WE
CAN DO
SO MUCH
TOGETHER

Multiphysics Analyses for Offshore Wind

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EphysLab, Ourense
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DSS2016.EU

DSSINNOVA 2016

Index

INTRO

R&D Activities

INTRO

- 2004. **Marine Energy area** creation
- 2009. Floating solutions for **offshore wind**
- 2012. I joined the group to focus on multiphysics, on dynamic design and analysis. Before I researched on experimental and numerical determination of railway induced vibrations for 3 years
- 2017. Area was renamed to **Offshore Renewable Energy** (ORE)
- During these years, tight collaboration with industry (as example: Oceantec in wave energy and and Nautilus Floating Solutions start-ups). From design to certification and coordination of operations.

INTRO \ Offshore Renewable Energy at TECNALIA

Offshore Wind technologies

- Innovations for cost reduction in fixed offshore wind farms
- Design and analysis tools for fixed and floating structures
- Station-keeping systems design and analysis
- Experimental laboratories
- Control strategies for RNA and floating structure
- Test and analysis of materials and components for harsh environments

Wave and Tidal Energy

- Design tools for the optimisation of arrays
- Performance assessment
- Station-keeping systems design and analysis
- Optimisation of Power Take-Off and Control systems

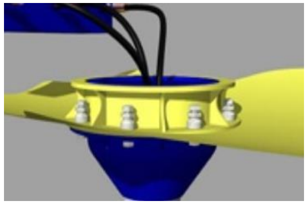
Electrical connections

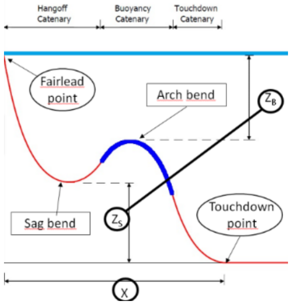
- Power cable and underwater connectors design and analysis
- Cable installation procedures and new devices
- Superconductor generators

INTRO \ Offshore Renewable Energy at TECNALIA

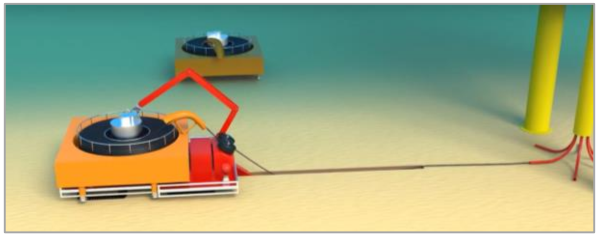
Electrical engineering

- Bottom-fixed and floating **power cable design** and analysis



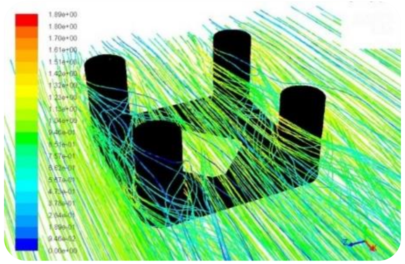


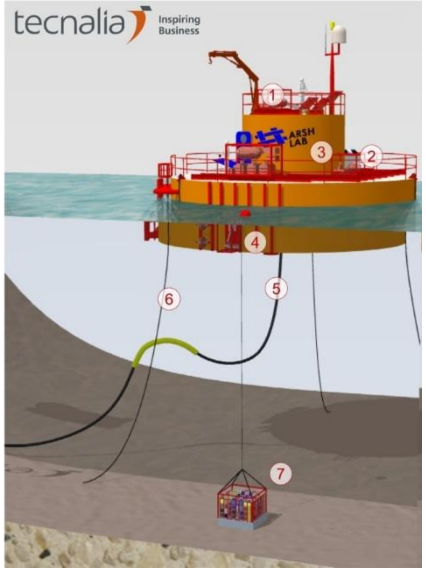
- Electrical **underwater connector** designs
- **Cable installation solutions** for significant cost reductions (SCARGO) [1]



Offshore technologies

- HARSH-Lab, a floating offshore laboratory moored at BiMEP (corrosion, special tests, offshore crew training) [2]



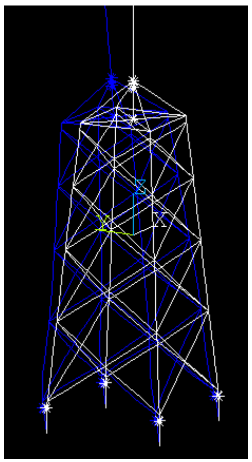


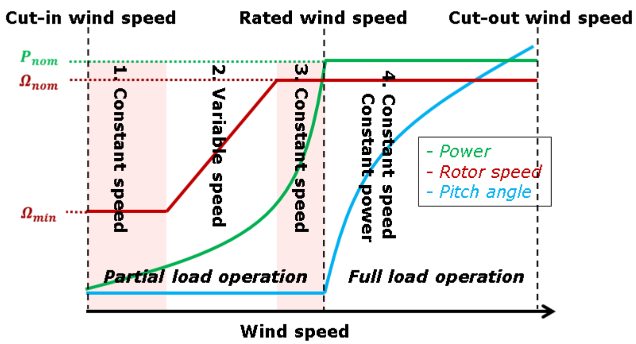
- **Numerical wave basin** models for hydrodynamics characterisation of offshore devices and components

INTRO \ Offshore Renewable Energy at TECNALIA

Offshore bottom-fixed technology

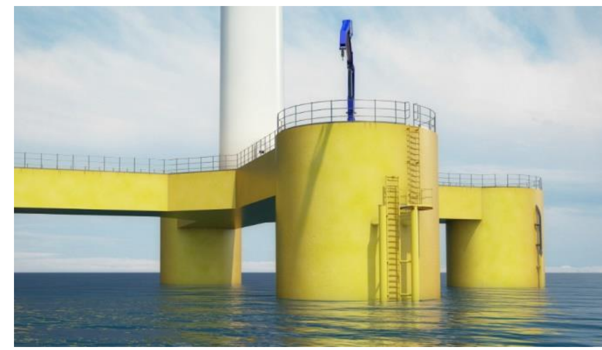
- Offshore Wind Turbine design, analysis and optimisation

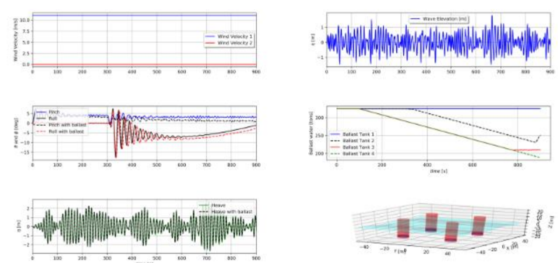




Floating offshore wind technology

- Floating Offshore Wind Turbine design (processes reviewed by Ramboll and DNV-GL), analysis and optimisation, mainly focused on NAUTILUS development [3]





Control engineering

- WT controller tuning
- Floating Platform Trim System (PTS) design and analysis

INTRO \ R&D Activities \ **FLOTTEK**

- En 2010 TECNALIA promueve el proyecto FLOTTEK, con GAMESA e Iberdrola Ingeniería, entre otros socios.
- La estrecha colaboración GAMESA-Iberdrola-TECNALIA permite el diseño y ensayo en canal de la solución TLP de Iberdrola.
- **Descripción de nuestra contribución**:
  - Responsables del diseño de la estructura flotante a partir de una idea de Iberdrola IC: diseño, modelización, simulación (hidrodinámica y estructural)
  - Definición, supervisión y análisis de los resultados de las pruebas en canal (CEHIPAR)
  - Colaboración con GAMESA e IBERDROLA IC para proporcionar información que les sirva para sus modelos acoplados.

Fig. 1: TLP Wind. (Source: energias-renovables.com)

IBERDROLA

Gamesa

INTRO \ R&D Activities \ **HiPRWind**

- En 2010 TECNALIA participa en el proyecto HiPRWind, con Fraunhofer IWES, ACCIONA, VICINAY, IDESA, NTNU, Olav Olsen, SINTEF, TECHNIP…
- Diseño y construcción de un demostrador a escala de un aerogenerador flotante (1,5MW) para hacer pruebas durante dos años en la Costa Vasca.
- **Descripción de nuestra contribución**:
  - Responsables del paquete de trabajo de "operación del aerogenerador flotante" que incluye la definición de las pruebas a realizar y la transmisión de la información, la definición de los protocolos de acceso, el mantenimiento, etc.
  - Participación en el diseño de la estructura flotante y los fondeos. Proporcionar información océano-meteorológica de bimep.
  - Participación en el paquete de trabajo de definición de nuevos sistemas de control y estrategias de conexión a red para grandes aerogeneradores (>10MW)

Fig. 2: HiPRWind platform (Source: tu.no)

INTRO \ R&D Activities \ **NAUTILUS**

- En 2012 TECNALIA presenta su apuesta a posibles inversores (empresas industriales) y consigue el apoyo de cuatro empresas: Astilleros Murueta, Tamoin, Velatia y Vicinay.
- En 2013 se constituye Nautilus Floating Solutions S.L. para desarrollar soluciones flotantes para eólica offshore

nautilus floating solutions

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ASTILLEROS DE MURUETA

VICINAY CADENAS S.A. The future of mooring

TAMOIN

velatia

Acuerdo de colaboración

IBERDROLA

INTRO \ R&D Activities \ **LIFES50+**

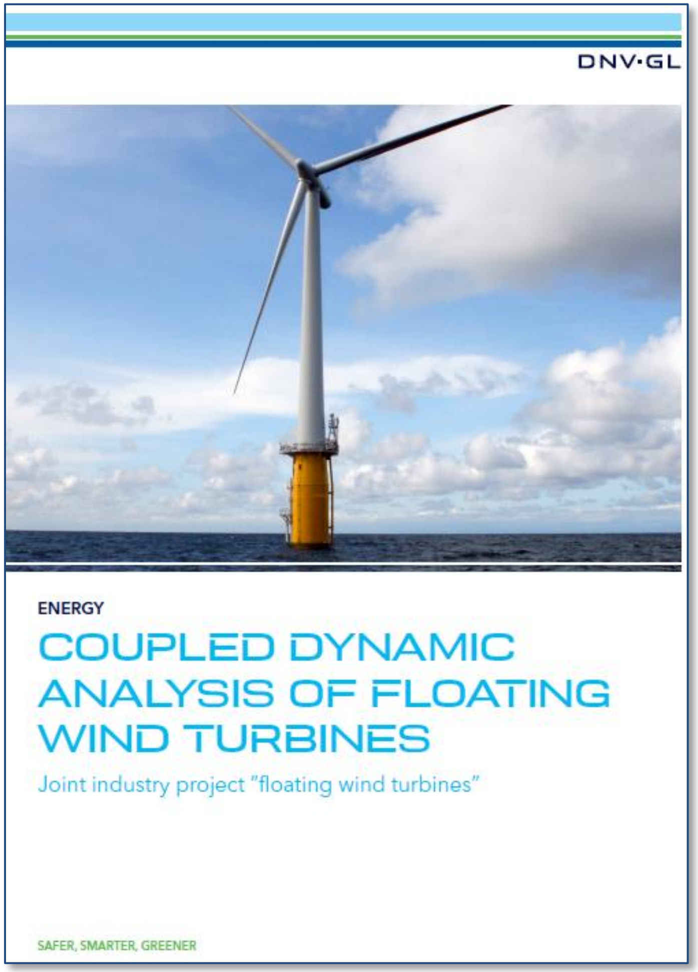
LIFES50+ Qualification of innovative floating substructures for 10MW wind turbines and water depths greater than 50m.

- Optimizar y llevar a TRL5 dos diseños de subestructuras innovadoras para eólica flotante y turbinas de 10 MW.
- Desarrollar una metodología basada en KPI (Key Performance Indicators) para el proceso de evaluación y calificación de subestructuras flotantes.

