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

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 to ensure reliability by actions during design, fabrication, installation, operation, and decommissioning. The assessment should be based on response analysis that properly accounts for the effect of different sub-systems (rotor, drivetrain, tower, support structure, and mooring) on the system behavior. Moreover, the load effects should be determined so as to be proper input to the integrity check of these sub-systems. The response analysis should serve as the basis for design and managing inspections and monitoring, with due account of inherent uncertainties. 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 as during operation to aid inspection and monitoring. Typical features of offshore wind turbine behavior are also illustrated through some numerical case studies. [DOI: 10.1115/1.4046196]

Keywords: floating wind turbines, design standards, design criteria, integrated dynamic analysis, dynamic behavior, reliability, design of offshore structures, ocean energy technology, system integrity assessment

Introduction

An increased focus on renewable energy is needed to deal with 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 U.S. and China (Fig. 1). In Europe (Fig. 2), we have already seen low-bid offshore wind farms in The Netherlands and Denmark, with an estimated LCOE of 60–70 Euro/MWh, and even subsidy-free farms in Germany and The Netherlands [4]. 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 of cost reduction for the 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 [5]. 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 the offshore wind industry 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[2] is an ambitious successor of the EU UpWind project,[3] where the vision of a 20 MW 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 have a horizontal axis with three blades, however, two bladed rotors are also of interest. A geared drivetrain 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. But, most of the wind turbines today use a gearbox. 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., Refs. [7,8]. Various types of vertical axis turbines have been proposed but are only commercial on small scale.

For traditional horizontal axis wind turbine (HAWT) with gear transmissions (Fig. 4), the gearbox is among the most expensive components and has a relatively large downtime in case of faults or failures. Therefore, it is necessary to develop methods to better understand the behavior of drivetrain components under dynamic loading conditions. Since 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 properly account 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 such as 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

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[2] http://www.innwind.eu

[3] http://www.ewea.org/our-activities/eu-funded-projects/completed%20projects/upwind

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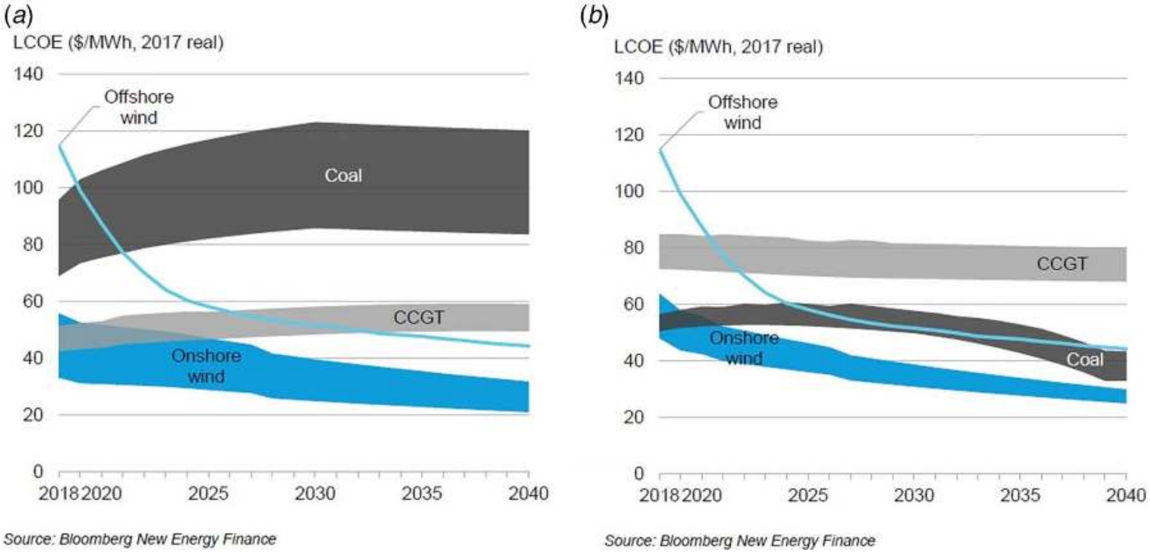
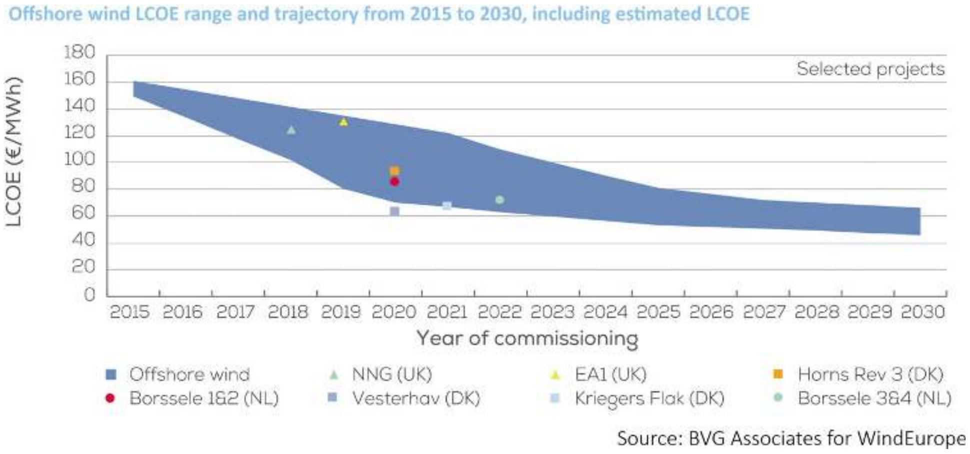


Source: Bloomberg New Energy Finance

Source: Bloomberg New Energy Finance

Fig. 1 **Cost of wind energy versus coal and combined cycle gas turbine (CCGT) in the (*a*) U.S. and (*b*) China [2]**


Offshore wind LCOE range and trajectory from 2015 to 2030, including estimated LCOE

Source: BVG Associates for WindEurope

Fig. 2 **Offshore wind LCOE range and trajectory from 2015 to 2030 [3]**

also a classification based on the type of support structure should be used.

In recent years, various floating wind turbine concepts have been developed, including spar- [9–12], or semi-submersible [13–19][4] concepts with catenary, taut, or tension-leg mooring system. Comparative studies of several types of floating concepts have been presented in Refs. [20–24]. The first small wind farm of floating turbines was opened in the fall of 2017 (Equinor[5]) and others are emerging [25]. While most studies have involved HAWT also some research has been done on vertical axis wind turbines (VAWTs) on different support structures [26–29].

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 [30] and DTU 10 MW turbines [31]. 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 [32], a three-stage gearbox with two main bearings developed for the NREL 5 MW turbine [33] in Fig. 5; and the medium speed drivetrain for the DTU 10 MW turbine developed by Wang et al. [34] 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 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.

The transfer of knowledge from other sectors to the emerging offshore wind energy sector is important. This has already taken place by using support structures from the oil and gas industry and rotors and turbines from the aerospace field. Moreover, the aerospace industries are based on mass-production which is important for the wind energy sector to adapt.

International Standardization Organization defines reliability as follows: "ability of a structure (system) to fulfill the specified requirements during the working life". This implies satisfying requirements for serviceability (use) and safety (avoidance of failures or escalation of failures), e.g., Ref. [35].

The purpose of this paper is to highlight the reliability criteria and the development of response analysis methods for the assessment of serviceability and safety. The focus is on methods for integrated

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[4] http://www.olavolsen.no/en/business-areas/renewable-energy

[5] https://en.wikipedia.org/wiki/Hywind_Scotland

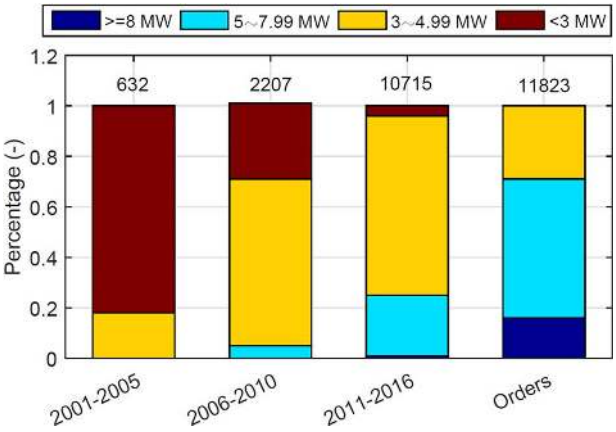

Fig. 3 Development of offshore wind turbine size based on commercial orders since 2001: segmented by grid connection date (orders include turbines planned to be installed in 2017 and beyond [6])

dynamic analysis with respect to the operational phase of floating wind turbines, in a reliability context; i.e., in a structural integrity management perspective.

