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LNG Transfer in Harsh Environments - Introduction of a New Concept

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Abstract

One of the most challenging questions with regard to the technical part of the LNG (Liquefied Natural Gas) supply chain has not been answered satisfactorily yet: How can LNG be safely and reliably transferred between a floating terminal platform (Floating Production, Storage and Offloading – FPSO or Floating Storage and Re-gasification Units – FSRU or comparable) and a shuttle tanker in harsh environmental conditions?

The problem consists of two main technical issues: The first is the vessel mooring configuration (e.g. side-by-side (SbS), tandem); the second is the type and appropriate handling of the transfer lines for the cryogenic liquid. As both problems are interacting, no convincing solution has been developed until now. .

The innovative offshore LNG loading system "Maritime Pipe Loading System 20" (MPLS20) is proposed by the project partners Nexans and Brugg, leading manufacturers of vacuum insulated, flexible cryogenic transfer pipes, IMPaC, an innovative engineering company that has been involved in many projects for the international oil and gas industry for 25 years and the Technical University Berlin, Department of Land- and Sea Transportation Systems, with great expertise in numerical analyses and model tests.

The new concept is based on a unique tandem mooring configuration (see Fig. 1). In comparison to standard operations used in the oil business for about 40 years, the concept introduces a mooring bay for the shuttle tanker. Extensive numerical simulations are conducted to determine the envelope of motions and mooring forces.

As the Nexans/Brugg corrugated metal pipes provide a double containment system all relevant safety issues are well addressed, as required by EN1474-2/-3. Thus, LNG transfer can take place even under severe environmental conditions which makes this new concept superior to other approaches such as side-by-side configurations using composite hoses.

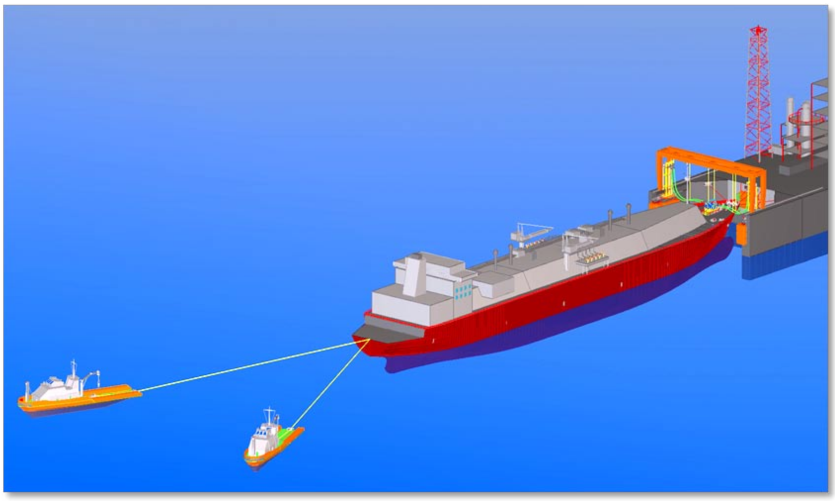

Fig. 1: Impression of the new offshore LNG transfer system with a LNGC moored to the LNG terminal for loading

Introduction

Motivation

Market developments show an increasing demand for marine LNG transportation from the production and processing areas to worldwide located consumers. Not only onshore plants shall contribute to meet this demand but increasingly also offshore LNG plants installed on moored floating terminals. Those terminals are either located right above production fields or connected via risers and subsea pipelines to onshore gas processing plants.

The first objective of the new system is a significant time reduction 'to first LNG' by overcoming environmental constraints, e.g., seismic tolerance, or national and international regulatory obstacles, e.g., public concerns known as NIMBY ('not in my backyard') or BANANA ('build absolutely nothing anywhere near anything'). In general, all these constraints are well known from onshore plant development projects.

The second objective is to significantly increase production flexibility due to the capability of easy upgrade (or downgrade) of LNG production by 'simply' adding further (or reducing existing) floating LNG terminals.

One major challenge still is the save and reliable offshore transfer of LNG (natural gas stored and transported as a liquid at atmospheric pressure at a temperature of abt. -162 degrees C (-260 degrees F)) between the LNG terminal and the LNG carrier (LNGC).

Based on existing techniques used for offshore crude oil transfer, a number of studies on LNG transfer have been carried out, resulting in potential vessel mooring configurations and designs for suitable transfer techniques.

State-of-the-Art

Two mooring configurations have been identified to work satisfactorily for the connection of shuttle tankers (either LNGC or crude oil tanker) and terminals (for LNG or oil production) for offshore cargo transfer:

The first is the side-by-side configuration, which is based on the emergency unloading technology and which proved to work in smooth and moderate weather conditions (Ref. 6).

An example for this configuration is the Exmar / Excelerate Energy Bridge with one application in the Gulf of Mexico delivering gas to the U.S. grid. Here, LNG is transferred from the LNGC to the re-gasification vessel (FSRU) by means of non-insulated flexible 8-inch inner diameter (ID) hoses (composite type). Every two hoses are combined to one line to be connectable to one 16-inch receiving flange to meet the required cargo transfer rate (Fig. 2).

Fig. 2: The Exmar / Excelerate Energy Bridge uses composite hoses for LNG transfer in side-by-side configuration (Source: TNO)

The second is the tandem configuration which is today's standard for crude oil transfer between FPSOs and shuttle tankers especially for use in harsh environmental conditions like the North Sea (Fig. 3). With dozens of installations and hundreds of operations every year, this configuration has shown a very good tracking record in terms of safety and reliability for decades.

The turnaround time of the shuttle tanker depends on the production rate and storage capacity of the terminal vessel. According to current rules and regulations for mooring of crude oil shuttle tankers to terminals in tandem configuration, a distance between the terminal stern and the shuttle tanker bow in the range of 50 to 90 m should be achieved (e.g. Ref. 7, Fig. 4). Due to the specific thermodynamical properties of the liquid crude oil and the required transfer rate, the transfer line can be designed as a single floating or submerged hose with a length of up to 100 m or more. Here, the coupling of the hose flange to the shuttle tanker receiving flange is realized by means of a specialized and well approved pull-in device located amidships or in the bow of the tanker (see Fig. 3). Operations with the transfer line in aerial mode (no water contact of the hose or flexible pipe) are rare.

