Proceedings of OMAE 2004
23rd International Conference on Offshore Mechanics and Arctic Engineering
20-25 June 2004, Vancouver, Canada

OMAE2004-51520

MANEUVERING LARGE TANKERS ALONGSIDE A FLOATING LNG (FLNG) FACILITY

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ABSTRACT

The FLNG concept involves the use of a large, turret-moored floating facility that processes natural gas from local production fields and stores the products for export. The products are transferred through conventional hard arms located on side of the FLNG to tankers moored alongside.

This concept requires an evaluation of the arrival and departure maneuvers of the large tankers servicing the FLNG. As this is a new concept on this scale, it is not possible to investigate this aspect in prototype. It is however possible to carry out the evaluation with the aid of computer simulations. Important aspects to incorporate in the simulations are the hydrodynamic and aerodynamic interactions between the different bodies (FLNG, tankers and tugs) and the effect of these continuously changing interactions on the actions of the ship's pilot.

The paper presents a case study in which real-time maneuvering simulations were carried out with the multi-body version of Alkyon's simulation model SHIP-NAVIGATOR. Experienced and active pilots ran the maneuvers.

Wind, waves and currents influence both the FLNG and the tankers. Furthermore, the presence of each of these facilities can influence environmental conditions experienced by the other. The paper discusses the importance of modeling these influences properly assess the feasibility of the marine operations.

INTRODUCTION

FLNG facilities (Floating LNG production and export facilities) are increasingly being seen as a viable way of retrieving LNG from remote locations. This paper deals with one aspect of the use of FLNG's, the export of the products using tankers and, in particular, the safety of tanker arrival and departure operations.

When the main export product is LNG this places some specific demands that do not apply to all export products. In particular, the necessity for side-by-side mooring makes the arrival and departure procedures more demanding.

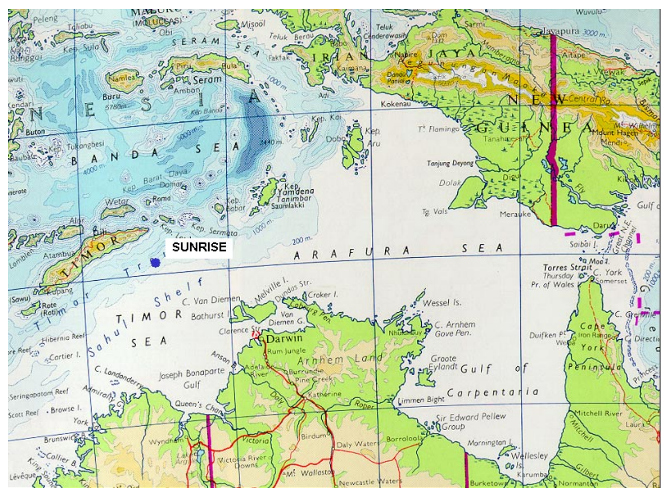

Figure 1 Location of the Sunrise Field

The safe and continuous export of products is an important aspect of the design of an FLNG facility. There is little direct experience of the export of products from FLNG's using tankers and the situation is different from that with traditional jetties and GBS structures for reasons including the following:

- The conditions on open sea are generally considerably more severe than close to the coast at a jetty or in shallow water where most GBS's are situated. This makes the effective operation of the tugs much more difficult. The effectiveness of tugs diminishes significantly in waves higher than 1 or 2 meters, particularly in swell;
- The FLNG facility tends to align itself according to the wave, wind and flow direction. This sometimes makes the operations easier but sometimes also more difficult;
- The FLNG facility can make significant low frequency movements stimulated by non-linear wave forces and the variability of the wind force.

This means that there are no standard rules regarding the safe limits for tanker operations. Considering that every FLNG will respond differently to the environment and that the climate at every possible location will have different combinations of flow, wind, sea wave and swell wave conditions, we do not expect that standard limits will be developed in the near future. We therefore expect that real time simulations can make a useful contribution in the determination of the feasibility of FLNG solutions and in their design.

In this paper, a case study is presented for an FLNG facility in the Sunrise field (see Figure 1). In the study, the maneuvers during arrival and departure operations of an LNG carrier and two other vessels at the FLNG were simulated. The relative size of the FLNG and the LNG carrier are shown in Figure 2.

