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Osaka University
Doctoral Dissertation

Ship Maneuvering Mathematical Model Using System Identification Technique with Experimental and CFD Free Running Trials in Calm Water and Astern Waves

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December 2012

Graduate School of Engineering
Osaka University
3. MANEUVERING IN FOLLOWING AND QUATERING WAVES

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1.1 BACKGROUND AND OBJECTIVES

One of the most basic requirements for ship performance is intact stability, an ability not to capsize without damage of enclosed buoyant space. Nowadays, thanks to large efforts of ship designers, it is true that most of intact ships have little possibility to capsize in calm water but still risks of capsizing do exist in wave cases. Especially, in high speed and rough conditions in following and quartering waves, the risks of pure loss of stability and broaching-to are well known by seafarers from olden time (Du Cane and Goodrich, 1962). In 1951, when Portuguese destroyer Lima was steaming with Froude number (Fr) 0.43 in following waves, she experienced broaching. Just after one of the waves captured her, she suddenly started sharp turning and her heel angle reached to 67 degrees, caused by the centrifugal force due to the turn, in spite of maximum steering effort to keep her course (Saunders, 1965). When a ship is running in following or stern quartering waves with high-speed, the ship speed approaches to the wave celerity, roll and maneuvering motions can be easily affected by waves because the wave encounter frequency is close to the roll and maneuvering natural frequencies. Herein it is clear that one of the important elements for the broaching-to is the maneuverability in following and stern quartering waves.

Moreover, in the 54th session of International Maritime Organization (IMO) Sub-committee on Stability and Load Lines and on Fishing Vessels Safety (SLF), the broaching is recognized as one of the major stability failure modes (IMO, 2012). SLF started its work on the second generation intact stability criteria, in which their vulnerability criteria on level 1 and 2 are basically deterministic (Kobylinski, 2012). The vulnerability criterion on the level 1 judges a ship vulnerable if her length between perpendicular is smaller than 200m and her operational Froude number is larger than 0.3. On the level 2, surf-riding threshold would be calculated either by Melnikov's method or by a direct numerical bifurcation analysis (Maki et al., 2010, Belenky et al., 2011). Then the ship is judged
vulnerable for broaching if the long-term probability for surf-riding is greater than $10^{-6}$. On the level 3, direct stability assessment is required. In this process, numerical time-domain simulations would be required with numerous wave conditions and operational conditions. Moreover the pure loss of stability cannot be disregarded in the high-speed ship running in astern seas. As well as the broaching criteria, the 54th session of SLF concluded the vulnerability criteria for pure loss of stability on the level 1 and 2 are basically determined (Kobyliński, 2012). However the direct stability assessment, i.e. the level 3 criterion, is still remained in the discussion table. According to systematic free running model experiments and 2DOF (surge-roll) and 4DOF (surge-sway-yaw-roll) simulations in astern waves, Kubo et al. (2012) suggested that the coupling between roll and maneuvering motion, as well as restoring reduction in longitudinal waves, should be taken into account for accurate direct stability assessment. From these points of view, it seems that multiple degrees of freedom mathematical maneuvering model with wave forces taken into account could be one of the candidates for the solution method.

However, to start running simulations using the multiple degrees of freedom mathematical maneuvering models still has some troublesome steps. Numbers of captive model experiments are requested for the reliable simulations (Matsumoto and Suemitsu, 1980). Although the free running simulation itself is simple enough for the direct stability assessments, the captive model experiments, the preliminary steps for the simulations, are time and cost consuming. To overcome this drawback, system identification (SI) techniques were developed in control engineering around 1970s (Eykhoff, 1974). The SI predicts or tunes the system parameters in the mathematical model of dynamic system from measured data of free running experiment. This means that single free running data could provide all parameters included in the maneuvering model. Several researchers (Nonaka, 1972, and Abkowitz, 1980) started to apply the SI techniques for the parameter estimation of the maneuvering models. However, even with single free running, it is necessary to prepare several equipments and the ship model herself. Moreover there are some limitations on SI using free
running model experiments that the added mass and added moment of inertia cannot be estimated with this methodology. Because the added mass are at the left hand side of the equation of the motion and multiplied with acceleration term which makes it impossible to determine the other maneuvering coefficients. Therefore normally researchers assumed and fixed the added mass term estimated empirically.

Meanwhile, with remarkable developments of computer technology, computational fluid dynamics (CFD) becomes a practical tool for naval architects. Moreover several CFD codes started to show quantitative agreements with free running experiments (Stern, 2011). These large developments of CFD could make it possible to replace the conventional free running experiments in future. The important benefits using CFD simulation is not just cutting the experiment cost but providing hydrodynamic force during the free running simulation which is impossible in experimental free running. The SI would be easier with comparing the hydrodynamic force directly helps estimating add mass terms. Moreover it is easy to measure hydrodynamic force at any position we need, i.e. rudder, bilge keel, which can also help the SI. However the computational time and costs are still expensive, i.e. one case of the CFD free running needs nearly a month using Cray XE6 410.04TFLOPES supercomputer in this thesis. In this case, it is difficult to compute all cases the architects need.