While we strive toward referring to published research in general within the scope of this paper, we primarily use our own research in figures and tables to illustrate the features relating to integrated dynamic response analysis to document reliability.

Outline of the Paper

The main content of this paper consists of two subjects, namely a description of the reliability perspective in terms of lifecycle system integrity management and assessment of dynamic behavior.

The first part deals with a framework for the assessment of serviceability and safety through the life cycle phases. In particular, the role of assessment of dynamic response as a basis for design, inspection, and monitoring during operation, is emphasized. The following topics are dealt with.

Lifecycle System Integrity Management
Failure experiences
System integrity management
– General
– Design criteria
– Simplified response-based design criteria for concept screening
– Inspection, monitoring, maintenance, and repair during fabrication and operation
– Response-based analysis to support inspection and monitoring planning

The second part deals with the assessment of dynamic behavior of a coupled offshore wind turbine system or the determination of load effects for use in different design criteria or limit states or detection

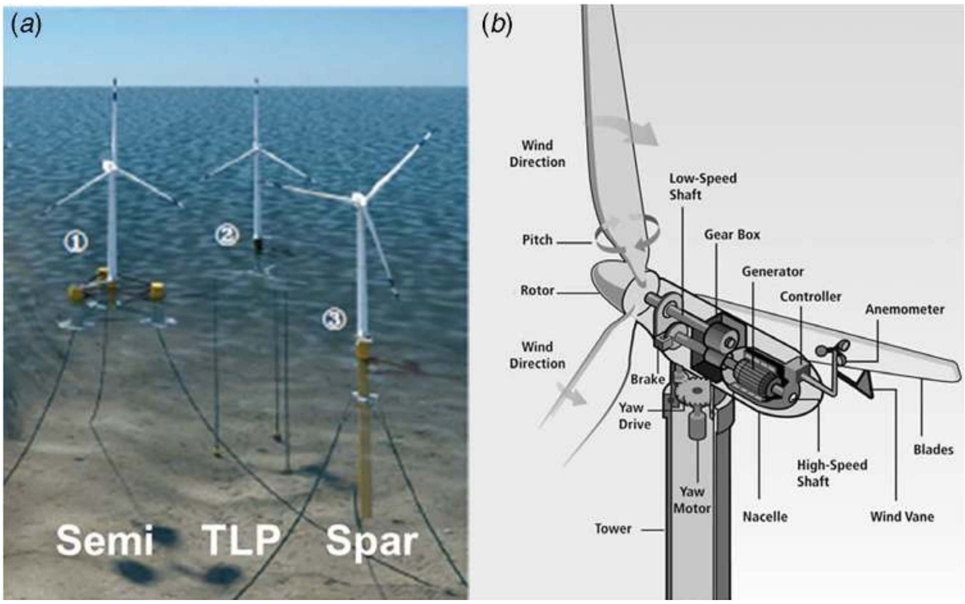

Fig. 4 Floating wind turbine systems and components (courtesy of NREL): (*a*) floating wind turbine systems and (*b*) HAWT drivetrain

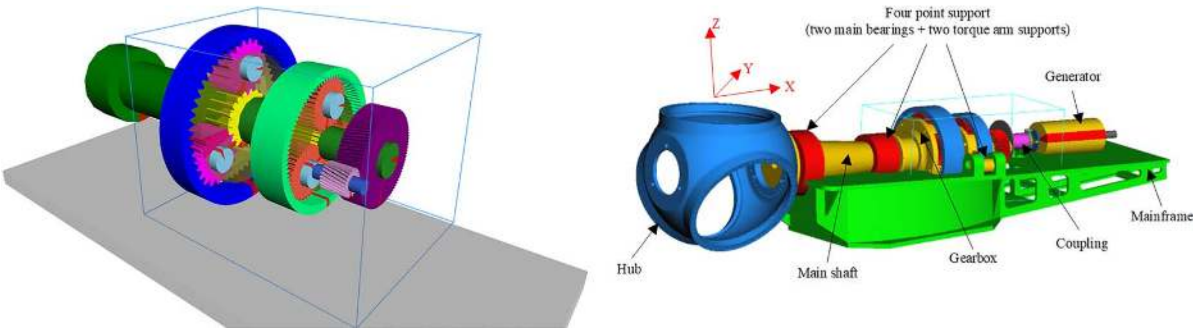

Fig. 5 Drivetrain design for a 5 MW (left) [33] and 10 MW turbine (right) [34]

and localization of faults or damages. The focus is on integrated dynamic analysis considering wave and wind loads and the dynamic features of the different sub-systems to obtain relevant load effects in different sub-systems for use in design and reassessment and planning of inspections and monitoring to detect and localize faults or damages during operation. Account of the stochastic variation in the loads and other uncertainties relating to data and methods are briefly addressed. The following topics are dealt with:

Assessment of Dynamic Behavior (Determination of Load Effects)
General
Importance of dynamic behavior
Dynamic modeling and analysis
– General
– Integrated analysis
– Equations of motion and modeling of the dynamic properties of sub-systems
Automatic control
– Operational control
– Fault-tolerant control
Account of the variability in environmental conditions
– General
– Short-term probabilistic analysis
– Long-term probabilistic analysis
Physical testing
– General
– Comparison of numerical predictions and laboratory measurements of the load effects in a novel semi-submersible wind turbine
Account of uncertainties
– General
– Uncertainties in software and execution of computer analysis
– Decision-making in lifecycle system integrity management under uncertainty
Handling faults and accidental events in design and operation
– General
– Effect of faults
– Modeling of wind turbine subsystems and faults
– Damage detection based on vibration measurements

Relevant research results and standards are referenced and reviewed according to the outline above. However, case studies presented in tables and figures are essentially based on the research work done by the involvement of the authors.

Lifecycle System Integrity Management

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

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.

During their service life, turbines experience operational, start-ups, shutdowns, idling, and parking 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 [36]; implying that these components do not reach a 20-year service life expectancy. The annual failure rate of the rotor and tower was estimated by Ref. [37] to be of the order of 10^{-1}–3×10^{-3} and 7×10^{-4}–1×10^{-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 [38].

Table 1 Causes of structural failures and risk reduction measures (adapted from Ref. [35])

Cause	Structural integrity mitigation measure	Quantitative method
Less than adequate safety factor/margin to cover "normal" inherent uncertainties	– Increase safety factors or margins in ultimate limit state (ULS), fatigue limit state (FLS); – Improve inspection of the structure (FLS)	Structural reliability analysis
Gross errors or omissions during – design (d) – fabrication (f) – operation (o)	– Improve skills, competence, self-checking (for d, f, o) – QA/QC of engineering process (for d) – Direct design for damage tolerance – accidental collapse limit state (ALS) – with adequate damage condition (in f, o)—NOT d – Proof or prototype testing of the whole or parts of the facility – Event control relating to fire, explosion, and other accidental scenarios – Inspection/repair of the structure (for f, o)	Quantitative risk analysis
Unknown phenomena	– Research and development	Technology readiness level

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 [35,39]. Yet the differences between the oil and gas and wind energy sectors should be recognized; with respect to serviceability, safety criteria, and economic conditions. Among the lessons learned with relevance for wind turbines is that human and organizational errors and omissions represent the 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 essentially chain catenary mooring lines for floating oil and gas platforms, is noted [35]. Experiences with fiber rope mooring, especially relating to wind turbines, are limited. 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 in light of the observed failure rates and the uncertainty associated with the performance of novel types of mooring systems.

System Integrity Management

General. 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 [40] design standard specifies the design requirement for land-based wind turbines and the IEC 61400-3 [41] design standard supplements the IEC 61400-1 [40] with design requirements for bottom-fixed offshore wind turbines. The guidelines and standards from Germanischer Lloyd and Det Norske Veritas are also extensively used [42–44]. For the design of floating wind turbine structures, standards are slowly emerging as experiences are being gained, e.g., Refs. [44–46]. Design specifications, e.g., for wind turbine gearboxes are given in Ref. [47]. Current design approaches, especially for the drivetrain, are semi-empirical and based on allowable stress approaches, even with respect to fatigue.

zFor 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 and provide load effects for detailed assessments of the subsystems, see e.g., the section on Integrated Analysis.

A rational approach for the development of standards and performing safety assessment should be based on Ref. [35]:

- 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.
- Balance of safety elements; not hardware only.

Failure of wind turbines on site normally implies only economic consequences and no fatalities, nor environmental damages, that are potentially occuring in offshore oil and 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 especially be kept in mind when transferring technology/knowledge from the offshore oil and gas sector for use in connection with novel floating wind turbine concepts.

