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Research Article

Ships and sea structures with a hydrodynamic perspective*

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ABSTRACT

This article concentrates on aspects of marine technology such as fish cages, ships, sea structures, and marine operations. It addresses net cages and closed-containment fish farms through sloshing while discussing both displacement and high-speed vessels. The ship topics under consideration include CO_2 emissions in waves, dynamic instabilities, whipping and springing, maneuvering in waves, and sloshing-induced slamming in prismatic LNG tanks. The considered sea structures include offshore platforms used for gas and oil exploration and production and for renewable energy. The article also discusses lowering and lifting of objects through the free surface from ships and addresses the accidental dropping of pipes during lifting operations from a vessel onto drilling rigs. The emphasis is on simplified theoretical modelling and scaling of model tests.

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1. INTRODUCTION

A broad variety of ships and sea structures are involved in transportation, oil and gas exploration and production, marine operations, oil-spill recovery, renewable energy, infrastructure, and aquaculture. Hydrodynamics, whether alone or in combination with structural mechanics and automatic controls, matters in design and operation. The hydroelastic effects of ultra-deep and ultra-long structures play a part in hydrodynamic scenarios. Oil and gas production moves into increasingly deeper water toward depths of 3000 m.

The challenges for platforms in ultra-deep water involve the profiles of complex currents acting through the whole water column, internal waves associated with vertical density variations, the weights of risers and mooring systems, complex installation and retrieval operations, low ambient temperature, and large hydrostatic pressures. The fact that about 80% of the oceans are deeper than 3km opens the path to challenging explorations, mappings, and industrial developments from a long-term perspective. Submersible developments and ocean mining are part of these scenarios. Examples of ultra-long structures include seismic cables, floating airports, and the submerged floating bridges with lengths of about 4km, which are intended for crossing fjords on Norway's West Coast Membrane structures involving strong hydroelastic coupling with internal and external flow have been proposed for fresh water transportation and fish farming.

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The hydrodynamic toolbox contains approximate rational and empirical numerical methods, experiments, and computational fluid dynamics (CFD). A broad variety of CFD methods exist involving grid and particle methods (Faltinsen & Timokha, 2009). CFD has a great advantage in flow visualization and modeling complex configurations. CFD has gained increased in popularity, but the computational time limits the ability to obtain probability distributions of wave-induced loads and responses in designing sea states.

This article mainly concentrates on the aspects of marine operations and marine technology with regard to fish cages, ships, and sea structures and discusses both displacement and high-speed vessels. The sea structures taken under consideration include offshore platforms used for renewable energy and for gas and oil exploration and production.

2. AQUACULTURE

The expected increase in world population will require more food. A large potential exists for increasing marine food production. The total bio production measured in calories is equally divided between land and water. However, only about 2% of the food production used for human consumption comes from water. Increased aquaculture is therefore expected in the future. The trend is found toward moving marine fish farms to more exposed areas. Fish farms will be subjected to more energetic waves and stronger currents. Furthermore, the dimensions of the fish farms are expected to increase, and new designs will appear. Consequently, the importance of marine technology will also increase. Damaged and collapsed floating fish farms have led to fish escaping and thereby major economic losses. Damages can be caused by operational failures, broken mooring lines, anchor pull out, or chains/ropes contacting the net. Escaped farmed salmon may breed with wild salmon and lead to genetic pollution of the wild fish. Salmon lice is another concern. Multi-trophic aquaculture is used to deal with feces and feed spills from fish net cages to give nutrients to mussels and kelps, for example. Feed availability is a critical factor for the sustainable growth of aquaculture. The use of red feed has been proposed in fish oil production, which requires designing fishing nets with very small openings.

2.1. Net cages

A variety of floating fish farms exist with net cages, such as those with circular plastic collars and interconnected hinged-steel fish farms. The floater of the circular plastic collar fish farm is made of high- density polyethylene (HDPE) pipes, commonly with two nearly semi-submerged concentric pipe circles (Fig. 1). An example of net cage dimensions in protected water is 50 m in diameter and 30m in height. The solidity ratio (Sn) is an important parameter of netting and for plane netting is the ratio of the area of the shadow projected by wire (twine) meshes on a plane parallel to the screen to the total area contained within the frame of the screen. A net's typical twine diameter is 3 mm. The solidity ratio of the netting may vary from 0.15 to 0.32, but biofouling can substantially increase the effective solidity ratio. A bottom weight ring (sinker tube) is often used instead of bottom weights to ensure sufficient volume of the net cage.

Figure 1. Floating fish farm with circular plastic collar consisting of two tori that are nearly semi-submerged in calm water, the railing, jump net, netting, dead fish removal system, rope framework, and bottom weights (Sintef Fisheries and Aquaculture).

Sufficient water exchange in a net cage matters for fish health and growth. Important factors are: a) available support of oxygen compared to the size and amount of fish, b) removal of refuse from and under the cages, and c) natural current velocity for fish's exercise and well-being. One consideration is minimum net deformation to ensure sufficient net cage volume. Currents deform the net cage, thereby reducing the net cage volume and affecting current loads. The netting may consequently come in contact with the weight rope or with the chains supporting a bottom weight ring with the possibility of damaging the netting. An improperly designed bottom weight ring may considerably deform under severe weather conditions and damage the net. Large snap loads due to the elastic behavior of the net structure and the relative motion between the floater and the net can occur. Bardestani and Faltinsen (2013) experimentally and numerically predicted the latter under approximated 2D flow conditions.