According to these situations, SI using CFD free running data is proposed in this thesis. In the previous researches, most of the SI techniques are using experimental free running data and applied for the maneuvering model in calm water (Abkowitz, 1980, and Kang, 1984). However no SI research can be found using CFD free running data which provides more fruitful results than experimental free running for the SI. Moreover few SI researches had challenged for wave cases (Terada et al., 2012). Therefore, in this thesis, SI using CFD free running data is applied to following and quartering wave cases as well as calm water cases.
1.2 HISTORY OF THE MODEL DEVELOPMENT

First numerous methods are proposed to predict and reproduce ship maneuverability in calm water during the long history of ship dynamics researches. First, zigzag maneuver was proposed by Kempf (1932) and Nomoto (1956) established the relationship between maneuvering motion and rudder action by applying a concept of control engineering into the zigzag maneuver. On the other hands, Davidson and Schiff (1946) developed the ship maneuvering equation as following equations.

\[
\begin{align*}
(m + m_x)u - (m + m_y)v + r &= X \\
(m + m_z)\dot{v} + (m + m_y)ur &= Y \\
(I_z + J_z)\dot{r} &= N
\end{align*}
\] (1.1)

Motora (1960) provided an empirical method for estimating the added masses and added moment of inertias from systematic model tests with various ship dimensions, which is known as Motora’s chart. The right hand side of the equation (1.1), hydrodynamic forces, were investigated by Inoue (1956) and Sugai (1965) applying a lifting surface theory for rectangular wings of small aspect ratio (Bolley, 1939). From the practical point of view, Abkowitz (1946) described the hydrodynamic forces as the reaction forces due to ship motions and developed a mathematical model to describe the hydrodynamic forces with polynomial expressions of state variables using the Taylor expansion. Moreover the maneuvering mathematical modeling group (MMG) (Ogawa and Kasai, 1978; Ogawa et al., 1980) developed a coupled 3DOF (surge-sway-yaw) mathematical model, which explicitly includes the individual open water characteristics of the hull/propeller/rudder and their interactions. The MMG model has shown good results for maneuvering in calm water (Ogawa et al., 1980; Stern et al., 2011). Coupled 4DOF (surge-sway-yaw-roll) model was developed and applied into calm water and following seas (Son and Nomoto, 1981, 1982). The study of the
time-domain simulation for stern quartering seas initiate by Paulling (1974) and followed by Böttcher (1986), Hamamoto (1988, 1989), and de Kat (1989) developed into further elaborated and complex models with using 6DOF nonlinear model, nonlinear Froude-Krylov force, and memory effects for linear hydrodynamic forces taking into account. On the other hands, the CFD code using single-phase level set with dynamic overset grids developed by Carrica et al. (2007) makes it possible to simulate the free running with full appended ship model. Today this CFD code show quantitative agreements with free running experiments even in highly nonlinear broaching conditions (Sadat-Hosseini et al., 2011). However the computational time is remarkably huge because of using dynamic overset grid which requires modifying the grids every single time step. Therefore the CFD simulations are not suitable for long time and systematic simulations. Meanwhile it is known that the capsizing phenomenon is one of the first-excursion probability problems which means large number of independent and long term simulations are required to predict such probability (Kastner, 1975). In this sense, the simulation model for the direct stability assessment is expected as simple as possible. Incidentally it is clear that the wave encounter frequency becomes much smaller than the natural frequencies in heave and pitch when ship is running in oblique following seas with high-speed. Therefore the heave and pitch motions can be reasonably treated as quasi-static motion (Matsuda, 1997). Ohkusu (1986) concluded using a slender body theory, with low encounter frequency assumption, not just the Froude-Krylov force but also the hydrodynamic lift due to wave particle velocity, here so-called diffraction component, and the effect of the interaction of the Kelvin waves with disturbed incident waves are not to negligible. Umeda et al. (1995) systematically measured wave-induced forces acting on a ship model in quartering waves and showed the linear diffraction component, as well as linear Froude-Krylov component, well predicts the wave-induced sway force, yaw and roll moments even in heavy quartering seas up to the wave steepness 1/10. Herein the 4DOF (surge-sway-yaw-roll) model was developed by Umeda and Renilson (1992) and Umeda (1999) for capsizing associated with surf-riding in following and quartering waves. Hashimoto et al. (2004) showed that nonlinear maneuvering coefficients and other high-order terms
estimated by captive model tests could improve the simulation results. Araki et al. (2010) also proposed highly nonlinear 6DOF model, several nonlinear effects taking into account, e.g. rudder and propeller emersions, maneuvering coefficients variation and restoring variations in longitudinal waves. Although these models successfully showed qualitative agreements with model experiments on broaching, there are still some discrepancies with free running model experiments.

Regarding to the history of the model developments, the model is started from the simplest one as equation (1.1) and developed into very accurate and complex model, after that, according to the requirement for practical use; it is going back to simple model which is more refined one than the early models. However, now on, it starts to go back to complex model again. In this thesis, totally different approach is proposed. The SI using CFD free running data could be used not just for removing captive and free running model experiments to estimate coefficients in the simulation model but also wedging to the endless discussions of the model style. In the SI, some errors of the model can be included or replaced into the coefficients. However the importance of designing the simulation model still remains. The simulation model needs to be tuned and designed for each situation such as beam waves or following waves. In this thesis, the choice of the model is also meticulously discussed for this delicate challenge.

