HYDRODYNAMIC ASPECTS OF WATERWAY DESIGN AND OPERATION

by

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ABSTRACT

As a ship sails through a waterway there are many considerations that influence the path of the ship. Obvious culprits include the bathymetry of the waterway, the presence of waterborne traffic, the availability of maneuvering devices, such as tugs and thrusters, and the environment. The less obvious, factors include the hydrodynamic effects acting within confined waterways. Hydrodynamic phenomena including shallow water effects, forces from passing vessels and confined water forces such as bank suction can be significant and can be the dominant force contribution on a vessel in a waterway. To assess all of the hydrodynamic effects, a combination of simulation tools is required. Model tests, potential flow codes, and complete Navier-Stokes CFD methods are used to develop high fidelity numerical models that can accurately predict the hydrodynamic forces acting on vessels operating in ports and waterways. To study in detail all the hydrodynamic effects present on a vessel during a specific maneuver or operating area is not a cost effective option for most simulation studies. Fortunately, software programs are available that use hydrodynamic databases to predict the motions of vessels in response to confined water hydrodynamics. A combination of software packages is required to assess the full cycle, from transit to berthing, of a vessel in a waterway. Linear potential flow software such as diffraction codes can be used to gain an initial insight into the effect of shallow water on vessel motions and maneuvering software or model tests can be used to determine maneuvering coefficients. Using a set of hydrodynamic databases allows the numerical models of vessels to switch to the most appropriate coefficients for the given surrounding area. Programs such as SHIPMA utilize combinations of depth-to-draft dependent numerical models, that include multiple sets of maneuvering models, first order wave responses, drift forces and interaction models. SHIPMA also allows for the inclusion of maneuvering devices (propellers, thrusters, tugs) combined with an autopilot in order to assess the accessibility of waterway designs for a variety of vessels and environments. In addition to the environmental and area forces acting on in-port vessels, forces from passing ships can be of significant importance when analyzing the limitation of vessels within a port. The ROPES software can be used to predict the effect of a passing vessels on a moored vessel and programs such as aNySIM XMF can be used to study mooring systems and vessel response to environmental and mechanical loading. The hydrodynamic effects experienced in waterways can greatly influence the behavior of vessels, however, it is also important to address the operational feasibility of the maneuvers and operations being simulated. Real-time bridge simulations combined with sophisticated maneuvering models can be used to assess the operational feasibility of maneuvers with input and feedback from operators such as pilots, captains and tug masters. This allows for operational input to be considered in the design process. The models produced at each stage of a study can be used in combination to produce a numerical model that can be used in time domain simulation software in both real-time and fast-time. This type of encompassing model can be efficiently transferred between simulation platforms to allow for accurate and consistent results between tools.

This paper will discuss the use of software to aid and improve simulations of vessels operating within waterways. Cases will be discussed to demonstrate the importance of modeling the complex hydrodynamic effects experienced by vessels in confined water. The utilization of simulation tools and model tests can assist waterway designers and operational personnel with engineering and operational design. This paper focuses on the software and processes used to assess the feasibility and limitations of ports, waterways, mooring systems and operations.

1. INTRODUCTION

U.S. ports are responsible for 4.5 trillion in economic activity, approximately 26% of the U.S. economy (ASCE, 2017). Globalization and the rise of large economies such as China and India are causing ship builders to rapidly scale up the size of vessels. Since 1970, container ships have increased in size 15 fold, with a doubling occurring in the last ten years. Due to the rapid increase in vessel size, ports are encountering new requirements for larger channels, deeper berths and new terminals. The recent expansion of the Panama canal to a depth of 50 feet is passing container ships beyond the capacity of most U.S. ports. Currently, only seven ports in the U.S. can accept vessels with drafts between 45 and 50 feet. In addition to the container ship trade, the U.S. has started exporting liquefied natural gas (LNG) resulting in a demand for new LNG export terminals. LNG vessels have a shallower draft than the large container ships, but have a wide beam and stringent safety requirements that require a maneuvering space greater than most U.S. ports can offer. The culmination of the expanding shipping sector, the increase in vessel size and the expansion of the Panama canal has spurred a “race to the bottom” among U.S. ports.

The U.S. Army Corps of Engineers is tasked with the challenging job of maintaining all U.S. ports and waterways with a limited budget. A large part of improving the waterways of the U.S. includes the work to deepen and widen ship channels and inland waterways. In order to efficiently utilize the limited improvement resources, efficient analysis techniques and tools are required. Organizations such as the Permanent International Association of Navigation Congresses (PIANC) and International Association of Maritime Aids to Navigation and Lighthouse Authorities Maritime Buoyage System (IALA) were established to provided design guidelines for ports and waterways. The PIANC guidelines utilize empirical methods to determine the required depth and width of waterways based upon safety factors applied to considerations such as vessel size, maneuverability, access to tugs and environmental considerations such as wind, wave and current. The outcome of this type of calculation alone can often air on the side of caution creating a costly design that is beyond the system’s requirements. For this reason, American ports have not adopted PIANC guidelines in the way that major European and other international ports have. The lack of design guideline implementation in U.S. ports combined with a vessel control center lacking routing authority has lead to a high frequency of vessel collisions when compared to European and other international ports. With the recent desire to expand U.S. ports, port designers should make use of simulation programs in order to design efficient, optimized and cost effective ports and waterways. With tools that can accurately predict the effect of confined water, engineers can effectively design waterways to the vessel requirements. In order to model these scenarios correctly, the software and maneuvering models must account for the complex hydrodynamic interactions between vessels and their surroundings including both the surrounding area and the applied environment.