The fact that netting may have 10 million meshes limits CFD and the complete structural modeling. Kristiansen and Faltinsen (2012) proposed an experimentally based screen type of force model for the viscous hydrodynamic loads on nets in ambient currents. The model divides the net into a number of flat net panels (i.e., screens). The normal and transverse force components on a panel are functions of the solidity ratio, the inflow angle, and the Reynolds number, with the twine diameter as the characteristic length. Knots are neglected, and circular twine cross-sections are assumed. Shielding effects from the twines are implicitly accounted for and matter for large net deformations. A uniform turbulent wake is assumed inside the cage based on Løland's (1991) formula for cross-flow past a plane net. The fact that some of the incident flow goes around the net cage is neglected. The importance of the latter effect increases with increases in the solidity ratio. A dynamic truss model based on Le Bris and Marichal (1998) and Marichal (2003) describes the net structure. The number of trusses and their arrangement follow from convergence studies. The net shape is analyzed in a time-stepping procedure that involves solving a linear system of equations for the unknown tensions at each time step. This means that the problem in ambient current is solved as an initial value problem instead of iterating to find the steady net configuration. Satisfactory agreement has been documented between the experimental and numerical predictions of drag and lift on circular bottomless net cages in steady current as a function of the solidity ratio of the net and the current velocity. The screen model can easily be generalized to combine waves and current by applying the wake model inside the cage only to the steady flow (Kristiansen & Faltinsen, 2014). The bottom weight system implies Froude scaling in model tests. Reynolds number scale effects are minimized by keeping the full-scale solidity ratio in the model scale.

Shen et al. (2018) presented a comparison of numerical calculations with model test results for mooring loads of a marine fish farm in waves and current. The physical model is representative for a single cage commonly used in Norway. A linear hydroelastic curved-beam model with tension effects were used for the floater, similar to what Li et al. (2016, 2017) did for waves without current. Current loads on the floater were added using an empirical viscous drag formulation. The bottom weight ring was handled similarly. Kristiansen and Faltinsen's (2014) truss and screen models were applied for the net.

Modeling the floating collar and the sinker tube as rigid bodies has a small effect on the anchor force in ambient currents without waves. The most important factor in the last environmental conditions is the wake inside the net. If the wake is not considered, the anchor force will increase up to 22%. Satisfactory agreement has been documented for the mooring loads in the front two anchor lines and front two bridle lines in both regular and irregular waves. A sensitivity analysis was performed for the system in regular waves and in regular waves combined with current. The focus was on the peak (total) values of the mooring loads. Modeling the sinker tube as a rigid body has the most pronounced effect on the anchor load for the case of waves only. A possible reason is that a rigid sinker tube will change the deformation of the net in the vertical direction. Modeling the floating collar as a rigid body has a pronounced effect on the bridle load because the rigid floating collar significantly changes the force distribution along the bridle lines.

Experimental anchor line and bridle line loads under long-crested irregular sea conditions with full-scale current velocity (0.5m/s) in the wave propagation direction were compared using the numerical model. Each sea state had a 1.5 hr. duration under the full-scale current. The numerical results indicate the effect from the elasticity of the floating collar on the anchor load to be rather moderate and the simplified hydrodynamic model for the floating collar to be sufficient for achieving the desired accuracy. The ratio of the maximum anchor load (minus mean value) to the standard deviation varies from 4.6 to 6.7 according to the experimental data. The latter fact implies that a Rayleigh distribution does not apply. Numerical simulations with different random phase seeds (20 in total) for generating the incident irregular waves were performed; the comparison of the maximum values of the mooring loads between the numerical and experimental results shows a clear variation of the maximum loads to exist in the anchor line and in the bridle line when different random phase seeds are used in the numerical simulations. The maximum anchor loads from numerical predictions vary from 98% to 136% of that from the experiment, with the maximum bridle loads varying from 74% to 105% of the experimental data. As an engineering practice, at least 10-20 realizations of the same wave spectrum are needed to have a robust estimation of the most probable largest value. Experiments are traditionally done with one realization.

Shen et al. (2016) numerically investigated a well boat moored at a fish farm in waves and current. Studies such as this can provide guidance in establishing operational limits for the loading/offloading phase. The loading/ offloading condition in waves and current can significantly affect the mooring tension and structural stresses on the floater.

He et al. (2017) experimentally studied the impact of fish in a net cage on mooring loads. Model tests at a scale of 1:25 were performed with more than 800 salmon of length 16 cm inside a net cage in waves and current. The salmon occupied approximately 2.5% of the net cage volume at rest, which is representative of the full-scale condition. The current was able to cause the fish to touch the netting, and waves can cause the fish to go to the cage bottom. The latter effects caused more than a 10% increase in the mooring loads. If the fish do not touch the netting, the load influence was on the order of 3%. One important question is if the fish behavior in model tests are representative of a full-scale scenario.

Submersible fish cages have been proposed, with the benefits being fish's comfort, reduced wave loads on the net in submerged condition, and reduced exposure to sea lice in the

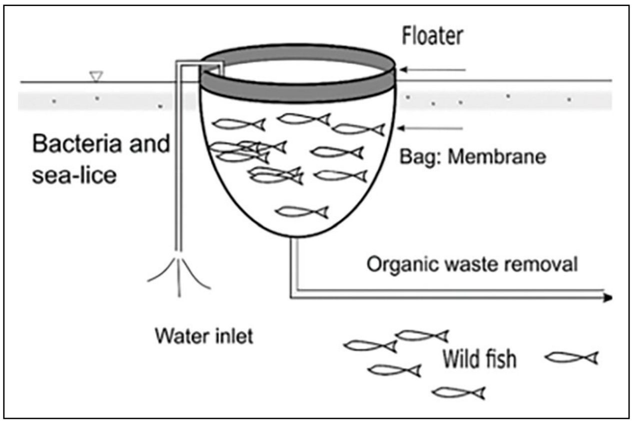

Figure 2. Schematic drawing of a flexible cage (Strand, 2018).

upper layer. The challenges are excitation from the floating collar and reliable and efficient operations. Furthermore, submergence of salmon causes stress over longer periods.

2.2. Closed fish cages

Closed fish cages can be divided into flexible cages (e.g., fabric; Fig. 2), semi-flexible cages (e.g., glass-reinforced plastic [GRP]), and rigid cages (e.g., concrete or steel). They typically have a vertically symmetrical axis at rest. The shape of a flexible cage depends on the density differences between the water inside and outside the cage as well as overfilling of the cage. When considering current effects, we need to rely on CFD in order for the flexible cages to account for hydroelasticity. However, wave-structure interactions without current can be based on the potential flow of incompressible water. Wave-induced sloshing becomes an issue, as is well-known from many engineering applications (Faltinsen & Timokha, 2009). Because marine applications involve relatively large excitation amplitudes, resonant sloshing can involve important nonlinear free-surface effects. Damping of the viscous boundary layer is very small. However, if breaking waves occur, the associated hydrodynamic damping is no longer negligible. Experimental and theoretical studies of sloshing in a vertical circular cylinder with horizontal forcing show that different overlapping wave regimes involving planar waves, swirling waves, and irregular chaotic waves occur under steady-state conditions (Faltinsen & Timokha, 2009). Swirling and chaotic waves are a consequence of the nonlinear transfer of energy between sloshing modes. Which wave regime occurs depends on the initial and transient conditions. Swirling waves have been of particular concern in designing spherical LNG tanks. One reason is the large horizontal forces occurring with components in-line and perpendicular to the forcing direction, which matters for the tank support and the buckling analysis of the sphere. Excitation around the lowest natural sloshing frequency is of particular concern. The latter sloshing frequency will be influenced by the structural elastic membrane effects for flexible cages (Strand & Faltinsen, 2017).

