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LIFTING WIND TURBINE COMPONENTS FROM A FLOATING VESSEL: A REVIEW ON CURRENT SOLUTIONS AND OPEN PROBLEMS

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ABSTRACT

Offshore wind energy is experiencing rapid development and is expected to make up an even bigger part of the worlds 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. While enhancements on the vessel and crane can help to achieve this goal as well, this paper only deals with 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 adaptations. Additionally, we miss hydraulic seafastening mechanisms, which are remotely controlled and synchronized with the lifting operation. Consequently, we argue that standardized interfaces between the component and the crane as well as remotely controlled and synchronized seafastening mechanisms are best suited to enhance the lifting process.

NOMENCLATURE

Grillage	”Structural load distributing elements installed to avoid excessive local loads” [1]
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

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	as: –attachment rings, shackles, swivels, balls, pins –sheaves, hook-blocks, hooks, load cells –loose gear." [2]
Lifting points	"The attachment points for slings on the lifted object. Lift point [sic] are normally designed as padeyes or trunnions/padears." [3]
Seafastening	"Structural elements providing horizontal and uplift support of an object during sea transport operations" [1]

INTRODUCTION

Offshore wind energy is experiencing rapid development and is expected to have a promising future [4]. In 2016 2,219 MW of offshore wind capacity was newly installed worldwide [5]. The new wind farms increased the global cumulative capacity to 14,384 MW, which is more than a 3-fold increase compared to 5 years earlier (4,117 MW in 2011) [5]. Despite the growth, the annual newly installed offshore capacity is still lacking behind onshore wind and the levelized cost of electricity (LCOE) 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 and foundation. The installation of an offshore wind farm typically happens in two steps. In the first step the wind turbine's foundation is installed and in the second step the actual turbine, sometimes referenced as the upper structure [6], is installed on top of the foundation. The installation of the upper structure can be realized with a variety of different concepts [6, 7]. 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. Different concepts can be analyzed via economic [8–11] and mechanical simulations [12–14]. While in some concepts the wind turbine is fully assembled onshore and transported in that state [15, 16], usually the wind turbine is split up in sub-assemblies and gets fully assembled at the wind farm site. The latter is sometimes called split installation procedure [12] and comprises a variety of specific sub-assembly arrangements, which have been used in the past. These different arrangements are summarized by Sarker and Faiz [17] and Ahn *et al.* [7]. The current practice is to either pre-assemble the hub and blades in the harbour (called rotor star [10] or star assy [7] method) or to transport the rotor blades individually while the hub is in a sub-assembly with the nacelle [7].

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 harbour 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 [18].

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 [11, 19, 20]. The feeder ship concept uses the jack-up vessel, which has a daily charter rate of EUR 70,000-140,000 [21], more economically and consequently offers cost-saving potential. While there is experience 'feeding' the foundation, with monopiles [22–24], transition pieces [23], jackets [25] 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 weather conditions as possible, that means even at sea states with high significant wave heights and consequently strong vessel movements.

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. As described, the components can be transported in different sub-assemblies. Different assembly groups and different deck layout ask for different lifting processes. 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.

SCOPE AND METHODS

This paper analyzes and classifies current solutions to lift the components tower (split into two tower segments), nacelle, hub and rotor blade from a floating vessel. It is restricted to solutions concerning the interface between the vessel and the component as well as the interface between the component and the crane (Figure 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. Solutions dealing with wind turbine foundations are considered out of scope as well. We set this restricted scope, because we want this paper to have a clear focus. The vessel and the crane are different products, which are often designed and owned by different companies than the wind turbine components. The installation of the foundation is a process, which is often handled by another company than the turbine installation.

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 currently used 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 solution into its sub-functions [26]. Sub-functions can be further divided into main functions and auxiliary functions [26]. Then, we used these sub-functions to classify different solutions of the lifting process. Classifying by sub-functions is recommended by Pahl and Beitz [26]. Further, we used the applicable interfaces of the solutions (e.g. vessel-tower or nacelle-crane) and the energy supply (e.g. hydraulic) as additional classifiers.

In the next section, 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. Lastly, we discuss the found solutions, point out open problems and suggest future developments.