Several options are available to study the response of a vessel to confined water. Frequency domain programs can provide an initial insight into the response of vessels in shallow water, however frequency domain programs can miss the non-linear effects associated with shallow water vessel response. Combining frequency domain software with time domain software allows for a better estimate of the response of vessels to non-linear wave effects and allows for the study of different environments, external systems and maneuvers. Fast-time simulations programs, such as SHIPMA, Dolphin and aNySIM XMF can be used to study a variety of cases. SHIPMA can simulate the maneuvering behavior of vessels in ports and fairways and is particularly useful for comparative studies to evaluate several different design possibilities. aNySIM allows for multi-body simulations with the inclusion of mooring systems, thrusters, and other external forces. Advances in CFD are now allowing engineers to study the complex viscous forces at work in confined water hydrodynamics. The use of these programs and the hydrodynamic effects to consider for vessel behavior in ports and waterways is discussed in this paper.

This paper addresses the hydrodynamic aspects of waterway design. The design of a port, harbor or channel can greatly influence the behavior of the ships operating within the waterway. A poorly designed waterway can lead to an increase in downtime, reduced operability and unsafe operating conditions. Hydrodynamic effects such as shallow water effects, bank suction and passing vessels are a few of the challenges facing waterway designers and potentially the captains of vessel’s operating within confined waterways. Predicting the effects of confined water and allowing port pilots to experience a waterway design at an early stage can help engineers and designers to improve design, efficiency and safety of waterway designs. To effectively achieve this, high fidelity hydrodynamic software must be used to capture the complex hydrodynamic aspects of waterway design.

Several cases studies will be presented to provide examples of how simulation software can be used for cases of ship design, operation design and waterway design. The cases will demonstrate the effect of hydrodynamics in confined waters. The first topic discusses the importance of considering the effect of shallow water on the response of vessels operating within ports and confined waterways. This section will demonstrate the effect shallow water has on the hydrodynamic coefficients for a vessel. Second, the effect of a passing vessel on a moored vessel will be discussed through the description of a case study. Finally, a maneuvering study will be presented that presents the importance of including shallow water interaction effects in maneuvering models.

2. CONFINED WATER HYDRODYNAMICS

2.1 Effect of shallow water on vessel motions

Wave exciting forces such as added mass and potential damping depend upon wave frequencies and are influenced by the boundary conditions of the area. Figure 1 shows the added mass for three depth to draft ratios of a 175m loaded bulk carrier with a draft of 11.5m. The considered depth to draft ratios are shallow (h/T=1.1), intermediate (h/t=2) and deep (h/t>5). For shallow water cases, the reduced water depth and the resulting low under keel clearance creates a restricted area that limits the flow of the water surrounding the hull. The added mass and potential terms can be calculated by the pressure distributions on a hull mesh. The added mass plays a significant role in determining the natural periods of the vessel's motion and is known to increase significantly as the under keel clearance decreases. The added mass is also used in the equations of motions and can therefore influence the response of the vessel. The most noticeable differences in added mass as the seabed approaches are observed in the vertical degrees of freedom. Comparing the added mass for the bulk carrier with a 10% under keel clearance (h/T=1.1) to the deepwater case (h/T>5), Figure 1 shows that the added mass (left side figure) can be more than three times greater for the horizontal motions and 8 times greater for the vertical motions. The differences in the horizontal added mass are most noticeable for low frequency waves, below 0.8 rad/s, since for higher frequencies the dispersive relation becomes negligible. In general, greater added mass decreases the motion response of the vessels since more force is needed to move the vessel. However, potential damping also increases as the seabed approaches which reduces the vessel response.

In addition to the added mass, the potential damping also varies considerably over different depth to draft ratios. The potential damping for the low depth to draft ratio is greatest due to the increase in radiated waves for shallow water cases. More radiated waves are produced for shallow water cases for two reasons, the close proximity of the seabed and the increase in free surface fluctuations.. The right figure in Figure 1 shows the potential damping of the same bulk carrier. Similar to the added mass, the potential damping is greatest for the vessel with the 10% UKC. The range in potential damping is also greatest for the lower frequency waves.

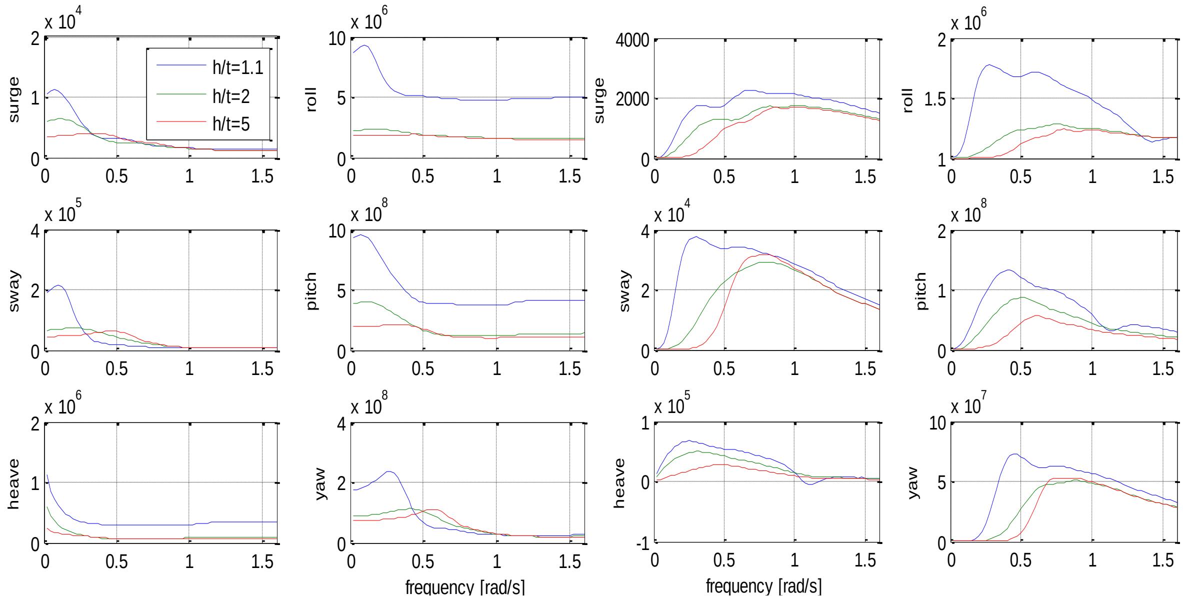

Figure 1: Effect of UKC on added mass and potential damping (mt, kNms)