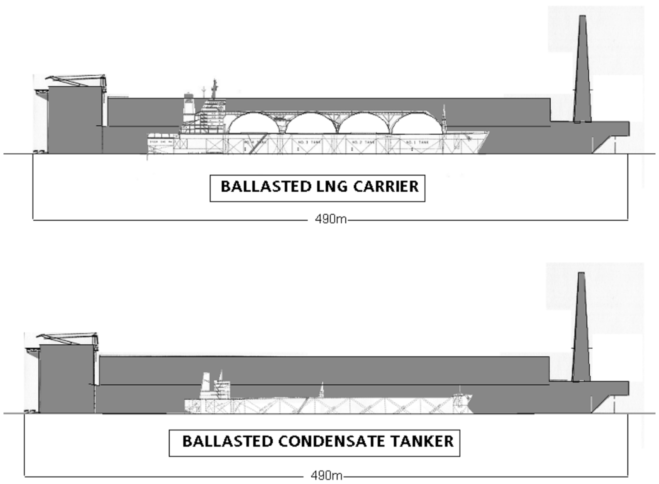

Figure 2: Relative dimensions of FLNG facility and export vessels

Based on such simulations, recommendations were made on infrastructure that should be available and the procedures that should be followed. Further, limiting conditions for safe maneuvers were determined and applied to assess the downtime and the persistency of downtime for offloading operations.

NOMENCLATURE

FLNG Floating Liquid Natural Gas facility;
LNG Liquid natural gas;
LOA Length over all;
B Breadth;
D Depth of ship to main deck;
T Draught of ship.

SIMULATION TOOLS

In principle, three tools are available for testing the safety of maneuvering operations:

- Fast time simulations using an auto-pilot;
- Real time simulations with active pilots;
- Real time simulations with active pilots in a full mission simulator.

We consider that fast time simulations are of limited use for this sort of operation because they miss the essential human aspects that determine the risks involved. This is particularly the case for FLNG operations, since the pilots not only have to consider the movements of the tanker and the use and the effectiveness of the tugs but also the movements of the FLNG and the possible use of the thrusters.

The use of real time simulations with active pilots makes it possible to combine the inclusion of the human aspects with the advantages of a flexible facility and the possibility of carrying simulations for many different conditions and maneuvering strategies. A tool such as SHIP NAVIGATOR can be operated on any reasonably fast PC with the facility to support a double screen. This makes this type of tool ideal for optimizing the approach and departure maneuvers and determining the required infrastructure and number of tugs.

Full mission simulators provide a good final check on the selected strategy and the limiting safe conditions. They also offer advantages for training the pilots that will actually command the operations. However, they generally have to be reserved some time in advance and are more expensive to use than non full mission real time simulations.

This study was carried out with the simulation software SHIP NAVIGATOR.

MODELING

The modeling of the tankers and tugs included the following aspects:

- Characteristics of rudder and propeller with detailed modeling of the interaction between rudder, propeller and hull. This gives realistic ship maneuvering in all modes of operation (maneuvering ahead, astern, sideways, accelerating, stopping, being towed or pushed).
- Detailed tug modeling with towing and pushing possibility; control of their towing-line length, towing position and towing angle; tug effectiveness is restricted depending on the speed and relative direction of the tow, on the tugs own speed and on the waves at the tug location.
- Close quarter maneuvering is facilitated using an instrument panel with mouse operated control of the ship, winches and tugs (Figure 3 – see next page) and with real-time birds-eye visualization of the ships, the tugs and the surroundings (in this case very limited).
- Control of the FLNG thrusters and monitoring of the FLNG movements.
- Possibility to replay an earlier executed run.
- Partial sheltering of the maneuvering tanker from sea waves, swell waves, wind and flow by the moving FLNG;
- The influence of the wave conditions on the tugs at their actual location including the effects of wave sheltering by or wave reflection from the FLNG and / or the tanker;
- The effects of wind gustiness expressed in terms of changes in the wind strength and direction during the simulation;

- The turning effect on the tanker as it enters or leaves sheltered areas behind the FLNG;

Southeast or the East. Between the monsoon seasons, the winds are light (less than 7 m/s) and from variable directions.