Depending on environmental constraints at the specific operational location, the terminal can be spread moored or turret moored to the seabed, the latter allowing the coupled floating vessels to weathervane in 360 degrees around the mooring center. Once the shuttle tanker is moored to the terminal, a phenomenon called fishtailing may happen at the coupled multi-body system, where the carrier periodically swings behind the stern of the terminal (see Fig. 3, middle and right).

Fig. 3: Tandem mooring configuration for standard offshore crude oil transfer, using floating (middle) and submerged (right) hoses, with fishtailing movements of the shuttle tankers moored to the FPSOs (Sources: Kongsberg, APL)

To prevent fishtailing, modern shuttle tankers are often equipped with dynamic positioning systems (DP2 or higher) and/or offshore tugs are employed to support station keeping and alignment to the terminal vessel.

Important design criteria result from approved location specific mooring operations as well as from current rules and regulations, the latter defining safe working envelopes, tolerable vessel positions as well as misalignments during tandem mooring operations, each influencing the activation of ESD 1/ 2 (Emergency Shut-Down) procedures (see Fig. 4, Ref. 7).

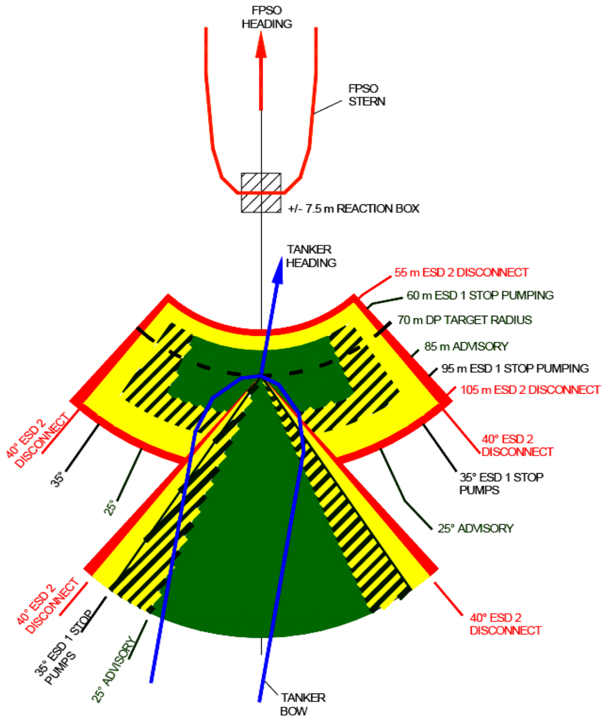

Fig. 4: Working envelopes defining ESD stages for today's standard tandem mooring configurations (Source: UKOOA, Ref. 7)

It should be noted that these rules and working envelopes apply only for today's regular tandem mooring configurations used in the crude oil transfer business.

No LNG transfer system for offshore use with related harsh environmental conditions has been realized up to now. Nevertheless, latest designs show mooring configurations with cargo dependent adaptations to the crude oil transfer systems, considering differences in number, stiffness and diameter of the transfer hoses or flexible pipes, often using aerial mode operations.

Innovations

In conclusion, none of the ‘conventional’ vessel mooring configurations and transfer techniques can easily be adapted to meet the requirements of LNG transfer operations, especially when designed for harsh environmental conditions with significant wave heights up to e.g. 5.5 m, zero-up-crossing periods between 8 and 12 seconds as well as significant wind and current loads for transfer durations of 18-24 hours.

It is evident that the choice of the mooring configuration is one major key to the successful development of a suitable offshore LNG transfer system.

Such a new concept should ideally combine the main advantages of the proven configurations – i.e. side-by-side and tandem: A short free span distance of the transfer lines (as features for SbS configurations) as well as minimum relative motions between carrier and terminal and tolerable mooring forces (as featured for tandem configurations) allowing save and reliable handling, approach and coupling of the transfer lines.

The new offshore transfer system introduced in this paper meets those requirements: The system, which is developed by the project consortium MPLS20, is based on Nexans’ and Brugg’s newly developed CRYOFLEX flexible LNG transfer pipe with ID 16-inch. The unique design of the corrugated and super-insulated pipes with their seamless manufacturing principle these pipes provide a flexible and monitorable double containment system for most types of cryogenic fluids.

The overall design of the transfer system is based on IMPaC’s newly developed and patented offshore mooring bay concept. It allows simultaneous handling and approach of up to four flexible LNG transfer pipes in aerial mode, which allows safe, robust and efficient operations.

In the following sections, selected results from numerical motion and mooring analyses performed with the two software packages WAMIT and ANSYS AQWA for the environmental conditions mentioned above are presented.

The new LNG Transfer System

The proposed transfer system features a generic LNG terminal design with the new mooring bay concept, a modified standard LNGC and the approach and handling system for the newly developed transfer pipes. The main components of the system are illustrated in Fig. 5.

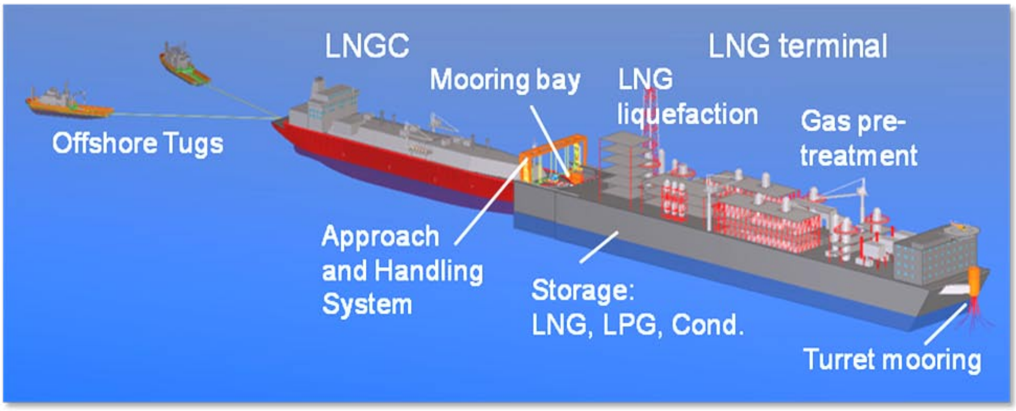

Fig. 5: Main components of the new Offshore LNG transfer system: Offshore Tugs, LNGC, mooring bay, approach and handling system, LNG terminal with turret mooring

The main dimensions of the terminal and the carrier are listed in Table 1.

