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A SUMMARY OF THE RECENT WORK AT NTNU ON MARINE OPERATIONS RELATED TO INSTALLATION OF OFFSHORE WIND TURBINES

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ABSTRACT

In this paper, a summary of the recent work at NTNU on the installation of offshore wind turbines using jack-up and floating vessels will be reported. The wind turbine components considered here are the monopile foundations and the blades. The detailed discussions are given to the crane operations for installing wind turbine blades as well as novel installation methods for pre-assembled rotor-nacelle-tower. It includes numerical modelling and analysis for global dynamic responses of the installation system (installation vessels plus wind turbines) and for local structural responses of the blades in case of contact/impact. In particular, the stochastic nature of the environmental conditions (mainly wind and waves) and their influence on the global dynamic responses of the installation system will be assessed based on time-domain simulations. In addition, tugger line tension control is introduced for the final connection to the hub in order to reduce the motions of the blade and therefore the potential damages to the blades. It is then followed by a discussion about nonlinear structural analysis of the blade in contact with tower or surrounding structures using ABAQUS. Damages in the composite plies and sandwich core materials of the blade due to contact/impact for a given initial velocity are then estimated. The obtained damage distribution formulates the basis for a probabilistic assessment of structural safety during installation. Novel installation methods in which the rotor-nacelle-tower structure is pre-assembled onshore and installed on top of the foundation offshore, and the corresponding installation vessels are discussed at the end of the paper. Finally, the main conclusions and the recommendations for future work are drawn.

KEYWORDS

Offshore wind turbines, crane operation, installation method, jack-up vessel, response-based criteria, contact/impact analysis.

INTRODUCTION

Through the last decade, the offshore wind industry is developing very fast and in particular in Europe, there is an average annual increase of 30% in installed wind power capacity. By end of 2016, the total installed offshore wind capacity reaches 12.631GW in Europe and 14.384GW worldwide (GWEC, 2017a). Moreover, there is a very promising sign of significant cost reduction for some of offshore wind farms in the bidding phase (GWEC, 2017b). In particular, several offshore wind farms in 2016, including Borssele 3 & 4 in the Netherland, Krieger's Flak and Vesterhav in Denmark, have reached quite low bids, ranging from 72 Euro/MWh to 60 Euro/MWh, which is even lower than the normal bid for onshore wind farms (Hundleby & Freeman, 2017). In 2017, Dong Energy and EnBW won the bids to build first subsidy-free offshore wind farms in the North and Baltic Seas in Germany (Offshore Wind Industry, 2017).

The recent trend of offshore wind development shows that more wind turbines were installed in deeper waters, farther from shore and in bigger farms. Most importantly, the rated power and the turbine size are continuously increasing. The average rated power for those installed in 2016 is 4.8MW (WindEurope, 2017), which is a 15% increase as compared to those in 2015. The first 8MW turbines (Vestas' V164 turbines) have already entered into the market in 2016 and have been installed at the Burbo Bank Extension in the Irish Sea in UK, as shown in Figure 1. The trend of increasing turbine size seems to continue and this will be beneficial for the overall cost reduction. However, it will lead to more challenges for offshore installation, due to longer blades and larger lifting height.

The world first floating wind turbine farm was commissioned in Scotland in late 2017 based on the Hywind technology from Statoil, Norway, as shown in Figure 1. It consists of five 6MW Siemens turbines. Turbine blades, nacelle and tower are pre-assembled onshore and then installed by one of the largest semi-submersible crane vessels, SAIPEM 7000, onto the spar floaters in the deep fjord of Norway. Then, they are wet-towed to offshore Scotland and connected with mooring systems. However, Statoil also realized that the cost should be further reduced and new installation methods which rely less on expensive large crane vessels are preferred when developing commercial wind farms. In that respect, semi-submersible floating wind turbines may have the advantage to be pre-assembled in one piece in the shipyard and towed to the offshore deployment site.

