Co-engineering with a wind turbine OEM: a floating substructure designer’s view

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SUMMARY

Offshore wind engineering brings together major equipment designers from two worlds: wind turbines and offshore structures, each with distinctive views and requirements. Both must cooperate to integrate their products in an optimal system functioning as a whole; hence the need for ILA (integrated load analysis) to assess performances and component loads for each party.

In fixed-bottom offshore wind, established processes exist to interface design iterations involving both the wind turbine manufacturer and the substructure EPC (engineering, procurement, construction) contractor. These are not transposable to floating, where decoupling simplifications are unviable and both parties' design choices are more tightly interconnected, making fully coupled simulations a must (i.e. substructure "talking" to the turbine and vice-versa in runtime). Given this constraint, a criticality appears: the little availability and/or adoption of simulation tools which i. include both wind turbine generator and floating substructure physics in full, whilst ii. ticking the boxes in terms of quality-cost-time and model confidentiality. This entirely reshapes the floating ILA process.

Past technical FEED (front-end engineering design) works as a floating substructure designer cooperating with multiple wind turbine original equipment manufacturers revealed radically different co-engineering strategies for global design iterations, each with specific challenges and project implications. These strategies are described based on real-life experience, compared in terms of risks / opportunities, and related to the typical floating wind project context and quality-cost-time balance. Critical process aspects not to be overlooked are highlighted, especially around the topics of model validity (including frequency reliability in "Campbell" terms) and accountability.

Sofresid Engineering is a French consulting firm, 100% subsidiary of Ekium (SNEF Group), a European player in industrial engineering, especially active in the energy and naval sectors. Our floating wind team possesses a 12+ year experience as substructure designer, with track record from being integral part of EPC contractors Naval Energies and SAIPEM. This includes both floater product development and project-specific activities, covering engineering design (up to certified FEED level with WTG OEMs), industrialisation, and execution preparation works. Our broader team also took part in design & execution tasks for multiple fixed-bottom offshore wind projects.

> *"It is vitally important that the substructure design team and the WTG OEM engineering team build a strong working relationship with a joint understanding of areas of importance to achieve the common goal of an optimised design. Open sharing of data and honest discussion are key, all of which can be supported by an active and well-informed developer to provide oversight. Over several projects I have built strong relationships with the technical teams from substructure designers to a point that these connections remain today, many years after our joint working has finished."*
>
> **Chris Vibert**, previously supported WTG OEM Floating Wind Engineering

CONTEXT

A FROZEN TURBINE ON A CHANGING FLOATER

A floating wind project is born. Soon the developer will launch tenders for Tier 1 contractors to come up with technological solutions fit for the future windfarm. For the supply of the floating units, the main contractors are the wind turbine generator "original equipment manufacturer" (WTG OEM) and a marine "engineering, procurement, construction" firm (EPC) typically delivering the substructures including floater and station-keeping system[1]. The two scopes have different technological approaches:

- **Turbine supply agreement** (TSA): as of today, wind turbine OEMs will position an off-the-shelf standard WTG model on the tender, minimising the adaptations from an existing or perspective fixed-bottom offshore wind product: most visibly, tower and controls are redesigned. A prototype will be thoroughly tested and obtain a type certificate before project usage, which sets in stone most machine properties in a project-unspecific way.
- **Substructure EPC**: contractors will respond either with their own concept or by relying on 3rd party technology. Different from the WTG, this comes with a significant engineering (re)design effort during the project, for concept adaptation to both the site and the turbine: the lower standardisation of floating substructures makes them a major recipient of project-specific demands.

DESIGNER CULTURE SHOCK

In many industries, the system integration of components coming from design specialists of different nature creates cultural challenges. This is true for offshore wind, which "*brings together industrial sectors that have nothing to do with each other, and cannot easily sub-contract work to each other*" [1], but in floating the impact is even larger, as the inherent strong coupling between WTG and floating substructure cannot be eluded during design. Here, the project needs to gather the WTG OEM design (e.g. micrositing) team and the EPC design (e.g. naval architecture) team for a tight **parallel co-engineering** endeavour, despite each having a different background: a few prominent cultural differences are listed in the table below.