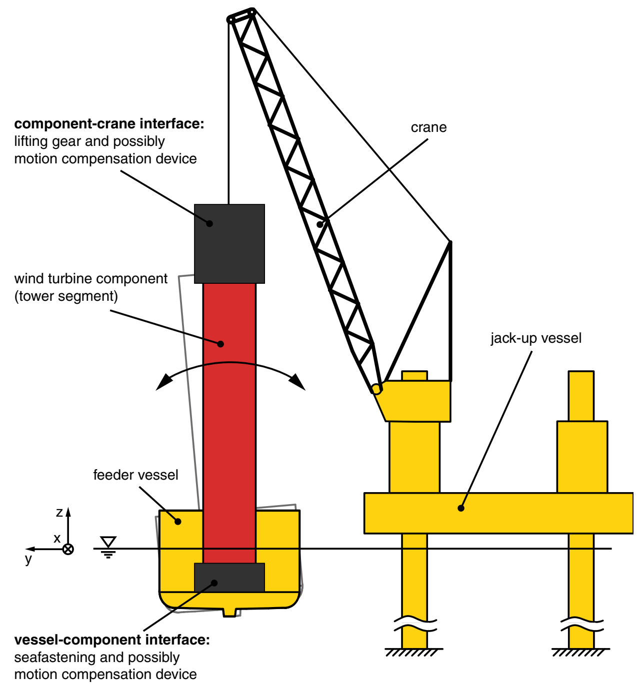

FIGURE 1. LIFTING PROCESS OF WIND TURBINE COMPONENTS FROM A FLOATING FEEDER VESSEL. THE TWO BLACK BOXES SHOW THE INTERFACES WHERE TECHNICAL SOLUTIONS CAN ENHANCE THE PROCESS.

LIFTING PROCESS

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 which are welded to the vessel. The standard DNV-OS-H202 [1] describes, how grillages and seafastenings should be designed. Typically the tower and 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 Figure 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 is owned by Amasus Offshore BV and has an overall length of 107.95 m and a beam of 16.00 m [27]. In this layout, the wind turbine is split into 6 sub-assemblies: 2 tower segments, the nacelle-hub assembly and 3 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 so-called most probable extreme value [28] is a useful statistical quantity to describe the maximum motions, which must be considered when mechanical devices and processes for the lifting operation are designed. In the presented deck layout of the Eems D vessel a hydrodynamic diffraction analysis showed that the tower segment's lifting points experience the highest motions (ANSYS Aqwa version 18.2, Ansys, USA). This was expected since the tower segment's lifting point is the farthest away from the vessel's center of gravity (Figure 2).

