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Lifting Wind Turbine Components From a Floating Vessel: A Review on Current Solutions and Open Problems

Offshore wind energy is experiencing rapid development and is expected to make up an even bigger part of the world's future energy mix. New installation concepts for offshore wind farms involve lifting operations of wind turbine components from floating vessels. These installation concepts will only be economic if the lifting operations are performed safely at sea states with high significant wave heights. In this paper, we give an overview of current technical solutions, which could be used to lift the components tower, nacelle, hub, and rotor blade from a floating vessel. We classify and analyze solutions found in patents and the academic literature and point out open problems, which need to be addressed to enable lifting operations at higher sea states than what is currently feasible. However, we restrict the paper to technical solutions concerning the interface between the vessel and the component as well as the interface between the component and the crane. Consequently, we analyze, classify, and discuss solutions for the seafastening, the lifting gear as well as motion compensation systems. We find that there exists a large number of solutions, which are specific for a single component, but few solutions, which are applicable to all components without major adaptations. Additionally, we miss hydraulic seafastening mechanisms, which are remotely controlled and synchronized with the lifting operation. Consequently, we argue that versatile interfaces between the component and the crane as well as remotely controlled and synchronized seafastening mechanisms are best suited to enhance the lifting process. [DOI: 10.1115/1.4042385]

1 Introduction

Offshore wind energy is experiencing rapid development and is expected to have a promising future [1]. In 2016, 2219 MW of offshore wind capacity was newly installed worldwide [2]. The new wind farms increased the global cumulative capacity to 14,384 MW, which is more than a threefold increase compared to 5 years earlier (4117 MW in 2011) [2]. Despite the growth, the annual newly installed offshore capacity is still lacking behind onshore wind and the levelized cost of electricity is higher for an average offshore site compared to an average onshore site. Important cost drivers of offshore wind are the transportation and installation processes, which are performed with specialized vessels and lifting equipment.

An offshore wind turbine consists of the main components tower, nacelle, hub, rotor blade, substructure, and foundation [3]. The installation of an offshore wind farm typically happens in two steps. In the first step, the wind turbine's substructure and foundation, for example, a monopile, is installed, and in the second step, the actual turbine, sometimes referenced as the upper structure [4], is installed on top of the substructure. The installation of the upper structure can be realized with a variety of different concepts [4,5]. Open variables are the type and number of transport and installation vessels, the assembly states of the wind turbine components on the vessels, and the method to erect the wind turbine.

While in some concepts the wind turbine is fully assembled onshore and transported in that state [6–8], usually the wind

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turbine is split up in subassemblies and gets fully assembled at the wind farm site. The latter is sometimes called split installation procedure [9] and comprises a variety of specific subassembly arrangements, which have been used in the past. These different arrangements are summarized by Sarker and Faiz [10] and Ahn et al. [5]. The current practice is to either pre-assemble the hub and blades in the harbor (called "rotor star method" [11] or "star assy method" [5]) or to transport the rotor blades individually, while the hub is in a subassembly with the nacelle (called "single-blade installation method") [5].

When a split installation procedure is chosen, two main logistics concepts to transport the components to the wind farm can be differentiated. In the classic concept, a jack-up vessel goes back and forth between a base harbor and the wind farm. All components from the production sites are delivered to the base port beforehand. Accordingly, the base port can be considered a central hub. This concept is sometimes called the all-in-one concept, because one vessel does both, transportation and erection [12].

In the newer feeder ship concept, the jack-up vessel remains at the wind farm and a feeder vessel transports the wind turbine components to the jack-up vessel [13–15]. The feeder ship concept uses the jack-up vessel, which has a daily charter rate of EUR 70,000–145,000 [16], more economically and consequently offers cost-saving potential [17]. While there is experience "feeding" the substructure and foundation, with monopiles [18–20], transition pieces [19], jackets [21], and pin piles, until now no wind farm has been installed with a feeder ship concept for the upper structure. The concept's main challenge is the lifting of wind turbine components from a floating feeder vessel. In order to achieve significant cost savings, the lifting operations must be performed safely and quickly at as many environmental conditions as possible, that means even at sea states with high significant wave heights and consequently strong vessel movements.

Potential logistics concepts can be evaluated by economic modeling [11,15,17,22,23] and by performing numerical simulations of the dynamic mechanical behavior of vessels and wind turbine components during transport and installation [9,24–26]. Economic modeling is used to determine the total installation costs of a logistics concept and "mechanical simulations" are used to test and challenge the operational (weather) limits of installation and transportation processes. Kaiser and Snyder [22] proposed a detailed deterministic model to estimate the installation costs for projects in the U.S. They considered an all-in-one-concept and found that installation costs might range from $130,000 to $370,000 per MW. Later, Muhabie et al. [11] used discrete event simulation to analyze the installation costs and pointed out that discrete event simulation has the advantage that it can simulate the probabilistic nature of individual process times. They analyzed an all-in-one-concept that uses a rotor star installation method. Recently, Ait Alla et al. [15] and Oelker et al. [17] used discrete event simulation to determine the costs of a feeder ship concept. Oelker et al. [17] found that under the assumed model assumptions (for example, an operational limit of $H_s = 2\,\mathrm{m}$ for the transfer of the wind turbine components from the feeder ship to the jack-up vessel) the feeder ship concept can save costs compared to an all-in-one-concept.

Three types of "mechanical simulations" that are relevant for the assessment of logistics concepts can be differentiated: the simulation of structural mechanics (often done with the finite element method), the simulation of fluid mechanics (computational fluid dynamics), and the simulation of multibody dynamics (multibody simulation). Acero et al. [25] explored how a pre-assembled tower-nacelle-rotor-assembly could be installed using the inverted pendulum principle. Their analysis was conducted with multibody and computational fluid dynamics methods. Jiang et al. [26] used mechanical simulations to determine the operational limits of the single-blade installation method. Concerning the feeder ship concept, we are not aware of any published studies that simulated the lifting process of a wind turbine component from a floating feeder vessel. However, the work of Jeong et al. [24] is related: they simulated the lift-off of subsea equipment from a floating vessel and analyzed the amount of wire tension and the occurrence of collisions.

Currently, the weather limitations on the lifting process negatively affect the economic feasibility of the feeder ship concept at many wind farm sites. However, it is believed that the weather limitation can be improved with an advanced lifting process. Yet, there exists no standard solution to lift wind turbine components and different concepts are actively being developed and tested. The key role that the lifting process plays in the feeder ship concept and the high amount of different concepts for that process motivated us to give an overview about current solutions for the lifting process in this paper.

2 Scope and Methods

This paper is a revised version of the work published in the proceeding of the ASME 2018 37th International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2018) [27]. Here, we analyze and classify current solutions to lift the components tower (split into two tower segments), nacelle, hub, and rotor blade from a floating vessel. We consider both, solutions which are part of the current industrial practice and solutions which have not been used in commercial projects yet. This paper is restricted to solutions concerning the interface between the vessel and the component as well as the interface between the component and the crane (Fig. 1). These solutions concern the seafastening, the lifting gear as well as motion compensation systems. Out of scope are solutions concerning the vessel or the crane itself. The vessel and the crane are different products, which are usually designed, manufactured and owned by different companies than the wind turbine components. Solutions dealing with wind turbine substructures and foundations are considered out of scope as well. The installation of the substructure and foundation is a process that is often handled by another company than the installation of the upper structure. We set this restricted scope, because we want this paper to have a clear focus.

The data basis for this work are solutions found in patent databases, in the academic literature as well as in the industrial practice, which are not documented as formal literature. The research consisted of varying search terms, following citations as well as drawing from our experience. We included solutions, which either specifically reference wind turbine components, or which are generic enough that they could be used for wind turbine components without adaptations. While we tried to include as many as possible solutions, we do not claim that our overview is exhaustive.

To classify the variety of different solutions, which can enhance the lifting process, we first dissected the complex lifting process using a function structure. A function structure splits up the overall function of a design into its subfunctions [28]. Subfunctions can be further divided into main functions and auxiliary functions [28]. Then, we used these subfunctions to classify different solutions of the lifting process. Classifying by subfunctions is recommended by Pahl and Beitz [28]. Further, we used the applicable interfaces of the solutions (e.g., vessel-tower or nacelle-crane) as an additional classifier.

In Sec. 3, we describe the lifting process. The description includes the presentation of a typical deck layout of a feeder vessel and the calculation of the motions that the components' lifting points experience on such a vessel. Based on that description, we formulate the requirements of the lifting process and establish a function-structure. As described, the function structure served us to classify the technical solutions, which are presented in the succeeding section. Finally, we discuss the found solutions, point out open problems and suggest future developments.

