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Impact of hydrodynamics on ship handling characteristics in training simulators

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Abstract

Currently, ship operators (ship masters and pilots) are trained on ship simulators, either Full Mission Bridge (FMB) simulators, or Manned Model (MM) simulators. Both types of simulator increase an operator's skill in manoeuvring a ship, and both incorporate the impact of hydrodynamic forces on the handling characteristics of a simulated ship. However, all forces affecting manoeuvring are the result of flow patterns that build up around the hull. These flow patterns may have extremely complex effects on many practical manoeuvres. Recent advances in hydrodynamic theory allow the impact of hydrodynamic forces on manoeuvrability to be simulated quite accurately so long as the simulated ship is moving straight ahead or performing standard manoeuvres. These advances also allow the simulation of such external influences as bank effects, shallow water effects, and canal effects, as well as the effect of the passage of other ships in the immediate vicinity. With a measure of simplification, these effects can be incorporated in FMB simulators. They can also be simulated by MM simulators provided both the models and training areas are properly prepared. As they are now, training simulators do not contribute to a trainee's understanding of the way in which flow patterns develop or of the forces they create. This article discusses this deficiency and proposes a solution for it. Several examples of specific manoeuvring scenarios are used to illustrate the solution.

Introduction

Issues related to manoeuvrability are among the most frequent causes of accidents at sea. A recent analysis of maritime accidents shows that CRG (Collision, Ramming, Grounding) casualties account for about 53% of all accidents leading to ship loss (Samuelides & Friese, 1984). In turn, 70 to 80% of CRG casualties are attributable to human and organization errors (HOE), a fact that indicates these kinds of errors warrant special attention (Payer, 1994).

According to Kobyliński (Kobyliński, 1987), the combination of design and construction faults that impair manoeuvrability, and force majeure, is responsible for about 20% of all HOE casualties. As indicated by Figure 1, the remaining 80% is attributed to such operational factors as:

- society and safety culture;
- organisation;
- system;
- human performance (individual).

In the context of the safe operation of a ship, human performance depends strongly on the operator's skill

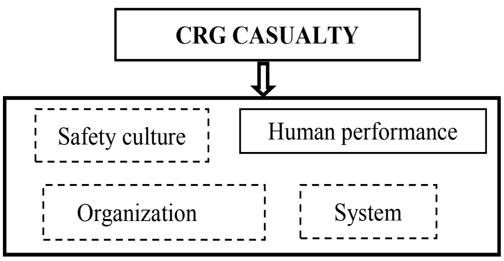

Figure 1. Safety system for CRG casualties (Payer, 1994)

and understanding of the physical phenomena governing the motions of a vessel at sea. Human performance depends on several factors, training being one of the most important. Accidents associated with CRG events occur most frequently such confined areas as ports, the approaches to ports, and canals, especially when manoeuvring is complicated by external factors like currents. Therefore, it is critical that mariners are very well trained handling a ship in confined waterways in which hydrodynamic interactions have a powerful effect on manoeuvrability.

Training for prevention of CRG casualties

Training mariners in ship handling is required by the International Maritime Organisation. Part A of the Seafarers' Training, Certification and Watchkeeping (STCW) Code includes mandatory standards in the Annex to the STCW Convention. These standards require a demonstration of competence by all ship operators in ship manoeuvring and handling. This demonstration may occur either on an actual ship, or on an approved training simulator.

Clearly, the best way to train officers and pilots in ship handling and manoeuvring is to perform training on board real ships, with simulators being used only as supplements to hands-on training aboard real ships. However, gaining required skill levels solely by "on the job training," by emulating an experienced practitioner at work, is a long and tedious process. Moreover, certain handling situations, especially scenarios in which the vessel is endangered, are unlikely to occur during a training period on an actual ship. Indeed, confronting trainees with hazardous situations aboard real ships would entail unconscionable risks. Thus, if training is restricted to real ships under regular service conditions, trainees will have little or no experience in dealing with hazardous situations. Simulators are widely used to correct this deficiency by allowing trainees to learn how to cope with simulated dangerous situations.