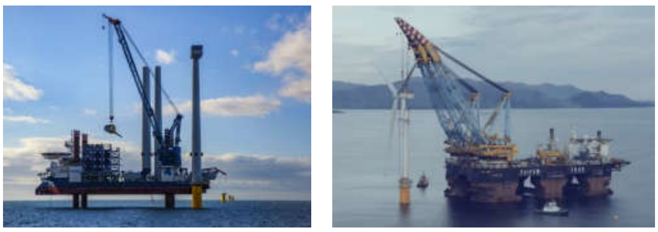


Figure 1: Examples of offshore wind farms during installation (left: First MHI Vestas 8MW wind turbine installed by A2Sea jack-up Sea Installer in Burbo Bank 2 offshore wind farm in UK (Renews, 2017); right: Spar floating wind turbine assembled in Norway by SAIPEM 7000 before towed to Statoil Hywind offshore wind farm in Scotland (Statoil, 2017))

Moreover, according to the wind energy scenario towards 2030 presented by EWEA (2015), the total installed capacity of wind power could reach 320GW in 2030, including 66GW of offshore wind power. This implies a significant number of offshore wind turbines, roughly 650 6MW turbines that need to be installed every year.

The cost of offshore wind power today is still too high. In order to reduce the cost of offshore wind farms, it is important to look at marine operation aspects related to different phases of an offshore project, including transport, installation, operation, maintenance and decommissioning.

Although tripod, jacket, GBS and even floating foundations were developed and used to support wind turbines, monopiles still represent the majority in today's offshore wind farms. Monopile wind turbines are normally transported by barges and installed component-by-component offshore. Large floating crane vessels have been used to install foundations. But, due to the high precision required in the mating operation of the blades into the hub, wind turbine blades, nacelle and tower are typically installed using jack-up vessels, which provide a stable platform for installation operation.

One of the main challenges for installation is to increase the weather window and to avoid any unexpected delays. This is particularly important when many units in a farm configuration need to be installed. This requires a good understanding of the performance of the installation vessels in waves. Therefore, numerical methods and models have been developed to estimate dynamic responses of the system during installation, including Collu et al. (2014), Li et al. (2015) and Li et al. (2016), in which static, steady-state as well as non-stationary dynamic responses of the installation systems were analysed.

In this paper, a brief review on the recent work on installation of offshore wind turbines at NTNU will be carried out. In particular, the focus will be given to the numerical modelling and analysis for wind turbine blade installation, motion reduction by active tugger line force control, as well as blade damage assessment in case of contact/impact with the surrounding structures during installation. Moreover, novel installation methods for pre-assembled rotor-nacelle-tower structures will also be reviewed.

MARINE OPERATION REQUIREMENTS

Typically, for any marine operation, there exists one or multiple operational limits of sea states, which are established considering the safety requirements (e.g. personnel, environmental and property safety). As a special case of marine operations, installation of offshore wind turbines are normally carried out in low sea states (for example with Hs in the order of 1-3 m). Operational limits are strongly dependent on the installation methods and vessels that are used for the task. Detailed information about the limiting environmental conditions for different installation vessels can be found in Table 1 (Ahn et al., 2017).

Table 1: Limiting environmental conditions of various installation vessels (Ahn et al., 2017)

Vessel type	Operating equipment	Capacity	Transit condition		Operating condition	
			Speed (knots)	Wave height (Hs, m)	Wave height (Hs, m)	Wind speed (m/s)
WTIV	Jack up/down + crane	Crane capacity: 800−1500 ton	12	3.0	2.5	16
Jack-up barge	Jack up/down + crane	Crane capacity: 800 ton	4	2.5	1.65	16
Crane barge	Shear crane	3000 ton	4	1.5	1.0	10
Cargo barge	Stacking (without crane)	2000−5,000p	4	1.5	1.5	14
Tug boat	Towing	750 hp, 1000 p	13	2.5	1.0−1.65	14

Currently, such environmental limits are obtained based on industrial experiences, but they are preferably established using response-based criteria. A generic methodology for assessment of the operational limits and the operability of marine operations was proposed by Guachamin-Acero et al. (2016). The basic idea is to estimate structural dynamic responses during operations in all possible sea states using numerical models and then backwards derive the limiting environmental conditions that will lead to the allowable response level. This methodology was applied to monopile foundation installation (Li et al., 2016) and transition piece installation (Guachamin-Acero et al., 2017a).

A similar approach, called reliability-based decision support model, was developed by Gintautas et al. (2016), in which response statistics of the installation equipment were obtained based on simulations and used to estimate the weather windows in combination with the ensemble weather forecast model.