3 Lifting Process

3.1 Deck Layout and Motions of the Lifting Points. Despite the variety of possible ways to transport a wind turbine on a vessel, some typical design elements can be identified. The nacelle and the tower segments are often connected via seafastenings to grillages,

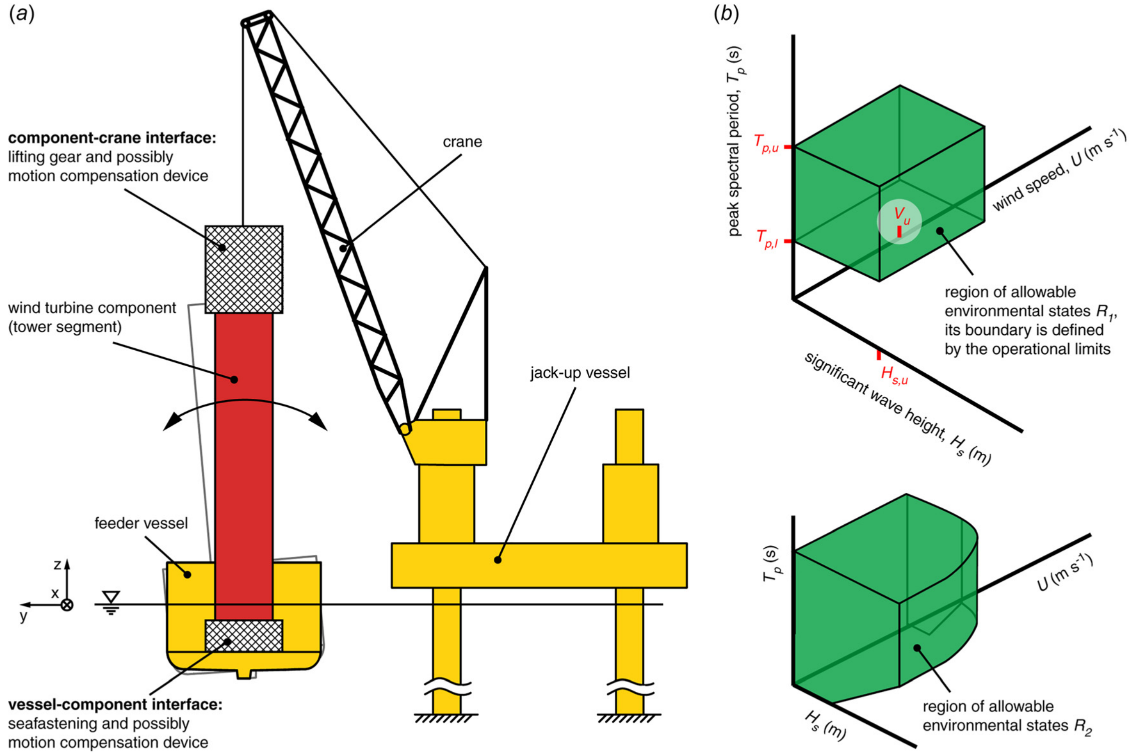

Fig. 1 (*a*) Lifting process of wind turbine components from a floating feeder vessel. The two crosshatched boxes show the interfaces where technical solutions can enhance the process. (*b*) The lifting operation is only allowed to be performed when the current environmental state is within the operational limits. To make the feedership concept economically feasible, the region of allowable environmental states should be as big as possible. Top: In the simplest case, the operational limits are defined by an upper limit for the significant wave height $H_{s,u}$, an upper limit for the wind speed, V_u, and a lower and an upper limit for the peak spectral period, $T_{p,l}$ and $T_{p,u}$. Bottom: A complex definition of the operational limits can increase the probability of occurrence of an allowable environmental state, Pr(R_2)>Pr(R_1).

which are welded to the vessel. The standard DNV-OS-H202 [29] describes how grillages and seafastenings should be designed. Typically, the tower and the nacelle's seafastening is ensured with a bolted connection, which has to be unscrewed before the actual lifting operation. Rotor blades, however, are usually not bolted to a grillage but are transported using special transport frames.

One possible deck layout is presented in Fig. 2. There, one complete wind turbine is transported on an Eems D vessel with a dynamic positioning system of category 2 (DP 2 vessel). The particular vessel has an overall length of 107.95 m and a beam of 16.00 m [30]. In this layout, the wind turbine is split into six subassemblies: two tower segments, the nacelle-hub assembly and three rotor blades. The tower and the nacelle are bolted to a grillage and each rotor blade is mounted to two transport frames.

The difficulty to lift the components from a feeder vessel is due to the components' movements. Hydrodynamic simulations can be used to calculate the expected motions of the component's lifting points at site-specific sea states. Since lifting becomes more difficult at stronger movements, extreme values of the expected motions are important design values. The most probable extreme

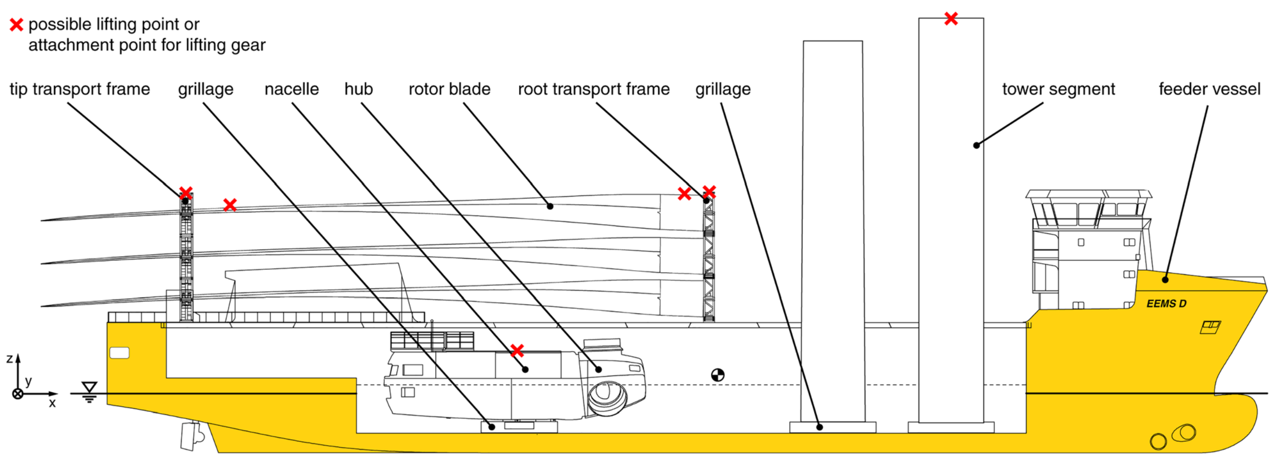

Fig. 2 Deck layout of a feeder vessel used to transport wind turbine components. The shown vessel, an Eems D type owned by Amasus Offshore BV., has a dynamic positioning system of category 2. It has an overall length of 107.95 m and a beam of 16.00 m.

value [31,32] is a useful statistical quantity to describe the expected maximum motions, which should be considered when mechanical devices and processes for the lifting operation are designed. For the presented deck layout of the Eems D vessel, the authors used hydrodynamic diffraction analysis to compute hydrodynamic parameters, which were used to assess dynamic responses. Results from the state-of-the-art code ANSYS Aqwa (version 18.2) showed that the tower segment's lifting points experience the highest motions. This was expected since the tower segment's lifting point is the farthest away from the vessel's center of gravity (Fig. 2).

3.2 Requirements of the Lifting Process. Like many designers do, here we also first define requirements before we analyze the different solutions for the lifting process. Some of the requirements are based on the authors engineering judgment and are consequently to some degree subjective. However, this is a necessity when requirements are formulated and we believe that making requirements explicit serves for better understanding of the lifting process. We consider the following requirements as most important:

(1) The moving component must be caught and then securely connected to the crane. For orientation, in a configuration similar to the presented one (Fig. 2), movements in the order of 0–5 m double amplitude (that is the distance from minimum to maximum) in each direction (x, y, z) can be expected.
(2) The vessel's crew safety must be ensured. The component is not allowed to move unpredictably when personnel is in close distance. The operations for catching and attaching the lifting gear must be designed such that the involved personnel can remain at safe positions.
(3) The component's structural integrity must be preserved. The component is not allowed to hit anything. Tuglines, winch systems, or other guiding equipment must prevent uncontrolled contact. When the component is in a safe distance, the installation vessel's winch system should take over the guiding function.
(4) An overloading of the crane must be prevented. The floating vessel's downward movement must not pull down the crane. Consequently, either the seafastening must be released before the component is connected to the crane or enough slack in the crane's rope must be provided. Peak loads due to the component's movement must not exceed the crane ultimate strength.
(5) The seafastening should allow a remotely controlled release of the component. The release mechanism must be reliable and quick. The timing of the release and the lifting operation should be synchronized.
(6) The lifting process should work at as many environmental conditions as possible. Important restricting conditions are the sea state with the variables significant wave height, H_s, and peak spectral period, T_p, as well as the wind speed, U. The direction of the phenomena, that is wave direction and wind direction, as well other environmental phenomena like current should be taken into account as well. Together the environmental variables constitute the environmental state, $(H_s, T_p, U, \ldots)$. The lifting process should be designed such that its region of allowable environmental states has a high probability of occurrence (Fig. 1(*b*); for further reading how the allowable environmental states and its boundary, the operational limits, could be determined, we refer to the work of Acero et al. [25], who proposed a methodology for assessing the allowable sea states during the installation of a transition piece). For orientation, we expect economic advantages over the all-in-one concept to require operational limits of roughly $H_s = 2$ m and a 10-min wind speed of $U_{10} = 12$ m s^{-1} (these values have been used in an economic simulation by Oelker et al. [17]).
(7) The lifting process should be finished in as little time as possible. For orientation, the complete lifting operation is expected to be finished in about 60 min (blade) or 180 min (tower or nacelle; assumptions by Oelker et al. [17]).
(8) Any lifting gear should be applicable to as many different components as possible.
(9) Any transport frame and seafastening should be applicable to as many different components as possible.

