Proceedings of MARTEC 2010
The International Conference on Marine Technology
11-12 December 2010, BUET, Dhaka, Bangladesh

ASSESSMENT OF SHIP MANOEUVRABILITY IN SHALLOW WATERWAYS

Osman Md. Amin[1] and Kazuhiko Hasegawa[2]

[1]Department of Naval Architecture and Ocean Engineering,
Graduate School of Engineering, Osaka University,
2-1 Yamadaoka, Suita, Osaka 565-0871, Japan
E-mail: osmanamin@naoe.eng.osaka-u.ac.jp

[2]Department of Naval Architecture and Ocean Engineering,
Graduate School of Engineering, Osaka University,
2-1 Yamadaoka, Suita, Osaka 565-0871, Japan
E-mail: hase@naoe.eng.osaka-u.ac.jp

ABSTRACT

Navigation of ships in inland waterways faces many difficulties in terms of ship manoeuvrability. While the ships are operating in the restricted waterways such as channels, canals or rivers, manoeuvring characteristics of ships get significantly changed from those in deep and wide waterways. The reduction in water depth contributes significantly to the loss of turning ability of ships. In this research, the manoeuvring characteristics of a particular type of ship have been investigated considering the shallow water influence. Mostly through numerical simulations, the particular behavioral change of the navigating ship at different depths of water has been thoroughly analyzed. The simulations were carried out on the basis of a mathematical model which describes the ship motion properly at different conditions of ship navigation. From theoretical point of view, some proposals also have been made on the basis of previous research works which may provide reliable tools for the prediction of manoeuvrability of ships in shallow water.

Key words: Shallow water, ship manoeuvrability, hydrodynamic interaction coefficients, MMG model, advanced vortex method, slender body theory.

1. INTRODUCTION

Manoeuvrability of ships in shallow water is one of the most sought after problems in the field of ship motion. Ships, operating in harbor and port areas, encounter a significant change in their manoeuvrability characteristics because of the change in the water depth in restricted areas. The main intention of this paper is to introduce the readers with several techniques, which are available now-a-days, to predict the manoeuvrability of ships in shallow waterways. The focus would be directed upon the vertical constraints that the ship faces in those areas. On the basis of experiment data, Fujino [7] had shown that the water depth to ship draft ratio when exceeds 2.5, the shallow water effect becomes less remarkable. And he concluded that at intermediate water depths ship becomes very unstable, whereas in very shallow water it again becomes stable. As the main concern of predicting manoeuvrability is to measure the hydrodynamics forces and moments acting on the ship, a simplified simulation technique serving this purpose would provide a great tool to the navigators for safe operation of ships in narrow waterways.

Hull induced forces and moment are considered to comprise the biggest portion of the total forces acting on the ship while in motion, whereas the interaction between hull, propeller and rudder has a significant bearing on the manoeuvrability of ships. On this premise, here a special attention has been put forth in determining those interaction effects through numerical simulations.

2. VALIDATION OF SHIP MANOUEVRABILITY

Manoeuvrability of a ship signifies the predictability and controllability of the motion of ships at different situations of sea conditions. Qualitatively the manoeuvrability of a ship is measured through some manoeuvring tests, which when performed on the ship would provide us with a comprehensive way to understand the behavior of the operating ship. In this context, the quantitative measurement is done through the determination of the incurred upon hydrodynamic forces and moments by varying flow patterns around the ship. Either theoretical approach or numerical simulation - none could so far provide a reliable method to simulate appropriately the manoeuvring characteristics of ships in shallow water without conducting the captive model tests. Several of these treatments are explained below.

2.1 Analytical Methods

Slender body theory is one of pioneering theory for ship hydrodynamics. It exploits the slenderness of the ships (longitudinal scale is far greater than the beam and depth) in transforming the boundary conditions (B.C.) to simpler forms. In this approach, perturbation technique [6] is applied to obtain the first order and second order equations of the B.C. [16] on the basis of the perturbation parameter (in this case, the slenderness ratio - the ratio of ship beam to length). This would require a matching of the solutions in outer region and inner region of the body, which through the application of distinct B.C. for different regions would render a unique solution of the velocity potential. Then on the basis of this outcome the pressure distribution on the body can be achieved. E.O.Tuck [31] has shown that, the trim and sinkage predicted in shallow water using the above mentioned method provides a significant lack of dissimilarity between theory and experiment, which may have occurred due to the linearization of the B.C. On this premise, Yeung [36] has proposed a general theory of motion to provide a six D.O.F. motion model of the slender body ship. A chronological survey done by Maruo [17] shows that, the non-effectiveness of this method to predict ship motion is fixed in the nonlinear B.C. For this reason, the authors have taken measures to solve those boundary conditions, keeping the nonlinearities intact, using a non-perturbative mathematical method, named Homotopy Analysis Method. Homotopy is a concept related to the field of topology (set theoretic form of geometry). Liao [15] has proposed this method to solve the differential equations by taking into consideration of the nonlinearities. Systematic solution of the B.C. using this method, as converging series, would provide a suitable base to rely on for further analytical derivations involving ship motion in shallow water.