INSTALLATION OF MONOPILE FOUNDATIONS

In the last few years, there are a significant amount of work that were carried out at NTNU regarding dynamic response analysis of offshore wind turbine foundations during installation. In the current offshore wind industry, monopile foundation is the mostly-used foundation and therefore it was chosen as a typical foundation for installation study. Normally, crane operations using either jack-up or floating installation vessels are performed to install bottom-fixed offshore wind turbine components. The focus of these studies was on the nonstationary environmental loads acting on the lifted object during installation and their effects on the dynamic responses of the installation system (including an installation vessel and the lifted object). The goal for numerical installation analysis is to derive the operational limits in terms of sea states using response-based criteria. Such operational limits are obtained in the design phase and can be used for planning of marine installations based on the knowledge of the long-term statistical data of the environmental conditions, or for decision-making during execution of installation operations using weather forecast data, typically with 3-6 hours of leading time.

A generic methodology was developed and exemplified by the monopile foundation installation. The following studies were performed and summarized in the MOSS conference paper (Gao et al., 2016) and the individual papers (Li et al., 2015; Li et al., 2016; Guachamin-Acero et al., 2017). Therefore, we will not repeat to explain these studies in this paper. Instead, we will focus on the recent work on blade installation and novel installation concepts for pre-assembled rotor-nacelle-tower structures.

- Numerical analysis of the monopile lift-off and lowering process
- Modelling and analysis of the installation system (including a floating vessel and a monopile) during the initial hammering operation
- Analysis for installation of the transition piece onto the monopile foundation

INSTALLATION OF OFFSHORE WIND TURBINE BLADES

Blades and nacelle are the most critical components of an offshore wind turbine and they are normally installed using jack-up vessels which provide a stable platform for lifting operations. In most of the cases today, they are installed piece by piece via crane operations. The blades are long and they have to be installed at a high position (on top of the tower). This challenges the offshore onsite installation operations. In particular, wind loads acting on the blades may induce large motions, which makes it difficult to position it during the final phase of connection to the hub. Therefore, it is important to explicitly model these loads and estimate the induced responses as well as to control the blades during the final mating phase. In this section, we will summarize the work on blade installation analysis and control (Zhao et al., 2018; Verma et al., 2017; Ren et al., 2017), including the global response analysis and the local damage analysis due to contact/impact of the blade cross-sections with surrounding structures.

Global response analysis of the blade motions during installation

A wind turbine blade typically experiences less aerodynamic loads during installation as compared to the situation under normal operations for electricity generation. This is because the relative wind speed seen by a blade cross-section during installation is much smaller than that of a rotating blade during normal operations. Nevertheless, the blades are lifted in air and need to be installed at the hub position on top of the tower. The required precision for the final connection of the blade root to the hub before it is bolted is very high. Under the dynamic wind loads in a turbulent wind field, the blade will oscillate mainly due to the pendulum motions. A coupled simulation tool SIMO-Aero, as shown in Figure 1, was developed by Zhao et al. (2018) for blade installation in which an aerodynamic code is fully coupled to the motion simulation code SIMO.

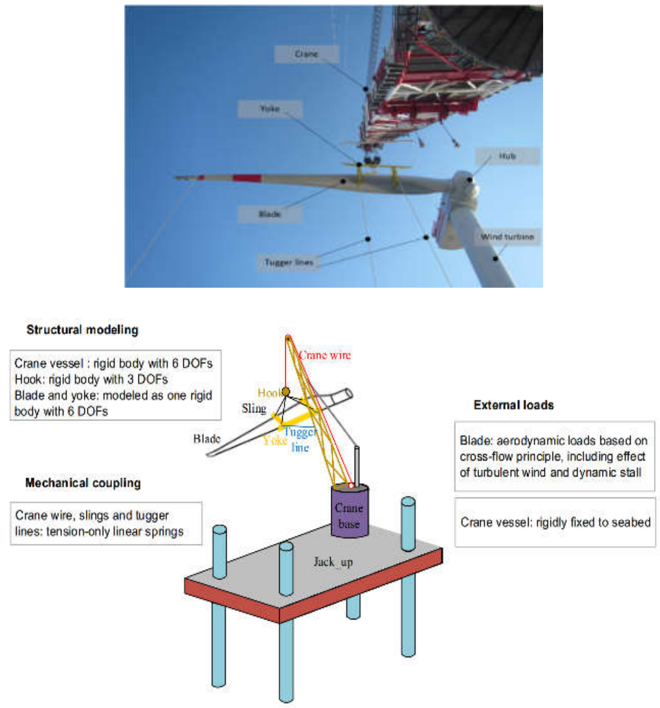


Figure 1: Blade installation (top) and the coupled simulation tool SIMO-Aero (bottom)