Important coupling occurs between sloshing and body motions. When considering flexible cages, we have to account for the dynamic normal and tangential deformations of the membrane structure that depend on the static tension in the membrane. In Strand's (2018) 2D analysis, the motion of the membrane is represented as the sum of rigid body motions and Fourier series with zero displacement at the attachment to the floater. The finite static curvature of the membrane provides coupling between the normal and tangential deformations. The fact that the tangential deformations depend on the elastic properties of the membrane must be recognized when doing model tests. Using Froude scaling and geometric similarity for this is not enough. Strong coupling occurs between elastic modes and rigid body motions. Structural damping is an unknown parameter. Slack in the membrane is also a concern. Proper scaling of model tests requires that the Froude number and $Ed/\rho gL^2$ are the same in model and prototype scales. Here E, d, ρ, g, and L are Young's modulus of elasticity, membrane thickness, water density, acceleration of gravity, and characteristic cage length, respectively. Finding materials with proper $E \times d$ values in model scales is difficult with the common length ratios in model and prototype scales. Strand (2018) analyzed the problem in 2D using the linear frequency domain in the theory on potential flow of incompressible water. Extensive verifications were performed. For instance, conservation of energy for the external flow problem relates uncoupled radiation wave damping for the flexible mode to far-field wave amplitudes. Furthermore, generalization of the Newman (1962) relations relate generalized excitation force of different normal modes to the wave radiation damping of these modes. The wave-induced behavior is very different from rigid body cases, and performing experiments to validate the method will be important in the future.

While nonlinearities must be considered for sloshing, the exterior potential flow can to some extent be based on linear time-domain boundary conditions within the theory on the potential flow of incompressible water. However, mean and slowly varying loads are needed for a mooring analysis, which can be based on a second-order analysis for the exterior flow problem. If sloshing occurs under non-shallow liquid conditions without breaking waves, the nonlinear multimodal method (Faltinsen & Timokha, 2009) can describe the global sloshing loads in a time-efficient way. The multimodal method represents the free-surface elevation in terms of a Fourier-type series and the velocity potential as a sum of the product of generalized coordinates and the linear eigenmodes of sloshing. The boundary value problem is transferred to a system of nonlinear ordinary differential equation for the generalized coordinates of the free surface elevation using the Bateman-Luke formulation. One advantage of the multimodal method is that acceleration dependent loads are explicit, which stabilizes the numerical time integration. Empirical viscous damping and other loads due to things such as mooring have to be added to the equations for motions. The procedure is partly described in the 2D studies by Rognebakke and Faltinsen (2003), which shows zero sway response to occur at a natural sloshing frequency for pure sway motions and linear sloshing theory. The reason is the infinite added mass associated with the interior flow. Because the added mass associated with sloshing is frequency dependent, resonances occur in the sway motion.

Violent sloshing implies nonlinear transfer of energy from the lowest sloshing mode. We can avoid exciting a sloshing mode by properly moving a tank wall in an elastic manner (Faltinsen & Timokha, 2009). This requires a control system where the body motions are monitored. Another possibility to be further explored is the use of air turbines to extract sloshing wave energy. One could also introduce compartments to prevent swirling and lower the highest natural sloshing period to a range where operational and extreme wave conditions do not cause significant resonant sloshing. Using flow separation from the baffles to cause sufficient damping of sloshing is difficult.

Many net cages operate in close vicinity, which raises questions about spatial variations of the current and wave environment as well as hydrodynamic interactions among the net cages. For instance, upstream cages modify the incident current to downstream cages.

3. SHIPS

Environmental concerns have led the International Maritime Organization (IMO) to introduce an energy-efficiency-design index in terms of grams of CO_2 emissions per nautical mile divided by deadweight tonnage that applies to oil tankers, bulk carriers, gas carriers, general cargo, container ships, refrigerated cargo, and combination carriers. Super-hydrophobicity and shark-skin analogues have been suggested for reducing calm-water resistance. Use of renewable energy from solar panels and retractable sails and the introduction of new weight-saving materials are other ideas. However, replacing fuel oil with methanol and LNG and the use of fuel cells seem more promising with regard to significantly reducing CO_2 emissions in the future.

3.1. Predicting CO_2 emissions

Estimating CO_2 emissions is generally based on calm-water conditions. However, Prpić-Oršić and Faltinsen (2012) have studied the influence of sea waves. Their method involves information about the time trace of long-crested sea waves obtained through wave spectra. The wave between subsequent zero crossings is approximated as a regular wave with a certain amplitude and period. In addition, information is needed about the engine dynamics, still water resistance, added resistance in waves and wind, as well as how open-water propeller characteristics are affected by waves. The longitudinal speed variation due to slowly varying added resistance in waves is found by applying Newton's second law. Time series for fuel consumption and CO_2 emission are obtained.

