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# Recent Advances in Response Analysis of Floating Wind Turbines in a Reliability Perspective

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**Abstract.** Offshore wind provides an important source of renewable energy. While wind turbines fixed to the seabed in shallow water have already been industrialized, floating wind turbines are still at an early stage of development. The cost of wind power is decreasing fast. Yet, the main challenges, especially for novel floating wind turbine concepts, are to increase reliability and reduce costs. The reliability perspective here refers to the lifecycle integrity management of the system. Wind turbine concepts should be developed in a life cycle perspective – i.e. design, fabrication, installation, operation and decommissioning. Moreover, the assessment of global behaviour should properly account for the effect of different sub-systems (rotor, drivetrain, tower, support structure and mooring) and the load effects should be determined so as to be proper input to the integrity check of these sub-systems. In this paper recent developments of methods for numerical and experimental response assessment of floating wind turbines are briefly described in view of their use to demonstrate system integrity in design as well during operation to aid inspection and monitoring. Typical features of offshore wind turbine behaviour are also illustrated through some numerical studies.

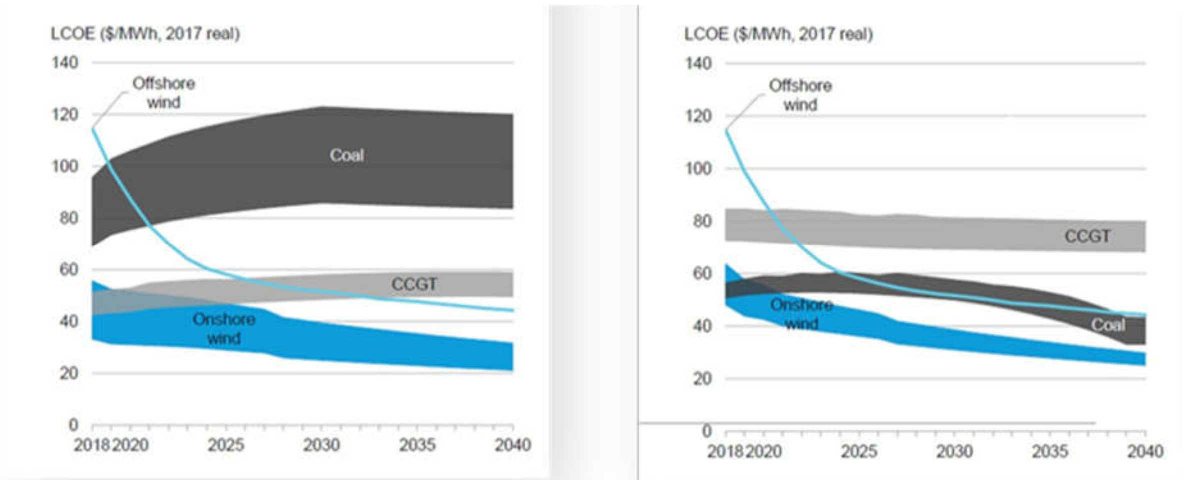
**Keywords.** Floating wind turbines, Design standards, Design criteria, Integrated dynamic analysis, Dynamic behaviour, Reliability

## 1 Introduction

An increased focus on renewable energy is needed to deal with the climate challenges [1]. While wind energy on land is already cost-competitive, offshore wind power is also forecasted to become competitive in relatively few years, e.g. in the US and China (Fig. 1). In Europe (Fig. 2), we have already seen low-bid offshore wind farms in the Netherland and Denmark, with an estimated LCOE of 60-70 Euro/MWh, and even subsidy-free farms in Germany [2]. The reduction in costs is mainly due to the maturation of offshore wind technology and the use of large-scale wind turbines. This trend is in line with the overall goal for offshore wind industry by 2030.

While offshore wind made up 1.8 % of the wind energy capacity in 2011, it was increased to 3.5 % in 2017 [3]. Offshore wind energy is more expensive than that onshore, although there are other advantages with harvesting wind energy offshore. Yet, increased reliability and decreased costs are needed for offshore wind technology to fully utilize the significant potential for offshore wind energy, especially by using floating wind turbines in deep water. By using larger wind turbines (Fig. 3), industrialized manufacturing etc., cost reduction has been achieved – and is expected to continue. Industry projects based on 8 MW turbines are being realized. The EU Innwind project [6] is an ambitious successor of the EU UpWind project [7], where the vision of a 20MW wind turbine was explored.

Wind power is produced offshore by wind turbines that consist of a rotor, a drivetrain and an electric generator, supported on a tower and a bottom-fixed or floating structure as well as a power cable. The core unit is the rotor with a drivetrain to the electric generator. Most turbines are horizontal axis with 3 blades, however, 2 bladed rotors are also of interest. A geared drive train is applied to increase the rotational speed from about 10 rpm to 1800 rpm for traditional generators. Alternatively, a direct drive, i.e. without gear, is applied. The balance between advantages/ disadvantages of geared and direct drive solutions, in terms of cost, is not yet clarified. A significantly different alternative would be to use a vertical axis wind turbine – with different types of rotors envisaged, using curved or straight blades, see e.g. [8-9]. Various types of vertical axis turbines have been proposed but are only commercial in small scale.




a) USA b) China

Fig. 1 Cost of wind energy vs coal and CCGT in the US and China [4].

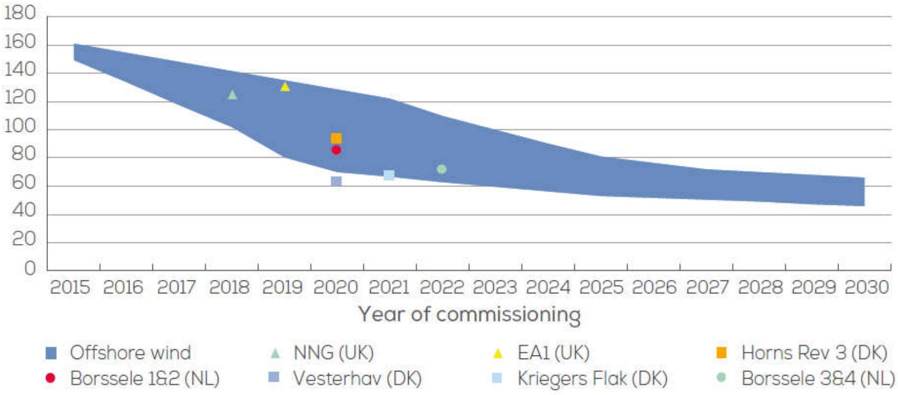



Fig. 2: Offshore wind LCOE range and trajectory from 2015 to 2030 [5].

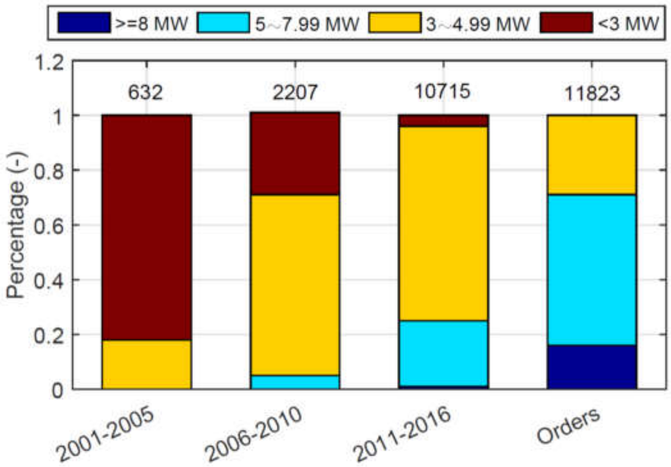


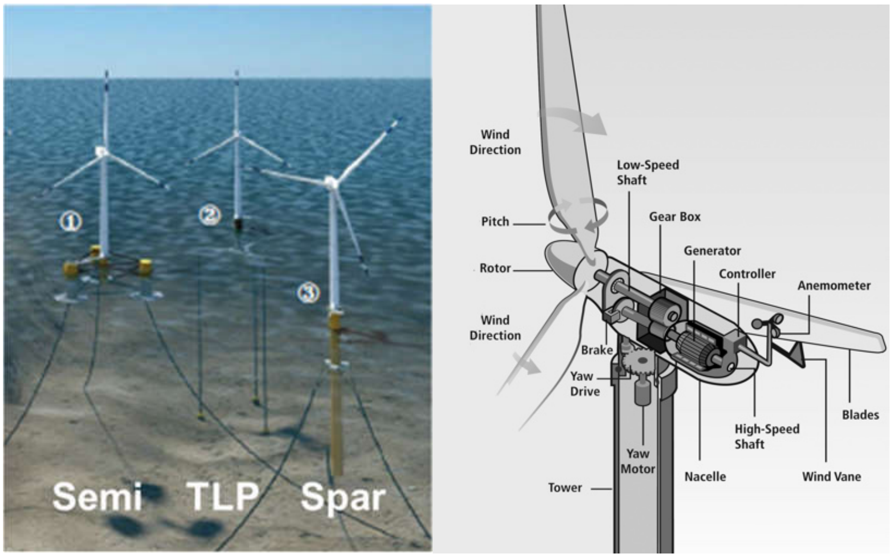

Figure 3 Development of offshore wind turbine size based on commercial orders since 2001: segmented by grid connection date. Orders include turbines planned to be installed in 2017 and beyond [10].

For traditional HAWT with gear transmissions (Fig. 4), the gearbox is among the most expensive components and has a high failure rate. Therefore, it is necessary to develop methods to better understand the behaviour of drivetrain components under dynamic loading conditions. Moreover, the load effects in the drivetrain are a result of the global performance of the wind turbine system, an integrated analysis becomes crucial. This is partly to provide for the various sub-systems' (drivetrain, mooring, power cable) features and also the determination of load effects in the different sub-systems.

Yet, a wind turbine system partly consists of serial products like the drivetrain components and partly site-specific subsystems (support structure, gravity/bucket/pile foundation or mooring/anchoring system). Certification is normally based on wind classes. This classification system is a bit awkward in view of the fact that e.g. drivetrain responses might depend on the type of support structure. Hence, the question might be raised whether also "concept classes" should be used.

In recent years, various floating wind turbine concepts have been developed, including spar- [11-14], or semi-submersible- [15-22] concepts with catenary, taut or tension leg mooring system. Comparative studies of several types of floating concepts have been presented in [23-27]. The first small wind farm of floating turbines was opened in the fall of 2017 ([28] Equinor) and others are emerging [29]. While most studies have involved HAWT also some research has been done on VAWTs on different support structures [30-33].

The development of floating wind turbines is still at an early stage and further studies are required to demonstrate which of the concepts is best for certain site conditions, i.e. water depth and met-ocean conditions. The support structure, rotor and drivetrain make up a tightly coupled system with interacting subsystems.




a) Floating wind turbine systems b) HAWT drivetrain

**Fig. 4.** Floating wind turbine systems and components (Courtesy NREL).

Transfer of knowledge from other sectors to the emerging offshore wind energy sector is important. This has already been done regarding support structures from the oil and gas industry and rotors and turbines from the aerospace field. Moreover, the aerospace aircraft industries are based on mass-production which is important for the wind energy sector to adapt.

Various floating structures have been developed – of the spar, tension-leg and semi-submersible type. Information about the blades, tower and support structures are readily available for realistic research studies, especially for the widely studied reference turbines such as the NREL 5 MW [34] and DTU 10 MW turbines [35]. However, less information about drivetrains or commercial control systems is in the public domain. For the drivetrain, published information includes the 750 kW device in the test bench at NREL [36], a three stage drivetrain with two main bearings developed for the NREL 5 MW turbine [37] in Fig. 5; and the medium speed drivetrain for the DTU 10 MW turbine developed by Wang et al. [ 38 ] also shown in Fig. 5. While the reference turbines include simplified control system definitions, the lack of publicly available information regarding details of the blade pitch and generator torque control, in particular for floating wind turbines, results in challenges for comparisons against full scale measurements (of which few are available) and for detailed study of wind turbine subcomponents.

The purpose of this paper is to highlight recent developments of criteria and methods for the assessment of serviceability and safety, especially methods for integrated dynamic analysis with respect to the operational phase of floating wind turbines, in a reliability context; i.e. in a structural integrity management perspective.

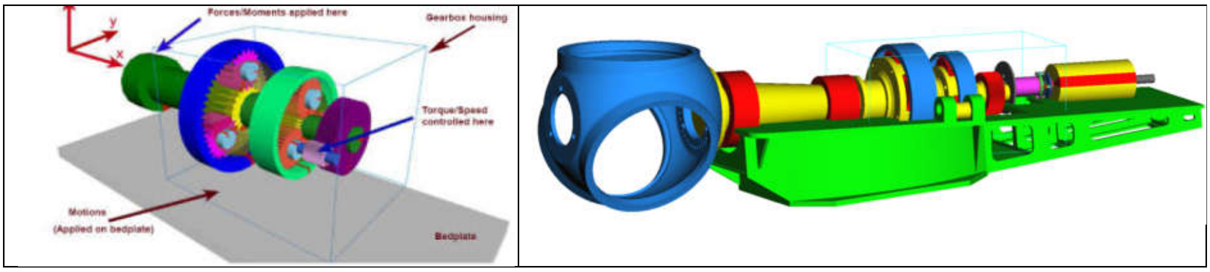



**Fig. 5.** Drivetrain design for a 5 MW (left) [37] and 10 MW turbine (right) [38].

## 2 Lifecycle Integrity Management

### 2.1 Failure Experiences

Service experiences with failures and accidents serve as an important basis for formulating an integrity management strategy for any engineered facility.

During their service life, turbines experience operational, start-ups, shutdowns, idling and parked conditions. Moreover, they are exposed to a variety of load conditions that can lead to failure in different modes. Structures supported on the seafloor can experience failure of the structure, foundation or soil, while buoyant structures can experience capsizing or sinking, hull or mooring system failure. In addition, the tower, rotor and drivetrain experience various failure modes. While the experienced annual failure rates for electrical and mechanical components can be of the order of 0.5, large mechanical components/gears/bearings have a failure rate of the order 0.05-0.25 [39]; implying that these components don't reach a 20-year service life expectancy. The annual failure rate of the rotor and tower was estimated by [40] to be of the order of $10^{-1}$ - $3 \cdot 10^{-3}$ and $7 \cdot 10^{-4}$ - $1 \cdot 10^{-4}$, respectively. Support structures are usually designed to have an even smaller likelihood of failure. Although the failure rate of gearboxes is much lower than that of other mechanical/electrical components in the drivetrain, gearbox failures contribute to a significant amount of downtime because of the complexity to repair or replace the gearbox [41].

Offshore wind turbines involve a bottom fixed or floating support structure. While there are already some service experiences with fixed support structures in shallow water, there are very limited experiences with floating support structures. For the latter experience with oil and gas platforms is a valuable source of information [42-43]. Yet the differences between the oil and gas and wind energy sectors should be recognized; both with respect to serviceability and safety criteria and economic conditions. Among the lessons learned with relevance for wind turbines is that human and organizational errors and omissions represent a main contributor to failures and accidents. This is for instance apparent in connection with the occurrence of crack-type weld defects with abnormal size due to fabrication errors and omissions and ship impacts due to operational errors relating to vessels adjacent to the structure. The high failure rate, 0.01 per line-year, of catenary mooring lines is noted. Hence, a combination of adequate design criteria, inspection, repair and maintenance as well as quality assurance and control of the engineering processes, is required to ensure adequate safety.

**2.2. Structural Integrity Management**

The causes of failures or accidents can be organized in three categories in view of the relevant measures to mitigate the associated risk as shown in Table 1.

Table 1 *Causes of structural failures and risk reduction measures (adapted after [42] )*

| **Cause** | **Structural Integrity Mitigation Measure** | **Quantitative method** |
|---|---|---|
| Less than adequate safety factor/ margin to cover "normal" inherent uncertainties | - Increase safety factors or margins in ULS, FLS;<br>- Improve inspection of the structure (FLS) | Structural reliability analysis |
| Gross errors or omissions during<br>- design (d)<br>- fabrication (f)<br>- operation (o) | - Improve skills, competence, self- checking (for d, f, o)<br>- QA/QC of engineering process (for d)<br>- Direct design for damage tolerance (ALS) –with adequate damage condition (in f, o) – NOT d<br>- Proof or prototype testing of the whole or parts of the facility<br>- Event control relating to fire, explosion and other accidental scenarios<br>- Inspection/repair of the structure (for f, o) | Quantitative risk analysis |
| • Unknown phenomena | - Research & Development | Technology Readiness Level |

In the following, a brief overview of design criteria and follow-up of the structure during fabrication and operation through inspection, maintenance and repair, will be addressed.
The International Electrotechnical Commission (IEC) 61400-1 [44] design standard specifies the design requirement for land-based wind turbines and the IEC 61400-3 [45] design standard supplements the IEC 61400-1 [44] with design requirements for bottom-fixed offshore wind turbines. The guidelines and standards from Germanischer Lloyd (GL) and Det Norske Veritas (DNV) are also extensively used [47-49]. For the design of floating wind turbine structures, standards are slowly emerging as experiences are gained, e.g. [46, 49-50]. Design specifications e.g. for wind turbine gearboxes are given in [51]. Current design approaches, especially for the drivetrain, are semi-empirical and based on allowable stress approaches, even with respect to fatigue.