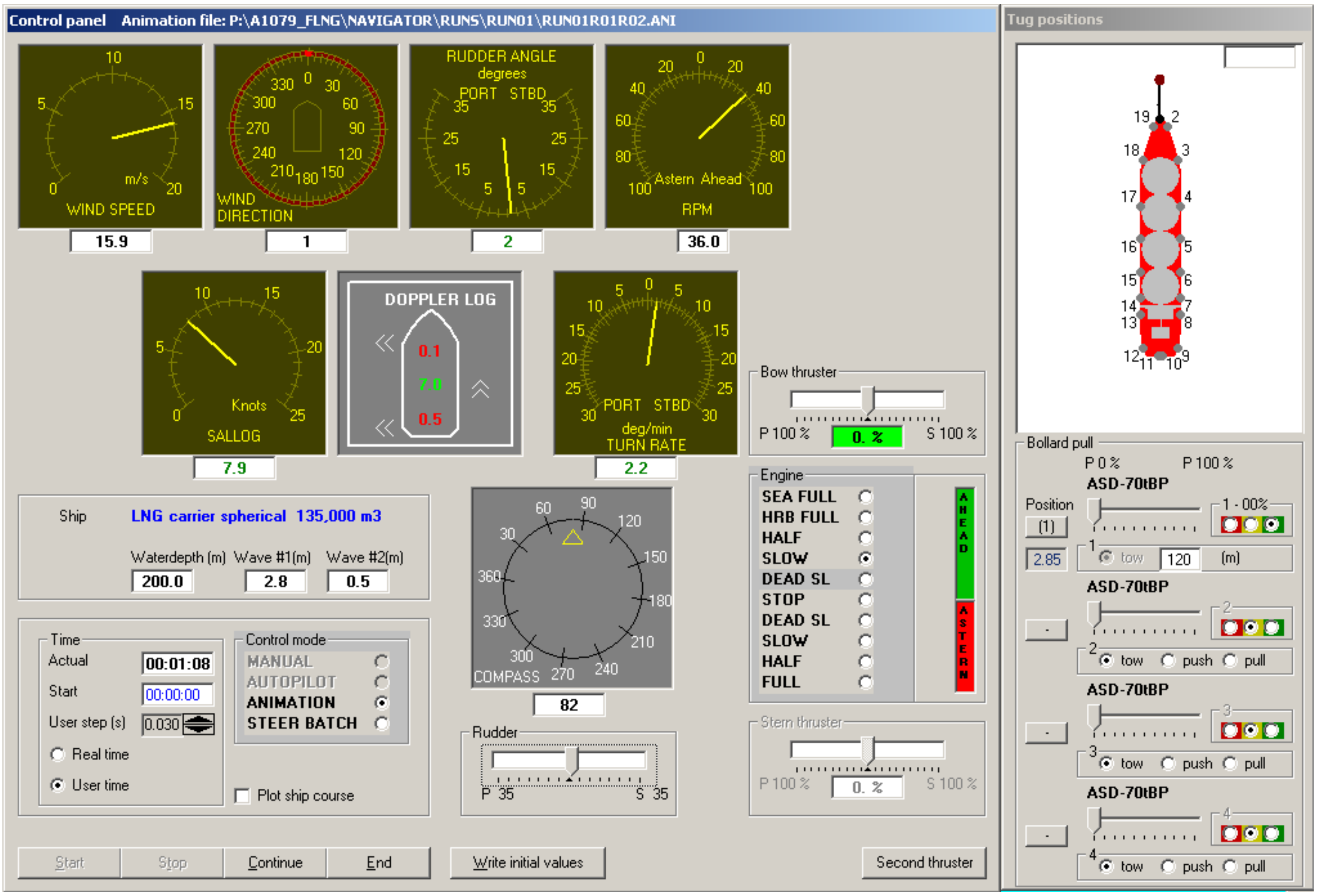

Figure 3: Instrument panel.

The effects of the turning moments on the tanker as it enters the sheltered area behind the FLNG are particularly important since these influence the behavior of the tanker during the last critical phases of the arrival maneuver.

The FLNG was turret moored using composite lines consisting of chains and nearly neutrally buoyant man made fibers. The equilibrium position and orientation of the FLNG is determined by the flow wave and wind conditions. The FLNG oscillates around the equilibrium position with a period of about 200 seconds under the influence of slowly varying wave drift forces and variations in the wind strength. These movements were successfully reproduced in the simulations.

SITE CONDITIONS

The climate is an equatorial maritime climate that is hot and humid throughout the year. The wind (and rainfall) regime is, however, seasonal with two monsoon periods: the Northwest Monsoon (from December to February) and The Southeast Monsoon (from April to September). During the Northwest Monsoon, the wind tends to blow from westerly directions with the strongest winds blowing from the West or the Southwest. During the Southeast Monsoon the wind is generally from The

Numerical information on the site conditions was available based on wind, wave and flow measurements taken between 2000 and 2002. The conditions are represented in the roses shown in Figure 4 for the “all year” conditions.

The following aspects are noteworthy:

- The directional characteristics of the wind climate are distinguishable, but not highly pronounced. Analysis of the monthly roses (not shown here) shows that during the “Northwest” monsoon, the winds generally come from the Southwest, West or Northwest. In December there is a distinct Southwesterly / Westerly peak. The direction of the winds in the Southeast Monsoon is more pronounced with winds mostly coming from directions between Southeast and East, particularly between May and August.
- The wave climate is highly directional with waves from the Southwest and from the East. Monthly analysis of the data confirms that the waves from the Southwest occur during the Northwest monsoon and from the East during the Southeast monsoon.