As a ship most often encounters moderate sea conditions, added resistance (mean second-order longitudinal force) in small wavelengths relative to the ship length is of practical interest. Difficulties in accurate predictions relative to model tests occur for ships with bulbous ballast and head sea conditions. A rough analogy is incident waves to a beach, which implies limitations of a second-order theory. When large relative vertical motions occur at the propeller plane, the propulsion loads depend on the distance between propeller shaft and free surface. Propeller ventilation is a worst-case scenario. An empirical formula was used to estimate the influence of waves on propulsion loads by calculating the relative vertical motion of the propeller shaft using linear wave-induced ship motion theory and averaging propulsion forces over one wave period. The container vessel S175, with a length of 175m and 26000 kW of power, was selected as an example. The fuel consumption and CO_2 emissions under calm water conditions with a speed of 21.9 knots were 104.39 kg/km and 331.21kg/km, respectively. Weather statistics along six main North Atlantic trans-oceanic routes were used. When neglecting voluntary speed loss, average CO_2 emissions increased by about 10%. However, when accounting for voluntary speed reduction using standard criteria, the influence of waves on CO_2 emissions was generally small (Prpić-Oršić et al., 2016a). When the ship is caught in heavy seas, the shipmaster can undertake two maneuvers to avoid excessive ship motion and hull damage: changing course or voluntary speed reduction. No strict rule exists for determining under which conditions the shipmaster would reduce speed, so various authors have proposed different criteria. Prpić-Oršić et al. (2015, 2016b) presented studies on the effect of various voluntary speed reduction criteria on the attainable speed of a ship on a seaway.

3.2. High-speed vessels

High-speed ships are presently not so popular due to factors such as fuel consumption and CO_2 emissions. The tendency exists that activities repeat themselves over a period on the order of 30-40 years after adopting new advances in enabling technologies to take advantage of things such as new materials; hybrid power plants (e.g., batteries, gas, diesel, renewables); and guidance, navigation, and motion control systems. Integrated design and analysis involving hydrodynamics, structural mechanics, and automatic control may open the way to lighter and marginally dimensioned concepts. Automatic control is used for hydrofoil vessels with a fully submerged foil system to minimize the cobblestone oscillations from surface effect ships (SES) that occur due to resonances in the air cushions in very small sea states. Faltinsen's (2005) textbook describes the very different fluid mechanical aspects of semi-displacement vessels, planing vessels, and air cushion and foil-supported vessels. Far-field waves (wash) are a particular concern for semi-displacement vessels under supercritical shallow-water conditions involving small far-field wave decay. Seakeeping is an important consideration, and SES and hydrofoil vessels with a fully submerged foil system have generally better seakeeping characteristics than semi-displacement and planing vessels. Leakage from the air cushion of an SES in waves can cause significant speed loss. Cavitation limits the speed of existing commercial high-speed vessels. Care must be shown to avoid cavitation on the aft foil of a hydrofoil catamaran due to influence from the vortex system created by the upstream foil(s). For example, ventilation is a concern at the water jet inlet of an SES or during a turning maneuver of a hydrofoil vessel with free-surface piercing struts. Fully ventilating rudders are used for some planing hulls. When performing model tests, the cavitation numbers must be the same in the model and the prototype scales. The latter require depressurized air conditions during the model tests.

3.3. Dynamic instabilities

The importance of the dynamic instabilities of ships increases at greater speeds (Faltinsen, 2005). The influence of cavitation and ventilation on stability must be recognized for high-speed vessels. Porpoising (vertical instability) and spinouts are examples for planing vessels. Spinout happens when a boat slows down while turning. The consequence of the decreased speed is reduced trim and draft at the stern. The fact that reduced draft at the stern of a directionally stable ship is well known for increasing the probability of directional instability in displacement vessels (Faltinsen, 2005). Broaching in calm water can happen for semi-displacement vessels above a certain Froude number. Coupled surge-sway-roll-yaw and the associated wave generation are contributing factors. Broaching in following and stern quartering waves of small vessels can lead to capsizing.

Parametric roll can lead to container ships losing their containers. Parametric roll for ships in regular waves is a Mathieu-type instability, because the restoring coefficient in roll is proportional to the sum of the metacentric height GM and the time-dependent term $\delta GM \sin(\omega_e t+\alpha)$, where ω_e is the frequency of encounter. A critical domain for instability is for ω_e near $2\omega_n$, where ω_n is the undamped natural frequency of roll motion. The instability domain depends on $\delta GM/GM$ and the ratio of damping and critical damping (Faltinsen, 2005). The smaller the damping, the smaller $\delta GM/GM$ is for instability to occur for the given ω_e. δGM for ships is associated with the quasi-steady change in the water-plane area due to relative vertical motion between ship and waves. In other words, δGM is significant for a ship with a large flare. Because parametric roll takes time to develop, the time-dependent change of the zero-crossing period in irregular sea becomes a factor. Predicting parametric roll for container ships seems possible using relatively simple methods. For instance, Ghamari et al. (2015) assumed a system with 5 degrees of freedom using strip theory and accounted for nonlinearities by considering the nonlinear Froude-Krylov and hydrostatic loads. They documented satisfactory agreement with parametric resonance experiments for a C11-class container carrier ship. Ghamari et al. (2017) needed to use Greco and Lugni's (2012) weakly nonlinear method to achieve reasonable agreement for experiments on a fishing vessel with a hull form more challenging than a container ship from a hydrodynamic point of view. Greco et al. (2014) showed experimentally and numerically that Mathieu-type instability of roll motion could happen due to green water on a floating production storage and offloading (FPSO) unit with small flare and no forward speed in regular waves under head sea conditions.

3.4. Maneuvering

Analysis of ship maneuvering requires integrated knowledge about resistance, propulsion, ship machinery, seakeeping, steering, and automatic control. Froude number dependency must be recognized for high-speed vessels. Maneuvering is analyzed traditionally under calm-water conditions. However, broaching in waves represents a potentially dangerous situation for smaller vessels and must be accompanied with proper steering strategies. Furthermore, replenishment and lightering operations are influenced by environmental conditions. Accurate maneuvering simulations using rational methods for a damaged ship in waves and wind to find the time to capsize are beyond state-of-the-art. Physical complexity can make theoretically predicting the time to capsize difficult. One example is the accident with the car ferry Estonia where 852 people died. Slamming loads damaged the bow visor and resulted in flooding of the car deck, subsequently filling other parts of the ship. Waves, wind, ship maneuvering, and complex internal flow influenced the vessel dynamics.