INTRO \ R&D Activities \ **DNVGL-JIP**

Joint Industry Project - Coupled Dynamic Analysis of Floating Wind Turbines

- Promoted by DNV-GL
- Participants:
  - Siemens WP, EDF, Gicon, Glosten, Ideol, Marin, NREL, Olav Olsen, Ramboll, STX Europe, NAUTILUS (TECNALIA), Esteyco (IH Cantabria) and MARINTEK
- Extension of IEA Wind Task 30: 2014-2022
  - A Recommended Practice intended to provide an internationally acceptable design standard for the dynamic analysis of floating wind turbines. The document will be subject to a wider industry stakeholder consultation and later become publicly available.



International Energy Agency

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OC5 **O**ffshore **C**ode, **C**omparison, **C**ollaboration, **C**ontinued, with **C**orrelation

- Code-to-data validation of offshore wind modelling tools.
- Extension of IEA Wind Task 30: 2014-2018
- Three phases – examining three different systems
  - Semisubmersible tested by DeepCwind in 2011 was re-tested at MARIN in 2013 with new, better perfo
  - Turbi stock 5MW
  - Serie tests

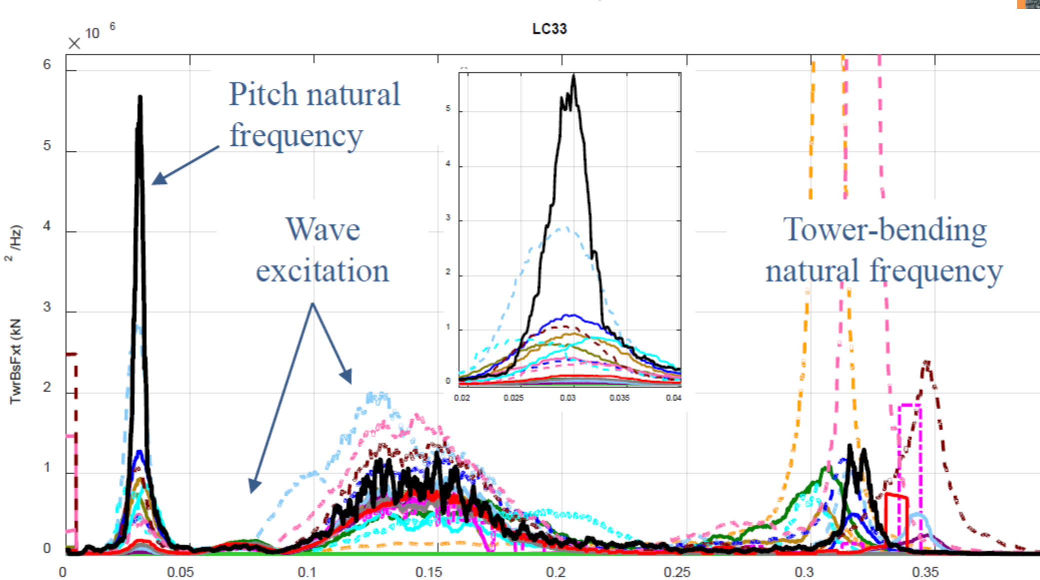


Fig. 5: OC5 Phase II results, motivating the extension of IEA task 30

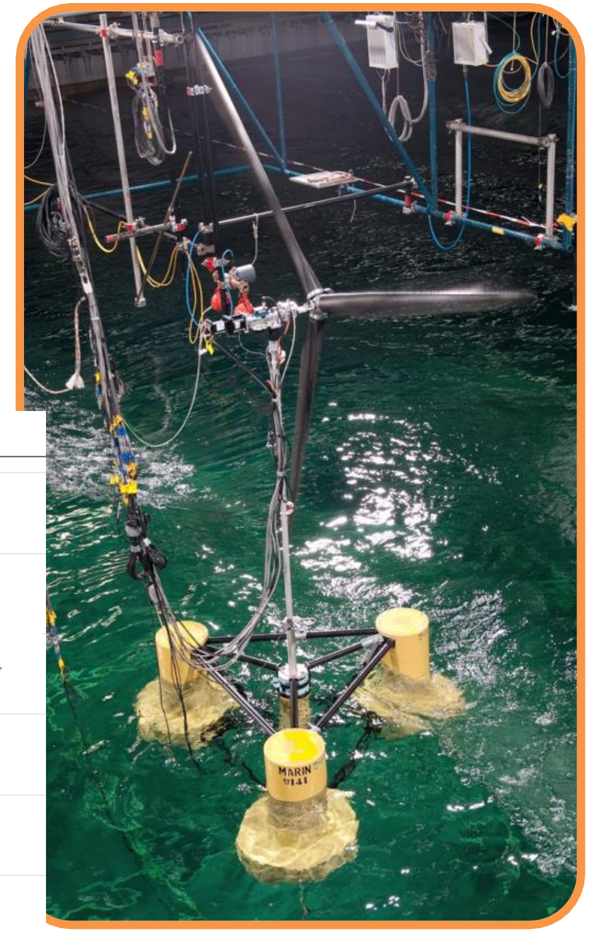
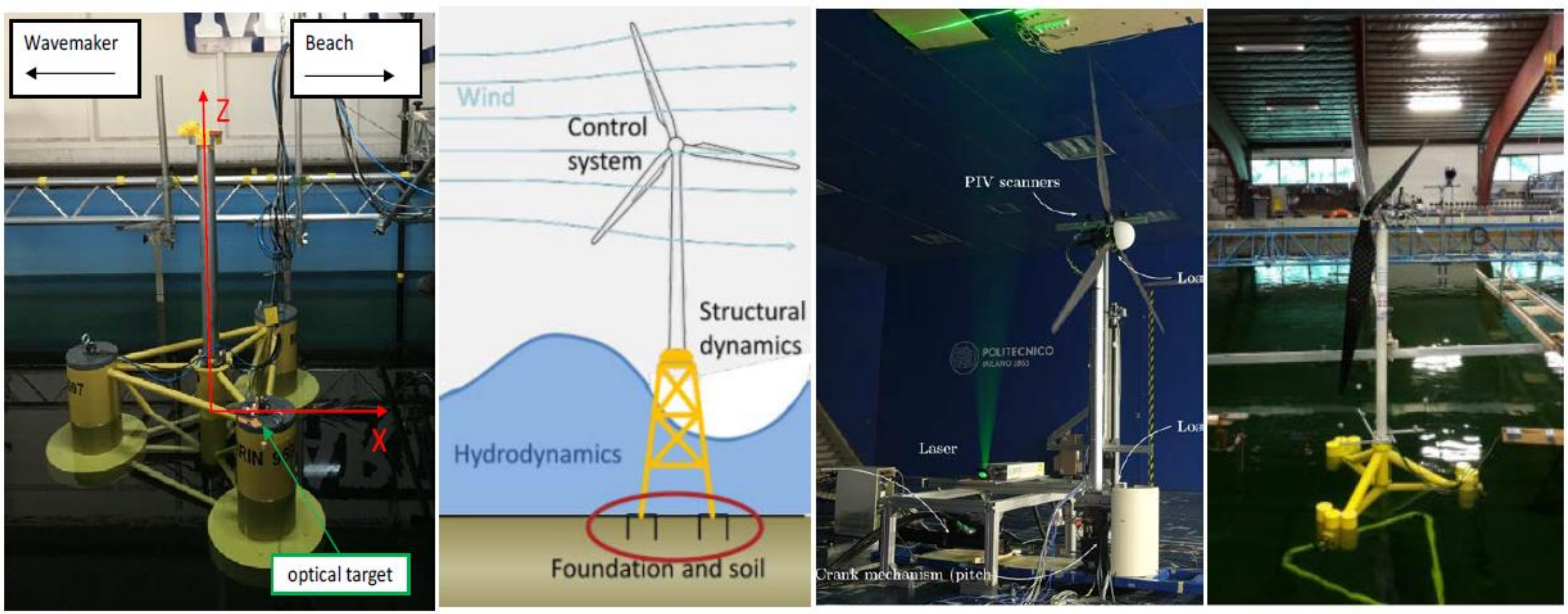


Fig. 4: OC5-DeepCWind semisubmersible 1/15 scale model, tested at MARIN. (Source: OC5 IEA project)

OC6 **O**ffshore **C**ode, **C**omparison, **C**ollaboration, **C**ontinued, with **C**orrelation and Un**C**ertainty

OC6 Project Phases

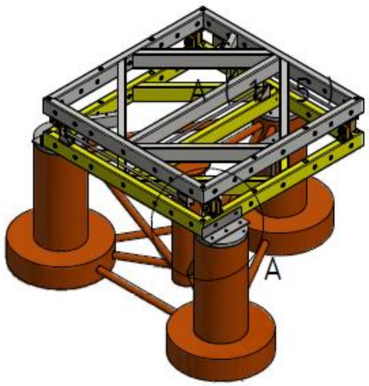


Phase I: Nonlinear Hydrodynamics Jan 2019 – Dec 2019 (OWN TESTING)	Phase II: Soil/Structure Interaction Jan 2020 – June 2020 (REDWIN)	Phase III: Aerodynamics under Motion July 2020 – June 2021 (LIFES50+)	Phase IV: Hydrodynamic Challenges July 2021 – June 2022 (STIESDAL)

Fig. 6: International Energy Agency, task-30 extension OC6 –Project phases. (Source: OC6 IEA Project, phase I, CFD kick-off meeting)

OC6 **O**ffshore **C**ode, **C**omparison, **C**ollaboration, **C**ontinued, with **C**orrelation and Un**C**ertainty

Phase I – Non-linear hydrodynamics



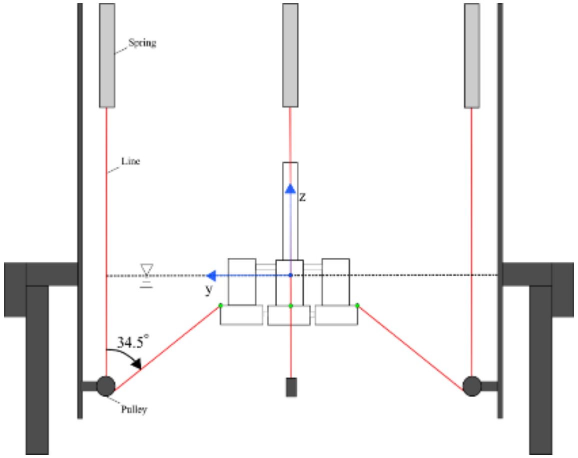
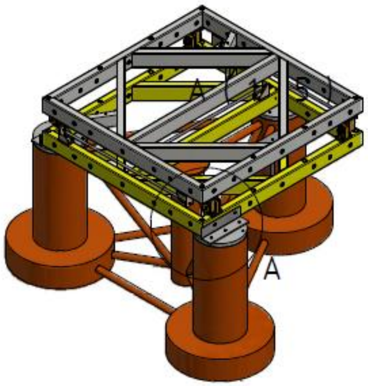


Fig. 6: Constrained and moored configuration of the floating platfrom

- Focus on the study of hydrodynamics only
- Low-uncertainty experimental tests campaigns at MARIN (220 x 4 x 3.6 m)
  - Current only tests
  - Waves only with model moored and constrained
  - Decay tests

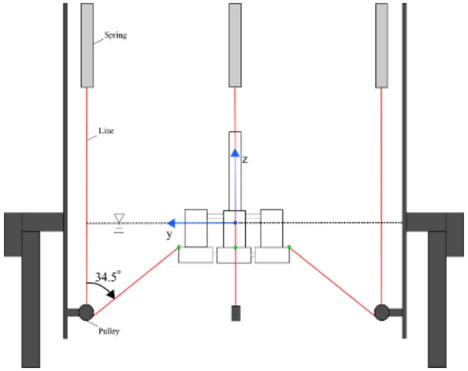
OC6 – Phase I – Non-linear hydrodynamics: **Constrained tests at MARIN**

- Towing test (only surge): 0.5:0.5:3 m/s
- Forced oscillations in surge: 3 periods x 2 amplitudes
- Test in waves: 2 regular waves + Jonswap + White noise
- Additional tests in waves: Bicromathic wave