Parameter	LNG Terminal	LNG Carrier
Length over all	360 m (+40 m mooring bay)	285 m
Breadth	65 m	42 m
Draught	12 m	12 m
Height	33 m	26 m
Displacement	275.087 m³	103.921 m³
LNG storage cap.	280.000 m³	138.000 m³

Table 1: Main dimensions of LNG terminal and LNG carrier

As the system design is based on a generic approach, no specific operational location is considered. Nevertheless, the transfer system is exemplarily moored at a water depth of 100 m, which is representative e.g. for the North Sea with the associated JONSWAP spectrum.

LNG Terminal

The LNG terminal hull is of barge type with a wave flattening bow, providing an optimum cargo loading capacity of up to 280.000 m³ LNG in five independent SPB tanks (Self-supporting, Prismatic, IMO Type B) which are sloshing-proof and offer a flat deck (see Fig. 5, Ref. 8). With this LNG buffer storage, even today's largest LNGC with transport capacity up to 265.000 m³ can be handled. Additional storage capacity for the gas byproducts LPG (Liquefied Petrol Gases) and hydrocarbon condensate of 25.000 m³ each is also provided. Other relevant contributions to the weight and volume magnitude of the terminal result from standard marine equipment like cranes, power generators, ballast control system etc. as well as from gas pre-treatment and LNG cooling facilities and accommodations and life saving equipment for the personnel. Due to active ballasting, the barge is outlined to work with a nearly constant draught of abt. 12 m, which equals the LNGC draught.

The barge is permanently moored to one location by means of a passive 12-point external turret mooring system, allowing the terminal and the coupled multi-body system to weathervane in 360 degrees (Fig. 6).

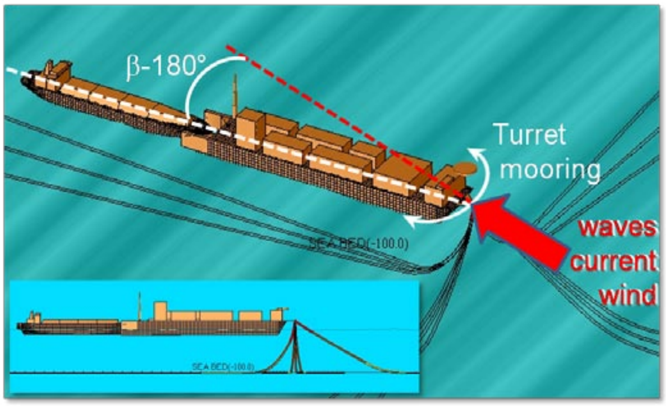

Fig. 6: Weathervaning effects due to the turret mooring of the system

(It should be noted that the design of the turret mooring system is not subject of the MPLS20 project. Such a system must generally be optimized case by case for each specific location condition, as it significantly influences the motion and mooring behavior of both, the terminal and the coupled LNGC.)

The aft end deck area is dedicated to accommodate the loading bridge and the transfer pipes with the handling header when in standby or during maintenance works. Due to the LNG and methane gas specifications, it must be checked whether the related deck area has to be classified as explosion-protection-zone (if ex-zone 1 or 2 is not yet defined) so that all equipment mounted to that area complies with related rules and regulations.

LNG Carrier

Generally, the concept is independent from tank types, so that spherical Moss or SPB can be used. In the following investigations, the LNGC is equipped with four membrane tanks whose main dimensions and cargo capacities are given in Table 1. Due to active ballasting, the LNGC also operates at a constant draught of abt. 12 m, the same as for the LNG terminal barge.

The carrier must be slightly modified compared to today's standards, as one additional and especially designed receiving manifold is placed at the deck bow area. This bow manifold completely enters the mooring bay at the aft end of the terminal when the LNGC is moored for cargo transfer, significantly reducing the free span lengths of the transfer pipes compared to crude oil transfer techniques.

The bow deck area accommodates standard anchor winches and – if necessary – chain stoppers as well as Quick Release Hooks (QRH) for mooring to the mooring wings. Due to the LNG and methane gas specification, the bow deck area around the manifold also has to be classified as ex-zone (if zone 1 or 2 is not yet defined) so that all equipment mounted to that area complies with related rules and regulations.

LNG Transfer System

Mooring System

The new mooring system features a mooring bay, framed by two steel structures, the so called 'mooring wings' (Fig. 7), which are fixed to the terminal's aft end at starboard and port side, respectively.

Each wing provides mooring hawsers for the LNGC resulting in a symmetrical arrangement of four moorings (two 'fore springs' and two 'fore lines').

Together with two additional ‘nose lines’ reaching from the aft end of the terminal to the bow center of the LNGC, all moorings are fixed to QRHs at the LNGC deck (Fig. 7, right).

The mooring lines are operated by load adequate winches and heave compensation systems, reducing line peak loads.

As the LNGC is actively pulled into the mooring bay, the wings with the mooring arrangement provide a unique solution to stop the incoming vessel in a controlled manner at the required position right below the loading bridge.

A number of foam fenders are installed at each inner wall of the mooring bay to prevent hard impacts if the LNGC exceeds the tolerable working envelope inside the mooring bay (see Fig. 14).

The cargo is transferred via rigid pipes from the terminal LNG tanks through the wings into three separate export flanges at each wing. These rigid pipe flanges are reaching high above the barge’s weather deck so that the handling as well as draining and purging of the flexible transfer pipes can be carried out in a safe, efficient and reliable way (see paragraph ‘Operating Phases’).