In general, simulators may be either equipment or situations. A simulator is defined as any system that imitates real working conditions to enable trainees to acquire and practice skills, knowledge and attitudes. Thus, Sorensen (Sorensen, 2006) attributed two basic characteristics to simulators:

- the ability to imitate real situations and/or equipment, including provisions for omitting some aspects of simulated operations for training purposes;
- provisions that allow the user to control aspects of the operation being simulated.

Training in ship handling is performed on two basic types of simulators, either Full Mission Bridge (FMBS) simulators or on Manned Model (MM) simulators. Both types of simulator help the trainee to understand hydrodynamic and other types of forces affecting ship behaviour. It is, however, unclear whether the training they provide is adequate. The central question of this paper is the adequacy of the training provided by simulators relative to manoeuvring a vessel impacted by hydrodynamic factors in close quarters.

Full Mission Bridge and Manned Model simulators

Full Mission Bridge simulators

Computer controlled FMB simulators are widely used in the training of ship officers, pilots and students of marine schools, as well as for studying various manoeuvring problems, including problems associated with the design of ports and harbours.

Currently, a considerable number of such simulators are in use around the world, ranging from desk simulators to sophisticated FMB simulators in which the trainee stands on a bridge mock-up with actual bridge equipment, a realistic visual display of the environment and, sometimes, rolling and pitching motions and engine noise.

These FBM simulators work in the real time, and are controlled by computers programmed to simulate ship motion controlled by rudder and engine, thrusters, or tugs, under different environmental conditions.

Almost all modern FMB simulators are capable of accurate simulations of manoeuvring and ship handling characteristics in open water. Usually they are also capable of simulating close proximity effects, such as bank effects and shallow water effects, or the impact of the passage of nearby ships. These simulations are based on a simplification of hydrodynamic theory. Details of the computer codes used in FMB simulators are rarely described, because they represent proprietary information. One of the few cases in which this coding has been described is a report by Ankudinov (Ankudinov, 2010).

The most advanced FMB simulators derive the manoeuvring characteristics of ships in shallow water and as affected by banks from a generalized flow pressure function describing the motions and variable pressure fields associated with a ship manoeuvring in a restricted channel of variable bottom and banks in the presence of other stationary or moving ships. The technique is fairly complex, and is best suited for scenarios incorporating solid, immovable objects in the channel. Memory effects and the proximity of other manoeuvring ships moving with various heading angles and velocities are not included (Ankudinov, 2010).

The possibility of simulating shallow water and bank effects with FMB simulators was investigated by an EU AZIPILOT project conducted by Gronarz (Gronarz, 2010). Gronarz analysed the results of simulations of speed loss in shallow water, and increases in turning diameter in shallow water, for the four most modern FMB simulators. Figure 2 shows the results of this analysis for four simulators, designated A, B, C, and D.

In deep water, a ship can reach its highest velocity using a constant revolution of the propeller. With reduced UKC – that is, increased T/h – the speed loss will increase. In general, all simulators show increasing loss of speed as water depth decreases, as is seen in Figure 2. However, for $T/h = 0.3$, which is the case when UKC is more than twice the draught of the ship gap, speed losses should only be marginal. This phenomenon was accurately characterised for simulators C and D, but not for simulators A and B, which overestimated the loss of speed. Simulators A & B also mischaracterized the loss of speed in very shallow water ($T/h = 0.8$), although this time speed loss was underestimated. Simulated turning circle diameters in shallow water were also overestimated.

This means that shallow water effects are not represented correctly by all simulators. This conclusion

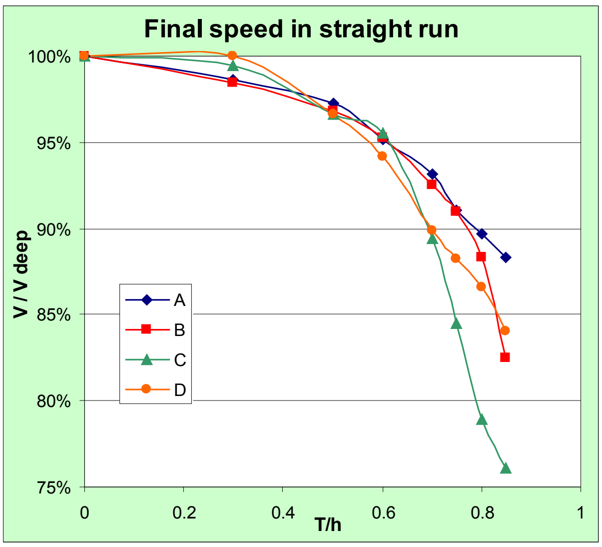

Figure 2. A comparison of simulated speed in straight runs in shallow water by four FMB training simulators, A, B, C and D (Gronarz, 2010)

refers to stationary motions. It is not known whether non-stationary motions and memory effect are accurately factored into the simulations generated by any FMB simulator.