Skejic and Faltinsen's (2008) maneuvering model for a ship in waves assumes different time scales for the maneuvering and the linear wave-induced loads. The theory on the potential flow of incompressible water can largely be used in seakeeping analyses apart from viscous roll damping. The fact that maneuvering models operate with a body-fixed accelerated coordinate system while linear and weakly nonlinear seakeeping problems are traditionally solved in an inertial system must be recognized in the analysis. The effects from regular waves on ship maneuvering in the horizontal plane is expressed in terms of mean wave forces and moments acting on the ships as functions of the slowly varying ship heading relative to the incident waves, the ship speed, and the frequency with which the ship encounters waves. The procedure may be generalized to a short-term irregular sea by creating a time history of the wave elevation and approximating the wave elevation between two successive zero-crossings as a regular wave. Calculating mean wave loads are done interactively with the ship maneuvering. Faltinsen et al. (1980) gave the needed mean wave load expressions for all wave directions and ship speeds in terms of an asymptotic small wavelength formulation and a direct pressure integration method in the wave-frequency range of non-negligible ship motions. A direct pressure integration method can be numerically sensitive to wrongly predicted flow details at the ship hull. Examples involve non-vertical hull sides at the waterline and sharp corners. Using far-field methods based on the conservation of fluid momentum/energy seems to not be as sensitive to details as that. Mean wave load results depend on how the linear wave-induced ship motions are evaluated. Skejic and Faltinsen (2008) used the Salvesen-Tuck-Faltinsen strip theory (Salvesen et al., 1970). Skejic and Faltinsen (2013) also generalized the method to long-crested irregular seas. Some maneuvering models in waves are incomplete in the way they account for mean wave loads, such as only considering the effect to be due to integrating the linear pressure over the instantaneous wetted surface. That accounting only partly for terms is well known from direct pressure integration methods of mean wave loads to be able to lead to erroneous answers. Faltinsen (1990) illustrated this fact by applying the direct pressure integration method while estimating the mean wave loads on a 2-D body. The method can be generalized to include mean wave loads in six degrees of freedom and applied to submarine maneuvering in the wave zone.

Thys and Faltinsen (2014) numerically and experimentally examined the steering of a fishing vessel with a relatively small length-to-breadth ratio in following wave conditions with similar time scales for maneuvering and seakeeping. The theoretical model combined a modular maneuvering model possessing four degrees of freedom with a seakeeping model, which generalized the strip theory (Salvesen et al., 1970) using the 3-D Laplace equation as the governing equation. The model further included nonlinear Froude-Krylov and hydrostatic loads and a simplified surge equation in waves. Resistance, rudder forces, and wake factors were based on experimental results in calm water, while other propulsion data were empirically determined. The calm water results were generalized to include incident wave effects, with the steady and unsteady responses being solved simultaneously. The experiments did not show broaching, while the numerical simulations showed surf riding and broaching. The reason was numerical over-prediction of the wave excitation force in surge, which resulted in too large a ship speed. The finding illustrates that a more advanced theoretical method must be developed that may have to include the interactions between local steady and unsteady flows and a more proper description of the wave systems generated by the ship. Uncertainties in the wave effect on rudder forces, wake, and propulsion also need further studies.

3.5. Whipping and springing

Whipping and springing of container vessels are concerns. Springing of ships is wave-excited resonant global hydroelastic vibrations that are important for the fatigue life of large bulk carriers and container ships. Whipping is slamming-induced transient global ship vibrations. Whipping can be difficult to distinguish from springing. Simplified numerical methods have to be applied to properly predict the relevant probability functions for different sea states (Tuitman, 2010). The 2-D generalized Wagner method is commonly applied to predict slamming loads on bow flare sections. 3-D flow is also important but cannot be integrated in a simplified way. The forward ship speed's effects on the rate of change of the wetted area (and thereby the slamming loads) are ignored. Non-viscous flow separation is not considered and may happen during water entry of the bulb and at the keel as a consequence of roll and sway. Excitation and damping of springing are equally important. Structural damping is generally dominant and difficult to estimate. Shao and Faltinsen (2012c) found that the second-order velocity potential for a Wigley hull in head sea greatly contributes to the second-order wave excitation of springing with a two-node vertical mode in the wave frequency region where sum-frequency springing occurs. The blended methods for nonlinear wave-induced loads on ships at forward speed represent state-of-the-art engineering tools yet provide wrong results because nonlinearities in the wave radiation and diffraction are not considered. Nonlinear springing has been observed in regular waves in model tests (Miyake et al., 2008) when the encounter frequency is equal to $1/n$ of the structural natural frequencies where n is an integer; in other words, second-order, third-order, up to n^{th}-order nonlinearly excited springing can be discussed. Going beyond second-order nonlinearly excited springing is hard from a numerical and theoretical point of view. Furthermore, a perturbation scheme becomes increasingly tedious with the higher orders of nonlinearly excited springing. Larger sea states with bow-flare slamming and green water on deck cannot be based on a perturbation solution.

The boundary value problems for the linear and higher-order potential-flow solutions for external wave- body interactions are traditionally formulated in an inertial coordinate system. The body-boundary and free-surface conditions are formulated using Taylor expansions expressed over the mean body and free-surface positions. Because steady flow does not satisfy the body-boundary condition on the instantaneous body surface, the m_j -terms influenced by second-order derivatives of local steady velocity potential occur in the linear body-boundary conditions for ship motions at forward speed. The second-order solution involves second-order derivatives of the first-order unsteady velocity potential and second- and third-order derivatives of the steady velocity potential on the mean body surface. If the body has sharp corners with interior angles less than 180°, the procedure fails at the sharp corners and flow singularities occur. Using a body-fixed coordinate system when solving higher-order potential-flow problems does not include any derivative of the velocity potential on the right-hand side of the body-boundary conditions. Shao and Faltinsen (2010, 2012a, 2013) formulated the boundary value problem in the body-fixed coordinate system for analyzing weakly nonlinear wave-body interaction problems without and with forward speed/current velocity. Shao and Faltinsen (2012c) numerically studied the complete second-order weakly nonlinear 3-D potential-flow problem of a displacement ship at forward speed by accounting for interactions between the local steady and unsteady flows. They used the double-body flow as the basis flow. Both monochromatic and bichromatic head-sea waves were considered using different Froude numbers. A time-domain higher-order BEM based on cubic shape functions was used, and a forward difference scheme was applied over the free-surface conditions in order to better numerically stabilize the solution. Generalization to semi-displacement vessels implies that flow separation from the transom stern with a hollow in the water behind must be incorporated.

