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Review

Current practice and research directions in hydrodynamics for FLNG-side-by-side offloading

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ABSTRACT

The offloading of LNG from a ship-shaped FLNG facility to a carrier in a side-by-side configuration in the open sea is a new operation in the offshore industry. Its novelty means that there is limited guidance available for potential FLNG operators when undertaking operability assessments. The criteria for design of side-by-side offloading operations at sea are reviewed, largely based on the pioneering work by Shell. Whilst many advances have been made, several areas of uncertainty remain, particularly associated with the underlying complex non-linear hydrodynamics. To this end, a review of the relevant hydrodynamics associated with side-by-side offloading is presented. Within this scope, the key factors that are likely to play an important role in determining side-by-side offloading operability include roll motions of LNG carriers, liquid cargo sloshing and free surface motions in the gap between vessels. Each of these phenomena can exhibit resonance, with the response amplitude of roll motions, sloshing and free surface motions in the gap being sensitive to damping levels and excitation frequencies. To explore the present understanding of the hydrodynamic excitation and damped response of these phenomena, recent developments have been reviewed and critiqued; these encompass numerical simulations, physical model tests and full scale measurements. Recommendations for future work directions to expand the current understanding and address shortcomings are also provided.

1. Introduction

Floating liquefied natural gas (FLNG) facilities are novel offshore superstructures which have been developed to unlock previously stranded gas reserves. Early adopters of the technology include Shell, who pioneered the concept for the Prelude field on the North West Shelf of Australia, and Petronas for Sarawak Malaysia. Shell's Prelude FLNG, at 488 m long and with a displacement of 600,000 tonnes will be the largest offshore floating structure in the world to date.

A typical FLNG development incorporates the full supply chain, including gas extraction, treatment, liquefaction and offloading of LNG to standard LNG carriers (LNGC) for delivery to markets, as illustrated in Fig. 1. The success of the FLNG concept is underpinned by being able to process and liquefy LNG on a floating vessel and then transfer the LNG from the FLNG vessel to the LNGC in the open sea and to achieve high operability in this operation. Operability is defined as the probability of success of an offloading operation in a specified time-frame. For Prelude, for instance, Shell requires a high probability of success at any random time of arrival of the LNGC to minimize the likelihood of lost LNG production as a result of reaching tank tops within the FLNG due to the inability to offload. Lost production implies lost revenue, so offloading operability is clearly a critical aspect of design.

Offloading of LNG may theoretically be undertaken in a tandem arrangement, where an LNGC is moored at the stern of the FLNG vessel, or in a side-by-side configuration where the LNGC is moored alongside the FLNG vessel. Tandem offloading could be executed in a harsh environment, however, at present the technology required to allow this to be performed (e.g. flexible cryogenic conduits) is undergoing maturation and qualification. Furthermore, tandem offloading of LNG will require the addition of bow loading arrangements/modifications to existing LNGCs which are currently equipped only with mid-ship cargo transfer arrangements. Hence, side-by-side offloading will remain the preferred method where it is feasible. In such a scenario, LNGCs that typically load cargo whilst berthed at a jetty in a protected environment, e.g. a port

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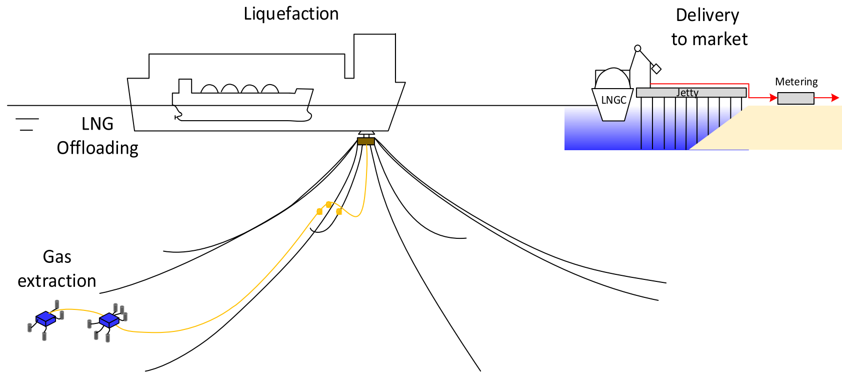

Fig. 1. Schematic of a typical FLNG supply chain.

with breakwaters, are now required to do so whilst moored to an FLNG in open seas. SBS offloading of LNG in open seas is, therefore, a novel procedure requiring new hardware development (e.g. offloading arms) and new methods of analysis. Therefore, there is a need to establish best practice guidelines for side-by-side offloading operations and to identify the directions for future research in this area.

To this end, a review of the current offloading best practice is provided which has been informed by pioneering work of Shell for Prelude. Key hydrodynamic factors are highlighted which include the roll of the LNGC during the side-by-side offloading; the influence of liquid cargo sloshing on global roll motions of LNGC and the resonant response of the sea surface in the narrow gap between the two side-by-side moored vessels. The state-of-the-art of each of these areas is reviewed and future research aimed at addressing and resolving knowledge gaps is identified.

2. Side-by-side offloading and evaluation of operability

In side-by-side offloading operations, the LNGC is moored alongside the FLNG vessel (Fig. 2) with fenders protecting the hulls from contact. Mooring lines are deployed to moor the LNGC to the FLNG mooring deck (mooring lines are supplied by carriers in the case of Prelude) to keep the vessels together and close to fixed relative positions (see example of ship to ship transfer guide by Oil Companies International Marine Forum, 2013). At the time of writing the largest fender available is of diameter 5 m, meaning that the typical separation between vessels is ∼4 m. Larger fenders will be developed as FLNG projects become more common, but this will then have implications for offloading arm design.

A typical quayside offloading operation at an import terminal takes 24 h, between 12 and 16 h of which involve actually pumping LNG (Tusiani and Shearer, 2007). Side-by-side offloading operations from FLNG are expected to be similar but the size of LNGCs are increasing and this increases the duration of offloading. In this review the total duration is taken as lasting about 30 h and may be considered to comprise three stages: (i) the LNGC approach and berthing operation, (ii) offloading of LNG, (iii) departure of LNGC. The berthing operation is limited by the ability of the assisting tugs to operate and maintain control of LNGC berthing velocities. During offloading the two vessels are connected together and operability is governed by relative motions, line loads and fender loads. Operability criteria are discussed in Section 2.1. Departure is generally less critical than berthing.

As operability is key to the viability of an FLNG project, operability must be rigorously assessed in design and then forecast in operations.

2.1. *Criteria for side-by-side offloading*

There are several aspects which affect side-by-side offloading operability. We provide an overview of the offloading criteria which need to be satisfied for successful offloading, based largely on the pioneering work of Shell. Typical criteria are summarised in Table 1. Limiting values are generally based on the mechanical limitations of the offloading systems

Fig. 2. Side-by-side offloading from an FLNG facility to a LNG carrier. (courtesy of Shell).

Table 1
Typical criteria for side-by-side offloading.

Criterion	Description
Tug operability (for both berthing and departing)	$H_{s,sea} \leq x_1$ m for $T_{p,sea} = y_1$ sec, based on the ability of the tug to provide assistance (Buchner et al., 2005)
Wind speed	$< x_2$ m/s, associated with line tensions and stability of vessel motions, may be a function of FLNG heading
Wave height $H_{s,total} = \sqrt{H_{s,sea}^2 + H_{s,swell}^2}$	$< x_3$ m, which limit vessel motions and thus swells may be more important than short period seas. (see Fig. 4)
Mooring line load	$< x_4$% of maximum breaking load, to avoid line failure
Fender deflection	$< x_5$% of fender diameter, to avoid damage to fenders
Relative motions of the vessels	$X_{max} < x$ m; $Y_{max} < y$ m; $Z_{max} < z$ m; may be determined by the offloading arms. Other sets of relative motion criteria may be adopted, depending on reference locations on the vessels.
Clearance between the vessels	$> x_6$ m, to avoid any potential collision.
LNGC roll	$< x_7^o$, to avoid collision.