Requirements of the 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

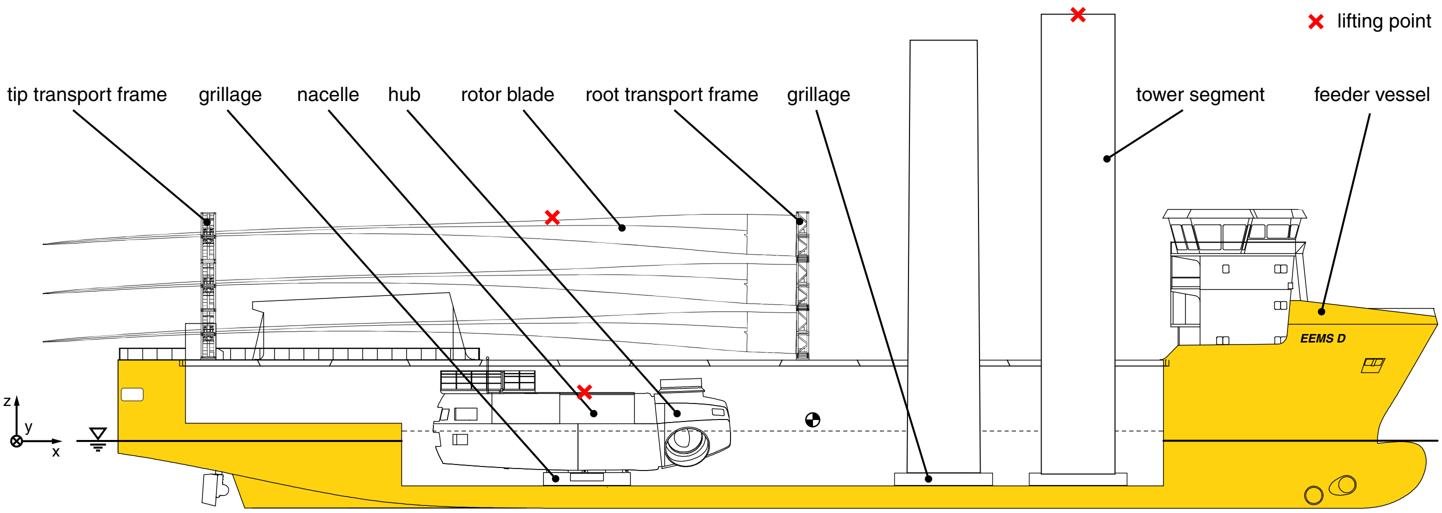

FIGURE 2. DECK LAYOUT OF A FEEDER VESSEL USED TO TRANSPORT WIND TURBINE COMPONENTS. THE SHOWN VESSEL, AN EEMS D TYPE OWNED BY AMASUS OFFSHORE BV., HAS A DYNAMIC POSITIONING SYSTEM OF CATEGORY 2. IT HAS AN OVERALL LENGTH OF 107.95 m AND A BEAM OF 16.00 m.

the 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. In a configuration similar to the presented one (Figure 2), horizontal movements of the component's lifting point of up to 3.5 m peak-to-peak amplitude and vertical movements up to 4.5 m peak-to-peak amplitude must be considered.
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 downwards 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 weather conditions as possible. The 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 with its most import variable wind speed, V. We expect significant economic advantages over the all-in-one concept to require weather restriction of $H_s > 2$ m, $> 95\%$ of the T_p values occurring at $H_s \leq 2$ m and $V > 12\,\mathrm{m\,s^{-1}}$.
7. The lifting process should be finished in as little time as possible (depending on the component about 20 minutes for the take-off and between 60 and 120 minutes for the complete lifting operation).
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.

Function structure: overall function and sub-functions

The process' overall function is to *lift a component from a floating vessel* (Figure 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 is the main flow of the process.

We decided to split the process' overall function into five sub-functions (Figure 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 sub-function *pull the crane's rope* is fulfilled by the crane, which 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*.

CURRENT SOLUTIONS

Based on our classification scheme we differentiated 18 solutions, which fulfill either one or multiple different sub-functions to lift a component from a floating vessel. We identified 7 solutions to release the closure between the component and the vessel, 7 solutions to connect the component and the crane, 3 solutions to reduce peak loads on the crane and 1 solution to compensate the component's motion relative to an earth-fixed coordinate system (Table 1, 2 and 3).

In the next sub-sections, we describe the solutions for each of these four sub-functions. After the presentation of these existing solutions, we point out, which problems are not solved yet and ask for future research and development.

Release closure between component and vessel

During the transport towards the wind farm, the components must be safely secured to the vessel such that the first step of the lifting 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 [1]. 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.* [36] and Steck and Singer [31]. Based on our classification scheme, we identified 7 different solutions to release the closure between a component and the feeder vessel.

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; Figure 4). In that case, several bolts run through the clearance holes of 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; Figure 4). One embodiment of such a device is described by Behr's patent [29]. 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 bolts.

There exist also release solutions, which can be actuated remotely. Hoeksema [37] 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, Figure 4). Possibly the simplest embodiment of a flange-clamping seafastening is an array of vertical jacks, which press the flange towards the transport frame. Other embodiments are wedge-shaped clamps and rotating clamps [37]. 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 nuts. The patent by Jepsen *et al.* [30] describes remotely controlled bolt tensioners (S_4; Figure 4). 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

