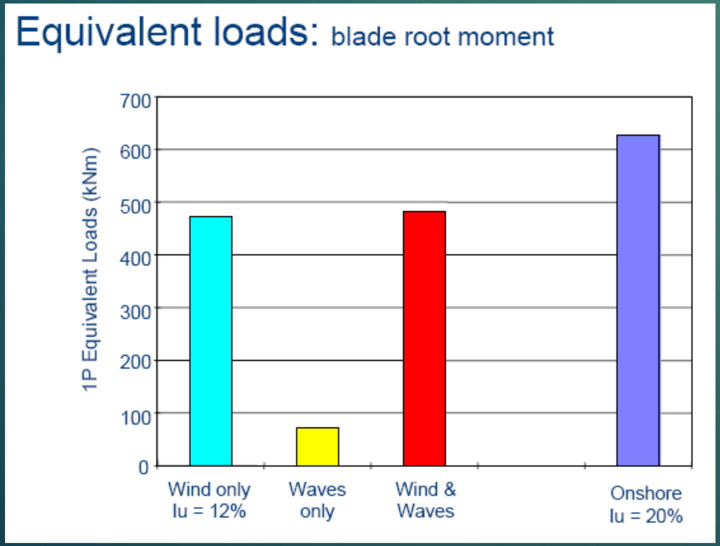
$$F_{wav_i}(t) = \frac{F_{wav_i}(\omega)}{A}\cdot A\cdot\cos(\phi_i(\omega)\text{-}\omega t+\varepsilon_i)$$

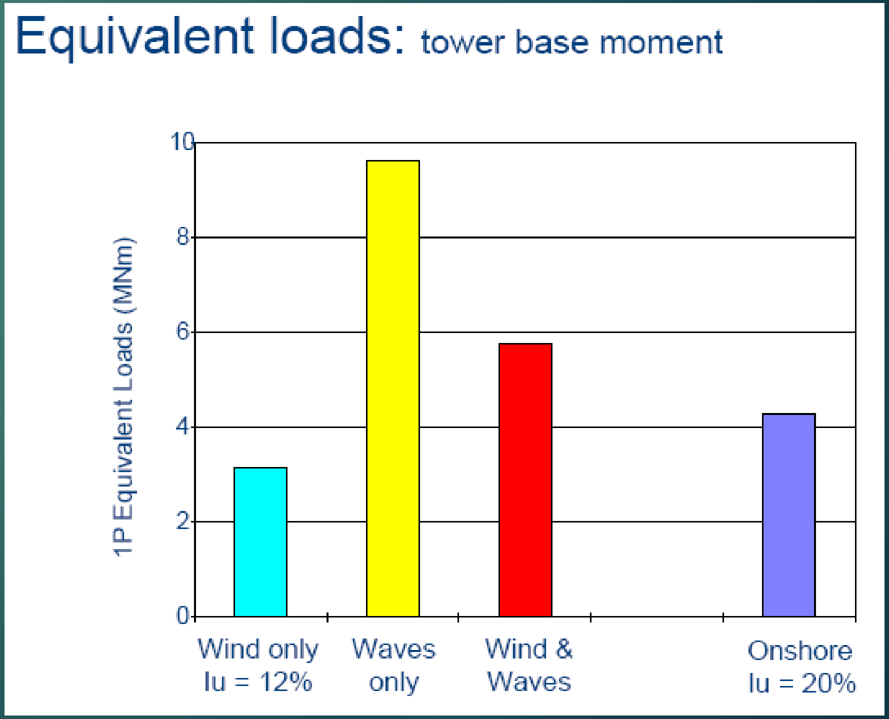
$$F_{wav_i}(t) = \sum_{i=1}^{n}\frac{F_{wav_i}(\omega_i)}{A}\cdot\sqrt{2S(\omega_i)d\omega}\cdot\cos(\phi_i(\omega_i)\text{-}\omega_i t+\varepsilon_i)$$