(Fig. 3) and (personnel) safety or safety of marine operations, and thus they are project dependent. It should be noted that the probability of success of the offloading operation depends on satisfying all of these criteria during the offloading operation. This aspect is discussed later.

2.2. Hydrodynamic modelling of side-by-side arranged vessels

To determine offloading operability, numerical simulations need to be carried out. In practice these are mainly based on potential flow solvers due to (1) the validation for various marine and offshore applications, (2) the low computational burden and (3) the resulting high time efficiency of this method. The numerical models should be able to simulate the vessel motions accounting for mechanical and hydrodynamic interactions between the vessels, weather vaning and the characteristics of the side-by-side mooring system including fenders and mooring lines. To reduce computation time all mooring lines may be modelled as simple linear springs, or other relatively efficient numerical representations, such as analytical catenary equations, springs with up to 4th or 5th order polynomial stiffness. Their uses are dependent on how the operability is being quantified (e.g. using spectral methods, simple time-domain analysis, etc).

Met-ocean conditions for the site of interest may be obtained from direct measurements or based on hindcast models. Such a set of met-ocean conditions (measured or hindcast) is required to be continuous and to cover a period (e.g. typically 10 years or longer) that should be able to include inter-annual variability and seasonal variability. This period required may be dependent on the location characteristics.

Combining the potential flow solvers with the met-ocean conditions, each (3 h) sea state in the met-ocean dataset can be analysed in the time domain, solving the wave diffraction/radiation problem for the two floating bodies. From these analyses it is possible to check at any time if the criteria listed in Section 2.1 are met or not. Thus each 3 h sea state may be marked as Uptime or Downtime.

2.3. Assessment of side-by-side offloading operability

For an entire offloading operation to be successful all criteria need to be satisfied for the duration of an offloading operation. For example, if the duration of offloading is taken to be 30 h, and sea states evaluated every 3 h, it is possible to evaluate 10 successive 3 h periods to determine for which 30-h windows offloading would be possible (Fig. 5). This is referred to as Window Operability where window refers to the entire offloading operation lasting 30 h (3 h for LNG carrier berthing, 24 h for a typical offloading and 3 h for LNG carrier departing).

Once this is completed the probability (percentage chance) of success of the offloading operation is calculated for every month of the year and for the whole year, simply by examining the proportion of the 30-hr windows which are marked as uptime. The above procedure can be used during design in hindcast mode, or during operation in forecast mode.

2.4. Seasonality

The window-based operability provides insights into the mean offloading operability for a complete N-year time trace. To account for seasonal trends, the window based results can be sorted by month, in

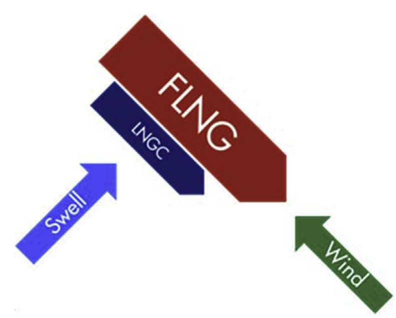

Fig. 4. A possible heading condition of the side-by-side system, in which the swell may result in large roll responses.

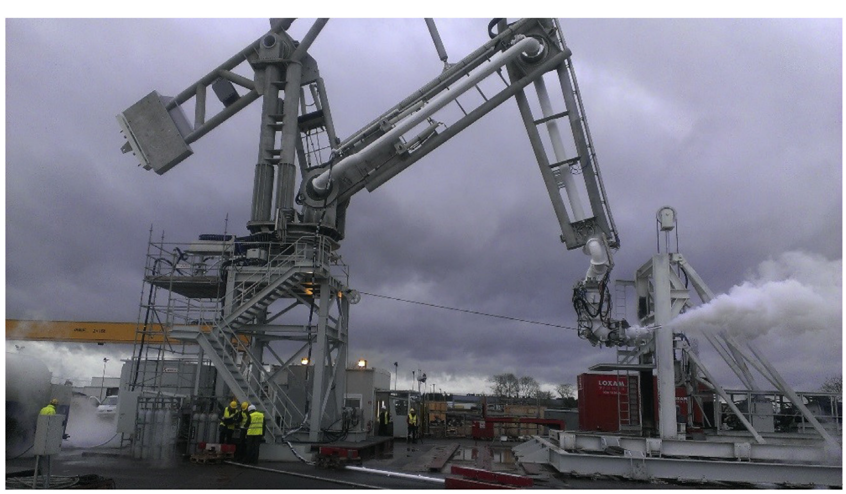

Fig. 3. Offloading arm undergoing factory acceptance test. (courtesy of Shell).

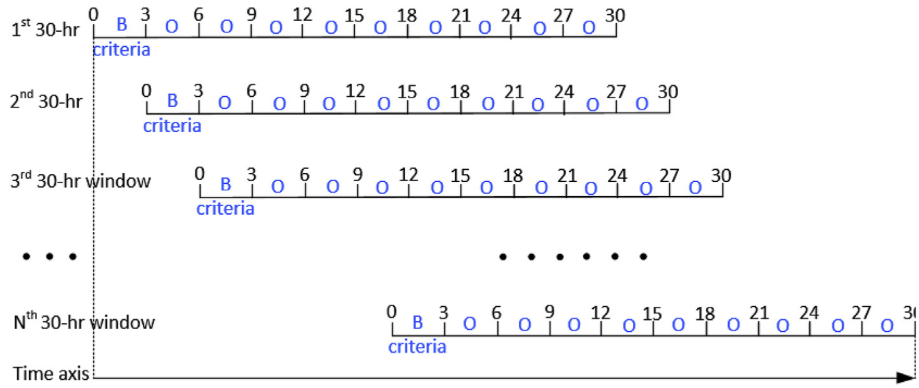

Fig. 5. Window based operability analysis. The character "B" refers to Berthing criteria and "O" indicates Offloading criteria.

which case at least a complete calendar year needs to be analysed. Since some (perhaps considerable) variability from year to year is expected, analysis of several years is needed to assess annual variability. Averaging results obtained from several years (e.g. 10 or 20 years) is a practical way to cope with inter-annual variability.

2.5. Estimation of required operability

The results from operability analyses are used as input to logistics analyses for transporting LNG to the market. This step takes into account the available LNG storage volume on the vessel, the production rate (including planned periods of downtime for plant maintenance), LNGC arrival time, offloading operability (month-by-month), LNG offloading duration, duration for transport to market, etc. Monte Carlo simulations are carried out which lead eventually to estimate of potential loss of revenue due to reaching tank tops, caused by inability to offload. Such a calculation provides an assessment of the percentage of operability that is needed in order to reduce the probability of reaching tank tops to a low level.

2.6. Design simplifications and assumptions

The operability calculations need to account for parameters which may affect the response of the FLNG or the LNGC. As an example, this should account, in principle, for differences in roll response of the LNGC during the filling operation (since the filling changes the natural period for roll motion), size of LNGC, type of LNGC tanks (membrane or spherical), effect of sloshing in LNGC tanks on motion of LNGC. If it is not practicable to evaluate all of the above in the course of the design, simplifications may be made but one should verify that the conditions selected for design are the most onerous from the set of conditions that the vessel is likely to experience.