For proper design of the wind turbine system ( rotor, tower, floater and mooring system), a global dynamic response analysis of the wind turbine to simultaneous action of wind and wave loads needs to properly account for the sub-systems and provide load effects for detailed assessments of the subsystems, see e.g. Section 3.5.2.

A rational approach for development of standards and performing safety assessment should be based on [42]:

- Goal-setting; not prescriptive
- Probabilistic; not deterministic
- First principles; not purely experiences
- Integrated, total; not separately
- Consideration of the lifecycle (design, fabrication/installation, operation) integrity management by proper design, inspection, monitoring, maintenance, repair and replacement (DIMMRR).
- Balance of safety elements; not hardware only.

Failure of wind turbines on site normally implies only economic consequences, and not fatalities nor environmental damage, e.g. such as offshore oil & gas platforms. Safety criteria could therefore simply be decided on a cost-benefit basis, in economic terms, and could, hence, be different from that inherent in oil and gas platforms or public infrastructure. This fact should be especially be kept in mind when transferring technology/knowledge from the oil and gas sector for use in connection with novel floating wind turbine concepts.

Standards and guidelines should represent best practice and correspond to certain serviceability and safety target levels. However, it is noted that criteria relating to deflections, vibration level, and structural strength are quite explicitly formulated in terms of formulae. Load effects, however, are described by analysis procedures. Typically, there are alternative choices of model refinement (e.g. aerodynamic loads based on the thrust force, BEM methods for loads on individual blades or CFD methods). The uncertainties involved vary and need to be reflected in the decision process. This fact can also be observed in software benchmark studies where the case and methods are specified, yet analyses results show a large scatter – see Section 3.9.2.

Moreover, a hierarchy of methods, ranging for simple conservative approaches for conceptual studies to high fidelity methods for detailed design, are required.

## 2.1 Design Criteria

### 2.1.1 General

Wind turbine systems are in general designed for serviceability and safety.

Design implies decision under uncertainty – which needs to be reflected in design principles, methods and procedures, see Section 3.9.

The main *serviceability* criterion relates to a constant power production beyond the rated wind speed and maximum power in the below-rated wind speed regime. The power depends on the wind conditions on the site – implying that the capacity factor (relative time the rated power can be produced) for offshore may be up to 50-60 % while on-land it is about 35%. Even if a proper control system can compensate e.g. motions of a floater, it is relevant to introduce criteria for steady tilt and motions, say of the order of 5-8$^o$ to limit reduced power production. The drift-off and motions may also have to be limited due to the response in the power cable. The tilt and motion responses also have implications on the performance of the drivetrain and the load effects for tower and hull components.

In detailed design for safety, compliance with limit state criteria for ultimate, fatigue and possibly accidental collapse (ALS) criteria should be demonstrated. For floating wind turbines, criteria for overall stability as well as ultimate and fatigue strength apply.

ALS is based on the principle that a small damage/fault shall not lead to disproportionate consequences (e.g. [52]). For instance the Norsok N-001 approach [53] is based on a two-step limit state check:

- Estimate damage due to accidental scenario with an annual probability of exceedance of 10-4
- Check that the damaged structure survives an annual, 10 or 100 years max. environmental load.

Floating structures are normally designed for intact and damage stability corresponding to ULS and ALS criteria, respectively. Whether ALS criteria should be applied for the stability of floating turbines, e.g. damage stability relating to ship impact damage, or a strength check of the mooring system after failure of mooring line(s), is still under debate. A cost benefit assessment should be the basis for such a criterion, considering e.g. a mooring line failure consequences for the relevant farm. The standards for floating wind turbines are still at an early stage and further deliberations are necessary.

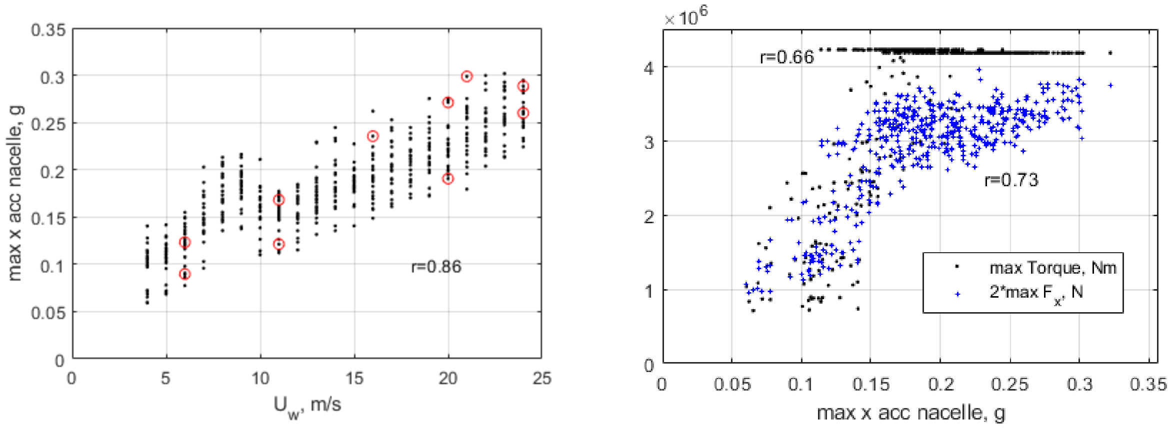
On the other hand the IEC codes (e.g. IEC61400 series) require explicit ULS design checks considering a fault, e.g. internal faults due to control system and grid, combined with a certain environmental condition. This is because these faults occur relatively frequently, as discussed in Section 3.6.

### 2.1.2 Simplified response-based design criteria for conceptual screening

While rotor blades, tower and hull structure are designed based on explicit ultimate and fatigue strength criteria and predicted response for the different load cases, simplified empirical safety criteria are applied to the drive train. Sometimes, it is assumed that the simplified design check of the drivetrain (in conceptual design studies) is acceptable if the axial acceleration of the nacelle is limited to 0.2 - 0.4 g (g being the acceleration of gravity). Here, the inertia forces on the rotor are implicitly referred to. However, the inertia forces only represent part of the loads acting on the drive train shaft and hence governing the loads in the gear and bearings. The thrust and all the three moments acting on the shaft, as obtained in an integrated global dynamic analysis, should be considered in a limit state design check of the drivetrain mechanical components. The rationality of such an acceleration limit was investigated in [54] by evaluating the correlation between the acceleration and the real drivetrain responses.

A 5 MW reference drivetrain on a spar-type floating wind turbine in 320 m water depth, was applied, considering a set of relevant environmental conditions for the Northern North Sea. For each condition, global analysis using an aero-hydro-servo-elastic tool is carried out for six one-hour realizations. The load effects obtained in the global analysis are applied on a detailed drivetrain model in a multi-body system (MBS) analysis tool. The local responses on bearings are then obtained from MBS analysis and post-processed for the correlation study. Although the maximum acceleration provides a good indication of the wave-induced loads, it is not seen to be a good predictor for significant fatigue damage on the main bearings in this case.

The results suggest that the wave-induced motion has the biggest contribution to the axial acceleration, followed by the tower shadow and turbulence effects at the 3P frequency. Fig. 6 shows the correlation between maximum axial acceleration and bending moment in the tower (rotor shaft). It was found that the torque and axial force are mainly affected by the pitch control system, and are not significantly correlated with the maximum axial acceleration. A correlation was observed between the maximum axial acceleration and the radial load on the first main bearing (INP-A – see the later Fig. 14) which carries the radial load only. However, the spectrum of the radial load on INP-A showed that wind and tower shadow are the dominant players, therefore, the correlation with the axial acceleration - which is wave-dominated, - is not a good measure for judging the loadings on this bearing or its fatigue life assessment. For the second main bearing (INP-B) which carries the axial force, extreme bearing loads are correlated with the axial acceleration. However, it was found that there is less correlation between the maximum acceleration and fatigue in this bearing. There are other environmental conditions with lower axial acceleration which reduce the fatigue life of the main bearings more than those with high axial accelerations.




a) Max acceleration for operational conditions b) One-hour max. torque and axial force vs max acceleration

Fig. 6 Axial nacelle acceleration versus drive train response in the 5 MW turbine in Fig. 5 mounted on a spar in 32 water depth [54].

There is clearly a need for further development of rational design criteria for different failure modes, especially for drivetrain components, e.g. based on assessment of load effects by first principles.

Luan et al. [55] describes the design of a 5 MW semi-submersible wind turbine, addressing stability, dynamic behaviour and a simplified ultimate strength check.

## 2.2 Inspection, Monitoring, Maintenance and Repair during Fabrication and Operation

### 2.2.1 General

Operational expenditures (OPEX) include maintenance and service costs in addition to other variable operational costs. O&M costs make up 21% (11 %) of the costs offshore (onshore) [56]. The items considered in OPEX may vary somewhat. In addition, O&M also affects the wind farm availability and lifetime, and hence the LCoE. Hence, O&M is an important area for improvement in order to reach the goal for offshore wind LCoE reduction [56]. Due to the high repair and replacement costs for offshore wind turbines a focus on reliability and availability by design needs to be explored. Moreover, new solutions for operation and maintenance, condition monitoring and transport logistics are needed. One such approach is to use a robot moving along the guides in the nacelle to inspect the drivetrain/generator, drones to inspect blades and autonomous vessels for underwater inspection (Fig. 7).


a) A robot for drivetrain inspection  b) A remotely piloted Aircraft system for blade inspection  c) Underwater snake robot vehicle

Fig. 7 Tools for enabling inspections in areas with difficult access [58-60].

Inspection and condition monitoring (IM), and, if necessary, maintenance and repair (MR) are important measures for maintaining an adequate safety level with respect to fatigue, wear, corrosion and other degradation phenomena. The main challenge is concerned with deterioration phenomena, especially crack growth, because of the significant cyclic loading. An inspection and repair approach can contribute to the safety only when there is a certain structural damage tolerance. This implies that there is an interrelation between design criteria (fatigue life, damage tolerance) and the inspection and repair criteria [42-43]. While the initial IMMR plan is made at the design stage, it is updated depending upon the findings during inspections.

While inspection and repair strategy serves as basis for ensuring the safety of the hull structure, tower and blades, condition monitoring is important for the drive train, especially vibration-based monitoring of the drivetrain [61]. Gearbox-oil based condition monitoring is also gaining importance as a complementary system.

Performance (SCADA) data also yield information about abnormal behaviour; i.e. health condition [62-63]. Additional Condition Monitoring of machinery or electrical components depends on a cost-benefit consideration. A vast number of sensors are installed on a modern wind turbine to detect and isolate faults. Faults such as bearing wear or gear tooth wear are hard to detect at early stages, but they may result in a total breakdown of drivetrain [64]. The EU Reliawind project provided wind turbine reliability profiles by analysing the long-term operational data and fault records of 350 onshore wind turbines [39]. The pitch system has the highest failure rate among the components. Because of this, the contribution of the pitch system fault to downtime is also large. There exist a suite of techniques for fault detection and isolation. Methods to diagnose damages include

- Acoustic emission, vibration,
- oil sampling/filter content (debris, cleanliness): damaged gearboxes release particles at an increased rate, but this method does not pinpoint the location of damage
- temperature
- (blade pitch) sensors

Moreover, the huge amount of SCADA data suggest use of data-driven methods (machine learning/AI). However, such approaches, including time/frequency data analysis, neural networks, regression analysis, can be enhanced by model-based or physics-based (machinery) approaches. The development of reliable, accurate and practical methods for damage diagnostics and prognosis is an important research area.

### 2.2.2 Response based analysis to support inspection and monitoring planning

Structural reliability methodology (SRM) [65-66] provides a tool to plan inspection and monitoring in view of the uncertainties associated with the behavior and reliability of detecting damages by inspectors or the sensor system used, especially in connection with deterioration phenomena like crack growth and wear. Such methods are extensively applied in the oil and gas industry for hull structures [42]. While classical reliability methods [64] is typically used for machinery and electrical systems, it is found that SRM is useful for drivetrains [67, 68]. A ranking for inspection/monitoring of gear and bearing components based on fatigue damage estimates, was established in [68].

A crucial element in the reliability analysis is to predict the load effects and carefully assess the associated uncertainty. The limitation of SRM should be observed, namely that it does not account for gross (human) errors and omissions. Chapter 3 is devoted to these aspects.

# 3 Assessment of dynamic behaviour (determination of load effects)

## 3.1 General

Design criteria are expressed by displacements/motions, strength measures in terms of forces or stresses, and the corresponding measures of load effects are then needed to demonstrate compliance with the criteria. Both extreme values and load effect histories are required.

It follows that in order to determine the load effects in the support structure and towers, a model of the whole system, including e.g. the rotor/drivetrain, is needed in order to account for all relevant loads and system dynamics features. The integrated dynamic analysis provides load effects in all subsystems, such as the rotor, drivetrain, tower, support structure, mooring or foundation and can serve as a basis for the design of them. Normally, the global analysis can be done with a simplified model of e.g. the drivetrain, while the responses for the design checks of the gears and bearings will be based on a high fidelity model using the global analysis results as input, as illustrated later.

Moreover, load effects during operation at the offshore site as well in temporary phases such as transport and installation are needed.

## 3.2 Importance of dynamic behaviour

Offshore wind turbines are subjected to dynamic wind, wave, and current loads, possibly ice and seismic loads, as well as rotor loads with a wide range of excitation frequencies [8-9]. A wind turbine experiences loads at the rotation frequency of the rotor, denoted 1P (typically 0.12 – 0.2 Hz) and multiples of the blade passing frequency of N (number of blades) times the frequency P.

Aerodynamic loads cause steady and random effects in a broad frequency range and can excite not only rigid-body motion modes of floating wind turbines but also flexible bending modes of blades and towers of both bottom-fixed and floating wind turbines. First order wave excitation corresponds to frequencies in the range of 0.04 - 0.3 Hz. Moreover, second-order difference-frequency wave forces can excite the resonance of horizontal rigid-body motions (surge, sway and yaw) with typical natural frequencies of 0.005 - 0.02 Hz. Second-order sum-frequency wave forces may excite flexural modes of bottom fixed wind turbines as well as heave, roll and pitch modes with typical natural frequency above 0.2 Hz of tension-leg turbines.

An indication of the lowest natural frequencies for current types of floating turbines with turbines above 2 MW is given in Table 2.

For a spar WT, the natural frequencies of heave and pitch (or roll) motions could be close and the so-called Mathieu instability (e.g. [69]) might occur. Hence, the design should aim at differentiating the natural frequencies in heave and pitch (or roll). The unsymmetrical aerodynamic forces on the rotor may lead to a large yaw moment. With a conventional mooring system with radial lines through the center of the spar, the yaw stiffness will be small. However, a delta-configuration adjacent to the spar hull ensures an adequate yaw stiffness and yaw natural frequency.

The pitch/roll natural frequency of a tension-leg WT with a rigid tower may be of the order 0.2 – 1.0 Hz which is usually close to the lowest natural frequency of a flexible tower fixed at the transition to the floater [27, 70]. This fact would imply a coupled pitch and flexible tower mode.