Standards and guidelines should represent best practices 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, blade element momentum (BEM) methods for loads on individual blades or computational fluid dynamics (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 or software are specified, yet analyses results show a large scatter—see the section on Uncertainties in Software and Execution of Computer Analysis.

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

The remaining part of this chapter deals with design criteria, including an example of simplified response-based criteria for concept screening as well as aspects of response-based inspection and monitoring.

Design Criteria. 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 the section on Account of Uncertainties.

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 and the turbine design. The capacity factor is the average power generated divided by the rated peak power. Recent data for Europe show an average capacity factor of 22% and 37% for wind turbines on land and offshore, respectively.[6] For the most recent offshore turbines, the trend is an increased capacity factor.[7] 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. The tilt should be limited to 5–8 deg to limit reduced power production, according to operators, however, without much substantiation. The drift-off and motions may also have to be limited due to the response in the power cable, to avoid high strain in the copper conductors or "buckling" of the cable. The tilt and motion responses also have implications on the performance of the drivetrain and the load effects for a tower, hull components, and mooring lines.

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., Ref. [48]). For instance, the Norsok N-001 approach [49] 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 wind 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., mooring line failure consequences for the relevant farm versus the costs of adding redundancy in the mooring system. 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 the control system and grid, combined with a certain environmental condition. This is because these faults occur relatively frequently, as discussed in the section on Handling Faults and Accidental Events.

Luan et al. [50] describe the design of a 5 MW semi-submersible wind turbine, addressing stability, dynamic behavior, and a simplified ultimate strength check.

Simplified Response-Based Design Criteria for Conceptual Screening. While rotor blades, tower, and hull structures 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 drivetrain. Sometimes, it is assumed that the simplified design check of the drivetrain (in conceptual design studies) is acceptable if the maximum axial acceleration of the nacelle is limited to 0.2–0.4 g (g is the acceleration of gravity) [51]. Here, the inertia forces on the rotor are implicitly referred to. However, the inertia forces only represent part of the loads acting on the drivetrain 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 Ref. [51] 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 1-h realizations. The load effects obtained in the global analysis are applied to a detailed drivetrain model in a multibody 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 axial acceleration provides a good indication of the wave-induced loads, it is not seen

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[6] https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Statistics-2018.pdf

[7] https://energynumbers.info/capacity-factor-of-wind

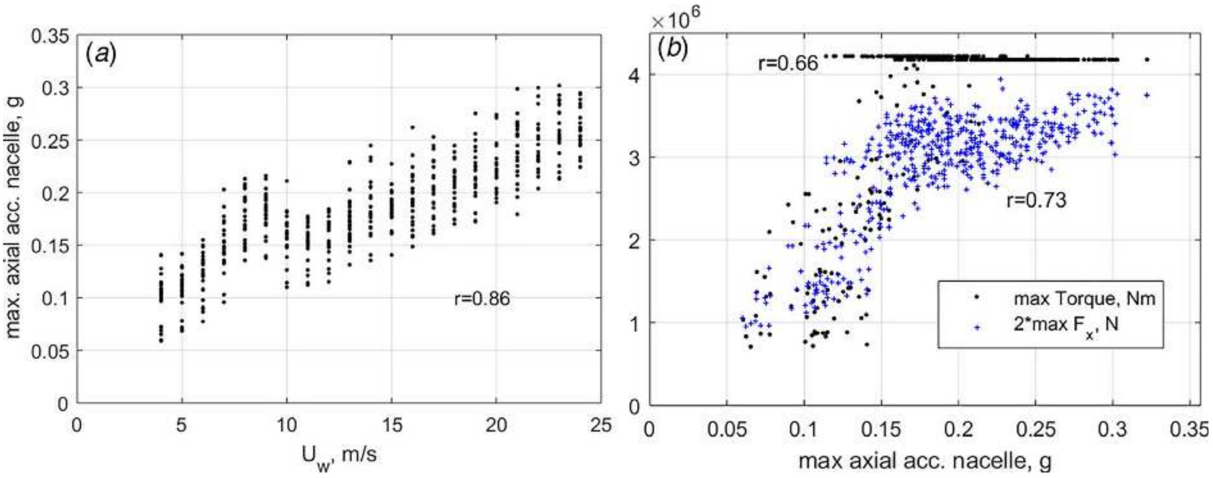

Fig. 6 Axial nacelle acceleration versus drivetrain response in the 5 MW turbine in Fig. 5 mounted on a spar in 32 water depth [51]: (*a*) max axial acceleration for operational conditions and (*b*) 1-h max torque and axial force versus max axial acceleration

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. Figure 6 shows the correlation between maximum axial acceleration and bending moment in the top of 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 effects are the dominant players; therefore, the correlation with the maximum 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 found to be correlated with the axial acceleration, but not with the maximum axial acceleration. It was found that there is less correlation between the maximum axial acceleration and fatigue in this bearing. There are other, more frequent, environmental conditions with a lower axial acceleration which contributes more to the fatigue damage of the main bearings than those with high axial accelerations.

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

Inspection, Monitoring, Maintenance, and Repair During Fabrication and Operation. 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) [52,53]. 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 [52]. 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).

Inspection and condition monitoring, and, if necessary, maintenance and repair 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 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 [35,39]. While the initial inspection, monitoring, maintenance and repair (IMMR) plan is made at the design stage, it is updated depending upon the findings during inspections.

While inspection and repair strategy serves as the basis for ensuring the safety of the hull structure, tower, and blades, condition monitoring is important for the drivetrain, especially vibration-based monitoring of the drivetrain [57]. Gearbox-oil based condition monitoring is also gaining importance as a complementary system.

Performance (SCADA) data also yield information about abnormal behavior, i.e., health condition [58,59]. 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 [60]. The EU Reliawind project provided wind turbine reliability profiles by analyzing the long-term operational data and fault records of 350 onshore wind turbines [36]. 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 the damage
- Temperature
- (Blade pitch) sensors

Moreover, a huge amount of SCADA data suggest the 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.

Fig. 7 **Tools for enabling inspections in areas with difficult access [54–56]: (*a*) a robot for drivetrain inspection, (*b*) a remotely piloted aircraft system for blade inspection, and (c) underwater snake robot vehicle**

Table 2 **Indicative natural frequencies (Hz) and natural periods (s) of "rigid-body motion modes" of floating offshore wind turbines based on Refs. [9–25][10] and information from projects according to the authors' experience**

		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

Response-Based Analysis to Support Inspection and Monitoring Planning. Structural reliability methodology (SRM) [61,62] 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 such as crack growth and wear. Such methods are extensively applied in the oil and gas industry for hull structures [35]. While classical reliability methods [60] are typically used for machinery and electrical systems, it is found that SRM is useful for drivetrains [63,64]. A ranking for inspection/monitoring of gear and bearing components based on fatigue damage estimates was established in Ref. [64].

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, as briefly touched upon at the end of this paper.

Assessment of Dynamic Behavior (Determination of Load Effects)

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.

Importance of Dynamic Behavior. 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 [7,8]. 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 load 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 of TLP wind turbines with a natural frequency above 0.2 Hz. An indication of the lowest natural frequencies for current types of floating turbines with turbines above 2 MW is given in Table 2[8] based on data from Refs. [9–25][9] and different projects.

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., Ref. [65]) 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 [24,66]. This fact would imply a coupled pitch and flexible tower mode.

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[8] See Notes 4 and 5.
[9] See Notes 4 and 5.
[10] See Notes 4 and 5.

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 [67] 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.[11]

The natural frequencies of the mechanical drivetrain between the rotor and generator are much higher than the rigid and flexible structure and blade modes. Hence, the drivetrain responses can 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 [68], the effects of tension-leg platform (TLP) hull flexibility are anticipated to be more important [69,70]. 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 which the coupling effect between hydrodynamic loads and elastic structural deformation needs to be considered. In that case, generalized modes for the system may be applied.

Due to the facts described above, it is important to analyze 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.

Dynamic Modeling and Analysis

General. Most of the offshore wind turbine research on system analysis focuses on load effect analyses while the ultimate and fatigue strength are primarily based on component testing in laboratories, supported with analyses. Knowledge and experiences on strength analysis from the offshore oil and gas industry can be applied to the offshore wind industry. Analyses of the dynamic behavior 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 Ref. [71]. The 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 to achieve an optimal design.

The response analysis needs to be carried out for different design load cases (Ch. 5 of Refs. [8], [41,45]), which include combined environmental and operational conditions and a variety of design situations such as power production, power production plus the occurrence of fault, normal shutdown and parked condition. Some of the load cases come from "abnormal" events of the wind turbine such as shutdown, loss of electrical grid connection, faults in the control system, faults in the protection system, and so forth [40,41,45]. 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.

