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Review paper

The Influence of Shallow Waters on the Maneuvering of Large Ships[*]

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Abstract: The increasing demand for goods that can be transported by sea and the reduction in transportation costs have led to a trend toward larger ships. The increase in ship capacity leads to an increase in ship length and, thus, a decrease in transportation costs. The maneuverability of large ships in shallow water when calling at ports is becoming increasingly difficult. This is due to the discrepancy between increasing ship dimensions and unchanged waterway structures such as approach channels, harbors, and ports. The maneuverability of a vessel in shallow waters is different from the maneuverability in deep waters. The reasons for this are due to the shallow water effect. Shallow water affects the maneuverability of ships due to hydrodynamic forces caused by the current, shallower depth under the keel and proximity to the shore. It is a major challenge both for shipbuilders to design such vessels and for shipowners to have trained and well-educated officers who can navigate large vessels in shallow waters. This article presents the effects of shallow waters on large ship maneuvering and mathematical models that have been used to predict ship behavior under the influence of these forces.

Keywords: Large ships, Maneuvering, Shallow water, Hydrodynamic forces, Mathematical models.

1. Introduction

Large ships are generally defined as vessels with a length of more than 100 meters and a displacement of several thousand tons or more, depending on their purpose and design. A ship's maneuverability in shallow waters differs significantly from its maneuverability in deep waters. In addition to deep waters, ships also navigate channels and port approaches known for their shallow water depths. The master and watchkeeping officers must be thoroughly familiar with the maneuvering characteristics of their own vessel, as this is critical to issuing correct maneuvering orders when

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navigating in shallow waters. The maneuvering characteristics of one's own vessel are derived from the maneuvering diagram of sea trials in deep, unconfined waters. However, sea trials cannot provide information on the maneuverability of the ship in shallow waters. Therefore, it is of utmost importance to understand the influence of shallow waters on the maneuverability of the ship [1].

In navigable areas such as ports and their approach channels, the ship's maneuverability depends on the depth of water in the navigable area relative to the ship's draft. In addition to the shallow water depth in approach channels, vessel movement is also restricted by the side's proximity and the bank effect's influence. Waters with such restrictions are referred to as restricted waters. The combination of shallow and restricted water is called confined water [2]. The influence of shallow water, proximity to the shore, and strong ocean currents significantly limit the ship's ability to manoeuvre, especially when the navigation channels are curved and the ship must frequently alter its course [2]. Ship handling in such conditions is a significant challenge for pilots, masters, and watch officers. Predicting the ship's maneuvering characteristics in such situations is very important [3].

In recent years, there have been a number of noticeable accidents involving large container ships running aground. Two notable incidents are the grounding of the Ultra Large Container Vessel (ULCV) Ever Given on March 23, 2021, in the Suez Strait, Egypt, and the grounding of the Very Large Container Ship (VLCS) Ever Forward on March 13, 2022, in the Craighill Channel, USA. Both incidents were attributed to the influence of hydrodynamic forces, which can be particularly difficult to control in narrow or shallow waterways.

The article consists of three sections. An introduction describing the maneuvering limitations of large vessels when sailing through narrow channels and shallow waters. Section two describes the hydrodynamic forces acting on ships in narrow channels and shallow waters and the mathematical models used to calculate these forces on the ship. The following mathematical models are analyzed: system identification techniques, computational fluid dynamics (CFD) and captive model test method. In the third section, the conclusions are presented.

This article analyzes the hydrodynamic forces that act on a ship when it navigates in narrow channels and shallow waters and the mathematical models used to predict the behavior of these forces on the ship.

2. Hydrodynamic forces acting on a ship

The difference between increasing ship dimensions and unchanged navigation infrastructures has raised awareness of navigational analyzes for navigation in shallow waters. Predicting the ship's maneuverability under such conditions is critical and has led to the increasing use of ship handling simulators [3].

When navigating in shallow waters, the depth restriction significantly changes the pressure distribution around the ship, leading to an increase in hydrodynamic forces due to ship motion and a decrease in the ship's maneuverability [4, 5].

In maneuvering, the hydrodynamic forces in the longitudinal and transverse directions and the yaw moment are the most important [6]. Actually, a ship moves in water with six degrees of freedom (DOF), known as surge, sway, heave, roll, pitch, and yaw (Figure 1). However, only three motions derived from the above forces and one moment (sway, heave, and yaw) are usually used to study the maneuverability of ships. This simplification is because they occur at a lower frequency than the frequencies of the wave impacts [7].