Due to the differences in added mass and potential damping, the same vessel operating in varying water depths will exhibit different motion characteristics. Vessel motions are usually calculated in frequency domain from potential theory programs such as DIFFRAC. These programs give a initial approximation of the vessel response considering the incoming wave is linear and non-breaking. The motion amplitude and phase shift of the vessel can be written in proportion to the wave amplitude through transfer functions known as response amplitude operators (RAO)s. Figure 2 shows the response amplitude operators for the bulk carrier for the three depth to draft ratios. The response is shown for a short, 4 second wave of 1 m height encountering the vessel at 35 degrees off the bow. The response in the vertical plane is greatest for the depth to draft ratio of 1.1. The maximum resonance dominated roll response and the maximum excitement dominated pitch response shifts towards a lower frequency for the vessel in shallow water due to the additional added mass. For mooring simulations, all degrees of freedom can greatly influence the results, however, for maneuvering simulations, the horizontal motions are of greatest importance.

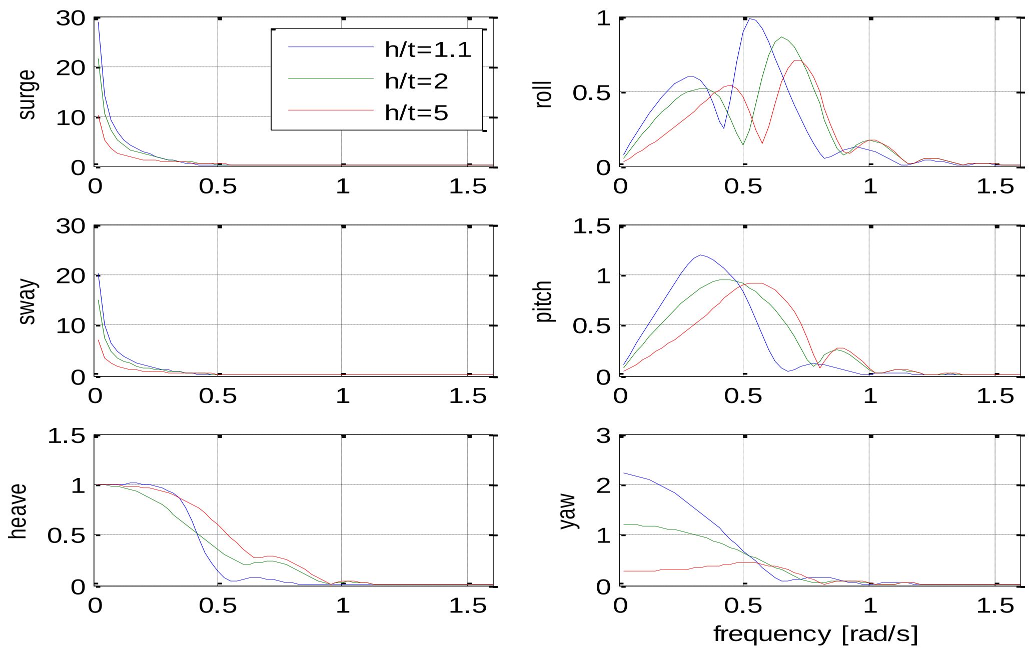

Figure 2: Effect of UKC on RAO (motion [m, deg]/m wave)

Second order difference frequency drift forces are also affected by water depth. The difference frequency drift forces can increase significantly due to the second order velocity potential. For an undisturbed, second order wave, the second order component of the wave group is known as the "set down". For shallow water, the set-down effect plays an important role for the slowly varying drift forces, but less noticeable in the mean drift forces. It is therefore important to consider the difference frequencies and compute the full quadratic transfer functions (QTF)s in order to predict the effect of the shallow water wave drift forces. Figure 3 shows the wave drift forces from the main diagonal and from an off diagonal with a difference frequency of 0.1rad/s. The differences in drift forces between the deepwater and shallow water cases is most prevalent in the off-diagonals.