Integrated Analysis. For proper design of the floating wind turbine system (rotor, tower, floater, and mooring system), a global dynamic response analysis of the wind turbine to the simultaneous action of wind and wave loads needs to be addressed by a proper account of all the sub-systems. Moreover, such an integrated approach is necessary to provide load effects for further assessments of the subsystems (e.g., gearbox) 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 referring to tension capacity and limiting radius of curvature.

To assess 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., one degree-of-freedom system) of the rotational dynamics of the drivetrain, followed by a sub-system analysis based on inputs (loads in the low-speed shaft and motions of the nacelle) from the global analysis. As long as the global natural frequencies are significantly 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 [72]. Both external low-frequency excitation and internal high-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 models 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. [72] 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, and (3) flexible multibody model. Xing and Moan [73] 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 the design of wind turbine drivetrain and comparison of drivetrain responses for bottom-fixed and floating foundations.

Equations of Motion and Modeling of the Dynamic Properties of Sub-Systems. The response needs to be determined in terms of extreme values for ultimate strength check and response histories for fatigue and wear assessment.

The governing equations are formulated in the time domain (TD) or frequency domain (FD), considering wind and wave loads and possibly current and 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 has been made e.g., in Ref. [74]. The applicability of frequency-domain methods for floating turbines has been investigated in Refs. [66,75] based on separate analyses of wind and wave-induced responses but carefully accounting for the aerodynamic damping from the rotor and hydrodynamic damping in calculations of the wave motions.

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[11] https://lifes50plus.eu/wp-content/uploads/2018/04/GA_640741_LIFES50_D4.2.pdf

The support structure, tower, and blades are commonly modeled as linear elastic beam elements to determine the global load effects while shell or solid element models are used in a quasi-static post-processing to obtain local stresses directly from time-domain simulations for fatigue and wear analysis. Structural damping is modeled based on empirical data.

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 modeled as nonlinear springs to represent the restoring effect on floater motions when global responses are determined. More proper FE models of mooring line stiffness (restoring property) and 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 [76]. Moreover, when determining the first-order wave load effects, a representative stiffness of the mooring system should be used, that is the stiffness relevant when mooring lines are already subjected to 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, pitch, roll, and heave become smaller than the periods of the main waves components.

The 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 [33,72,73,77,78]. 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 modeled as flexible elements often with a reduced degree of freedom and bearings with their stiffness and damping. Guo et al. [79] elaborate on modeling of drivetrain dynamics in wind turbines.

As an example, global aero-hydro-elastic-servo time-domain analyses are first performed using software like HAWC2, FAST, or SIMA or in-house software to determine the loads (such as low-speed shaft loads) acting on the drivetrain which is modeled as a multibody using, e.g., SIMPACK [80], see e.g., Ref. [33]. 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 [73]. As shown by Nejad et al. [81], there are differences between the drivetrain responses on land-based versus different types of floating turbines. This study was carried out for the NREL 5 MW turbine using the reference drivetrain [33] 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 loads is higher in floating wind turbines than land-based ones, primarily due to the wave-induced motions. 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 [82,83], as well as load effects in the bearings of the drivetrain [84] and the structural reliability of the gear [83] (Fig. 8). This method has also been employed for developing a reference 10 MW drivetrain for offshore wind turbines [34].

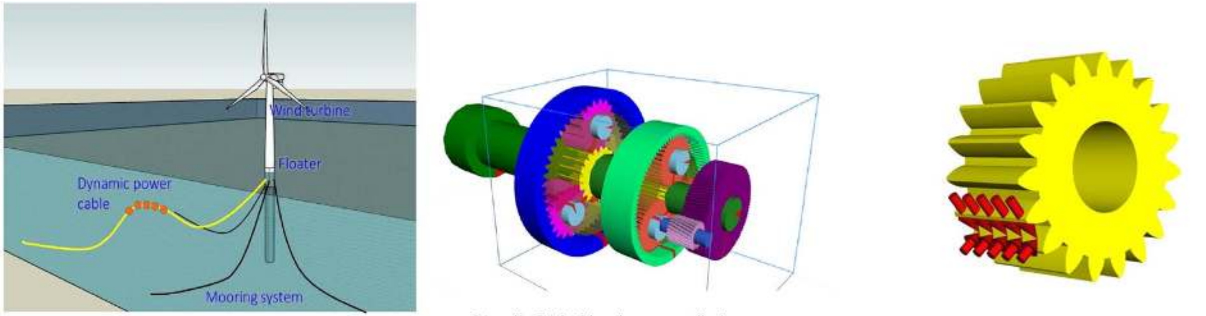
A similar uncoupled approach can also be used for the power cable. Similarly, post-processing of the stresses based on sectional forces and moments in the hull, tower, and blade components can be readily accomplished.

Hydrodynamic loads for slender structures can normally be modeled with acceptable accuracy by using the Morison formula with fluid particle velocities and accelerations based on wave and current kinematics, e.g., Ref. [65].

The wave loads on large volume structures should be estimated by potential theory, considering the incoming and diffracted wave pattern, which are important when the wavelength 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 gives rise to a memory effect. Viscous effects are normally modeled as drag forces and added to the potential forces.

In addition, particular phenomena, such as wave slamming and elastic ringing responses at frequencies higher than the primary wave frequencies, need to be considered. For tension-leg platforms, second-order high- and low-frequency loads as well as (third-order) ringing loads should be considered, e.g., Refs. [66,85]. The overview of wave loads and load effect calculation for floating offshore platforms described in Ref. [86] is also relevant for different types of floating wind turbines. Finally, vortex-induced motions might be a feature to consider, e.g., for spar floater under current loads.

Determination of the internal forces in hull structures directly from time-domain simulations 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 modeled as a frame consisting of beams. In general, the 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



Step I: Global analysis.

Step II: Global loads are applied on a detailed gearbox model.

Step III: Gear/bearing load and load response analysis.

Fig. 8 Integrated dynamic analysis of floating wind turbine concepts—global response analysis and post-processing oil and gas platforms under the first-order wave loads and induced motions. However, most of the wind turbine analysis codes are based on time-domain simulations. 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 Ref. [87], as exemplified in the section on Comparison of Numerical Predictions and Laboratory Measurements of the Load Effects in a Novel Semi-Submersible Wind Turbine.

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 BEM, generalized dynamic wake (GDW) method, vortex method, panel method, and Navier–Stokes solver, e.g., Refs. [7,8,88–91]. The BEM method is widely used and often combined with structural analysis tools, e.g., the finite element method, to obtain the dynamic responses of wind turbine towers 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 [92].

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 aerodynamic load model, proposed by Equinor [93], is convenient to apply to model the integrated rotor loads (i.e., the thrust) as a point force on the tower top [9,94], especially for spar turbines [24]. It has been shown that this simplified model gives global responses within 10% accuracy compared with the model using the BEM method [94]. It is noted that the computer time is significantly reduced by the use of the simplified method. However, simplifications and hence the limitations of the method should be observed [24].

The development of other low-order dynamic analysis methods is an active field and can be of particular interest for controller design [95–97].

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 [92]. 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. In addition, accidental loads (such as those from collisions due to service vessels) should also be accounted for.

Automatic Control

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 Ref. [7]). 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 Ref. [7], Ch. 8.2 of Ref. [8]) 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 3–12 m/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 [7,8]. 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. Figure 9 indicates a typical power-wind speed relationship for a turbine with a rated power of 5 MW. Namik and Stol [98] studied individual blade pitch control as an alternative to collective pitch control for FWTs.

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 [99,100], 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. 9(*b*).

The initial studies especially focused on spar turbines. This issue was addressed in Ref. [101] for a tension-leg spar system, but it is also relevant for semi-submersible wind turbines.