**Table 2.** Indicative natural frequencies (Hz) and natural periods (s) of "rigid body motion modes" of floating offshore wind turbines.

| | | Spar | Semi-submersible | TLP |
|---|---|---|---|---|
| Surge/Sway | Nat. frequency (Hz) | 0.005-0.025 | 0.008-025 | 0.015– 0.05 |
| | Nat. period (s) | 40-185 | 40-120 | 20-60 |
| Heave | Nat. frequency (Hz) | 0.02-0.05 | 0.025-0.07 | 0.2-2 |
| | Nat. period (s) | 20-50 | 15-40 | 0.5-5.0 |
| Pitch/Roll | Nat. frequency (Hz) | 0.02-0.04 | 0.02-0.04 | 0.2-1.0 |
| | Nat. period (s) | 25-50 | 25-50 | 1.0-5.0 |
| Yaw | Nat. frequency (Hz) | 0.025-0.2 | 0.0125-0.02 | 0.03-0.2 |
| | Nat. period (s) | 5-40 | 50-80 | 5-30 |

In general, compared to a cantilevered tower, the first bending mode of the tower placed on a floating platform will be coupled to pitch and surge motions of the platform, and the lowest frequency of rotation is no longer the first bending mode, but rather a rigid body pitch mode. This effect pushes the first bending natural frequency higher [71] and may require re-design in order to avoid the tower resonance being excited by loads related to blade passing. Evidence of this challenge can be seen in the LIFES50+ tower designs, which are 1.4-2.0 times as heavy as the original DTU 10 MW tower [72].

The natural frequencies of the mechanical drivetrain between the rotor and generator are much higher than the rigid and flexible structure and blade modes which allow the drivetrain responses to be determined in an uncoupled manner.

Most analysis considers the platform hull to be rigid, assuming that the hull is much less flexible than other components. Recently, there have been several attempts to quantify the effects of structural flexibility in the hull. Although limited consequences were observed for a spar [73], the effects of TLP hull flexibility are anticipated to be more important [74-75]. Torsional modes in semi-submersible designs should also be assessed. If the hull elasticity becomes important, it may be necessary to consider hydro-elasticity. In that case, generalized modes for the system may be applied.

Due to the facts described above, it is important to analyse the dynamic responses, especially of floating wind turbines by taking into account the wind and wave loads simultaneously. In other words, a coupled analysis tool is needed, considering aerodynamic and hydrodynamic loads, as well as models of the structure, mooring and drivetrain in an integrated analysis. Moreover, automatic control is needed to ensure maximum power at low (below rated) wind speeds; stable power and limited structural responses in the operational conditions.

Moreover, since most of the wind turbine responses are governed by resonant motions or vibrations, a proper estimation of various damping (including aerodynamic damping, hydrodynamic potential and viscous damping, and structural damping) becomes very important.

## 3.3 Dynamic Modelling and Analysis

The response analysis needs to be carried out for different design load cases, (Ch.5 of [9], [45-46]) which include a variety of design situations such as power production, power production plus occurrence of fault, normal shutdown and parked condition. Some of load cases come from ‘abnormal’ events of the wind turbine such as shutdown, loss of electrical network connection, faults in control system, faults in protection system and so forth [44-46]. Metocean conditions such as gusts, turbulence and shift in wind direction are also important. Some of these loads imply transient events. The load conditions specified for bottom-fixed wind turbines are taken to be relevant for floating turbines also, but the time-domain analysis for floating wind turbines is much more demanding because of the low frequency excitations and responses require much longer samples to limit the statistical uncertainty in the simulation.

The response needs to be determined in terms of extreme values for ultimate strength check and response histories for fatigue and wear assessment.

**The equations of motion for floating wind turbines.** The governing equations are formulated in the time- (TD) or frequency domain (FD), considering wind and wave loads and possibly ice loads. The advantage of FD methods is the computational efficiency and ease of dealing with frequency-dependent features, while the disadvantage is the need for linearization of possible nonlinear features, handling transient response effects, and control. Frequency domain analysis of land-based and bottom-fixed offshore turbines have been made e.g. in [76]. The applicability of frequency domain methods for floating turbines has been investigated in [70, 77] based on separate analysis of wind and wave-induced response but carefully accounting for the aerodynamic damping from the rotor and hydrodynamic damping in calculations of the wave motions.

**Mooring system.** The catenary mooring system primarily prevents drift off due to steady wind, wave and current loads and also affects the low frequency excitation due to wind and wave loads. The mooring system does not significantly influence the magnitude of the first order wave-induced motions (which however cause dynamic mooring tension). Mooring lines could be modelled as nonlinear springs when global responses are determined. More proper FE models of mooring lines including the line dynamics (inertial forces, hydrodynamic mass and drag lateral forces) should be considered when the line tension is estimated in an integrated global analysis [78]. Moreover, a representative stiffness of the mooring system should be ensured when determining the first order wave load effects, by accounting for the steady drift-off and low frequency wind loads and second order difference frequency wave loads.

A tension-leg mooring makes up an integrated part of the hull system. The natural periods of the vertical motion modes, pith, roll and heave become smaller than the periods of the main waves components.

**Drivetrain** is obviously a crucial component in a wind turbine system. The simplest elastic model of the drivetrain is a torsional spring while more accurate models involve elastic multibodies (Peeters et al [79], Oyague [80], Xing [81-82], Nejad et. al [37]). In order to predict the responses in the different drivetrain components more refined models considering gear contact and bearings are employed. In such models shafts are modelled as flexible elements often with reduced degree of freedom, and bearings with their stiffness and damping. Guo et al. [83] provides recommendations for drivetrain dynamic modelling in wind turbines.

**Hydrodynamic loads** for slender structures can normally be modelled by using the Morison formula, e.g. [69].

$$F = \frac{1}{2}\rho D C_d v|v| + \frac{1}{4}\rho D^2 C_m a \quad (1)$$

which expresses the lateral force per unit length on a slender member with a diameter $D$ and particle velocities and accelerations of v and a, respectively. $C_d$ and $C_m$ are drag and inertia coefficients, respectively and ρ is the water density. For structures with significant motions, the relative velocity is used instead of v and an additional inertia term proportional to the acceleration of the structural component should be included.

The loads on large volume structures should be estimated by potential theory, considering the incoming and diffracted wave pattern, which are important when the wave length is less than, say, five times the cross sectional dimension of structural components. The hydrodynamic loads on floating structures need to be estimated by simultaneously calculating the motions of the structures. Both the first- and second-order wave loads according to the potential theory need to be considered, implying difference- and sum-frequency effects. In the linear analysis, both the diffraction and radiation effects are addressed, which results in the wave excitation forces and the added mass and potential damping forces, respectively. Second-order difference-frequency wave loads might be calculated using a full quadratic transfer function or based on the Newman's approximation, while a fully quadratic transfer function is normally used for sum-frequency loads. The wave forces on floating structures are in general frequency-dependent, which give rise to a memory effect. Viscous effects are normally modelled as drag forces and added to the potential forces.

In addition particular phenomena, such as wave slamming and ringing loads e.g. on large diameter wind turbines need to be considered. For tension leg structures second order high and low frequency loads as well as (third order) ringing loads should be considered, e.g. [70, 84].

The overview of wave loads and load effect calculation for floating offshore platforms described in [85] is also relevant for different types of floating wind turbines. Finally, vortex induced motions (VIM) might be a feature to consider for floating wind turbines consisting of a single or a few large diameter columns.

**Aerodynamic loads**. The wind loads acting on the rotor blades, depend strongly on both the inflow wind velocity and the induced velocity due to the presence of the rotor. Numerical methods have been developed with different levels of detail, such as Blade Element Momentum (BEM), Generalized Dynamic Wake (GDW) method, vortex method, panel method and Navier-Stokes solver, e.g. [8-9, 86-89]. The BEM method is widely used and often combined with structural analysis tools, e.g. the Finite Element Method (FEM), to obtain the dynamic responses of wind turbine tower and blades, by accounting for aero-elasticity.

Refined methods are particularly relevant to establish or validate simplified methods and partly develop fast simplified methods for design analyses. An example of the former type of analysis is the study of the effect of icing on rotor blades by combining using wind tunnel experiments and a CFD method to determine aerodynamic coefficients for the BEM method [90].

Coupled analysis of floating wind turbines is time consuming. It is of interest to establish simplified methods especially for use in conceptual studies. A simplified method, proposed by Equinor [102], is convenient to apply to model the integrated rotor loads (i.e. the thrust) as a point force on the tower top [11, 91], especially for spar turbines [27]. It has been shown that this simplified model gives global responses within 10% accuracy compared with the model using the BEM method [91]. It is noted that the computer time for is significantly reduced by the use of the simplified method. However, simplifications and hence the limitations of the method should be observed in [27].

The development of other low-order dynamic analysis methods is an active field, and can be of particular interest for controller design [92-94].

For VAWTs a variety of aerodynamic models have been developed, including the single streamtube model, multi-streamtube model, Double Multi-Streamtube (DMS) model, Actuator Cylinder (AC) flow model, panel method, vortex method and CFD method. A numerical comparison of these models were conducted in [32-33].

**Other loads.** Placing wind turbines in the marine environment requires consideration of other factors in addition to the wind, waves, currents, and hydrostatic pressure. Variation of the water level due to tides and storm surges especially affects tension-leg turbines (and fixed turbines). So does earthquakes. In cold weather regions, offshore wind turbine support structure design should also account for ice loads and icing. Icing on the turbine and support structure can cause increases in gravitational and inertial loads, and icing on the blades modifies their aerodynamic performance, with possible consequences for the aerodynamic loading [90]. Sea ice can cause direct loads on the support structure, and dynamic interaction with the breaking ice around a support structure can excite structural natural frequencies [95-96]. In addition accidental loads (such as those from ship collisions) should also be accounted for.

## 3.4 Automatic Control

### 3.4.1 Operational control

The purpose of control systems at the wind farm, turbine, and component levels is to manage the safe, automatic operation of the turbine (Ch. 8 of [8]). In order to respond to environmental changes or changes in the operational condition, the turbine-level controller provides some input to dynamic controllers, such as generator torque or blade pitch controllers. Large horizontal axis wind turbines are normally of pitch-regulated variable speed control (Ch.8.3 of [8], Ch.8.2 of [9]) type to regulate the power output and structural loads. For such systems both the rotor speed and the blade pitch can be varied.

For wind speeds between cut-in and rated speed (typically 3 to 12m/s), the blade pitch is kept constant and the generator torque varies such that the WT operates as close as possible to the optimal tip speed ratio. In this region, the thrust and torque increase quadratically with wind speed. At the rated wind speed, the wind turbine reaches the rated torque, rotational speed, and thrust. In the above-rated wind speed region, the blade pitch is varied in order to minimize the structural loads and the generator torque is chosen to give the rated power output. Fig. 8 indicates a typical power-wind speed relationship for a turbine with a rated power of 5 MW. Namik and Stol [97] studied individual blade pitch control (IBPC) as an alternative to collective pitch control for FWTs.

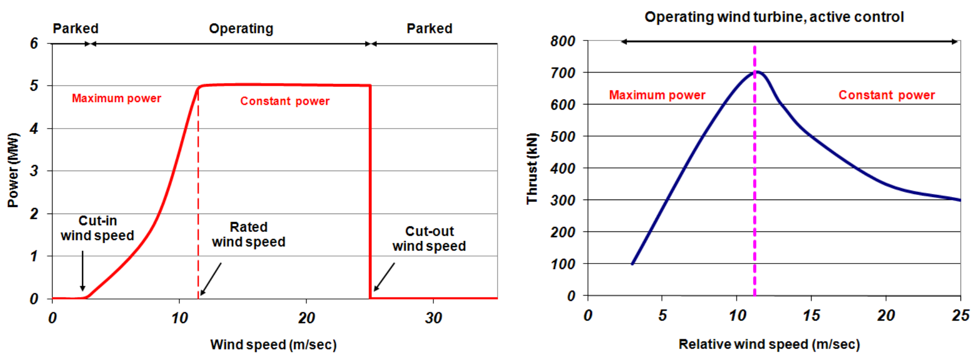



**Fig. 8.** Power (Fig. 8a) and thrust curve (Fig. 8b) of the NREL 5 MW HAWT.

The "large" nacelle motions of FWTs present an additional challenge for the control system. For systems with low-frequency surge or pitch motions, there may be a negative feedback mechanism between the nacelle velocity and the blade pitch controller [98-99], as implied by the negative "damping" at over-rated wind speeds. This feature can be seen as a negative slope of the thrust force with respect to the relative wind speed, as indicated in Fig. 3b.

The initial studies especially focused on spar turbines. This issue was addressed in [100] for a tension-leg spar system, but it is also relevant for semi-submersible wind turbines.

For a TLPWT, the platform pitch natural frequency is generally higher than the controller frequency, thus eliminating the need for control system modifications in most operating conditions. On the other hand, the surge natural frequency is lower than the control frequency and could theoretically lead to instability [101]. In the studies [22, 70-71] the land-based controller was applied to all TLPWTs except in certain studies, particularly related to ringing.

The control strategy for large megawatt VAWTs is somewhat different from that of HAWTs, since large scale VAWTs usually operate with variable rotational speed at a fixed blade pitch angle, and the aerodynamic loads acting on the rotor vary periodically when it rotates [103-104].

So far the control issues relating to normal operational conditions, have been briefly addressed. However, the design standard [44] requires the consideration of control system fault or loss of electrical network. The exact nature of the faults to be analyzed is, however, not specified and needs to be identified by a Failure Mode and Effect Analysis (FMEA). Obviously the fault conditions to consider depend on the possible use of fault tolerant control to mitigate the effect of the faults.

#### 3.4.2. Fault tolerant control

Upon the detection of faults, the supervisory controller selects a remedial action based on existing protection strategies. If the fault is controllable, it will be accommodated by techniques such as signal correction and fault tolerant control. If the situation is severe and the turbine is not in a safe state, the supervisory controller brings the turbine to stop. In the worst case, if the main control system fails to stop the turbine safely, the safety system takes over. It normally consists of a hard-wired fail-safe circuit linking a number of normally open relay contacts [9]. If any of the contacts is lost, the safety system trips, causing the appropriate fail-safe actions, to operate. In the present context it is assumed that severe faults are detected and actions to get the turbine is taken. Turbine shutdowns can either be normal or emergency. For emergency shutdown, the common practice is to pitch all blades to feather simultaneously at the maximum pitch rate. For wind turbines, the change of the aerodynamic loads is the key driver to the dynamic responses of turbines in fault and shutdown conditions.

For pitch-regulated wind turbines, the blade pitch control system contributes significantly to the failure rate [39]. The control system must then identify and isolate the fault and in some way mitigate the fault, typically by shutting down the turbine (by pitching the remaining functional blades to full feather) [100]. The detection and effect of fault cases involving pitch actuator that becomes stuck for various reasons, and grid faults in terms of a short circuit resulting in a complete loss of torque, were considered in [105-110]. Detection and isolation of faults in drivetrain and rotor blades were investigated in [111-115].

Currently, the IEC series of design codes requires design check of various combinations of faults and operational and environmental loads. Due to the severity of the load effects, e.g. as indicated in Fig. 12 a true fault tolerant control might be considered to reduce the load effects; i.e. actions ( shut-down etc.) are automatically initiated based on detection and isolation of a fault [116-117].

### 3.5 Computational Strategy

#### 3.5.1 General

Most of the offshore wind turbine research focus on load effect analyses while resistance primarily is based on component testing in laboratories, supported with analyses. Knowledge and experiences on strength analysis from the offshore oil & gas industry can be applied to the offshore wind industry. Analyses of the dynamic behaviour of the wind turbine need to be carried out for the in-site condition as well as temporary phases such as transport and installation. The focus herein is on the in-site condition while analyses of installation processes are exemplified in [118]. Design takes place in stages – from conceptual to detailed design, requiring different degrees of refinement. A variety of methods – refined and simplified – is hence desirable for dealing with the aerodynamics, hydrodynamics, structural and possible soil mechanics. In general, simplified, efficient methods are required to accomplish analysis in the early design stages when alternative designs need to be assessed.

In the design of wind turbines many load conditions need to be considered to account for the variation in the combined wave and wind conditions, operational versus parked (survival) conditions. It is noted that operational conditions include also start up and shut down, fault occurrence and emergency shutdown. Hence, the reference is a so-called long-term analysis, in which results from a set of short term analyses for stationary met-ocean conditions, are combined based on the probability of occurrence of the various short term met-ocean conditions, e.g. [126]. The long-term variability is accounted for by considering relevant short-term conditions and their probability.

While there are methods, like the contour (line) surface method to select a sufficient number of short-term conditions to determine extreme load effects, fatigue analysis would generally have to include a large number of short-term conditions. Use of the contour method to determine extreme load effects for wind turbines is illustrated in [119]. Cyclic load histories for fatigue (and possibly wear) design checks normally need to be based on long term analysis.