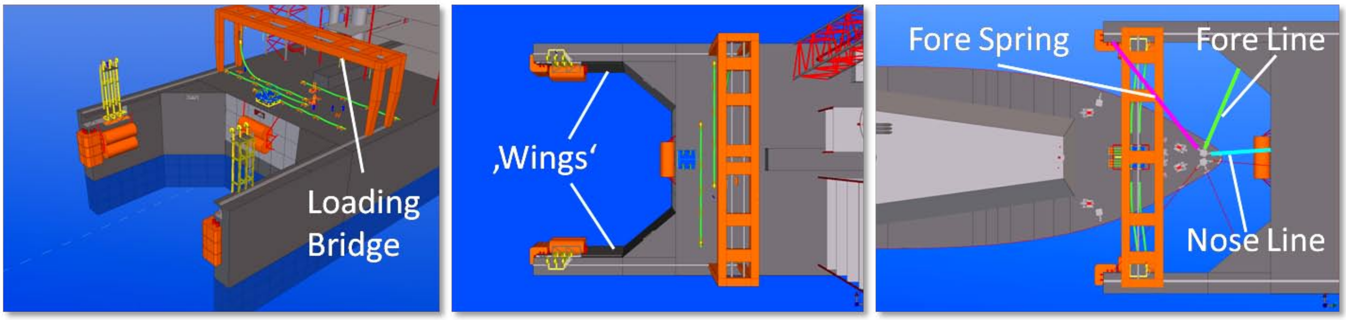

Fig. 7: The mooring bay concept features two side ‚wings’ with six moorings in a symmetrical arrangement (right)

LNG transfer pipes

The flexible transfer pipe developed by Nexans and Brugg is a pipe in pipe system called CRYOFLEX, which is used since the late 1970s for various cryogenic applications (Fig. 8). Together with the R&D institute CERN, the combination of a flexible pipe system with vacuum insulation was further developed to a vacuum insulated pipe, which can be bent and installed like a cable and proved to maintain the vacuum insulation for many years without maintenance.

Fig. 8: The LNG transfer pipe system CRYOFLEX offers a newly developed 16-inch inner diameter design

The selection of materials and the required cleanliness during the manufacturing process allows reliable evacuation and subsequent leak testing of the vacuum. In general, this vacuum keeps its integrity for more than 15 years without the need for any reconnection to vacuum equipment.

Nevertheless, in case of a leakage of the inner medium pipe, the double containment system prevents the environment from contamination with natural gas. In case of a failure of the inner pipe, the vacuum insulation area is flooded with natural gas. This significantly reduces the insulation properties, which are nevertheless sufficient to keep the outer pipe material in a tolerable temperature range while keeping its overall structural stability. A vacuum supervision will detect such leakages and forward a signal to the system control. In the case of this event, the system can safely drain and purge the single pipe. The loading process can be continued with the remaining pipe. After successful loading, the pipe can be safely exchanged.

Various designs of CRYOFLEX are available and under further development. For the most common type, the pipe is designed with an inner and an outer pipe with vacuum insulation in between both pipes and with terminations on its end. This is the preferred design for static or quasi static applications up to 8-inch. For such designs, the corrugation profile and material thickness is selected to fulfil minimum flexibility requirements and maximum allowable working pressure requirements.

In the most robust and stable version, the entire pipe also consists of an inner and outer pipe with vacuum insulation. In addition, the pipe is reinforced by different PE (Polyethylene) layers and two or more layers of flat wire steel armour (Ref. 4). This is to maintain pressure stability up to 20 bar maximum allowable working pressure for bore diameters of up to 16-inch and more with reasonable flexibility in dynamic applications for section lengths up to 150 m – 200 m in harsh environmental conditions. It is a common design for flexible pipes in submerged or aerial applications and it guarantees long lifetime even in severe conditions (Ref. 3, Ref. 4).

For higher demands in flexibility, another pipe design is under development, which features an improved corrugation profile to allow smaller bending radii (Fig. 8). To avoid the reduction of flexibility due to the PE layers and steel armour of the design, the armour is applied directly on the inner pipe as a stainless steel braiding.

The corrugated inner pipe (5) of the 16-inch CRYOFLEX contains the LNG and provides a flow rate up to 5.000 m^3/h (Fig. 8). Together with the corrugated outer pipe (2), the annular (3) for vacuum insulation and leak supervision is established. The required tensile armour forms additional layers of stainless steel braiding (4), which are applied directly on the inner pipe. These layers of stainless steel provide the required reinforcement without significantly stiffening the pipe. Depending on system requirements, the pipe can be protected by a conventional PE sheath (1) on the outer surface.

Approach and Handling System

When moored to the mooring bay, a rail mounted moveable gantry crane (the so called loading bridge) bridges the bay from one wing to the other (see Fig. 7).

The loading bridge is designed to handle all four transfer pipes simultaneously by means of a header structure. For coupling of the flexible transfer pipes to the receiving flanges of the LNGC, standard components for Quick Connect/Disconnect Couplers (QCDC) and Emergency Release Couplers (ERC) can be used.

At the terminal side, the transfer pipes are connected with manual couplers to the rigid conductor pipes. Here, two out of three available rigid pipes can be used to feed LNG for transfer; one flange per wing is spare. Three pipes are dedicated for LNG transfer, one pipe for vapor return. Motion analyses show tolerable torsion in the pipes during operations, so that swivels are not required (refer paragraph ‘Motion and Mooring Analysis’ and Fig. 14).

The two part header structure combines the following active functionality (Fig. 9):

- simultaneous support and operation of all four flexible pipes with related QCDC and ERC
- winch driven fine approach, alignment and landing at the LNGC receiving manifold aided by guide posts
- damping of the touch down at the manifold by means of hydraulic dampeners
- operation (closing and disconnection) of all four QCDCs
- operation (closing and disconnection) of all four ERCs in an ESD situation
- remote controlled departing of both header parts (and subsequent lifting of the upper part to a safe position by means of pre-tensioned wires suspended from the loading bridge) in an ESD situation