2.7. Concluding remarks

The results of operability calculations typically suggest that the criterion that contributes most to Downtime is the LNGC roll. This is particularly true for periods where waves may approach the two side-by-side vessels from the beam (e.g., under the combined effect of swell, wind-sea, current and wind), leading to too small clearance between the two vessels. For other headings, roll motions may contribute to large relative displacements in a translational plane at certain reference locations. Because of this, aspects which contribute to roll response or help to mitigate roll response become important. These include:

- ➢ the LNGC hull geometry and the effect of the close proximity of the LNGC to the FLNG on the roll damping;
- ➢ the effect of partially-filled LNGC tanks on sloshing and on roll of the LNGC;
- ➢ gap resonance and the effect of gap resonance on LNGC motions;
  - use of thruster assistance to change FLNG heading during offloading operation so as to reduce roll, where tugs are used to achieve a requested heading for FLNG prior to offloading operation;
  - use of larger fenders so as to increase allowable roll response.

Among these items, the latter two depend on the availability of fender size, availability of thrusters and captain's decision in the field. In this review we focus further discussion on the first three items, which warrant further fundamental research efforts.

3. Roll estimation and roll damping

3.1. Importance of viscosity and flow separation in roll motions

The above discussions have highlighted the importance of quantifying the roll motion of LNG carriers. For small amplitude waves, the hydrodynamic responses of a ship are generally predicted satisfactorily using linear potential flow theory, except for roll. Viscous forces are important for the damping of the roll response, for which the wave radiation damping is small.

In the absence of a bilge keel, the viscous force can be considered to consist of two contributions, that due to skin friction and that due to the separation of the boundary layer and vortex shedding. The skin friction effect is likely to be rather small at the high Reynolds numbers relevant to a full-scale ship (Kato, 1958). For a vessel with no forward speed, as is the case for the LNG offloading operation, the damping due to the pressure associated with flow separation and vortex shedding from the corners of the hull is therefore of most importance (Vugts, 1968). This is generally more pronounced for cases of bilges with small radii of curvature where the corner is much smaller than the boundary layer thickness (i.e. a sharp corner).

A key non-dimensional parameter relevant to ships in roll and the resulting flow separation regime is the Keulegan-Carpenter number, which for a ship hull oscillating in roll is defined as $KC = UT/L = 2\pi|\xi_4|$, where U is the oscillatory velocity amplitude, T is the period of roll response, L is a representative length-scale and ξ_4 is the roll amplitude (in radians). Visualisation studies such as those by Singh (1979) and Jung (2006) have aided the understanding of the viscous roll damping phenomena and processes. For oscillations at low KC numbers, owing to the small amplitude of angular displacement, the vortices shed from the separation points on the cylinder (representative of a ship hull) are swept back past the body on the next half cycle. In this process, which is generally stable and regular, a vortex pair is created which self-convects away from the separation point and the residual vorticity is engulfed in subsequent vortex generation. This regime is distinct from that occurs at high KC numbers in which a local separated shear layer is commonly observed.

The addition of a bilge keel can be particularly effective in promoting flow separation and enhancing damping. The bilge keel damping comprises components due to the normal force acting on the bilge keel plates, which will result in a strong restoring force in the presence of flow separation, and the hull pressures which result from the shed vortices. Additional discussion of the phenomena associated with viscous roll damping of ship-like structures and the effects of bilge keels, in particular, is provided by Faltinsen (1990). The introduction of bilge keels gives rise to additional complexities in the flow physics as their influence on the total roll damping is dependent on both the roll amplitude (i.e. the *KC* number) and the length of the bilge keel. It is also important to consider that bilge keels can also increase the fluid added mass and, consequently, affect natural period of the roll response.

3.2. Experimental studies

Amongst the earliest reported attempts to quantify the viscous damping was the laboratory study of Vugts (1968) which considered rotating cylinders representative of ship hulls. Two-dimensional damping coefficients were estimated from sinusoidal harmonic motion experiments with roll amplitudes of between 2.9° and 11.5° (i.e. $KC \sim 0.3$ to 1.3) at a range of oscillatory frequencies and aspect ratios. For the sharp-edged rectangular boxes investigated the contribution to the total damping from wave generation was an order of magnitude smaller than the viscous effects, emphasizing the importance of accounting for flow separation and vortex shedding. Furthermore, the beam to draught ratio was found to have a significant effect on the damping. Whilst LNG carriers may be expected to utilise ballast tanks to maintain a near constant draft during offloading, it would be important to consider a range of aspect-ratios in a roll damping assessment if different LNG carriers are to be accommodated.

A series of experimental results for rectangular boxes which were geometrically similar to that used by Vugts (1968) were also reported by Yeung et al. (1998). Forced roll responses for non-dimensional frequencies $\tilde{\omega} = \omega\sqrt{B/2g}$ of between 0.8 and 1.0, where ω is the radial oscillatory frequency and B is the beam, were presented and similar trends were identified in the variation in the damping coefficients with oscillatory frequency and amplitude. Differences in results were found for several cases, however, which were attributed to experimental errors as originally reported by Vugts (1968). The comparatively large structural inertia and the effect of the hydrostatic moment made elucidating the viscous roll damping difficult. This issue is therefore important to consider for experimentalists who aim to obtain reliable estimates of damping coefficients for use in numerical models.

The well-documented Japanese research programmes (collated by Himeno, 1981) have also contributed a wealth of damping data to the literature and have been used to develop empirical correlations based on both geometric and flow parameters. These studies have also reinforced the notion that the damping is influenced by the degree of rounding at the bilge. However, the results for rounded sections presented by Ikeda et al. (1978) exhibited a significant degree of scattering which makes identifying relationships between forcing parameters more challenging. Scaling effects are also expected to be more pronounced compared to sharp corners as the location of the point of flow separation on smooth surfaces is generally dependent on the Reynolds number. This increases the difficulty in applying these results to full-scale vessels, in contrast to the scaling results obtained for sharp corners. Additional literature on the effect of the bilge rounding is scarce, which therefore warrants further investigation.

The challenge in relating these model scale tests to full-scale is further compounded by the lack of reported measurements on ships at full-scale. One of the few reported studies which compared full-scale measurements with model tests was presented by van Dijk et al. (2003) which was based on the Girsassol FPSO in the relatively benign environment of West Africa. The vessel draft, motions, and directional wave properties were acquired over a one-year period and compared with motion transfer functions developed using linear diffraction analyses from which viscous damping contributions could subsequently be inferred. The observed trends in the response of the damping with the sea state were shown to agree qualitatively with model-scale experimental results which is encouraging. Also of interest was the finding of significant roll motions in head seas. This was attributed to directional spreading of the waves, emphasizing the need to account for this phenomenon in any predictions of the vessel roll response in an open sea. However, it is evident that additional full-scale data would be welcomed, particularly for sites where the wave climate is more energetic (e.g. Prelude or Browse on the North West Shelf of Australia, during storms).