### 3.5.2 Integrated analysis

For proper design of the wind turbine system ( rotor, tower, floater and mooring system), a global dynamic response analysis of the wind turbine to simultaneous action of wind and wave loads needs to be addressed by proper account of all the sub-systems. Moreover, such an integrated approach is necessary to provide load effects for further assessments of the subsystems with a detailed model. If beam models for the rotor blades and the hull are used in the global analysis, local stresses in beam cross-sections can be obtained by post-processing. For mooring lines the tension is obtained in the global analysis and particular focused local stress analysis might be performed as post-processing at fairleads and anchor connection etc. For the power cable, tension and the deformed shape (curvature) are important as the design criteria refer to tension capacity and limiting radius of curvature.

Regarding the performance of the drivetrain, uncoupled analysis is useful to limit the computational efforts. Then a global analysis of the system is first carried out based on a simple representation (e.g. 1DOF system) of the rotational dynamics of the drivetrain, followed by a sub-system analysis based on inputs (load effects and motions) from the global analysis. As long as the global natural frequencies are significantly different from (much lower than) those of the sub-system this is a viable approach. However, it does not cover the complete range of phenomena that can occur in the drivetrain (Peeters, et al. [79]). Both external low-frequency excitation and internal higher-frequency excitation of the drivetrain exist, which might introduce energy in the range of the internal natural frequencies. This addresses the importance of more refined numerical simulation methods for the drivetrain to get further insight into the dynamics of the drivetrain. The multibody simulation technique, can be used to perform the detailed analysis of the loads on internal components of drivetrains. Peeters et al. [79] performed a comprehensive study on the internal dynamics of a drivetrain in a wind turbine using three types of multibody models (1) torsional vibration model (2) rigid multibody model (3) flexible multibody model. Xing et al. [81] made a comprehensive study on the gearbox planet carrier of the National Renewable Energy Laboratory's 750 kW land-based Gearbox Reliability Collaborative wind turbine. Such models are useful for design of wind turbine drivetrain and comparison of drivetrain responses for bottom-fixed and floating foundations.

As an example, global aero-hydro-elastic-servo time domain analyses are first performed using software like e.g. HAWC2, FAST or SIMA or in-house software to determine the loads (such as low-speed shaft loads) acting on the drivetrain which is modelled as a multibody using e.g. SIMPACK [120], see e.g. [37]. The gears and bearings responses are then obtained from the multibody simulation and used for further fatigue calculation or extreme response analysis, including fault conditions [81], As shown by Nejad et al. [121] there are differences between the drivetrain responses on land-based versus different types of floating turbines. This study [121] was carried out for the NREL 5 MW turbine using the reference drivetrain [37] on land-based, TLP, spar and two types of semi-submersible support structures. It was found that the fatigue damage on the main bearing carrying axial is higher in floating wind turbines than land-based ones, primarily due to the wave induced motion. It was also shown that the non-torque loading can significantly influence the fatigue life of the gearbox components.

Moreover the decoupled approach for drivetrain response analysis has been employed for further post-processing to obtain such as contact forces on gear teeth surface and the corresponding fatigue damage [122,123] and load effects in the bearings of the drivetrain [124] and the structural reliability of the gear [123]. This method has also been employed for developing a reference 10 MW drivetrain for offshore wind turbine [38].

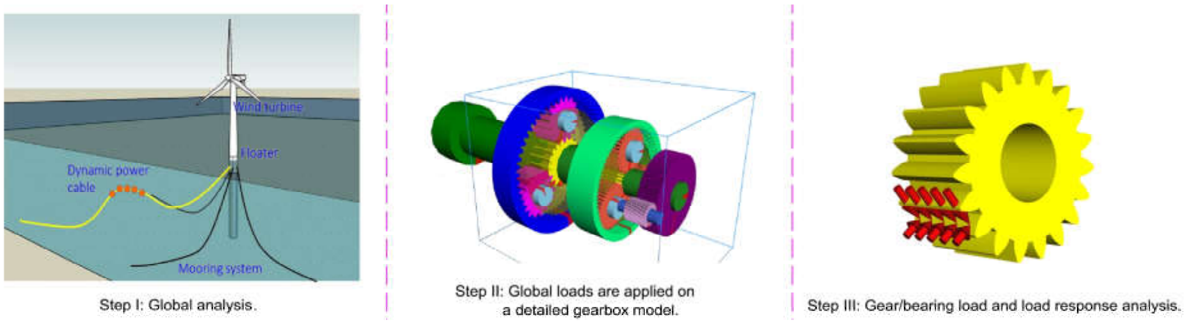



Fig. 9 Integrated dynamic analysis of floating wind turbine concepts – global response analysis and post-processing.

A similar uncoupled approach can also be used for the power cable. Postprocessing of the stresses based on sectional forces and moments in hull, tower and blade components can be readily accomplished.

### 3.5.3 Fluid-structure modelling to determine hull sectional forces and moments

Various models are envisaged for the structure, wave and wind loads, as discussed in Section 3.2. Determination of the internal forces in hull structures is possible in some computer codes for special cases; i.e. when the hydrodynamic loads are determined by the Morison's formula and the structure is modelled as a frame consisting of beams. In general, determination of internal forces and thereafter the stresses in large volume floating wind turbines requires a finite element model of the hull, with applied hydrodynamic pressure based on a potential flow theory that accounts for radiation and diffraction effects and inertial loads due to the motions of the floaters. Frequency-domain approaches have been used to estimate the hull sectional forces and moments for floating oil & gas platforms under the first-order wave loads and induced motions. A general time-domain method for determining internal forces in rigid floating wind turbine support structures is presented and applied for a semi-submersible wind turbine in [125], as exemplified in Section 3.8.

### 3.5.4 Short-term probabilistic analysis

Environmental conditions and the corresponding loads are conveniently modelled as a sequence of short-term conditions assumed to be stationary. The short-term sea-state is characterized by a wave spectrum with significant wave height $H_s$ and spectral peak period $T_p$ etc as parameters, while the wind is characterized by the mean wind speed and a turbulent wind field. In addition the mean directions are specified. The long-term variation is described by the probability density function (pdf) of the mentioned parameters; e.g. [126].

The basic integrated dynamic analysis is a short term analysis considering the stochastic nature of waves and turbulence of wind. Since the natural frequencies for horizontal motions may be as small as 0.02 Hz, a long sample is needed for time-domain simulations to capture the load effects (motions) due to wind and low frequency hydrodynamic loads. On the other hand the time step needs to be small enough (in the order of 0.01-0.05s) to capture all phenomena – including high-frequency vibrations of structural components (blades, tower and maybe floater and mooring lines). When a detailed model for wind turbine sub-systems or components (such as mechanical or hydraulic drivetrain) is coupled to the global analysis model, even smaller time steps are required. Jiang et al. [127] found that analysis of a hydraulic drivetrain for a 5 MW wind turbine required time steps of the order of $10^{-4}$ s to yield stable numerical solution. In such cases, uncoupled analysis is clearly necessary.

Sampling time for short-term simulations should be sufficiently long to limit the statistical uncertainty, especially when determining extreme values. Stress ranges for fatigue analysis essentially depend on the standard deviation of the load effects (at least for a narrow band process) and are less sensitive to the sampling time [128]. Moreover, when estimating extreme values, efforts should be made to use realistic methods to fit the sample and then extrapolate to extreme values at the required exceedance of probability. Alternative methods, such as Weibull tail, global maxima and a recently proposed extrapolation method (ACER) based on the mean upcrossing rates, can be used for extreme response analysis, see e.g. [129].

It is important to ensure that the sample used for extrapolation is of the same type as the extreme phenomenon to be estimated by the extrapolation. This is because the phenomenon in question might change; for example from a well-behaved wave to a breaking wave condition; tension to slack in a mooring line etc.

A particular issue in connection with wind turbines subjected to wave and wind loads is that the short-term states refer to a 3 hour and 10 min averaging period, respectively, which are considered to be the period in which they are considered stationary. Despite the "unphysical" approach by considering a 1 hour period, it still might be practical. The long-term joint probability density function needs to refer to these averaging reference periods.

### 3.5.5 Long-term probabilistic analysis

A full long-term analysis (FLTA), in which all possible environmental conditions are considered to obtain the long-term response distribution, is the most accurate approach to determine the effects due to environmental loads, both in terms of extreme load effects for ULS design check and load effect histories (i.e. stress ranges) for FLS design check [126]. Since the full long-term analysis is time consuming, simplified methods such as the simplified full long-term analysis (SLTA) [114, 119, 130] and the environmental contour method (ECM) [131-132] have been proposed.

An important issue in connection with the time domain analysis is the discretization of the met-ocean parameter space (significant wave height, spectral peak wave period and mean wind speed) which determines the number of short-term conditions and simulations that need to be carried out – to determine extremes or fatigue load effects.

SLTA is the same as FLTA except that it only includes the important environmental conditions and ignores the others that do not contribute much to the long-term results. SLTA has been studied for offshore structures and wind turbines. For both bottom fixed and floating wind turbines, it is found that less than 10% of all the environmental conditions are required to simulate to achieve practically the same result for long-term extreme response prediction as the FLTA [119].

One way to reduce the computational efforts is to use the so-called environmental contour method, in which the long-term extreme response, for example the 50-year extreme response, is obtained using the short-term analysis considering only the extreme sea states (the 50-year extreme conditions), with a certain correction factor. The basic assumption is that the responses of the structure increase with the severity of the sea states. This method has been widely used for permanent offshore oil & gas platforms.

However, modern large-scale wind turbines typically apply blade pitch control for wind speed larger than the rated value to keep the power output constant and to reduce the aerodynamic loads. In extreme wind conditions with wind speed beyond the cut-out value, the wind turbines are not in operation and the rotor blades are parked to further reduce the aerodynamic loads. Therefore, the extreme wind conditions do not necessarily result in the most extreme wind turbine responses [133-134]. Some modifications about the contour method needs to be considered, for example to run simulations for other critical conditions, such as the rated wind speed and the cut-out wind speed conditions, extrapolate the responses to the 50-year level and take the largest value. This modified environmental contour method (MECM) has been successfully used for extreme response prediction of wind turbines [119]. A similar approach has also been proposed in [135].

For bottom-fixed offshore wind turbines, extreme responses are typically governed by wind loads, for which MECM has to be used. However, for floating wind turbines, the traditional ECM can still be used for responses that are governed by the wave loads, such as the cross-sectional loads of the braces in the semi-submersible. While, the wind turbine blade and tower responses are still governed by wind loads and the MECM needs to be used. Fig. 10 shows an example of the accuracy of the ECM and MECM for different responses of a semi-submersible wind turbine [119].

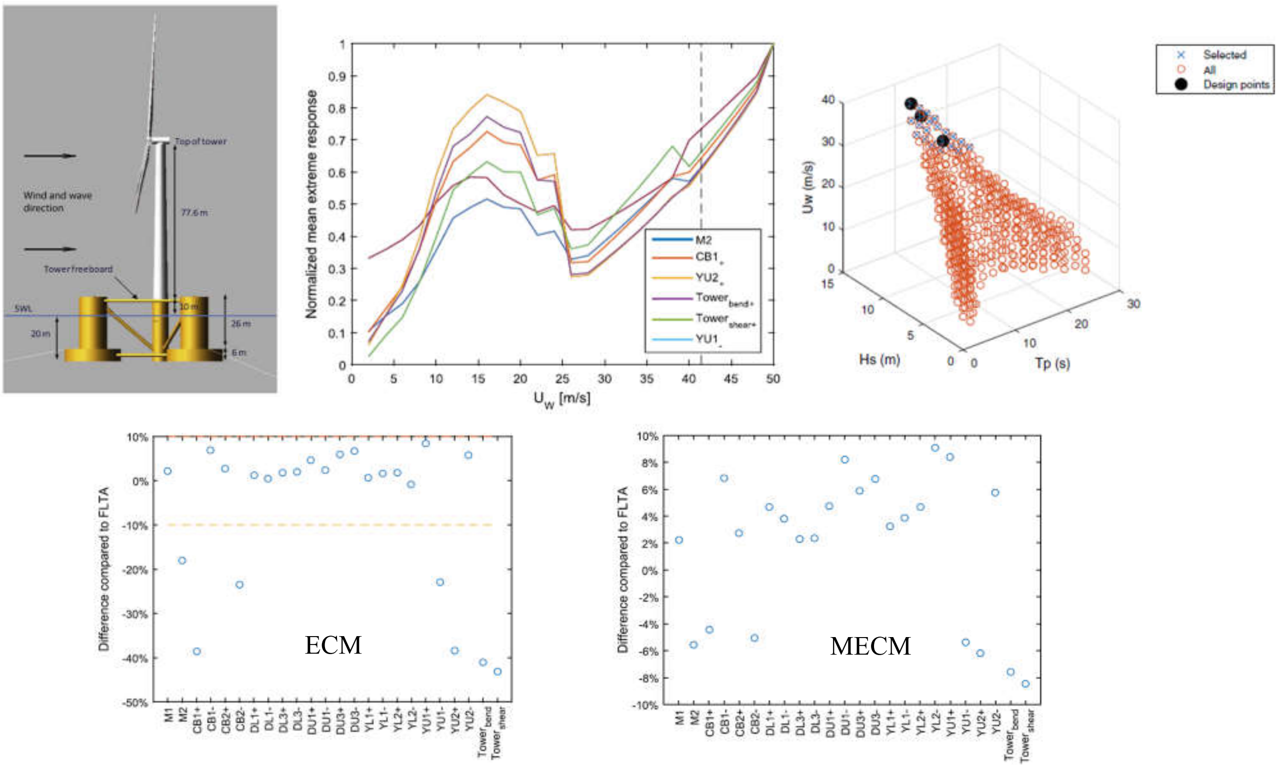



Fig. 10 Accuracy of the traditional environmental contour method (ECM, bottom-left) and the modified environmental contour method (MECM, bottom-right) for the 50-year extreme structural responses of a semi-submersible floating wind turbine (top, left), as compared to the full long-term approach (FLTA). The normalized mean short-term extreme response of the tower and the braces as function of the mean wind speed (top, middle) and the design point for the FLTA are also shown (top, right). ([119])

### 3.6 Handling faults and accidental events

Offshore wind turbines consists of many electrical/electronic and mechanical subsystems (gearbox and blade pitch actuator) that need to be properly designed to ensure a normal operation of wind turbines. However, faults (i.e. damages or failures in such subsystems) often occur and as requested in design rules, their effects on structural responses should be considered. In this section, the effects of faults on the global responses of offshore wind turbines are discussed first, followed by numerical modelling of subsystems and their corresponding faults, as well as fault detection and diagnosis based on structural response measurements.

#### 3.6.1 Effect of faults on global responses of wind turbines

Various mitigation actions might be implemented to reduce the consequences of faults and damages, see fault tolerant control (Section 3.3). Yet, the design of wind turbines according to IEC 61400 [45] should include considerations of the transient responses caused by faults, e.g.

grid loss and blade blockage due to loss of pitch control. Understanding the effect of faults also provides a basis for judging the cost-benefit of further actions to mitigate the failure consequences.

Fig.11 shows the effect of a seized blade (blade pitch fault). It is clearly seen that the response increases if nothing is done to mitigate the effect of the fault, like shutting down the rotor. However, the shut-down should be carried out over a few seconds to avoid the impact of a sudden brake force.

In Fig. 12 extreme response in the upper part of the tower, which corresponds to the shaft bending moment, for land-based and floating wind turbines are compared, considering extreme environmental and fault conditions. The met-ocean conditions are specified in Table 3 and the fault cases A-D are defined as follows:

A) Fault-free: normal power generation in ECs F1-F5 and F7, idling in EC F6 (see Table 3).
B) Blade seize: the pitch actuator of one blade is blocked at time and the turbine continues to operate, with the controller trying to maintain the desired rotational speed by pitching the other two blades.
C) Blade seize followed by shutdown: the pitch actuator of one blade is blocked at time, and the controller reacts by shutting down after detection time.
D) Grid loss followed by shutdown: the grid is disconnected at time, and the controller reacts by shutting down after detection time.

When shutdown occurs, the grid is disconnected and all lades with working actuators are pitched to feather (90º) at the pitch rate. In the current work, the pitch rate during shutdown is chosen to be 8 deg/s, the maximum pitch rate suggested in [136]. The pitch rate can have a significant impact on the loads and motions, as studied in [106,137].

For fault types B, C, and D, the fault occurred after 400 seconds of normal operation. An additional 600 seconds after fault were simulated in order to capture several subsequent cycles of low-frequency events. For fault types C and D with second, which is approximately 10 times the sampling frequency of the controller [105].