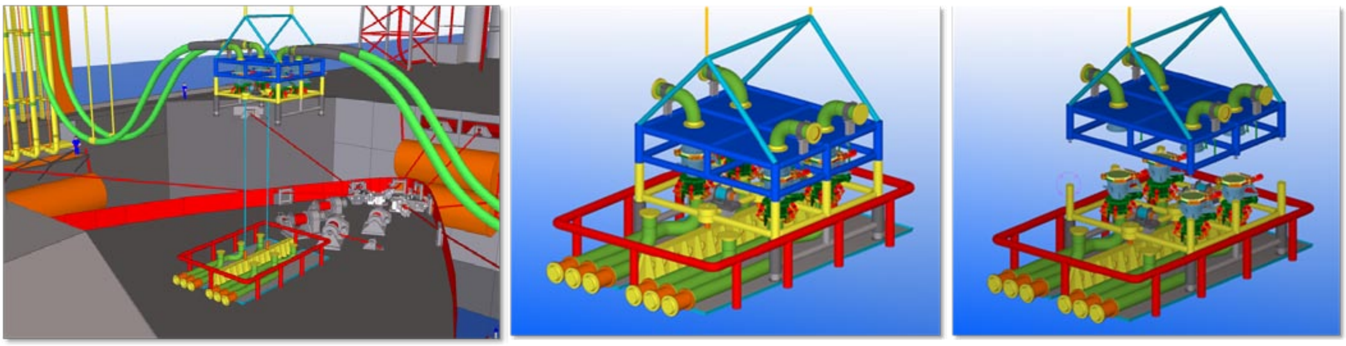

Fig. 9: Pull-in of the header to the manifold (left); header and flanges connected for cargo transfer (middle); ESD situation (right): ERCs disconnected, header departed and upper part lifted off the lower part to a safe position

The flexible transfer pipes are mounted to rigid pipe elbows fixed to the upper part of the header. A bending stiffener is mounted to the endings of each pipe to prevent excessive bending moments. In addition, pre-tensioned wires reaching from air-winches mounted on traveling trolleys at the loading bridge support the header as well as the free spanning section of the pipes (Fig. 9, left).

During standby or maintenance, the loading bridge can be moved on rails and secured onto the service deck area at the very aft end of the terminal (see Fig. 7, left and middle). At the current design status, a depth of 10-15 m at the deck will be necessary for this purpose which will be part of the transfer system ex-zone.

In analogy to the terminal flanges, the LNGC receiving manifold provides two rows of three flanges, offering flexibility in case of connectivity problems. The flange openings are horizontally oriented, but in case of minor spillages of LNG after decoupling of the QCDCs or ERCs, collecting trays filled with water are mounted below the manifold.

Operating Phases

The proposed transfer system has to guarantee the same safe and reliable system behavior during all operating phases as existing systems known for crude oil transfer or onshore LNG transfer (Ref. 6).

Based on the new 16-inch ID transfer pipes as well as the new concepts for the mooring bay and the approach and handling system for the transfer lines, the following specific operating phases can be identified (Table 2, Fig. 10, Fig. 11):

Distance between LNGC and mooring bay entrance	Operations	Operating Phase
> 100 m	The LNG terminal stand-alone: Transfer system standby, waiting for next LNGC or ready for carrying out maintenance works	Standby / maintenance
100 to 80 m	Shoot over of mooring pilot lines from the terminal to the LNGC; start of the terminal winches for slow controlled pull-in of the LNGC to the terminal aft end; LNGC thrusters slowly backwards; tug(s) assisting at heading alignment	phase 1
50 to 30 m	slow motion of winches; employment of next moorings; final alignment of the vessels aided by LNGC thruster and (two) offshore tug(s); further slow pull-in with winches; LNGC thrusters slowly backwards	phase 2
0 to -20 m	very slow pull-in of the LNGC via bow mooring lines; loading bridge is in standby	
-20 to -30 m	Full stop of pull-in; stopping aided by backward pulling moorings reaching from mooring bay entrance; tightening of all six mooring lines in a symmetrical arrangement	
~ -30 m	Loading header coupled to the LNGC bow manifold; transfer pipes cooled down and start of cargo transfer; mooring winches and heave compensation systems act for reduction of peak loads in the mooring lines	Cargo transfer phase
~ -30 m	Emergency Situation: Cargo pumps stopped; valves closed in less than 30 s; disconnection of the ERCs; parting and lifting of the upper header part; activation of the QRHs and cast off of the LNGC from the mooring bay	ESD 1 / ESD 2

Table 2: Main operating phases of the LNGC and the terminal during approach and cargo transfer via the new transfer system

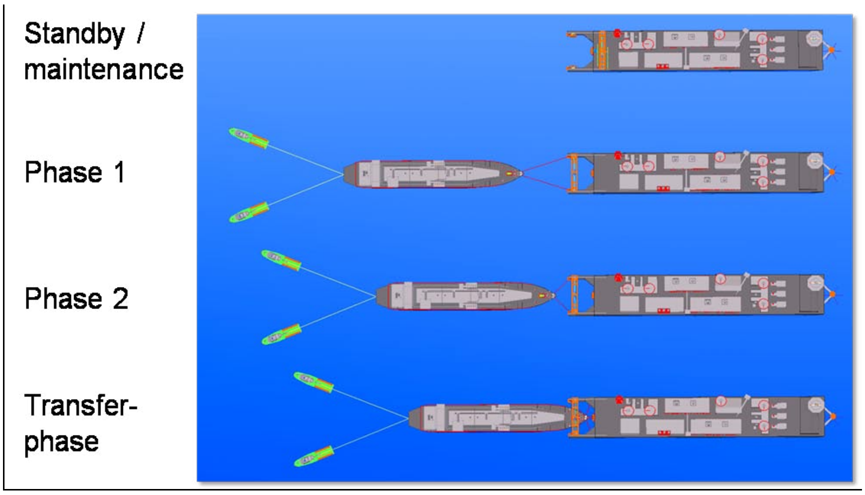

Fig. 10: Operation of the LNGC close to the LNG terminal: Terminal stand-alone (standby/maintenance), first moorings connected to the LNGC, start of pull-in operation (phase 1), near approach and alignment to the mooring bay prior to entering (phase 2), final moored position during cargo transfer (transfer phase)