These requirements guided the design of the function-structure and at the end of this paper the discussion of the various solutions.

3.3 Function Structure: Overall Function and Subfunctions. The process' overall function is to *lift a component from a floating vessel* (Fig. 3, top). At the beginning of the process the component is fixed to the vessel, which is the input state of the function, and at the end the component is lifted off the vessel, which is the output state of the function. Further, the process uses energy and signal. For example, the crane needs energy as a power supply and a signal to control the position of the hook. However, in the function–structure we did not consider energy and signal, because we saw them as auxiliary flows and do not want to go into the details on how the process can be supplied with power (energy flow) and can be controlled (signal flow). Instead, we concentrate on the material flow, the transport of the component, which we consider to be the main flow of the process.

We decided to split the process' overall function *lift a component from a floating vessel* into five subfunctions (Fig. 3, bottom):

(1) Release closure between component and vessel,
(2) connect component and crane,
(3) compensate component's motion relative to an earth-fixed coordinate system,
(4) reduce peak loads on the crane, and
(5) pull the crane's rope.

Of these, we considered *reduce peak loads on the crane* and *compensate component's motion relative to an earth-fixed coordinate system* as auxiliary functions and the rest as main functions. One can perform a lifting operation without compensating the component's motion on the vessel and without reducing peak loads on the crane. However, then limitations increase. In that case, the process might only work for low-weight components at low sea states. Consequently, we defined these functions to be auxiliary.

The subfunction *pull the crane's rope* is fulfilled by the crane and is consequently not considered in this paper. This left us four remaining functions to classify the solutions: the two main functions *release closure between component and vessel* and *connect component and crane* plus the two auxiliary functions *compensate component's motion* and *reduce peak loads on the crane*.

4 Current Solutions

Based on our classification scheme, we differentiated 18 solutions, which fulfill either one or multiple different subfunctions to lift a component from a floating vessel (Fig. 4(*b*)). We identified seven solutions to release the closure between the component and the vessel, seven solutions to connect the component and the crane, three solutions to reduce peak loads on the crane and one solution to compensate the component's motion relative to an earth-fixed coordinate system (Tables 1–3) [33–60]. Most of the solutions we found were documented in patents (22 sources), some in the academic literature (seven sources) and two were not present in publicly available documents, but are state-of-the-art industrial practice (Fig. 4(*a*)).

In Secs. 4.1–4.4, we describe the solutions for each of these four subfunctions. After the presentation of these existing solutions, we point out, which problems are not solved yet and ask for future research and development.

4.1 Release Closure Between Component and Vessel. During the transport toward the wind farm, the components must be safely secured to the vessel such that the first step of the lifting

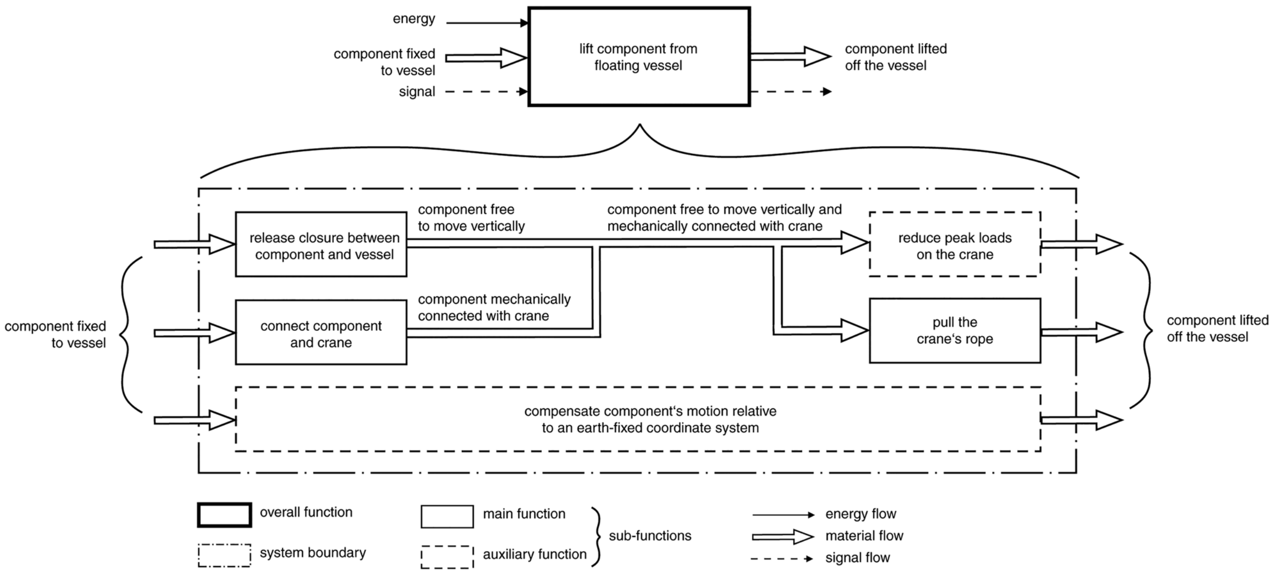

Fig. 3 Overall function (top) and function structure with several subfunctions (bottom) of the lifting process. For simplicity, in the function structure only the main flow, the material flow dealing with the component, is shown.

process is to release the closure between component and vessel. Often the components are connected to the vessel via various forms of transport frames or grillages. Grillages are used to place the tower section and the nacelle on top of it. They serve as structural load distributing elements and therefore avoid excessive local loads [29]. Rotor blades, on the other hand, are usually transported with two transport frames per blade. A root frame supports the root and a tip frame supports the blade at a position close to the tip. Examples for such arrangements are described in the patents by Lieberknecht et al. [41] and Steck and Singer [36]. Based on our classification scheme, we identified seven different solutions to release the closure between a component and the feeder vessel.

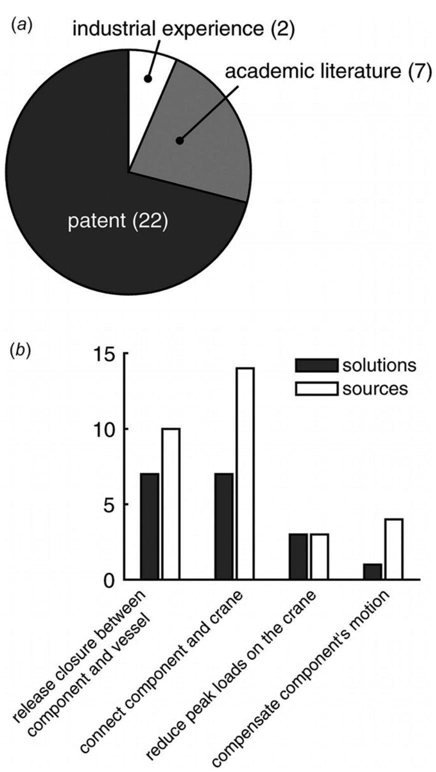

Fig. 4 Overview about the analyzed sources (*a*) and identified solutions (*b*). We analyzed 31 sources and found 18 conceptually different solutions.

A simple solution to fix a tower segment to the vessel is to have a bolted connection between the grillage and the tower segment (S_1; Fig. 5). In that case, several bolts run through the clearance holes of the tower segment's flange and are secured with nuts. When the connection should be released, the bolts have to be loosened manually by unscrewing the nuts. Besides the tower, such a bolted connection can be used for the nacelle as well.

Alternatively, a flange-clamping locking device can be used for the tower (S_2; Fig. 5). One embodiment of such a device is described by Behr's patent [33]. The patented device is a simple assembly. A bolt is used to hold the device via a clearance hole at a fixed position at the grillage and a locking component ensures the connection with the tower segment's flange. Several of these devices are used along the flange such that a form-closed connection is established. To release the tower the locking devices must be manually opened by loosening the bolts.