**Table 3.** Met-ocean/Fault conditions. The wind and wave direction is in the positive x-direction, and the wind speed is reported for the hub height. The NTM and ETM models are applied for Class C.

| Condition | F1 | F2 | F3 | F4 | F5 | F6 | F7 |
|---|---|---|---|---|---|---|---|
| $H_s$ (m) | 2.5 | 3.1 | 3.6 | 4.2 | 4.8 | 14.1 | 3.1 |
| $T_p$ (sec) | 9.8 | 10.1 | 10.3 | 10.5 | 10.8 | 13.3 | 10.1 |
| U (m/sec) | 8.0 | 11.2 | 14.0 | 17.0 | 20.0 | 49.0 | 11.2 |
| $I$ | 0.17 | 0.15 | 0.14 | 0.13 | 0.12 | 0.10 | 0.24 |
| Faults | all | all | all | all | all | Fault free | |
| Num. Seeds | 30 | 30 | 30 | 30 | 30 | 6 | 6 |
| Sim Length (sec) | 1000 | 1000 | 1000 | 1000 | 1000 | 10800 | 10800 |

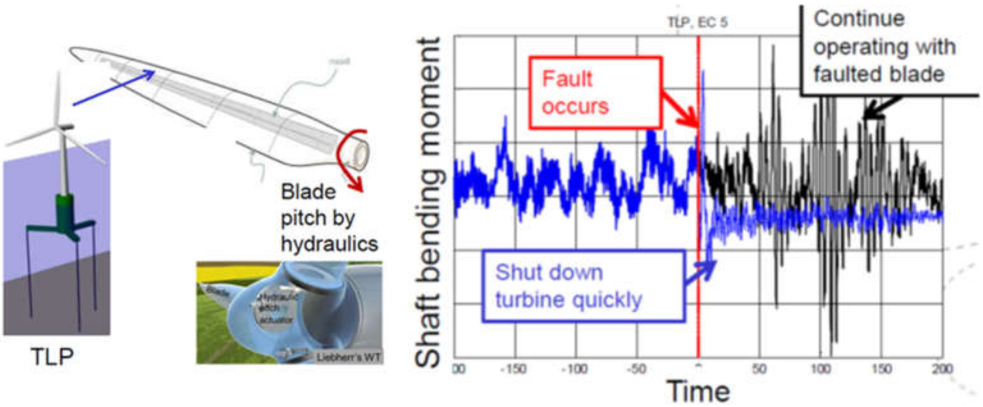



Fig. 11 Effect of pitch control fault (blade seize) in a Tension-leg wind turbine

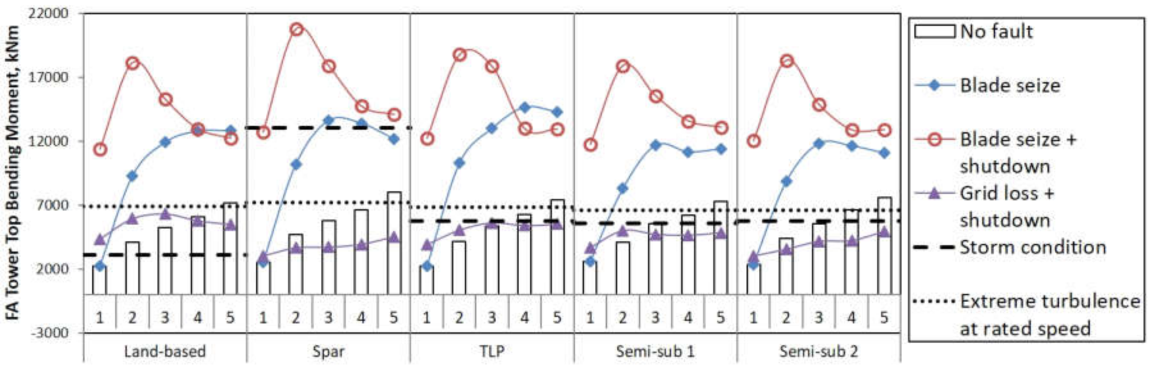



Fig 12 Numerical calculation of the effect of selected faults conditions on the extreme bending moment in the top of the tower of a 5 MW turbine with various support structures. The expected maxima for F6 and F7 for each concept are shown as horizontal lines for comparison [105].

### 3.6.2 Modelling of wind turbine subsystems and faults

In order to do a proper design of the subsystems in wind turbines (for example, gearbox or blade pitch actuator) or to investigate the root causes for faults in such components, a detailed modelling of these subsystems and their dynamics is necessary.

As discussed above, structural design of the bearings and gears in the wind turbine drivetrain requires direct simulations of the responses using a detailed FE model of the drivetrain and considering the loads in the low-speed shaft as input, which are typically obtained from a global dynamic analysis of offshore wind turbines, [110].

In addition, the faults in gearbox, for example the damages in bearings, may induce significant loads and damages in gears, which can lead to a significant economic loss. A detailed gearbox model with introduced bearing damages can be used to study such effects. In the previous section the global performance of HAWT under fault conditions was illustrated. The global-local analysis approach may also be used to determine the drivetrain response in fault conditions [110]. Two load cases for a land based turbine with the 5MW reference gearbox as shown in Fig. 5 were analysed and compared: one for normal operation and one in which an actuator fault occurred after 400 s, resulting in a seize of blade 2 (fixing its pitch angle). After 0.1 s an emergency shut-down is initiated by pitching to feather the other two blades at the maximum pitch rate of 8 deg/s. The generator remains disconnected during this period. The results for the wind speed of 14 m/s and the normal turbulence model (NTM) of class A indicate high torque variation and gear rattle for the fault case.

Similarly, a detailed numerical model was developed by Cho et al. [109] to directly simulate the faults in the blade pitch actuator, which consists of a hydraulic pump, a set of directional control valves, a fluid tank and a hydraulic cylinder, as shown in Fig. 13. The blade pitch angle can be changed by the oil flow to and from the cylinders that is controlled by a number of valves. The mechanical faults in valves that are related to oil contamination and sludge, increasing the friction in the valve, and the electrical faults that are related to additional and residual current through the solenoid due to the damage or dirt armature, may lead to blade pitch delay, stuck or runaway. These faults are simulated in [109] using the developed hydraulic pitch actuator model and the effects on the global responses of a spar floating wind turbine were investigated by coupling this model to the global response analysis model in the aero-hydro-servo-elastic code Simo-Riflex.

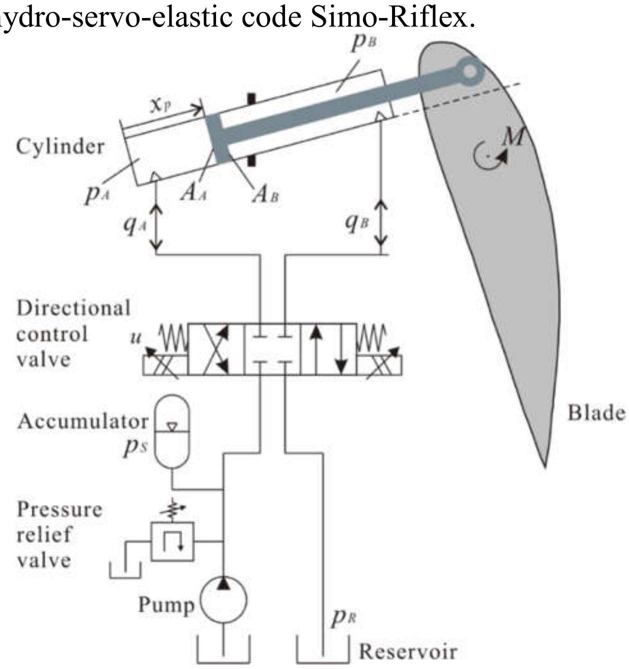


Fig. 13 A schematic diagram of the hydraulic pitch actuator [109]

### 3.6.3 Damage detection based on vibration measurements

Damages or failures in wind turbine components may lead to significantly increasing loads and may develop into catastrophic failures or total loss of the complete wind turbine system. Therefore, early detection of such damages or failures and subsequently shut-down of the rotor become crucial for the safety of offshore wind turbines.

An important part of fault tolerant control is to identify and isolate damages. The direct load effect analysis approach relating to drivetrains has been further employed in wind turbine drivetrain maintenance planning and condition monitoring. A prognostic method for fault detection in wind turbine gearboxes was developed [111], addressing the performance of a 5 MW three stage reference gearbox supported by a land-based tower, spar, TLP and two semi-submersible, respectively. The fatigue damage of mechanical components inside the gearbox and main bearings was compared for different environmental conditions.

Damage detection methods are typically based on statistical hypothesis tests of real-time measured response signals for fault-free and faulty systems. Ghane et al. [112] have applied the Cumulative Sum Method (CUSUM) to investigate the feasibility to detect the wear damages in the downwind main bearing (INP-B as shown in Fig. 14) of a 5MW three-stage gearbox for a floating wind turbine, based on the measurement of acceleration of the main shaft. It detects damages when the test statistics is higher than a threshold. This method is better than the conventional frequency-domain detection method, but it can only be applied when the magnitude of the damages and therefore the probabilistic distribution of the response signals for both fault-free and faulty systems are known. The Generalized Likelihood Ratio (GLR) test was then used in [113] for damage detection when the magnitude of the damage is unknown, in which the probabilistic distribution of the responses for a given level of damages follows a univariate t-distribution with the parameters estimated from the measured data. A closed-form expression was then derived for the GLR test and used for detection of damages in the main bearing of the 5MW wind turbine gearbox. Fig. 14 shows the GLR test statistics when a damage in the main bearing occurs, with the response distribution parameters for the faulty system estimated by the moment estimators. Moreover, Ghane et al. [115] improved the GLR test by integrating the frequency information into the statistical hypothesis tests. That is to use both the threshold and the duration for which the test statistics stays above the threshold for damage detection. The Extended GLR (EGLR) test was then derived using the results of a semi-analytical derivation of the joint distribution of the excursion duration and amplitude for a narrow-band Gaussian process [114]. The EGLR test was shown to be more effective for damage detection since it can significantly increase the probability of detection for a given probability of false alarm.

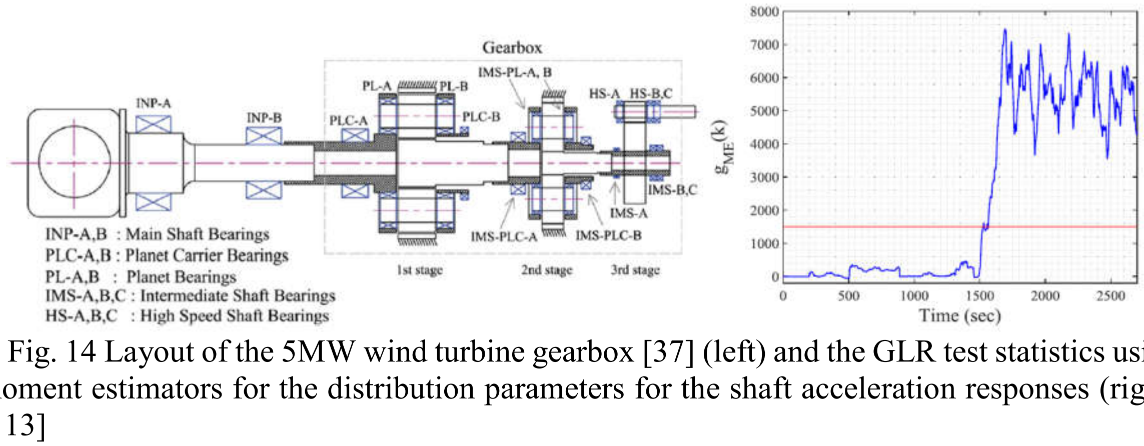



Fig. 14 Layout of the 5MW wind turbine gearbox [37] (left) and the GLR test statistics using moment estimators for the distribution parameters for the shaft acceleration responses (right) [113]

### 3.6.3 Data driven versus model-based assessment of operations

Monitoring the performance of wind turbines yield a significant amount of data (SCADA and other data) that can be used to understand the condition of the turbine during operation. Moreover, special condition monitoring systems could be used for fault detection and life prediction.

The significant amount of data amendable to treatment data - driven machine learning [138]. On the other hand the numerical methods available provide a basis for model-based prediction of the wind turbine behaviour. Eventually, prediction of long-term performance requires numerical models, because experience data only covers limited periods. Hence, it is important to relate observations to the methods inherent in the numerical methods.

## 3.7 Physical testing

Physical testing might be conducted to
- demonstrate feasibility of or document a product
- provide data to support design
- provide a basis for assessing the uncertainty in numerical models

Small-scale experiments in controlled laboratory environments and field measurements, especially in demonstration projects in natural environments, are commonly used to validate or assess uncertainties of predictions of the global behaviour, while full-scale laboratory tests of components such as blades, drive-train or generators are commonly carried out to validate the strength or durability of the components. Large scale field tests are especially important for testing control features. It is noted that the performance of the system or its components can be validated only for short-term load conditions. To account for the long-term variability, the validated numerical methods need to be used in combination with long-term environmental data. The proof testing (of prototypes) is particularly important part of the QA/QC of systems that are going to be mass-produced.

Small-scale tests relevant for the global behaviour of the turbine include tests which consider only hydrodynamic loading, purely aerodynamic tests, soil-structure interaction tests, as well as combined wave and wind (and -current) tests which include the complete system.

The scaling considerations, choice of facility, and design of the model and sources of loading depend on the purpose of the testing. For global wind-wave-current tests in wave basins, Froude scaling is convenient for generating gravity waves (and practical due to the velocity reductions at model scale), but presents two important challenges with regards to model testing of OWTs: elastic scaling of flexible structures, and a mismatch in Reynolds number for viscous and aerodynamic phenomena. The elastic scaling considerations may be addressed through the use of different (softer) materials or by changing the internal structure to reduce the stiffness, provided that the mass distribution can be correctly maintained.

To deal with this mismatch between Froude and Reynolds scaling in combined wind-wave tests, non-geometric scaling of the rotor, either by replacing the rotor with a drag disk (e.g. [139-140]) or so-called “thrust-scaled blades” (e.g. [141-142]), or the use hybrid testing techniques may be chosen.

Non-geometric scaling of the rotor requires generation of a wind field in the basin, which may be challenging [143]. A drag disk is designed such that the force on the disk due to the Froude-scaled wind velocity provides the correct mean thrust force (at least at certain wind speeds). A rotating mass may also be included in order to model the gyroscopic effects. The drag disk cannot model non-thrust loads or the effects of control actions on the thrust force. Drag disk models may not provide the correct thrust force slope – implying incorrect modelling of the dynamic wind loads and the aerodynamic damping effects.

Several generations of "thrust-scaled blades" have been applied in wave basins [141,144, 145]. These blades are designed with modified chord and airfoil shape, while maintaining tip speed ratio and mass distribution, to obtain correct Froude-scaled thrust forces (Fig. 15a,b,c). Control effects have also been included in recent tests with thrust-scaled blades. In order to obtain similar effects, the controller logic at model scale must deviate from the full scale controller, and the actuators required for such high-speed control add complexity (and mass) to the model.

In general, hybrid testing consists of a combination of a physical model, which is subjected to physical loads, and a numerical model, which is run in real-time with feedback from measurements of the physical model and is used as the basis for actuating additional loads or motions. For instance, the physical model may consist of the support structure subjected to wave loads and a mass model of the turbine, while the numerical model is used to calculate aerodynamic and generator loads [146-148] with a numerically generated wind field. Several methods for actuating the aerodynamic/generator loads have been tested: small thrusters on the model (Fig. 15d ) [146, 149], or wires connected to motors attached on the side of the basin (Fig 17) [147-148]. By including a larger number of thrusters or wires, one may be able to include more components of the aerodynamic/generator loads. An important challenge in hybrid testing is to obtain sufficiently accurate simulation results in real-time, and to apply the loads accurately including all of the frequencies of interest. Hybrid testing can also be applied in a wind tunnel, where the displacement of the floating platform is actuated based on the measured wind-induced loads and the simulated wave and current loads [150-151].