1.3 OVERVIEW OF THE THESIS

This thesis is constructed with four chapters, acknowledgments, appendix, and references. The background and objectives of this thesis are shown already in this chapter. In Chapter 2, SI techniques are applied for maneuvering in calm water. Herein extended Kalman filter (EKF) and constrain least square method (CLS) are used for the SI with CFD and experimental free running data. The details of these SI techniques are given in the appendixes. In Chapter 3, the SI technique, CLS, is applied for the ship motion in following and quartering waves and the wave
model is tuned. Herein CFD free running data and CFD forced motion data are used for the SI. Some trials are given to combine some results from captive model experiments with the system identified model. The system identified model and the combined model are also applied for the broaching conditions and whether these models improve the broaching predictions or not is discussed. The final chapter reviews the conclusions and achievements of the second and third chapter.
2 MANEUVERING IN CALM WATER

2.1 INTRODUCTION

A definition of the broaching is a phenomenon in which a ship cannot keep her desired course despite the maximum steering effort (Du Cane and Goodrich, 1962). Moreover the sharp turning due to the broaching will cause serious heel or capsizing due to the centrifugal force. Herein ship maneuverability is one of the most important topics to predict and avoid broaching. Therefore reliable ship maneuvering simulations are required for incident analysis and prevention. Before stepping into wave cases, the SI techniques are applied to the calm water cases in this chapter.

System-based (SB) and computational fluid dynamics (CFD) methods are major simulation methods to predict ship maneuverability. The SB approach in this thesis means an approach consisting of two-layer sub systems. In the lower layer, hydrodynamic forces mainly due to potential flow are calculated by solving partial differential equations of potential flow and hydrodynamic forces mainly due to viscosity flow are estimated with captive model experiments or empirical formulae. In the upper layer, ship motions are calculated by solving ordinary differential equations with initial conditions. Computation time of the SB simulation is much shorter than that of CFD since such a method only needs to solve the equations of motion using a prescribed mathematical model and maneuvering coefficients. SB simulation requires approximately one minute for one free running trial while CFD needs a few weeks or a month depending on the turbulence and propulsor modeling and size of the grids. However, there are many issues in derivation of accurate mathematical models and maneuvering coefficients, especially for wave conditions. In most cases captive model planar motion mechanism, rotating arm or circular motion tests is used, which requires many static and dynamic conditions. On the other hand, CFD just requires the ship geometry and the propeller characteristics for the simulation (along with expert user and high performance computing resources).
Several SB models have been developed. Abkowitz (1964) developed a mathematical model to describe the hydrodynamic forces/moments acting on the ship with polynomial expressions using Taylor expansion on state variables. The Maneuvering Mathematical Modeling Group (MMG) (Ogawa and Kasai, 1978; Ogawa et al., 1980) developed a mathematical model, which explicitly includes the individual open water characteristics of the hull/propeller/rudder and their interactions. The MMG model has shown good results for maneuvering in calm water (Ogawa et al., 1980; Stern et al., 2011) and qualitative results for extensions for wave conditions (Araki et al., 2010; Yasukawa 2006). Issues for improvement include both wave terms in the mathematical model and methods for obtaining the wave maneuvering coefficients. Usually the maneuvering coefficients are assumed constant, which could be realistic for high encounter frequency wave conditions. In contrast, Son and Nomoto (1982) and Araki et al. (2010) showed a large variation of maneuvering coefficients in following waves in which the encounter frequency is very low. Recently, CFD has been extended for free running simulations, including quantitative agreement with experimental fluid dynamic (EFD) ship maneuvers in calm water (Stern et al., 2011) and waves (Sadat-Hosseini et al., 2011).

System identification techniques are developed in control engineering to build mathematical models for dynamical systems often using the system coefficients based on experimental data. The least square (LS) method is the one of the simplest and the extended Kalman filtering (EKF) (Lewis, 1986) is one of the most widely used methods in engineering. For ship hydrodynamics applications, the advantage of SI is that all the maneuvering coefficients can be estimated by one or a few free running trials as opposed to numerous captive model tests. Nonaka et al. (1972) employed LS to estimate maneuvering coefficients from EFD free running data with random rudder motions and the Abkowitz mathematical model. However the estimated maneuvering coefficients were not accurate (i.e., large differences from those from the captive model tests), which is due to some of the derivatives drifting to the wrong values known as the simultaneous drift problem (Kang et al., 1984).
Since some maneuvering coefficient signs or rough values are known from physical reasoning or previous research, the constrained least square (CLS) method using the generalized reduced gradient algorithm as developed by Lasdon et al. (1978) could be useful for estimating the maneuvering coefficients. The generalized reduced gradient algorithm is one of the optimization algorithms that makes it possible to set general constraints on the optimization. The constraints could help avoiding the simultaneous drift problem.

Abkowitz (1980) employed EKF using full-scale trial data and the Abkowitz mathematical model. The 10/10 zigzag trial data was used to estimate the linear maneuvering coefficients and the $\delta=35$deg turning circle trial data was used for the nonlinear coefficients. The simulation using estimated maneuvering coefficients showed reasonable agreement with not only the 10/10 zigzag and $\delta=35$deg turning circle trial data, but also 20/20 zigzag trial result which were not used for the SI.

Rhee and Kim (1999) employed EKF for SB free running trial data (zigzag, turning circle, large angle zigzag tests, etc.) and the MMG mathematical model to find best trial type for SI. The maneuvering coefficients reconstructed from the large angle zigzag test showed the smallest error with the original coefficients. Zhang and Zou (2011) employed support vector machine, one of the artificial intelligence methods, for SB free running trial data (zigzag test) and the Abkowitz mathematical model for which the reconstructed coefficients showed close agreement with the original maneuvering coefficients. Several other researchers (for instance Shi et al., 2009) have employed EKF to estimate ship maneuvering coefficients. However most of them just used simulation data to estimate maneuvering coefficients. The focus of the studies using SB free running trial data is on the capability of SI techniques and no EFD trial data was used for validation.