3.3. Current industry practices

For early concept selection or preliminary operability studies for which efficient initial estimates of the roll damping are sought, the effect of viscosity is commonly incorporated into potential flow models by introducing an effective damping factor. Himeno (1981) reviewed various methods used by practitioners, many of which remain common practice in the industry today. More recent reviews of the prediction methods have been provided by Ikeda (2004), Falzarano et al. (2015) and Piehl (2016), for instance. The most frequently employed approach, which is referred to as Ikeda's method (see also Kawahara et al. (2012) for a simplified version), involves computing the total damping as a sum of contributions from skin friction, eddy making, lift, bilge keels (due to the normal force, hull pressure and wave damping effects) and potential flow (wave radiation) damping, i.e.

$$B_e = B_F + B_E + B_L + B_{BK} + B_W. \tag{1}$$

These frequency- and geometry-dependent coefficients are estimated through semi-empirical correlations which were devised from the extensive series of experiments undertaken by Ikeda and coworkers for a select series of ship hulls. For a ship-like body, the model is typically applied in a strip-like sense where the damping coefficient is computed for each section and then integrated along the entire length of the hull. As the damping coefficients are functions of the roll amplitude which is not known prior, the use of an iterative procedure is typically adopted. For stochastic-based predictions in irregular seas the ‘equivalent’ linearized damping B_e, is also typically computed through energy considerations (via stochastic linearization), yielding the relation

$$B_e = B_1 + \sqrt{\frac{8}{\pi}}\sigma_{\dot{R}} B_2, \tag{2}$$

where B_1 and B_2 are the linear and quadratic damping coefficients and $\sigma_{\dot{R}}$ is the standard deviation of the roll response amplitude.

There are several shortcomings of this approach which are important to consider. For instance, the damping is typically based on a single operating state without accounting for variations in the mass properties (e.g. draft, position of gravity centre, moments of inertia) of the vessel.

Other limitations which are particularly relevant to the application to side-by-side offloading include the inherent assumption that the skin friction losses and eddy shedding can be treated independently and that the eddy shedding coefficient is independent of the *KC* number. This may not be true if there are large relative motions between the vessel(s) and the surrounding water body, as would be the case for resonant gap free-surface responses. Furthermore, given that the empirical data are based on a single free-floating vessel, it is not clear whether the damping coefficients are appropriate in the case of a LNGC in close proximity to a nearby FLNG where interactions between the two vessels may be significant. This is likely to be the case when the scale of the shed vortices is similar to the size of the gap. This issue is highlighted in the initial two-dimensional analyses by Milne and Graham (2018) of a hull rolling adjacent to a second hull, in which the interaction was attributed to a reduction in the roll damping of the hull by 50%, relative to the isolated hull case.

3.4. Vortex methods

The use of vortex models offers one method of circumventing the reliance on empirically based values in numerical predictions of eddy damping. Vortex models have been employed in various capacities by a range of practitioners as a means of estimating the contribution from shed vortices at sharp corners such as hull bilges. The numerical methods which have been applied to calculate the vortex shedding from sharp corners are discussed by Graham (1977).

Graham (1980) applied a discrete vortex method to model the shedding of vortices about an infinite wedge in oscillatory flow with no forward speed. This condition is kinematically similar to an oscillation of the edge in still flow with the exception of the Froude-Krylov contribution which is in phase with the acceleration. At the low *KC* numbers for which the model was applied it is assumed that the vortices at either edge do not interact and as such the infinite edge is analogous to the flow about an edge of a finite body. Using conformal mapping techniques for simple geometries, the vortex force on a finite body was calculated by matching the local flow about the edge to the flow about the edge of the finite body.

Motivated by the need for a computationally efficient method of incorporating analytical estimates of viscosity into inviscid models, Downie et al. (1988) for a six degree of freedom implementation) extended the model developed by Graham (1980) for a single edge to calculate the roll response of a rectangular barge. An inviscid panel code was used to calculate the velocities at the shedding edge of the barge, thus allowing for complicated geometries to be considered. The flow conditions at the corner were then matched with the isolated edge results of Graham (1980) in a transformed plane to compute the viscous force. More recently Hajiarab et al. (2010) and Graham and Downie (2015) have also demonstrated this approach for calculating the roll response of barges in both regular and irregular waves. The ability to couple the model with a potential flow code of a type commonly utilised in the industry is particularly attractive for operability studies.

Other researchers have also employed the vortex method for predicting roll, including Brown and Patel (1985) and Yeung and Vaidhyanathan (1994). The Free-Surface Random Vortex Method (FSRVM) that was developed by Yeung and Vaidhyanathan focused on solving the Navier-Stokes equations in the presence of a free surface. Several applications of the model have been reported in the literature to demonstrate its performance. In the aforementioned study by Yeung et al. (1998), experimental results on the roll for a rectangular box were successfully compared with numerical predictions from the FSRVM model.

A key advantage of vortex methods over Navier-Stokes solutions is that they are likely to be much faster to apply. Hence, they are an attractive approach provided that they can be proved to be sufficiently accurate. In particular, a single computationally expensive vortex solution can be employed to obtain results for the complete range of motions of the vessel (Downie et al., 1988). Whilst vortex models are very well suited to sharp-edged corners (such as square bilges), they generally require ab initio knowledge of the separation point, which for rounded hull corners will vary with hull form and flow parameters. As such, their application to complex hull forms is challenging. Furthermore, it remains to be established whether vortex models for an isolated corner can be suitably applied in the case of a hull rolling very close to a second hull (as in the case for side-by-side offloading) for which its own eddy shedding may lead to strong vortex-vortex interactions. Finally, it is also worth noting that there is limited literature on 3D applications of vortex methods and the three-dimensional structure and subsequent evolution of vortices have been ignored.

3.5. Navier-Stokes solutions

Applications of the full Navier-Stokes solutions have been comparatively more limited in offshore station-keeping analyses, for which the number of load cases that are required to be considered can be prohibitively large and for which stable simulations remain a challenge. Navier-Stokes solutions may, however, have particular value in situations where the physics is significantly non-linear or for complex geometries, such as roll damping of vessels in a side-by-side configuration. Furthermore, with the increasing availability of computational resources these methods are likely to become more widely adopted in practice.

There are now numerous examples of the application of CFD schemes for two-dimensional forces on ship-like hull sections in the research literature which focus on roll damping. Jaouen (2011) for instance, presented computations of the damping for a completely submerged (i.e. single phase flow) two-dimensional hull with sharp and rounded bilges in roll using both in-house and commercial CFD codes. The use of a single phase fluid enabled the eddy damping to be explicitly quantified. The results were validated against the experimental data of Ikeda by removing the effect of radiation damping at the surface (estimated from a potential flow solution). Whilst favorable agreement was found, the results were demonstrated to be sensitive to both the mesh resolution and the time step, emphasizing the care that is required in order to obtain reliable numerical results.

Simulations which include a free surface are inherently more challenging since it is very difficult to implement an appropriate radiation condition to prevent outgoing waves from reflecting at the computational boundary. This generally necessitates relatively large (and computationally expensive) domains and, typically, the use of blending functions or relaxation methods for the absorption of outgoing (or even introduction of incident) waves. Examples of such a simulation were provided by Kinnas et al. (2007) for instance, who computed pressure distributions and moments for the forced roll motion of a rectangular cylinder with a sharp-edged bilge, a rounded bilge, and a bilge keel. In an attempt to overcome the difficulty imposed by the free-surface, an irrotational/vortical split-flow technique based on a Helmholtz decomposition was utilised by Kendon (2005). A linear potential flow solver was applied to the outer domain while a spectral Navier-Stokes model was utilised to model the rotational field in the vicinity of the body. The model was validated in two-dimensions for a stationary body in regular waves and for the steady sway and roll motion of rectangular barge sections. While favorable results were generally found, the comparisons with forced oscillation literature of Vugts etc. showed that the viscous damping was either underpredicted or overpredicted depending on the aspect ratio investigated. However, given that the computations are inherently quicker than a full CFD solution and the ability to couple a vortex model with a three-dimensional potential solver as commonly used in industry, it is expected that such a combined method is likely to remain popular.