Table 1 Cultural differences between co-engineering design parties.

Contractor characteristic	WTG OEM	Substructure EPC
Industrial culture	Product	Tendentially project
Engineering mindset	Mechanical	Marine
Possible "target fixations"	Flexible frequencies Fatigue design	Rigid-body motions Strength design
Model data posture	Protective	Tendentially sharing

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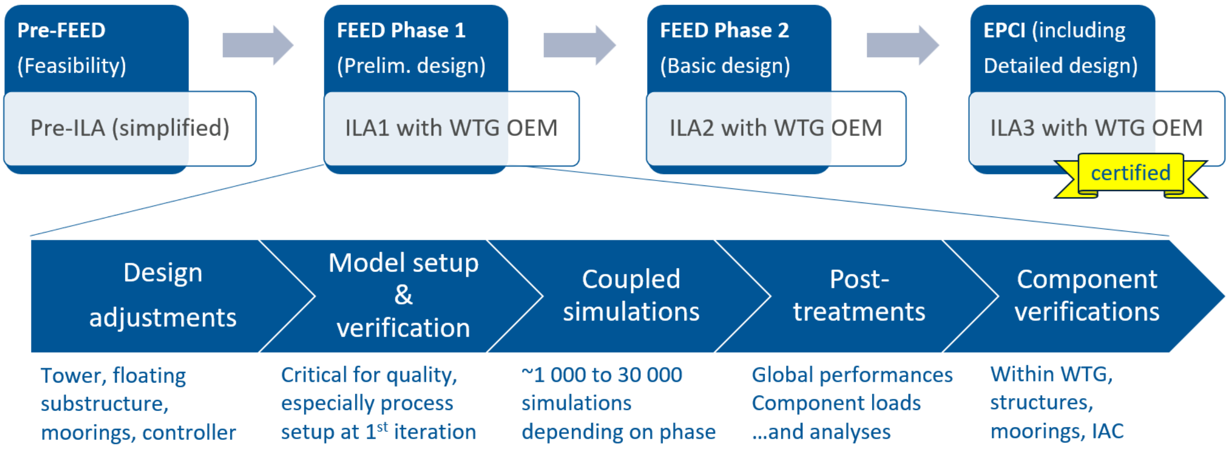
[1] For simplicity, substation and electrical equipment supply is left out of the discussion, and T&I implicit. Also, different contracting schemes are possible: this dimension is not developed.

Obviously, the floating wind turbines ultimately need to function well as a whole despite any cultural differences, as physics are continuous across the WTG and the substructure. This is the challenge of design integration. In this setting, a successful project marries both teams by establishing a common vocabulary, communication channels, incentives to cooperation, and strong interfaces to properly distribute accountability across parties. System engineering can greatly help in shaping this process.

ENGINEERING PROCESS

Once the WTG OEM and the substructure EPC(s) are selected, the engineering process can begin, entering a sequence of design phases whose "ideal" structure is reproduced in Figure 1. Each revolves around a new evaluation of system responses through integrated load analysis (ILA), bringing in the latest system configuration including substructure, WTG, and controller properties. In principle, each phase is more detailed (accuracy), exhaustive (design situations) and work intensive than the previous one, progressively reducing risk until a converged, certified configuration is reached.

Figure 1 Floating wind engineering process as seen by the floating substructure designer.



From the floating substructure designer's standpoint, the typical features of the above design iteration phases are the following:

- A pre-FEED is generally competitive and performed by candidate EPC designers using an employer-provided WTG: either a stock aeroelastic model, or aggregated data from the actual WTG OEM including a technical specification note and a generic tower configuration for floating. In the latter case, simplified aerodynamic/aeroelastic models of the turbine are employed for load assessment – see e.g. the punctual lift & drag model for a parked WTG by Naval Energies [2].
- FEED Phase 1 can be either competitive or exclusive to a single substructure designer. Co-engineering with the WTG OEM begins, as well as interaction with the certification body.
- FEED Phase 2 is a fully detailed and exhaustive co-engineering iteration, including sensitivity analyses, and using the "quasi-final" DLC list and floating system configuration.
- EPCI - Detailed design. The enclosed ILA, using the final DLCs and system properties, will serve the purpose of project certification. It can be seen as a confirmation of the latest FEED ILA, supposed to prove system integrity and performance after incorporation of the final design adjustments.