There exist also release solutions, which can be actuated remotely. Hoeksema [34] discusses several hydraulic seafastening solutions for transition pieces, which are transported vertically, on a sketch level. Some of his solutions clamp a flange. These hydraulic flange-clamping seafastenings could be used for standing tower segments as well (S_3; Fig. 5). Possibly the simplest embodiment of a flange-clamping seafastening is an array of vertical jacks, which press the flange toward the transport frame. Other embodiments are wedge-shaped clamps and rotating clamps [34]. The hydraulic seafastening could be activated remotely to release the tower segment.

Another solution, which can be remotely controlled, represents an alternative to the simple bolted connection (S_1), where the bolts are secured with nuts. The patent by Jepsen et al. [35] describes remotely controlled bolt tensioners (S_4; Fig. 5). This solution applies to a vertically positioned tower segment, which is placed on top of a transport frame. Several bolts run through the tower segment's flange and connect it with the transport frame. On the top side of the flange sit several bolt tensioners, one tensioner for each bolt. Depending on the particular version, the bolt tensioners can be actuated electrically, hydraulically or pneumatically and a corresponding power supply sits in the center of the tower segment. To release the connection, all bolt tensioners can be activated remotely to simultaneously loosen the bolts.

Possibly the simplest solution to release the closure between the component and the vessel is to not secure the component

Table 1 Solutions addressing the subfunction *release the closure between the component and the vessel*

Addressed subfunction	Solution	Applicable interfaces
Release closure between component and vessel (the transport frame or grillage remains on the vessel)	S_1: *bolted connection between component and grillage:* ⟨the component is bolted to a grillage, which is welded to the vessel⟩ manually loosen bolts, which connect the component with the grillage	Vessel-tower, vessel-nacelle
	S_2: *flange-clamping locking device:* ⟨the tower segment is either positioned horizontally and supported at its two ends with two transport frames or transported vertically and connected at the lower side to a transport frame, the tower's flange is connected to the transport frame via a special securing element, which is fastened by manually fastening a bolt [33]⟩ open locking device by manually loosening a bolt	Vessel-tower, vessel-nacelle[a]
	S_3: *hydraulic flange-clamping seafastening:* ⟨the tower segment is positioned vertically on top of a transport frame, a hydraulic system presses on the top side of the tower segment's flange⟩ the hydraulic systems releases the clamping when a signal activates it to do so (described for a transition piece by Hoeksema [34])	Vessel-tower[a], vessel-nacelle[a]
	S_4: *remotely controlled bolt tensioners:* ⟨the tower segment is positioned vertically on top of a transport frame, a high number of bolts connect the tower segment's flange with the transport frame, the bolts are not secured with a nut, but with bolt tensioners [35]⟩ the bolts get loosened when a signal activates the bolt tensioners to do so	Vessel-tower, vessel-nacelle[a]
	S_5: *gravity-based connection:* ⟨the blade is positioned horizontally and supported by two transport frames, the connections between the blade and the frames are based on frictional forces due to gravity [36]⟩ no closure has to be released	Vessel-blade
Release closure between component and vessel (the transport frame is lifted off the vessel too)	S_6: *twist-locks between vessel and transport frame: tower segment:* ⟨the tower segment is either positioned horizontally and supported at its two ends with two transport frames [33,37] or transported vertically and connected at the lower side to a transport frame [33,38,39], the transport frames are connected releasable with heavy-duty twist-locks to the vessel's deck [33,37–39]⟩ *blade:* ⟨the blade is held in transport frames, the blade will be lifted off together with the transport frame, the transport frames are connected releasable with twist-locks to the vessel's deck [40]⟩ open twist-locks	Vessel-tower, vessel-blade, vessel-nacelle[a]
	S_7: *locking pins* ⟨the blade is positioned horizontally and supported by two transport frames, close to the tip an airfoil clamp provides the connection between frame and blade, at the root end the blade is supported by a counterpart providing a gravity-based connection, both transport frames are connected via locking pins to the vessel's deck or to the transport frames below them [41]⟩ manually pull out the locking pin	Vessel-blade

[a]Not mentioned in the source, but should be applicable with minor adaptations.
Note: The situation before the closure is released is described between angled brackets.

Table 2 Solutions addressing the subfunction *connect the component and the crane*

Addressed subfunction	Solution	Applicable interfaces
Connect component and crane	S_8: *bolted connection between tower and lifting gear*: either a lifting beam or multiple lifting brackets [42–44] are bolted to the tower segment's flange as an assembly to provide a lifting point, in the lifting operation a sling, shackle or hook connects with the lifting point	Tower-crane
	S_9: *flange-clamping lifting tool*: a lifting tool with movable parts is inserted into the tower segment, then the parts are moved such that a form-closed connection with the flange is ensured, various forms exist which can be characterized as *beam-based* [45] *hand-shaped* [46–48], or *internal lifting tool* [49–51]	Tower-crane
	S_{10}: *external lifting tool*: the tower is gripped at its cylindrical outer surface, hydraulic clamping ensures a friction-locked connection	Tower-crane
	S_{11}: *connect to nacelle's integrated lifting points:* the nacelle is designed to have several integrated lifting points on its top, in the lifting operation a sling, shackle or hook connects with the lifting point	Nacelle-crane
	S_{12}: *hub gripper:* the hub gripper's connection interface is inserted into one of the blade bearings, the connection interface has a geometry corresponding to the geometry of a root of a blade, the interface is connected to the blade bearing of the hub in the same way the blade would be connected to the hub, the hub can be rotated with respect to the hub gripper [52]	Hub-crane
	S_{13}: *connect to blade's transport frame:* the transport frames has integrated lifting points such that during the lifting operation a sling, shackle or hook connects with the lifting point [41,53]	Blade-crane
	S_{14}: *grip blade directly:* the lifting gear is designed together with the transport frame, the lifting gear can slide up and down on the transport frame and lifts the blade without the transport frame, the lifting gear connects to the blade at two positions: a belt supports the blade at its root section and another belt at a position close to the blade's tip [36]	Blade-crane

Table 3 Solutions addressing the subfunction *reduce peak loads on the crane* and *compensate the component's motion*

Addressed subfunction	Solution	Applicable interfaces
Reduce peak loads on the crane	S_{15}: *passive heave compensation system*: gas and liquid tanks together act as a spring-damper system, the spring and damping properties can be actively changed with valves [54]	Tower-crane, nacelle-crane, blade-crane
	S_{16}: *active heave compensation system*: the hook's vertical position is actively controlled using a hydraulic actuator, movements are amplified by a winch system, the hook can follow the component's movement, described for subsea operations by Southerland [55]	Tower-crane, nacelle-crane, blade-crane
	S_{17}: *active-passive hybrid heave compensation system*: integrated combination of S_{15} and S_{16}, gas and liquid tanks act as a passive heave compensation system, a hydraulic actuator, which movements are amplified by a winch system provides closed-loop control, the hook can follow the component's movement, described for subsea operations by Hatleskog and Dunningan [56]	Tower-crane, nacelle-crane, blade-crane
Compensate component's motion	S_{18}: *active motion compensation platform*: the component's motion is compensated relative to an earth-fixed coordinate system using multiple hydraulic units, which stabilize a platform [57–60]	Vessel-tower, vessel-nacelle, vessel-blade

vertically at first hand (S_5; Fig. 5). In that case, the connection is gravity-based and solely depends on the frictional forces between the component and the transport frame. Steck and Singer's patent [36] describes special transport frames for the blade. These frames provide support structures, which correspond to the geometry of the blade. One support structure holds the blade at the root and one support structure holds it close to its tip.