CFD free running trial data has yet to be used for the SI. Total and component hydrodynamic forces/moments acting on the ship/appendages/propeller can be estimated by CFD simulations while it is unknown for ship and difficult for appendages/propeller in experimental free running
measurements. Moreover it could be possible to compute reliable SB maneuvering simulations without any captive or free running model experiments, and rather using SI with CFD free running trial data which offers significant benefits for ship design. CFD also has the capability of performing simulations at full-scale Reynolds numbers and environmental conditions (Bhushan et al., 2009).

Herein, maneuvering coefficients for a 4DOF SB method based on the MMG mathematical are estimated initially from captive tests (original maneuvering coefficients) and subsequently from CFD and EFD free running trail data for calm water maneuvers using SI to evaluate the mathematical model and determine the optimum approach for estimating the maneuvering coefficients. SB using the original maneuvering coefficients and CFD are validated using EFD for turning circle and zigzag maneuvers. EKF and CLS SI techniques are used with the SB, EFD and CFD free running trail data to obtain new maneuvering coefficients, which are compared with the original ones. The new coefficients are then used with the SB method to predict the original and blind trajectories showing that CFD provides the optimum approach for estimating the maneuvering coefficients.

### 2.2 EFD METHOD

The Most of EFD free running data in this thesis were acquired in Iowa Institute of Hydraulic Research (IIHR) wave basin facility (Fig.2.1). The IIHR wave basin has dimensions of 40×20 square meters with 3 meters water depth and is designed to test captive or radio-controlled model scale ships. There are six plunger-type wave makers on the one side of the basin to generate regular or irregular waves. The x-direction (length) main-carriage and y-direction (width) sub-carriage with yaw-direction turntable (heading) track or tow the model. The sub-carriage supports the model launch system and local flow measurement system traverse. The model launch system enables specification and replication of the initial conditions of free running trials.
The 1/49 scaled model of ONR tumblehome (ONRT) appended with skeg, bilge keels, rudders, shafts and propellers with propeller shaft brackets was used for the experiments (Figs.2.2, 2.3 and Table 2.1). Roll, pitch and yaw angles of the model ship were measured by a fiber optical gyroscope (FOG). The accuracy of roll and pitch angles is ±0.5 deg, while that for yaw angle is ±1.0 deg without considering the error due to the gyro drift. However the drift effect may be negligible because the gyro’s yaw angle was reset through wireless communication just before the each trial is started.

The number of propeller revolutions (RPM) is counted by a photo micro sensor and the rudder angle is estimated from the number of pulse signals transmitted to the rudder-driving stepping motor. All the data of the free running system is recorded with a frequency of 20 Hz. Meanwhile, the plane trajectory of a model is recorded with a frequency of 10 Hz by the tracking system, which uses two-camera vision. The tracking cameras capture two LED lights placed on the deck of a model. The mid-point of two LEDs corresponds to the longitudinal center of gravity (LCG) of the model, but 0.250 m higher than the vertical center of gravity (CG) point due to space restriction. The model’s horizontal position can be estimated indirectly by monitoring the rotational speed of each x and y direction-motor. The maximum tracking speeds in the longitudinal x and transverse y directions are 2.5 m/s, while that for the rotational speed is 60 deg/s. Although the free running and tracking systems are fully independent, all data can be synchronized receiving the start-signal of radio control.

With an onboard FOG and the carriage model tracking system enables a 5DOF measurement of a free running model including xy-position, roll angle, pitch angle and yaw angle. In order to increase the reliability and accuracy of the 5DOF measurement and to enable measurement for all 6DOF of the free running model, i.e. the heave motion, a 6DOF visual motion capture system (6DOF-VMCS) was developed and added to the tracking system. As shown in Fig.2.4, a CCD camera is installed on the turntable of the sub-carriage that focuses on a calibration target plate
attached on the deck of the free running model. Digital images of the calibration target plate are acquired at a frame rate of up to 30 fps. The target images were analyzed with OpenCV library to determine the 6DOF motion of the free running model relative to the carriage and sub-carriage/turntable. Comparative tests show that the angles and displacements obtained with 6DOF-VMCS have good agreement with those obtained with the FOG and the carriage model tracking system.

The IIHR experimental procedure is as follows. First the model ship is fixed on the launch system by electromagnetics while the heave, roll and pitch are free. Just before launching, FOG is reset to zero through wireless communication to avoid the gyro drift problem. After the propeller starts to rotate, the model is accelerated by the launch system to the target speed and tows the model with constant speed for a specified period and then releases it. After the model is released from the launch system, the model runs straight without any rudder deflection for a specified period and starts maneuvering after pre-set time. The propeller RPM is kept constant while running.

A detailed description of the wave basin and the wavemakers, the carriage model tracking, the 6DOF visual motion capture and free running 6DOF systems, model geometry and ballasting, and free running trials tests in calm water and waves is provided by Sanada et al. (2011).

A few EFD data were acquired from National Research Institute of Fisheries Engineering (NRIFE) seakeeping and maneuvering basin (Fig.2.5). Herein the NRIFE seakeeping and maneuvering basin has dimensions of 60×25 square meters with 3.2 meters water depth and is designed to test captive or radio-controlled model scale ships. There are 80 plunger-type wave makers on the one side of the basin to generate regular or irregular waves. The x-direction (length) main-carriage and y-direction (width) sub-carriage with yaw-direction turntable (heading) tow a model. During the free running, the ONRT 1/49 model is also used. The trajectories are measured by a total station automatically chasing a prisms setting the on a model ship (Furukawa et al., 2012).
The ship rotation motions are measured with FOG. Moreover the rudder normal force is measured with strain gages pasted on the rudder shafts (Fig.2.6). Not like IIHR, the model is released manually in NRIFE. Therefore the initial condition used in NRIFE is different from IIHR.