For a tension-leg platform wind turbine, 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 [102]. In the studies [19,66,67], 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 the variable rotational speed at a fixed blade pitch

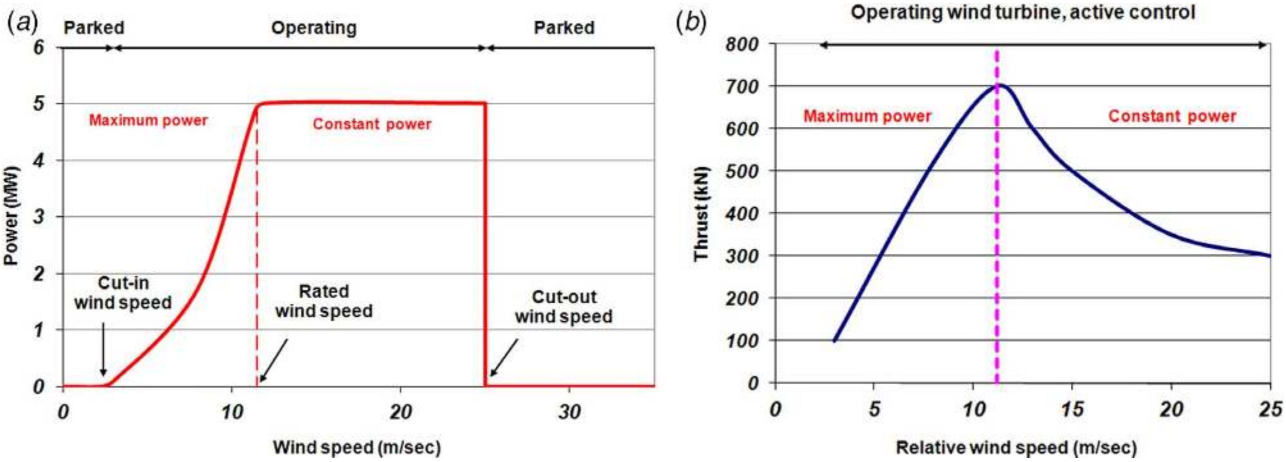


Fig. 9 Power (*a*) and thrust curve (*b*) of NREL 5-MW HAWT

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 [40] 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. Obviously, the fault conditions to consider depend on the possible use of fault-tolerant control to mitigate the effect of the faults.

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 [8]. If any of the contacts are 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 under control are 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 [36]. 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) [101]. 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 Refs. [105–110]. Detection and isolation of faults in drivetrain and rotor blades were investigated in Refs. [111–113].

Currently, the IEC series of design codes requires design check of various combinations of faults and operational and environmental loads. Due to the potential severe effect of faults, e.g., as indicated later in Fig. 16, a true fault-tolerant control might be considered to reduce the load effects; i.e., actions (shutdown etc.) are automatically initiated based on detection and isolation of a fault [114,115].

Account of the Variability in Environmental Conditions in Load Effect Analysis

General. Environmental conditions and the corresponding loads are conveniently modeled 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 characterized by a turbulence intensity. In addition, the mean direction of waves and wind needs to be specified. The long-term variation is described by a joint probability density function (pdf) of the mentioned parameters which is established using either measured or hindcast data, e.g., Ref. [116].

In general, load effects should be assessed based on the so-called long-term approach, in which results from a set of short-term analyses for stationary met-ocean conditions are combined based on the probability of occurrence, e.g., Ref. [116].

While there are methods, such as the environmental contour (line) surface method to select a few short-term conditions that are sufficient to determine extreme load effects, fatigue analysis would generally have to include a large number of short-term conditions.

Short-Term Probabilistic Analysis. 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 (Table 2), a long sample is needed for time-domain simulations to capture the load effects (motions) due to the wind and low-frequency hydrodynamic loads. On the other hand, the time step needs to be small enough (in the order of 0.01–0.05 s) to capture all the 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 with the global analysis model, even smaller time steps are required. Jiang et al. [117] 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 a stable numerical solution. In such cases, uncoupled analysis is clearly necessary.

The 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 [118]. 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 (average conditional exceedance rate, ACER) based on the mean up-crossing rate, can be used for extreme response analysis, see e.g., Ref. [119]. 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 simultaneous wave and wind loads is that the short-term states refer to a 3 h and 10 min averaging period, respectively, in which they are considered stationary. As a practical approximation, both the wave and wind conditions might be considered stationary in a 1 h period. The long-term joint probability density function then needs to refer to the same reference periods.

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 [116]. Since the full long-term analysis is time-consuming, simplified methods such as the simplified long-term analysis (SLTA) [120,121] and the environmental contour method (ECM) [122,123] 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.

Simplified long-term analysis (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 [120].

One way to reduce the computational efforts is to use the so-called ECM, in which the long-term extreme response, for example, the 50-year extreme response, is obtained by using the short-term analysis considering only the extreme sea states (the

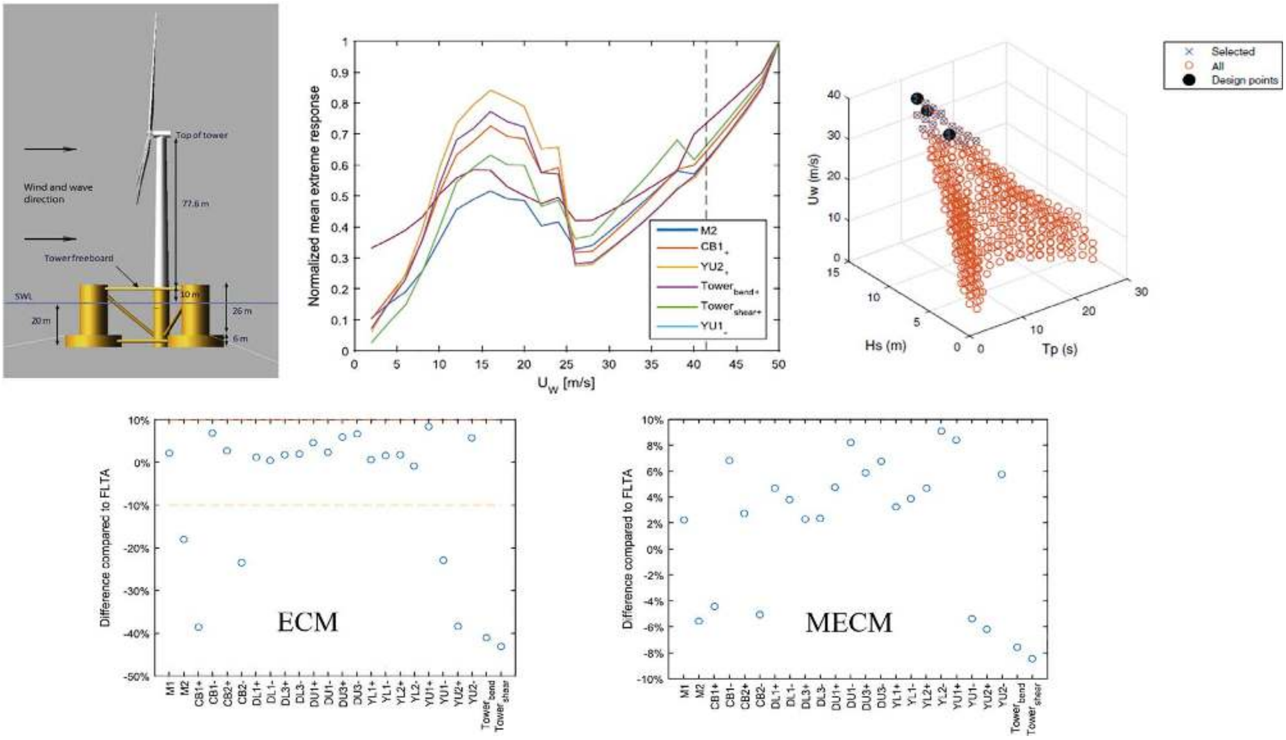


Fig. 10 Accuracy of the traditional environmental contour method (ECM, bottom-left) and the modified environmental contour method (MECM, bottom-right) for the 50-year extreme structural responses of a semi-submersible floating wind turbine (top, left), when compared with the full long-term approach (FLTA) (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) [120])

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 and 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 [124,125]. Some modifications about the ECM need 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 [120]. A similar approach has later also been proposed in Ref. [126].

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 semi-submersibles. However, the wind turbine blade and tower responses are commonly governed by wind loads and the MECM needs to be used. Figure 10 shows an example of the accuracy of the ECM and MECM for different responses of a semi-submersible wind turbine [120].

Physical Testing

General. Physical testing might be conducted to

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

Small-scale experiments, typically with a scale of 1:30 to 1:100 (see e.g. Refs. [127–131], in controlled laboratory environments and field measurements, especially in demonstration projects in natural environments, are commonly used to validate or assess uncertainties of numerical predictions of the global behavior, while full-scale laboratory tests of components such as blades, drivetrain, or generators are commonly carried out to validate the strength or durability of the components. The proof testing (of prototypes) is a particularly important part of the QA/QC of systems that are going to be mass-produced. 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 a particularly important part of the QA/QC of systems that are going to be mass-produced.