OC6 – Phase I – Non-linear hydrodynamics: **Moored tests at MARIN**

- Decay tests: 3 DOF, 2 amplitudes
- Test in waves: 2 regular waves + Jonswap + White noise
- Additional tests in waves: Bicromathic wave



TOOLS, MODELS AND PROCEDURES

Approaching the problem

Numerical tools

Verification, calibration and validation

Floating offshore-wind concepts

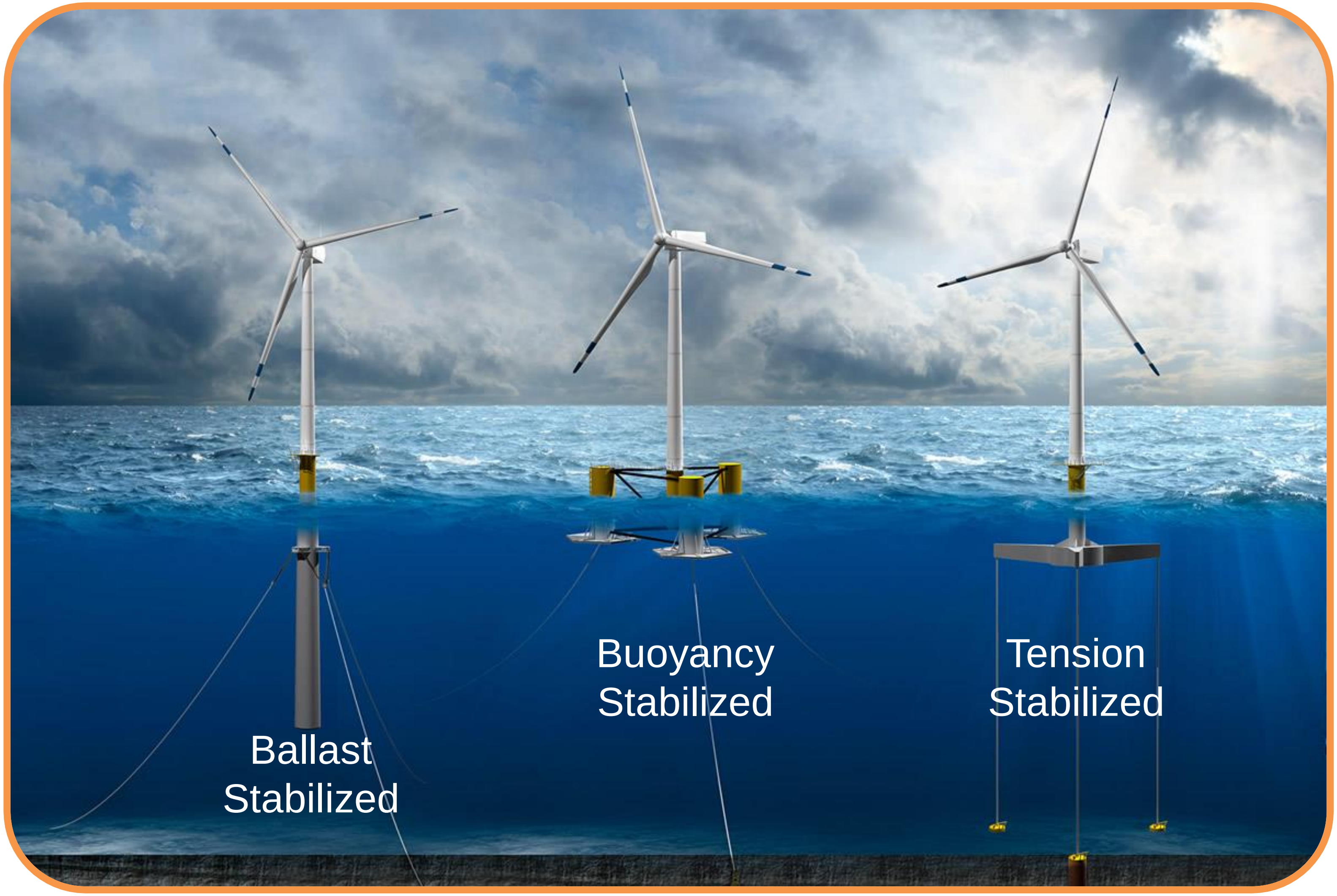


Fig. 5: Floating offshore wind concepts (Source: dnv-gl.com)

Tools, Models and Procedures \ **Approaching the problem**

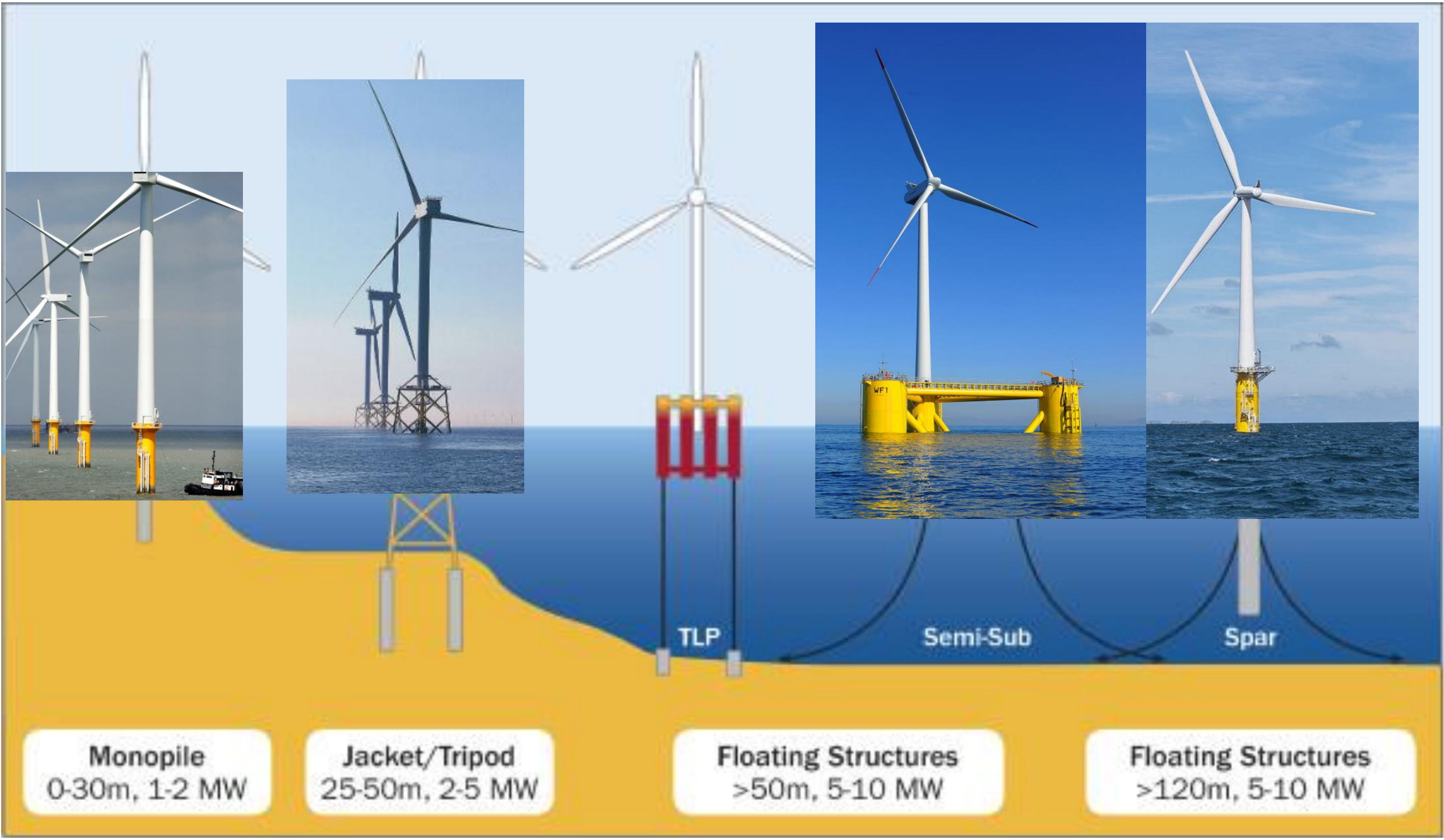


Fig. 6: Offshore wind concepts (Source: researchgate.net; power-technology.com; ihearth.org; pagerpower.com)