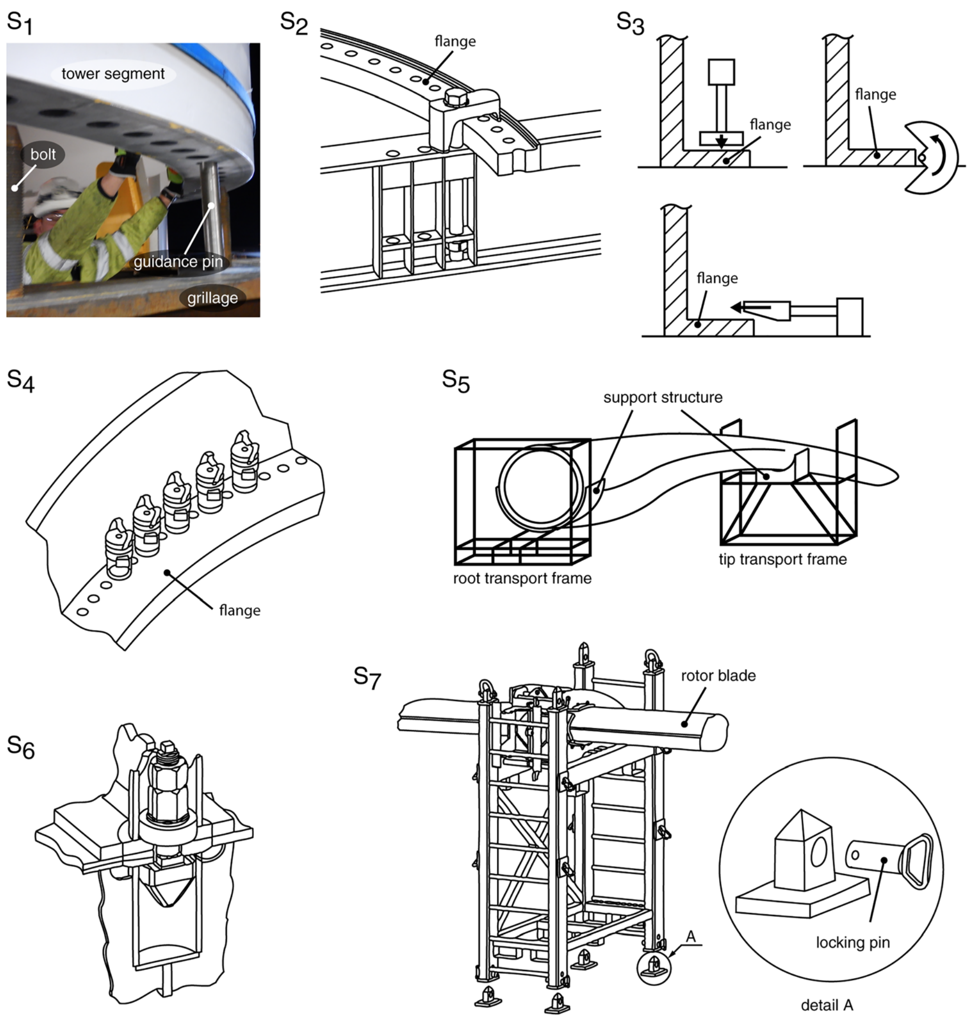

Fig. 5 Solutions to release the closure between the component and the vessel. S_1: The solution "bolted connection between component and grillage" is currently widely used in the industrial practice. S_2: A flange-clamping locking device (adapted from Ref. [33]). S_3: Three embodiments of hydraulic flange-clamping locking devices (adapted from Ref. [34]). S_4: Remotely controlled bolt tensioners (adapted from Ref. [35]). S_5: A gravity-based connection. S_6: Twist-locks between the vessel and the transport frame (adapted from Ref. [39]). S_7: Locking pins (adapted from Ref. [41]).

In the solutions described so far, the connection between the component and the transport frame is released, such that the transport frame (or grillage) remains on the feeder vessel. However, alternatively, the component can be lifted together with the transport frame. In that case, the connection between the transport frame and the vessel's deck must be released. In our research, we found two solutions for such a configuration.

A well-known connection mechanism to transport goods on a vessel are twist-locks. Twist-locks can be used to connect a transport frame with the vessel (S_6; Fig. 5). Several patents [33,37–39] describe this option. While standard twist-locks, which are used to secure containers, might be too weak to secure some wind turbine components, Behr's patent [39] describes a heavy-duty twist-lock specifically designed for the transport of wind turbine components. We found patents describing the use of twist-locks in conjunction with the horizontal transport of tower segments [33,37], the vertical transport of tower segments [33,38,39], and the transport of rotor blades in transport frames [41].

Another solution to connect the transport frames of rotor blades with the vessel is the use of locking pins (S_7; Fig. 5). The patent by Lieberknecht et al. [41] describes special transport frames, which can be fixed to the vessel's deck via a locking mechanism secured with locking pins. Additionally, the transport frames can be stacked. Then the connection between two transport frames is ensured via locking pins. To release the connection in this solution, the locking pins must be manually pulled out of their clearance holes.

In summary, most of the found solutions require personnel to manually release the seafastening (S_1, S_2, S_6, S_7). We also found two remotely controlled systems (S_3, S_4). However, they are specific for the tower segment and interact with its flange. These solutions could possibly be adapted to work with the nacelle's flange, but they are not applicable to secure and release rotor blades.

4.2 Connect Component and Crane.

There exist very different solutions to connect a component with the crane. They range from lifting tools, which are specifically designed for one particular version of a component, to using extremely generic lifting gear. An interesting consideration, when a solution to connect the component to the crane is designed, is whether special lifting devices should be added as an assembly to the component. Such components can strongly enhance the lifting process, but they have to be removed afterward, which is an additional process step.

One such solution, which is widely used, is to have a bolted connection between the tower and the lifting gear (S_8; Fig. 6). In that case, either a lifting beam or multiple lifting brackets are bolted to the tower segment's flange as an assembly. The lifting beam or lifting brackets then provide lifting points, which allow an easy connection to the crane via slings, shackles, or hooks. We found three patents describing lifting brackets specifically designed for the wind turbine tower [42–44]. After the lifting process, the bolted connection between the tower segment and the lifting beam or the lifting bracket has to be manually loosened.

A solution, which does not need any extra parts assembled to the tower segment, is a flange-clamping lifting tool (S_9; Fig. 6). Such a lifting tool comprises movable parts, which are inserted into the tower segment. Then, the parts are moved such that a form-closed connection with the flange is established. There exist

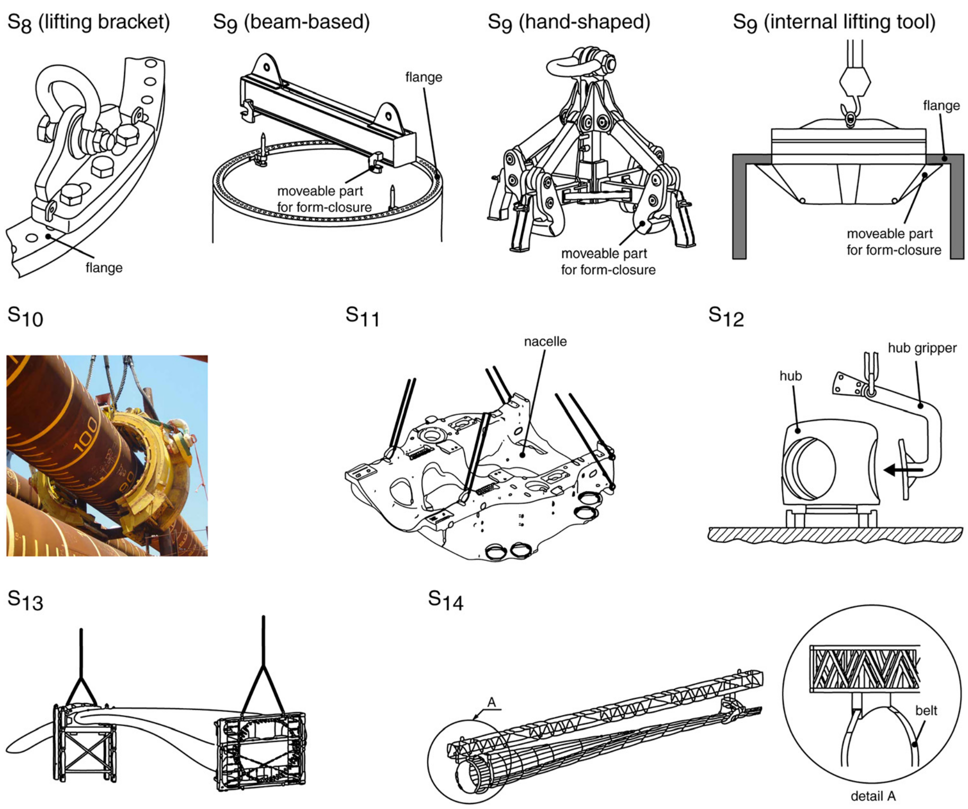

Fig. 6 Solutions to connect the component and the crane. S_8: Bolted connection between tower and lifting gear, embodied as a lifting bracket (adapted from Ref. [42]). S_9: Flange-clamping lifting tools in different embodiments. The solution can be embodied as a beam-based configuration (adapted from Ref. [45]), as a hand-shaped configuration (adapted from Ref. [46]), or as an internal lifting tool (adapted from Ref. [49]). S_{10}: External lifting tool (image kindly provided by IHC IQIP). S_{11}: The solution to "connect to the nacelle's integrated lifting points" is the current industrial practice. S_{12}: A hub gripper (adapted from Ref. [52]). S_{13}: Solution "connect to the blade's transport frame" (adapted from Ref. [41]),. S_{14}: An embodiment of the solution "grip blade directly" (adapted from Ref. [36]).

several different embodiments, which can be characterized as beam-based [45], hand-shaped [46–48], or internal lifting tool [49–51]. While most of the flange-clamping lifting tools use a hydraulic energy supply, we also found a patent of a hand-shaped tool [46]. This tool does not require an energy supply, but works via a passive mechanism controlled by applying force to the tool's top connection point.