2.3 SYSTEM-BASED METHOD

Ship motions can be described with a 6DOF mathematical model as shown in Eq. (2.1). The mass distribution is symmetric with respect to the ship center line, thus the $y_{CG}$, $l_{xy}$ and $l_{yz}$ are zero. Additionally $I_{xz}$ is neglected as small for ships with approximate fore and aft symmetry.

\begin{align*}
  m(\ddot{u} - v + wq) &= X \\
  m(\ddot{v} - wp + ur) &= Y \\
  m(\ddot{w} - uw + vp) &= Z \\
  I,\dot{p} + (I, - I,)qr &= K \\
  I,\dot{q} + (I, - I,)rp &= M \\
  I,\dot{r} + (I, - I,)pq &= N
\end{align*}

(2.1)

In calm water, if the order of the forward velocity is assumed to be first order, the sway, yaw motion would be second order because the forward velocity is much larger than the sway or yaw velocities. The heave, roll and pitch motions would be third order. Therefore ship motions in calm water can be simplified to 3DOF motions (surge-sway-yaw). However in practice roll motion can be observed during sharp turning in calm water because of the rudder and centrifugal forces. Therefore, the roll motion is included and a 4DOF mathematical model (surge-sway-roll-yaw) is used, as shown in Eq. (2.2), which can be extended to following and quartering wave cases. In astern waves with specific forward speed, the wave encounter frequency becomes smaller and close to the roll and maneuvering natural frequency simultaneously, while it recedes from heave and pitch natural frequency. Therefore the heave and pitch can be treated as quasi-static motions and can be
separated from the maneuvering equations. Here $I_y$ is assumed to be the same as $I_z$ because the ship is slender.

\[
m(\dot{u} - vr) = X
\]
\[
m(\dot{v} + ur) = Y
\]
\[
I_x \dot{\delta} = K
\]
\[
I_y \dot{\gamma} = N
\]

Therefore a 4DOF MMG mathematical model is used for the SB simulations as shown in Eqs. (2.3)-(2.7). Horizontal body axes, shown in Fig. 2.7, are used for the coordinate system (Hamamoto and Kim, 1993). MMG rudder model (Ogawa et al., 1980), shown in Eqs. (2.8)-(2.24), is used rudder forces/moments.

\[
(m + m_0)\ddot{u} + (m + m_y)\dot{v}r = T(u; n) - R(u) + X(u)\nu r
\]
\[
+ X_{\nu u}(u)\nu^2 + X_{\nu v}(u)v^2 + X_{\nu \nu}(u)v^2 + X_{\nu \gamma}(u)\nu \gamma + X_{\gamma \nu}(u)\nu \gamma + X_{\gamma \gamma}(u)\gamma^2 + X_{\gamma \gamma}(u)\gamma^2 + X_{\gamma \gamma}(u)\gamma^2 + X_{\gamma \gamma}(u)\gamma^2 + X_{\gamma \gamma}(u)\gamma^2 + X_{\gamma \gamma}(u)\gamma^2 + X_{\gamma \gamma}(u)\gamma^2 + X_{\gamma \gamma}(u)\gamma^2
\]

\[
(m + m_0)\ddot{v} + (m + m_y)\dot{u}r = Y(u)\nu + Y_{\nu u}(u)\nu^2 + Y_{\nu v}(u)v^2 + Y_{\nu \nu}(u)v^2 + Y_{\nu \gamma}(u)\nu \gamma + Y_{\gamma \nu}(u)\nu \gamma + Y_{\gamma \gamma}(u)\gamma^2 + Y_{\gamma \gamma}(u)\gamma^2 + Y_{\gamma \gamma}(u)\gamma^2 + Y_{\gamma \gamma}(u)\gamma^2 + Y_{\gamma \gamma}(u)\gamma^2 + Y_{\gamma \gamma}(u)\gamma^2
\]

\[
(I_z + J_z)\ddot{\delta} + (m + m_y)\dot{\nu}r = N(u)\nu + N_{\nu u}(u)\nu^2 + N_{\nu v}(u)v^2 + N_{\nu \nu}(u)v^2 + N_{\nu \gamma}(u)\nu \gamma + N_{\gamma \nu}(u)\nu \gamma + N_{\gamma \gamma}(u)\gamma^2 + N_{\gamma \gamma}(u)\gamma^2 + N_{\gamma \gamma}(u)\gamma^2 + N_{\gamma \gamma}(u)\gamma^2 + N_{\gamma \gamma}(u)\gamma^2 + N_{\gamma \gamma}(u)\gamma^2
\]

Here

\[
\begin{bmatrix}
K_{\nu} & K_{\gamma} & K_{\nu u} & K_{\gamma u} & K_{\nu \gamma} & K_{\gamma \gamma}
\end{bmatrix}^T = z_{\nu}[Y_{\nu} \ Y_{\nu} \ Y_{\nu} \ Y_{\nu} \ Y_{\nu} \ Y_{\nu}]
\]

\[
X_{\nu} = -(1 - t_{\nu})F_{\nu} \sin \delta
\]

\[
Y_{\nu} = -(1 + a_{\nu})F_{\nu} \cos \delta \cdot \cos \phi
\]

\[
K_{\nu} = z_{\nu}(1 + a_{\nu})F_{\nu} \cos \delta
\]

\[
N_{\nu} = -(x_{\nu} + a_{\nu}x_{\nu})F_{\nu} \cos \delta \cdot \cos \phi
\]

\[
F_{\nu} = \frac{1}{2} \rho A_{\nu} U_{\nu}^2 \frac{r}{f_{\nu} \cdot \sin \alpha_{\nu}}
\]
The propeller race is only effective on about 2/3 of the rudder area as shown in Fig. 2.8. Therefore the effective rudder inflow velocity should be described by Eqs. (2.13)-(2.23) (Kose et al., 1981) taking account the influence of the ship motions. Fujii’s rudder model (Fujii and Tsuda, 1961), shown in Eq. (2.25), is used for the rudder lifting slope.