Tools, Models and Procedures \ **Approaching the problem**

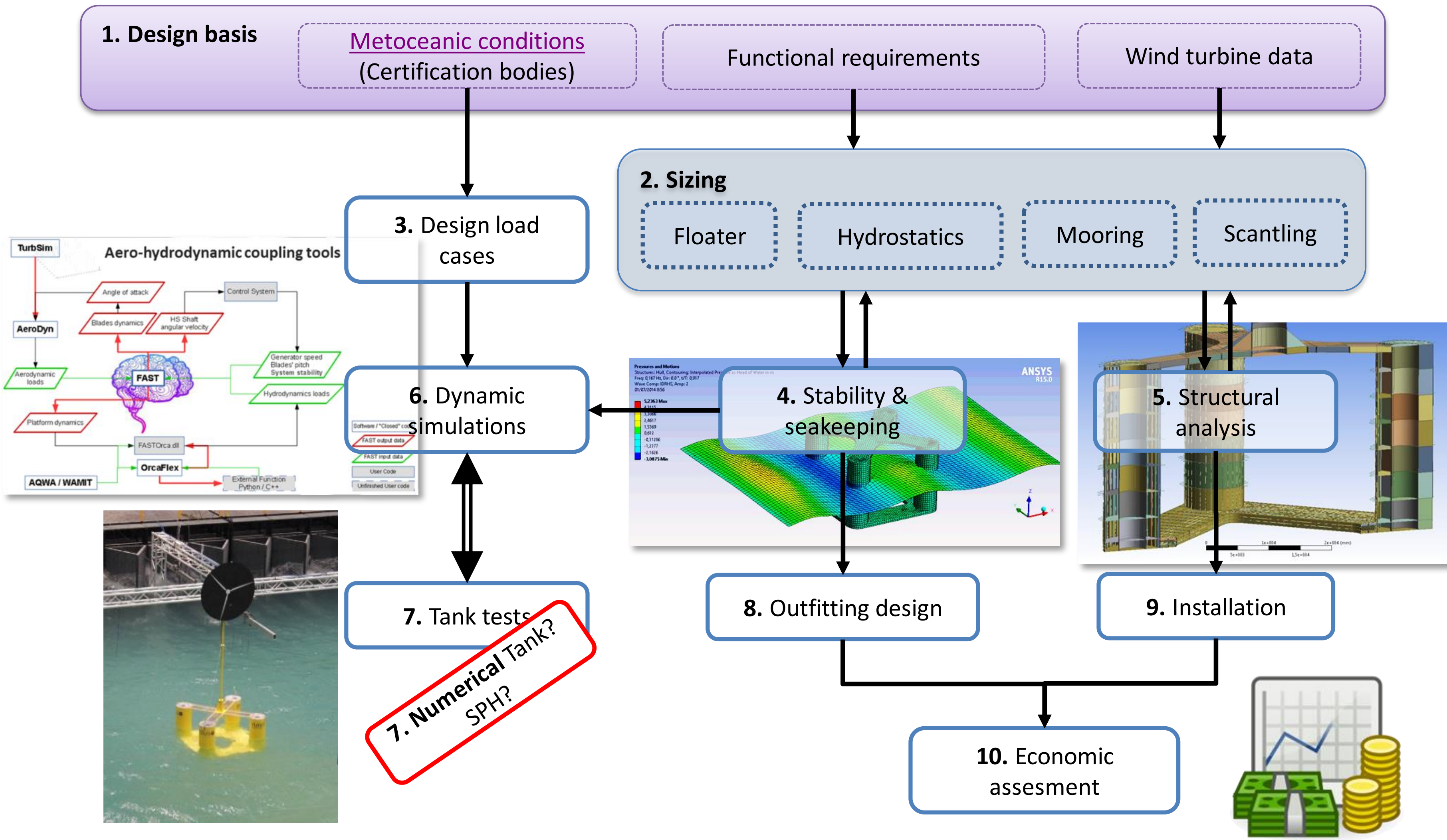


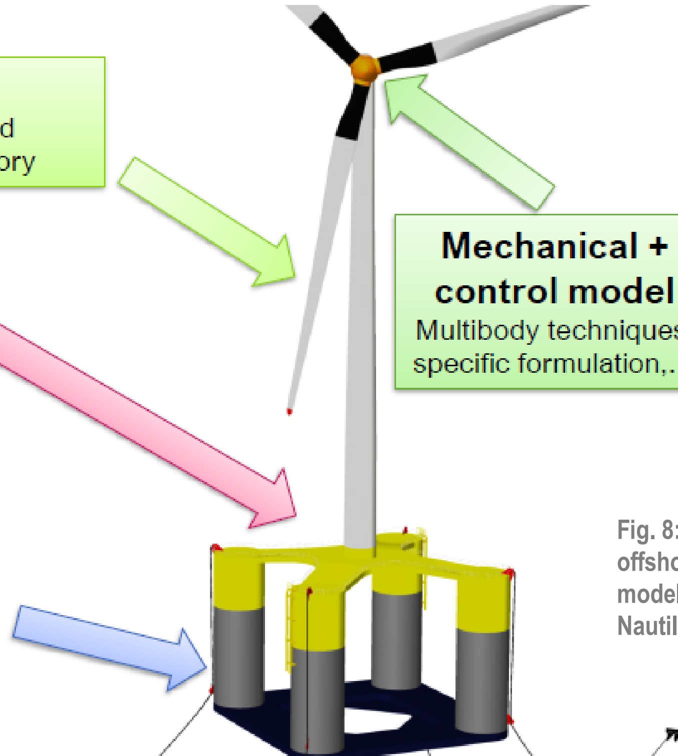
Fig. 7: Basic design flow chart

Tools, Models and Procedures \ Approaching the problem \
Modelling offshore wind turbines

Aerodynamic model
Blade Element Momentum (BEM) and generalized dynamic wake (GDW) theory

Structural model
Finite Element Model, modal representations,…

Hydrodynamic mode
- Wave kinematics:
  - Linear Airy wave theory
  - Stokes' 2nd and 5th order theory…
- Hydrodynamic forces
  - **Slender body:** Morison equation cover a range of slender & multi-structure
  - **Large volume body:** Potential flow panel models provide diffractive, radiative, Froude-Krylov and added mass forces
- Viscous forces
  - Global linear and quadratic damping matrix



Mechanical + control model
Multibody techniques, specific formulation,…

Mooring model
Static, quasi-static and dynamic

Fig. 8: Floating offshore wind modelling. (Source: Nautilus FS)

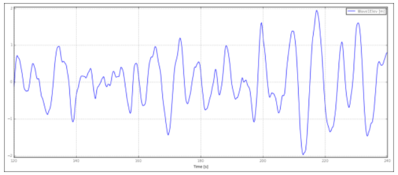
Equation of Motion

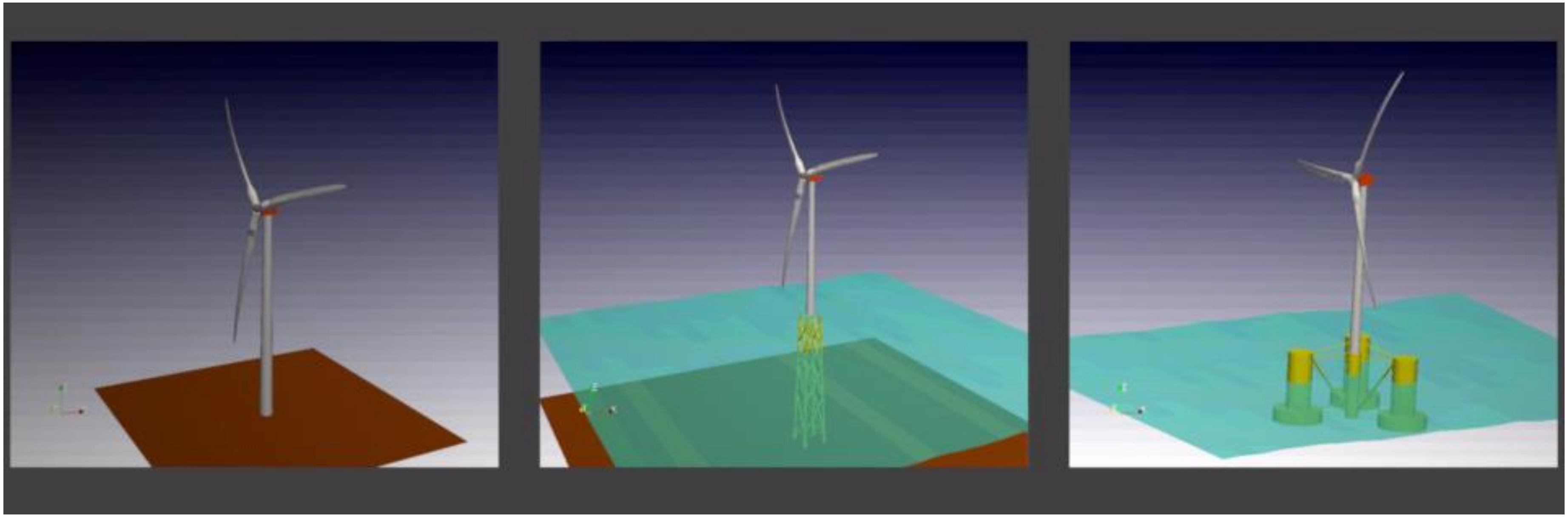
$$(m + A(\omega))\ddot{x} + B(\omega)\dot{x} + (K_{mooring} + K_{hydros})x = F_{hydrodyn} + F_{current} + F_{gravitational} + F_{aerodyn} + \cdots$$

Tools, Models and Procedures \ **Approaching the problem**

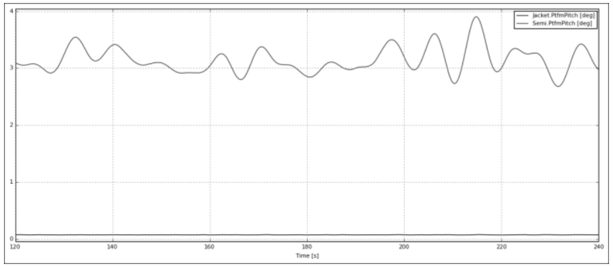
Configuration influence: onshore , jacket and **semisubmersible**

Using OC3-Spar control; wind=12m/s and Hs=3m, Jonswap





Video 1: 5 MW NREL WT supported by different concepts. (Source: TRI)



1. Generator power
2. Generator speed
3. Blade pitch
4. Tower base moment
5. Support pitch

FLOATING
Significant increment of dynamic effects

Modelling offshore wind turbines \ Waves & Hydrodynamics (I)

$$\overbrace{(m + A(\omega))\ddot{x}}^{\text{Mass}} + \overbrace{B(\omega)\dot{x}}^{\text{Damping}} + \overbrace{(K_{mooring} + K_{hydros})x}^{\text{Stiffness}} = \overbrace{F_{1st\ hydrodyn} + F_{2nd\ hydrodyn}}^{\text{External Forces}}$$

radiation

Froude-Krylov
Diffraction

Problem is split into separate and simpler problems:

- ***Diffraction***: seek loads on platform when it is fixed and incident waves are present → ***Froude-Kriloff***, ***mean drift***
- ***Hydrostatics***: seek loads on platform when it is in equilibrium and there are no waves present → ***buoyancy, stiffness***
- ***Radiation***: seek loads on platform when it oscillates in its various modes of motion with no incident waves present, but waves radiate away → ***added mass***, ***radiation damping***

Tools, Models and Procedures \ Approaching the problem \
Modelling offshore wind turbines \ Waves & Hydrodynamics (II)

Potential flow theory
Frequency domain
inviscuid fluid
Irrotational flow
Incompressible flow
Small waves and motions
No nonlinear wave kinematics
No 2^{nd} order effect
No vortex induced vibrations
Many codes available from O&G industry

Morison's equation
Time domain
Only valid for slender bodies
No wave radiation
Easy to implement and includes nonlinear effects

Non-linear time domain
Time domain
Frequency domain solution as input
Second order drift forces
Marine growth
Vortex Induced Motions
Preferable approach for FOWT global performance

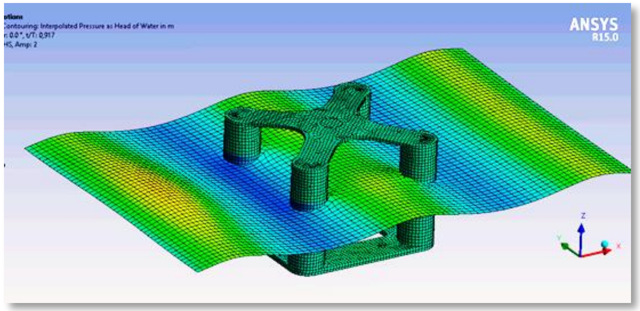
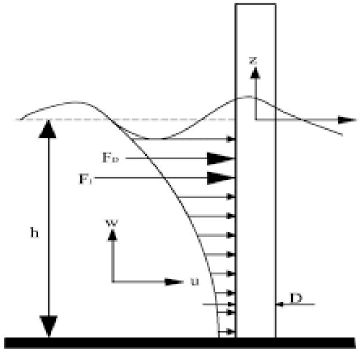
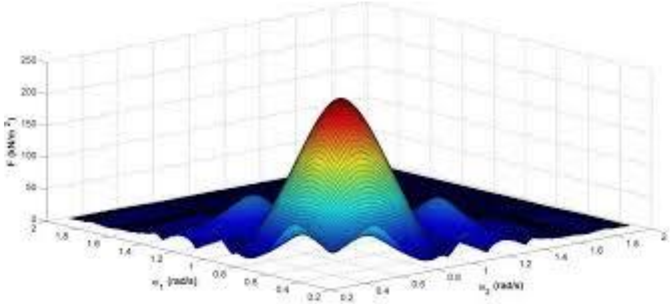


Fig. 9: FD analysis. (Source: NAUTILUS FS)



Morison`s equation



QTF sample (Source: ISSN 0976 – 7002)

Tools, Models and Procedures \ Approaching the problem \
Modelling offshore wind turbines \ Mooring

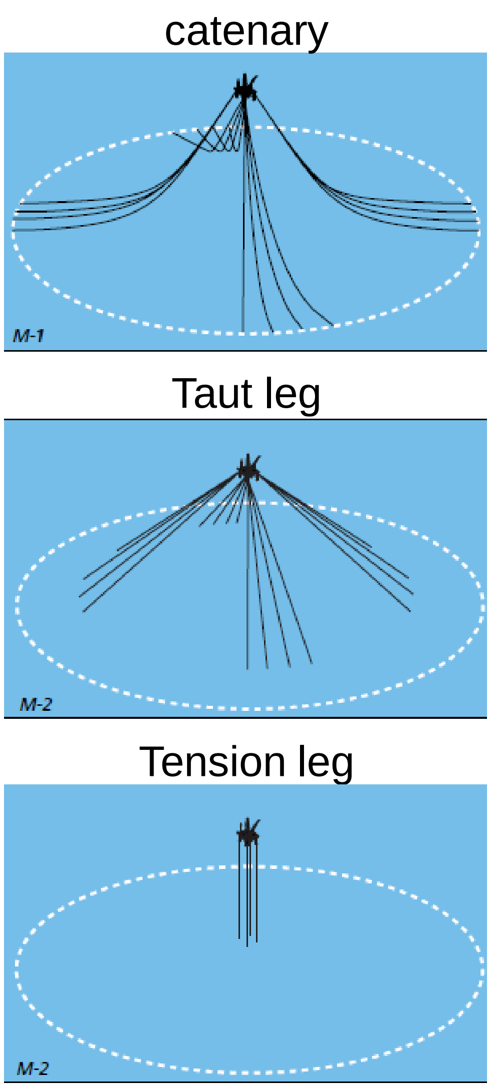


Fig. 10: Mooring configuration (Source: vryhof.com)