$$F_{D_i}(t) = \frac{\rho}{2}C_D S\left|U_{rn_i}(t)\right|\cdot U_{rn_i}(t)$$



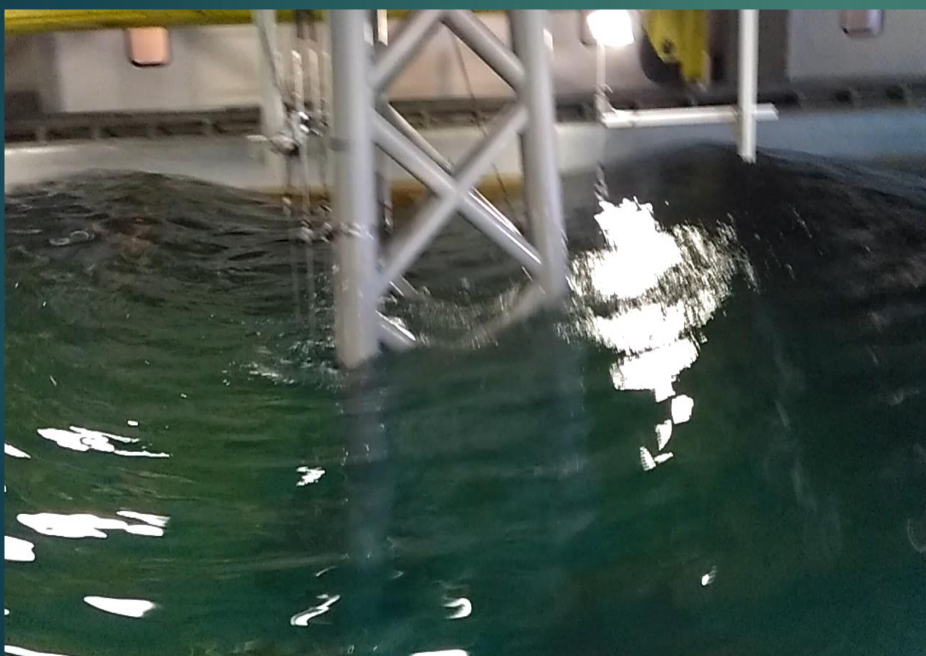
Wave loading is stochastic and therefore will add to fatigue but it seems that this goes on the support structure …