3.6. Research opportunities on roll motions

Whilst there exists a wealth of literature on roll damping for single hulls, few studies have investigated the roll damping of a vessel in proximity to a second vessel analogous to the LNG side-by-side offloading process. There remains a need to understand both the underlying physical flow phenomena and, most pressing from an industry viewpoint, obtain reliable damping factors which can be incorporated into efficient simulation tools. To facilitate this, several specific research opportunities that have been identified.

As the majority of model-scale experiments for side-by-side offloading have been performed with the vessels fixed and subjected to unsteady flow, experiments in which the vessel is rotated in forced oscillation, or able to rotate in response to waves should enable the roll damping to be quantified with more certainty. For instance, such a set-up could be expected to permit a more realistic varying gap width and relative velocity around the bilge. Given that the dynamic response of the FLNG facility is likely to be significantly smaller than the LNGC, initially, it appears advantageous to simplify the experiment by maintaining the FLNG fixed and releasing a single degree of freedom (roll) for the LNGC. Furthermore, given the comparatively greater draft of the FLNG, it is expected that informative results may be obtained by rotating the LNGC model in close proximity to an infinite wall (i.e. a wall of the wave basin). As confidence in the experimental methodologies develops, the experiments could increase in complexity to consider additional degrees of freedom and ultimately incorporate field data from LNGC's during the side-by-side offloading process.

Numerical modelling is also expected to facilitate a greater understanding of the complex fundamental hydrodynamics. Both two-dimensional and three-dimensional models should be developed and validated with the results of the aforementioned experimental testing. Given the relatively small gaps between the two vessels, specific attention should be directed to the meshing techniques and dynamic solvers utilised to simulate the dynamic motion. The use of sliding interfaces, remeshing or overset techniques are likely to be necessary in order to permit large mesh displacements and avoid high levels of skewness. Of particular interest will be utilising CFD to establish the effect of scaling and the bilge radius or bilge keel on the eddy component of the roll damping.

In order to develop efficient simulation techniques for the needs of the industry, it is of interest to demonstrate the applicability of incorporating both the experimentally and numerically acquired damping coefficients in a three-dimensional panel code. Methods which couple the solution for the local flow around the bilge, computed through a CFD or a discrete vortex model, to an inviscid outer flow similar to those described in the preceding sections are likely to be of most interest.

4. Sloshing of partially-filled liquid cargo

In a typical side-by-side offloading operation, both the FLNG and LNGC are expected to experience partially filled conditions, where a free surface exists within the liquid cargo tanks. The associated risks to SBS offloading are that wave-excited vessel motions may excite sloshing which could damage the internal tank walls or feedback to enhance the vessel motions. To demonstrate the complex coupling between vessel motions and liquid cargo sloshing, we provide the response spectra of a barge roll motions and the corresponding sloshing modes in Fig. 6 where details can be found in Zhao et al. (2018a).

It is common practice to conduct a free-surface correction of the metacentric height in the assessment of the stability of a floating vessel, which is in fact treated as a specific quasi-static tank sloshing phenomenon. This assumes that the tank motion frequencies are much lower than natural sloshing frequencies (Faltinsen and Timokha, 2015). The "sloshing" discussed here refers to resonant free-surface motions, where the natural frequencies and corresponding modes are governed by the tank shape and the ratio of the liquid cargo filling depth (h) to tank size (l) in the direction of the liquid cargo motions. Based on linear potential flow theory, Faltinsen and Timokha (2015) provided the natural frequencies of the sloshing modes for a 2D rectangular tank $\omega_n = \sqrt{g\frac{n\pi}{l}\tanh\left(\frac{n\pi}{l}h\right)}$, where n is the sloshing mode, equivalent to the usual finite depth version of the linear dispersion equation for water waves.

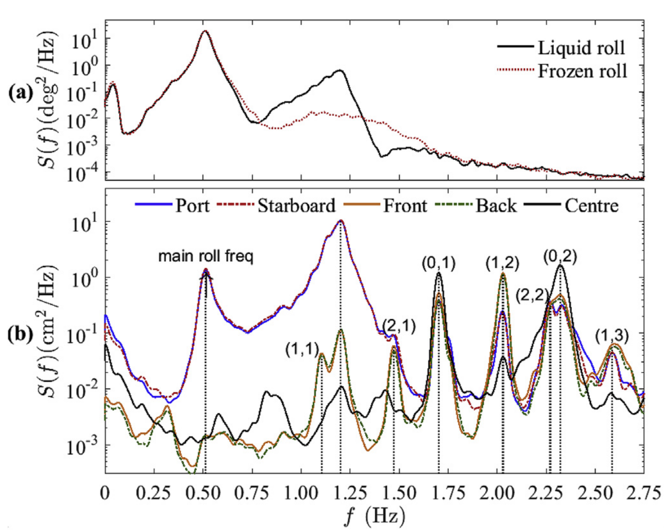

Fig. 6. Spectra of the coupled responses between liquid cargo sloshing in spherical tanks and global vessel roll motions. (a) is for global roll motions and (b) for sloshing measured at different locations in the same spherical tank, where 'Port' refers to the gauge located on the weather side, while 'Starboard' is on the opposite side. 'Centre' is the vertical gauge going through the centre of the spherical tank. The pairs in brackets represent different sloshing modes. Figure after Zhao et al., 2018a.

The influence of liquid cargo sloshing is related to the shapes of the storage tanks, which usually are prismatic or spherical. The main problem associated with prismatic tanks is the potential damage to tank walls from peak impact sloshing pressures as a result of the excitation and growth of standing sloshing waves. The sloshing phenomenon in spherical tanks may be severe due to the smooth internal surface (i.e. lack of baffles) and large tank size. However, it is hard to induce damage to the side walls due to the spherical shape (with a lack of edges or corners). As a consequence, few studies have focused on estimating impact pressures in spherical storage tanks, but rather more for prismatic tanks. Faltinsen (1978) undertook numerical simulations using a nonlinear model and the boundary integral technique for a 2D rectangular tank subjected to forced sway harmonic oscillations. A three-dimensional model based on the finite element method for the sloshing flows inside a rectangular tank under translational excitations was developed by Wu et al. (1998). Experimentally, Akyildiz and Unal (2005) investigated a rectangular tank excited in pitch with systematically changed amplitudes to assess the sensitivity of sloshing loads on the walls. In that work baffles were observed to reduce fluid motion significantly. In addition to the study of Akyildiz and Unal (2005), quite a few other studies focusing on the impact pressure induced by nonlinear sloshing have been undertaken. A comprehensive review of these is given in Ibrahim et al. (2001).

Compared to the possibility of significant internal sloshing motions inside storage tanks of an LNGC, the effect of sloshing on the global motions of an FLNG facility such as Prelude is unlikely to be significant due to its large size. Also Prelude has been designed with twin rows of storage tanks. Hence the effect of sloshing should be small even at offshore locations with swell approaching the vessels from the beam, a condition where roll motions of the vessels may be significant (see Fig. 3). In contrast, the wave-induced LNGC roll motions may induce relatively strong sloshing motion of the internal liquid cargo, which may in turn affect the global motions of the LNGC, in particular the roll motions. This is because LNGCs are smaller and they are usually designed with a single-row of LNG storage tanks. Roll motion of LNGCs is an important design criterion that may dominate side-by-side offloading operability, as illustrated in Table 1 and the discussion in Section 2.7. As a consequence, it is of primary practical interest to understand the sloshing effect on the global roll motions of LNGCs.