Whilst constructing the project, it is important to keep in mind that in each phase three significant activities must be performed on top of the strict **design load case (DLC) selection** and **coupled simulation & global performance** analysis: these are **design adjustments** (e.g. global sizing, structural design), **model setup & verification** at the interface between EPC and OEM, and **component resistance verifications** (e.g. fatigue in the substructure, see [3]) using the outputs of the coupled simulations. In addition, a **coupled simulation methodology setup** must be either planned upfront, or otherwise redeployed from previous projects jointly involving the specific WTG OEM and EPC pair.

Strong cost & time pressures apply on the above process, due to the combination of employer cash discipline on one side (e.g. starting a phase no earlier than project attribution, a permitting milestone, or FID / FC[2]), and a constrained official time-to-commissioning on the other. The result is partial parallelisation, where phase *N* preparatory work is performed within the timeframe of phase *N*-1. This is typically the case for DLC list construction and validation, a task on the critical path of the next ILA that can be decorrelated from ongoing engineering work. In case of special circumstances and/or high risk tolerance, a design phase may be removed altogether, which is not such an uncommon sight in early project roadmaps; a need for intermediate “remediation” iterations may then appear on the go.

DESIGN INTERFACES

THE CASE FOR A STRONG INTERFACE MANAGEMENT FUNCTION

As mentioned above, a strong interface management function is a must during engineering design. A first reason for this is that each party naturally focusses on its own **“local” optimisation** and has large **blind spots** on the other’s sensitive areas; however, both components’ details are critical to CAPEX, asset integrity, and productivity. An integration function must be present to foster system thinking (e.g. global optimisation). For instance, in their design choices:

- Is the WTG OEM motivated to bring up relaxations (e.g. in supervisory control, see [4]) and/or changes in standard design practices to unlock optimisation opportunities on the substructure side? Has it considered adaptations in construction, commissioning, etc., to ease up marine operations?
- Has the EPC considered impacts on wind turbine protection systems and availability? Has it incorporated all physical and regulatory requirements of WTG inspection and maintenance?

A second reason for a strong interface lies in physics: it is a well-known fact that a floating wind system is **strongly coupled** (see Table 2). How does this influence the engineering process? After a design adaptation, coupling-related “traps” can appear, which must be prevented by unilateral and cross-party sanity checks. Two examples:

- Vicious cycle – increase the sectional resistance in a soft-stiff floater to pass e.g. a fatigue life criterion. This will make it stiffer, increasing the 1st bending eigenfrequencies and, consequently, vibrational fatigue loading… and it’s back to the start.
- Side effect – optimise catenary mooring line composition, with care of keeping the horizontal mooring restoring behaviour comparable. All seems set for a more effective design, but once

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[2] Final Investment Decision / Financial Close.

coupled tilt is computed… the maximum tilt criterion is no longer satisfied. The nonlinear vertical restoring moment under offset has been inadvertently lowered.

Table 2 WTG-substructure coupling in floating wind systems. Adapted from [3].

	Loading side	Response side	Interdependency
Coupling	Strong coupling of all loadings through WTG controller and moving parts	Wave-induced motions and wind turbulence affect control, with effects on motions and vibrations Aerodynamic damping from revolving rotor & control actions	WTG sensitive to substructure responses, in both mechanics and **power performance** [5] Substructure sensitive to WTG weight, thrust intensity, thrust variations All parts sensitive to structural stiffness (and masses) everywhere through eigenfrequencies

A third reason for a strong interface lies in the **need for efficiency**, due to schedule compression (discussed above). Launching an ILA is a multi-month commitment: incidents causing rework must be kept to a minimum. Combine this with the contractors' limited resource availability for unplanned work and see that investing in a robust joint process pays back in terms of real-life project efficiency.