\[ U_{p} = \sqrt{u_{p}^2 + v_{p}^2} \]  
\[ u_{h} = \sqrt{\frac{A_{R_{1}}u_{p}^2 + A_{R_{2}}u_{p}^2}{A_{h}}} \]  
\[ u_{h} = (1-w_{h})u \]  
\[ u_{p} = u_{h} + 0.6(u_{h} - u_{p}) = u_{h}\left\{ \varepsilon + 0.6\left(\frac{u_{h}}{u_{p}} - 1\right)\right\} \]  
\[ u_{h} = u_{p}\sqrt{1 + \frac{8K_{p}}{\pi J^2}} \]  
\[ u_{p} = (1-w_{p})u \]  
\[ \varepsilon = \frac{1-w_{h}}{1-w_{p}} \]  
\[ \kappa = \frac{0.6}{\varepsilon} \]  
\[ \frac{A_{R_{1}}}{A_{h}} = \eta = 2/3 \]  
\[ \frac{A_{R_{2}}}{A_{h}} = (1-\eta) = 1/3 \]  
\[ \nu_{h} = -\gamma_{h}(v + l_{ur}) \]  
\[ \alpha_{h} = \delta - \gamma_{h}\frac{v_{h}}{u_{h}} \]
In the mathematical model, resistance is estimated from a captive model experiment and the thrust is estimated from propeller open water test and self-propulsion test in calm water as described in Umeda et al. (2008). Roll restoring moment, \( mgGZ \), is estimated from hydrostatic calculations in calm water. Maneuvering coefficients including heel-induced hydrodynamic derivatives are estimated from calm water captive model experiments (Hashimoto et al., 2008). Roll damping is estimated from roll decay model tests (Umeda et al. 2008). The values of all the original hydrodynamic and rudder maneuvering coefficients used in the SB mathematical model are listed in Table 2.2. For the ONRT, flow-straightening effect coefficients \( \gamma_R \), shown in Eq. (2.23), are adjusted to 0.70 because the rudders are situated far from the hull compared to other conventional ships which could weaken the flow-straightening effect. Thus the flow-straightening effect caused by the hull would be smaller i.e. the effect of rudders on sway and yaw motions would be larger. Also \(-1.0L\) is used for the correction coefficient for sway \( l_R \) shown in Eq. (2.23). The values of \( \gamma_R \) and \( l_R \) are empirically developed from other model experiments (Kose et al., 1981). The empirical values are also used for the interaction force coefficients induced on the hull by rudder nominal force \( f_R, a_H, z_{HR} \) and \( x_H \) as shown in Eqs. (2.8)-(2.11). All maneuvering coefficients values related to rudder force are listed in Table 2.2.

Eqs. (2.26) and (2.27) are used to compute the thrust. The value of the thrust reduction \( t_p \) and the effective propeller wake fraction \( w_p \), shown in Eqs. (2.26) and (2.27), are assumed to be zero because of the large space between the ship hull and the propellers as shown in Fig. 2.3b.

\[
T = (1 - t_p) \rho n^2 D_p^4 K_p(J) \quad (2.26)
\]

\[
J = \frac{(1 - w_p) u}{nD_p} \quad (2.27)
\]
2.4 CFD METHOD

The code CFDShip-Iowa v4 (Carrica et al., 2010) is used for the CFD computations. The CFDShip-Iowa is an overset, block structured CFD solver designed for ship applications using either absolute or relative inertial non-orthogonal curvilinear coordinate system for arbitrary moving but non-deforming control volumes. Turbulence models include blended $k$-$\varepsilon$/$k$-$\omega$ based isotropic and anisotropic RANS, and DES approaches with near-wall or wall functions. A single-phase level-set method is used for free-surface capturing. Captive, semi-captive, and full 6DOF capabilities for multi-objects with parent/child hierarchy are available. The actual propeller or body propeller model can be employed for propulsion. The PID controllers are available to correct the error between a measured process variable and a desired setpoint by calculating and then outputting a corrective action that can adjust the process accordingly. Numerical methods include advanced iterative solvers, higher order finite differences with conservative formulation, PISO or projection methods for pressure-velocity coupling, and parallelization with MPI-based domain decomposition. Dynamic overset grids use SUGGAR to compute the domain connectivity.

For the current simulations, absolute inertial earth-fixed coordinates are employed with $k$-$\varepsilon$/$k$-$\omega$ turbulence model using no wall function. The location of the free-surface is given by the 'zero' value of the level-set function, positive in water and negative in air. The 6DOF rigid body equations of motion are solved to calculate ship linear and angular motions. A simplified body force model is used for the propeller which prescribes axisymmetric body force with axial and tangential components. The propeller model requires the open water curves and advance coefficients as input, and provides the torque and thrust forces. The open water curves are defined as a second order polynomial fit of the experimental $K_T(J)$ and $K_Q(J)$ curves. The advance coefficient is computed using Eq. (2.27) with neglecting the wake effects. Also, the thrust force is
calculated using Eq. (2.26) without using $t_p$ factor. Herein, two PID controllers are used. The heading controller acting on the rudders is responsible to turn the rudders to keep the ship in the desired direction. The speed controller acting on the body force propeller model is responsible to rotate the propellers at appropriate RPM to keep the ship at the desired speed. The heading controller uses $P=1$ for the proportional gain and zero for both the integral and derivative gains mimicking EFD setup.