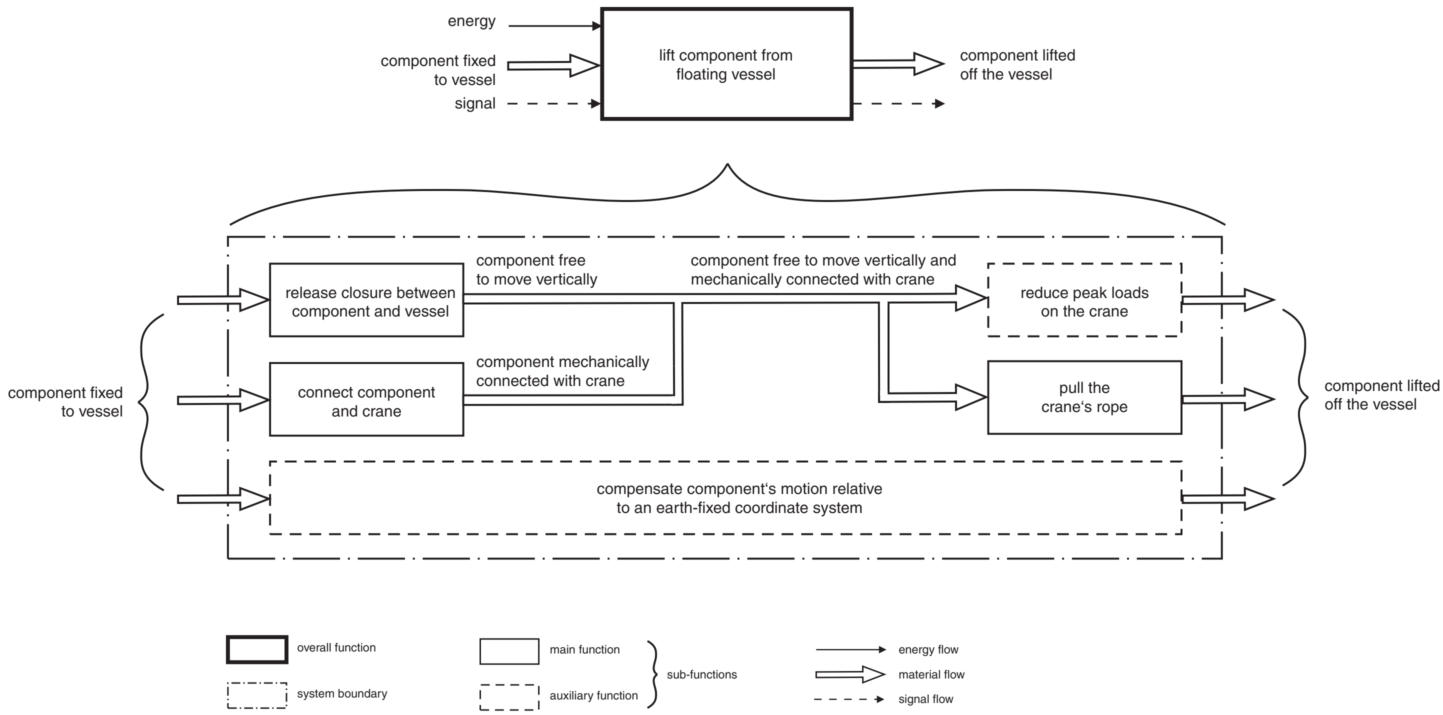

FIGURE 3. OVERALL FUNCTION (TOP) AND FUNCTION STRUCTURE WITH SEVERAL SUB-FUNCTIONS (BOTTOM) OF THE LIFTING PROCESS. FOR SIMPLICITY IN THE FUNCTION STRUCTURE ONLY THE MAIN FLOW, THE MATERIAL FLOW DEALING WITH THE COMPONENT, IS SHOWN.

the component and the vessel is to not secure the component vertically at first hand (S_5; Figure 4). 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 [31] 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 its close to its tip.

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 2 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; Figure 4). Several patents [29, 32–34] 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 [34] 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 [29, 32], the vertical transport of tower segments [29, 33, 34], and the transport of rotor blades in transport frames [36].

Another solution to connect the transport frames of rotor blades with the vessel is the use of locking pins (S_7; Figure 4). The patent by Lieberknecht *et al.* [36] 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.

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 version, 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 afterwards, which is extra effort.

One such solution, which is widely used, is to have a bolted connection between the tower and the lifting gear (S_8; Figure 5). 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 3 patents describing lifting brackets specifically designed for the wind turbine tower [39–41]. 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; Figure 5). 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 several different embodiments, which can be characterized as beam-based [42], hand-shaped [43–45] or internal lifting tool [46–48]. While most of the flange-clamping lifting tools use a hydraulic energy supply, we also found a patent of a hand-shaped tool, which works purely mechanically [43].

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}; Figure 5) 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}; Figure 5). These lifting points provide the interface to connect to it via slings, shackles or hooks. That way the nacelle can be lifted as a sub-assembly with the hub.

Alternatively, a hub-gripper can be used to provide the connection (S_{12}; Figure 5). This special device is described in Falkenberg's patent [49]. 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}; Figure 5) or the blade is gripped directly (S_{14}; Figure 5). In the former solution (S_{13}) the transport frame can be designed to have integrated lifting points [35, 36]. 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 [31] (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.

Reduce peak loads

During the lifting process, an overloading of the crane must be prevented. Especially dangerous are peak loads, which can occur during the initial take-off phase of the lifting process. Consequently, we added *reduce peak loads on the crane* as an auxiliary sub-function of the lifting process. Solutions, which address this sub-function are heave compensation systems ($S_{15} - S_{17}$; Figure 6). 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, Figure 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 [56, 57].