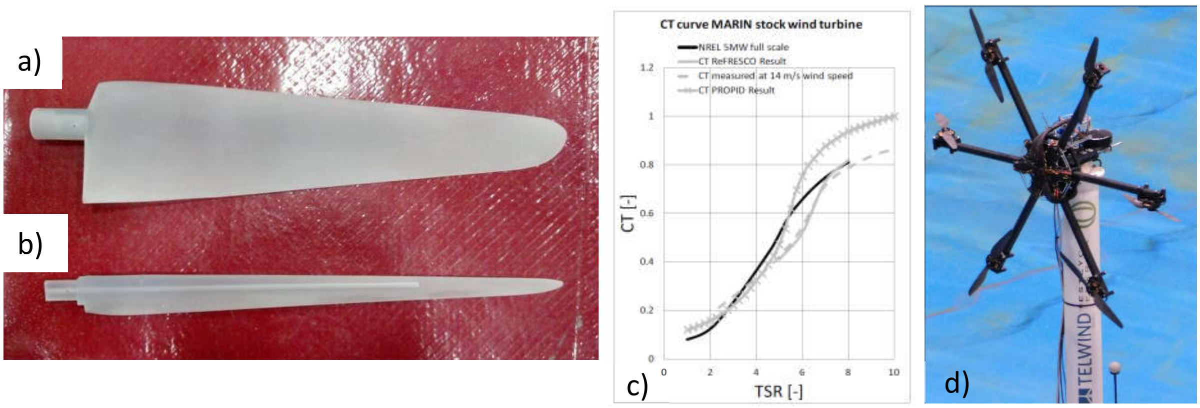



Fig. 15. Wave basin testing of floating offshore wind turbines: a) and b) thrust-scaled blade vs geometrically-scaled blade [152], c) thrust coefficient for a thrust-scaled 5 MW wind turbine [153], d) hybrid test model using multi-fan [154]. An example of a hybrid test model using motor and wire actuators [147] can be seen in Fig. 17.

### 3.8 Comparison of numerical predictions and laboratory measurements of the load effects in a novel semi-submersible wind turbine

The design of the steel 5-MW-CSC, initially inspired the concrete semi-submersible wind turbine concept by Dr. techn. Olav Olsen [21], is documented in [55]. It was initially intended to be combined with a wave energy converter in the Marina Platform project.

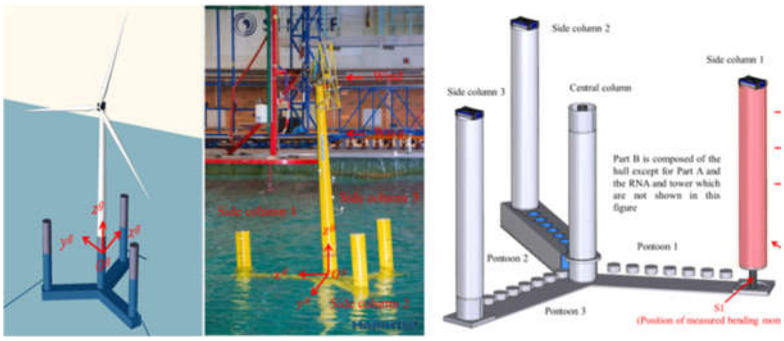



Fig. 16. Layout of the CSC wind turbine, the experimental set-up and details of the test model. Note that the configurations of the three pontoons (to the right) are identical. Some parts of the Pontoons 1 and 3 are not shown.

The 5-MW-CSC concept is a brace-less steel semi-submersible platform designed for supporting the 5-MW NREL reference wind turbine at offshore sites with harsh environmental conditions, e.g. the northern North Sea. Numerical analyses show that the 5-MW-CSC has very good intact stability and motion performance. Compared to spar and TLP wind turbines, the semi-submersible design has greater flexibility with respect to water depth and ease of installation. Conventional semi-submersibles consist of pontoons and columns that are connected by braces to form an integrated structure. Even though the column-pontoon joints in the novel concept are challenging, it might be a cheaper solution than the multiple tubular joints in a conventional semisubmersible.

A multi-body time-domain finite element model combined with the potential theory of the wave loads, to determine forces and moments in floaters, has been developed and applied to simulate rigid-body motions and sectional forces and moments of the CSC 5-MW brace-less semi-submersible wind turbine in a scale of 1:30 and subjected to turbulent wind and irregular waves corresponding at different conditions. Model tests were carried out by the ReaTHM^® testing approach [147-148]; i.e. using physical waves but applying the numerically predicted wind loads by mechanical actuators. Hence, the comparisons between predictions and measurements only indicate differences in the hydrodynamic loads on the hull and the mass properties of the numerical and experimental models [155]. The paper [156] focuses on validating a time-domain numerical approach for determining internal forces and moments in structural components of floaters. In general, it was found that the agreement between the simulations and measurements is very good. Fig. 16 shows an example comparison between the bending moment at the bottom of a side column. Systematic sensitivity studies were conducted to investigate the effects of various features of the modelling. It was for instance observed that the change of mean floating position due to wind and waves leads to a different wetted surface and a considerable change in resultant sectional forces and moments even through change in resultant of the hydro pressure forces on whole of the wetted body surface could be very limited. Further comparisons are presented in [157].

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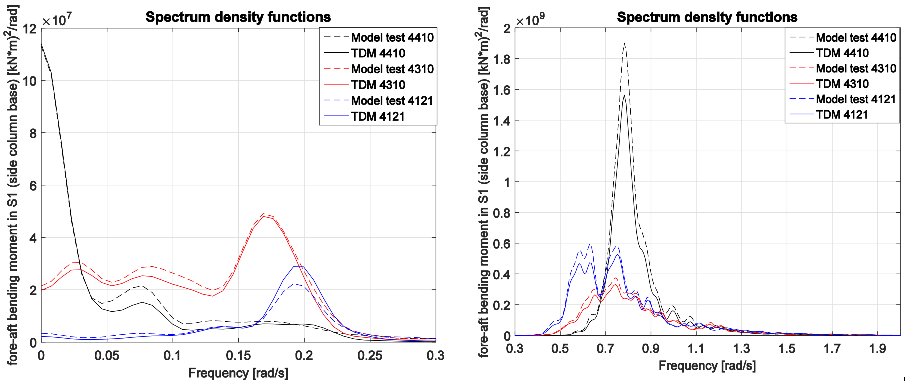


Fig. 17. Comparisons of spectral densities of simulated and measured fore-aft bending moments in S1. Note the difference in scale for the two frequency ranges plotted

### 3.9 Account of uncertainties
### 3.9.1 General

The design criteria in themselves as well as the predicted load effects (responses) are subjected to uncertainties. Measurements during testing in laboratory or in the field are subjected to uncertainties.

Managing of the integrity of wind turbines requires tools to cover the following items:

- Geometry representation, visualization of the relationship between the parts and the whole – while accounting for life cycle changes by means of CAD/CAM/CAE tools.
- Data about environmental conditions,
- Methods to determine overturning and stabilizing moment, calculate gravity and payloads, hydrodynamic, aerodynamic- and accidental actions and their effects, structural resistance,
- Approaches for carrying out code checks according to different limit states
- Reliability and risk analysis with respect to structural integrity in the life cycle in a wide sense to manage uncertainties due to normal variability and human errors

in view optimal lifecycle costs.

The uncertainties can be categorized as:

- normal variability and uncertainty, either due to inherent (fundamental) variability or lack of data. Ocean waves and turbulent wind are examples of fundamental uncertainty. The uncertainty in the methods (model uncertainty) are typically due to lack of data since by "infinite amount of data we will have a perfect method"
- human errors

Design is based on generic measures about uncertainties while the inspection of the as-built structure and observations about its behaviour during operation provide improved information about abnormal geometry, including defects, and, hence, the component strength.

In-service condition monitoring by e.g. acceleration and stress measurements may be used for validation or rather obtain measures of the uncertainty in the structural analysis and design assumptions and the occurrence of damages. Measurements of the change of vibration properties can be used to detect damage.

The hierarchy of methods at different fidelity levels and efficiency is needed for the different phases: conceptual via engineering to detailed design. It is therefore important to highlight the need to carry out R&D to develop methods at different level of refinement and computational efforts.

To illustrate the hierarchy of refinements, with inherently different uncertainty, consider for instance the determination of extreme wave-induced load effects at an annual exceedance probability level of $10^{-2}$ or $2\cdot10^{-2}$ for ULS design: a) the wave condition may be described by a full long-term model of met-ocean data, selected sea states or even selected regular waves ; b) Different wave theories may be applied; c) Hydrodynamic loads may be estimated by using a semi-empirical Morison formula, linear or nonlinear potential theory or full CFD methods; d) The determination of load effects can be done typically using Finite Element methods with different refinements, based on a static or dynamic frequency or time domain approach, considering linear or nonlinear behaviour.

An important aspect of choosing methods is the fact that high fidelity methods require “high fidelity data” to perform better than simplified methods and hence require expert users to avoid a false impression of accuracy or even human errors.

Normal uncertainties are dealt with in design by introducing conservative simplifications, or a more formal semi-probabilistic approach with safety factors. The latter commonly used approach can be calibrated by structural reliability methods (SRMs) to correspond to a desireable target probability of failure [65-66]. It is also noted that reliability methods can be used to update the failure probability based on inspection results [43]. However, it is emphasized that SRMs are only accounting for normal uncertainties.

As indicated in Table 1 human errors are in the first place prevented by using competent personnel and QA/QC. However, such an approach is never 100 % reliable and ALS criteria were introduced to ensure some robustness – damage tolerance as indicated in Table 1.

### 3.9.2 Uncertainties in software and execution of computer analysis

In general developers debug their software and users are supposed to have sufficient competence – i.e. knowledge about the method implemented and skills to use it. Yet errors and omissions do occur. The uncertainties might range from intentional simplifications and other normal uncertainties to gross errors. Part of the quality assurance relating to the development and use of software is addressed in the international Offshore Code Comparison Collaboration (OC3) and continuation projects (OC4, OC5, and soon OC6). These efforts have been extremely useful in showing the influence of different modelling approaches on the simulated response of different offshore wind systems [78,158-159]. Within these projects, softwares for analysing floating wind turbines such as Bladed, FAST, HAWC2, Simo-Riflex, etc., and general purpose program packages like Abaqus, Ansys–Aqua and some “in-house” programs are used to simulate a pre-defined system. The earlier project phases (OC3, OC4) focused on code-to-code comparison, while later phases have focused on validation by comparison against model-scale and full-scale measurements. So far, the software comparisons have been focused on global analysis models – typically Morison’s equation or potential flow models for hydrodynamic loads, BEM or GDW aerodynamic models, and beam element structural models. The OC3 and OC4 projects helped to obtain better agreement between different tools by identifying differences in results or in users' interpretations of the input, while the OC5 project has highlighted some important shortcomings of existing tools, especially for nonlinear wave loads. The OC6 project will incorporate higher fidelity models in an attempt to better understand some of the discrepancies between measured and simulated results.

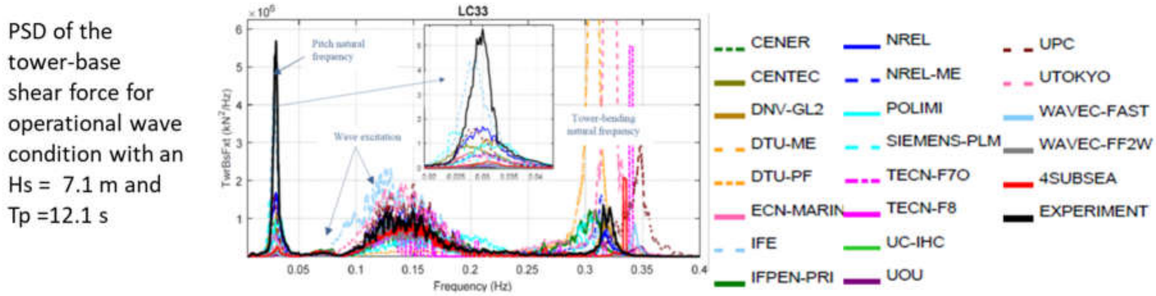


Fig. 18 Numerical code to code comparison and experimental results obtained by various organisations. Example: OC5 – Phase II : Num.comparisons with Deepsea Wind model tests at Marin [159].

For example, Fig. 18 shows the power spectral density of the bending moment in the tower of a semisubmersible as predicted by using different software and persons from different organisations, compared to experiments at 1:50 scale in MARIN's ocean basin. The variation in the results is significant and may be due to both intentional and unintentional actions. Recent work focused on quantifying the uncertainty in the experimental results, to try to better understand the discrepancies, suggests that the differences between simulations and experiments are larger than the experimental uncertainties [160-162]. Comparisons against full-scale data have also shown large discrepancies, however, the reasons for these discrepancies are more difficult to discern: difficulties in obtaining information about the exact wind and wave conditions, yaw misalignment, or details of the control system, contribute in addition to limitations in the software or user error [163].

The results from these projects cannot be directly used to estimate the uncertainty in the predicted load effects that affect the safety factors to be used in the design. One reason is that these uncertainties have to be attributed partly to normal uncertainties in doing engineering analyses and partly to human errors and omissions – including possible faults in the software but especially errors and omissions in conducting the analyses. In a real design situation, there will be an internal and third party QA/QC – that to some extent will reduce the effect of gross errors.

### 3.9.3 Decision under uncertainty

Decisions are made in all lifecycle phases and especially during design as well as during fabrication and operation relating to inspection/monitoring, maintenance, repair and replacement. As mentioned in Section 2 uncertainties can be broadly classified as normal variability and lack of information, and human errors and omissions. Physical testing in laboratory and field are important to estimate uncertainties, but are themselves subjected to uncertainties.

In practice normal uncertainties are handled by

- making conservative assumptions or
- using appropriately reliability-based calibration of safety factors or direct reliability analysis.
- Structural reliability analysis has matured in the last decades, e.g. as manifested in text books including applications in civil engineering [65-66] and applications in oil and gas industry [42-43].

Early applications of structural reliability analysis to the wind turbine support structures, blades and mechanical components in offshore turbines, relating to ultimate and fatigue failures, are presented in [164-166]. Studies of the implicit reliability in IEC-61400 codes are reported e.g. in [167-168]. Traditionally, classical reliability analysis is used to deal with mechanical and electrical components and systems. However, structural reliability methods are also proven to be useful in dealing with mechanical systems, including account of inspection in deteriorating components [67-68, 123].

Human errors and omissions are addressed by QA/QC, and ALS design check. Moreover, field testing of a prototype full-scale facility serves as an important measure to detect systematic errors, for facilities that are going to be mass-produced.

## 4 Conclusions

Floating wind turbines, with increasing turbine size, are expected to play an increasing role in harvesting the abundant wind energy resources offshore, when the wind industry moves into water depths, say, beyond 60-80 m. This paper deals with recent developments of analysis and design of floating wind turbines.

The need for carrying out an integrated dynamic analysis as a basis for design is highlighted, based on a hydro-, aero-, servo-elastic model with proper representation of the sub-systems: rotor, drivetrain, hull, mooring and power cable and in such a way that the load effects in the sub-systems can be determined for their integrity assessment. At the same time, efficient simplified models are needed, and higher fidelity models for components such as the drivetrain or pitch actuator system may be required. It is shown that a drivetrain supported by a floating support structure might have larger responses (especially a larger standard deviation) than the land-based one, and should be further pursued in the context of more rational design of drivetrains based on direct load effect analysis and first principle. Such models, developed during the design of drivetrains, can later be employed in monitoring and life prediction of the components in operational phase.

A wide range of environmental conditions must be considered and the results combined in a rational way; but the effect of pitch control and grid faults could be governing in the ultimate limit state design checks. More work needs to be carried out in the future to establish relevant fault conditions for floating wind turbines and estimate their effect on the response and hence, the turbine design. More efforts should also be devoted to fatigue analysis and design of floating wind turbines and ensure a proper balance between design and activities during operation (inspection, monitoring, maintenance, repair, replacement of components).

Several sources of uncertainty related to the analysis are identified, and further work is recommended for both validation of computer codes and quantification of uncertainty. In addition to future developments in model testing, full scale measurements with a fully described wind turbine control system and gearbox would provide valuable information.