The governing equations are discretized using finite difference schemes on body-fitted curvilinear grids. The time derivatives in the turbulence and momentum equations are discretized using 2nd order finite Euler backward difference. Convection terms in the turbulence and momentum equations are discretized with higher order upwind formula. The viscous term in momentum and turbulent equations are computed with similar considerations using a second order difference scheme. The PISO algorithm (Issa, 1985) is solved using the PETSc toolkit. SUGGAR (Noack, 2005) is used to obtain the overset interpolation information. A MPI-based domain decomposition approach is used, where each decomposed block is mapped to one processor.

In order to achieve a large size computational domain with reasonable number of grid points, a cylinder shape computational domain was used. The radius of domain is 4.5 times larger than ship length and the domain extends from $z = -1L$ to $z = 0.25L$ in vertical direction. The ship axis is aligned with $x$ axis, with the bow at $x = 0$ and the stern at $x = 1$. The $y$ axis is positive to starboard with $z$ pointing upward. The free surface at rest lies at $z = 0$. The free model is appended with skeg, bilge keels, superstructure, rudders, rudder roots, shafts, and propeller brackets mimicking the EFD conditions but not appended with actual propellers.

The computational grids are overset, with independent grids for the hull, superstructure, appendages, refinement and background, and then assembled together to generate the total grid. The boundary layer grids are generated with a hyperbolic grid generator using a double-O topology,
one each for the starboard and the port sides. Grid spacing at the hull is designed to yield $y^+ < 1$ for a wide range of $Fr$. The bilge keels and skeg use H topology grids and overset the boundary layer grids. The superstructure grid oversets the boundary layer grids and is constructed with wrapped face topology. Two double-O grids are used for each rudder such that inboard and outboard sides are conformal. O topology grids are used for propeller shafts and struts. A Cartesian grid is used to impose the far-field boundary conditions and to resolve the flow far from the hull, with a refinement Cartesian block closer to the ship. The total number of grid points is 12.1 M for free model simulations. Details of the grids are shown in Table 2.3 and Fig.2.9.

For boundary conditions, the no-slip condition is applied on the solid surfaces. The far field boundary conditions are imposed on the top and bottom of background. The inlet boundary condition with zero pressure gradients is used for the surrounding surface of large cylinder shape background.

The simulation test matrix is shown in Table 2.4. For all cases the RPM is fixed during the simulation mimicking EFD setup. The propeller RPM required to achieve the target ship speed is obtained by performing a self-propelled simulation starting from static ship conditions using speed controller.

The free running verification studies have not been done yet. For captive tests, a verification study has been performed for a much simpler geometry of ONRT (only bilge keels as appendages) with the absence of moving propellers and rudders (Sadat-Hosseini et al., 2011). The verification study was carried out for the grid size of 3.48M coarsened and refined by a factor of $\sqrt{2}$. The study was performed for 10 degrees of heel angle for full $Fr$ curve (Sadat-Hosseini et al., 2011) whereby the results were obtained for the full $Fr$ range of interest in a single simulation. The grid verification was investigated not only for resistance and sinkage and trim but also for side force and roll and yaw moments which are significantly important in complicated cases such as broaching.
The average of grid uncertainty error for resistance and side forces, roll and yaw moments and sinkage and trim motions was 2.75% in dynamic range (DR) with the maximum grid uncertainty of about 6% in DR for side force and yaw moment; see Eqs. (2.28) for %DR definition. The validation errors were reported for resistance, 10 and 20 degrees heel angle tests and 5, 10, 15 degrees drift angle tests. For resistance test, the average of validation errors for resistance force, sinkage and trim for full Fr curve was 2.88% and 2.5% in DR with largest error for sinkage 5.0%. For 10 degrees heel angle test, the average of validation errors for resistance and side forces, roll and yaw moments and sinkage and trim motions for full Fr curve was 17.3% and 9.9% in DR. The largest errors were obtained for side force, yaw moment and trim motion with 28.0%. The same order of validation errors were found for the 20 degrees heel angle test. For 5, 10 and 15 degrees drift angle tests, the average of validation errors of all cases for resistance and side forces, roll and yaw moments and sinkage and trim motions was 20.3% in DR and 1.4% in DR for full Fr curve. The largest errors were found for roll moment and trim motion.

\[ E(\%DR) = \frac{D - S}{D_{\text{max}} - D_{\text{min}}} \times 100 \]  

(2.28)

2.5 SYSTEM IDENTIFICATION

System identification is used with the SB mathematical model, shown in Eqs. (2.3)-(2.6), along with the EFD, SB and CFD free running trial data to obtain new maneuvering coefficients. In previous studies (Abkowitz, 1980), EFD free running state variables were used to evaluate both the right-hand and left-hand sides of the mathematical model. Empirical values were used for the added mass and added moment of inertia to estimate the maneuvering coefficients. Herein not only CFD state variables but also total forces/moments are used such that the added mass and added moment of inertia can be predicted without using empirical values. Furthermore, CFD propulsion forces, rudder forces and hydrostatic forces can be separated from the total hydrodynamic forces.
This helps evaluating the maneuvering coefficients and the empirical rudder coefficients effectively. Herein the extended EKF and CLS SI techniques are used.