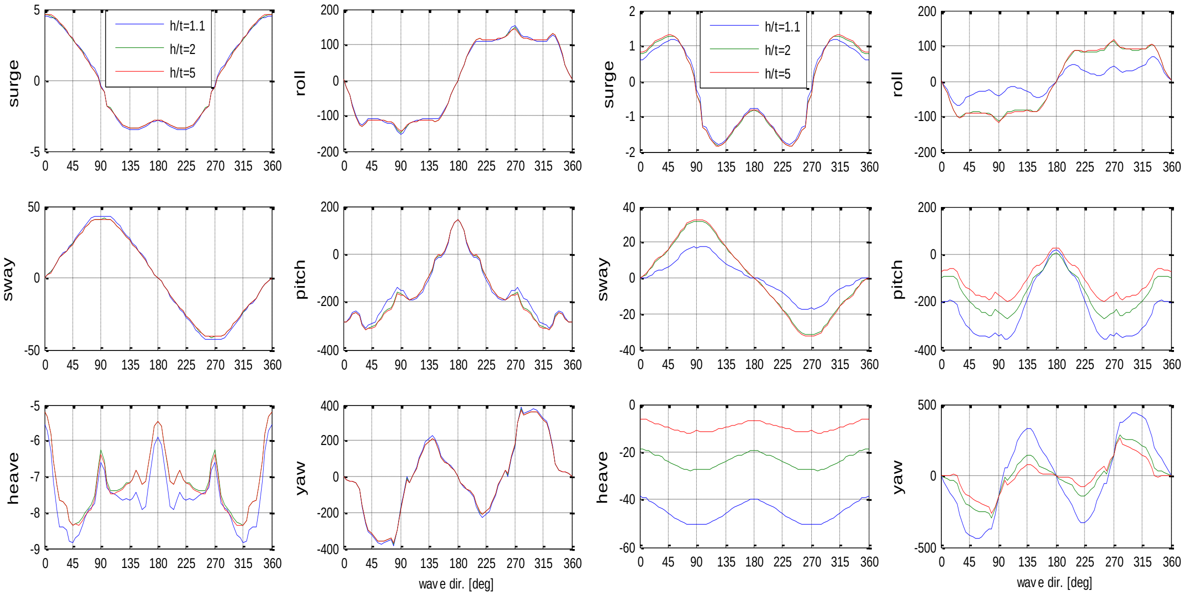

Figure 3: Effect of UKC on drift forces(mean on left, difference frequency on right [kN, kNm])

Figure 1 –Figure 3 demonstrate the importance of using a numerical model that correctly describes the vessel and the area surrounding the vessel. This is especially important for simulations within confined waterways due to the interaction of the vessel with the seabed.

2.3 Passing vessels

Passing vessels generate large suction forces which can influence the motions of moored vessels. The effect of the passing vessel on the moored vessel increases with the size and speed of the passing vessel. The force from a passing vessel in a restricted waterway can often be responsible for some of the largest excitation force contributions on the moored vessel. MARIN investigated the effect of passing vessels during the ROPES JIP through a series of monitoring trials in the port of Rotterdam, model tests and CFD experiments. As a result of the JIP, a fast and reliable tool was developed to calculate the excitation of moored vessels caused by passing vessels. The tool couples results from the RANS code ReFRESCO, which is used to predict the viscous effects associated with the passing vessel in a restricted waterway with the linear diffraction code, DIFFRAC, which is used to describe the resulting forces on the moored vessels. The tool was validated with data from model tests and full scale monitoring programs. This section discusses a case study of a large sailing vessel in a restricted waterway passing a large moored ship with a bunker vessel moored alongside.

The hydrodynamics associated with a vessel moored at a quay can be complex due to the interaction effects of the vessel with the quay. Waves reflect from the quay, water between the vessel and the quay can experience amplification due to resonance, interaction occurs between the vessel and the quay and the shallow water influences all the hydrodynamics. For the sailing vessel, viscous effects can be of importance to the flow of the water around the sailing vessel in a restricted waterway, especially for vessels sailing at drift angles or at high speeds.

The moored vessels in this case are a large cruise ship with a small bunker moored on the port side. The passing vessel and the moored vessel are both the same ship model and have an Lpp greater than 300m. The side-by-side bunker vessel is much smaller with a Lpp of 110m. The large cruise vessels have a depth to draft ratio of 1.2. The goal of the study was to determine the maximum speed vessels could sail at in the waterway without disturbing port operations. Figure 4 shows the mesh file used to describe the set up of the moored vessels in the channel.

The mesh files are used in the diffraction and second order drift force software packages Diffrac and Driftp. The Diffrac and Driftp software packages create a hydrodynamic database for the vessel and bunker that describe the added mass, potential damping and first and second order wave forces acting on the vessels. The interaction effects between the vessels and the quay are described in the hydrodynamic database. The vessel meshes are also used along with a larger port mesh for the passing vessel simulations. The port mesh is larger for the passing vessel simulations in order to capture the effect of the passing vessel as it moves through the waterway. Long sailing periods can be required to allow for the start-up effects to dissipate prior to the passing vessel arriving at the point of interest. The lower figure in Figure 4 shows the passing vessel mesh including the area and the moored vessels