In opposite to solution S_9, which makes use of the tower segment's flange and consequently must engage there, a so-called external lifting tool (S_{10}; Fig. 6) can grip a tower segment anywhere at its outer cylindrical surface. External lifting tools are hydraulically actuated and provide a friction-based connection by clamping the tower segment.

The nacelle is usually lifted via integrated lifting points on its top side (S_{11}; Fig. 6). These lifting points provide the interface to connect to it via slings, shackles or hooks. That way the nacelle can be lifted as a subassembly with the hub.

Alternatively, a hub-gripper can be used to provide the connection (S_{12}; Fig. 6). This special device is described in Falkenberg's patent [52]. To establish a connection, the hub gripper's connection interface is inserted into one of the hub's blade bearings. The connection interface has a geometry corresponding to the geometry of the root of a blade. Consequently, it is connected in the same way the blade would be mounted to the hub. By making use of the hub's pitch mechanism, the hub gripper can be used to rotate the hub, which can be advantageous in the installation process.

For the rotor blade two principal solutions can be differentiated. Either the blade remains in its transport frame and a connection between crane and transport frame is established (S_{13}; Fig. 6) or the blade is gripped directly (S_{14}; Fig. 6). In the former solution (S_{13}), the transport frame can be designed to have integrated lifting points [41,53]. Then, slings, shackles, or hooks can be used to provide a connection in a standard way. If the blade is gripped directly, however, there are no lifting points to engage with and consequently special handling devices are necessary to grip the blade. The patent by Steck and Singer [36] (S_{14}) describes equipment designed to grip the blade directly. In their patent the lifting gear is designed together with two transport frames such that the lifting gear can be positioned precisely relative to the rotor blade. The lifting gear grips the blade at two positions: a belt supports the blade at its root section and another belt holds it at a position close to its tip.

In summary, we found a diverse set of solutions to connect a wind turbine component with the crane. Each of these solutions is specifically designed for one particular component. Concerning the tower, we found bolted connections (S_8), flange-clamping lifting tools (S_9), and external lifting tools (S_{10}). The nacelle is usually lifted by using its integrated lifting points (S_{11}). Alternatively, it can be carried by a hubgripper (S_{12}). Rotor blades can be lifted in two principally different ways: either the blade is lifted with the help of a transport frame (S_{13}) or the blade is gripped directly (S_{14}).

4.3 Reduce Peak Loads. During the lifting process, an overloading of the crane must be prevented. Peak loads, which can occur during the initial take-off phase of the lifting process, are especially dangerous. Consequently, we added *reduce peak loads on the crane* as an auxiliary subfunction of the lifting process. Solutions, which address this subfunction, are heave compensation systems (S_{15}–S_{17}; Fig. 7). These are mechanical devices, which decouple the vertical motion between the load and the crane. Heave compensation systems are positioned between the component and the crane's hook (at the component-crane interface, Fig. 1). Based on whether the heave compensation systems use external energy, they can be divided into passive heave compensation system, active heave compensation system and active-passive hybrid heave compensation system [32,61].

While heave compensation systems were originally developed to reduce the effects of a heaving vessel on a suspended object, which should be stabilized, they also work the other way around:

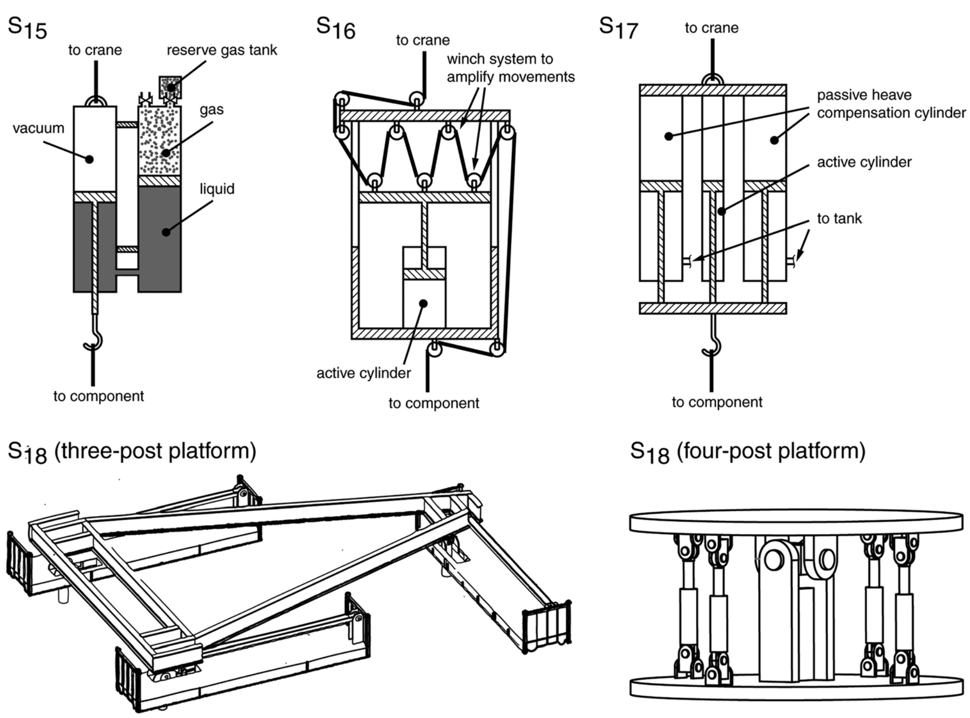

Fig. 7 Solutions to reduce peak loads on the crane and to compensate the component's motion. S_{15}: Passive heave compensation system (adapted from Ref. [54]). S_{16}: Active heavy compensation system. S_{17}: Active-passive hybrid heave compensation system (adapted from Ref. [61]). S_{18}: Active motion compensation platform, embodied as a three-post platform (adapted from Ref. [57]) and embodied as a four-post platform (graphic kindly provided by Shenghai Wang).

to reduce peak loads of a vertically moving object on a statically placed crane as it is the case in the feeder ship concept. This becomes clear if one sees a heave compensator as a dynamical system, which has a transfer function associated with it. The recommended practices DNV-RP-H103 [32] give a simplified dynamical model comprising mass, spring and damping terms. The model can be used to analyze the system using methods from the general shock and vibration literature (see, for example, Ref. [62]). Since simple spring and damper models do not have a preferred direction, reducing the effects of the load on the crane works similarly as reducing the effects of the crane on the load.

A passive heave compensation system (S_{15}; Fig. 7) is the simplest version of the three. It comprises one or several gas and liquid tanks, which together act as a spring-damper system. By tuning the spring to be sufficiently soft, peak forces caused by the component are reduced by the device. One embodiment of such a device is described in the patent by Bergem et al. [54]. In their patent, the heave compensator's spring-damper properties can be changed with valves. These valves are actuated electrically. Passive heave compensation systems are open-loop, they cannot be controlled to move differently than what the properties of the spring-damper system determine.

In opposite to that, active heave compensation systems (S_{16}; Fig. 7) allow closed-loop control. In the device described by Southerland [55], a hydraulic actuator is used to control the movement of the device. The actuator's movements are amplified by a winch system. Southerland's heave compensation system, however, is designed to stabilize a load suspended from a vessel. Consequently, control schemes to reduce peak loads, which are caused by the load, are not described in the publication.

It can be advantageous to combine the properties of a passive and an active heave compensation system. Such a combination is realized in a so-called active-passive hybrid heave compensation system (S_{17}; Fig. 7). Consequently, such a system has gas and liquid tanks, which act not only as a passive heave compensation system but also an active part based on a hydraulic actuator plus a winch-system to amplify the movements. Hatleskog and Dunningan [56] describe such a system, which is designed for subsea operations.

4.4 Compensate the Component's Motion.

As described, the main cause for the difficulties of lifting wind turbine components from a floating vessel are the strong movements of the component's lifting points. Consequently, solutions, which can compensate the component's motion to an earth-fixed coordinate system, enhance the complete lifting process. If the component's motion is reduced, connecting the component and the crane will become easier. Further, a component that moves less causes smaller peak loads.

While in principle one could imagine various solutions to reduce the motion of a component, we only found one solution, which addresses motion compensation for the heavy wind turbine components: an active motion compensation platform (S_{18}; Fig. 7) that comprises multiple hydraulic units to stabilize a platform relative to an earth-fixed coordinate-system.

Koppert's patent from 2012 [57] describes an embodiment of an active motion compensation platform with three hydraulic cylinders. Therefore, researchers refer to it as a three-post (direct ship motion compensation) platform [59]. It is designed to compensate heave, roll, and pitch motion. A numerical and an experimental study showed that one embodiment of a three-post platform, a product called Barge Master, can reduce more than 90% of the motions that the barge on which the platform was based on exhibited [58]. In that study, the motion reduction was defined by dividing the standard deviation of the platform's motion by the standard deviation of the barge's motion. The platform can withstand payloads of up to 700×10^3 kg [58], which is enough to support any component of a current wind turbine design.