4.1. Numerical studies of vessel motions coupled with sloshing

Based on the assumption of linear sloshing flows inside the tanks, there have been classical numerical studies on the coupled problem of sloshing and global vessel motions (Molin et al., 2002a,b; Malenica et al., 2003; Newman, 2005). These frequency domain analyses, based on linear potential flow theory, are able to generate results which agree fairly well with experimental data, as in Newman's keynote presentation (2004). However, it should be noted that the numerical simulations shown in Fig. 7 appear to suggest that the simulated natural frequencies of roll differ slightly from those measured. Unfortunately, there is no convincing explanation for this difference. With nonlinear analyses of the internal flow in tanks, Rognebakke and Faltinsen (2003) investigated ship motions coupled to internal sloshing, again based on potential flow theory. In their studies the vessel had a very simple geometry, namely a rectangular box. For a vessel with more complex geometry, Lee et al.

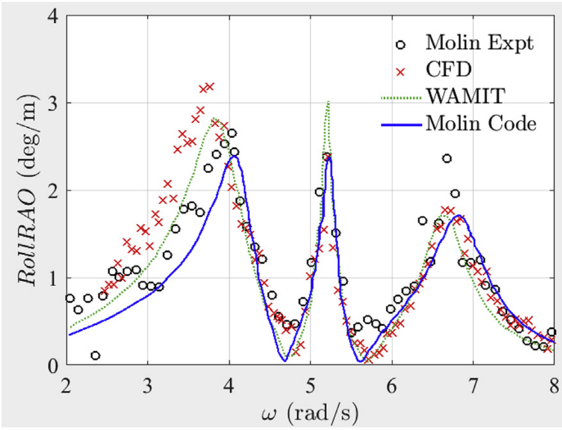

Fig. 7. Roll RAOs considering internal sloshing given by different methods: 'Molin Expt' and 'Molin Code' refer to the experimental and theoretical results in Molin et al. (2002a,b), 'CFD' refers to the numerical simulations in Serván-Camas et al. (2016), 'WAMIT' refers to the WAMIT results presented by Newman (2004).

(2007) and Lee and Kim (2010) conducted time domain simulations where linear potential flow was assumed for the external waves and the nonlinear internal sloshing was simulated based on a computational fluid dynamics (CFD) scheme using a finite difference method. A similar study was carried out by Jiang et al. (2015) based on the same assumption, where the nonlinear internal sloshing was considered through the volume of fluid (VOF) method. It was observed that the impact loads due to internal sloshing did not show a significant coupling effect on global ship response. Based on a finite element method (FEM) for the simulation of nonlinear sloshing, Mitra et al. (2012) went one step further to carry out numerical simulations in the time domain where nonlinear ship motion is adopted. Serván-Camas et al. (2016) carried out time-domain simulations where the nonlinear internal sloshing is modelled through a smooth particle hydrodynamics solver and the seakeeping problem is calculated through an FEM diffraction-radiation solver. The numerical results agree well with the experimental data presented by Molin et al. (2002a,b) at the first response peak, however there is an obvious difference at the second peak of the roll response amplitude operators. x7.

It appears that the methods based on linear assumptions fail to incorporate the strong nonlinearities of violent internal sloshing when this is potentially threatening to tank integrity, while CFD methods are computationally expensive and often require validation with experimental testing. For engineering practice, linear potential flow solvers are preferable due to their time efficiency. However guidance from CFD simulations or model tests may be necessary to identify the effects of the internal sloshing and visualize the complex sloshing flow in tanks. This is particularly true for the assessment of side-by-side operability, because LNGC roll is the limiting criterion. To obtain more reliable prediction of roll motions coupled to internal sloshing, a combination of a linear potential flow solver (for linear vessel motions) and CFD model (for nonlinear sloshing) is likely to be merited.

4.2. Experimental studies of vessel motions coupled with sloshing

Early experiments on vessel motions coupled to liquid cargo motions can be traced back to the work by Mikelis et al. (1984), in which the coupled problem was investigated based on a carrier with prismatic tanks. Francescutto and Contento (1994) experimentally studied the coupling between ship roll motions and the sloshing in a floodable compartment, with the ship subjected to a beam sea condition. Molin et al. (2002a,b) conducted experiments using a barge-like vessel with a partially filled rectangular tank on deck, subjecting it to the combined excitations of roll, sway and heave. As discussed in the previous section, Molin's experiments have been widely used by other researchers for validation. A series of experiments was conducted by (D) Zhao et al. (2018), providing insight into the coupling between ship motion and liquid sloshing in rectangular tanks. Nam and Kim (2007) carried out an experimental study on a barge equipped with two partially filled prismatic tanks, showing the importance of a fully-coupled analysis, in particular for roll motions. With a similar experimental set-up, Nasar et al. (2008, 2010) conducted an experimental study on the effects of intermediate load conditions. In their studies, the centre of gravity, the radius of gyration and the total mass are different as load conditions vary, for example when replacing the solid weights by water. Therefore, it is hard to identify the effects of the internal sloshing on global motions through these studies.

In an effort to provide improved understanding and to obtain a unique control parameter when load conditions vary, Zhao et al. (2014a, 2014b) conducted a series of experimental studies that considered sloshing coupled with roll only, as well as sloshing coupled with roll, sway and heave motions for rectangular tanks. These results have aided academic research and have served as benchmark data for numerical simulations, for instance in the study by Serván-Camas et al. (2016). However, it is useful to identify the most severe loading condition for the assessment of the side-by-side offloading operability. Zhao and McPhail (2017) carried out large scale model tests focusing on the global roll response coupled with liquid cargo motions inside spherical tanks such as are used on Moss-type LNG carriers. In their studies, they clarified the effect of the internal sloshing in spherical tanks on global roll motions for the first time. As another part of these experimental studies, Zhao et al. (2016a) identified the most severe loading conditions by considering the liquid cargo sloshing. These results have been used by industry for practical engineering projects.

4.3. Research opportunities on sloshing

As shown in Fig. 7, which shows results from the best practice for predicting roll motions coupling to sloshing, one can see that more efforts should be taken to understand the differences between numerical simulations and the experimental data. It is essential to develop a numerical model that is able to provide reliable predictions of the vessel motions coupling to sloshing, in particular the roll motion which is very sensitive to damping levels.

To the authors' knowledge, there is no publically available report which clarifies the most severe loading condition for LNGCs with prismatic tanks and provides guidance on whether it is worthwhile or even necessary to incorporate intermediate loading (partial fill) conditions when assessing side-by-side offloading. As a consequence, further experimental studies focusing on the coupling of vessel motions and prismatic tank sloshing may be valuable.

It should also be noted that the lowest natural period of internal sloshing is about 7.5 s at full scale and the natural period of LNGC roll is around 15 s. Therefore, the internal sloshing may couple to the second harmonic of the LNGC roll (Zhao et al., 2016b, 2018a). Further study in this area will be merited for safe operations.

5. Gap resonance between two side-by-side vessels

During side-by-side offloading operations, the water in the narrow gap between the vessels may be excited into resonant oscillation under certain incident wave conditions. The resulting vigorous free-surface motion may play an important role in limiting the side-by-side operation, e.g. resulting in green water on the deck of carriers, large drift force between the two vessels or increased relative motions. Gap resonance is of significant interest for academia due to the interesting geometry and the strongly resonant phenomenon where viscous damping plays an important role, as shown in Fig. 8. Recent developments in gap resonance studies are reviewed in this section for both numerical simulations and experimental studies, and directions for future studies are discussed.