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## References

1. International Energy Agency, World Energy Outlook 2016, 16 Nov 2016, ISBN:9789264264953 (PDF) / 9789264264946(print); 684 pp; DOI: 10.1787/weo-016-en
2. Offshore Wind Industry (2017) http://www.offshorewindindustry.com/news/germany-offshore-wind-farms-extremely-low
3. Global Wind Energy Council. (2018). Global Cumulative Installed Capacity 2001-2017. [Online] http://gwec.net/wp-content/uploads/2018/04/Global-Cumulative-Installed-Wind-Capacity-2001-2017.jpg.
4. Bloomberg New Energy Finance
5. Hundleby, G. & Freeman, K. (2017) Unleashing Europe's Offshore Wind Potential – A New Resource Assessment. BVG Associates.
6. http://www.innwind.eu
7. ewea.org/our-activities//eu-funded-projects/completed projects/upwind
8. Manwell J, McGowan JG & Rogers AL (2009) Wind Energy Explained. John Wiley & Sons, Ltd.
9. Burton T, Jenkins N, Sharpe D & Bossanyi E (2011) Wind Energy Handbook. John Wiley & Sons Ltd.
10. Deign, J, An illustrated guide to the growing size of wind turbines. https://www.greentechmedia.com/articles/read/an-illustrated-guide-to-the-growing-size-of-wind-turbines#gs.Ll3YGYQ, August 2017. (Accessed on 07/11/2018).
11. Nielsen FG, Hansen TD & Skaare B (2006) Integrated Dynamic Analysis of Floating Offshore Wind Turbines, Proc. EWEC Conf., Athens, Greece.
12. Karimirad M & Moan T (2011) Extreme dynamic structural response analysis of catenary moored spar wind turbine in harsh environmental conditions, Journal of OMAE, 133(4): 0411031.
13. Muliawan MJ, Karimirad M, Moan T & Gao Z (2012) STC (Spar-Torus Combination): A Combined Spar-Type Floating Wind Turbine and Large Point Absorber Floating Wave Energy Converter – Promising and Challenging, Proc. 31st OMAE Conf., 2012, Rio de Janeiro, Brazil.
14. Muliawan MJ, Karimirad M & Moan T (2013) Dynamic Response and Power Performance of a Combined Spar-Type Floating Wind Turbine with Large Point Absorber Floating Wave Energy Converter, Renewable Energy, 50: 47-57.
15. Henderson AR & Patel MH (1998) Floating Offshore Wind Energy, Proc. OMAE Conf.
16. Withee JE & Sclavounos PD (2004) Fully Coupled Dynamic Analysis of a Floating Wind Turbine System, Proc. 8th World Renewable Energy Congress, Denver, USA.
17. Suzuki H, Yamaguchi H, Akase M, Nakada S & Imakita A (2009) Development of TLP Type Floating Structure for Offshore Wind Farms, Technology Report of Mitsui Engineering and Shipbuilding Co. Ltd. (in Japanese).
18. Roddier, D., Cermelli, C. & Weinstein, A., Windfloat: A floating foundation for offshore wind turbines; Part I: Design basis and qualication process, Proc. 28th OMAE Conf., 2009, Honolulu, Hawaii, USA.
19. Roddier, D., Peiffer, A., Aubault, A. & Weinstein, J., A Generic 5 MW WindFloat for Numerical Tool Validation & Comparison against a Generic Spar, Proc. 30th OMAE Conf., 2011, Rotterdam, Netherlands.
20. Myhr A, Maus KJ & Nygaard TA (2011) Experimental and computational comparisons of the OC3-HYWIND and tensionleg-buoy (TLB) floating wind turbine conceptual designs, Proc. 21st ISOPE Conf., Maui, Hawaii, USA.
21. Olav Olsen AS. OO-Star Wind Floater (pat.) http://www.olavolsen.no/en/node/149

22. Bachynski EE & Moan T (2012) Design considerations for tension leg platform wind turbines, Marine Structures 29(1): 89–114.
23. Butterfield S, Musial W, Jonkman J & Sclavounos P (2007) Engineering challenges for floating offshore wind turbines, Technical report NREL/CP-500-38776, National Renewable Energy Laboratory, CO, USA.
24. Matsukuma H & Utsunomiya T (2008) Motion Analysis of a Floating Offshore Wind Turbine Considering Rotor-Rotation, The IES Journal Part A: Civil and Structural Engineering, 1(4): 268-279.
25. Jonkman JM & Matha D (2011) Dynamics of offshore floating wind turbines–analysis of three concepts, Wind Energy, 14(4): 557–569.
26. Robertson AN & Jonkman JM (2011) Loads analysis of several offshore floating wind turbine concepts, In Proc. 21st ISOPE Conf., Maui, Hawaii, USA.
27. Gao Z, Luan C, Moan T, Skaare B, Solberg T, Lygren JE (2011) Comparative Study of Wind- and Wave-Induced Dynamic Responses of Three Floating Wind Turbines Supported by Spar, Semi-Submersible and Tension-Leg Floaters, Proc. ICOWEOE Conference, Beijing.
28. https://en.wikipedia.org/wiki/Hywind_Scotland
29. Roddier, D., Cermelli, C., Aubault, A. Peiffer, (2017) A Summary and Conclusions of the Full-Cycle of the Windfloat FOWT Prototype Project. OMAE2017-62561. In Proceedings of the ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering, Trondheim, Norway.
30. Paraschivoiu I (2002) Wind turbine design: with emphasis on Darrieus concept, Montreal Polytechnic International Press.
31. Borg M, Shires A, Collu M (2014) Offshore floating vertical axis wind turbines, dynamics modelling state of the art. Part I: Aerodynamics, Renewable & Sustainable Energy Reviews, 39: 1214-1225.
32. Ferreira CS, Madsen HA, Barone M, Roscher B, Deglaire P & Arduin I (2014) Comparison of aerodynamic models for vertical axis wind turbines, Journal of Physics: Conference Series 524(1): 012125.
33. Cheng Z, Moan T and Gao Z (2016) Dynamic Response Analysis of Floating Wind Turbines with Emphasis on Vertical Axis Rotors, MARE-WINT. Springer International Publishing.
34. Jonkman JM, Butterfield S, Musial W & Scott G (2009) Definition of a 5-MW reference wind turbine for offshore system development, Technical report NREL-TP-500-38060, NREL,CO, USA.
35. Bak, C., Zahle, F., et al. Description of the 10 MW Reference wind turbine. DTU Wind Energy Report – I – 0092.Roskilde, Denmark, 2013
36. Keller, J.; Link, H.F.; Guo, Y.; LaCava,W.; McNiff, B.P. Gearbox Reliability Collaborative Phase 1 and 2: Testing and Modeling Results; Technical Report; National Renewable Energy Laboratory: Golden, CO, USA, 2011.
37. Nejad AR, Guo Y, Gao Z & Moan T (2015) Definition of a 5 MW reference gearbox for offshore wind turbine development, Wind Energy, 19: 1089-1106.
38. Wang S., Nejad A.R., Moan T. (2019) On initial design and modelling of a 10 MW medium speed drivetrain for offshore wind turbines. Journal of Physics, conference series (under review))
39. Wilkinson M, Harmann K, Spinato F, Hendriks B & van Delft T (2011) Measuring wind turbine reliability - results of the reliawind project. In European Wind Energy Conference (EWEA 2011), Brussels, Belgium.
40. Robinson CME, Paramasivam ES, Taylor EA, Morrison AJT & Sanderson ED (2013) Study and development of a methodology for the estimation of the risk and harm to persons from wind turbines, Health and Safety Executive, RR968 Research Report, UK.
41. Spinato F, Tavner PJ, van Bussel GJW & Koutoulakos E (2009) Reliability of wind turbine subassemblies, Renewable Power Generation, IET, 3(4): 387–401.
42. Moan T (2014) Safety of Offshore Structures, Keynote lecture, Offshore Structural Reliability Conference, Houston, USA. API
43. Moan, T. (2018): Life cycle structural integrity management of offshore structures, Structure and Infrastructure Engineering, 2018. Vol. 14, No. 7, 911–927. DOI: 10.1080/15732479.2018.1438478
44. IEC 61400-1 (2007) 61400-1 wind turbine. Part 1: Design requirements, 3rd ed. Geneva, Switzerland.
45. IEC 61400-3 (2009) 61400-3 wind turbines. Part 3: Design requirements for offshore wind turbines. 3rd ed. Geneva, Switzerland.
46. IEC 61400-3-2 (2018) Design requirements for floating wind turbines. Draft version.
47. GL (2010) Guideline for the certification of Wind Turbines, Germanischer Lloyd, Hamburg, Germany.
48. DNV (2014) Design of Offshore Wind Turbine Structures, DNV-OS-J101.
49. DNV (2018) Design of Floating Wind Turbine Structures, DNVGL-ST-0126.

50. Bureau Veritas (2015) Classification and Certification of Floating Offshore Wind Turbines. Guidance Note NI 572 DT R01 E. Paris, France.
51. IEC 61400-4 (2012) 61400-4 wind turbines. Part 4: Design requirements for wind turbine gearboxes, 1st ed. Geneva, Switzerland.
52. Moan, T. (2009). Development of accidental collapse limit state criteria for offshore structures. Structural Safety, 31(2), 124–135. doi:10.1016/j. strusafe.2008.06.004.
53. NORSOK N-001 Integrity of Offshore Structures. 2010. Standards Norway, Oslo.
54. Nejad, A.R., Bachynski, E.E. and Moan, T., 2019. Effect of axial acceleration on rivetrain responses in a spar-type floating wind turbine. Journal of Offshore Mechanics and Arctic Engineering, 141(3), p.031901.
55. Luan C, Gao Z & Moan T (2016) Design and Analysis of a Braceless Steel 5 MW semi-submersible wind turbine, Proc. OMAE Conference, Pusan, Korea.
56. Meadows R. (2012). “Offshore Wind O&M Challenges,” presented at Wind Turbine Condition Monitoring Workshop, Broomfield, CO, September 1911.
57. GL Garrad Hassan (2013) A Guide to UK Offshore Wind Operations and Maintenance. Scottish Enterprise, Glasgow, and the Crown Estate, London/Edinburgh.
58. Netland Ø, Gunnar DJ, Skavhaug A (2015) The Capabilities and Effectiveness of Remote Inspection of Wind Turbines. Energy Procedia, 80:177-184.
59. Scout Inspection : https://www.scoutdi.com/
60. Kelasidi, E. and Pettersen, K. Y. Modeling of Underwater Snake Robots. I: *Encyclopedia of Robotics*. Springer 2019 ISBN 978-3-642-41610-1.
61. Coronado D and Fischer K (2015) Condition Monitoring of Wind Turbines: State of the Art, User Experience and Recommendations, Fraunhofer, IWES, Bremerhafen.
62. Sheng, S. and Yang, W. (2013). “Wind Turbine Drivetrain Condition Monitoring –An Overview,” ASME Turbo Expo 2013, San Antonio, TX, June 3-7.
63. Yang, W., Tavner, P. J., Crabtree, C. J., Feng, Y. and Qiu, Y. (2014). "Wind Turbine Condition Monitoring: Technical and Commercial Challenges” Wind Energy, 17(5): 673-693.
64. Tavner, P. 2012 Offshore Wind Turbines. Reliability, Availability and Maintenance. Institution of Engineering and Technology.
65. Melchers, RE and Beck, AT (2017) Structural Reliability Analysis and Prediction (Third Edition) John Wiley & Sons, Chichester
66. Sørensen, J D. Reliability Assessment of Wind Turbines, Proc. 12th Int. Conf. on Applications of Statisticas and Probability in Civil Enginering, ICASP12, Vancouver, Canada July 12-15, 2015.
67. Dong, W.; Moan, T.; Gao, Z. Gear Contact Fatigue Reliability Analysis for Wind Turbines under Stochastic Dynamic Conditions Considering Inspection and Repair. In Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering, San Francisco, CA, USA, 8–13 June 2014.
68. Nejad AR, Gao Z & Moan T (2014) Fatigue reliability-based inspection and maintenance planning of gearbox components in wind turbine drivetrains, Energy Procedia, 53: 248–257.
69. Faltinsen OM (1990) Sea Loads on Ships and Offshore Structures, Cambridge University Press, UK
70. Bachynski EE & Moan T (2012) Linear and Nonlinear Analysis of Tension Leg Platform Wind Turbines, Proc. ISOPE Conf., Rhodes, Greece.
71. Bachynski EE, Kvittem MI, Luan C & Moan T (2014) Wind-wave misalignment effects on floating wind turbines: Motions and tower load effects, Journal of Offshore Mechanics and Arctic Engineering, 136(4): 041902.
72. https:// lifes50plus.eu/wp-content/uploads/2018/04/GA_640741_LIFES50_D4.2.pdf
73. Borg, M., Bredmose, H., and Hansen, A. M., 2017. “Elastic deformations of floaters for offshore wind turbines: dynamic modelling and sectional load calculations”. In Proceedings of the ASME 36th International Conference on Ocean, Offshore and Arctic Engineering (OMAE2017).
74. Zhao, Y., Yang, J., and He, Y., 2012. “Preliminary design of a multi-column TLP foundation for a 5-MW offshore wind turbine”. Energies, 5(10).
75. de Souza, C. E. S. & Bachynski, E. E. Effects of hull flexibility on the structural dynamics of a TLP floating wind turbine. Proceedings of the ASME 2018 37th International Conference on Ocean, Offshore and Arctic Engineering, 2018
76. Van der Tempel J (2006) Design of support structures for offshore wind turbines. PhD thesis, University of Technology, Delft.

77. Kvittem MI & Moan T (2015) Frequency versus time domain fatigue analysis of a semi-submersible wind turbine tower. Journal of Offshore Mechanics and Arctic Engineering, 137(1):011901.
78. Robertson A et al. (2014) Offshore Code Comparison Collaboration Continuation Within IEA Wind Task 30: Phase II Results Regarding a Floating Semisubmersible Wind System , 33rd International Conference on Ocean, Offshore and Arctic Engineering , San Francisco, California.
79. Peeters, J. L., Vandepitte, D. and Sas, P. (2006), Analysis of internal drive train dynamics in a wind turbine. Wind Energ., 9: 141-161.
80. Oyaque F (2009) Gearbox reliability collaborative (GRC) description and loading, Technical report NREL/TP-5000-47773, National Renewable Energy Laboratory, CO, USA.
81. Xing Y & Moan T (2013) Multi-body modelling and analysis of a planet carrier in a wind turbine gearbox, Wind Energy, 16(7): 1067–1089.
82. Xing Y, Karimirad M & Moan T (2014) Modelling and analysis of floating spar-type wind turbine drivetrain, Wind Energy, 17(4): 565–587.
83. Guo, Y., Keller, J., LaCava, W., Austin, J., Nejad, A., Halse, C., Bastard, L., and Helsen, J. (2015) Recommendations on model fidelity for wind turbine gearbox simulations, National Renewable Energy Laboratory, NREL/TP-5000-63444.
84. Bachynski EE & Moan T (2014) Ringing loads on tension leg platform wind turbines, Ocean Engineering, 84: 237–248.
85. Halkyard J (2005) Floating Offshore Platform Design. Chapter 7. In Handbook of Offshore Engineering. S Chakrabarti (ed) Elsevier.
86. Hansen MOL (2008) Aerodynamics of Wind Turbines, 2nd Ed. 2008, London, Earthscan, UK.
87. Hansen MOL, Sorensen JN, Voutsinas S, Sorensen N & Madsen HA (2006) State of the Art in Wind Turbine Aerodynamics and Aeroelasticity, Progress in Aerospace Sciences, 42(4): 285-330.
88. Hansen MOL & Madsen HA (2011) Review paper on wind turbine aerodynamics, Journal of Fluids Engineering, 133(11): 114001.
89. FLUENT. Theory Guide, ANSYS R.13, 2010.
90. Etemaddar M, Hansen MOL & Moan T (2014) Wind turbine aerodynamic response under atmospheric icing conditions. Wind Energy, 17(2), 241-265.
91. Karimirad M & Moan T (2012) A Simplified Method for Coupled Analysis of Floating Offshore Wind Turbines. Marine Structures, 27(1): 45-63.
92. Sandner, F.; Schlipf, D.; Matha, D.; Seifried, R. & Cheng, P. W. Reduced Nonlinear Model of Spar-Mounted Floating Wind Turbine German Wind Energy Conference DEWEK , 2012
93. Matha, D.; Sandner, F.; Molins, C.; Campos, A. & Cheng, P. W. Efficient preliminary floating offshore wind turbine design and testing methodologies and application to a concrete spar design. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, The Royal Society, 2015 , 373 , 20140350-20140350
94. Lemmer, F., Müller, K., Yu, W., Schlipf, D., & Cheng, P. W. Optimization of floating offshore wind turbine platforms with a self-tuning controller. ASME 36th International Conference on Ocean, Offshore and Arctic Engineering. (Trondheim, Norway) 2017
95. Gravesen H, Sørensen SL, Vølund P, Barker A & Timco G (2005) Ice loading on Danish wind turbines: Part 2. Analyses of dynamic model test results. Cold Regions Science and Technology, 41, 25-47.
96. Shi W, Tan X, Gao Z and Moan T (2016) Numerical study of ice-induced loads and responses of a monopile-type offshore wind turbine in parked and operating conditions. Cold Regions Science and Technology, 123: 121-139.
97. Namik H & Stol K (2011) Performance analysis of individual blade pitch control of offshore wind turbines on two floating platforms, Mechatronics, 21(4): 691-703.
98. Larsen TJ & Hanson TD (2007) A method to avoid negative damped low frequent tower vibrations for a floating, pitch controlled wind turbine, Journal of Physics Conf. Series, 75(1): 012073.
99. Skaare B, Hanson TD, Nielsen FG, Yttervik R, Hansen AM, Thomsen K & Larsen TJ (2007) Integrated dynamic analysis of floating offshore wind turbines, European Wind Energy Conference and Exhibition.
100. Karimirad M & Moan T (2011) Ameliorating the Negative Damping in the Dynamic Responses of a Tension Leg Spar-Type Support Structure with a Downwind Turbine, Sci. proc. the European Wind Energy Conference (EWEC2011), Brussels, Belgium.