This coupled code can account for aerodynamics of the installed blade, hydrodynamics of the installation vessel as well as mechanical couplings between different bodies in the installation system. The instantaneous displacement and velocity of the blade is calculated by SIMO at each time step. The blade velocity and the wind inflow velocity (obtained from a wind field simulator) are then transferred in the blade local coordinate system in the developed code Aero to update the relative velocity seen by the blade element and the angle of attack. The corresponding lift and drag coefficients are determined from a look-up table, and used to estimate the lift and drag forces. The blade is assumed to be rigid and therefore the integrated lift and drag forces along the blade length are obtained and used to solve the rigid-body motions of the blade in SIMO.

The aerodynamic loads on blade cross-sections in Aero are calculated based on the 2-D cross-flow principle and the turbulent wind inflow and the dynamic stall models are implemented. The aerodynamic code is verified against the HAWC2 results using the DTU 10 MW reference wind turbine blade (Bak et al., 2013). Figure 2 shows a good agreement between the results from the Aero code and HAWC2.

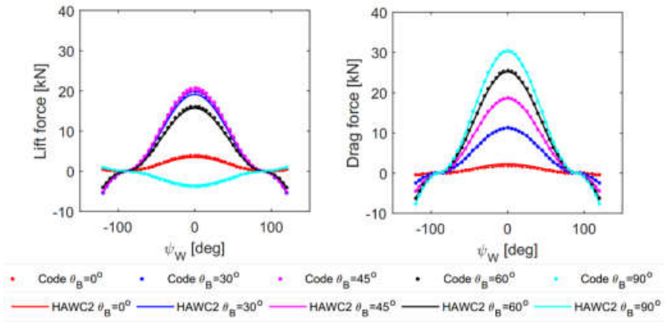


Figure 2: Comparison of the integrated lift and drag forces between Aero and HAWC2 for different blade pitch angle (θ_B) and yaw angle (ψ_W)

The developed code is then used to study the dynamic responses of the blade during installation using a jack-up vessel. In fact, the jack-up vessel was assumed to be rigid and fixed to the sea bed rigidly. An equivalent crane stiffness was considered in the modelling of the lift wire stiffness property. Figure 3 shows the spectra of the rigid-body motions of the blade for two cases of turbulent intensity factor. The main wind direction is perpendicular to the length of the blade and the sway motion of the blade is along the wind direction. The overall motions of the blade are not significant. It is observed from the figure that the blade motion responses in sway and roll are governed by the resonant motions at a natural period of 13s, which corresponds to the pendulum motion mode in roll of the lifted blade. While, another spectral peak exists for the yaw motion, which indicates a yaw resonant motion at a higher natural frequency due to the presence and the restoring effect of the two tugger lines, as shown in Figure 1. Furthermore, it is possible to obtain the lift wire tension time series from the time-domain simulations, which can be further used to check whether the dynamic tension exceeds the maximum allowable tension. More details can be found in Zhao (et al., 2018).

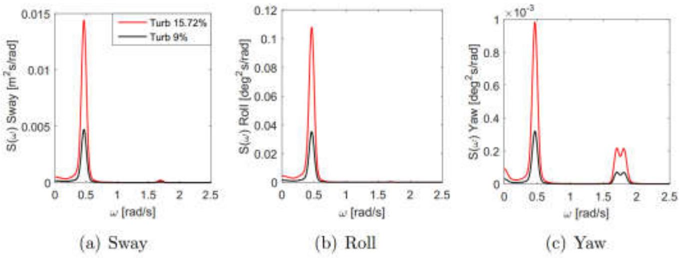


Figure 3: Spectra for sway, roll and yaw motions of the blade during installation (mean wind speed of 10m/s at the hub height)

Blade motion reduction for final connection

The critical phase during installation of a wind turbine blade is the final connection of the blade root to the hub. When the blade root enters into the hub, bolts are placed manually to fix the blade to the tower top. This requires an extremely high precision of the blade root for connection. It is therefore important to reduce the motion of the blade root relative to the hub. This can be achieved by controlling the forces of the two tugger lines actively, as shown in Figure 4.