But in many cases even simple manoeuvres, such as a circle or zig-zag manoeuvre in deep water, are often not simulated with sufficient accuracy. Gofman & Manin (Gofman & Manin, 2000) showed several cases in which simulation of turning circle manoeuvers on the Norcontrol SH simulator differed considerably from observations obtained from sea tests of actual ships.

The results of simulating manoeuvring capabilities of POD-driven ships on an FBM simulator were also analysed by Petey (Petey, 2008) and Heinke (Heinke, 2004). The code used by the tested simulator accounted for the following factors:

- propeller thrust;
- transverse propeller force;
- lift and drag forces of the POD body;
- interaction effects between different POD units;
- interaction effects between POD and hull;
- shallow water effects.

The authors concluded that the effects of these factors were simulated accurately. However, neither the Petey nor the Heinke study reported the results of a simulation of stopping with a reversed engine in a confined area.

Because FMB simulators are based on a mathematical model of ship motion, it is clearly important that the model properly describes the behaviour of a real ship. In spite of great progress in the development of theories explaining ship manoeuvrability (turning, course-keeping and stopping characteristics) in unrestricted waters, the effects of manoeuvers in the proximity of other objects (banks, shallow water, and other ships) has not yet been adequately characterised. To characterise such effects with requisite accuracy entails the use of sophisticated computer programmes that estimate hydrodynamic coefficients with advanced algorithms requiring powerful computers and extremely large memory. This cannot be done on FMB simulators because they must work "on line," and therefore can only make use of simplified methods.

Manned model simulators

Manned Model simulators use large models for training purposes in specially engineered waterways, ponds or lakes. These models are large enough to accommodate 2–4 people, students and instructors, and are constructed according to laws of similitude.

The basic law of similitude is William Froude's law. This means that not only is the proper geometry of the ship hull properly reproduced according to the chosen scale, but that such dynamic characteristics as speed, centre of mass, and mass moments of inertia are also correctly described. Additional requirements of such a model include accurately scaled descriptions of the propeller (thrust, rpm), the rudder engine (time from hard over to hard over), and the main engine (power, time of reversing, and so on). Models are fitted with anchors, thrusters and tug simulators when appropriate.

However, as is well known, MM systems cannot simulate forces consistent with the second law of similitude, Reynolds law. This means that the flow around the ship and its appendages, especially as is expressed in separation phenomena, might be not reproduced correctly in a scale model. Fortunately these effects are unimportant when the models are small. For models 8 to 15 m long, the Reynolds number is sufficiently high to avoid such effects.

Models are controlled by the helmsman, and manoeuvers are performed in and around mock ports, harbours, locks, canals, bridges, piers and quays. Shallow water areas and other facilities are constructed with routes marked out by leading marks or lights (for night exercises), all laid out all in the same reduced scale as the models. Currents are also generated in certain areas. Finally, a monitoring system allows the events occurring in the system to be recorded.

One important difficulty with MMs is the impossibility to reproducing properly scaled wind effects. Wind is a natural phenomenon and, according to laws of similitude, wind forces should be reduced by factor of λ^3 (where λ = model scale). Wind force is proportional to windage area and to the wind velocity squared. Windage area is reduced automatically by factor λ^2, but wind velocity apparently cannot be reduced. However, the actual windage area in models is usually reduced by more than by factor λ^2, and wind velocity is considerably reduced due to the sheltering of the training area and the low position of the model relative to a full-scale ship. Even so, simulated wind force is often larger than it should be.

The capability of MM simulators to simulate shallow water, banks, submerged and surface canal effects, currents, and proximity effects of other stationary or moving objects, is practically restricted only by local conditions in the training area. However, the possibility of simulating these effects depends on the way the training area is prepared, and adequate simulations may require the construction of costly infrastructure, as when a canal of specified cross-section of sufficient length is needed for a particular mock-up. However, certain flow patterns, including non-stationary phenomena and memory effects, may still not be correctly reproduced.