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: 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 to it. The recommended practices DNV-RP-H103 [57] 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 [58]). 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}; Figure 6) 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 patent describing such a device is EP2982636A1 by Bergem *et al.* [50]. In their patent the heave compensator's spring-damper properties can be changed by using 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}; Figure 6) allow closed-loop control. In the device described by Southerland [51], 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}; Figure 6). Consequently, such a system has gas and liquid tanks, which act 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 [52] describe such a system, which is designed for subsea operations.

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}; Figure 6) comprises multiple hydraulic units, which are continuously controlled, to stabilize a platform relative to an earth-fixed coordinate-system.

The patent US2012024214A1 by Koppert [53] 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 [55]. It is designed to compensate heave, roll and pitch motion. An experimental and numerical 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 [54]. 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 supply loads up to 700×10^3 kg [54], 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.* [55]. 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 feeder ship concept (Figure 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 [55]. Consequently, it can possibly support even higher loads than the three-post platform's 700×10^3 kg.

OPEN PROBLEMS AND FUTURE DEVELOPMENTS

Here, we were able to identify sub-solutions for all subfunctions of the lifting process. We even found an almost overwhelming amount of existing solutions for the function to *release the closure between the component and the vessel* as well as the function to *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 sub-function, 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 one component and not integrated into a central control process. Further, there is little data available properly describing the properties of the hydraulic seafastening systems. It remains unclear, how fast such system can open and close as well as how control schemes to synchronize the vessel-releasing and crane-connecting could look like. Additionally, there generally 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 high-tech seafastening solutions.

Another point for future development is standardization. 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 benefit strongly from standardization. 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 all components, therefore offer important time-saving potential.

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, to *release the closure between the component and the vessel* and to *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, there is no clear process yet, to synchronize the release of the seafastening with the lifting operation. We argue that standardized interfaces between the component and the crane as well as remotely controlled and synchronized seafastening mechanisms are best suited to enhance the lifting process.

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TABLE 1. SOLUTIONS ADDRESSING THE SUB-FUNCTION TO RELEASE THE CLOSURE BETWEEN THE COMPONENT AND THE VESSEL. THE SITUATION BEFORE THE CLOSURE IS RELEASED IS DESCRIBED BETWEEN ANGLED BRACKETS.

addressed sub-function	solution	applicable interfaces	energy supply
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	none (human muscle-power)
	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 [29]⟩ open locking device by manually loosening the bolt	vessel-tower	none (human muscle-power)
	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	vessel-tower	hydraulic
	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 [30]⟩ the bolts get loosened when a signal activates the bolt tensioners to do so	vessel-tower	electric, hydraulic or pneumatic
	S_5: *gravity-based connection:* ⟨the blade is positioned horizontally and supported by two transport frames, connections between the blade and the frames are based on frictional forces due to gravity [31]⟩ no closure has to be released	vessel-blade	none
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 [29, 32] or transported vertically and connected at the lower side to a transport frame [29,33,34], the transport frames are connected releasable with heavy-duty twist-locks to the vessel's deck [29, 32–34]⟩ *blade:* ⟨the blade is held in transport frames, the blade will be lifted off together with the transport frame [35]⟩ open twist-locks	vessel-tower, vessel-blade	none (human muscle-power)
	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 [36]⟩ manually pull out the locking pin	vessel-blade	none (human muscle power)