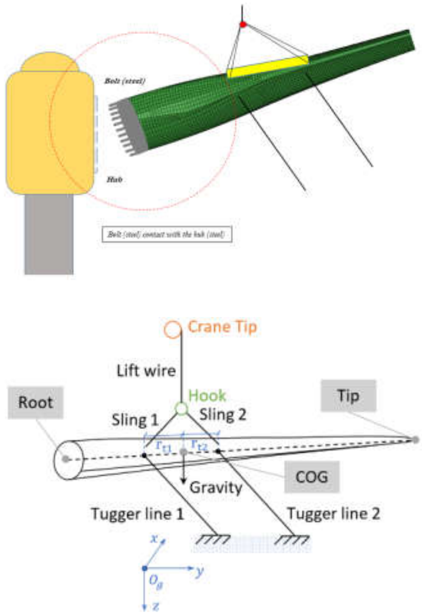


Figure 4: Blade root connection to the hub (top) and a simplified 3DOF model of the blade with lift wire and tugger lines (bottom)

A closed-loop scheme for active tugger line force control for single blade installation is developed by Ren et al. (2017), considering a reduced model of the blade with 3DOF. An extended Kalman filter (EKF), a state feedback linearization and feedforward compensation algorithm, and pole placement techniques were applied to design the proportional-integral-derivative controller, as shown in Figure 5.

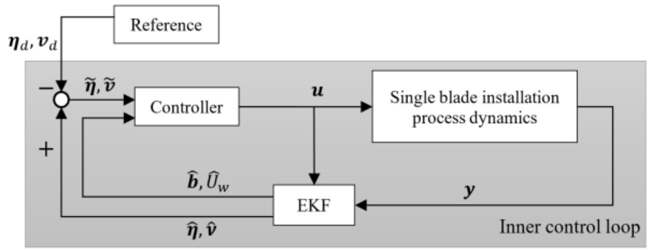


Figure 5: Block diagram of the active tugger line controller

At each time instant, an EKF receives the noisy measurements $\boldsymbol{y}$ from the sensors to estimate the blade position and orientation $\hat{\boldsymbol{\eta}}$, the blade velocity $\hat{\boldsymbol{\nu}}$, the wind velocity $\hat{\boldsymbol{U}}_{\boldsymbol{w}}$, and the bias compensation term $\hat{\boldsymbol{b}}$. When the controller is turned on at time $\boldsymbol{t_0}$, the EKF provides the initial value for the reference model and the controller. A reference module is applied to generate smooth trajectories of the real-time desired position and velocity, denoted by $\boldsymbol{\eta_d}$ and $\boldsymbol{\nu_d}$, to the preset setpoint where the blade is stabilized. All estimates and reference signals are fed back into the feedback controller. The controller calculates the corresponding tension input $\boldsymbol{u}$ to the two tugger lines according to the error between the estimated values and the desired trajectory, as well as some feedforward compensation of the estimated wind and bias loads.

To verify the performance of the controller, time-domain simulations were conducted for turbulent wind conditions, using a 6DOF system with aerodynamic loads on the blade calculated similarly as in Zhao et al. (2018). It was found that the proposed actively-controlled tugger line system works well as tested with the simulation verification model (Ren et al., 2017). A comparison of the blade translational motions at the root with and without the active tugger line control was shown in Figure 6. It is quite illustratable that the blade root motions along the wind direction have been reduced significantly for the case with active control, which demonstrates the good performance of the controller. The motions in y and z directions are not possible to reduce by the current tugger line configuration, but they are relatively small.