- The current direction is quite variable in all seasons. The strongest currents seem to occur between February and July. In February, the current flows mainly towards the Northwest. Between March and July, it generally flows towards the Southwest.

The difficulty of arrival and departure procedures depends on the wind speed, wave height, current speed and wind, wave and current direction relative to the FLNG. Once these relative directions are fixed, the actual orientation of the FLNG has almost no influence on the safety of the operations. Therefore, the simulation test conditions were derived considering wind, wave and flow conditions relative to the FLNG. The equilibrium orientation of the FLNG was computed for the period for which environmental data is available. This was based on the position of the turret mooring and the wave, wind and flow forces and moments exerted on the FLNG. Further, only those periods were considered during which the significant wave height was greater than 1.7 m.

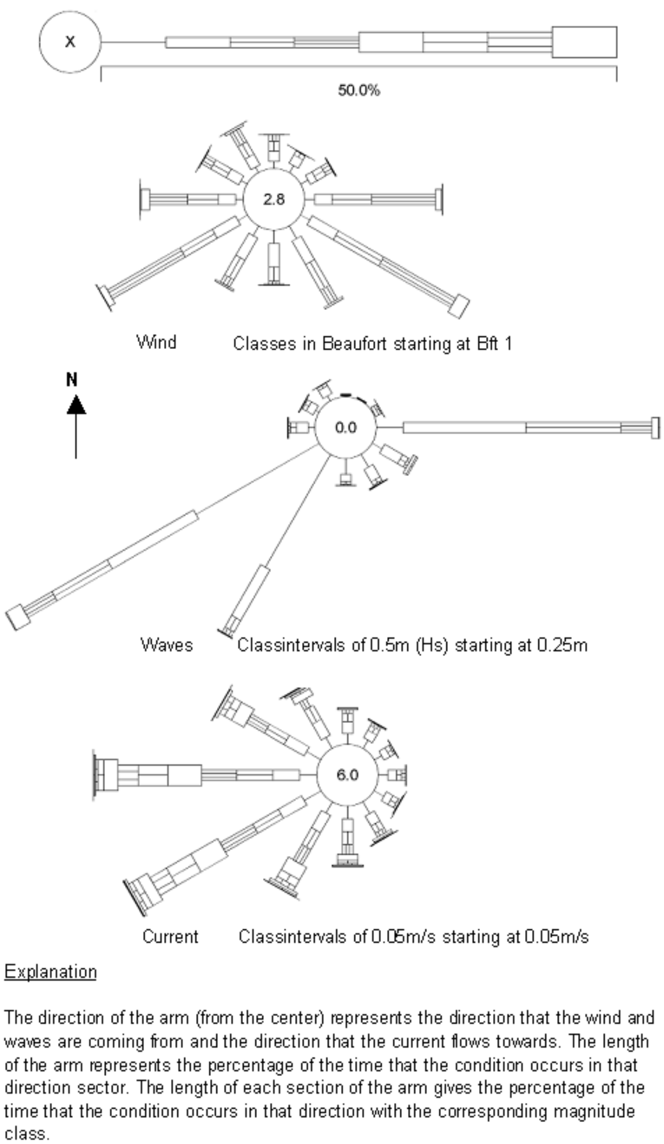

Figure 4 Wind, wave and current roses

Figure 5 illustrates the corresponding wind, wave and flow climate with directions expressed relative to the orientation of the FLNG. The following observations can be made:

- The orientation of the FLNG is generally in line or nearly in line with the wave direction. This is consistent with the experience that the wave direction has the greatest influence on the orientation of the FLNG.
- The relative wind direction is more variable with respect to the FLNG. However, most winds blow obliquely towards the starboard side of the FLNG with a direction of 30° to its axis. Other strong winds are either parallel or slightly more oblique (60°).
- The relative current direction is highly variable but tends to pass from the port side of the FLNG to the starboard side.

This analysis enabled us to select a limited number of environmental conditions for testing that are representative for the more severe conditions that may occur.