Small-scale tests relevant for the global behavior of the turbine include tests that consider only hydrodynamic loading, purely aerodynamic tests, soil-structure interaction tests, as well as combined wave and wind (and current) tests that 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 Reynolds number at the model scale is typically too small when compared with the full-scale value. The elastic scaling considerations may be addressed through the use of different (softer) materials or by

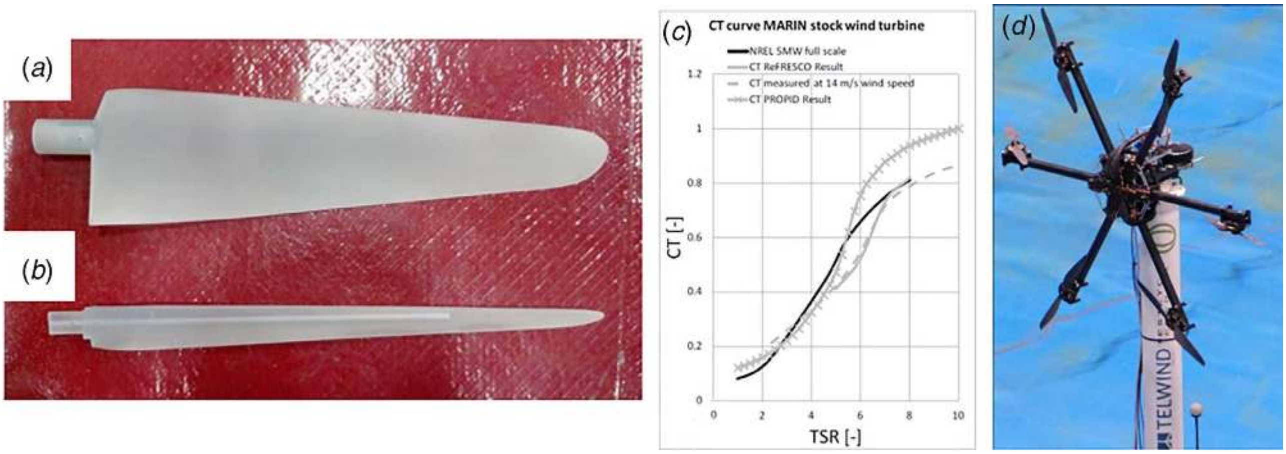


Fig. 11 **Wave basin testing of floating offshore wind turbines: (*a*) and (*b*) thrust-scaled blade versus geometrically scaled blade [130], (*c*) thrust coefficient for a thrust-scaled 5 MW wind turbine [136], and (*d*) hybrid test model using multi-fan [137] (an example of a hybrid test model using motor and wire actuators [138] can be seen in Fig. 12)**

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., Refs. [127,128]) or so-called "thrust-scaled blades" (e.g., [129,132]), or the use hybrid testing techniques may be chosen.

Non-geometric scaling of the rotor requires the generation of a wind field in the basin, which may be challenging [133]. 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 modeling of the dynamic wind loads and the aerodynamic damping effects.

Several generations of "thrust-scaled blades" have been applied in wave basins [132,134,135]. 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 (Figs. 11(*a*)–11(*c*)). Control effects have also been included in recent tests with thrust-scaled blades. In order to obtain similar effects, the controller logic at the 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 [130,131,139] with a numerically generated wind field. Several methods for actuating the aerodynamic/generator loads have been tested: small thrusters on the model (Fig. 11(*d*)) [139,140], or wires connected to motors attached on the side of the basin (Fig. 12) [130,131]. 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 [136–138,141,142].

Model tests are important in the assessment of the global behavior of floating wind turbines subjected to wave and wind loads. However, due to inherent scaling problems and other limitations, it is crucial that they are supported by careful numerical analyses.

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 (Fig. 12), initially inspired by the concrete semi-submersible wind turbine concept by Dr. techn. Olav Olsen,[12] is documented in Ref. [50]. It was initially intended to be combined with a wave energy converter in the Marina Platform project.

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 with 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 semi-submersible.

A multibody 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 [130,131]; 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 [143]. The paper [144] 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. Figure 13 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 modeling. It was, for instance, observed that the change of mean floating position due to wind and waves

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[12] See Note 4.

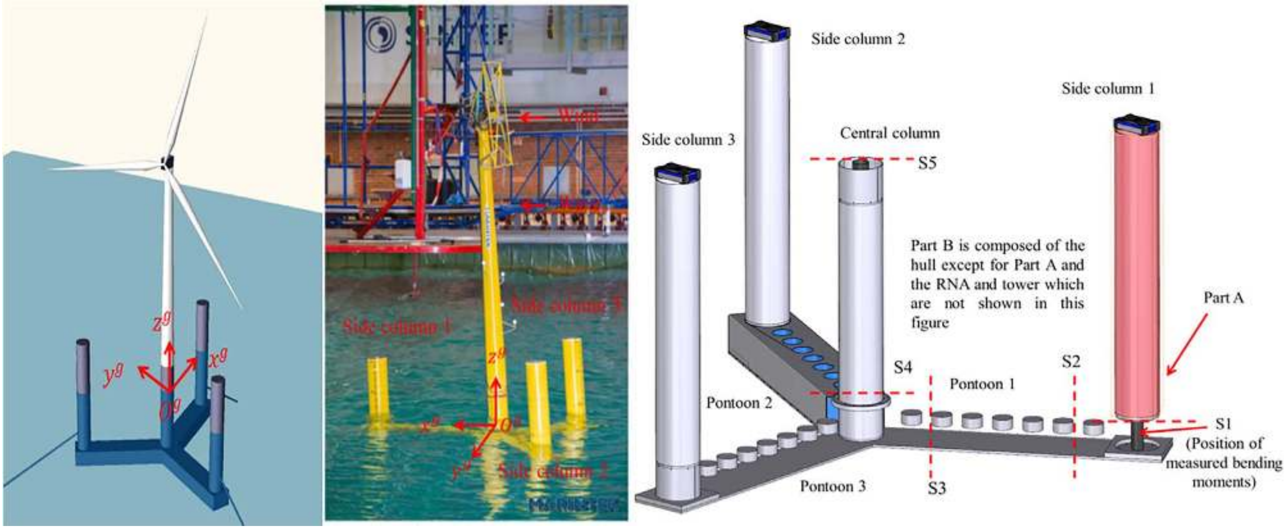

Fig. 12 Layout of the CSC wind turbine, the experimental set-up and details of the test model (note that the configurations of the three pontoons (to the right) are identical. Some parts of the Pontoons 1 and 3 are not shown.)

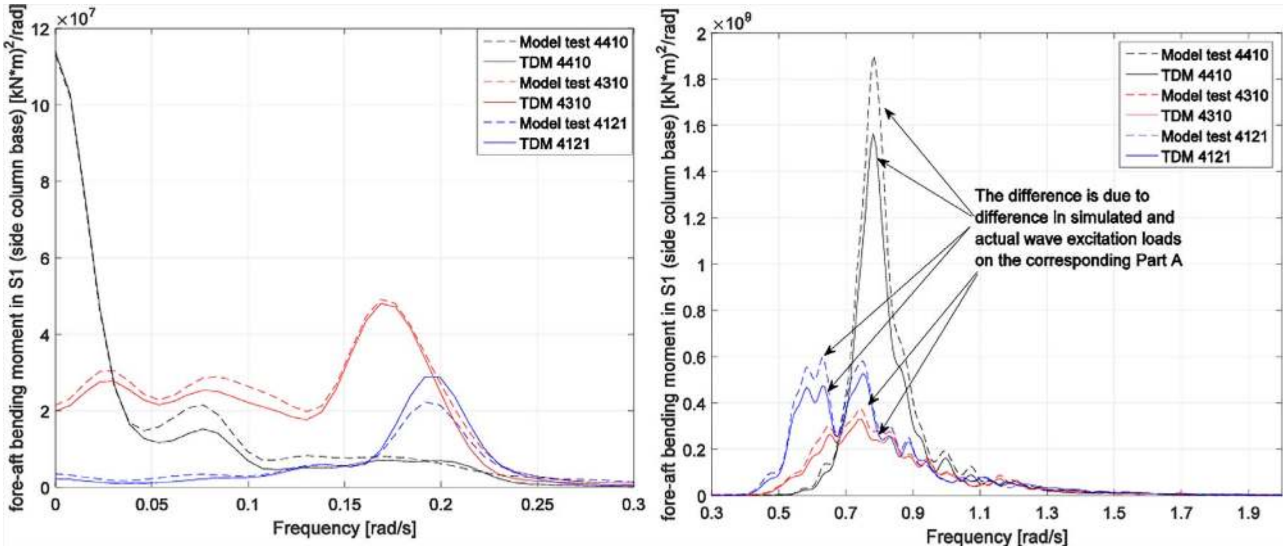

Fig. 13 Comparisons of spectral densities of simulated and measured fore-aft bending moments in S1 in the CSC semisubmersible (Fig. 12) (note the difference in scale for the two frequency ranges plotted.)

leads to a different wetted surface and a considerable change in resultant sectional forces and moments even through a change in resultant of the hydrodynamic pressure forces on the whole of the wetted body surface could be very limited. Further comparisons are presented in Ref. [145].