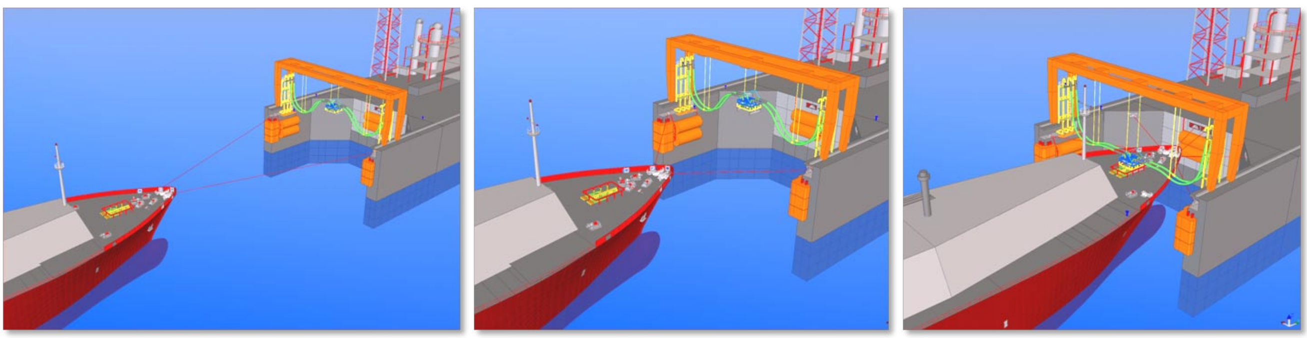

Fig. 11: Close-up view to the main mooring phases: Start of pull-in of the LNGC to the mooring bay at the terminal (left), near approach to the mooring bay, transfer system standby (middle), moored position during cargo transfer (right)

Motion and Mooring Analysis

The multi-body system is fixed to the seafloor by an external turret mooring arrangement, allowing the coupled vessels to weathervane. Consequently, each mooring and motion analysis starts with the determination of the resulting equilibrium position and heading when environmental loads from wind, current and waves are applied. In the current status of the analysis, only head seas with angles of attack β = 180 degrees have been applied for all load members (see Fig. 6). In the next step of the project, differing angles for incoming waves, wind and current will be considered.

The design criteria are resulting from the following environmental conditions, which are assumed to be maximum environmental conditions for the analyses:

Environmental Parameter	Design Values
significant Wave Height H_s	5.5 m
range of zero up-crossing Periods T_0	8-12 s
Wave Spectrum	JONSWAP, γ = 3.3
Wind speed v_w	30 m/s
Current speed v_c	1.0 m/s
angle of attack for all loads (current stage of analysis)	180°
Water depth	100 m

Table 3: Generic design criteria for the new offshore LNG transfer system

The two software packages WAMIT and ANSYS AQWA have been applied independently by the MPLS20 partners IMPaC and TUB to determine the motions and reaction forces of the multi-body system (Ref. 5, Ref. 1).

Both programs are based on potential theory, and good agreement for the results of frequency domain analyses have been achieved (see Ref. 2 for details). Due to different modeling capabilities, comparisons of time domain results have been carried out exemplarily for the same sig. wave heights and ranges of wave periods. Additional analyses for the combined set of environmental loads listed in Table 3 as well as time domain analyses for a standard three hour lasting short-time statistical approach are carried out with ANSYS AQWA only.

Note, that the given environmental loads are defined to be maximum values in which regular decoupling procedures of the transfer system as well as ESD operations should be possible in a safe and reliable manner. Normal cargo transfer is possible up to these values. It is assumed that the assisting offshore tugs are not the limiting factor for the operations, since they do not come into direct contact to the LNGC hull.

Model setup

The models used in the numerical analyses (as well as in the upcoming physical tank tests) feature the main dimensions as given in Table 1, but at model scale 1:100.

The panel discretization for the LNGC and the LNG terminal barge in ANSYS AQWA includes the wetted hulls as well as basic topside structures for allowing the estimation of wind load coefficients, which are based on the areas of attack (Fig. 12, left). The number of panels used for the wetted hull of the LNGC is 1284 and for the terminal barge 1654, respectively. Further 1922 (2071) panels are used to descretize the topside structures of the LNGC (the LNG terminal barge). Slightly higher panel numbers are used for the WAMIT model discretization.

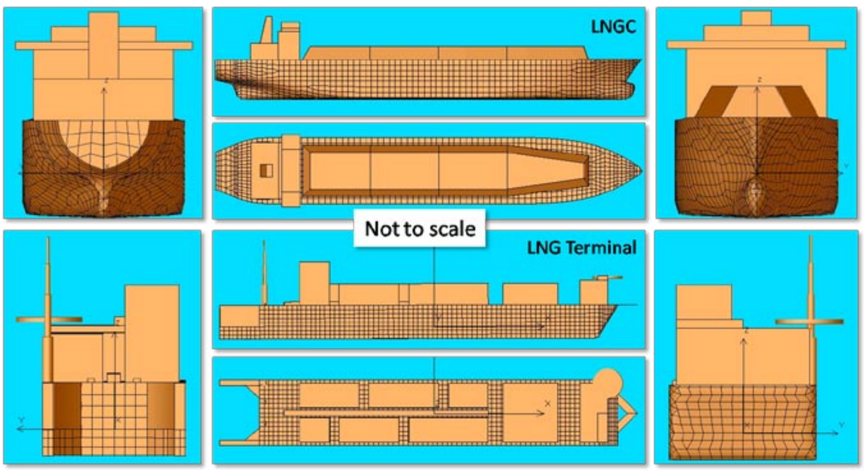

Fig. 12: (Left Figures) Panel discretization in ANSYS AQWA: LNGC (top) and LNG terminal barge with mooring bay (bottom); (right Figures) global (top) and local (bottom) coordinate systems used in the model

Results: Relative Motions

For the design of the offshore transfer concept, the most critical property that has to be assessed in detail is the relative motion between the LNGC and the terminal barge in dependency of the environmental conditions. Considering head seas exclusively, one point at the bow deck center of the LNGC and one point at the aft deck center of the terminal barge are specified to investigate the relative motion characteristics. Here, the focus lies on the determination of motion and mooring characteristics for vessels with completely filled cargo tanks and a mooring distance of abt. 10 m between the LNGC bow and the terminal stern.

The analysis of the relative motion behavior of the both coupled vessels is based on the hydrodynamic characteristics of the coupled bodies, which are described by the Response Amplitude Operators (RAOs) for surge, heave and pitch:

$$H_j(\omega) = \frac{s_{ja}(\omega)}{\zeta_a(\omega)} e^{i\varepsilon_j(\omega)} \qquad \text{with} \qquad j = 1 \text{ for surge, } j = 3 \text{ for heave and } j = 5 \text{ for pitch,}$$

where ω is the angular wave frequency, ζ_a is the wave amplitude, s_{ja} is the amplitude of the respective body motion and ε_j is the corresponding phase angle. The absolute value of this complex number is obtained by $\left|H_j(\omega)\right|$ whereas the phase shift is calculated by

$$\varepsilon_j(\omega) = \tan^{-1}\left(\frac{\Im\left(H_j(\omega)\right)}{\Re\left(H_j(\omega)\right)}\right) .$$

Comparative results for the spectral analysis of the basic motion characteristics determined with WAMIT and ANSYS AQWA as well as an application calculating the downtime for an exemplary location in the North Sea are given in Ref. 2.