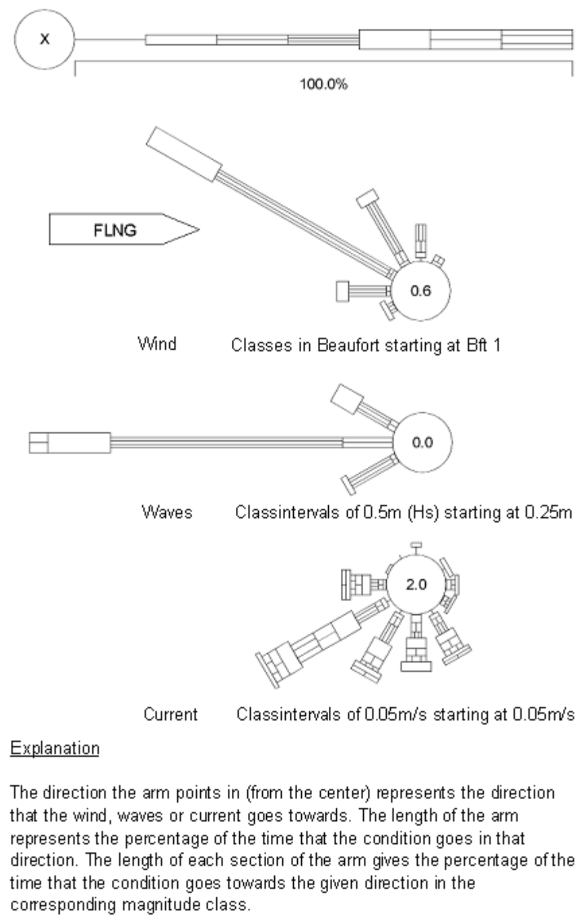

Figure 5 Wind wave and current roses with direction relative to FLNG orientation in periods with $H_S > 0.7$ m

When a maneuver proved to be too difficult in the simulations, the applied conditions were reduced to determine the safe limits for the maneuver.

INFLUENCE FIELDS

This section briefly deals with the influence of the FLNG and the carriers on the natural conditions at the maneuvering tankers and the tug boats. The simulations were made with several moving objects. This requires a careful approach to sheltering. For example, it is possible that a tug boat, may sometimes be protected from the waves by the FLNG, sometimes only by the carrier and sometimes by both the FLNG and the carrier. At other times the tug may be influenced by reflected waves from one or both of these objects.

The area downwind of the FLNG is sheltered from the wind. In addition, when the tankers are close to the FLNG, they will interact for some wind directions because of reduction in pressure between the two bodies. This may have a significant influence on the safety of the maneuvers because it pulls the carrier towards the FLNG during the last part of the maneuver.

Similarly, the current is reduced downstream of the FLNG.

The influence of the FLNG on the surrounding environment is described using coefficients given on a regular grid fixed to the moving FLNG. Locations and incident directions are converted to the co-ordinate system around the FLNG to obtain the factors and directions that should be applied. The resulting directions (obtained by application of the coefficients) are then converted back to the user co-ordinate system. The coefficients depend on:

- The incident wave, wind or current direction w.r.t. the FLNG;
- The wave period (in the case of waves);
- The total water depth (in the case of waves and current);

The coefficients describing the fields are as follows:

- A factor applied to the wind speed, current speed or wave height;
- The direction of the wave, wind or current.

The tankers are divided into segments along their length to allow prediction of the Yaw moments on the carrier due to gradients in the wave, wind and current fields. When the carrier is close to the FLNG, the environmental conditions are computed at the location of each segment accounting for the presence of the FLNG. This method represents the temporary yaw moments experienced by the tanker as it passes into the sheltered area.

Both the FLNG and the carrier may influence the sea and swell waves at the tugs. The following procedure is followed to obtain the wave conditions at each tug:

1. Obtain the wave height period and direction in the absence of the FLNG;
2. Introduce the FLNG and obtain the wave height factor and local wave direction at the tug. Use these to obtain the wave height and direction at the tug (in user co-ordinates) in the presence of the FLNG;
3. Introduce the Carrier and determine the effect on the wave with height and direction as determined in step 2. Apply the factor to the wave height obtained in step 2 to obtain the wave height at the tug.

The procedure is based on the observation that the wave direction does not change significantly between the FLNG and the tug.

Transformation of the wave conditions is carried out independently for sea and swell.

An example of the influence field of the FLNG on the wind is shown in Figure 6 for one of the 24 wind directions schematized.