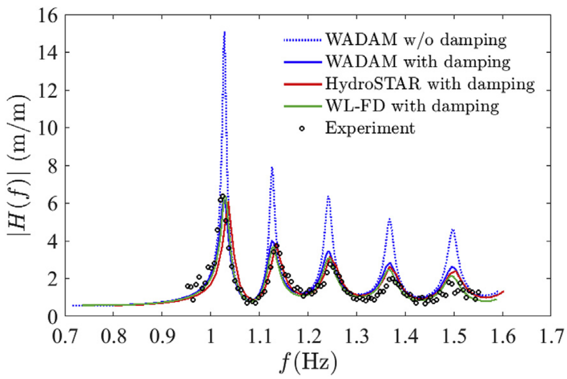

Fig. 8. Numerical and experimental RAOs for gap resonance using different commercial codes (gap width of 0.0667 m, depth of 0.185 m and length of 3.333 m). The dashed line is linear potential flow prediction without artificial damping and the solid lines for potential flow predictions with artificial damping introduced via different methods. Figure after Zhao et al., 2018b.

5.1. Moon-pool and gap resonance

Gap resonance problems share some features with moon-pool resonances, for which Molin (2001) derived an analytical formula to estimate the natural frequencies and associated modal shapes of the resonant modes based on linear potential flow theory. Modes with profiles both along and across the moon-pool were found. As suggested by Newman and Sclavounos (1988), the natural modes in the gap can be derived theoretically by applying a homogeneous Dirichlet condition at the ends. Molin et al. (2002a,b) extended his approach for the moon-pool problem, to provide an approximate prediction of the natural frequencies of the gap resonant modes. A comprehensive study of the frequencies, modal shapes and response amplitudes for the free surface in the gap between two fixed vessels was made by Sun et al. (2010) using potential flow diffraction theory at first and second order. Also as part of the Safe Offload JIP, Perić and Swan (2015) experimentally identified several different mode shapes, as well as contributions from higher harmonics.

Several investigations into the behaviour of 2D geometries consisting of rectangular boxes separated by a gap have been reported. This represents an idealisation of both the moon-pool and gap resonance problems, so it is important to note that all effects of fluid motion along the gap are removed. Several 2D investigations have shown that linear potential theory overpredicts experimentally determined peak resonant response amplitudes for sinusoidal excitation (e.g. Faltinsen et al., 2007; Lu et al., 2011). In 3D, the same effect has been reported for tests on side-by-side fixed vessels (e.g. Pauw et al., 2007; Molin et al., 2009; Zhao et al., 2017), although the overprediction is smaller.

Many methods to improve the level of agreement between potential flow calculations and the results of physical experiments have been proposed, including rigid (Huijsmans et al., 2001) or flexible lids at each (generalised) mode (Newman, 2001) and a dissipative damping term in the free-surface condition (Chen, 2005). The selection of the additional damping coefficient is generally empirical, being based on a fit to model test data, emphasizing again the importance of model tests.

The possible sources of this discrepancy between linear potential theory and model tests are generally held to be viscous effects associated with flow separation and nonlinear free-surface boundary conditions. Much work asserts, or assumes, that flow separation is the main source of the discrepancy (e.g. Kristiansen and Faltinsen, 2008; Molin et al., 2009; Kristiansen and Faltinsen, 2012). Feng and Bai (2015) carried out numerical simulations of the fully nonlinear potential flow equations, and reported that nonlinearity may slightly increase the resonant frequency, though with limited effect on the amplitude.

The recent linear potential flow calculations reported by Chua et al. (2016) showed good agreement with experimental results when damping due to flow separation and skin friction was incorporated. Chua et al. (2017) developed a framework to provide the damping coefficient for different components based on viscous CFD computations, which were further incorporated into a modified linear potential flow time-domain model. This type of model could be useful for the design of FLNG facilities when the operability of various hull forms may be assessed. It appears that the accuracy of potential flow theory is dependent on bilge geometry - in hull forms with square bilges, potential flow overestimates the resonant response amplitude by a larger amount compared to those with rounded bilge corners. This is likely due to larger dissipative effects arising from flow separation and shedding occurring at the square edge, compared to edges with rounding. Without performing dedicated model tests, Faltinsen and Timokha (2015) estimated the damping coefficient for sharp cornered boxes by combining the approximation of Molin (2001) and the pressure drop coefficient formula for a slatted screen. Their estimation of the additional damping coefficient is, however, based on the behaviour of slatted screens, and thus requires experimental calibration.

The primary importance of gap resonance in a side-by-side offloading context is that it can couple to vessel motions (though the size of the oscillation may be important for other reasons, such as water splashing onto deck). Although a variety of modes are present in the gap, only the lowest few modes tend to couple to motions, as shown, for example, by Sun et al. (2015) who numerically investigated RAOs and QTFs for an FLNG vessel next to a carrier using potential flow theory, so only including the effect of wave radiation damping. Sun's et al. (2015) results also showed that the frequencies at which large free surface oscillations occur in the case of linearly responding vessels are different from the frequencies of oscillation for fixed vessels, as expected for the coupled problem and borne out by the experiments of Peric and Swan (2015), where it was also shown that the mode shapes in the two problems may be different. It is worth noting that the motions of a LNGC next to a FLNG vessel may be complex even away from gap resonance frequencies – this is demonstrated in Sun et al. (2015), where, to take one example, non-negligible roll was predicted in head seas. Investigations of motions of side-by-side bodies have also been carried out by other researchers, for example, Hong et al. (2015) and Koo and Kim (2005).

One may note that the roll natural period of LNGCs is around 15 s, the natural periods of the lowest gap resonance and internal sloshing modes are around 7.5 s, and swells may have a period of 15 s. In such a scenario, second harmonics of the gap resonance may be driven by a frequency-doubling process (as observed by Zhao et al., 2017), which may enhance the roll motions of the LNGC which further couple to internal sloshing. This would be a very complex coupling phenomenon due to the nonlinearity of each process. However, this complex coupling process can be identified through well-designed model tests and novel analysis methodology (as in Zhao et al., 2018a).

To summarize, the majority of the existing studies have concentrated on the analysis of the maximum gap resonant amplitude at steady state in regular waves. Based on the literature to date, it can also be concluded that potential flow theory is able to provide a reasonable prediction only by introducing extra damping coefficients, which are generally empirical and need to be validated against experimental data. However, a few aspects have been missed, and are discussed in detail in the following section.