ACCOUNTABILITY AND QA/QC

With system parts strongly interdependent and a single global configuration output, which design party is accountable for what performance? In other words, how is trust propagated in the process? This is where accountability becomes a challenge.

A fundamental limitation is that **each party has only a <u>partial</u> "trusted" model** (e.g. certified WTG aeroelastic model for a specific simulator), with the highest practicable grade of accuracy, but does not (necessarily) have access to the other party's most trusted model. Because of strong coupling:

1) On the WTG OEM side, an explicit marine hydrodynamics model will be needed to work in tandem with the own trusted aeroelastic model.
2) On the EPC side, an explicit aeroelastic model with controller will be needed to work in tandem with the own trusted marine hydrodynamics model.

In this setting, **the amount and complexity of the data exchanged between parties will be high**; moreover, each party will likely not be able (or willing) to check the other's data and models as these are not their specialty! Given this challenge, projects will benefit from the following QA/QC principles:

- Use a **system engineering** workflow with clear breakdown and milestones (configuration freeze, transmittal, etc.), limiting drift and enabling to keep track of project decisions (e.g. hypotheses) and their ownership. Any potential inconsistencies appearing downstream may then be traced back.
- Constitute/require **QA/QC proofs** throughout the process: methodology qualification (e.g. a base justificative document plus project-tracking addendums), model setup checklists and cross-party verification, result spot checks and global integrity indicators, numerical object integrity reports[3].

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[3] For example, automated sanity check routines: checking the consistency of a large DLC table before launching the simulations, simulation folder/file matching after an over-the-wall data transmission; etc.

- The larger the amount of information handled at an interface, the higher the QA/QC investment required for robustness and the return on investment by suppression of avoidable mistakes.

Nota: not all contractors (or their subcontractors) are aligned on the same quality requirements and reporting habits. If unchallenged, some may by default fall short of the desirable level: make sure that project management documents include all necessary details.

JOINT ILA SCHEMES

The workhorse of an ILA is coupled simulation, deployed into 1000s to 10000s of single runs to satisfy normative DLC requirements. Past work as floating EPC with major WTG OEMs (iterations for the Sea Reed and Groix & Belle-Île projects between 2014 and 2020) saw the implementation of **two practicable schemes** to fulfil the previous chapter's conditions 1) and 2), which make sure that every design party can exploit simulation results of acceptable quality. Both are described and evaluated in the table below, with focus on the "high-grade" models needed for FEED+ work. These schemes correspond to the two identified variants of Carbon Trust's strongly coupled "Strategy B", see [6].

Table 3 The two strongly coupled joint ILA schemes practicable to date and respective pros and cons.

Two parties using →	**two parallel global models (a)**	**one global model for both (b)**
Model and software	Each party builds and runs a full model in its respective coupled solver of preference. WTG OEM imports (often simplified) substructure model data from the other party, and vice versa.	WTG OEM imposes the aeroelastic model and solver. Each party builds its part of the model in the resulting respective imposed solver. Co-simulation of two solvers (aeroelastic and marine).
Pros	• Easy for each party to run independent sensitivities • Aids in preserving detailed model confidentiality	• Unique loads source for every component's design • Likely reduced total CPU cost • No controller DLL issues
Cons	• **Time-consuming item on critical path**: two-party model cross-verification • No model with all parts at highest fidelity (e.g. better WTG in the OEM's global model): inconsistencies	• **Time-consuming item on critical path**: setup and qualification of inter-solver coupling • Large output dataset transmittal from "computing" party (typically WTG OEM) to the other

Next, applied examples with software names are provided for a better understanding of the concept. The first example illustrates scheme (a) using two parallel global models:

- **Software**: The EPC's reference coupled solver is Orcina OrcaFlex®, for which it possesses a trusted substructure model, the WTG OEM's is DNV Bladed®, for which it possesses a trusted WTG model.
- **Two-way constitutive model share**: the EPC creates and shares floating substructure model data for implementation in Bladed, the OEM creates and shares WTG model data (with controller) for implementation in OrcaFlex.
- **Model verification**: for each design iteration, construct a proof of correct model setup and convergence between the aggregated OrcaFlex and Bladed models.