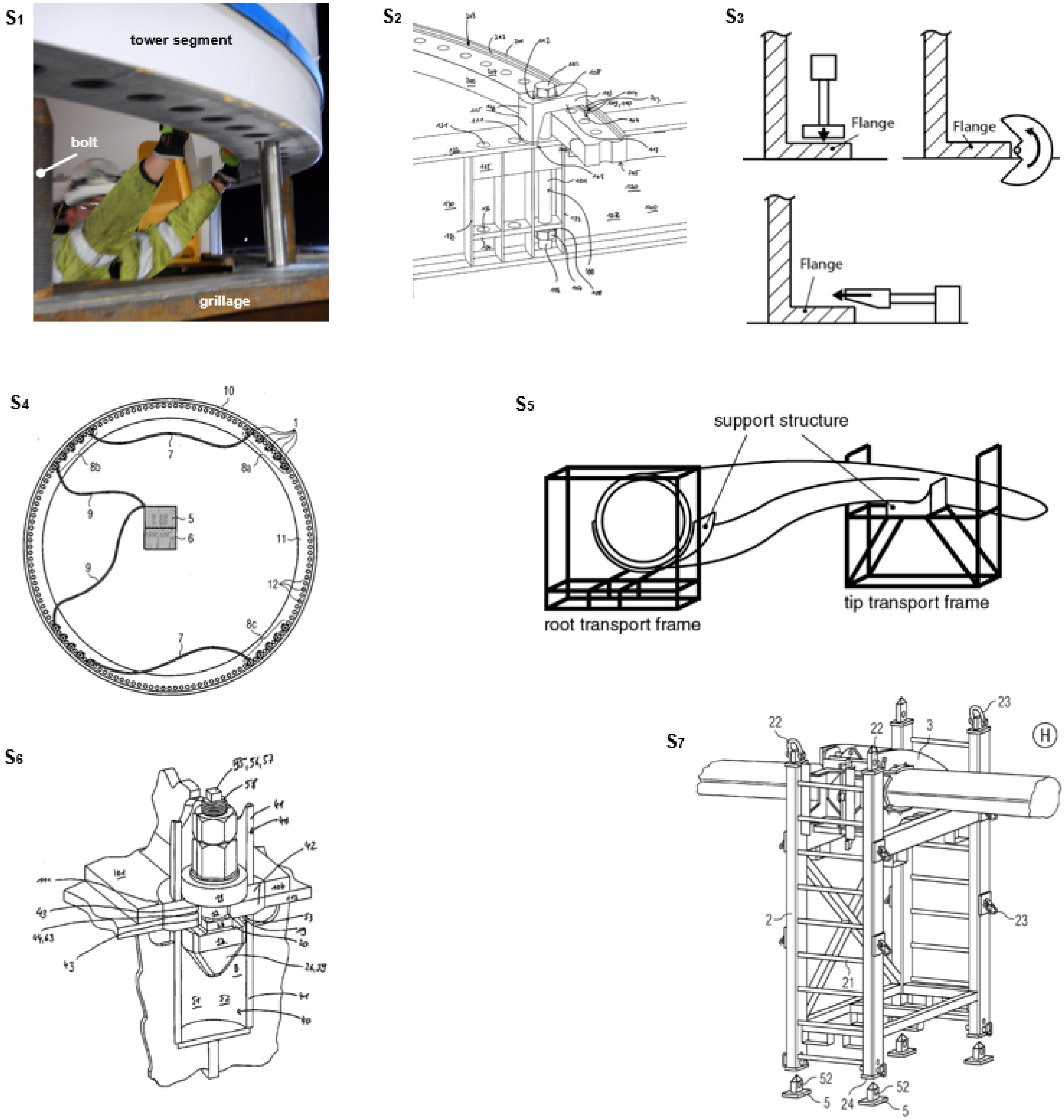

FIGURE 4. SOLUTIONS TO RELEASE THE CLOSURE BETWEEN THE COMPONENT AND THE VESSEL. IMAGE SOURCES: S_1: CREATED BY THE AUTHORS, S_2: [29], S_3: CREATED BY THE AUTHORS AFTER [37], S_4: [38], S_5: CREATED BY THE AUTHORS, S_6: [34], S_7: [36].

TABLE 2. SOLUTIONS ADDRESSING THE SUB-FUNCTION TO CONNECT THE COMPONENT AND THE CRANE.

addressed sub-function	solution	applicable interfaces	energy supply
connect component and crane	S_8: *bolted connection between tower and lifting gear*: either a lifting beam or multiple lifting brackets [39–41] 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	none (human muscle power)
	S_9: *flange-clamping lifting tool*: a lifting tools 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* [42] *hand-shaped* [43–45], or *internal lifting tool* [46–48]	tower-crane	depends on the specific type (none [43], electrical or hydraulic [47])
	S_{10}: *external lifting tool*: the tower is gripped at its cylindrical outer surface, hydraulic clamping ensures a friction-locked connection	tower-crane	hydraulic
	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	none (depending on specific connection possibly human muscle-power)
	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 [49]	hub-crane	electric and hydraulic
	S_{13}: *connect to blade's transport frame:* the transport frames has integrated lifting points such that in the lifting operation a sling, shackle or hook connects with the lifting point [35, 36]	blade-crane	none (depending on specific connection possibly human muscle-power)
	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 [31]	blade-crane	none (human muscle-power)