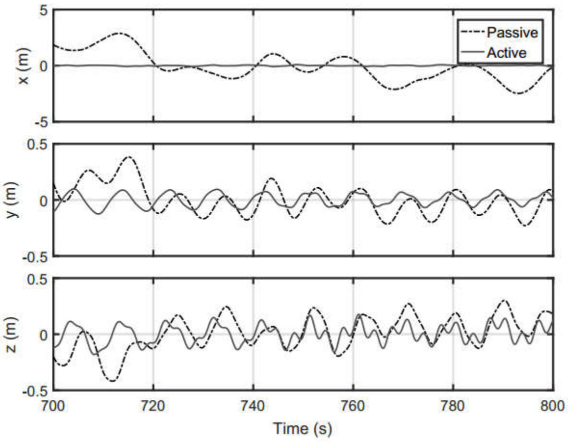
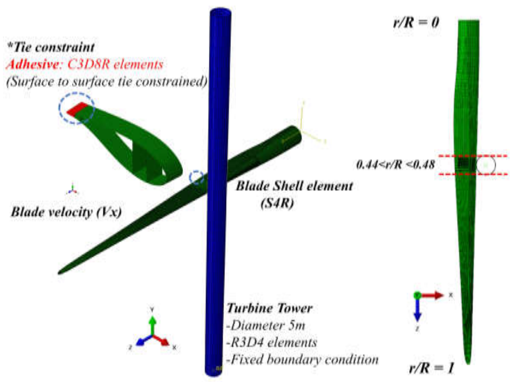


Figure 6: Comparison of the blade root motions with and without active tugger line control (mean wind speed of 10m/s at the hub height and the turbulent intensity factor of 0.157)

Blade damage modelling and analysis in case of contact/impact

Upon installation at the offshore site, blades are lifted up from a barge and then moved to the hub position for connection. During this process, the blades might be in contact with the surrounding structures which may cause damages in blade cross-sections and reduce the ultimate and fatigue strength. Blades are made of composite materials, typically GFRP (Glass Fiber Reinforced Polymer), and they are vulnerable to contact/impact loads. It is therefore important to reduce the possibility of such contact/impact events and if not avoidable, to estimate the damages due to contact/impact and their influence on blade strength. A study using ABAQUS was carried out by Verma et al. (2017) to estimate the blade cross-sectional damage when it is in contact with the steel tower, as shown in Figure 7.



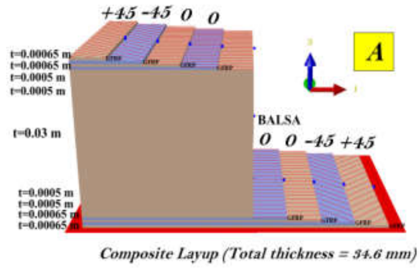
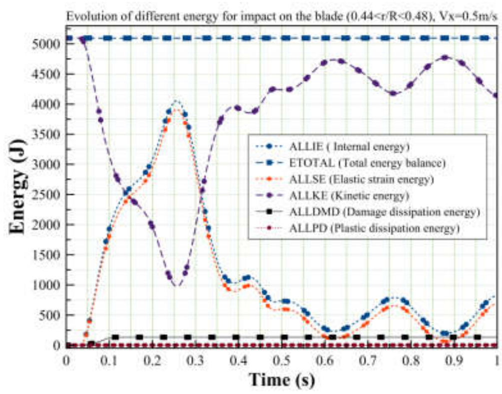


Figure 7: Blade-tower contact/impact scenario (top) and blade composite layup at the contact region (bottom)

The analysis assumes an initial velocity of the blade that will impact with a rigid steel tower and includes the global motion dynamics as well as the local damage assessment of the blade due to impact. A shell model of the blade was established considering the correct composite layup (including the multiple GFRP plies and the core material of balsa). The stress-based Hashin failure criterion (Hashin & Rotem, 1973) of damage initiation along with the energy based damage evolution (Camanho et al., 2003) were used to characterize the intra-ply damage of fibre and matrix due to tension and compression. Von Mises stress failure criterion was used for core material (balsa) failure.

Figure 8 shows the energy evolution and the contact force due to the blade-tower impact. It is quite clear that most of the initial kinetic energy of the blade (due to translational motions) were converted into the elastic strain energy during impact and then converted back to the kinetic energy (in the form of rotational motions). Only a small part of the energy was dissipated due to the plastic deformation and the damage in blades. This is due to an eccentric impact in which the centre of gravity of the blade and the contact point are not aligned with the path of movement of the blade. We also see two peaks in the contact force time series and this is because the vibration of the whole blade which changes significantly the contact area in a relatively short duration of impact.