Another embodiment of an active motion compensation platform is described by Wang et al. [59,60]. They propose a design with four hydraulic cylinders and call it four-post combined compensation. By itself, their four-post platform can compensate only pitch and roll motions. However, the platform is designed to place an offshore crane on top of it and the authors proposed to compensate heave motion with the crane's winch. In the lifting process of the considered feeder ship concept (Fig. 1), however, heave compensation would be missing, because the crane of the jack-up vessel is used. On the other hand, the four-post platform has the advantage that it requires less maximum actuator forces compared to the three-post platform [59]. Consequently, it can possibly support even higher loads than the three-post platform's 700×10^3 kg.

5 Discussion

5.1 Practical Implementation: Open Problems and Suggestions for Future Development.

Here, we were able to identify subsolutions for all subfunctions of the lifting process. We even found an almost overwhelming amount of existing solutions for the function *release the closure between the component and the vessel* as well as the function *connect the component and the crane*. This is not surprising as offshore wind farms are being erected since more than a decade now. However, the fact that various solutions exist, which address each subfunction, does not mean that an overall satisfactory solution can be found by combining the found subfunctions.

In particular, one requirement we formulated, is that the seafastening should be remotely controlled and synchronized with the lifting operation. While we found hydraulic systems to secure and release components (S_3, S_4), these systems are specific to the tower segment and possibly the nacelle and they are not integrated into a central control process. Further, there is little data available that describes the properties of hydraulic seafastening systems. It remains unclear, how fast such a system can open and close as well as how control schemes to synchronize the vessel-releasing and crane-connecting could look like. Additionally, there seems to be little academic research on seafastening mechanisms. The rise of offshore wind energy and the ongoing pressure to reduce the levelized costs of electricity provide challenges for future research and development. Faster and safer lifting processes demand remotely controlled, fast and reliable seafastening solutions.

Another point for future development is interface versatility. As we wrote in the requirements, any transport frame, seafastening, and lifting gear should be applicable to as many different components as possible. Especially, the interface between the component and the crane would strongly benefit from increasing its versatility. All of the solutions we found only work for a single component (tower: S_8–S_{10}, nacelle + hub: S_{11}–S_{12}, blade: S_{13}–S_{14}). Changing lifting gears takes extra time during the installation process. Solutions, which work with multiple components, therefore offer important time-saving potential.

5.2 Academic Research: Limitations and Future Studies.

In this work, we summarized various solutions that we found in the academic literature and in patents. For some of these solutions, we do not know how widely they are used in the industrial practice. A future study could systematically analyze, which solutions are currently used in practice. This could be done by either conducting expert interviews or by a survey. Both methods should address practitioners working on the installation of offshore wind turbines. In addition, expert interviews could be conducted to find out why certain solutions are not used. Possibly, some solutions are worse than the current industrial state-of-the-art, while other solutions might hold a big potential, but need additional development to become marketable products.

Another interesting future study would be a numerical simulation of the dynamics of the lifting process. To conduct this study, first, one would combine the presented subsolutions into a promising overall solution. Then, one could use multibody simulations and computational fluid mechanics to determine the operational limits and the process times.

6 Conclusions

By dissecting the complex lifting process into its subfunctions, we were able to find solutions for each of the functions. Especially for the two main functions, *release the closure between the component and the vessel* and *connect the component and the crane*, we found a multitude of solutions. However, most of the solutions for the seafastening and the crane-connection only work with a single component. Further, it is not clear yet, how the release of the seafastening is best synchronized with the lifting operation. We argue that more versatile interfaces between the components and the crane as well as remotely controlled and synchronized seafastening mechanisms are best suited to enhance the lifting process.

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Nomenclature

Grillage = structural load distributing elements installed to avoid excessive local loads (exact wording from DNV-OS-H202 [29])

Lifting gear = load carrying accessories used in combination with a lifting appliance, however, that are not necessarily a part of the permanent arrangement of the lifting appliance, such as attachment rings, shackles, swivels, balls, pins, sheaves, hook-blocks, hooks, load cells, or loose gear (adapted wording from DNVGL-ST-0378 [63])

Lifting points = attachment points for slings on the lifted object. Lifting points are normally designed as padeyes or trunnions/padears (adapted wording from DNV-OS-H205 [64])

Seafastening = structural elements providing horizontal and uplift support of an object during sea transport operations (exact wording from DNV-OS-H202 [29])

References

[1] Esteban, M. D., Diez, J. J., López, J. S., and Negro, V., 2011, "Why Offshore Wind Energy?," Renewable Energy, **36**(2), pp. 444–450.

[2] GWEC, 2017, "Global Wind 2016 Report: Annual Market Update," Global Wind Energy Council, Brussels, Belgium, Report.

[3] IEC, 2009, "Wind Turbines—Part 3: Design Requirements for Offshore Wind Turbines," International Electrotechnical Commission, Geneva, Switzerland, Report No. IEC 61400-3:2009-02.

[4] Sarkar, A., and Gudmestad, O. T., 2013, "Study on a New Method for Installing a Monopile and a Fully Integrated Offshore Wind Turbine Structure," Mar. Struct., **33**, pp. 160–187.

[5] Ahn, D., Shin, S. C., Kim, S. Y., Kharoufi, H., and Kim, H. C., 2017, "Comparative Evaluation of Different Offshore Wind Turbine Installation Vessels for Korean Westsouth Wind Farm," Int. J. Nav. Archit. Ocean Eng., **9**(1), pp. 45–54.

[6] Seidel, M., and Gosch, D., 2006, "Technical Challenges and Their Solution for the Beatrice Windfarm Demonstrator Project in 45M Water Depth," Eighth German Wind Energy Conference (DEWEK 2006), Bremen, Germany, accessed Nov. 22–23.

[7] Wåsjø, K., Bermúdez-Rico, J. V., Bjerkås, M., and Søreide, T., 2013, "A Novel Concept for Self Installing Offshore Wind Turbines," ASME Paper No. OMAE2013-11439.

[8] Ku, N., and Roh, M.-I., 2015, "Dynamic Response Simulation of an Offshore Wind Turbine Suspended by a Floating Crane," Ships Offshore Struct., **10**(6), pp. 621–634.

[9] Acero, W. I. G., 2016, "Assessment of Marine Operations for Offshore Wind Turbine Installation With Emphasis on Response-Based Operational Limits," Ph.D. thesis, Norwegian University of Science and Technology, Trondheim, Norway.

[10] Sarker, B. R., and Faiz, T. I., 2017, "Minimizing Transportation and Installation Costs for Turbines in Offshore Wind Farms," Renewable Energy, **101**, pp. 667–679.

[11] Muhabie, Y. T., Caprace, J.-D., Petcu, C., and Rigo, P., 2015, "Improving the Installation of Offshore Wind Farms by the Use of Discrete Event Simulation," World Maritime Technology Conference (WMTC), Providence, RI, Nov. 3–7, pp. 1–10.

[12] Vis, I. F., and Ursavas, E., 2016, "Assessment Approaches to Logistics for Offshore Wind Energy Installation," Sustainable Energy Technol. Assess., **14**, pp. 80–91.

[13] The European Wind Energy Association, 2009, "Oceans of Opportunity: Harnessing Europe's Largest Domestic Energy Resource," European Wind Energy Association, accessed Jan. 2, 2019, http://psew.pl/en/wp-content/uploads/sites/2/2017/01/6c1fd7949c499c04e829cfbdbbdb79e1.pdf

[14] Oelker, S., Lewandowski, M., Ait Alla, A., Ohlendorf, J.-H., and Haselsteiner, A. F., 2017, "Logistikszenarien für die Errichtung von Offshore-Windparks: Herausforderungen der Wirtschaftlichkeitsbetrachtung neuer Logistikkonzepte," Industrie 4.0 Management, Vol. 33, pp. 24–28.

[15] Ait Alla, A., Oelker, S., Lewandowski, M., Freitag, M., and Thoben, K.-D., 2017, "A Study of New installation concepts of Offshore Wind Farms by Means of Simulation Model," 27th International Ocean and Polar Engineering Conference (ISOPE 2017), San Francisco, CA, June 25–30, pp. 607–612.

[16] Meyer, M., 2014, "Reeder von Offshore-Spezialtonnage müssen spekulativer vorgehen," Hansa Int. Maritime J., **151**(10), pp. 54–55.

[17] Oelker, S., Ait-Alla, A., Lütjen, M., Lewandowski, M., Freitag, M., and Thoben, K.-D., 2018, "A Simulation Study of Feeder-Based Installation Concepts for Offshore Wind Farms," 28th International Ocean and Polar Engineering Conference (ISOPE 2018), Sapporo, Japan, June 10–15, pp. 578–583.