The mooring system restrains the platform due to line tension

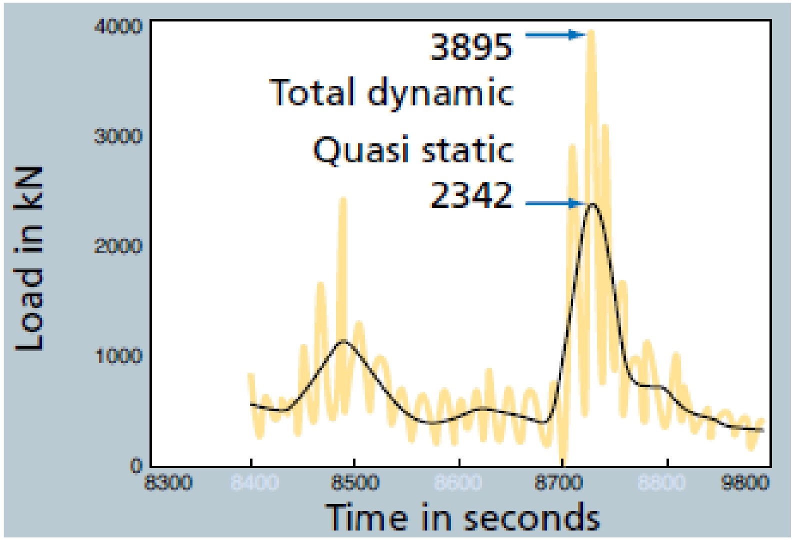
$$F_i = F_{i,0} - K_{1;i,j} \cdot x_i - K_{2;i,j} \cdot x^2$$

Quasi-static

Forces are taken into account by statically offsetting the hull using wave-induced hull motions. Low frequency.

Dynamic

It accounts for the time-varying effects due to mass, damping and fluid accelerations. High frequency.



Tools, Models and Procedures \ Approaching the problem \ **Modelling offshore wind turbines \ Structural**

Multibody structural model to determine OWT dynamics with a **modal approximation** reduction to represent blades' and tower's elastodynamics.

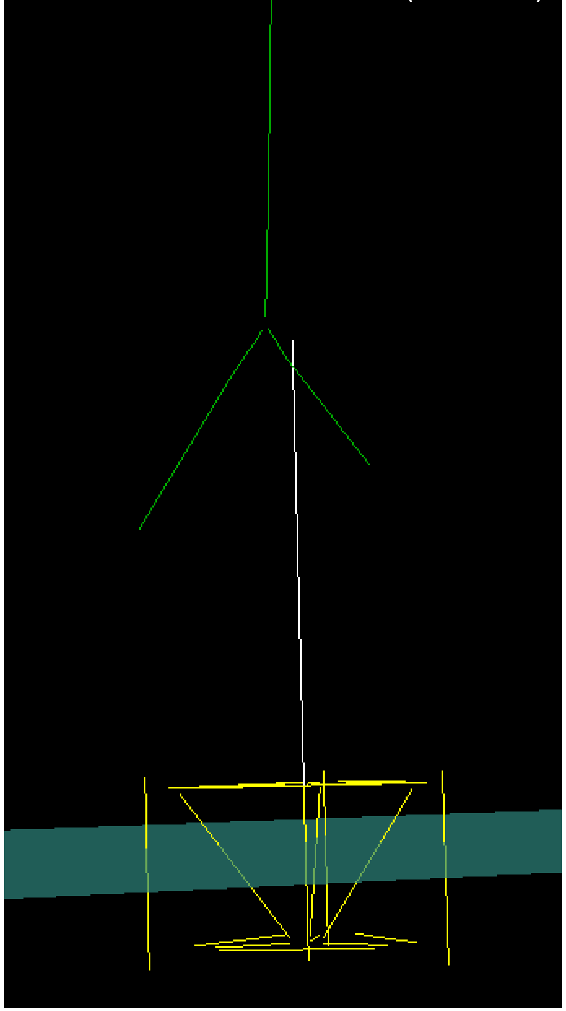
Advance in time is done using a RK-4 scheme.

Each of the physics (elasto-, aero- and hydrodynamics; this last if using Morison elements) employs an independent mesh.

Mesh mapping techniques are required to traslate loads to the structural model.

- **Modal analyses** of the tower should take into account influences of floating foundations and RNA.
- Structural damping of the tower and blades should be properly determined.

Fig. 11: Line mesh schematics of OC4-DeepCwind. (Source: TRI)



Tools, Models and Procedures \ Approaching the problem \
Modelling offshore wind turbines \ Wind & Aerodynamics (I)

Aerodynamics of a **rotor with 6 DOFs of freedom with large displacements**

1. Challenging problem!
2. Understand problem: rotor entering in the wake?
3. Numerical models for 3h simulations coupled with hydro-servo and structural physics?

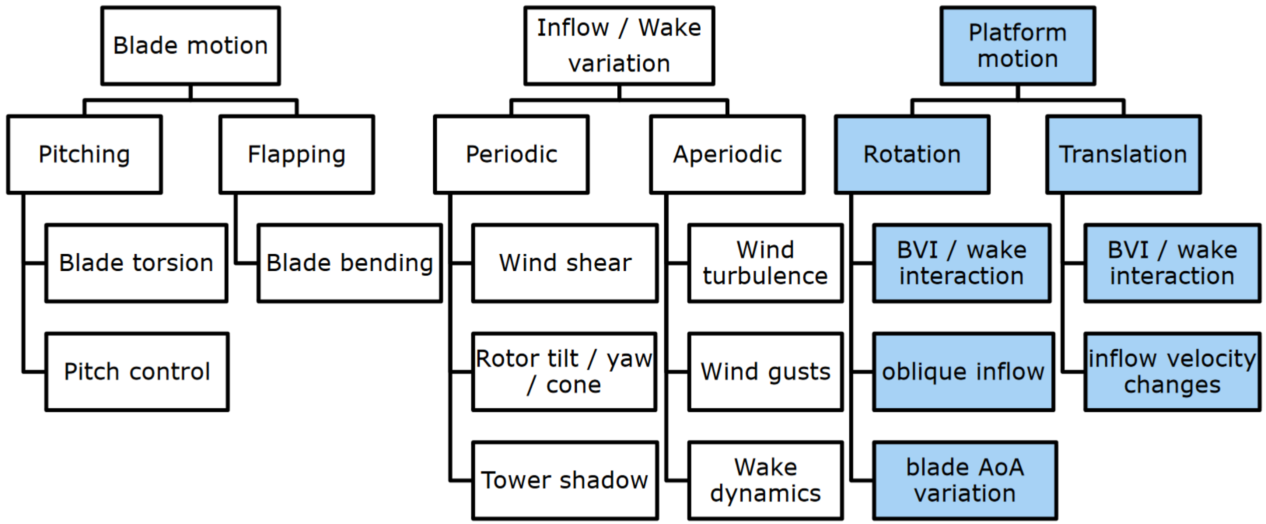


Fig. 12: Aerodynamics effects on floating offshore wind turbines. (Source: Vestas & TUDelft)

Concept	Inflow	Aerodynamics	Corrections
Offshore **fixed**	**Static** / Dynamic	**BEM** / GDW	• Dynamic stall
Offshore **floating**	**Dynamic**	**BEM / GDW**	• Unsteady aerodynamics • Dynamic stall, etc…

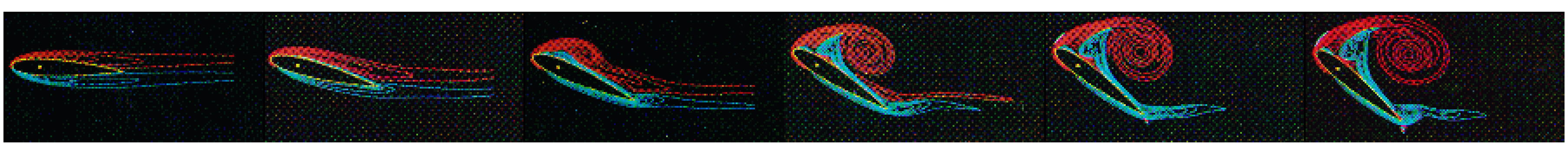


Fig. 12: Evolution of stall phenomena due to a rapid manouvring. (Source: http://www.ultralighthomepage.com)

Upcoming IEC 61400-3 -2 (FOWTs standard, Source: Ramboll)

"IEC 61400-3-1 clause 7.3.3 is generally applicable. **The aerodynamic interaction between the airflow and the FOWT is of special importance due to their additional compliance and increased dynamic response**."

When floating, aerodynamics of the FOWT shall consider:

- aero-elastic effects of blades and tower.
- **associated global and local dynamic and unsteady aerodynamic effects** (e.g. dynamic inflow, oblique inflow, skewed wake, unsteady airfoil aerodynamics including dynamic stall, blade-vortex interaction)
- Wind loads on the floating sub-structure

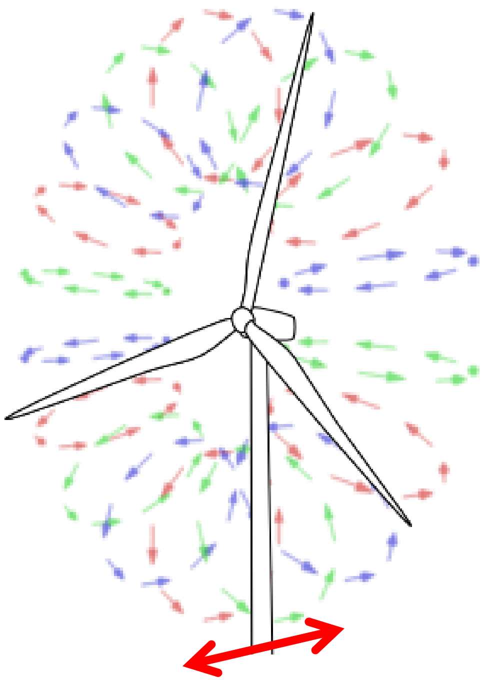


Fig. 13: Scheme of ring vortex generated by surge motion of the FOWT. (Source: http://en.wikipedia.org/wiki/Vortex_ring)

Tools, Models and Procedures \ Approaching the problem \
Modelling offshore wind turbines \ Control (I)

WT control system generally acts on:

- Generator torque
- Blade pitch control

WT control presents **high importance in FOWT dynamic behaviour**. (Must be included in coupled simulations)

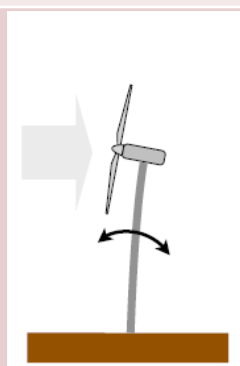
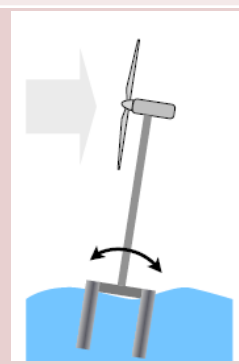
Property	Fixed (onshore or offshore)	Floating
Bending mode frequency [Hz]	~ 0.3	~ 0.03
Control frequency [Hz]	~ 0.03	**~ 0.03**
Mode shape		

Fig 14: Foundation or substructure influence on control stability. (Adapted from: Vestas & TUDelft)

Common **control modifications**:

1. Reduce controller bandwidth
2. Parallel compensation
3. Add control DOF
4. Pitch-to-stall operation

Tools, Models and Procedures \ Approaching the problem \
Modelling offshore wind turbines \ Control (II)

Do not exceed generator speed limit → shutdown

Aggresive control → More production → GREAT fatigue loads!