3.6. Slamming

Slamming can cause large vertical accelerations of planing vessels. The local and global effects from wetdeck slamming is a concern for catamarans and SES. The slopes of the wetdeck relative to the mean free surface must be small to avoid important forward speed effects regarding slamming loads at high speed. Both water entry and exit loads matter for global wetdeck slamming effects. The vertical wetdeck force is, roughly speaking, positive during the water entry phase and negative during the water exit phase, with maximum and minimum forces being similar in magnitude. The fine details of wetdeck slamming occur on a very small time-scale relative to the natural periods in heave, pitch, and two-node vertical elastic mode. The consequence is that the global response in terms of vertical shear forces and bending moments in transverse cuts of the catamaran in head sea at forward speed can be well-predicted using a considerably simplified water entry and exit model based on a modified von Karman method with additional nonlinear Froude-Krylov and hydrostatic loads (Ge et al., 2005). However, an accurate estimate of the trim angle is important for slamming occurrence.

Sloshing-induced slamming in prismatic LNG tanks is a particularly complicated slamming problem because many fluid mechanic and thermodynamic parameters as well as hydroelasticity may matter. Furthermore, membrane structures are far more complex than steel structures, and violent sloshing causes complicated in-flow scenarios of slamming (Faltinsen & Timokha, 2009). However, slamming is not a problem in spherical LNG tanks. Impact scenarios in prismatic tanks depend on the filling ratio. A sudden flip-through of the free surface at a vertical tank wall can happen with very large filling ratios (e.g., 0.98). A vertical jet flow with a high velocity will therefore impact the tank roof. Large filling ratios can cause impacts on the tank roof of a nearly horizontal free surface. Another case involves impacts where the geometry of the impacting free surface causes a gas cavity. A gas cavity has a natural frequency associated with the compressibility of the gas and a generalized added mass due to the liquid oscillations caused by the gas cavity oscillations. Steep waves impacting on a vertical tank wall are important for shallow and lower-intermediate liquid depths and are influenced by the spatial evolution of the breaking wave and by its phasing with respect to the vertical wall. Scenarios include: a) flip-through (i.e., impact of an incipient breaking wave without air entrapment resulting in a vertical run-up with very high accelerations causing large pressures), b) impact from an incipient breaking wave with air entrapment, and c) impact from a broken wave with air/water mixing.

The time scale of a fluid dynamic phenomenon relative to natural periods of structural models contributing to large structural stresses is important in judging if a particular fluid dynamic effect matters. Because no numerical methods currently exist that are able to fully describe sloshing-induced slamming pressures, one has to rely on experiments, which in practice means model tests. The challenges are how to scale the model-test results to full scale and properly account for the structural elastic reactions (Faltinsen & Timokha, 2009). A rigid model combined with Froude scaling and geometric scaling is common. Combining the measured dynamic pressure distributions on a rigid model with a dynamic structural analysis is difficult due to the difficulty of accounting properly for the added mass effects due to vibrations, which depend on the time-dependent wetted structural area, free-surface position, and possible presence of gas cavities. Lugni et al. (2014) illustrated this fact with model tests involving shallow-water sloshing with a flip-through event using a rigid tank and the same tank with a flexible side-wall portion made from aluminum in the impact area. Using results for a rigid model gave clearly non-conservative structural stresses. However, other fluid dynamic parameters are found to consider. Due to LNG partly being at a boil, the cavitation number is of concern. The consequence is that the ullage pressure must be lowered in the model scale. Furthermore, the ratio between the gas and liquid density matters for LNG. The effect from surface tension is believed to be negligible. Finding a model-scale liquid that satisfies both the Reynolds and Froude number scaling with realistic model scale dimensions is impossible. However, the viscous effect on slamming is believed to be secondary for sloshing in a clean tank with realistic excitations.

Model tests for slamming and sloshing are typically done with a prescribed tank motion, which may be found through calculations as a realization of ship motions in representative sea states. The calculations must account for the mutual interaction between ship motions and sloshing. Linear potential flow and empirical viscous roll damping can predict external wave loads to a large degree. However, nonlinear free-surface effects play a dominant role in internal sloshing loads. Even though CFD is generally not recommended for sloshing-induced slamming, it may better describe the global effects from sloshing. However, the computational speed of CFD methods makes it unrealistic in practice for long time simulations under at-sea conditions. The nonlinear multimodal method (Faltinsen & Timokha, 2009) is time-efficient but limited at describing all flow conditions.

4. SEA STRUCTURES

Viscous flows associated with vortex-induced vibrations (VIV) and vortex-induced motions (VIM) remain challenging problems. For example, VIV can cause fatigue damage to risers, pipelines, and floating submerged tunnels, while VIM concerns the mooring design of deep-draft floaters. For another example, galloping (i.e., instable body motions) can happen in separated cross-flow past two circular cylinders in tandem. Reynolds number scaling of model tests with non-negligible viscous effects is not always properly recognized. However, if viscous pressure drag dominates and flow separation occurs from sharp corners, Reynolds number scaling becomes secondary.

Floating offshore structures designed for ice conditions with non-vertical hull surfaces in the free-surface zone can suffer from Mathieu-type instabilities. Haslum and Faltinsen (1999) experimentally and numerically predicted the heave and pitch (roll) instabilities of a Spar buoy. Second-order forces, small damping, and time-dependent difference in the vertical positions of center of gravity and center of buoyancy explained the instabilities. Damping was low due to the mooring arrangement of the Spar buoy model being in the air, the flow separation being insignificant, and the wave generation being small. Later tests on submerged mooring systems increased the damping sufficiently to avoid instabilities.

Other important ocean engineering problems are station keeping for floating structures in deep and shallow water through dynamic positioning (Sørensen, 2011) and mooring systems, ringing (e.g., transient response of monotowers in survival wave conditions), green water on the deck of FPSO units, wetdeck slamming, and steep-wave impact on offshore platforms in deep and shallow water with possible hydroelastic effects. Wetdeck slamming is more complicated on offshore platform decks than for catamarans at forward speed, and both global longitudinal and vertical slamming forces are of concern. Steep-wave impact on columns of platforms in deep water has been detected in model tests in accidental wave conditions such as in a severe storm with significant wave height (18 m) and spectral peak period (17 s). Rigid models have also been applied. A quasi-static structural analysis caused failure in one case study, and hydroelasticity had to be taken into consideration. However, time-dependent, free-surface, and wetted body-surface configurations make estimating generalized added mass difficult due to structural vibrations. A challenge is to analyze the water pressure in a possible submerged crack in a concrete structure. Flow effects include flow separation at the gap entrance and air cavities in the crack.