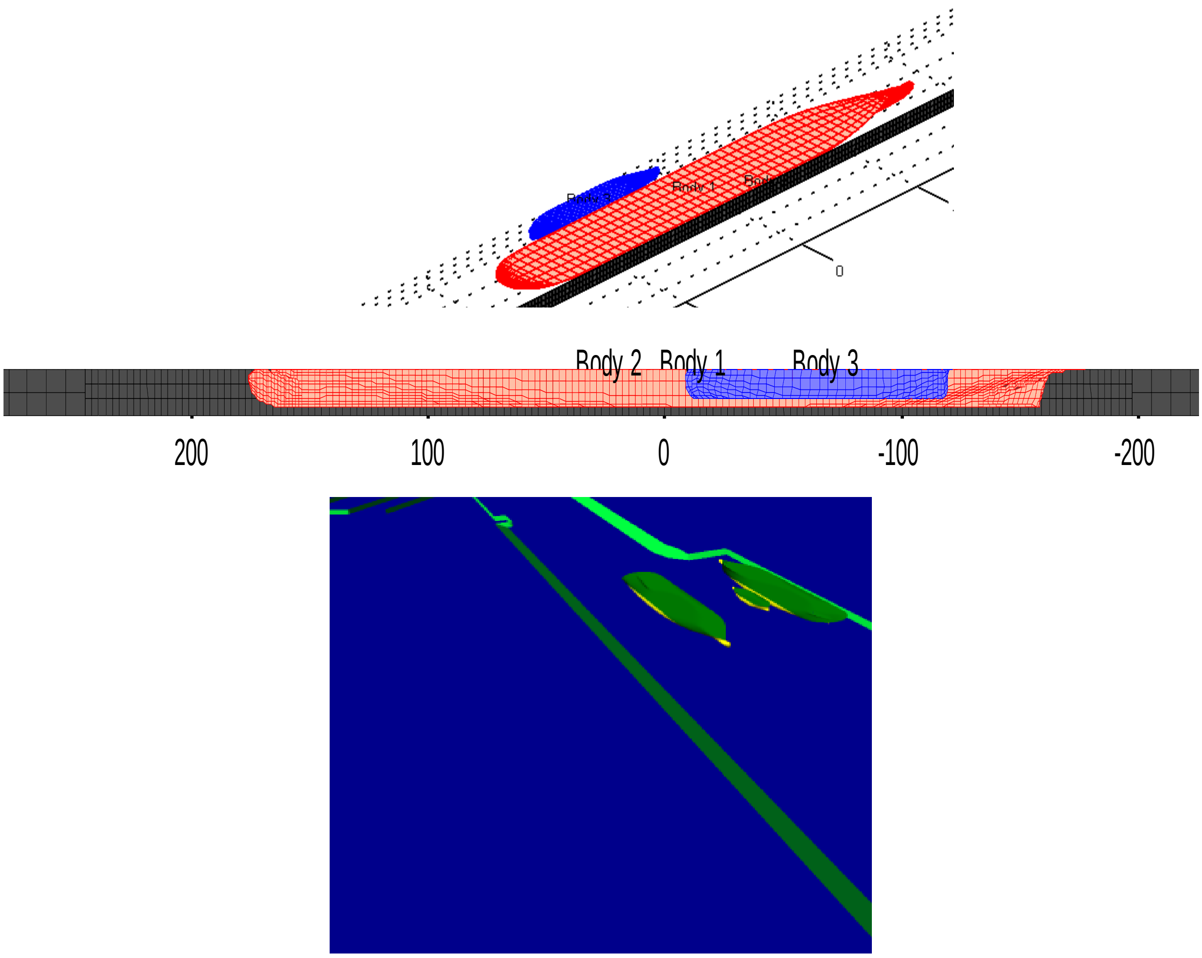

Figure 4: mesh files for motion/mooring analysis (top) and passing vessel analysis (bottom)

Passing vessel cases are run to examine the effect of the passing vessel speed on a moored vessel within a port. The port speed limit is used first and the passing speed is decreased until the moored vessel motions and mooring systems are within acceptable criteria. The first cases considers the passing vessel moving at 7 knots and the second case considers the passing vessel at 6 knots. For both passing vessel cases, no environmental forces are included. The passing vessel simulations consider the moored vessels as captive vessels in a force frame as the sailing vessel passes by. The forces exerted by the passing vessel on the captive moored vessels are determined by a double body potential flow method and stored as a 6 DOF time trace that can be input into time domain simulation software to assess the impact of passing vessels on a mooring system or maneuver. The passing vessel forces for both passing speeds are shown in Figure 5. The forces shown are the forces exerted on the moored cruise ship and bunker.

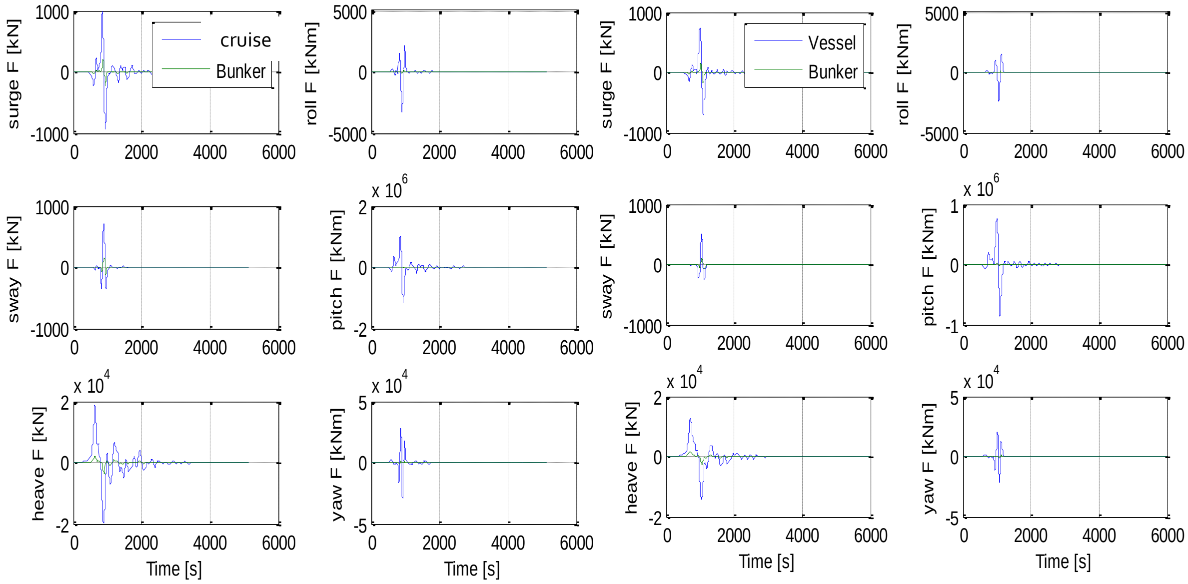

Figure 5: passing vessel forces (7kn right, 6kn left)

As Figure 5 shows, the forces from a passing vessel are substantial, horizontal surge forces for the cruise ship in this 7 knot passing case can reach 1000kN, the equivalent force of a 20knot beam wind for the larger vessel. The passing vessel force time trace is fed into time-domain simulations in order to assess the motions of the vessels and the limits of the mooring systems.