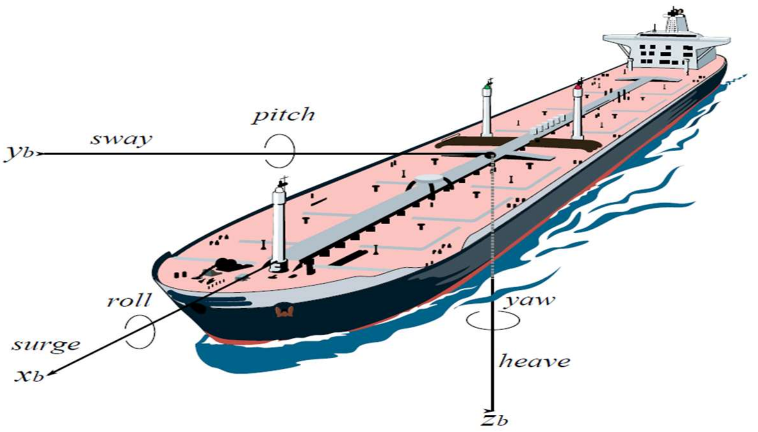

Fig. 1 – *The 6 DOFs motions of a marine surface ship in waves* [7].

When dealing with steering and manoeuvring ships, the primary motion can be considered to take place in the horizontal plane, and vertical motions can be neglected. Further, by choosing an axis system in the place of the symmetry of the body and assuming that the centre of gravity lies in the centre line plane, and neglecting the rolling and heeling, the equations of motion for a ship moving in the horizontal plane will be:

$$\begin{aligned} X &= m\left[\dot{u} - ru - x_G r^2\right] \\ Y &= m\left[\dot{v} + ru - x_G \dot{r}\right] \\ N &= I_Z \dot{r} + m x_G \left(\dot{v} + ru\right) \end{aligned} \tag{1}$$

where m is the ship's mass, and I_Z is the correspondent moment of inertia in yaw motion. The external forces *X* (surge), *Y* (sway) and the torque *N* at the ship's fixed reference frame (midship at a x_G distance from gravity centre CG) of the ship are induced by the flow around the ship's hull, propeller, and rudder. The current ship velocity V can be decomposed in the body axes x, y and z with projections u, v and w, respectively, while $\dot{u}$, $\dot{v}$ and $\dot{r}$ stands for longitudinal, lateral and angular acceleration.

3. Modeling methods for ship maneuverability in shallow waters

Various mathematical models have been proposed to describe ship dynamics in shallow waters. The most common mathematical models are: System Identification Techniques, CFD Calculations and Captive Model Test Methods [7, 8].

System identification is one of the most reliable techniques for improving mathematical models using collected data. It is a technique for building mathematical models from measured data and can be applied to free-running model test results, and it is well presented in recent work published by Hu and Soares [7].

With the development of computer capabilities and numerical techniques, the CFD method has become very popular, as it is now possible to predict the manoeuvrability of ships. The advantage of the CFD simulation is that one can obtain detailed results that contribute to a better understanding of the hydrodynamic forces that occur when a ship maneuvers in shallow waters [1]. The CFD method is widely used to study ship maneuvering in shallow waters, bank effect, ship-ship interaction, ship-bank (shore interaction), and ship-bottom interaction. Figure 2 shows the research methodology proposed by [1] for the free-running simulation CFD with four steps aimed at better understanding the influence of shallow water on ship maneuverability. The first step is the selection of a suitable ship that meets oceanic conditions. Starting points are simulations in calm seas with different water depths and in deep and shallow seas with different under-keel clearances. In the second step, numerical modelling is performed by selecting the guiding model and coordinate system, spatial and temporal resolution, and boundary conditions. In the third step, free-running simulations are performed, which include the standard zig-zag test, course keeping, and turning circle maneuvers. Many mathematical models use standard ship maneuvers and emergency manoeuvres in their simulations [9]. Manoeuvring tests are used to demonstrate the effectiveness of the ship's manoeuvring ability, especially in shallow waters. In the final step, an analysis is performed that focuses mainly on the results of the ship's course-keeping ability and maneuverability. Figure 3 shows the simulation of CFD free-running manoeuvres (zig-zag, course keeping, turning circle) in different depth to draft ratios.

One of the most used models is the Captive model test method. This is an effective method for determining the hydrodynamic coefficient for a mathematical model of ship manoeuvring motion [10]. The results of the captive model test can be used to verify numerical models and other functions related to vessel manoeuvring, research projects (most of which are related to approach channels and port approaches) and for the study of ship-shore and ship-ship interactions. The measured forces from research can be used as input data for ship simulators. The captive model test is also used to perform a rapid test of ship design to determine if the ship meets the manoeuvring criteria established by the International Maritime Organization (IMO) [10].