Physics of ship behaviour in manoeuvring situations

The manoeuvrability of a ship is understood as set of features characterizing the inherent ability of the ship to perform various required manoeuvers safely and efficiently. Required manoeuvres comprise basic actions performed in unrestricted waters, such as turning, course keeping, stopping, controlling yaw, and slow steaming. Additional manoeuvres must be performed when berthing and unberthing in different situations, using rudder, engine, and thrusters and tugs if necessary, sailing in shallow water, canals and other restricted areas, often in the proximity of other objects and under the influence of winds and currents.

Successful performance of all required manoeuvers depends on the operator's knowledge of the inherent handling characteristics of the ship, as well as knowledge of the physical phenomena affecting a manoeuvring ship and the ways in which these phenomena modify the motion of the ship. Forces are created are the result of flow patterns and the distribution of pressure building up around the ship's body. When a ship is moving on straight course in undisturbed water, a certain pressure distribution builds up around the ship's body, and this pressure field creates certain forces. In straight line motion, these pressure-mediated forces are balanced.

When a ship performs manoeuvres, the distribution of pressure around the hull is modified, creating forces that cause the ship to start moving on curvilinear path. In simple manoeuvres, like turning a circle, yawing, slowing down, or accelerating, it is possible to predict the forces created by altering the pressure distribution. These pressure-field-mediated forces also affect the ship's path. However, more complex manoeuvres create non-stationary and extremely complex flow patterns around the hull. Indeed, it is virtually impossible to calculate the time-dependent pressure distribution they cause, and therefore it is virtually impossible to simulate either the forces that result from the changing pressure distribution or their impact on the motion of the ship.

For example, a simple berthing manoeuvre entails a ship is approaching a berth, slowing down by reversing its propeller, using rudder, and then again accelerating forward, using pushing tugs or tugs pulling at the bow. All of these actions create extremely complex, non-stationary flow patterns around the ship's body, and these flow patterns may be further affected by the proximity of berth structures and a small clearance under the keel. This flow patterns is strongly affected by the construction of the berth, and specifically whether it consists of a solid wall pier or pier on piles. Moreover, the flow pattern at any instant in time is affected by memory effects of previous patterns.

Another example of extremely complex flow is created by most close proximity manoeuvres. Two ships meeting or overtaking each other in a narrow space, such as a narrow canal, affect each other and are also affected by the cross section of the canal. The instantaneous flow pattern, its associated pressure distribution and forces, must be countered by proper usage of the rudder and engine.

Similar conditions arise when the ship performs complex manoeuvres in currents, especially in the non-uniform currents typically found in shallow water or spatially restricted waterways. Such conditions greatly complicate the appropriate mathematical models of flow and pressure, making the accuracy of their output uncertain. Nevertheless, it is essential that mariners who have completing training courses on simulators understand the physical phenomena governing a ship's motion, and especially the close proximity effects that affect close quarter manoeuvring. They should realize how different hydrodynamic forces are created in close quarter manoeuvring, and how these forces affect a ship's behaviour.

As has been shown, close proximity effects are not always simulated accurately in FMB simulators because of the approximate nature of the methods of simulation. In MM simulators, those forces are represented correctly, provided the situation is simulated properly. However, although both types of simulators can create appropriate hydrodynamic forces, neither provides an explanation of the flow phenomena causing the forces.

Examples of complex flow phenomena affecting manoeuvres

From the multitude of situations in which very complex flow phenomena are created by a ship's manoeuvres, two examples have been selected below.

Coanda effect

Coanda effect is a well-known phenomenon that occurs when a tugboat is towing a ship at the bow or stern using a very short towline, as may be necessary in a very restricted area. The tug is orientated almost at right angle to the ship's bow with short towline. Propeller wash of the tug is hitting the bow, creating the force that almost cancels the pulling force of the tug and reduces the tug's effectiveness. With a blunt bow and small UKC, the flow around the bow of a ship towed in this way causes low pressure to build up on the other side of the ship, as shown in Figure 3. In turn, this low pressure causes a force *F* that creates a turning moment to the opposite side, totally cancelling the effectiveness of the tug.