Account of Uncertainties

General. The design criteria, e.g., in terms of strength, in themselves as well as the predicted load effects (responses) are subjected to uncertainties due to overlooking hazards or failure modes or inaccuracies of data or methods used to model known behavior. Measurements during testing in the laboratory or in the field are subjected to uncertainties. The uncertainties can be categorized as follows:

- 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) is typically due to lack of data since by "infinite amount of data we will have a perfect method."
- human errors—in design: by overlooking relevant hazards or failure modes, errors in methods or their software implementation, users of the software, etc., gross fabrication defects

Design is based on generic measures about uncertainties while the inspection of the as-built structure and observations about its behavior 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

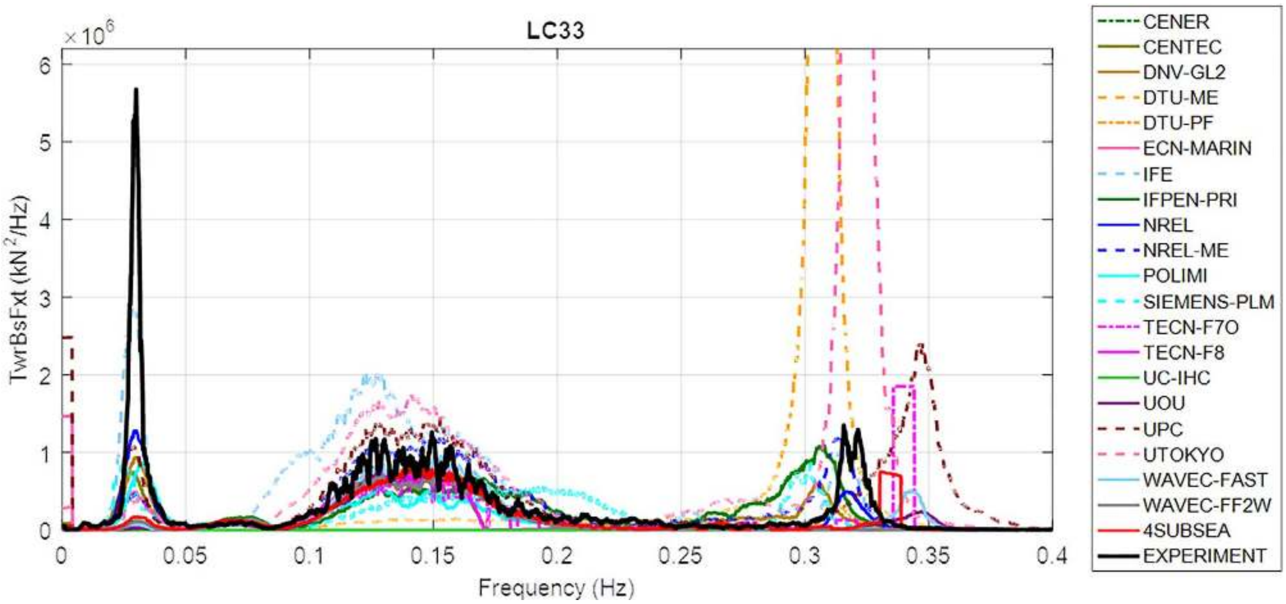

Fig. 14 Numerical code-to-code comparison and experimental results of the power spectral density of the shear force in the tower base for a sea state with an $H_s = 7.1$ m and a $T_p = 12.1$ s, as obtained by various organizations (Example: OC5—Phase II: Num. comparisons with Deepsea Wind model tests at Marin. The figure is an adapted version of a figure provided by dr. Amy Robertson [147]).

carry out R&D to develop methods at a 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 2×10^{-2} for ULS design according to Refs. [41,45]: (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; and (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 behavior.

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 SRMs to correspond to a desirable target probability of failure [61,62]. It is also noted that reliability methods can be used to update the failure probability based on inspection results [39]. 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.

In the following, the uncertainties in computational mechanics to determine load effects in floating wind turbines and how uncertainties are handled in decision-making are briefly addressed.

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 the 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 modeling approaches on the simulated response of different offshore wind systems [76,146,147]. Within these projects, softwares for analyzing floating wind turbines such as BLADED, FAST, HAWC2, SIMO-RIFLEX, etc., and general-purpose program packages such as ABAQUS, ANSYS–AQUA, and some "in-house" programs are used to simulate a pre-defined system. The earlier project phases (OC3, OC4) focused on the 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.

For example, Fig. 14 shows the power spectral density of the bending moment in the tower of a semi-submersible as predicted by using different software and persons from different organizations, compared with experiments at 1:50 scale in MARIN's ocean basin [147]. 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 [148–150]. 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 [151].

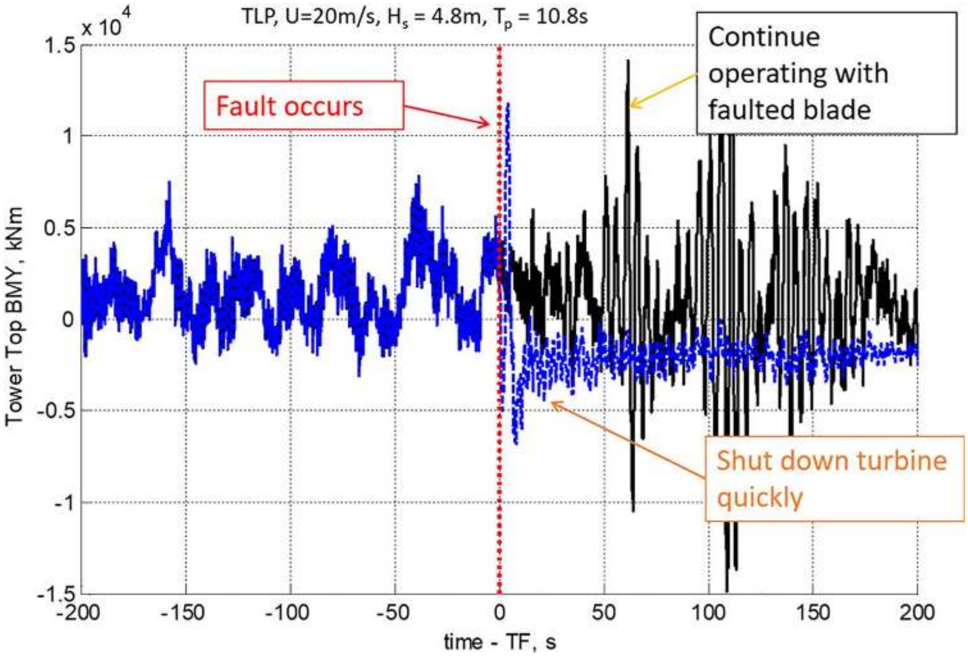

Fig. 15 Effect of pitch control fault (blade seize) in a tension-leg wind turbine

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.

Decision-Making in Lifecycle System Integrity Management 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 the section on System Integrity Management, uncertainties can be broadly classified as normal variability and lack of information, and human errors and omissions. Physical testing in laboratory and field is important to estimate uncertainties but are themselves subjected to uncertainties.

In practice, normal uncertainties are handled by

- making conservative assumptions or
- using the 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 textbooks including applications in civil engineering [61,62] and applications in the oil and gas industry [35,39].

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 Refs. [152–154]. Studies of the implicit reliability in IEC-61400 codes are reported e.g., in Refs. [155,156]. 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 an account of inspection in deteriorating components [63,64,83]. However, more information about uncertainty measures in load effects and strength in wind turbines is needed to consistently estimate the reliability level, especially relating to software and its use in integrated dynamic response analyses.

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.

Handling Faults and Accidental Events in Design and Operation. Offshore wind turbines consist of many electrical/electronic and mechanical subsystems (gearbox and blade pitch actuator) that need to be properly designed to ensure normal operation of wind turbines. However, faults (i.e., damages or failures in such subsystems) often occur and as requested in design standards, their effects on structural responses should be assessed and documented to satisfy design criteria. In this section, the effects of faults on the global responses of offshore wind turbines are discussed first, followed by numerical modeling of subsystems and their corresponding faults, as well as fault detection and diagnosis based on structural response measurements. This follow-up during operation hence represents an additional action to improve the reliability. In principle, design against faults and actions to mitigate faults should be balanced to correspond to a desirable target reliability level.

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 in the section of Dynamic Modeling and Analysis. Yet, the design of wind turbines according to IEC 61400 [41] 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.

Figure 15 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 shutdown should be carried out over a few seconds to avoid the impact of a sudden brake force.