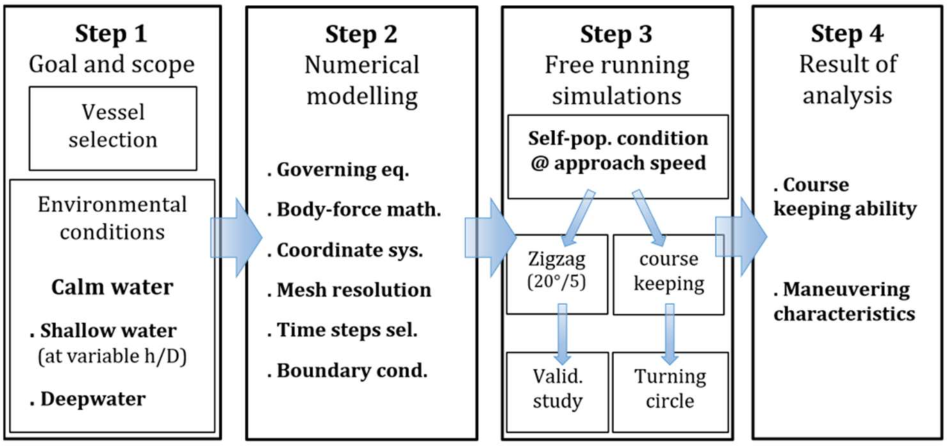

Fig. 2 - *CFD free-running simulations methodology* [1].

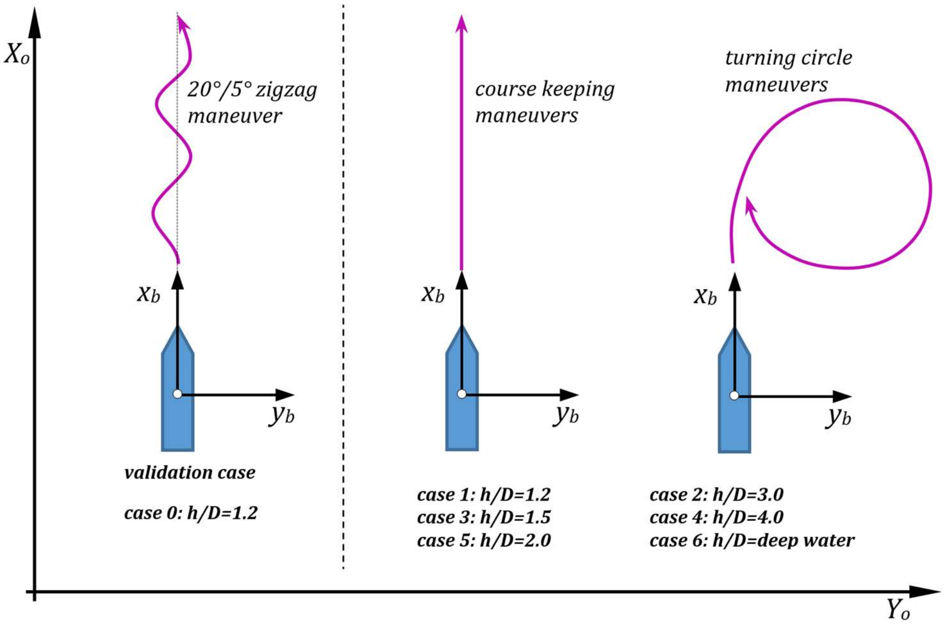

Fig. 3 – *Simulation cases of free-running manoeuvres* [1].

Mathematical models of ship manoeuvring typically focus on predicting longitudinal forces, sway forces, and yaw moments acting on the ship in its horizontal path. For mathematical models of manoeuvring in shallow water, models with 3 degrees of freedom (3 DOF) were successfully used. Later, a rolling motion was introduced as the 4th DOF. Sinkage and trim were not used in mathematical models, i.e., they were treated separately from other forces and occasionally added to mathematical models for squat calculations. Since IMO introduced regulations for manoeuvring criteria under the influence of wind and waves, the manoeuvring model with 6 degrees of freedom is mandatory [11]. Manoeuvring a ship is a very challenging task due to the influence of changing external factors such as wind, waves and sea currents. Due to these factors, the draft, trim and heel of the ship change [12]. For this reason, wind and waves must be included in a ship's manoeuvring criteria. 6 degree of freedom (6 DOF) manoeuvring models in a calm water are also used [11].