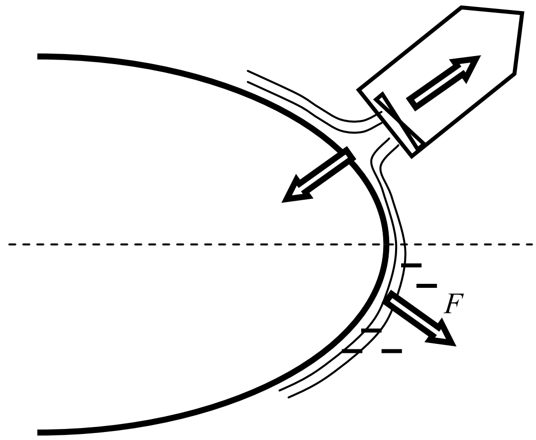

Figure 3. Schematic of the Coanda effect

Coanda effect is very sensitive to small changes in the parameters the affect it, such as the form of the bow or stern, the position of the tug, its distance from the ship, the characteristics of tug's propeller, the wash of the tug's propeller, and so on. Mathematical simulation of the Coanda effect is very difficult, because it entails a detailed analysis of the flow pattern using 3D computer programmes for each particular case.

As far as is known, no FMB simulator has attempted to simulate Coanda effect. Most MM simulators are also unable to simulate this effect properly, because reproducing the necessary flow patterns requires the use of a manned tug. Although the Coanda effect might be simulated in the Iława Training Centre, where manned tugs are used as shown (see Figure 4), no systematic investigations of the Coanda effect have yet been made.

It should be noted that some MM simulators use small radio-controlled tugs in their simulations, but because of their small dimensions and small

Figure 4. Manned tug working with model tanker

Reynolds number, the simulated flow pattern may differ from those generated by a real ship.

Bank or wall effect

This phenomenon occurs when the vessel is sailing close to a solid wall, bank, or shore line. In this case, force and yawing moments are created that tend to push the vessel towards the bank while swinging the bow away from the bank. The combination of movements results in the stern of the vessel swinging toward or hitting the bank. Experienced mariners know that if they swing the rudder towards the bank, this rotation is countered and the passage can be made safely.

This phenomenon is simply explained. When a ship is close to the bank, counter flow is created between the bank and the side of the ship, because of a reduction of the cross sectional area of the flow between the ship and the bank. This effect is governed by the continuity law. On the other side of the ship, the flow cross-section area is not reduced, and the water velocity does not change relative to the open-water situation.

If water velocity increases, then according to the Bernoulli's principle, the dynamic pressure increases and, in consequence, static pressure is reduced. The difference of pressures between the sides of a ship creates a force that is directed from the higher static pressure area towards the lower static pressure area. This is the suction force drawing the ship closer to the bank (Duffy, 2009).

On the other hand, the bow of is repelled or rejected from the bank because of the increased pressure around the bow induced by the bow wave of the moving ship and the proximity of the bank. As a result, a yawing moment pushes the bow away from the bank (Figure 5).

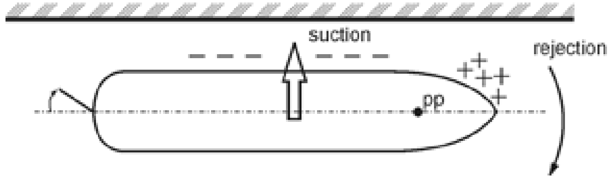

Figure 5. Effect of bank proximity on the motion of a ship

This is simple explanation of the bank effect as it is experienced in most cases. But it is not valid when the UKC is very small (viz., when the ship is in very shallow water). Model tests show that in very shallow water – with a keel clearance less than 15% of the draft of the ship – the ship is not pulled towards the wall, but is instead rejected by it (Lataireet et al., 2009). This is explained by changes in pressure distribution around the ship. Specifically, because of the small keel clearance, flow is blocked, and the bow cushion extends almost the full length of the ship (on the port side in Figure 5).