The time domain simulations are run to determine the speed limits for sailing vessels with respect to the moored vessels within a port. The simulations included a current running parallel to the channel and a wind speed of 25 knots for every 45° starting from North. It was quickly determined that the forces generated from the 7 knot passing vessel were beyond the limits of the bunker vessel mooring system despite the additional presence of an environment. The imparted forces from the passing vessel result in increased motions of the bunker and cruise vessel. The bunker vessel and bunker mooring system is especially impacted by the passing vessel due to its small size. The surge motions are most impacted for two reasons, first the mooring system springs are smaller in the surge direction than in the sway direction and second, the fenders limit the sway motions. As a result of the large surge motions, high tensions occur in the bunker vessel's spring lines. The wind directions that come from the port-aft side of the bunker vessel contribute to the positive surge forces from the passing vessel and result in the most critical cases. Wind from the starboard-aft side of the bunker vessel is shielded by the moored cruise ship and the total force acting on the bunker is therefore reduced. A time trace of the surge motions and the mooring line tensions for the north wind case and a 7 knot passing vessel speed is shown in Figure 6. The red lines in Figure 6 indicate the safe working load of the mooring lines for the bunker mooring system, 225kN. The motions and mooring system forces for the moored cruise ship were within the set criteria.

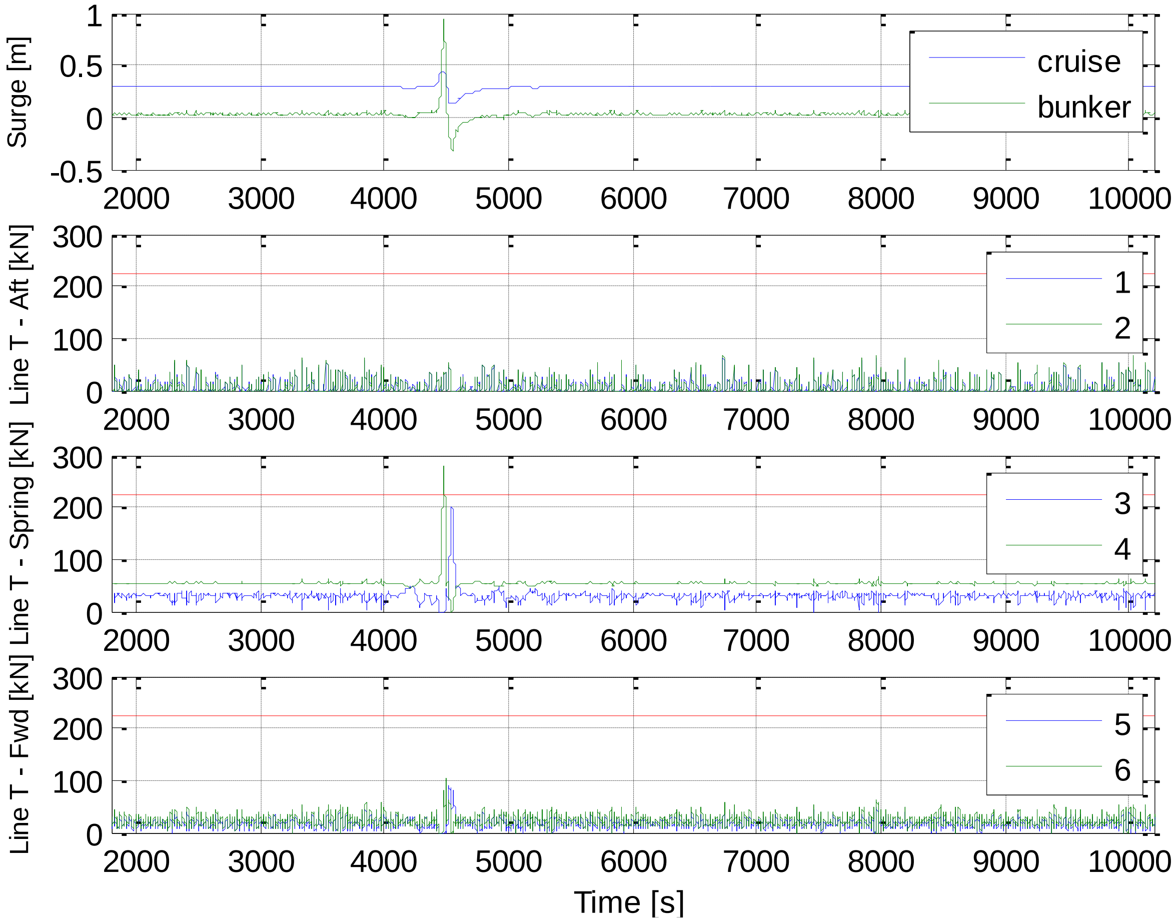

Figure 6: Time traces of motions and mooring forces for bunker vessel – N windw/ passing speed of 7 knots

Figure 6 shows that the maximum forces in all the mooring lines occur at the time of the passing vessel event. The maximum motions and mooring forces for all simulation cases always occurred at the time of the passing vessel for both the passing speeds studied and all environments considered. Both the cruise ship and bunker vessel mooring systems and motions were within the set criteria for all cases with the 6 knot passing vessel forces.

This case involved three phases, the passing vessel simulations, the time domain simulations and finally real-time bridge simulations. The passing vessel simulations were initially run to determine the passing vessel forces. Once the forces were determined, the force time-traces were run in the fast-time simulation program aNySIM to determine the environmental and passing speed limitations as a function of the moored vessel limitations. Once the limitations were determined, real-time simulations on a bridge simulator were run to assess the maneuvering limitations of the waterway. The effect of the moored vessels on the maneuvering ship were assessed through a real-time double body potential flow software coupled to the maneuvering model of the cruise ship.