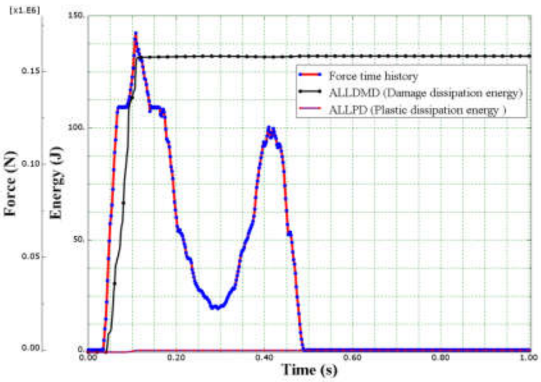


Figure 8: Energy evaluation during the blade-tower impact (top) and the contact force time series (bottom) (blade initial velocity of 0.5m/s)

The current numerical analysis is based on a shell model of the blade which fails to take into account the delamination failure mode of the composite material. Numerical modelling with solid elements is still ongoing at NTNU. The aim is to assess explicitly the blade damage as well as to evaluate the influence on the ultimate or fatigue strength of the damaged blade. Essentially, it is to answer the question that whether the blade due to accidental contact/impact loads can still be used or not.

Novel installation methods for pre-assembled wind turbine rotor-nacelle-tower

As the current practice of the offshore wind industry, offshore wind turbine components are mainly installed piece by piece via crane operations. The basic principle to reduce the installation cost is to reduce the number of lifting operations offshore. In that sense, installing pre-assembled structures (for example rotor-nacelle-tower) is preferred. Of course, this also depends on the possible installation vessels that are available for such installation methods, which require a higher crane capacity as compared to the component installation methods. Guachamin-Acero et al. (2017b) proposed a novel installation method based on the inversed pendulum principle using small crane vessels. As shown in Figure 9, the rotor-nacelle-tower assembly is transported by a barge and equipped with an upending frame. Upon the offshore site, the upending frame is attached to the pre-installed foundation and with the help of a small crane vessel, the rotor-nacelle-tower assembly can be lifted up and installed on top of the foundation. However, a coordination between the forward movement of the crane vessel and the lifting operation should be achieved in order to make the installation successful. A preliminary study shows the feasibility of such installation method (Guachamin-Acero et al., 2017b).

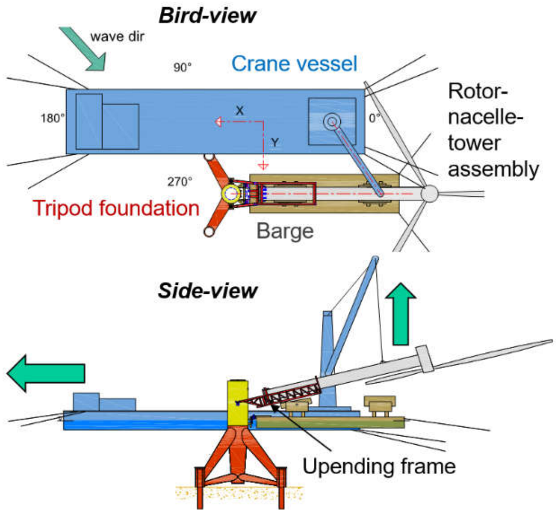
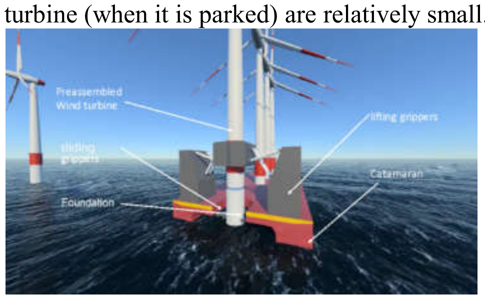


Figure 9: Novel installation method of pre-assembled rotor-nacelle-tower based on the inversed pendulum principle

Another installation concept using a catamaran vessel was developed at the research centre SFI MOVE at NTNU (Hatledal et al., 2017). As shown in Figure 10, a catamaran installation vessel can carry four pre-installed rotor-nacelle-tower assesmblies. At the offshore site, the catamaran vessel can connected to the spar foundation via a sliding gripper system which allows the relative vertical motions between the vessel and the foundation. The pre-assembled rotor-nacelle-tower system can then be installed on top of the spar foundation by its lifting mechanism. The most challenging design of the system is the gripper and the lifting mechanism. On one hand, the relative motions between the foundation and the rotor-nacelle-tower assembly should be minimized for the final connection. On the other hand, the loads in the lifting mechanism should also be limited. A preliminary study was carried out by Jiang et al. (2017) and the feasiblity of such installation concept was demonstrated.