Some of the primitive techniques like Prandtl's lifting-line theory have been implemented by Newman [18] to take account of the lateral restrictions along with the vertical one in narrow channel. Hess [8] using similar technique of slender body/porous wing model has shown that the rudder force increases with decreasing water depth and rudder moment gets reduced due to a shift in center of pressure toward amidships. This result conforms to the experimental data concerning the hull-rudder interaction of ship in shallow water.

Most of the analyses, as mentioned before, consider the double hull model to take account of the free surface B.C. That means, the free surface is considered to be rigid on assumption of low speed manoeuvring in shallow water. Chen et al [4] figured out that the ship moving in a narrow channel may produce waves which would counteract the bank suction force, transforming it into a repulsive one at supercritical speed. Although Ohkusu [20] has pointed out that, so far the number of experiments carried out to verify the above mentioned theoretical approaches are very few to justify the applicability of those methods.

Another powerful concept is the strip theory, which assumes that the fluid flow in a plane perpendicular to the longitudinal axis of the ship is identical to the two-dimensional fluid motion around a cylinder of infinite length with the same cross section as that of the strip of the ship. For low frequency range of motion this method cannot predict well the flow field because of the lack of consideration of interaction between the strips (three dimensional effect). The earliest strip theory concept (dubbed 'Ordinary strip theory') [34] didn't consider the forward speed in a rational way, which was later modified by Tasai [28] using conformal mapping technique to take account of the change in flow field due to the presence of forward speed. Keil [11] extended this technique for different water depths. Strip theory considers the dimensions of the strips to be much smaller than axial length, which in turn shows the equivalency of this method with the slender ship theory.

2.2 Simulation using Mathematical Models

The assessment of manoeuvrability at the initial design stage of a ship requires a good mathematical description of the manoeuvring motion of the ship. Apart from the theoretical formulation, the hydrodynamic forces acting on the ship can be represented mathematically in many forms, from the fairly simple Abkowitz [1] derivatives for prediction of first quadrant manoeuvres, to a full four-quadrant deep and shallow water simulator model.

The modular mathematical model, developed by MMG group of JTTC [19], was designed to express the stream behavior around the ship by considering the individual open water characteristics of the hull, propeller and rudder and the interaction effects among them. This model was intended to provide a rational way of deducing several hydrodynamic coefficients from Captive Model Test and also to establish an analytical model/full-scale correlation. This is why, the proper determination of the interference effect between hull, propeller and rudder comprises a significant proportion of the manoeuvrability prediction. Significant amount of research works have been done so far to confirm the validity of this model in case of shallow water manoeuvring. Among them Hirano et al [9] proposed a simplified method to predict the linear hull hydrodynamic coefficients on the basis of low aspect ratio wing theory. A more practical hull force prediction method was proposed by Kijima et al [13] through the formulation of some semi-empirical formulae to derive hull hydrodynamic coefficients. So far this method is considered to be the most congruent one in terms of its practical applicability. Other researchers [14, 33, 37] concentrated more on specific types of ships for the formulation of manoeuvrability characteristics in shallow water on the basis of MMG model. The dominant hydrodynamic forces acting on ship, when operating at low speed in shallow water are the inertial forces. Kan et al [10] used low-aspect-ratio wing theory and method of images to calculate two-dimensional added mass coefficients for body section in a channel of finite depth. Van Oortmerssen [32] has shown that the dependency of added mass, in case of shallow water manoeuvring, on frequency of motion should be taken into account for frequencies higher that $0.1s^{-1}$. Since the ships do not face that much high frequency of disturbance, while operating in calm shallow channels, the added mass and moment of inertia can be considered to remain constant throughout its operation in those areas. Sadakane et al [24] have proposed some semi-empirical formulae to predict the added masses and moment of inertia in terms of ship principle particulars. And they proved those equations on the basis of experiment and potential flow theory.

The Authors have extended the MMG model to take into account of water depth change, as faced by the ship in narrow waterways [2]. Some semi-empirical formulae to predict the hydrodynamic interaction coefficients, which comprise the MMG model, have been proposed for single-propeller single-rudder ship in that paper on the basis of available experimental data for shallow water manoeuvring. Several simulations have been carried out for a VLCC ship (Esso Osaka [5]) to judge the manoeuvrability at different depths of water. Figure1 shows the body plan of the tanker and Figure 2 depicts the turning circles for 35-degree turning test at different depths of water along with the experimental data. In these cases the initial speed is considered to be 0.3167 m/s. From Figure 2 it is apparent that the simulated turning trajectories closely resemble that of the experimental one.