In Fig. 16, 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 environmental conditions (ECs) are specified in Table 3, and the fault cases A–D are defined as follows:

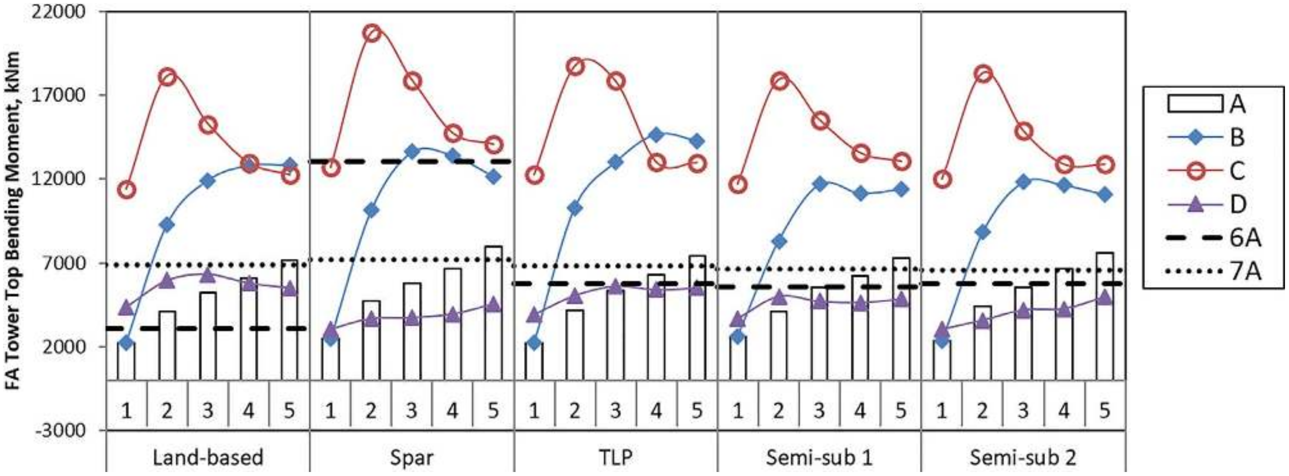

Fig. 16 Numerical calculation of the effect of selected fault conditions on the fore-aft (FA) extreme bending moment at the top of the tower of a 5 MW turbine with various support structures (The numbers 1…5 indicate the environmental conditions F1…F5 that are defined in Table 3. The expected maxima for the environmental conditions F6 and F7 for each concept are shown as horizontal lines for comparison [105].).

Table 3 Environmental/fault conditions

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 (s)	9.8	10.1	10.3	10.5	10.8	13.3	10.1
U (m/s)	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 (s)	1000	1000	1000	1000	1000	10,800	10,800

Note: The wind and wave direction is in the positive x-direction, and the wind speed is reported for the hub height. The normal turbulence model (NTM) and extreme turbulence model (ETM) are applied for Class C [41].

(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 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, and the controller reacts by shutting down after detection.
(D) Grid loss followed by shutdown: the grid is disconnected, and the controller reacts by shutting down after detection.

When shutdown occurs, the grid is disconnected and all blades with working actuators are pitched to feather (90 deg) at a certain pitch rate. In the current work, the pitch rate during the shutdown is chosen to be 8 deg/s, the maximum pitch rate suggested in Ref. [157]. The pitch rate can have a significant impact on the loads and motions, as studied in Refs. [106,158].

For fault types B, C, and D, the fault occurred after 400 s of normal operation. An additional 600 s after fault were simulated in order to capture several subsequent cycles of low-frequency events. For fault types C and D, the time of detection is 0.1 s, which is approximately 10 times the sampling period of the controller [105]. For the shown example (the fore-aft bending moment at the tower top), shutting down the turbine after blade seize error (C) tended to reduce the expected maximum response in high wind speeds for the land-based and TLP wind turbines but tended to increase the maximum load in lower wind speeds. Shutting down the turbine in high wind speeds was less effective for the spar and semi-sub platforms. These results suggest that shutdown effects can be severe and that better methods for shutting down the platform should be pursued.

Modeling 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 modeling 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 the 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 subsection on the Effect of Faults on Global Responses of Wind Turbines, 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]. For instance, the blade pitch actuator fault in one blade followed by emergency shutdown can lead to high torque variation and gear rattle in the drivetrain [110].

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. 17. The blade pitch angle can be changed by the oil flow to and from the cylinders that are controlled by a number of valves.

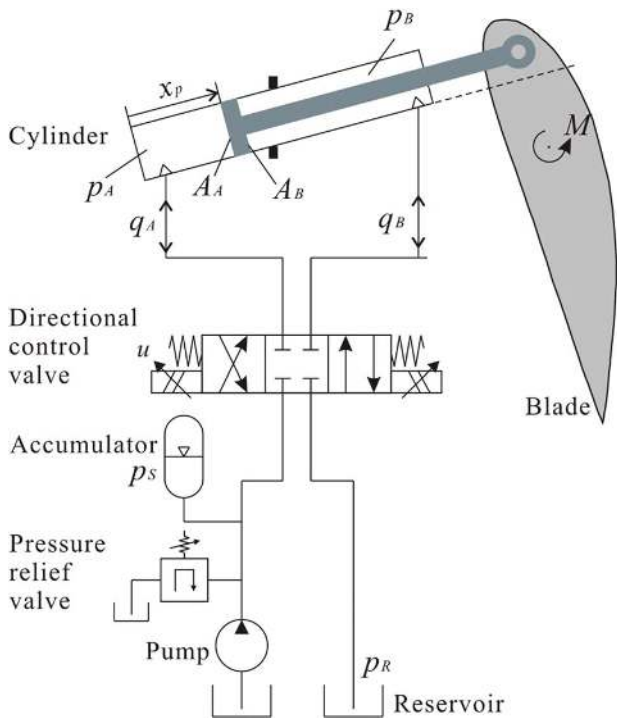

Fig. 17 A schematic diagram of the hydraulic pitch actuator [109]

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 Ref. [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.

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 shutdown 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 to investigate the feasibility to detect the wear damages in the downwind main bearing (INP-B as shown in Fig. 18) of a 5-MW 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 are 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 Ref. [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 the detection of damages in the main bearing of the 5-MW wind turbine gearbox. Figure 18 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. 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. These data can be processed by machine learning [159]. On the other hand, the numerical methods available provide a basis for model-based prediction of the wind turbine behavior. Eventually, prediction of long-term performance requires numerical models, because experience data only cover limited periods. Hence, it is important to relate observations to the methods inherent in the numerical methods.

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 integrated dynamic analysis of floating wind turbines in a reliability context. Examples to illustrate the developments are mainly based on research conducted at the authors' institution.

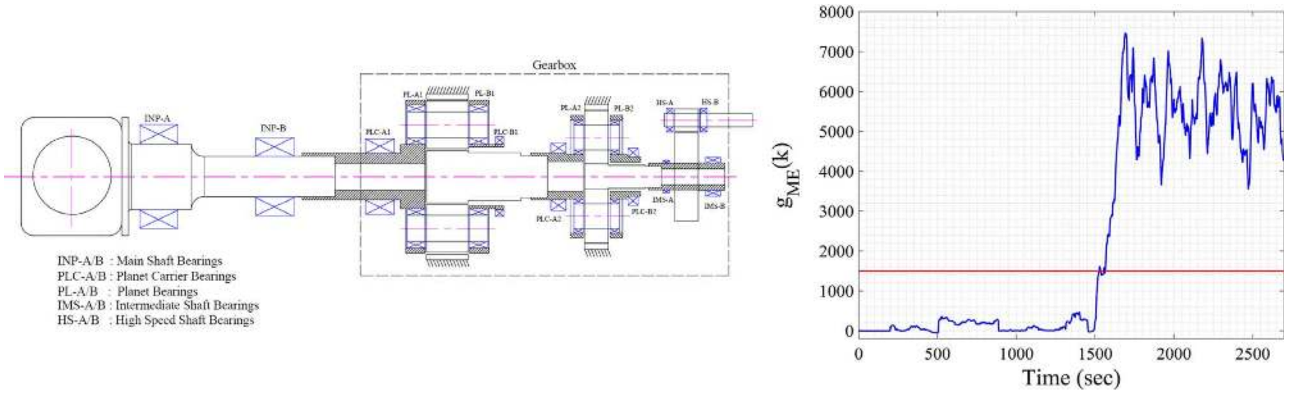

Fig. 18 Layout of the 5 MW wind turbine gearbox [33] (left) and the GLR test statistics using moment estimators for the distribution parameters for the shaft acceleration responses (right) [113]

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 use in 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 a 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 the 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 that ultimately can serve as a basis to establish a consistent reliability level for floating wind turbines. 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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