Figure 7: MARIN Houston real-time bridge simulator

2.4 Confined water effects for maneuvering cases

To study the effect of confined water during maneuvering, the mathematical vessel models need to account for the effect of the depth to draft ratio on the maneuvering ability of the vessels. To account for this, the numerical models have multiple sets of hydrodynamic coefficients available that can be used for the different depths and waterways encountered while maneuvering within a port. Fast-time software (SHIPMA, aNySIM) and real-time bridge simulation software (Mermaid Dolphin) are used to assess the feasibility of in port maneuvers and the spatial limitations of waterways. These programs solves a set of differential equations to obtain the behavior of the ship within a particular area. Within the simulation these maneuvering software accounts for:

- Hull forces
- Propeller forces through KT/KQ diagrams
- Rudder forces, including side forces
- Shallow water effects
- Current forces, through relative velocity substitution
- Wind wave drift forces
- Bank suction, through Norrbin model
- Tug assistance and other maneuvering devices

All simulation programs designed to predict vessel motions as the vessel sails through the water must use a hydrodynamic databases as input. Most simulation models use frequency domain diffraction programs based upon linear potential theory to build the wave response hydrodynamic databases used in the vessel's numerical model. This approach works well for stationary vessels (FPSO's, Semi-submersibles, Moored ships), vessel's operating in deep water, or vessel's operating within an area with a constant water depth, however, most in port simulations involve varying water depths as the ship moves in and out of channels and harbors. To account for the variation in water depths, numerical models use multiple sets of hydrodynamic coefficients to accurately describe the changes in depth to draft ratio. The coefficients are used to describe forces from the maneuvering model, the second order wave drift forces and first order wave response. For fast-time maneuvering simulations, the horizontal motions of the vessel are most important since the spatial limitations of the waterway are dependent upon their accuracy. The required maneuvering area of the ship is assessed by the swept path of the vessel along the defined track, and the maximum deviations from the track definition. The required maneuvering space of the vessel is compared to the guidelines from PIANC and the effective width of the channel. The vessels ability to maneuver in the waterway is of great importance and the maneuvering model needs to account for the effect of depth to draft variability. Figure 8 shows the effect of depth to draft ratio on the turning circle characteristics.

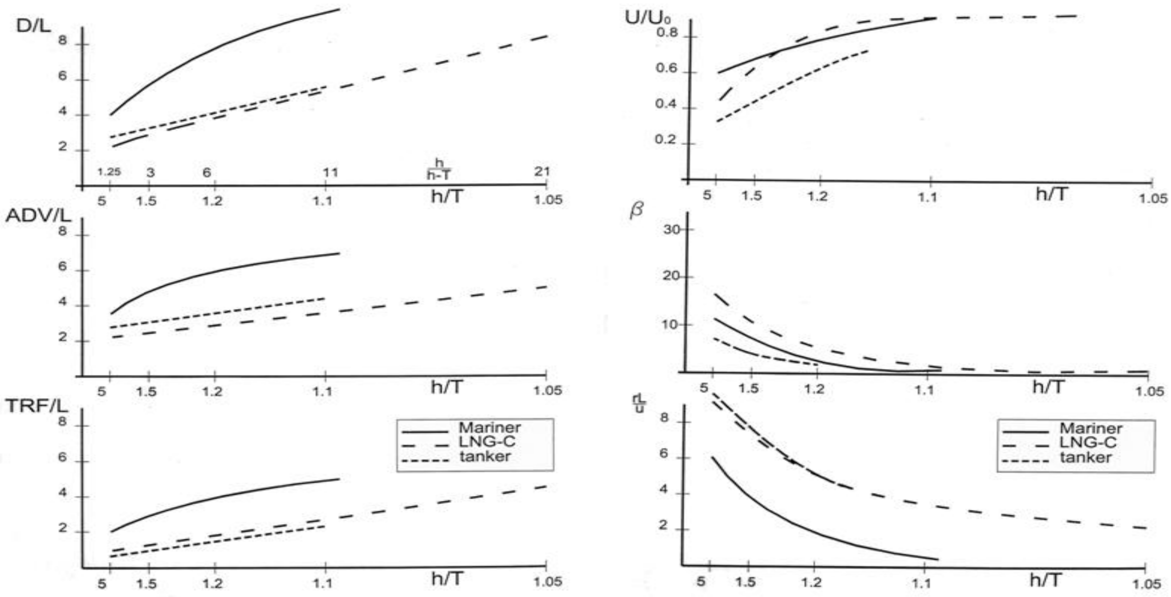

Figure 8: Effect of depth to draft ratio on turning circle characteristics

The ships interaction with the surrounding area such as channels and quays is also of consequence to the maneuvering behavior. Many complex non-linear, viscous dominated factors contribute to interaction effects such as bank suction and ship-to-ship interaction. To fully understand and model these effects, detailed CFD and model test studies are required. This type of study can be very costly and is often not a feasible option for smaller scale mooring or maneuverings studies. Fortunately, more generic and simplified methods can be used in numerical models to account for force contributions from vessel-to-area and vessel-to-vessel interactions. One such method is the Norrbin bank suction method. The Norrbin model makes use of a set of vessel specific coefficients that are used to calculate the additional surge, sway and moment forces applied to the vessel from bank suction. The Norrbin model uses a parameter based upon the relative distance from the vessel to a specified depth on the channel bank. The X, Y and N coefficients used in equations 1 through 3 below are used with the velocity of the vessel and the relative distance of the vessel to the bank to determine the additional suction forces acting on the vessels.

$$X_{suc} = \frac{X_{uuu/brh}U^3}{(a1+a2).h} + X_{u|v|B/br}\frac{U|V|B}{(a1+a2)} \qquad (1)$$

$$Y_{suc} = Y_{uvx}uvx + Y_{aaauu}a^3u^2 + Y_{aauv}a^2uv \qquad (2)$$

$$N_{suc} = N_{uvx}uvx + N_{aaauu}a^3u^2 + N_{aauv}a^2uv \qquad (3)$$

Where,

$$x = 0.333 - \frac{0.33(a1+a2)}{B} \quad \text{and} \quad a = \frac{B}{a2} - \frac{B}{a1} \qquad (4)$$