5.2. Research opportunities on gap resonance

5.2.1. Non-steady state gap resonant response

Gap resonance is of practical interest because the damping is low, which means that it may take a long time to reach steady state, particularly for narrow gaps. Fig. 9 shows a typical gap resonance time history under regular waves measured in a large wave basin, taking 35 cycles to reach a steady state. However, reaching steady state is not straightforward in tank experiments, as after the long build-up time, reflected waves may affect the experiments. In addition, real ocean waves are not regular. These points have led to interest in the behaviour of the fluid in the gap in

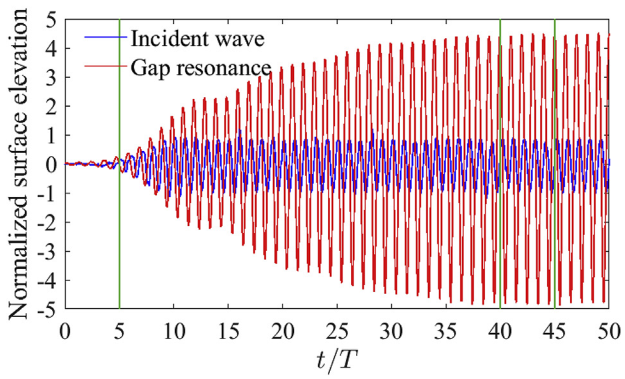

Fig. 9. Time history of gap resonance under regular wave excitations. The first vertical green line (left) indicates the instance when the wave arrives at the gap, the middle vertical one indicates the instance when the gap resonance reach a steady state, and reflected waves may arrive at the gap at the third vertical green line (right). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

transient wave groups as considered by Eatock Taylor et al. (2008), who numerically studied the gap resonant response under focused wave groups. Experimentally, wave groups have been used to examine gap resonances by Clauss et al. (2013) and Peric and Swan (2015), although in these cases the emphasis was on deriving regular wave response coefficients from the results rather than on the transient gap behaviour. Focusing on the transient behaviour of the gap, as was done numerically by Eatock Taylor et al. (2008), Zhao et al. (2017) carried out a series of large scale experimental studies, where the two fixed models had round bilges. Examining the free decay (after the forcing has vanished), the viscous damping of the gap resonance was found to be linear at the laboratory scale, and for wave amplitudes used and entirely consistent with Stokes-like oscillatory laminar boundary layer damping. In addition, Zhao et al. (2018c) investigated the designer wave groups that give the large gap resonant response.

CFD simulations of the gap resonance problem are mainly conducted in 2D, while very few studies have been reported in 3D. This may be due to the fact that the gap resonance will take quite a few cycles to reach steady state, which requires large computational resources. The transient wave group test results given by Zhao et al. (2017) provide very good benchmark data for 3D CFD simulations, and much shorter time needs to be simulated. Due to the narrow gap size, it is technically challenging to visualize the flow field in the gap in an experiment at a large size wave basin. Therefore, well resolved 3D CFD simulations are very important in examining gap resonance problems in more detail.

5.2.2. Scaling effects

As stated in Section 5.1, it is a common industry practice to introduce artificial damping to obtain the gap resonance (to limit it well below that predicted by potential flow modelling), where the determination of the damping coefficients is generally based on a fit to model test data. Due to the limitation of wave basin dimensions, the majority of the model tests have been carried out at small scales, e.g. around or less than 1: 100 (e.g. Perić and Swan, 2015). These small-scale tests have a problem in common: the flow regime for the parts of the flow where viscous effects are important is very different to that at full scale (e.g. Chakrabarti, 2001), and thus lab-scale results may suffer from scaling effects when extrapolated to full scale for engineering practice.

Therefore, a comprehensive study of the scaling effect, covering from small scale to large scale and ultimately to full scale, should be carried out. Unfortunately, large scale model tests are difficult and little field measurement information is publicly available, at least for FLNG facilities. Ship-to-Ship transfers of hydrocarbons are relatively regular operations worldwide, but they are carried out over typically much wider gaps than FLNG because of the ready availability of flexible hoses. Field measurement data will therefore be of great value (i) for future study and feedback for current design practice; (ii) in identifying new phenomena which are not possible based on numerical simulations and scaled model tests where a few assumptions have been made.

Field data will be measured for Prelude FLNG, including sea states, vessel motions and the gap resonance. This should provide the opportunity to explore the scaling effects based on numerical simulations (using both potential flow model and CFD), scaled model testing and field measurements in combination. To explore the scaling effects, the gap resonance phenomenon would be an ideal topic, because (i) it is a strongly resonant phenomenon, (ii) the radiation damping in gap resonance is small and thus viscous damping becomes important, and (iii) the flow regime in which is remarkably different from laboratory to field.

5.2.3. Large scale model tests and empirical estimation of viscous damping

The majority of existing experimental studies have been focused on gap widths which are wide and thus not directly relevant to side-by-side offloading, and thus experimental studies focusing on narrow gaps are warranted. The Stokes boundary layer assumption for the viscous damping (Zhao et al., 2017) makes it possible to obtain the damping coefficients theoretically, but this is likely to be true only at lab scale for round bilges. It remains unclear whether, at lab scale, viscous damping in gaps with square bilges is dominated by separation-induced losses or not. So further experimental study of gap resonance for the square bilge case is necessary.

The drift force between the two vessels is a very important design parameter for the connecting system between the two vessels. However, there are few studies measuring the drift forces. In future large scale model tests, these should be measured as well.

As the gap width gets bigger, potential flow theory is able to produce results which match the experimental data well. However, a systematic study is needed to identify the critical gap width at which viscous damping becomes important. Regardless, it will be very helpful to generate empirical formulas to estimate the viscous damping effects, as has been done for roll damping by Ikeda et al. (1978).

6. Concluding remarks and recommendations

This review has demonstrated that there is a clear need to develop guidelines to improve the assessment of side-by-side offloading operability for FLNG facilities. These guidelines must be backed by models to predict roll motion of LNGCs, which requires, in turn, reliable hydrodynamic models for roll damping (without forward speed), internal sloshing and gap resonance.

Recent developments associated with these areas have been reviewed in this paper and as a result research priorities have been identified. It is a challenge to build up a numerical model to fully take into account the roll damping of carriers, internal cargo sloshing and the gap resonance in between two side-by-side vessels. It is envisaged that scaled model tests would be able to capture much of the complex coupling responses. However, field data will be of significant value to aid in understanding different aspects of the physics, the effect of scaling and to test computational models. These field campaigns will require synchronising measurements of the vessel motions, the local wave field in the gap and the relevant incoming waves (so the sea state), thus necessitating careful planning. The industry best practice model which has been developed to assess the operability for side-by-side offloading (detailed in Section 2) is expected to be updated based on the acquisition of the field data so as to close the design loop.

It should be noted that this review has been conducted primarily in the context of side-by-side offloading operations of LNG in open seas. However, the knowledge in this study is also expected to provide valuable insights for a wide range of offshore operations where multiple offshore structures involved. These include the ship-to-ship transfer of liquids such as crude oil and cargos such as iron ore.

It is clear from this review that industry/academia collaboration has proved vital in achieving the advances to date, and it is recommended that such joint studies be continued in order to understand the complex hydrodynamic behaviour described here and the implications for design. The authors' various contributions in partnership with industry are examples of this, and have informed parts of this review. Two areas of work in progress concern the coupling between global roll motions and internal sloshing in spherical LNG tanks (e.g. Zhao et al., 2016a; Zhao et al., 2018c); and the combined effects on gap resonance responses of both linear wave excitation and frequency doubling effects. This latter phenomenon is of interest for practical applications where long period swells are involved (e.g. Zhao et al., 2017). Another issue is the effect of viscous damping: in the large scale experiments of Zhao et al. (2018a) the viscous damping in narrow gaps was observed to have a linear form, though bilge corner effects need further clarification. It has been found that a valuable methodology in this work is the use of NewWave-type analysis, which may be used in a variety of different applications; including for extracting important and robust features in responses to non-deterministic waves (e.g. Zhao et al., 2018a; Zhao et al., 2018c). It is expected that this approach will also be needed in the future when field data (random signals) from e.g. Prelude are compared with laboratory data (highly controlled deterministic signals), to inform the significance of geometric scaling from laboratory scale to full scale.

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