[18] Gille, D., 2018, "Offshore-Kosten sparen: Windparkfütterung," Schlütersche Verwaltungsgesellschaft mbH, Hannover, Germany.

[19] Van Oord, 2016, "Svanen Installs Foundations for the Burbo Bank Extension Offshore Wind Farm," Van Oord, Rotterdam, The Netherlands, accessed Mar. 6, 2018, https://www.vanoord.com/activities/sustainable-energy-united-kingdom

[20] E.ON SE, 2017, "Construction Begins for the Arkona Offshore Wind Project in the Baltic Sea," E.ON SE, Essen, Germany, Jan. 2, 2019, https://www.eon.com/en/about-us/media/press-release/2017/construction-begins-for-the-arkona-offshore-wind-project-in-the-baltic-sea.html

[21] OffshoreWIND.biz, 2015, "Blue Water Backs Baltic 2 Jacket Foundation Work," Navingo BV, Schiedam, The Netherlands, accessed Jan. 2, 2019, https://www.offshorewind.biz/2015/03/17/blue-water-backs-baltic-2-jacket-foundation-work

[22] Kaiser, M. J., and Snyder, B. F., 2013, "Modeling Offshore Wind Installation Costs on the U.S. Outer Continental Shelf," Renewable Energy, **50**, pp. 676–691.

[23] Ait Alla, A., Quandt, M., and Lütjen, M., 2013, "Simulation-Based Aggregate Installation Planning of Offshore Wind Farms," Int. J. Energy, **7**(2), pp. 23–30.

[24] Jeong, D.-H., Roh, M.-I., and Ham, S.-H., 2016, "Lifting Simulation of an Offshore Supply Vessel Considering Various Operating Conditions," Adv. Mech. Eng., **8**(6), pp. 1–13.

[25] Acero, W. G., Gao, Z., and Moan, T., 2017, "Numerical Study of a Novel Procedure for Installing the Tower and Rotor Nacelle Assembly of Offshore Wind Turbines Based on the Inverted Pendulum Principle," J. Mar. Sci. Appl., **16**(3), pp. 243–260.

[26] Jiang, Z., Gao, Z., Ren, Z., Li, Y., and Duan, L., 2018, "A Parametric Study on the Final Blade Installation Process for Monopile Wind Turbines Under Rough Environmental Conditions," Eng. Struct., **172**, pp. 1042–1056.

[27] Haselsteiner, A. F., Ohlendorf, J.-H., Oelker, S., Ströer, L., Thoben, K.-D., Wiedemann, K., De Ridder, E., and Lehmann, S., 2018, "Lifting Wind Turbine Components From a Floating Vessel: A Review on Current Solutions and Open Problems," ASME Paper No. OMAE2018-78659.

[28] Pahl, G., and Beitz, W., 1996, *Engineering Design: A Systematic Approach*, Springer, London.

[29] DNV GL, 2015, "Sea Transport Operations (VMA Standard—Part 2-2)," DNV GL, Standard No. DNV-OS-H202.

[30] ShipBuilding Industry, 2012, "Jaguar: Simply Unconventional," ShipBuilding Ind., **6**(4), pp. 46–51.

[31] Ochi, M. K., 1973, "On Prediction of Extreme Values," J. Ship Res., **17**(1), pp. 29–37.

[32] Det Norske Veritas, 2011, "Recommended Practice: Modelling and Analysis of Marine Operations," Det Norske Veritas, accessed Jan. 2, 2019, https://rules.dnvgl.com/docs/pdf/DNV/codes/docs/2011-04/RP-H103.pdf

[33] Behr, C. P., 2012, "Sicherungselement und Transportrahmen für Elemente einer Windkraftanlage," European Patent No. 2444656A2.

[34] Hoeksema, W., 2014, "Innovative Solution for Seafastening Offshore Wind Turbine Transition Pieces During Transport," M.Sc. thesis, Delft University of Technology, Delft, The Netherlands.

[35] Jepsen, A. W., Moeller, J., and Svinth, K. H., 2016, "Method and Arrangement to Transport a Tower of a Wind Turbine on a Vessel," European Patent No. 3088735A1.

[36] Steck, C., and Singer, F., 2016, "System and Method for Transporting and Lifting a Rotor Blade of a Wind Turbine," European Patent No. 3101271A1.
[37] Wessel, T., and Scott, P., 2009, "System and Method for Transporting Wind Turbine Tower Sections on a Shipping Vessel," European Patent No. 2133558A2.
[38] Behr, C. P., 2012, "Befestigungssystem für den Transport einer schweren Last auf einer Transportoberfläche," European Patent No. 2540567A2.
[39] Behr, C. P., 2012, "Vorrichtung zum Sichern von schweren Lasten," European Patent No. 2423046A2.
[40] Krogh, M. V., and Poulsen, H., 2012, "Lifting System and Method for Lifting Rotor Blades of Wind Turbines," European Patent No. 2487363A1.
[41] Lieberknecht, K., Mastrup, A., Svinth, K. H., and Wieland, M. R., 2014,"Wind Turbine Blade Holding Arrangement," European Patent No. 2796709A1.
[42] Krogh, M. V., 2011, "Lifting Fitting," WIPO Patent No. WO2011009500A1.
[43] Franke, B., 2011, "Connection Bracket," U.S. Patent No. 2011252721A1.
[44] Alba, T. J., 2014, "Tower Erection Lift Kit Tools," U.S. Patent No. 2014042763A1.
[45] Behr, C. P., 2011, "Hubvorrichtung für Turmsegmente," WIPO Patent No. WO2011154110A1.
[46] Moeller, J., and Svinth, K. H., 2015, "Raising a Tower Segment," European Patent No. 2824057A1.
[47] Belder, C., and Mulderij, K.-J., 2012, "Clamping Device," WIPO Patent No. WO2012093940A1.
[48] Belder, C., and Zuijdgeest, Q. W. P. M., 2016, "Flange Lifting Tool," WIPO Patent No. WO2016184905A1.
[49] Spence, R., 2013, "Tower Section Lifting Apparatus," WIPO Patent No. WO2013027047A1.
[50] Mulderij, K.-J., 2014, "Pile Upending Device," WIPO Patent No. WO2014084738A1.
[51] Mulderij, K.-J., 2017, "Lifting Device for Picking Up a Member From the Bottom of the Sea," WIPO Patent No. WO2017013197A1.
[52] Falkenberg, P. L., 2013, " "Installation/Dismounting of a Hub to/From a Nacelle of a Wind Turbine by Using a Blade Pitch Angle Adjustment Device of the Hub for Orientating the Hub," European Patent No. 2653716A1.
[53] Krogh, M. V., and Pulsen, H., 2012, "Lifting System and Method for Lifting Rotor Blades of Wind Turbines," U.S. Patent No. 2012192420A1.
[54] Bergem, O., Sannes, S., and Helland, K., 2016, "Subsea Heave Compensator," European Patent No. 2982636A1.
[55] Southerland, A., 1970, "Mechanical Systems for Ocean Engineering," Nav. Eng. J., **82**(5), pp. 63–74.
[56] Hatleskog, J., and Dunnigan, M., 2007, "Active Heave Crown Compensation Sub-System," OCEANS 2007—Europe, Aberdeen, UK, June 18–21, pp. 1–6.
[57] Koppert, P. M., 2012, "Motion Compensation Device for Compensating a Carrier Frame on a Vessel for Water Motion," U.S. Patent No. US2012024214A1.
[58] Jaouen, F., van der Schaaf, H., van der Berge, J., May, E., and Koppenol, J., 2012, "How Does Barge-Master Compensate for the Barge Motions: Experimental and Numerical Study," ASME Paper No. OMAE2012-83045.
[59] Wang, S., Sun, Y., Chen, H., and Han, G., 2017, "Kinematics and Force Analysis of a Novel Offshore Crane Combined Compensation System," J. Eng. Maritime Environ., **231**(2), pp. 633–648.
[60] Wang, S., Sun, Y., Chen, H., and Du, J., 2018, "Dynamic Modelling and Analysis of 3-Axis Motion Compensated Offshore Cranes," Ships Offshore Struct., **13**(3), pp. 265–272.
[61] Woodacre, J. K., Bauer, R. J., and Irani, R. A., 2015, "A Review of Vertical Motion Heave Compensation Systems," Ocean Eng., **104**, pp. 140–154.
[62] Harris, C. M., and Crede, C. E., 1976, *Shock and Vibration Handbook*, 2nd ed., McGraw-Hill, New York.
[63] DNV GL, 2016, "Standard for Offshore and Platform Lifting Appliances," DNV GL, Standard No. DNVGL-ST-0378.
[64] Det Norske Veritas, 2014, "Lifting Operations (VMO Standard—Part 2-5)," Det Norske Veritas, Standard No. DNV-OS-H205.