- **Parallel runs**: each party runs the (partial or full) DLC list on its respective computing infrastructure.
- **Independent exploitation**: each party independently post-treats and exploits own coupled simulation outputs for its design needs.

Next is an example of scheme (b), with a sole global model using two solvers linked by external coupling:

- **Software**: The WTG OEM's coupled solver is WTS (fictional: Wind Turbine Simulator), for which it possesses a trusted aeroelastic model. In the absence of marine capabilities, WTS has an external runtime coupling function, e.g. with OrcaFlex called by WTS through a bespoke DLL (see for example [7]). The OEM is ready and willing to deploy OrcaFlex on its computing infrastructure.
- **One-way constitutive model share**: the EPC creates and shares with the OEM an OrcaFlex floating substructure model[4], which is assembled with the rest by the OEM for co-simulation. The co-simulation "aggregated solver" with WTS as master and OrcaFlex as slave is denoted OrcaFlex-WTS.
- **Coupling qualification**: reused from past projects involving the same two parties, or else to be planned upfront. Validates the OrcaFlex-WTS methodology; i.e. that the runtime coupling with its approximations works acceptably, as well as the EPC's post-processing approach (the marine solver being "slave" in the simulation tends to create numerical challenges).
- **Model verification**: for each design iteration, create a proof of correct OrcaFlex-WTS model setup.
- **Unique ILA coupled run**: the WTG OEM runs the DLC list on its computing infrastructure.
- **Handover and exploitation**: the WTG OEM shares the relevant output time series (potentially up to tens of TB worth of data in a FEED) and each party post-treats and exploits its part for its design needs, all coming from the same batch run.

Note that the scope and goals of the model verifications (present in both approaches) highly depend on the joint ILA scheme. Another observation is that for scheme (b), substructure design adaptation will highly benefit from the EPC's ability to use well-calibrated simplified wind turbine models (e.g. [2]), to perform fast-track sensitivity and/or optimisation analyses independently from the WTG OEM.

How does one pick a scheme for a particular project? Once again, the stage is set (constrained) by WTG OEM standardisation. Depending on the capabilities of the solver running the certified WTG model:

- Marine capabilities OK → pick between (a) and (b) based on pros/cons and contractor experience.
- No or little marine capabilities (a very common case!) → obliged to take (b).

DESIGN TO FREQUENCY

This section focusses on a critical technical detail which deserves special attention: the management of flexible frequencies throughout the design process. While eigenfrequencies are a recognised driver of WTG design (interacting with blade pass excitation 3P, 6P, etc., and determining vibrations and controller reactions), it is much less so in the floating offshore structures mindset. Still, **the floating substructure is the rotating machine's macroscopic flexible bearing** and as such speaks in Campbell