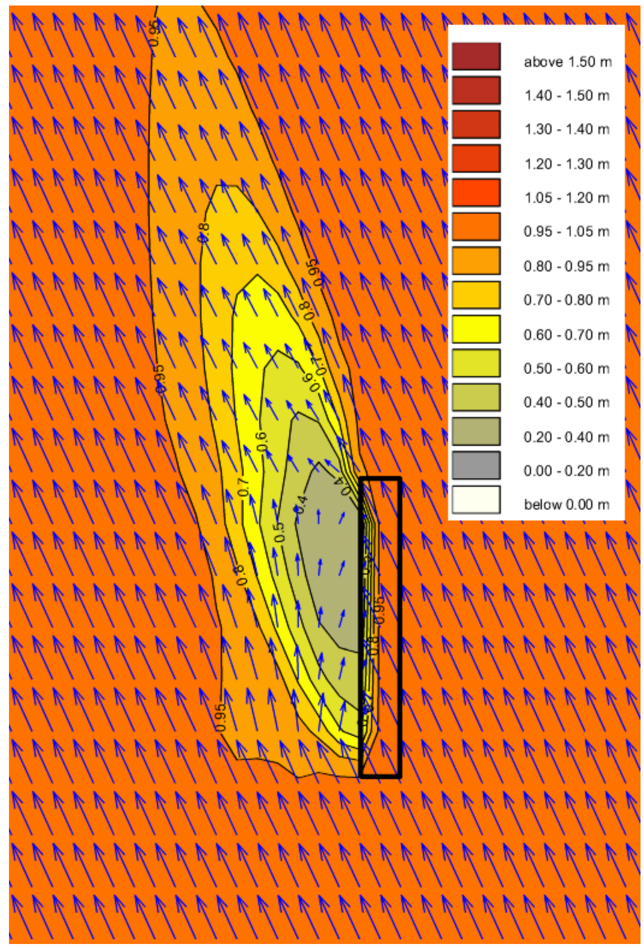

Figure 6 Influence field of FLNG on wind

SCHEMATIZATION

The main dimensions of the FLNG facility (see also Figure 2) used in this study are: length overall: 490m; breadth, 76 m; draught 15 m and depth 37 m.

Hydrodynamic coefficients (frequency dependent added mass, damping and wave load) and hydrostatic data were derived by modeling the underwater hull of the FLNG in a boundary element 3-D potential theory diffraction program. In addition, we derived coefficients for the 2nd order mean and slowly varying drift forces using the same software package.

Wind and current forces and moments (surge, sway and yaw) on the FLNG were computed by application of coefficients derived from measurements for similar objects.

The turret mooring system comprises 9 composite lines attached to the turret. Each of these lines consist of the following sections:

- Upper section: Chains. These ensure that the mooring lines remain reasonably steep and make practical connection of the composite lines easier.
- Middle section: Consists of low weight, low elasticity cable. The use of this middle section ensures that the mooring system remains stiff without putting undue vertical force on the FLNG.
- Lower section: Chains that lie on the seabed along the last part of the trajectory. These determine the stiffness of the mooring system.

The force exerted by each of the 9 composite lines was computed in advance for a range of horizontal and vertical displacements of the turret based on analytical solutions for a stationary catenary.

Six tanker models (three tankers each in two loading conditions) were prepared for the maneuvering simulations. The study on the approach and berthing involves mainly straight line, very slow speed sailing with strong wave and wind conditions dominating the maneuver. Therefore the emphasis of ship modeling was to correctly represent those situations. However, even though they were not directly relevant for this study the standard high and medium speed turning circle and zig-zag characteristics of the vessels were also modeled to match available prototype and model test data.

The main particulars of the various ships are presented in the Table 1.

Tugs were simulated with a capacity of 80-ton bollard pull of which a maximum of 70 tons was actually used during the simulations. The time required to change towing direction and towing effectiveness in waves were modeled to match an ASD type of tug, fitted with a bow thruster. The tugs were operating on a 120 m long synthetic (e.g. Dyneema) towing line connected to the bow.

Due to reflection of the sea and the swell on the FLNG and the maneuvering ship, the tugs will be operating in very rough, choppy sea conditions. This increases the chance of shock loads in the towing wires. In most runs the tug orientation is either beam-on or almost beam-on to the sea waves, or operating in quartering incoming (quartering bow) and reflected (quartering stern) sea waves with a combined H_s of well over 3 m. Further, this is combined with a low 0.5 m H_s swell at right angles to the sea.

The ability of tugs to assist maneuvering ships is hampered when they need to operate in severe wave conditions such as those described above. Under such conditions tugs use a considerable amount of their power to maintain their station. Further, the tugs avoid applying maximum pull because this increases the risk of the wire breaking or the tug capsizing following to a sudden wave-induced force or movement.

These effects are represented in the simulator in the form of reduced effectiveness. This effectiveness is implemented as a ratio of the force exerted on the ship in waves to the maximum force that can be exerted in still water.

The effectiveness depends on the wave condition at the tug location, the length of the towing line, the towing direction with respect to the motion of the ship, the velocity of the ship and the amount of wave shielding or reflection by the ship and the FLNG.