4.1. Higher-order wave load effects

Predicting the slow-drift oscillations of moored structures and sum-frequency springing excitation of tension leg platforms (TLPs) requires a second-order wave-body interaction analysis involving mean, difference-frequency, and sum-frequency body loads. Current can play an important role in the second- order wave loads and in assessing the air gap of a platform deck. Because slow-drift oscillations and springing are resonant steady-state oscillations, damping is crucial. Wave-drift damping, viscous hull damping, and anchor-line damping matter for slow-drift oscillations. Viscous damping contributes to springing in TLPs. The second-order potential is well-known to be essential in predicting the springing excitation of TLPs.

Newman's approximation is commonly applied to calculate slow-drift force and moment spectra. This implies that only mean wave loads are needed from the hydrodynamic calculations. The latter fact is a significant simplification. However, You (2012) demonstrated using comparisons with model tests of a VLCC under head sea and shallow-water conditions that Newman's approximation failed and that the second-order velocity potential associated with both the incident waves and ship-wave interactions had provided the dominant contributions.

A perturbation scheme implies that the second-order solution does not influence the first-order solution. Inaccuracies appear due the ability of large slow-drift in yaw to occur and the use of a mean wave heading in the linear problem. One suggestion is to generalize the two-time scale method for ship maneuvering in waves as proposed by Skejic and Faltinsen (2008), where the time scale of ship maneuvering is large relative to the time scale of the incident waves. The influence from the waves on ship maneuvering happens by slowly varying the heading and speed dependent mean wave forces and moments.

Ringing of gravity-based platforms and TLPs is a transient elastic response excited by third- and higher-order wave-body interactions under survival wave conditions. Shao and Faltinsen (2014) studied first, second, third, and fourth harmonic force amplitudes and phases on a surface-piercing vertical circular cylinder standing on the sea floor in regular waves by means of a new potential flow method called the harmonic polynomial cell (HPC) method. Exact nonlinear free-surface conditions were satisfied by time domain simulations without overturning waves. The water domain is divided into overlapping cells with free-surface fitted grids. In each cell, a complete set of polynomials that satisfy the Laplace equation is used. Using fourth-order polynomials provides high accuracy. The method is time- efficient, as relatively large grids can be used, and the equation system for the unknown constants associated with the polynomials results in a sparse matrix system. Shao and Faltinsen (2014) showed satisfactory agreement with the higher harmonic experimental results from Huseby and Grue (2000). The reason for some documented differences is not known. Other experiments at MARINTEK using a truncated surface-piercing vertical circular cylinder in relevant ringing conditions in deep water showed local steep waves due to the wave-body interaction that propagated in the incident wave direction on the two sides of the column. The local waves resembled hydraulic jumps that started on the “upstream” side and collided on the “downstream” side with a resultant large vertical water flow. The latter fact questions the possibility of using a perturbation scheme in deriving the velocity potential. Simplified rational theoretical models are needed that enable one to simulate a storm and describe sum-frequency loads that include third, fourth and fifth harmonic terms. This was the objective behind the FNV method (Faltinsen et al., 1995). It was originally developed for deep water but generalized to intermediate water depth by Kristiansen and Faltinsen (2017). It is a third-order potential flow theory without wave scattering for a vertical free-surface piercing a rigid circular cylinder. Kristiansen and Faltinsen (2017) made extensive comparisons using model tests with regular incident waves at an intermediate depth. Attention was paid to minimizing the wave-maker generated parasitic nonlinear waves. They demonstrated that FNV theory provides good results for moderate wave steepness regarding wavelengths that are long relative to the cylinder diameter. However, the results were unsatisfactory concerning steep waves. The reason was explained using CFD to be due to viscous flow separation during a quarter to a third of the wave period. The consequence was a significant uprise of the water at the rear of the cylinder, resulting in higher-order harmonic loads. The effect cannot be represented in terms of a drag coefficient, as it was done using Morison’s equation.

4.2. Renewable energy

Renewable energy from waves, current, and wind continues to draw interest. Important issues involve efficiency, survivability in extreme weather, site selection, energy cost, and subsidies. Tidal energy devices with impellers can be related to thrusters. Maximum thrust with minimum torque is desired for thrusters, while maximum torque with minimum thrust is desired for tidal energy devices. Floating offshore platforms used for gas and oil exploration and production can be related to floating wave energy devices. Maximizing the force in phase with velocity (work) at resonance while minimizing wave-induced platform motions and avoiding resonances is desired for the floating wave energy device. Falnes (2002) stated, “In order for an oscillating system to be a good wave absorber it should be a good wave generator.” Oscillating water columns in combination with a Wells turbine are popular wave energy devices (Falcao et al., 2016). Because the system involves an air chamber where compressibility of air matters, care must be shown in the model tests. The Froude number and the Euler number need to be the same in the model and prototype scale. The latter implies a depressurized model test condition. However, the model test air pressure must not be so low that cavitation occurs. The inflow/outflow between the air chamber and the Wells turbine also requires care so that the resulting damping effect on the flow is correct. It requires considering the opening area as well as the density ratio between water and air.

Offshore wind turbines currently have drawn large interest. Proposed structures are from a hydrodynamic point of view similar to offshore platforms used in oil and gas exploration and production (i.e., monotowers, jackets, semisubmersibles, Spar buoys, and tension leg platforms). Hydrodynamic studies involve marine installations and ship access as well as combined wave, current, and aerodynamic load effects.

5. MARINE OPERATIONS

Replenishment operations in the open sea are “the most dangerous naval operations in peacetime.” When one vessel approaches or leaves the area of another, large interacting, strongly time-dependent, and alternating transverse forces, yaw moments, and associated rudder angles happen. Xiang and Faltinsen (2011) presented a potential-flow method without lift to predict the calm-water interacting loads in open or restricted water for small and moderate Froude numbers. The method can consider several objects with different speeds and motion directions. Additional interacting mean wave loads can be analyzed by state-of-the-art numerical methods using a two-time scale method.