101. Matha D (2009) Model development and loads analysis of an offshore wind turbine on a tension leg platform, with a comparison to other floating turbine concepts. MSc thesis, University of Colorado-Boulder.
102. Priv. communication with the Wind Turbine Group, Statoil (now: Equinor), 2012, Bergen, Norway.
103. Merz KO & Svendsen HG, A control algorithm for the Deepwind floating vertical-axis wind turbine, Journal of Renewable and Sustainable Energy, 5(6): 063136.
104. Cheng Z, Madsen HA, Gao Z & Moan T (2017) A fully coupled method for numerical modelling and dynamic analysis of floating vertical axis wind turbines, Renewable Energy, 107: 604-619.
105. Bachynski EE, Etemaddar M, Kvittem MI, Luan C & Moan T (2013) Dynamic analysis of floating wind turbines during pitch actuator fault, grid loss, and shutdown, Energy Procedia, 35: 210–222.
106. Jiang Z, Karimirad M & Moan T (2014) Dynamic response analysis of wind turbines under blade pitch system fault, grid loss, and shutdown events, Wind Energy, 17: 1385–1409.
107. Etemaddar M, Blanke M, Gao Z & Moan T (2016) Response analysis and comparison of a spar type and a land-based wind turbine under blade pitch controller faults, Wind Energy, 19: 35-50.
108. Cho S, Gao Z & Moan T (2016) Model-based fault detection of blade pitch system in floating wind turbines, Journal of Physics, Conference Series, 753: 092012.
109. Cho, S.P., Bachynski, E.E., Nejad, A.R., Gao, Z. & Moan, T. (2019) Numerical Modelling of Hydraulic Blade Pitch Actuator in a Spar-type Floating Wind Turbine Considering Fault Conditions and Their Effects on Global Dynamic Responses. To be submitted.
110. Nejad AR, Jiang Z, Gao Z & Moan T (2016) Drivetrain load effect in a 5 MW wind turbine under blade-pitch fault condi-tion and emergency shutdown, J. Phys.: Conf. Ser., 753: 112011.
111. Nejad A R, Odgaard PF, Gao Z & Moan T (2014) A prognostic method for fault detection in wind turbine drivetrains, Engineering Failure Analysis, 42: 324-336. REPLACE Nejad, Amir Rasekhi; Odgaard, Peter Fogh; Moan, Torgeir. Concep-tual study of a gearbox fault detection method applied on a 5-MW spar-type floating wind turbine. Wind Energy 2018, 21(11): 1064-1075.
112. Ghane, M., Nejad, A.R., Blanke, M., Gao, Z. & Moan, T. (2016). Statistical Fault Diagnosis of Wind Turbine Drivetrain Applied to a 5MW Floating Wind Turbine. Journal of Physics: Conference Series - The Science of Making Torque from Wind (TORQUE2016), 753: 052017.
113. Ghane, M., Nejad, A.R., Blanke, M., Gao, Z. & Moan, T. (2018). Condition Monitoring of Spar-type Floating Wind Turbine Drivetrain Using Statistical Fault Diagnosis. Wind Energy, 21 (7): 575-589.
114. Ghane, M., Gao, Z., Blanke, M. & Moan, T. (2018). On the Joint Distribution of Excursion Duration and Amplitude of a Narrow-Band Gaussian Process. IEEE Access, 6: 15236-15248.
115. Ghane, M., Blanke, M., Gao, Z. & Moan, T. (2019) Enhanced Statistical Hypothesis Testing Using Threshold Exceedance Duration. To be submitted.
116. Isermann R. Model-based fault-detection and diagnosis – status and applications Annual Reviews in Control 2005; 29 71-85
117. Blanke, M., Kinnaert, M., Lunze, J., & Staroswiecki, M. (2015). Diagnosis and Fault-tolerant Control, 3rd Edition. (3. edition ed.) Springer. DOI: 10.1007/978-3-662-47943-8
118. Guachamin Acero WI (2016) Assessment of marine operations for offshore wind turbine installation with emphasis on response-based operational limits. PhD thesis Department of Marine Technology, NTNU.
119. Li, Q.Y, Gao, Z. & Moan, T. (2017). Modified Environmental Contour Method to Determine the Long-term Extreme Responses of a Semi-submersible Wind Turbine. Ocean Engineering, 142: 563-576.
120. Rulka W (1990) SIMPACK-a computer program for simulation of large-motion multibody systems, Multibody System Handbook. Springer-Verlag Inc., New York, USA.
121. Nejad, A.R., Bachynski, E.E., Kvittem, M.I., Luan, C., Gao, Z. and Moan, T., 2015. Stochastic dynamic load effect and fatigue damage analysis of drivetrains in land-based and TLP, spar and semi-submersible floating wind turbines. Marine Structures, 42: 137-153.
122. Dong W, Xing Y, Moan T & Gao Z (2012) Time domain-based gear contact fatigue analysis of a wind turbine drivetrain under dynamic conditions, I.J. of Fatigue, 48: 133–146.
123. Nejad AR, Gao Z & Moan T (2014) On long-term fatigue damage and reliability analysis of gears under wind loads in offshore wind turbine drivetrains, I.J. of Fatigue, 61: 116–128.
124. Jiang Z, Xing Y, Guo Y, Moan T & Gao Z (2014) Long-term contact fatigue analysis of a planetary bearing in a land-based wind turbine drivetrain, Wind Energy, 18(4): 591-611.

125. Luan C, Gao Z & Moan T (2017) Development and verification of a time-domain approach for determining forces and moments in structural components of floaters with an application to floating wind turbines. Marine Structures. 51: 87-109.
126. Naess A & Moan T (2013) Stochastic Dynamics of Marine Structures. Cambridge University Press.
127. Jiang Z, Yang L, Gao Z & Moan T (2014) Numerical simulation of a wind turbine with a hydraulic transmission system, Energy Procedia, 53: 44-55.
128. Kvittem MI & Moan T (2015) Time domain analysis procedures for fatigue assessment of a semi-submersible wind turbine, Marine Structures, 40: 38-59.
129. Saha N, Gao Z, Moan T & Naess A (2014) Short-Term Extreme Response Analysis of a Jacket Supporting an Offshore Wind Turbine, Wind Energy, 17(1): 87-104.
130. Videiro PM & Moan T (1999) Efficient evaluation of long-term distributions. In Proceedings of the 18th International Conference on Offshore Mechanics and Arctic Engineering.
131. Haver S & Winterstein S (2009) Environmental contour lines: A method for estimating long term extremes by a short term analysis, Transactions, Society of Naval Architects and Marine Engineers, 116: 116–127.
132. Winterstein S, Ude T, Cornell C, Bjerager P & Haver S (1993) Environmental parameters for extreme response: Inverse form with omission factors, In Proceedings of 6th International Conference on Structural Safety and Reliability.
133. Saranyasoontorn K & Manuel L (2004) On assessing the accuracy of offshore wind turbine reliability-based design loads from the environmental contour method, In International Society of Offshore and Polar Engineers, 1: 128–135.
134. Agarwal P & Manuel L (2009) Simulation of offshore wind turbine response for long-term extreme load prediction. Engineering Structures, 31: 2236 –2246.
135. Horn, J.-T. & Winterstein, S. R. (2018) Extreme Response Estimation of Offshore Wind Turbines with an Extended Contour-line Method. Journal of Physics: Conference Series, Vol. 1104, 012031.
136. Jonkman JM & Musial W (2010) Final Report – Subtask 2 - The Offshore Code Comparison Collaboration (OC3), IEA Wind Task 23 - Offshore Wind Technology and Deployment.
137. Jiang Z, Moan T & Gao Z (2015) A comparative study of shutdown procedures on the dynamic responses of wind turbines, J. Offshore Mech. Arct. Eng, 137(1): 011904.
138. Sheng, S. (2015). "Improving Component Reliability Through Performance and Condition Monitoring Data Analysis," presented at Wind Farm Data Management & Analysis North America, Houston, TX, March 25-26.
139. Roddier D, Cermelli C, Aubault A & Weinstein A (2010) WindFloat: A floating foundation for offshore wind turbines. Journal of Renewable and Sustainable Energy, 2(3): 033104.
140. Wan L, Gao Z & Moan T (2015) Experimental and numerical study of hydrodynamic responses of a combined wind and wave energy converter concept in survival modes. Coastal Engineering, 104: 151 - 169.
141. Bottasso CL, Campagnolo F & Pectrović V (2014) Wind tunnel testing of scaled wind turbine models: Beyond aerodynamics. Journal of Wind Engineering and Industrial Aerodynamics, 127: 11-28.
142. Kimball R, Goupee AJ, Fowler MJ, de Ridder EJ & Helder J (2014) Wind/wave basin verification of a performance-matched scale-model wind turbine on a floating offshore wind turbine platform. In Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering, San Francisco, California, USA, June.
143. Courbois, A.; Flamand, O.; Toularastel, J.-L.; Ferrant, P. & Rousset, J.-M. Applying relevant wind generation techniques to the case of floating wind turbines European-African Conference on Wind Engineering, 2013.
144. Yu, W.; Lemmer, F.; Bredmose, H.; Borg, M.; Pegalajar-Jurado, A.; Mikkelsen, R.; Larsen, T. S.; Fjelstrup, T.; Lomholt, A.; Boehm, L.; Schlipf, D.; Armendariz, J. A. & Cheng, P. The Triple Spar Campaign: Implementation and Test of a Blade Pitch Controller on a Scaled Floating Wind Turbine Model. Energy Procedia, 2017 , 137 , 323 – 338
145. Chujo T, Minami Y, Nimura T, Ishida S. Experimental Study for SPAR Type Floating Offshore Wind Turbine With Blade-Pitch Control. ASME. International Conference on Offshore Mechanics and Arctic Engineering, Volume 8: Ocean Renewable Energy ():V008T09A034. doi:10.1115/OMAE2013-10649.
146. Azcona J, Bouchotrouch F, González M, Garciandía J, Munduate X, Kelberlau F & Nygaard TA (2014) Aerodynamic Thrust Modelling in Wave Tank Tests of Offshore Floating Wind Turbines using a Ducted Fan. Journal of Physics: Conference Series, 524: 012089.

147. Bachynski EE, Thys M, Sauder T, Chabaud V & Sæther LO (2016) Real-Time Hybrid Model Testing of a Braceless Semi-Submersible Wind Turbine: Part II: Experimental Results. In Proceedings of the ASME 2016 35th International Conference on Ocean, Offshore and Arctic Engineering, Busan, South Korea.
148. Sauder T, Chabaud V, Thys M, Bachynski EE & Sæther LO (2016) Real-Time Hybrid Model Testing of a Braceless Semi-submersible Wind Turbine: Part I: The Hybrid Approach. in 35th International Conference on Ocean, Offshore and Arctic Engineering.
149. Kanner, S.; Yeung, R. W. & Koukina, E. Hybrid testing of model-scale floating wind turbines using autonomous ac-tuation and control OCEANS 2016 MTS/IEEE Monterey, 2016
150. Bayati I, Belloli M, Facchinetti A & Giappino S (2013) Wind Tunnel Tests on Floating Offshore Wind Turbines: A Proposal for Hardware-in-the-Loop Approach to Validate Numerical Codes. Wind Engng., 37(6): 557-568.
151. Bayati, I.; Facchinetti, A.; Fontanella, A.; Giberti, H. & Belloli, M. A wind tunnel/HIL setup for integrated tests of Floating Offshore Wind Turbines Journal of Physics: Conference Series, 2018, 1037
152. Fowler, M. J.; Kimball, R. W.; Thomas, D. A. & Goupee, A. J. Design and testing of scale model wind turbines for use in wind/wave basin model tests of floating offshore wind turbines. 32nd International Conference on Ocean, Offshore and Arctic Engineering, 2013
153. de Ridder E, Otto W, Zondervan G, Huijs F, Vaz G. Development of a Scaled-Down Floating Wind Turbine for Offshore Basin Testing. ASME. International Conference on Offshore Mechanics and Arctic Engineering, Volume 9A: Ocean Renewable Energy ():V09AT09A027. doi:10.1115/OMAE2014-23441
154. A. Jurado, J. Sarmiento, J. A. Armesto, A. Meseguer, R. Guanche, B. Couñago, J. Urbano and J. Serna, "Experimental Modelling and Numerical Model Calibration of Telwind: An Innovative Floating Wind Offshore Concept," in Marine Energy Week, Bilbao, Spain, 2017.
155. Berthelsen PA, Bachynski EE, Karimirad M & Thys M (2016) Real-time hybrid model testing of a braceless semi-submersible wind turbine. Part III: Calibration of a numerical model, In 35th International Conference on Ocean, Offshore and Arctic Engineering.
156. Luan C, Gao Z & Moan T (2017) Comparisons of simulated and measured motions and sectional loads in a floating wind turbine hull subjected to combined wind and waves. Submitted for publication.
157. Gao Z, Moan T, Michailides C & Wan L (2016) Comparative numerical and experimental study of two combined wind and wave energy concepts. Journal of Ocean Engineering and Science, 1(1): 36-51.
158. Robertson, A. N., et al. (2015, July 27). OC5 Project Phase I: Validation of Hydrodynamic Loading on a Fixed Cylinder. International Society of Offshore and Polar Engineers ???
159. Robertson, A N et al. , OC5 Project Phase II: Validation of Global Loads of the DeepCwind Floating Semisubmersible Wind Turbine, Energy Procedia, Volume 137, 2017, Pages 38-57, ISSN 1876-6102, https://doi.org/10.1016/j.egypro.2017.10.333.
160. Robertson, A. N. Uncertainty Analysis of OC5-DeepCwind Floating Semisubmersible Offshore Wind Test Campaign Proceedings of the Twenty-seventh (2017) International Ocean and Polar Engineering Conference, 2017, I, 482-489
161. Robertson, A. N.; Bachynski, E. E.; Gueydon, S.; Wendt, F.; Schünemann, P. & Jonkman, J. Assessment of experimental uncertainty for a floating wind semisubmersible under hydrodynamic loading Proceedings of the ASME 2018 37th International Conference on Ocean, Offshore, and Arctic Engineering, 2018
162. Robertson, A.; Bachynski, E. E.; Gueydon, S.; Wendt, F. & Schünemann, P. Total Experimental Uncertainty in Hydrodynamic Testing of a Semisubmersible Wind Turbine, Considering Numerical Propagation of Systematic Uncertainty, submitted to Ocean Engineering, 2018.
163. Popko, W. et al. Validation of numerical models of the offshore wind turbine from the alpha ventus wind farm against full-scale measurements within OC5 Phase III Proc. 38th OMAE Conf. , 2019
164. Ronold, K.O.; Wedel-Heinen, J.; Christensen, C.J. Reliability-based fatigue design of wind-turbine rotor blades. Eng. Struct. 1999, 21, 1101–1114.
165. Ronold, K.O.; Larsen, G.C. Reliability-based design of wind-turbine rotor blades against failure in ultimate loading. Eng. Struct. 2000, 22, 565–574.
166. Tarp-Johansen, N.J. Examples of Fatigue Lifetime and Reliability Evaluation of Larger Wind Turbine Components; Technical Report; Risø National Laboratory: Roskilde, Denmark, 2003.
167. Tarp-Johansen, N.J. Partial safety factors and characteristic values for combined extreme wind and wave load effects. Trans. ASME-N-J. Sol. Energy Eng. 2005, 127, 242–252.
168. Sørensen, J. D. & Toft, H S (2012) Safety Factors – IEC 61400-1 ed.4. Background document. DTU Wind Energy-E-Report 0066 (EN).