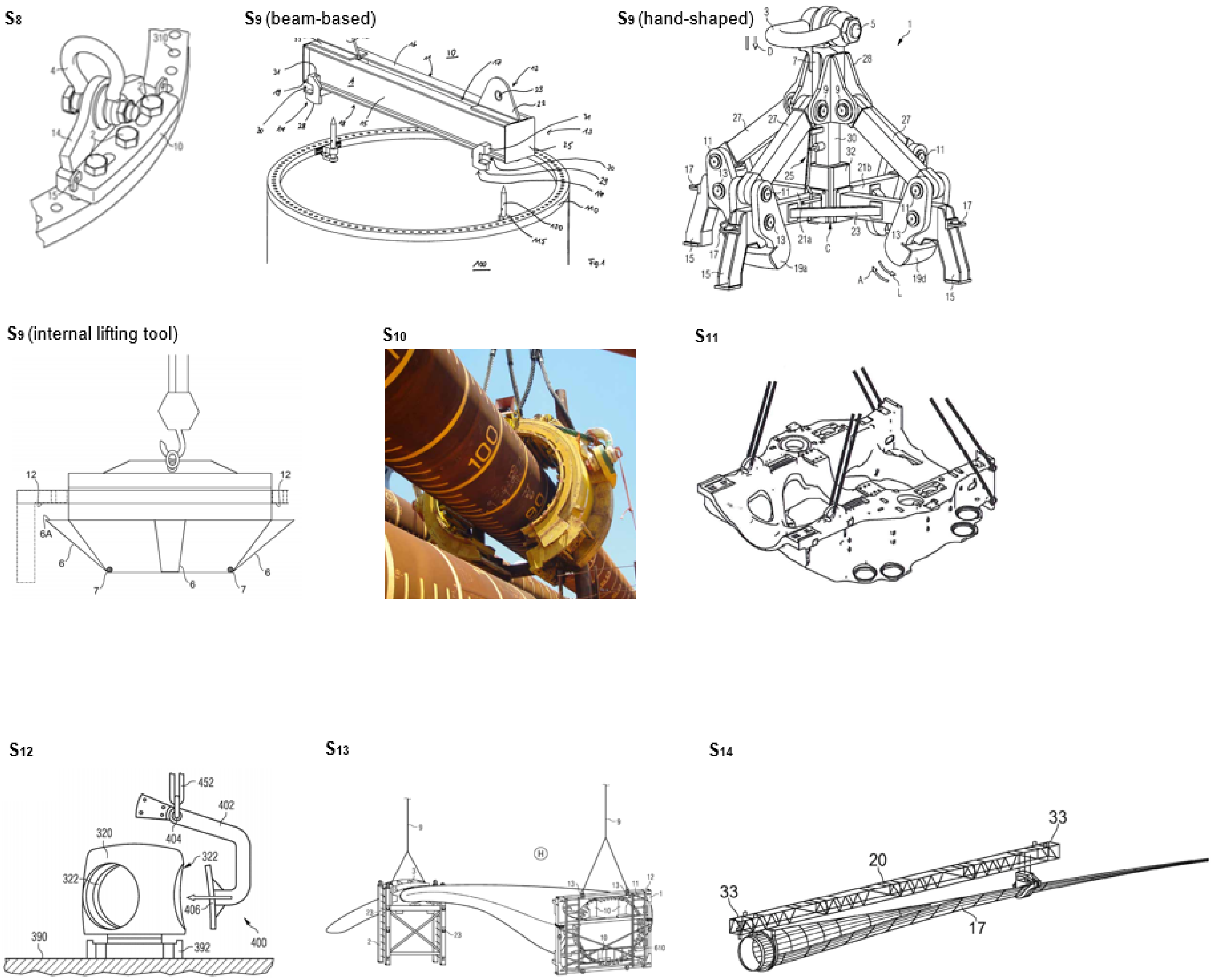

FIGURE 5. SOLUTIONS TO CONNECT THE COMPONENT AND THE CRANE. IMAGE SOURCES: S_8: [39], S_9 beam-based: [42], S_9 hand-shaped: [43], S_9 internal lifting tool: [46], S_{10}: KINDLY PROVIDED BY IHC IQIP, S_{11}: CREATED BY THE AUTHORS, S_{12}: [49], S_{13}: [36], S_{14}: [31].