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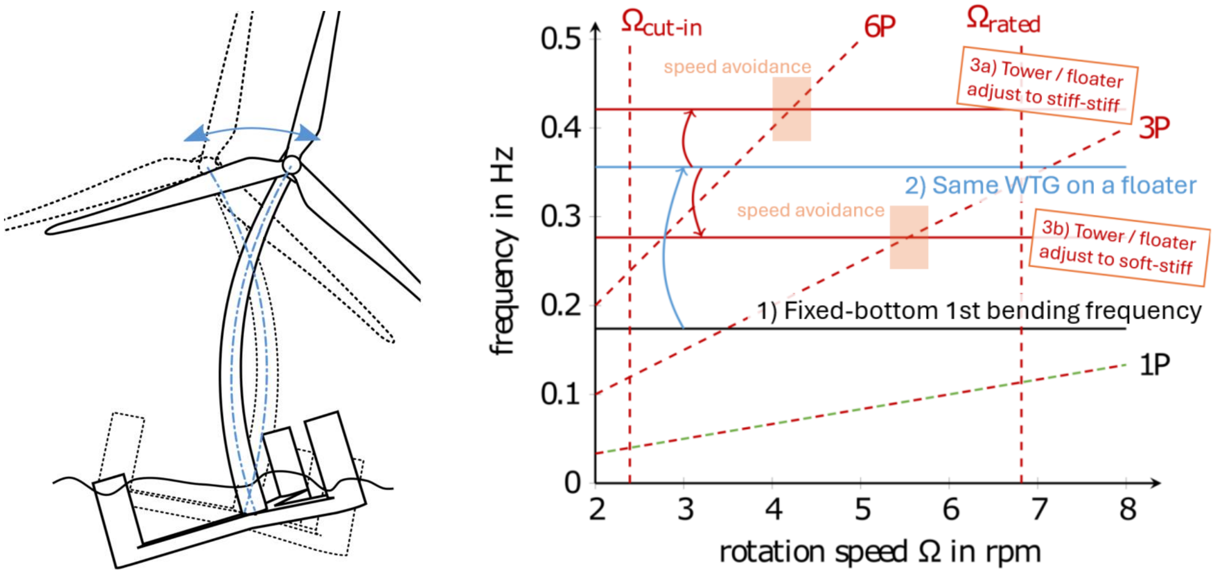
[4] Note that in the example, OrcaFlex may not be the EPC's default marine hydrodynamics software for which internal productivity aids, qualifications, and work instructions are already in place. This occurrence must be detected upfront as it brings extra work and risk in the project.

diagram frequencies: its mass, added mass, and structural stiffness distributions have a major impact on system frequencies, most critically on the fore-aft and side-side tower bending modes.

Figure 2 Global floating wind turbine bending mode (left) and example of frequency design adjustment represented on the Campbell diagram (right). Adapted from [8].



Below are a few telling modal analysis facts for common semi-submersible floater architectures, affecting both frequency assessment per se and coupled model setup:

- For a free-floating substructure, the global bending mode shape is that of a free-free beam (blue in Figure 2, left). Applying a clamp boundary condition, e.g. at keel, leads to meaningless frequencies.
- A rigid floater approximation[5] has been observed to alter first bending frequencies by **at least 10%**.
- A reduction-point added mass/inertia approximation[5] (as opposed to distributed) has been observed to alter first bending frequencies by at least 3-5%.
- Off-centred (non-axisymmetric) architectures will present different floater inertias and structural stiffnesses respective to bending in the XZ and YZ plane, causing cyclic eigenfrequency variations as a function of nacelle yaw. This has been documented on operational units [9].

Properly managed system frequencies will prevent bad surprises when moving to the next (more accurate) design phase and, more importantly, after construction. Surprises in the "as-built" Campbell diagram can be a source of commissioning headaches, reduced asset availability, and even repair works further down the line.

In conclusion, this section highlights the need to i. systematically incorporate global flexible frequency considerations in floating substructure design choices, and ii. make sure that frequencies are estimated reliably (for both global mechanical design and controller design) and then represented correctly in the coupled model. This is easier said than done, as direct flexible modelling of all parts is often impracticable in time domain; hence the need for a careful frequency calibration by expert hands.

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[5] Warning: standard floating offshore structure modelling practice.

CONCLUSION

Wind turbines and floating offshore structures are two originally far-removed worlds coming together in a single asset. The respective Tier 1 contractors must express a common design effort into a relatively new engineering application; how does one get the best value from it?

Learnings from past work as part of EPCs (floater product owner), including design iterations jointly performed with major WTG OEMs, permit to identify the key challenges, opportunities, and requirements of such co-engineering to maximise the project’s value and chances of success.

What are the take-home messages? On the project management side: implement a cooperative process with strong interfaces and QA/QC. On the technical side: aim at global (as opposed to local) system optimisation, address the complexities specific to the chosen ILA scheme, address flexible frequencies early on and systematically. Challenge each party’s assumptions and habits, in pursuit of added value.

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