The propeller race created by a turning propeller may also affect the flow around the ship such that the effect is increased. This effect increases with increasing speed and reduced keel clearance. In that has been observed that the wave created in the space between the bank and the ship is larger than the wave on the other side (Vantorre et al., 2003). In some situations, this phenomenon may lead to unexpected behaviour like that reported by, Gweon, Hak & Hong (Gweon, Hak & Hong, 2015).

Figure 6 shows the situation at port Pohang. Ore carriers are docking at the No. 10 berth while, at position No. 1, a ship is approaching at speed of 5 or 6 knots accompanied by two tugs forward and two at the stern.

To reduce ship's speed, all tugs are pulling the ship in the 6 o'clock direction. At the No. 2

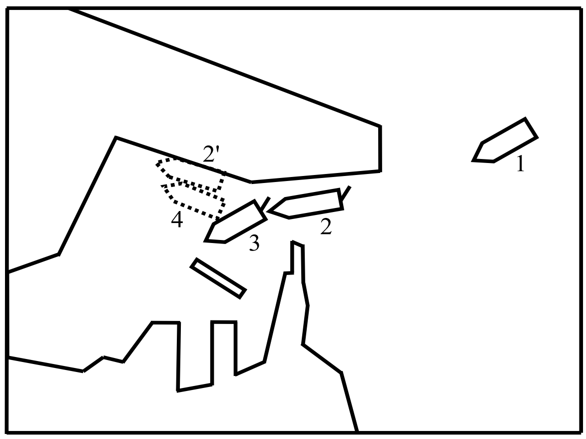

Figure 6. Sketch of situation at port Pohang (Gweon, Hak & Hong, 2015)

position, the ship takes the starboard rudder and then stops the engine to proceed to No. 2' position. Because the distance from the ship to the berth is very short, the ship is using astern engine. Therefore the command "Slow astern" or "Half astern" is given. The bow of the ship is turning to starboard due to effect of the starboard rudder being used, but stops turning in a minute and turns unexpectedly rapidly to the left. Turning to the left moves the ship to the No. 3 position, and puts it in such danger that it can be controlled only with the help of tugs. Therefore ship stops the engine at once. Then, with the command "Slow ahead," the ship with starboard rudder stops turning to the left and proceeds to position No. 4.

It was observed that this effect is stronger when the keel clearance is smaller and when the approaching speed of the ship is higher. The phenomenon of the left turn may be caused by presence of rejection forces, as explained above. This is in line with the results of model tests performed by Vantorre et al. (Vantorre et al., 2003).

Conclusions

The above two examples are selected from the multitude of situations where the flow phenomena accompanying manoeuvres can be extremely complex. If the behaviour of a ship in such situations is not properly understood by the master, the ship can be put in a dangerous situation. Therefore, during the simulation training those complex, close-quarter scenarios should be reproduced and explained in order to achieve ensure the full understanding of the trainee. Without such understanding, the man at the controls may be surprized by the counterintuitive behaviour confronting him, leading to a collision or a grounding.

From the above comparison of the abilities of the two types of simulators, it may be concluded that this may be a difficult task. Very sophisticated computer codes analysing such phenomena are not yet available; even if they were, it is unlikely they could be used in FMB simulators. It might be possible to arrange separate training sessions that include flow patterns expected for selected manoeuvring situations, accompanied by thorough explanation provided by specialists in hydromechanics. This might not be possible for standard courses, but clearly would be an option for advanced courses targeting mariners who already have extensive experience of ship handling under various situations.

In MM simulators with a proper arrangement of the simulated training area, the behaviour of the model should correspond exactly to the real situation. However, it may be very expensive and time consuming to build a model of a canal with a particular cross-sectional geometry, or a mock-up of a harbour basin entrance with a proper bottom configuration and depth. However, if these details are faithfully reproduced, the results should be satisfactory – especially if clear explanations of the physics at work are provided. This has been tried in Iława Training Centre during some courses, and occasionally at the request by individual pilots, and usually the results were quite satisfactory. However, systematic attempts to use this training method have not yet been undertaken.

Despite the current lack of a standardized training procedure, it seems clear that MM simulators could be used to model a number of educationally interesting situations and manoeuvers that could be taught during special advanced courses. Explanations of the hydrodynamic phenomena just experienced would be provided after the simulations. These explanation might profitably include visualisation of the flow patterns at issue with appropriate projection media.

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