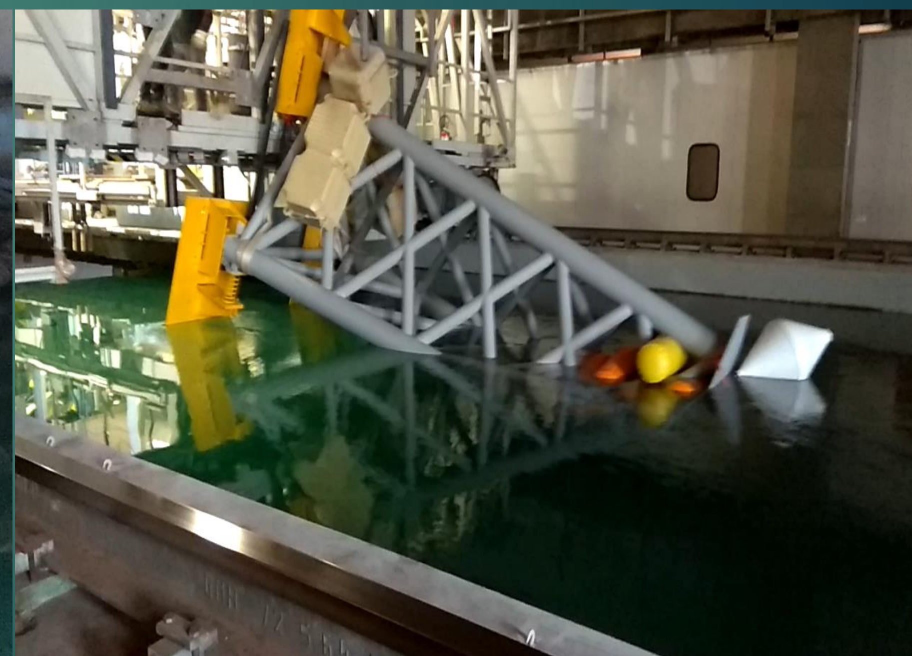




Research at NTUA

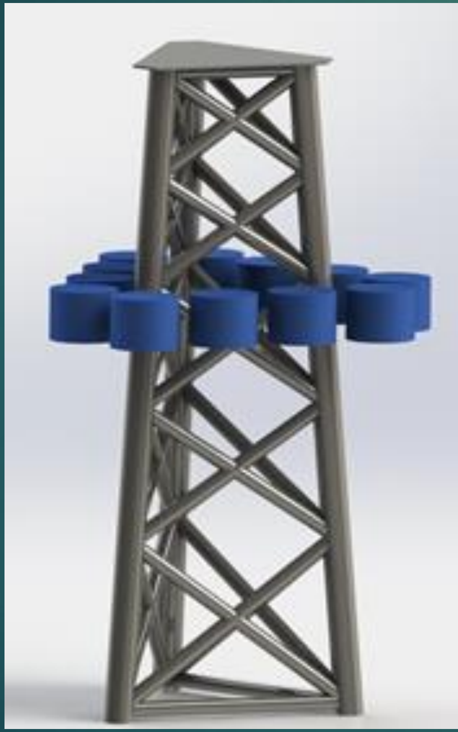
The VIHYDRO II project
Experiments performed at CNR-INM Basin in Rome Italy to assess the soil structure interaction with a three-legged jacket platform for large output OWT

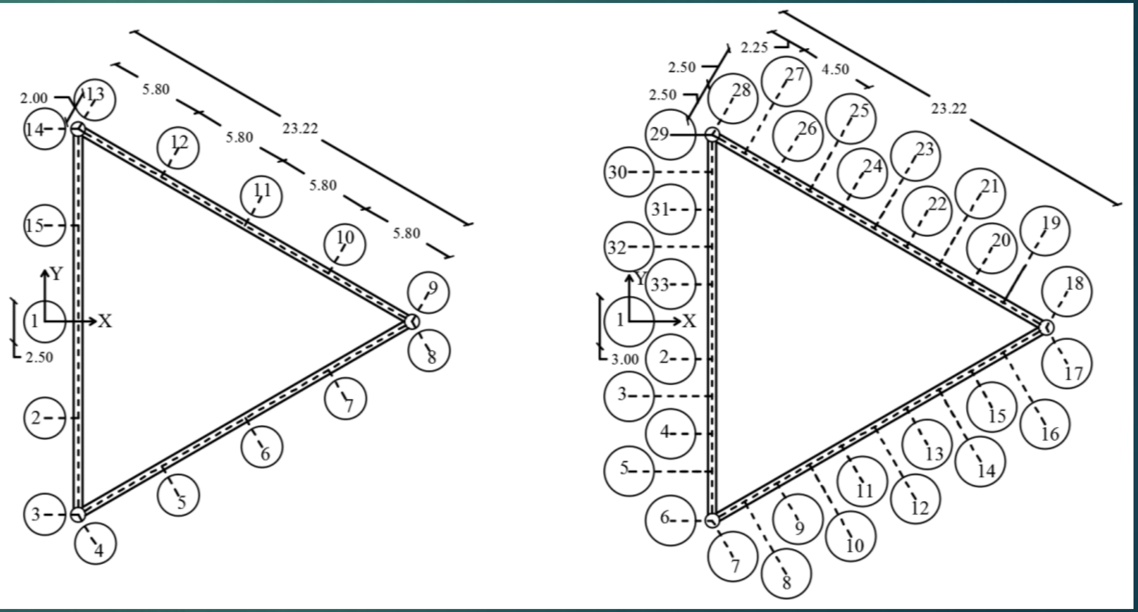




Hybrid Offshore Wind Energy Systems – hybrid jacket

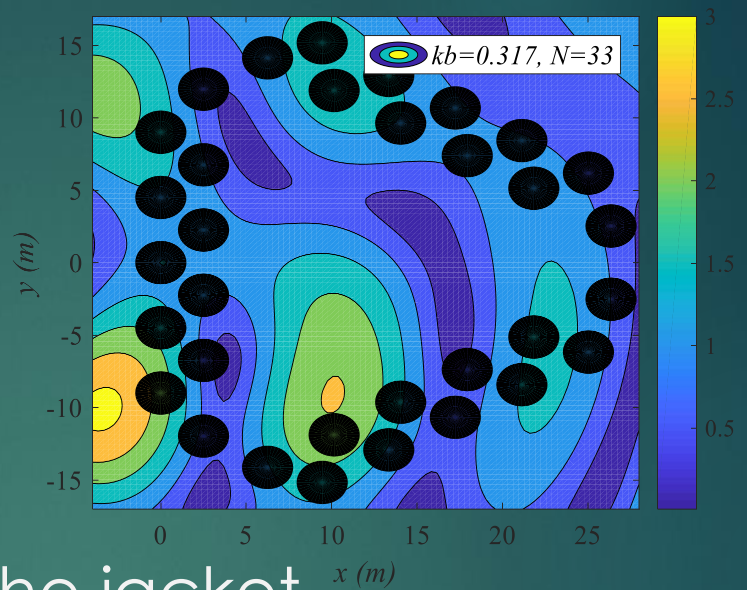
- A novel, pioneering concept that aims at exploiting both wind and wave energy offshore
- By increasing 2% of the an OWT power output, one could absorb the OWT construction cost, during its lifetime