Figure 11 shows the trajectory and the corresponding spectra of the relative motions between the spar foundation and the rotor-nacelle-tower assembly at the connection point. It is clearly shown that the wave loads on the catamaran vessel and the spar foundation are the main external loads, while the wind loads on the wind turbine (when it is parked) are relatively small.



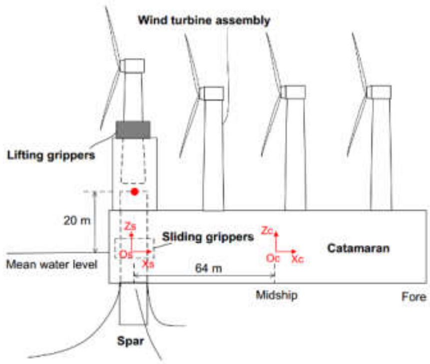


Figure 10: The catamaran installation vessel for pre-assembled rotor-nacelle-tower

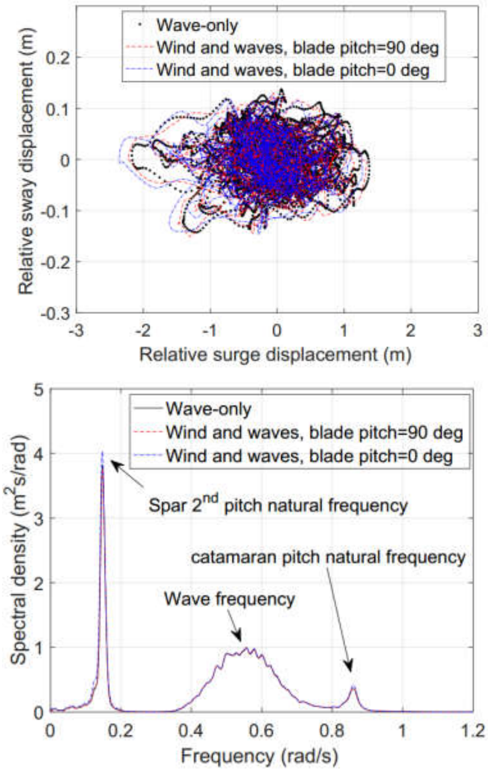


Figure 11: Relative motion trajectory between the spar foundation and the rotor-nacelle-tower assembly at the connection point (top) and the corresponding spectra (bottom) considering wave-only and wind/wave conditions (Hs=2.5m, Tp=12s, Uw=10m/s at the height of 10m, wave direction along the surge motion direction of the catamaran and the spar)

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

In this paper, the recent work at NTNU on installation of offshore wind turbines are summarized. This includes the numerical modelling and analysis of crane operations for wind turbine blade installation considering the aerodynamic loads on blades in a turbulent wind field. Pendulum resonant motions of the blade during lifting operation were revealed. An active tugger line force PID controller was developed to reduce the blade root motions relative to the hub position for the final connection phase. In case of blade contact/impact with the surrounding structures during installation, a shell model of the blade with composite material was analysed considering Hashin failure criterion of damage initiation and the energy-based damage evolution law. Eccentric impact of the blade with the tower leads to a significant rotational motions of the blade after impact and therefore the energy dissipated in the plastic deformation and in the damage of the blade cross-sections is limited. Novel installation methods using inversed pendulum principle and using a catamaran vessel were introduced for pre-assembled rotor-nacelle-tower structures, which can potentially reduce the number of lifting operations offshore and therefore reduce the installation cost.

In the future, the developed numerical methods and models for installation analysis need to be validated against model test or field measurement data. Model tests of marine operations are difficult to perform in hydrodynamic labs. In that sense, measurements from actual installation operations are preferred for comparison with numerical analysis. Further development of novel installation methods should also be considered.

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