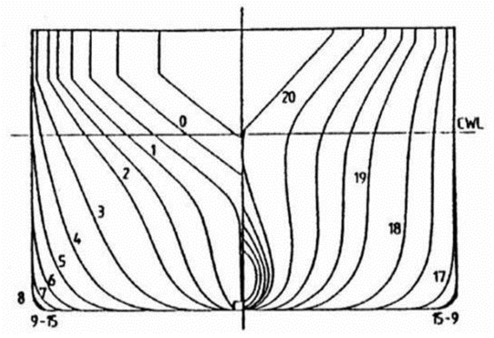

Figure 1. Body Plan of VLCC tanker (Esso Osaka)

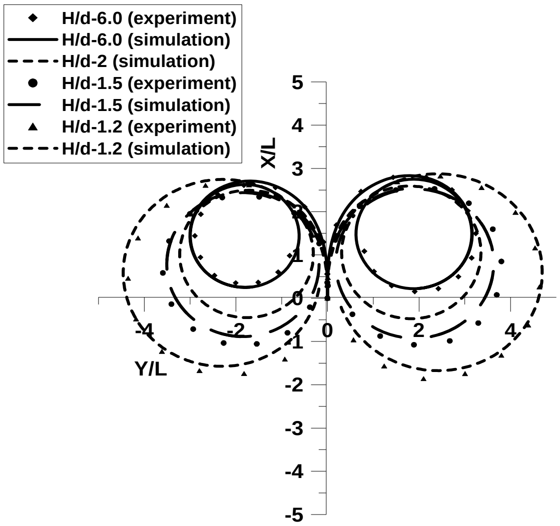

Figure 2. 35^0 turning circles at different depths of water

Kijima's regression model for hull hydrodynamic forces along with the proposed model for interaction coefficients have been adopted in this analysis to establish a generalized mathematical model for the prediction of ship manoeuvrability in shallow water.

2.3 Numerical Techniques

The analytical methods explained in section 2.1 consider the flow around ship to be inviscid and incompressible. To take account of the viscosity and to simulate the flow field in detail around the ship several numerical techniques are so far being tried out by many researchers. CFD technique such as RANS (Raynolds Averaged Navier-Stokes) code is becoming more and more popular to predict the wave resistance and manoeuvrability fairly well in deep water. Although the treatment of hull, propeller and rudder interaction still seems be far fetched from the point of view of CFD simulation [22, 25, 27, 30]. Progresses are still under way to predict the flow around the ship properly and to measure the propeller-hull interaction at full scale Reynolds number.

There are plenty of other numerical techniques which rely on large computational power. One of them is the LES (large eddy simulation) of the wake field behind the moving ship. The LES method considers the large eddies created in the wake to be composed of tiny discrete elements, such as vortex blobs, vortex particles etc., and simulates the flow field on the basis of shed vortices from the body of the ship. The advantage with this method compared to the RANS code is that the flow field does not have to be discretized to simulate its characteristics [12]. The Authors have implemented a certain Vortex shedding method [21, 26] to replicate the flow pattern around the Esso Osaka hull at certain drift angle, as can be seen in Figure 3.

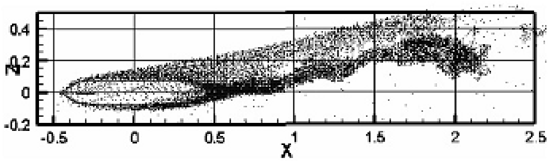

Figure 3 . Flow pattern around Esso Osaka at drift angle =12^0,Ut/L=0.5, boundary layer thickness=0.005

To take account of the interaction effect in shallow water, this method is adopted on the hull along with a sink model for propeller as proposed by Yamazaki et al [35] and also with a lifting surface for rudder.

The principle concern with the methodology involved with computational fluid dynamics is the lack of availability of mathematical model to formulate the turbulent flow around ship. Turbulence is considered to be a feature of the flow, not of the fluid. On this basis the instantaneous characteristic quantity of the turbulent flow is decomposed into the mean average value and a fluctuating part, which allows us to develop a statistical treatment of equations of motion. This extra random part gives rise to the additional turbulent stress, which arises from convective derivative of the Navier-Stokes equation. Several methods are available in deriving this turbulent stress, such as RANS method and spectral methods [3], which provides us a way to figure out the energy exchange between the different sized eddies. Another approach is to find a 'hidden' parameter besides other parameters, like Reynolds stress, the viscous dissipation rate etc, which would influence the property of turbulent flow [23]. As mentioned before, the LES is another concept which has huge popularity in simulating the turbulent behavior of flow around ship. Despite of all of these efforts, still there remained a lack in the understanding of the fundamentals behind the generation of Turbulence. As Lumley [29] pointed out - "In turbulence, the equations do not give the entire story. One must be willing to use simple physical concepts based on experience to bridge the gap between the equations and actual flows".

3. CONCLUSION

The extensive amount of techniques which are available for the prediction of ship manoeuvrability in shallow water are thoroughly explained in this paper. The requirement of fast time simulation in ship handling simulators has put on a challenge for the researchers to find out an appropriate method to predict the manoeuvrability of ships in narrow waterways. In this context, only the mathematical model approximation of the ship manoeuvring dynamics provides practical way of simulating the ship behavior, where captive model tests are necessary to verify the model. Although CFD and other numerical techniques are gaining in popularity because of the enhancements in the computing powers, the model tests are still the most reliable means to predict the ship behavior in shallow waterways.

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