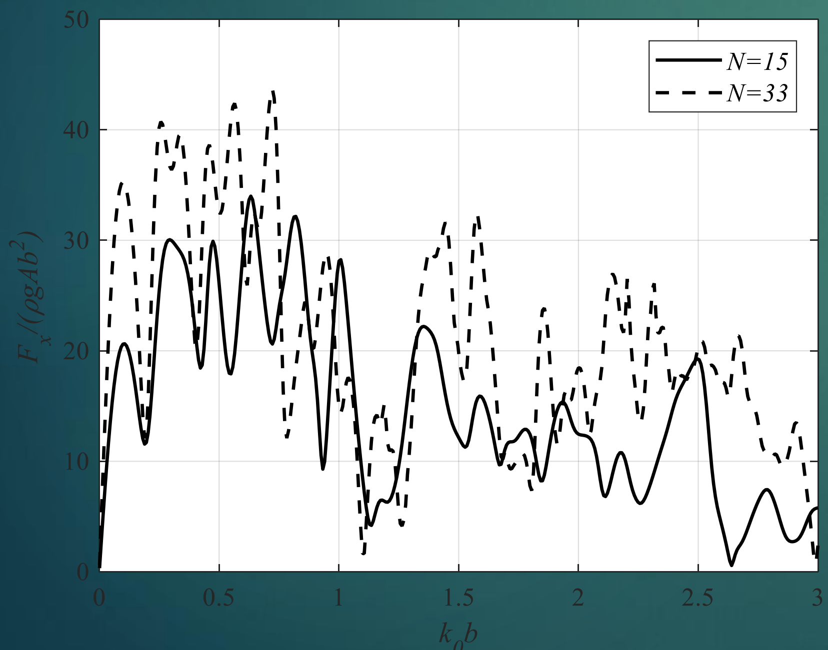


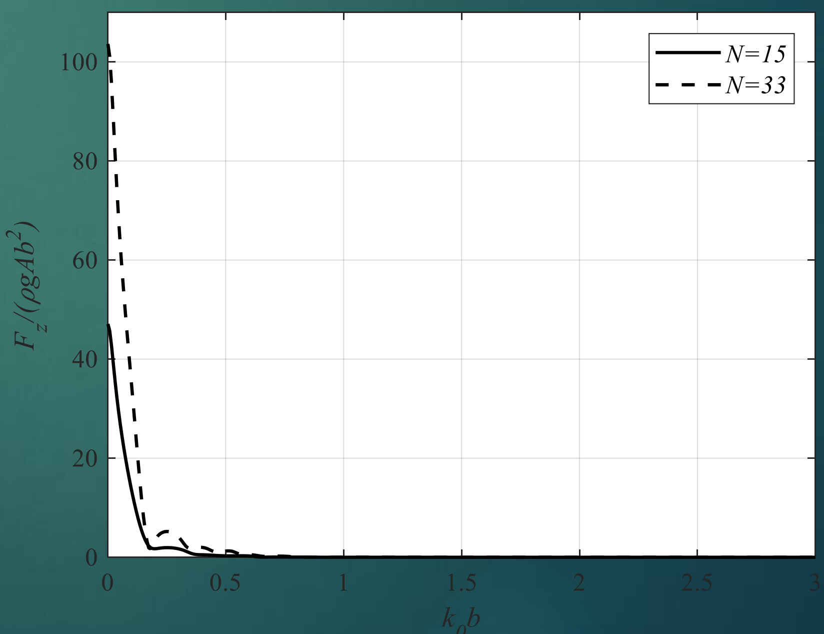
Hybrid Jacket

A fully diffracted wave field is generated
– the structure within heavy disturbances



Loading on the jacket





Thank you for listening