			LNG carrier	Condensate tanker	LPG Carrier
Capacity		m^3	135,000		
Deadweight		t		100,000	55,000
Length over all	Loa	m	285	241	235
Breadth	B	m	48	42	36
Depth	D	m	27	20.6	21.8
Draught	T	m	11.5	14	12.5

Table 1 Main characteristics of visiting carriers in laden condition

RESULTS

FLNG MOVEMENTS

In all of the simulations the FLNG oscillated about its equilibrium position in sway and in yaw under the influence of the slowly varying wave drift forces and the unsteady wind forces. The period of these oscillations varied between 230 s and 300 s. The amplitude of the yaw oscillations was generally between 0.5° and 1° with corresponding movements of the stern of between 5 and 10 m. In one of the simulations the stern thruster was used to turn the FLNG to shelter the maneuvering area from the wind waves. In this case, the wind waves arrive obliquely at the FLNG and exert much larger drift forces on it. This leads to yaw oscillations of 2.5°. We therefore would not recommend this strategy unless some king of active control system for the thruster is implemented to suppress these oscillations.

The amplitude and period of the oscillations of the FLNG coincide with those expected based on model results for similar objects.

MANEUVERING SIMULATIONS

The results of two of the twenty-three simulations carried out are illustrated in Figures 8 and 9. The following paragraph discusses these simulations.

Figure 8 illustrates the approach of the LNG carrier (LNGC) with waves, wind and flow coming from the same direction and swell waves coming from the side. The FLNG oscillates with a yaw amplitude of about 0.6° in these conditions – a movement that is barely visible in the Figure.

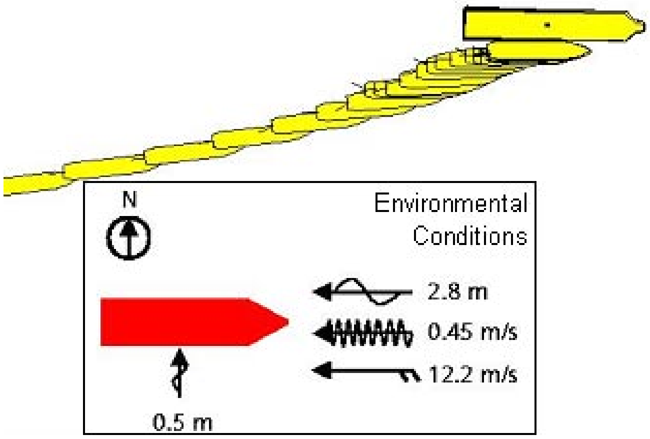

Figure 8 Example of simulation results

The run starts with the LNGC at a distance of 2 nautical mile west and 0.4 nautical mile south of the FLNG. In this run only one tug is used, connected to the bow (in other simulation runs two tugs were used). In this particular case using the single tug is no problem since all the important elements (sea, wind and current) are head-on to the ship and no additional stopping power is needed.

During the approach the engine is mostly at slow ahead and only small rudder angles are needed for course corrections. When the ship is 1 nautical mile from the FLNG the speed has dropped to 4.5 kn (over the ground). The engine is then set at dead slow ahead and the ship's speed is reduced even further.

The ship's bow passes the stern of the FLNG at a distance of approximately 150-m with the ship sailing with less than one knot over the ground. The LNGC then starts to approach the FLNG under a small angle and the forward tug is deployed to a sideways position. Engine and rudder are used to create small heading changes that control the lateral speed.

When the ship's shoulder is some 30 m from the FLNG's side the ship is slowly turned to an almost parallel orientation with the FLNG and the tug is employed to control the lateral speed of the bow.

In the last stage mooring lines fore and aft are made fast. They are kept tight but are not used to pull the ship.

The ship touches the fender with a sideways speed of less than 0.1 knot.

The conclusion of this run is that arrival under this (theoretical) condition is safely possible from a maneuvering point of view.

Figure 9 illustrates the approach of the LNG carrier (LNGC) with sea and swell waves coming from the Southwest, current flowing to the Northwest and wind coming from the West (condition B in Fig. 6). The FLNG oscillates with yaw amplitude of about 1.0° in these conditions.

The simulation starts with the LNG carrier at a distance of 2 nautical miles directly astern of the FLNG. The speed is 8 knots. The engine is set at slow ahead and the rudder is kept hard to port most of the time to counter the tendency of the LNG carrier to turn into the wind. At 1 nautical mile from the FLNG, the speed has dropped to 5.5 knots and the ship has moved to a parallel position, laterally approx. 75 m away from the FLNG.