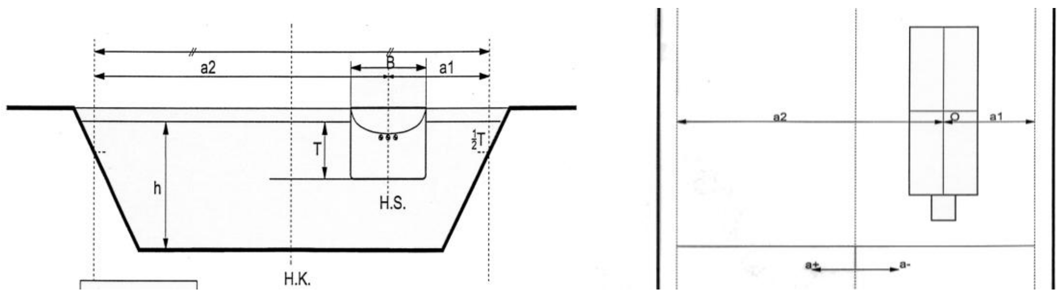

Figure 9: Dimensions used in the Norrbin bank suction model

The effect of bank suction can be of critical importance to assessing channel width requirements and limitations for maneuvering vessels in channels. Figure 10 below shows the swept path of a vessel with and without the bank suction forces calculated with the Norrbin bank suction effect included. The swept path of the vessel from the simulation without bank suction considered is over 20m less than the simulation considering bank suction. Shallow water and bank suction greatly influence the maneuvering characteristics of vessels and must be included correctly to obtain a reliable assessment of a waterway.

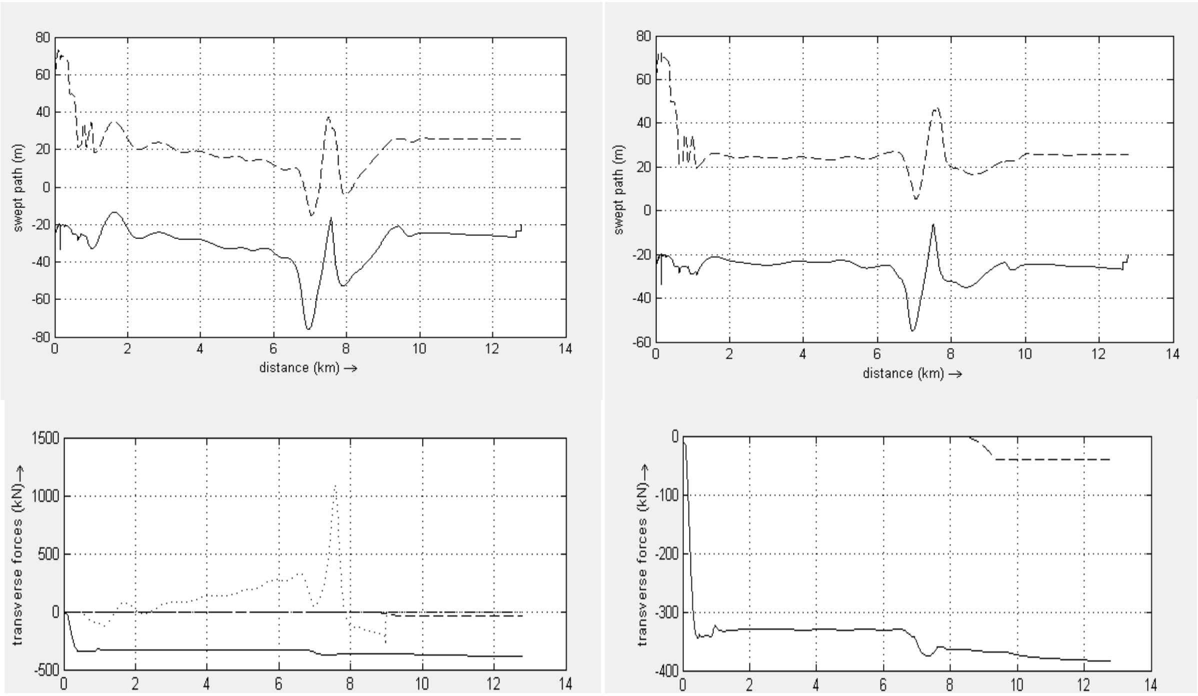

Figure 10: Effect of bank suction on swept path

3. CONCLUSION

United States ports and waterways are in need of improvements to accommodate the increasing size of future vessels. To analyze how vessels interact with the design of these ports numerical tools and model tests can be applied. Studying the interaction of vessels with ports and waterway designs allows engineers to understand the limitations of the waterways at an early stage. Combining hydrodynamic simulation models with real-time bridge simulators provides port pilots and tug boat captains a means to practice maneuvers and operations with large vessels in advance, thereby including operational feedback into the design at an early stage. For these tools to accurately assess the feasibility of waterways, the tools must realistically predict the behavior of vessels in confined water.

With the advancement of hydrodynamic knowledge, testing facilities, computational tools and computational capacity, engineers can now give detailed information on the behavior of ships in open as well as confined waters before designing waterways. The hydrodynamic models describing sailing and maneuvering in waves provide new insights into the relation between waterway design, ship design and downtime. New computational tools such as computation fluid dynamics and advanced bridge simulators give the option to optimize the hull for special environmental conditions and to train the crew for specific operations such as maneuvering in confined areas, ship-ship interaction, berthing and mooring. Large computer clusters have opened the opportunity to systematic variation studies and extensive time domain simulations for optimizing hulls, choosing sailing routes, scheduling operations or assessing the number of ships needed for a specific task while bridge and voyage simulations tools can give insight in the critical sections of a channel.

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5. KEYWORDS

Hydrodynamics, Vessel response, shallow water effects, passing vessels, vessel maneuvering, bank suction, vessel-to-vessel interaction, computational fluid dynamics, CFD, model tests, bridge simulations, time domain simulations, port design, waterway design, ship channels, motion analysis