TABLE 3. SOLUTIONS ADDRESSING THE SUB-FUNCTIONS TO REDUCE PEAK LOADS ON THE CRANE AND TO COMPENSATE THE COMPONENT'S MOTION.

addressed sub-function	solution	applicable interfaces	energy supply
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 using valves [50]	tower-crane, nacelle-crane, blade-crane	none (however, spring-damper properties can be changed using electric energy)
	S_{16}: *active heave compensation system*: the hook's vertical position is actively controlled using a hydraulic actuator, which movements are amplified by a winch system, the hook can follow the component's movement, described for subsea operations by Southerland [51]	tower-crane, nacelle-crane, blade-crane	hydraulic
	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 [52]	tower-crane, nacelle-crane, blade-crane	hydraulic
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 [53–55]	vessel-tower, vessel-nacelle, vessel-blade	hydraulic

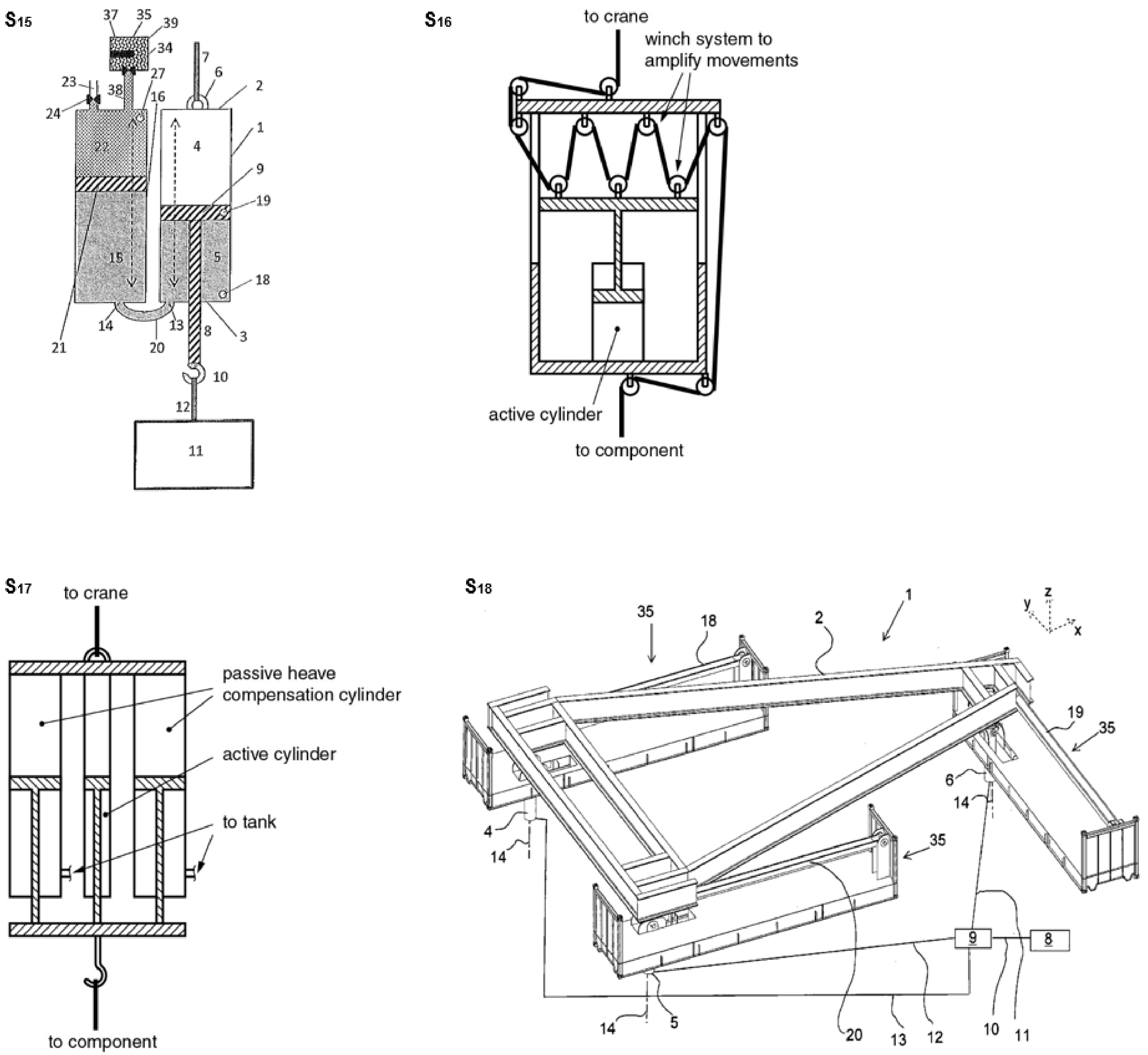

FIGURE 6. SOLUTIONS TO REDUCE PEAK LOADS ON THE CRANE AND TO COMPENSATE THE COMPONENT'S MOTION. IMAGE SOURCES: S_{15}: [50], S_{16}: CREATED BY AUTHORS, S_{17}: CREATED BY AUTHORS AFTER [56], S_{18}: [53].