Results achieved with ANSYS AQWA for the generic approach with the complete set of environmental loads listed in Table 3 are shown in Fig. 13. The time series for the oscillating relative motions in x-direction (top) shows periods with sets of larger amplitudes and extreme values of +1.75 m/-1.55 m. Compared to that, the relative motions in z-direction oscillate almost constantly according to the irregular sea state with peak values of +4.72 m/-4.37 m for the entire time series (bottom). No curve for the relative motion in y-direction is shown here as these motions turn out to be negligibly small with maximum values of +0.17/-0.15 m.

It can be stated that the relative motions in the relevant directions x and z of the multi-body system (LNGC, LNG terminal barge) exposed to extreme head seas, can be accommodated with the mooring bay concept.

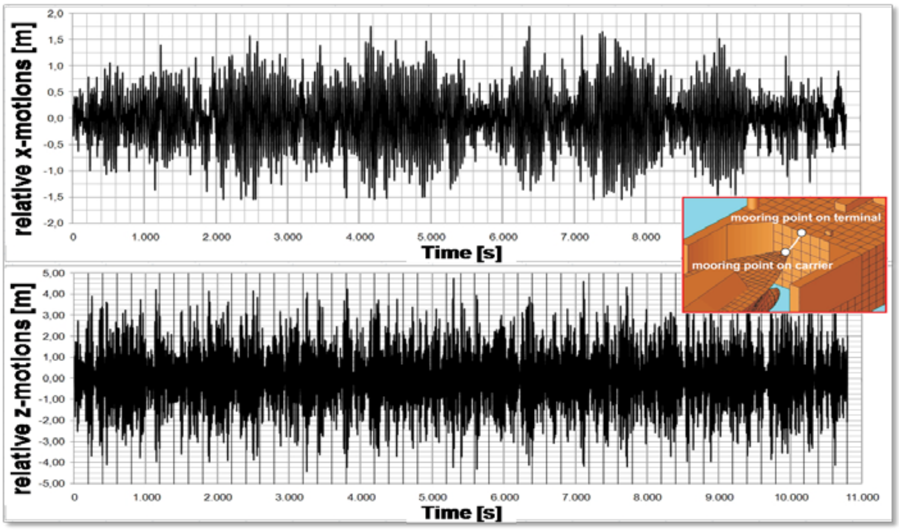

Fig. 13: Time history for three hour time domain analysis of the relative motions of the LNGC bow and terminal stern in irregular head seas: H_s=5.5 m, ω_p=0.5 rad/s (top: x-direction, bottom: z-direction)

The following maximum amplitudes have been determined by the analysis:

Motion Direction	Max. Amplitudes
x	+ 1.75 m / - 1.55 m
y	+ 0.15 m / - 0.17 m
z	+ 4.72 m / - 4.37 m

Table 4: Results for maximum motion amplitudes of the new offshore LNG transfer system in head seas with concurrently applied environmental loads (see Table 3 for generic design parameter)

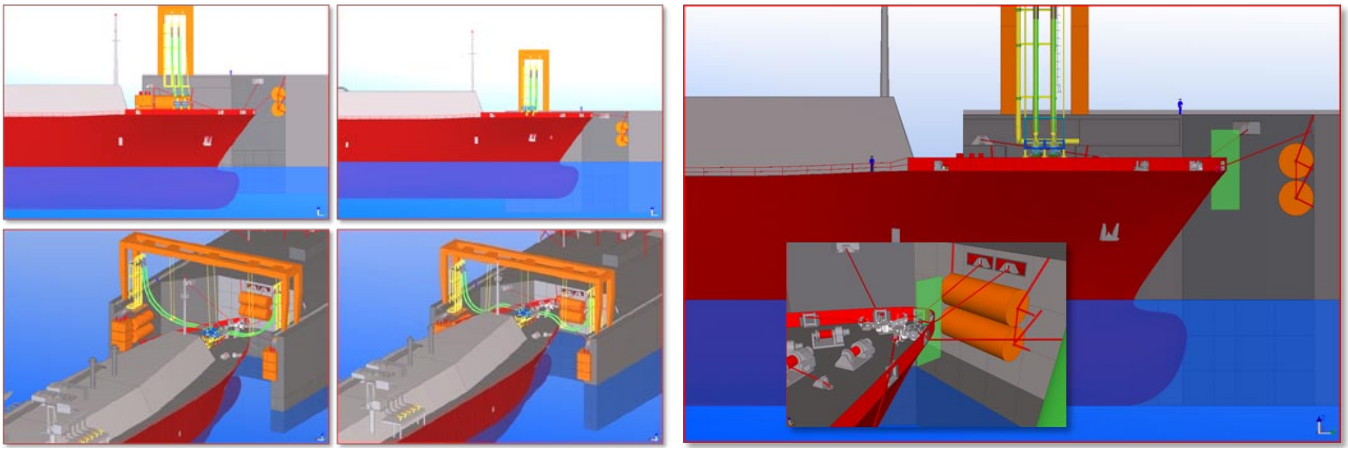

Fig. 14: Extreme positions of the LNGC relative to the terminal barge during cargo transfer:
(both left) minimal x-distance / maximal z-distance; (both middle) maximal x-distance / minimal z-distance;
(right) resulting working envelope of the LNGC during mooring visualized by a green rectangular space at the vessel bow

Results: Mooring Forces

After controlled towing into the mooring bay, the LNG carrier is moored in a symmetrical arrangement of six hawsers - two 'fore springs', two 'fore lines' and two 'nose lines'. The mooring lines are dimensioned to absorb second-order forces, resulting from non-linear drift motions of the system. Taking the given geometry of the mooring bay into account, a certain free span lengths of each hawser with specific stiffness is required to cope with position dependent maximum holding forces (Table 5). Fig. 16 shows the time series of second-order forces for the three line types for irregular seas based on a JONSWAP spectrum with H_s=5.5 m, ω_p=0.5 rad/s and γ=3.3 as well as the extreme current and wind loads listed in Table 3.