When studying ship motions in 6 DOF, it is recommended to define a body-fixed and an earth-fixed coordinate frame [13]. Figure 4 shows the ship and earth fixed coordinate system in 6 DOF, where Oxyz is a body-bound (ship), and $O_0x_0y_0z_0$ is an Earth-bound (towing tank) coordinate system. The body origin O is located at the vessel midship section equal to one-half of ship LPP. The positive longitudinal Ox-axis is directed from stern to bow, the positive transversal Oy-axis runs along the breadth or beam of the ship and is positive towards the starboard side. In contrast, the positive vertical Oz-axis is directed down - towards the ship keel. For a right-handed axis system looking in the positive direction of each axis, the rotation angles are positive clockwise in standard notation and sign conventions. Furthermore, O'x'y'z' defines a horizontal-bound coordinate system which always remains horizontal i.e., does not change with vessel heave, pitch, and roll motion.

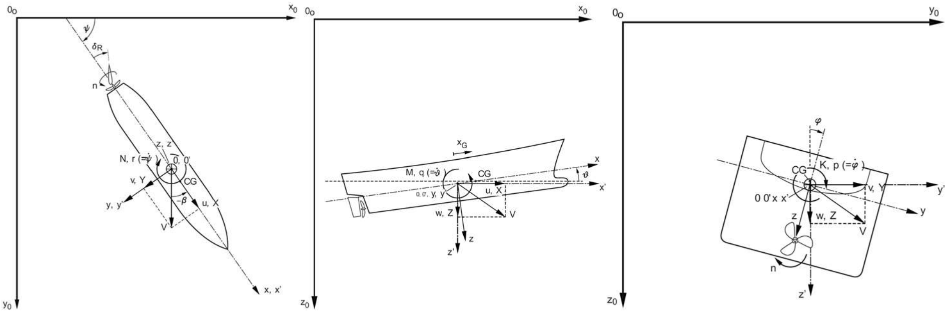

Fig. 4 - *Ship and earth fixed coordinate systems in 6 DOF* [11].

Hydrodynamic interaction between two large ships in a narrow channel is also a subject of research using mathematical models. The reason for this is the increased density of ships in narrow channels and shallow waters. When passing or overtaking, there are unpredictable interactions between ships that can lead to a collision. The hydrodynamic forces between two vessels in narrow channels and restricted waters are more complex than in open (unrestricted) waters and are the subject of research [14].

Regardless of the mathematical models used to control a ship in shallow waters, the skill of ship handling can only be learned and improved through theoretical training and practice. Theoretical training is undoubtedly important because officers gain knowledge of the hydrodynamic forces acting on the ship. The theoretical basics of manoeuvring are the starting point. Exercises on the ship simulator complement the theoretical basics with a series of manoeuvre simulations and are certainly a valuable tool to practise and improve ship manoeuvres. Finally, good manoeuvring skills are achieved through many years of practice, of course, with the best possible knowledge of the manoeuvring characteristics of own ship. By understanding the influence of hydrodynamic forces on the ship when navigating in shallow waters, officers can think ahead and plan ship manoeuvres [15].

4. Conclusion

Ship maneuvering in shallow waters and narrow channels remains a significant challenge and a great responsibility for the Master of the ship and his officers. For efficient and safe maneuvering of the vessel, planning ahead with sound theoretical knowledge of resistance, trim, stability, and maneuvering characteristics (turning circle, rate of turn, stopping ability) is of utmost importance.

Mathematical models are a great help in calculations for maneuvering in shallow waters. They are the basis for creating simulations of the maneuvering of large ships. Although various mathematical models have been developed for predicting ship behavior under the influence of hydrodynamic forces in shallow waters, it is undeniable that to maneuver a ship safely, it is necessary to understand the maneuvering characteristics of own ship and to have good maneuvering skills resulting from years of experience at sea.

Sound theoretical knowledge and familiarity with the maneuvering characteristics of one's own vessel in shallow waters enable the Master to make the correct maneuvering decisions, significantly reducing the risk of collisions and groundings and increasing the safety of navigation at sea. Due to the increasing trend of building large ships in the global market, scientists and engineers need to use mathematical models for ship maneuverability in shallow waters and improve existing models where necessary. Mathematical models are of great help in calculating and predicting maneuverability. At the same time, the practical knowledge of navigators in ship handling will be crucial for handling large ships in confined and restricted waters.

Computational fluid dynamics is currently a standard technique worldwide for solving hydrodynamic problems of ships. The results of numerical simulations are promising and can be improved by increasing the time steps and changing the mesh precision, increasing the accuracy of the overall drag results.

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