Challenging marine operations involving the lowering and lifting of geometrically complex subsea structures through the splash zone are planned for the Aasgaard field in the North Sea in significant wave heights of up to 4.5 meters.

Non-functioning modules of a seabed gas compressor need to be replaced with minimum economic loss for gas production. Because the lowering/lifting velocity is small, both water entry (slamming) and exit happen as a result of the relative motion between the waves and the ship involved in the operation.

5.1. Moonpools

Moonpools are openings located in the hull of a sailing vessel that permit access to the water. Resonant wave motion in a moonpool limits lowering and lifting operations of items such as subsea modules or remotely operated underwater vehicles (ROVs) through the ship's moonpool. Fredriksen et al. (2015) theoretically and experimentally studied a freely floating body with a moonpool and sharp corners using intended 2-D flow in incident regular waves. Potential flow calculations largely overpredicted the maximum wave elevation in the moonpool, the reason being that flow separation at the lower moonpool entrance provides important damping. Using a hybrid method that combined the Navier-Stokes equation in the vicinity of the body and potential flow at a distance from the body provided good results. No resonances occurred at the moonpool resonance frequency. The latter fact results from the excitation due to heave motion and diffraction canceling. Instead, the maximum moonpool wave elevation occurs at a heave resonance with large motion amplitude due to small wave radiation damping. The body has three heave resonance periods as a consequence of the presence of the moonpool. The roll motion was also examined. Nonlinear body boundary conditions were essential in predicting roll amplitude at roll resonance, the reasons being that the roll eddy-making damping is the most important contribution to damping and that vorticity flux at the separation points is affected by nonlinear body boundary conditions.

5.2. Accidental pipe drops

Accidental dropping of pipes during lifting operations from a vessel to a drill rig represents damage risks to the platform and subsea structures. Because many scenarios need to be investigated as part of a risk analysis, using CFD is unrealistic. Alsos and Faltinsen (2018) proposed a simplified method that was divided into a water entry phase and a submerged phase. One error source was that air cavities were neglected during water entry. The presence of air cavities was documented experimentally by Bodily et al. (2014) for water entry of slender axisymmetric bodies with entrance angles close to 90 degrees between the mean free surface and body axis. The submerged phase considers motions in six degrees of freedom. Lifting effects and cross-flow separation with possible asymmetric vortex shedding are important. Aanesland (1987) made comparisons with model tests for drops starting below the free surface. A pipe can fall like a leaf falling from a tree. It starts with a directional instability that turns the pipe such that the weight in water causes the pipe to stop longitudinal motion along the leading edge. During the subsequent fall, the leading edge reverses until the pipe's longitudinal motion stops again, and so on. Asymmetric vortex shedding causes non-planar motions.

6. CONCLUSIONS

The article has concentrated on aspects of marine technology for fish cages, ships, sea structures, and marine operations and discussed both displacement and high-speed vessels. The sea structures it has taken under consideration are gas and oil exploration and production and offshore platforms used for renewable energy. Even though CFD has gained increasing popularity, the article has focused on model tests and simplified theoretical models.

The behavior of fish net cages in waves and current is influenced by hydroelasticity and can be adequately described using an approximate truss model for the netting and a hydrodynamic screen model for the loading. The wake inside the net due to current must be accounted for, with fish possibly having a non-negligible influence on mooring loads. Sloshing is also important for closed fish cages.

A seaway does not significantly influence CO_2 emissions for ships when accounting for voluntary speed loss. Parametric roll for container vessels may be reasonably described through simplified methods involving strip theory as well as nonlinear Froude-Krylov and quasi-hydrostatic loads. Parametric roll for fishing vessels may be more difficult to adequately describe using a simplified method. Broaching is also a difficult phenomenon to describe theoretically. The importance of dynamic instabilities increases with higher speeds for high-speed vessels. Waves can significantly influence ship maneuvering. The article discussed a two-time scale model where the slowly varying time scale includes maneuvering. Slowly varying second-order yaw moment and longitudinal and transverse forces due to wave-ship interactions play important roles. Simplified numerical methods for whipping and springing of ships in waves have been applied to predict the probability functions for different sea states. Springing damping seems to be dominated by structural damping. Error analysis of the prediction methods needs future attention. Sloshing-induced slamming in prismatic LNG tanks is a particularly complicated slamming problem, because many fluid mechanic and thermodynamic parameters as well as hydroelasticity may matter. Furthermore, membrane structures are far more complex than steel structures, and violent sloshing causes complicated in-flow scenarios of slamming. Model tests suffer from scale effects, and predicting slamming loads in all possible scenarios is difficult using CFD.

Important ocean engineering problems involve viscous flows associated with VIV and VIM, station keeping of floating structures in deep and shallow waters using dynamic positioning and mooring systems, ringing, green water on deck of FPSO units, wetdeck slamming, and steep-wave impact on offshore platforms in deep and shallow waters through possible hydroelastic effects. Renewable energy from waves, currents, and wind continues to attract interest. Model tests using oscillating water columns must properly scale the air compressibility of the air chamber as well as the inflow/outflow of the air chamber. No simplified method exists that can describe non-linear wave loading on monopiles in steep waves.

Objects that are lowered and lifted from ships through the water surface can be very complex from a hydrodynamic point of view, and model tests are needed that describe the water entry/exit loads. Many forced oscillation investigations on moonpool resonance exist and have pointed out the damping importance of flow separation at the lower moonpool entrance. More attention should be paid to the behavior of ships with moonpools in waves. 2-D theoretical and experimental studies have shown that the maximum free-surface elevation in the moonpool does not occur at the moonpool resonance period. Accidental dropping of pipes during lifting operations from a vessel to a drill rig represents a damage risk to the platform and subsea structures. A simplified numerical method that accounts for the water entry and submerged phases is needed due to the many possible scenarios that must be considered. A falling-leaf trajectory has been described for this motion. Nonplanar motions can develop because of asymmetric vortex shedding.

DATA AVAILABILITY STATEMENT

The published publication includes all graphics and data collected or developed during the study.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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