The curves show line forces up to 2511 kN for each of both fore spring lines. Minor forces are received for both fore lines with 1860 kN for each line. The overall maximum values are calculated for both nose lines with 2820 kN for each line.

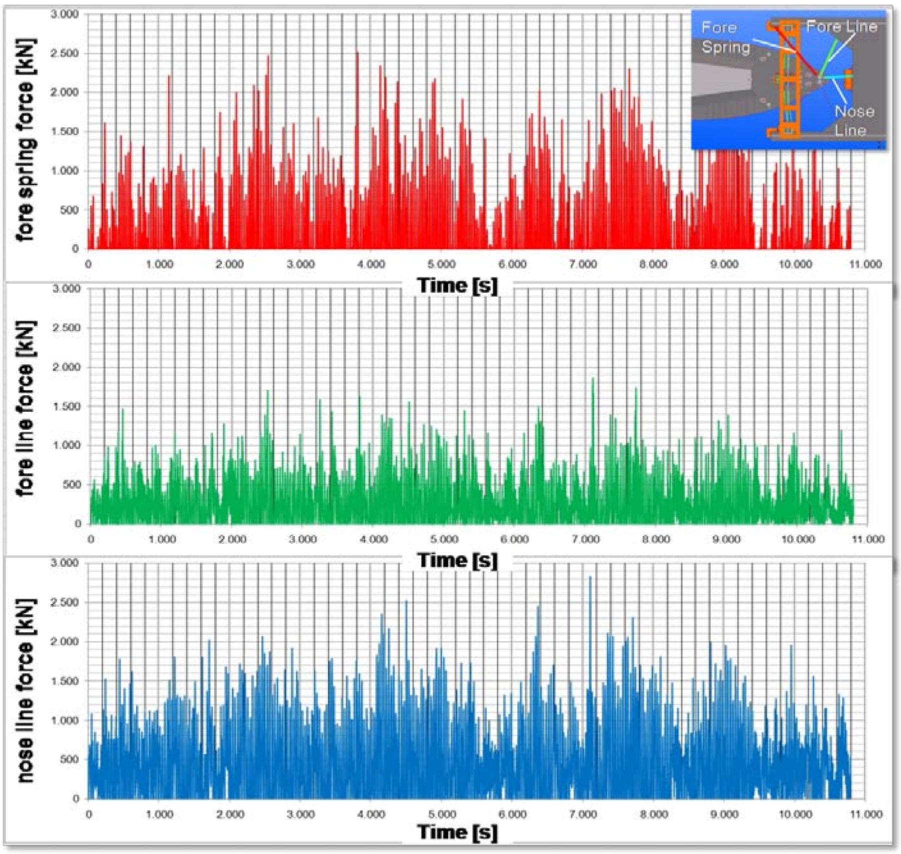

Fig. 15: Time history for a three hour analysis of second-order line forces in irregular head seas: H_s=5.5 m, ω_p=0.5 rad/s (from top to bottom: 'fore spring', 'fore line', 'nose line')

The following maximum line forces have been determined by the analysis for the given main hawser characteristics:

Mooring Lines	Max. Forces per Line	Line Stiffness	Free Span Line Lengths
Fore Spring	2511 kN	2000 kN/m	~ 35 m
Fore Line	1861 kN	2400 kN/m	~ 20 m
Nose Line	2820 kN	1140 kN/m	~ 13 m

Table 5: Resulting maximum forces and main characteristics of the three different mooring hawsers 'nose line', 'fore line' and 'fore spring'. Note that each line appears twice in the symmetrical arrangement (see Fig. 7 (right) for the line naming convention)

Compared to second-order forces, first-order forces resulting from linear sea state induced body motions are significantly higher and cannot be absorbed. Thus, the moorings have to be veered and hauled up by individual heave compensation systems and/or active winches in order to reduce excessive peak loads and prevent damages in the mooring lines.

Note the line lengths as listed in Table 5 refer to outstretched free span lengths. The overall length of the lines may differ according to the final positioning of the related heave compensation system and winch.

Nevertheless, it is important to state that moorings with the required characteristics are available on the market.

Conclusion

An innovative offshore LNG transfer system is introduced, where the shuttle carrier is towed into a mooring bay at the stern of the LNG terminal. By using six hawsers in a symmetrical arrangement with the unique geometry of the mooring bay, the LNGC can be stopped in a distance of abt. 10 m behind the terminal, right below a standby loading crane.

The loading crane is founded on the mooring wings and bridges the mooring bay. By means of pre tensioned wires reaching from the crane, four flexible transfer pipes with an inner diameter of 16-inch (or more) are operated via a dedicated header structure, which provides all required functionality even in ESD situations.

The transfer pipes introduced are newly developed by Nexans and Brugg and feature 16-inch ID. They provide a double containment system for the cryogenic cargo, allowing monitoring of the vacuum super-insulation for more than 15 years without intervention.

Extensive numerical analyses for the newly developed system prove that LNG transfer can take place in open seas even at harsh environmental conditions.

Perspectives

Within the joint project MPLS20, the focus is on the development of a new offshore LNG transfer system. This system may require new operational procedures for safe loading and unloading of cargo at sea. One issue to be investigated in detail is the influence of partly filled tanks with associated free fluid surfaces on the motion behavior of the carrier vessel during loading and unloading operations. Thus, one focus will be the investigation of sloshing effects on the LNGC motion behavior as part of the new offshore LNG transfer system.

Since the superposition of waves, wind and currents from different directions can lead to a range of headings from 150 to 210 degrees, further investigations have to be conducted. For these cases, the influence of the roll motion is no longer negligible and requires detailed knowledge of viscous damping coefficients in order to obtain reasonable results.

Extensive tank tests will be carried out in the next project phase aimed at the determination of the damping coefficients as well as on the verification of the numerical analysis. It is planned to model and visualize the main operations in a Ship-Handling-Simulator; results will be discussed with experienced mooring masters.

The project developments are accompanied from the beginning by a Failure Mode and Effects Analysis (FMEA) carried out by Germanischer Lloyd. The objective is to consider critical feedback in the early design phase to receive an 'Approval in Principle' for the offshore LNG transfer system and its related operations.

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