The two tugs are connected at the bow and at the stern. When the bow of the carrier is 500 m away from the FLNG the aft tug is employed to reduce the ship's speed, which at that time is 4 knots. When the speed is reduced to 3 knots the forward tug is deployed to a lateral position. Engine and rudder are needed to avoid the ship turning and drifting away from the FLNG.

In general, it is much more difficult to find a steady heading in this condition than in the previous one. This is especially so when the ship enters the wave reflection zone / current lee zone at the side of the FLNG.

The carrier is turned towards the FLNG with the aid of propeller and rudder. The aft tug is then also deployed to a lateral position and the LNG carrier is allowed to drift sideways to the FLNG. At that moment, the clearance is over 100 m. Both tugs are now pulling at the maximum capacity possible in these wave conditions. However, the forward tug is unable to control the bow's lateral speed. Fender impact is at 0.4 knots lateral speed. The fact that the lateral movement is not under control means that regular arrivals with the LNG carrier under these conditions are not safely possible.

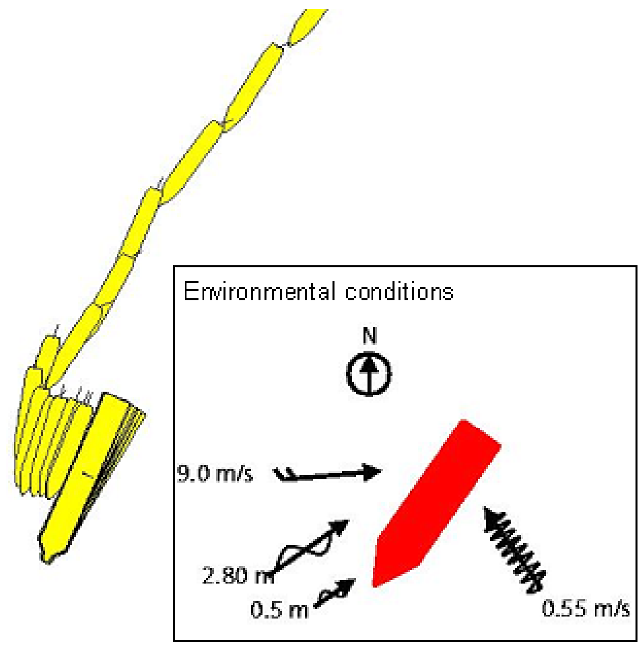

Figure 9 Example of simulation results

SUMMARY

Because it is not possible to present all the results here, a selection of some of the aspects highlighted by the simulations is now presented:

- The heading of the FLNG is primarily determined by the wave direction. The FLNG heading can only deviate significantly from the wave direction if there are high winds or currents from other directions acting on the FLNG.
- On open sea the balance of forces on the carrier is similar to the balance of forces on the FLNG. This means that they have a similar equilibrium heading. When the carrier passes into the sheltered / reflection area close to the FLNG, this balance is disrupted, giving changes in the natural heading of the carrier and making the maneuver difficult.
- Arrival and departure operations with the condensate carrier and the LPG carrier are generally significantly easier than with the LNG carrier.
- The limiting wind speeds, wave heights and current speeds for safe approach of the various carriers was established. These values were strongly influenced by their angle to the equilibrium orientation of the FLNG.
- The motions of the FLNG play a significant role in determining the safety of the approach and departure maneuvers.
- The use of the FLNG thruster to turn it to head into the waves can be beneficial;
- Turning the FLNG heading away from the waves (e.g. to provide sheltering for the tugs and the carrier from the waves) is not beneficial because the slowly varying wave drift forces cause large FLNG sway and yaw motions. Use of an active control system may mitigate this effect such that it is a useful tactic.

Further, resulting form the simulations a series of recommendations were made regarding such aspects as: training; fendering; provision of a fixed ground station; RPM control from the bridge of approaching ships; strategy for tug use; approach speed and emergency procedures.

CONCLUSIONS

The use of real time maneuvering simulations gives useful insight into the safety of approach operations at FLNG facilities. For these simulations to be useful, it is important that not only the movements of the carriers can be represented but also the movements of the FLNG facility.

Further, it is important to model the influence of the moving FLNG facility on the environmental conditions experienced by the approaching carrier and the influence of both of these bodies on the wave conditions experienced by the tugs.

In the case of the proposed FLNG facility at the Sunrise field, analysis of the environmental conditions there enabled test conditions to be selected such that the limiting conditions for safe operation could be found for the most frequently occurring combinations of wave and current conditions. In this process, it was necessary to consider wave, wind and current directions relative to the equilibrium orientation of the FLNG.

ACKNOWLEDGMENTS

The authors kindly thank Shell International Trading and Shipping Co. Ltd. for commissioning the original study and giving permission to publish the results.