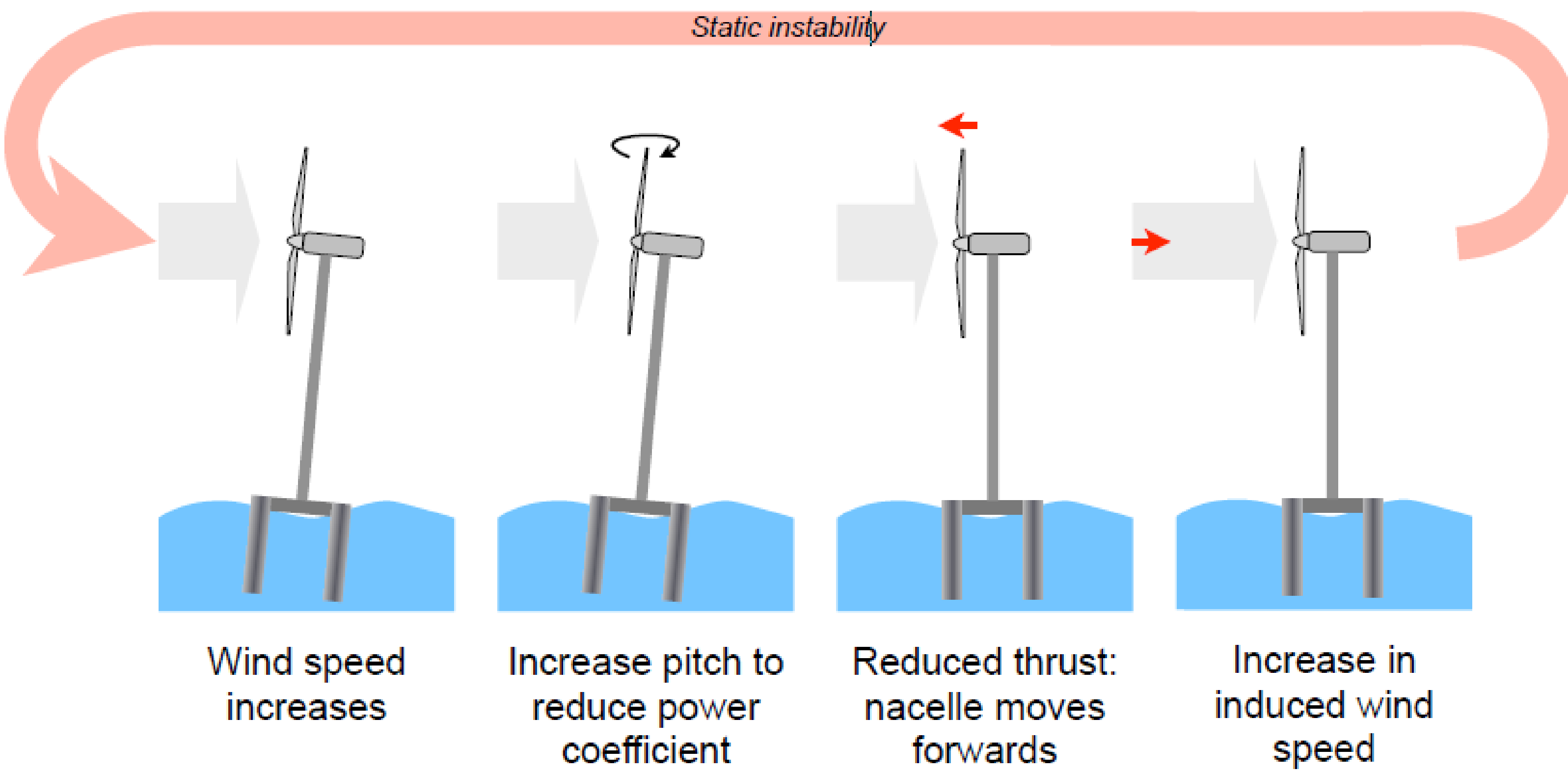
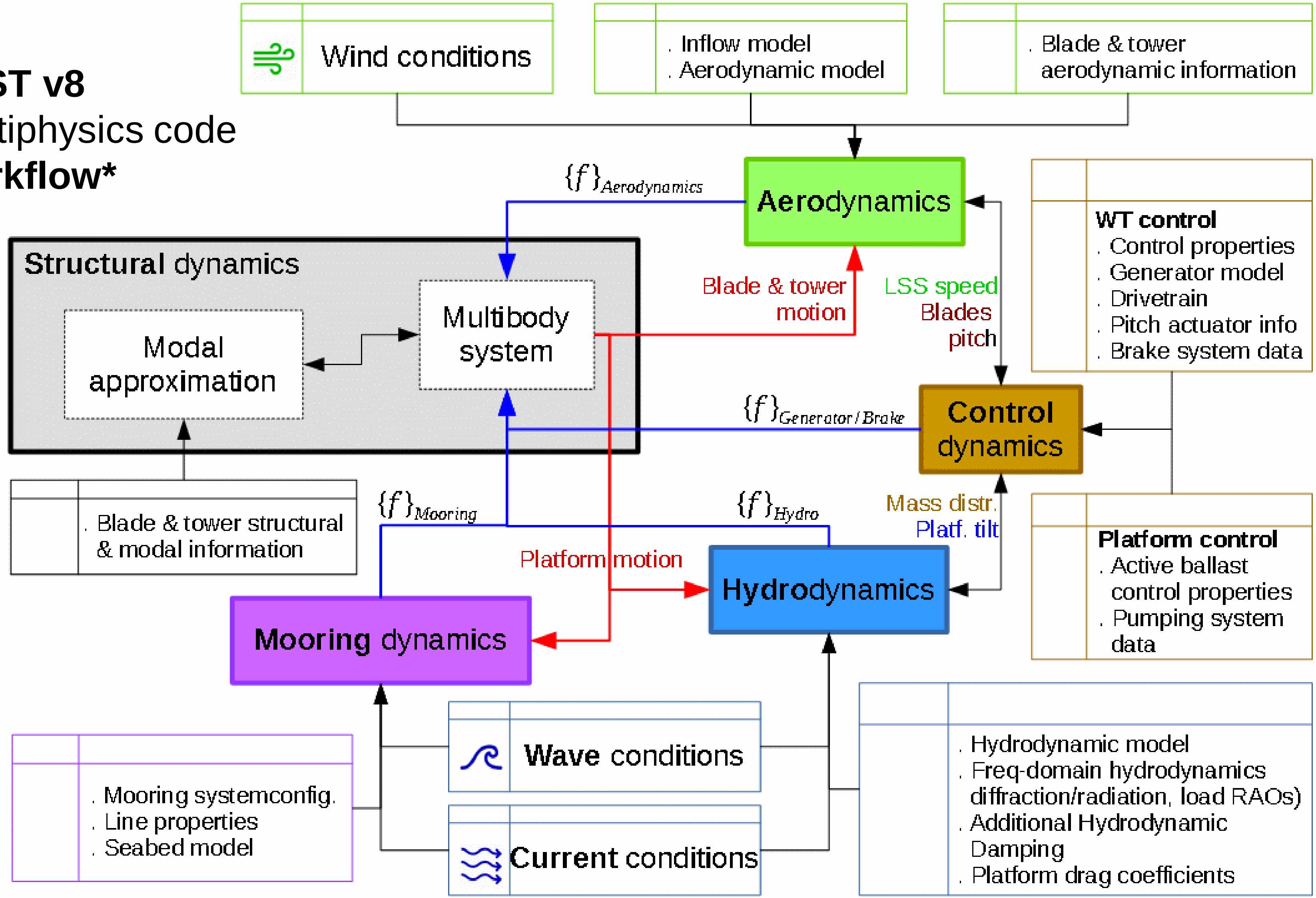


Fig. 15: Potential instability problem of the FOWT due to an incorrect control design. (Source: Vestas & TUDelft)

FAST v8
multiphysics code
workflow*



*as used in TRI up to date.

Tools, Models and Procedures \ **Numerical tools**

OrcaFlex is a well-known hydrodynamics and cable dynamics commercial code inside the Oil&Gas industry.

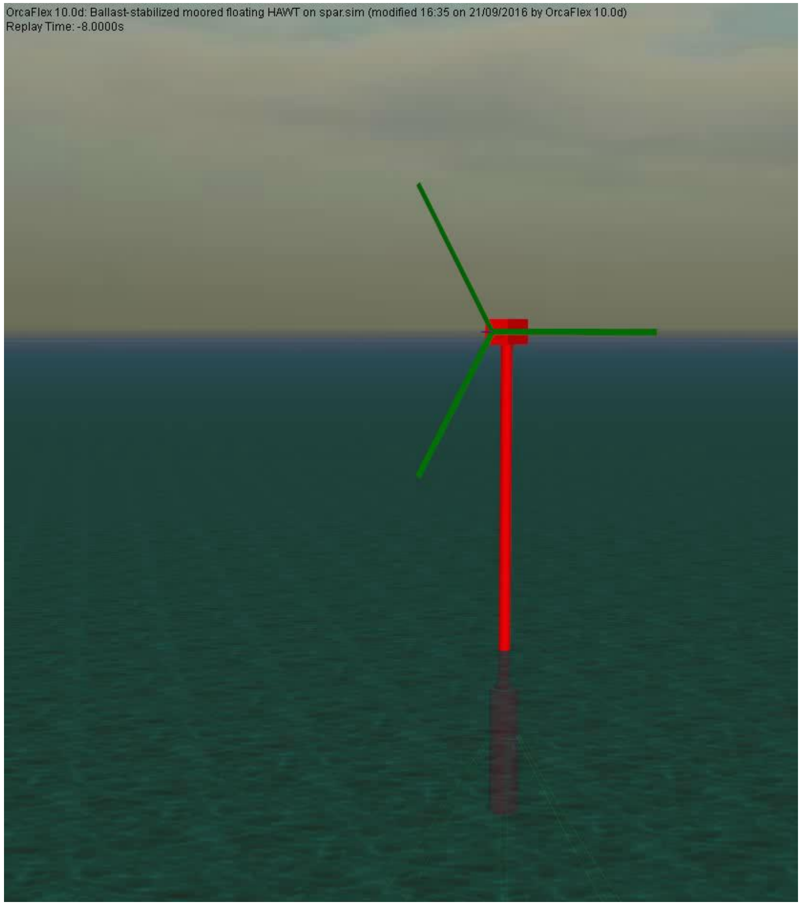


Fig. 16: Orcaflex model with aerodynamics

The **coupling of FAST and OrcaFlex** to resolve time-domain problems **improves FAST's features**, mainly:

- A wider catalogue of wave models and flexibility to reproduce sophisticate concepts
- High-fidelity cable dynamics models: mooring & umbilical
- High-fidelity mooring system equipment modellisation (Libraries, standards)
- Hydrodynamic interaction between FOWTs and support vessels
- Simpler implementation of active ballast routine (no recompilation needed)

Independent procedures that are used together

- Model *verification*: Verify that the computer code is correctly implemented.
- Model *calibration*: Modification of input parameters to improve results' accuracy.
- Model *validation*: Validate results against field experiments.

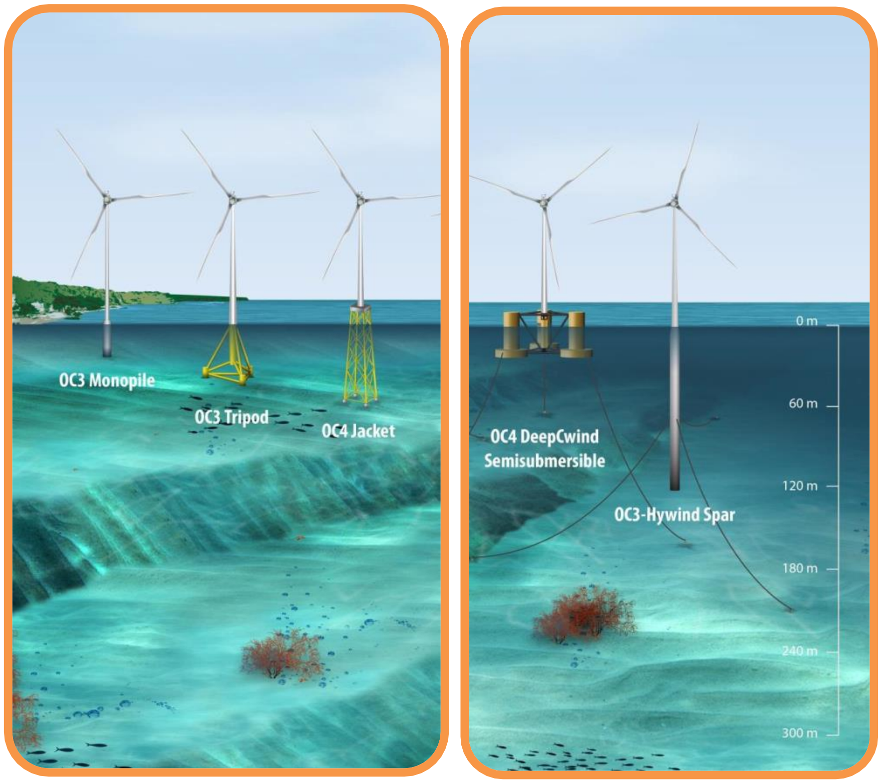


Fig. 17: OWT concepts studied inside OC3 and OC4 IEA activities.
(Source: OC5 IEA project)

- **Implementation of auxiliary functions** to complement the earlier version of FASTOrca.dll for FAST v7 & OrcaFlex 9.6 (programming UDFs).
- FAST v7 & OrcaFlex 9.7 verification (direct contact with Orcina).
- **Active monitoring of IEA** (International Energy Agency) OC3 and OC4 **code verification activities.**

Tools, Models and Procedures \ Verification, **Calibration** and Validation \ **Tank test**

Scaling laws

- **Geometry (facility limitation)** — $\boxed{l_p = \lambda \cdot l_m}$
- **Hydrodynamic**
  - **Froude** — $F_d = \sqrt{\frac{inertia}{gravitational}} = \sqrt{\frac{\rho u^2 l^2}{\rho g l^3}}$ — $\boxed{u_p = \sqrt{\lambda} \cdot u_m}$
  - **Strouhal** — $S_n = \frac{u\,T}{l}$ — $\boxed{T_p = \sqrt{\lambda}.T_m}$
  - **Reynolds** — $R_e = \sqrt{\frac{inertia}{viscous}} = \sqrt{\frac{\rho u^2 l^2}{\mu u l}}$ — $\cancel{u_p = \lambda \cdot \frac{\rho_m}{\rho_p}\frac{\mu_m}{\mu_p} \cdot u_m}$
- **Structural** — **Cauchy** — $\cancel{E_p = \lambda \cdot E_m}$

Conventional test	Target
Inclining test	hydrodynamic stiffness
Decay test	Eigen periods, hydrodynamic damping
Forced oscillation test	Added mass and damping coefficients
Mooring system test	Mooring stiffness
Towing	Drag coefficient
Regular waves	Response Amplitude Operator
Wave grouping	Code validation

Tools, Models and Procedures \ Verification, **Calibration** and Validation \ **Tank test**

Aero & hydrodynamic experimental coupling solution

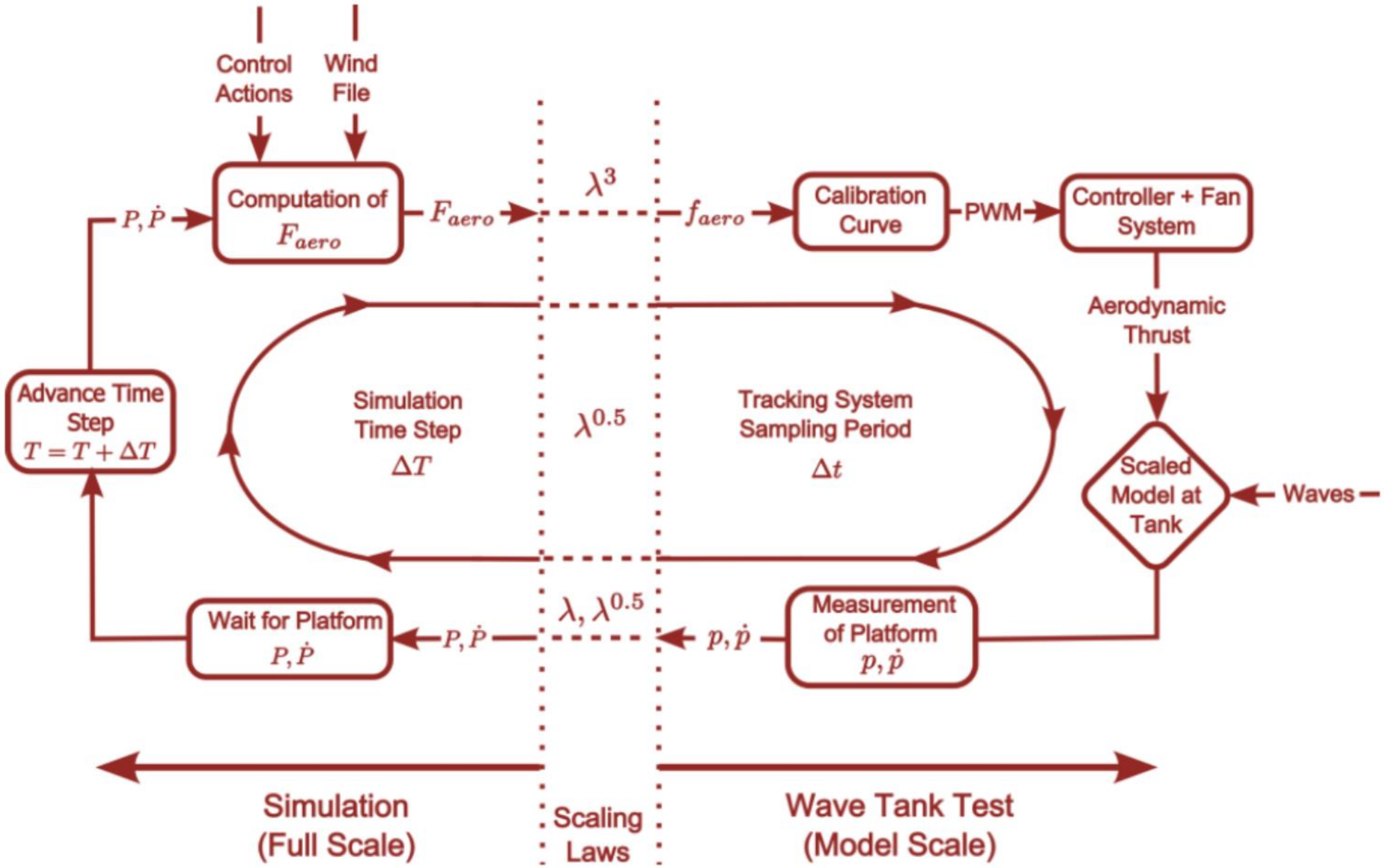


Fig. 18: Software in the loop method diagram.
(Source: Aerodynamic Thrust Modelling in Wave Tank Tests of Offshore Floating Wind Turbines Using a Ducted Fan. CENER)

Tools, Models and Procedures \ Verification, **Calibration** and Validation \ **Tank test**

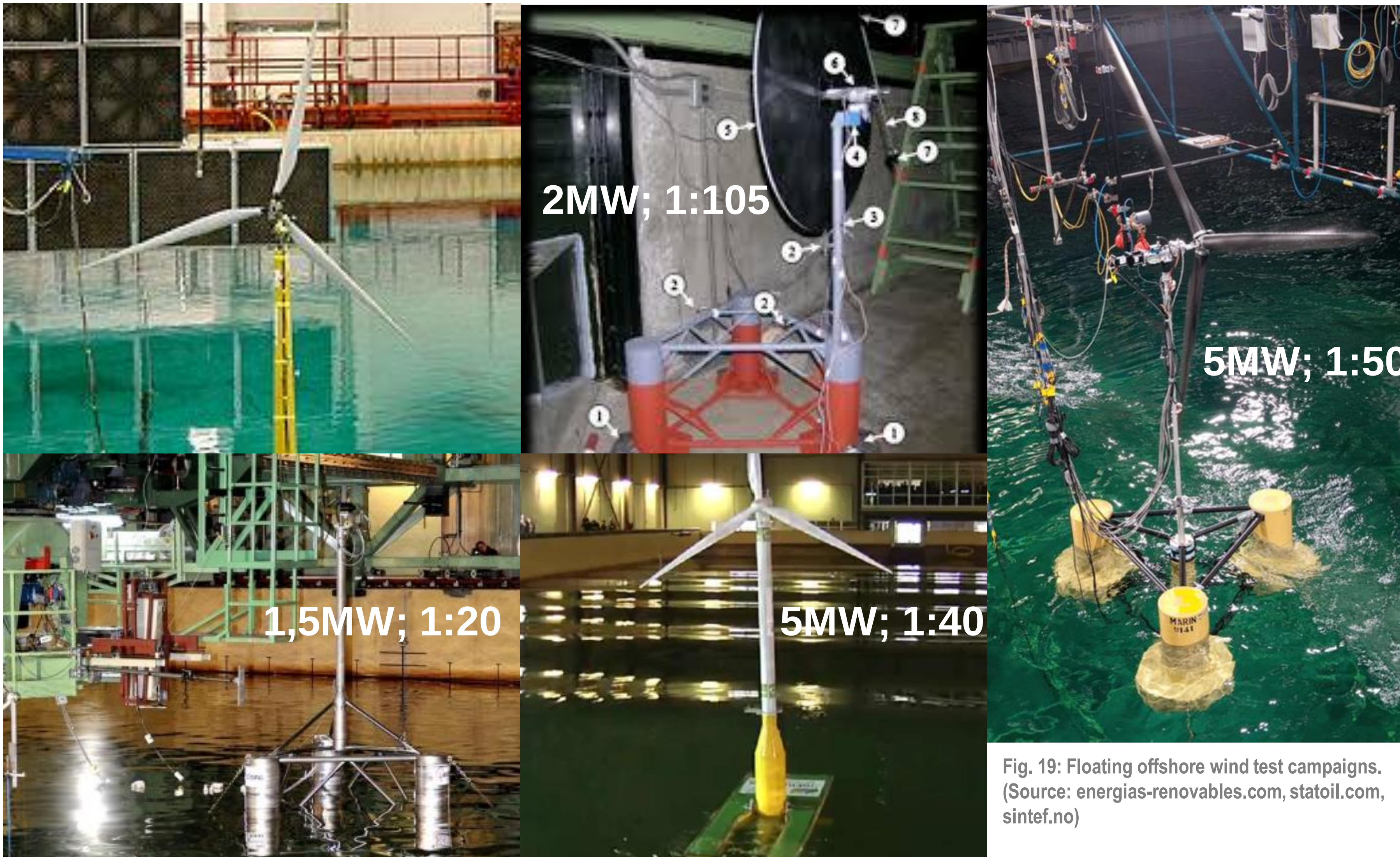


Fig. 19: Floating offshore wind test campaigns. (Source: energias-renovables.com, statoil.com, sintef.no)

Tools, Models and Procedures \ Verification, **Calibration** and Validation \ **Tank test VIDEO**

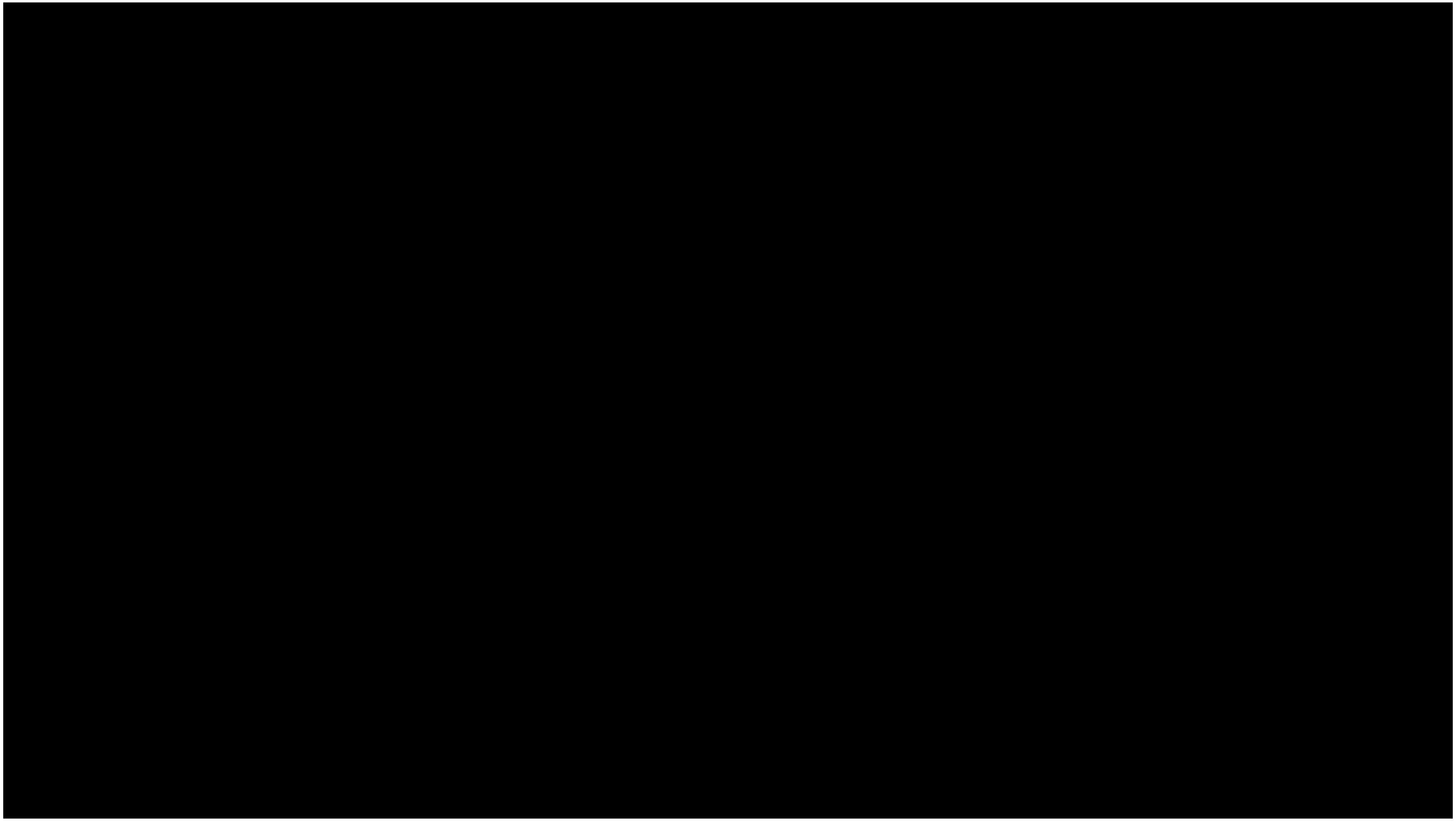


Fig. 20: Nautilus test campaign. (Source: Nautilus FS)

Tools, Models and Procedures \ Verification, **Calibration** and Validation

One of the most important outcome from tank tests is the information that permits the **identification of the system's properties**.

Tank tests' results postprocessing is a time-consuming signal processing task

The **numerical model is updated according to experimental results**. Some of the properties that are not identified during experimental tests campaign are obtained using **Computational Fluid Dynamics** analysis.

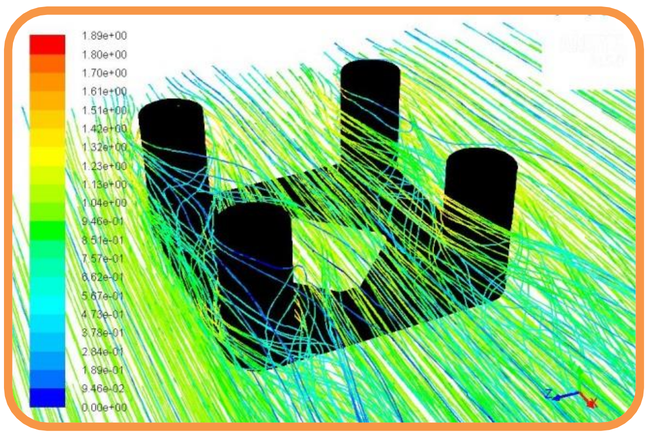


Fig. 21: Streamlines indicating flow velocity. (Source: TRI)

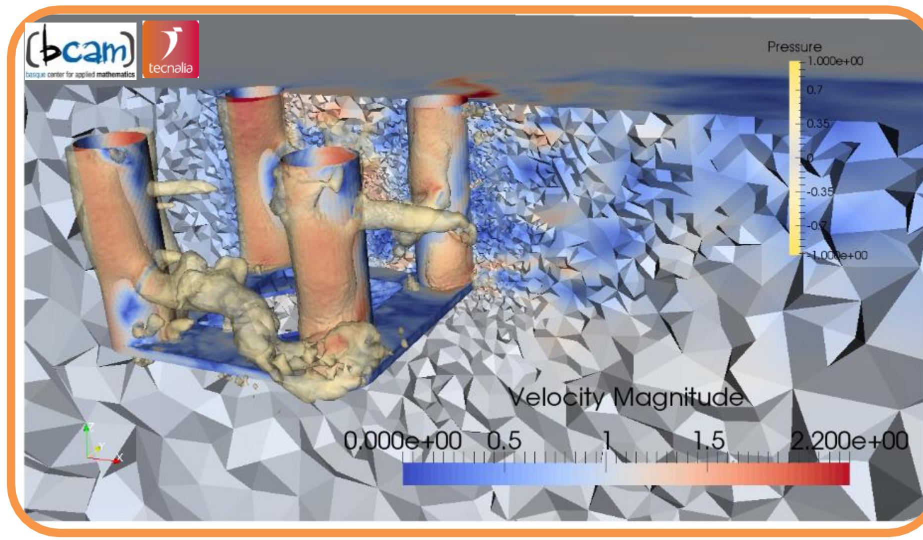
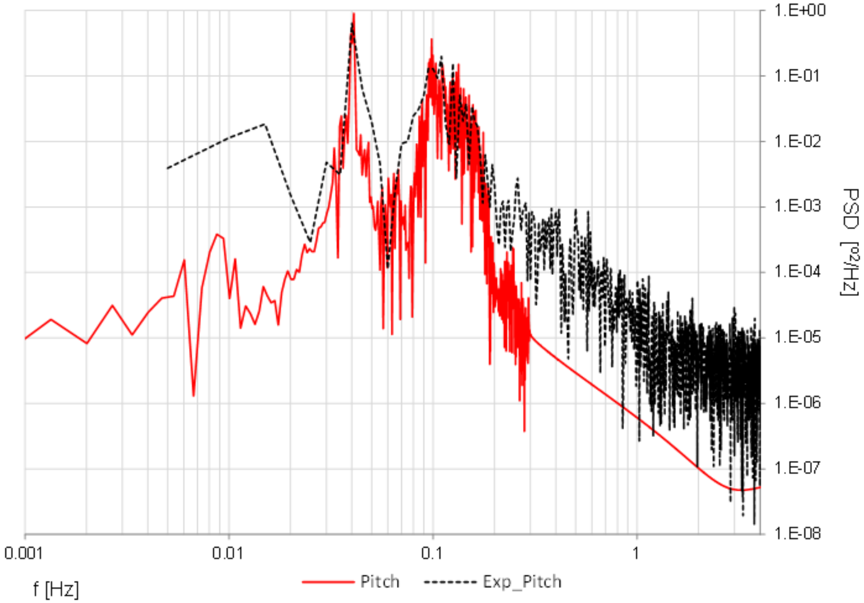


Fig. 21: Flow velocity around Nautilus. (Source: BCAM, TRI)

Numerical results are compared against several experimental LCs during **model fitting** procedure.

Tools, Models and Procedures \ Verification, Calibration and **Validation**

Once the numerical model is calibrated, **experimental and numerical results are compared in time- and frequency-domain in order to validate the numerical model**.



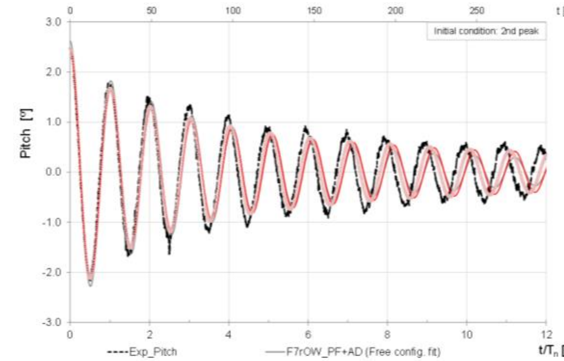


Fig. 25: pitch decay test (Source: TRI)

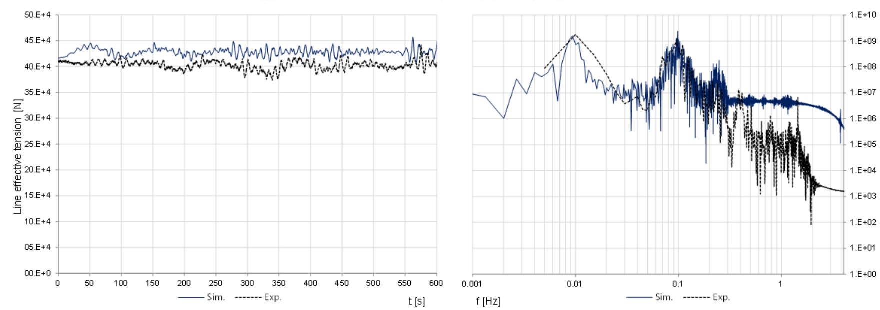


Fig. 23: Pitch PSD irregular waves. (Source: TRI)

Fig. 24: Time history and PSD of line #4 tension under regular wave (H_S=3m;T=18s). (Source: TRI)

A **<u>validated numerical model is a powerful tool</u>** that enables the simulation of a plethora of LCs, where the behaviour of the offshore wind turbine can be studied in order to **optimise the design of the WT, the support structure** (fixed or floating) and **auxiliary equipment**.

OPEN DISCUSSION

Conclusions

Open discussion

Multiphysic analysis target is:

- To determine environmental loads on the FOWT among 10,000s of LCs.
- To enhance dynamic performance and increase generated power.
- To reduce risk, identifying failure modes.
- To optimize offshore-wind designs.

Detailed analysis target is:

- To characterize the system and its components behaviour (elastic, aero, hydrodynamic) among decens of LCs.
- To fit the engineering level numerical models.
  - Regarding hydrodynamics: fitting PF solution to include viscosity influence against RAOs and other metrics.
- Detailed analysis of components over a short time of the most critical DLCs identified during the multiphysics simulations with engineering level tools.

Open discussion \ **Conclusions**

- Wide range of numerical tools are used for floating substructure design.
- The numerical tools are in reasonable agreement with measurements for normal operating conditions, however in transient and adverse conditions they do not satisfactorily predict extreme loads.
- Due to the transient and nonlinear loading from wind and waves time-domain simulations are needed.
- The numerical design process usually starts with basic design stage. Importance of input: **Design Basis**.
- TECNALIA is well positioned to continue with the development of numerical models, and their application to the design of floating structures.
- One part of the thesis will try to automatically fit the hydrodynamic models using Experimental and Operational Modal Analysis (EMA and OMA) techniques taking the results of the numerical tank as reference.

Thank you for your attention

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