2.5.1 Extended Kalman Filtering

The EKF method optimizes the target parameters based on the equations of motion and the specified state variables. Therefore it does not require any acceleration terms for input which are noisy in the EFD data. This is one of the largest advantages of the EKF. The EKF method is used with SB, EFD and CFD inputs to estimate the maneuvering coefficients. The details of EKF are provided in Appendix A.

2.5.2 Constrained Least Square Method

CLS is employed to estimate the hydrodynamic and rudder maneuvering coefficients with SB and CFD inputs. The constraints are set as shown in Table 2.5 according to physical reasoning and previous research (Kose et al., 1981). As shown in Fig.2.10, the searching starts from initial values and aims at a minimum point of the error with constraints/interruptions. Therefore the optimized solutions do not reach to the minimum point at times. Herein the thrust, rudder forces, hydrostatic forces and the resistance for x force are excluded from the total forces. The details of the generalized reduced gradient algorithm are provided in Appendix B.

2.6 COMPARISONS BETWEEN EFD, CFD, AND SB

2.6.1 Speed Test

For CFD, the required propellers RPM for each Froude number is predicted with 2DOF sinkage and trim simulations in calm water with a speed controller set at the desired Froude number. The
resulting RPM is later prescribed in the free model simulations. This propeller model is the simplest that can be applied to the CFD simulation and has some limitations. The most important one is that the thrust and torque do not depend on the local flow field near the propellers, but on the average velocity of the ship. In addition, the body force is axisymmetric and side forces are neglected. Restrictions on the ability of the propeller model to handle strong unsteady flows can also be expected. For SB, RPM is predicted from the open water curves similar to CFD. Also, the wake effect and side forces are neglected. Figure 2.11 shows the results of EFD, CFD and SB speed tests. The error between SB and EFD is 11% at $Fr=0.20$ and the error between CFD and EFD is 14%. These discrepancies are likely due to the non-interactive nature of the propeller model that neglects the wake effect.

2.6.2 Turning Circle, Zigzag and Large Angle Zigzag

The EFD, CFD and SB maneuvering test conditions are listed in Table 2.4. The large angle zigzag test is a combination of turning circle and zigzag tests. Hereafter, turning circle test ($Fr=0.20$, $\delta=25$deg) is entitled as T25, zigzag test ($Fr=0.20$, $\psi_c/\delta=20/20$) as Z20, and large angle zigzag test ($Fr=0.20$, $\psi_c/\delta=90/35$) as Z90. Trajectories of T25, Z20, and Z90 are shown in Fig.2.12. EFD trajectories are the average of 5 trials. In Fig.2.10, the standard deviation error bars of EFD trajectories are fairly small which show the good reproducibility of the EFD tests. Hereafter typical cases are chosen for each EFD data.

Trajectories of T25 are shown in Fig.2.12a. The errors of CFD and SB turning circle simulations and EFD results are listed in Table 2.6. Here the values in Table 2.2 are used for the SB maneuvering coefficients. The steady state variables errors ($u\ E\%D$, $v\ E\%D$, $r\ E\%D$, $\phi\ E\%D$) are computed by averaging each state variable ($u$, $v$, $r$, $\phi$) after the model motion converges to a steady state. "SSV Av. E\%D" in Table 2.6 indicates the average of all steady state variables errors.
Turning indices (A, T, R), shown in Table 2.6, are computed based on the American Bureau of Shipping's (ABS) maneuvering guide (2006). Here “A E%D” indicates error of advance distance, “T E%D” for transfer distance, “R E%D” for turning radius, and “ATR Av. E%D” is the average of all turning index errors. And “Total Av. E%D” is computed by averaging “SSV Av. E%D” and “ATR Av. E%D”. The CFD trajectory shows close agreement with EFD while SB shows small error. The time series of the turning circle tests are shown in Fig.2.13. The CFD errors are smaller than those of SB in general. Since the roll angle values are small (approximately -3 to -2 degrees), the error of the roll angle seems to be larger than the other state variables. Moreover these small roll angles are not effective to the maneuvers.

The errors of CFD and SB’s Z20 and EFD result are listed in Table 2.7. From zigzag test, the ship maneuverability can be defined by steering quality indices Ks, Ts and Ns (Norrbin, 1963). Ks, Ts and, Ns are estimated by fitting the time series to nonlinear 1st order Nomoto model Eq. (2.29) using least square method. In Table 2.7, the errors of Ks, Ts and Ns are shown as “K20 E%D”, “T20 E%D” and “N20 E%D”. The average of these errors is “KTN Av. E%D”. The errors of 1st and 2nd overshoot angles are “1st OS E%D” and “2nd OS E%D” and the average of these overshoot angles are “OS Av. E%D”. “Total Av. E%D” is the average of “KTN Av. E%D” and “OS Av. E%D”.

In Table 2.7, CFD shows small errors while SB shows larger errors.

\[ T \dot{r} + N_\tau r^3 + r = K_\delta \]  

(2.29)

Figure 2.12b shows trajectories of the Z20. In Fig.2.12b, the CFD trajectory shows good agreement with the EFD while the SB trajectory shows smaller turning than that of EFD and CFD. The time series of the EFD, CFD and SB zigzag test are shown in Fig.2.14. In surge velocity (Fig.2.14a), CFD and SB show better agreement than that of EFD. Similarly CFD shows good agreement for the other state variables. However SB overpredicts the sway velocity. In roll angle (Fig.2.14d), SB overpredicts the peak of the roll motion just after the rudder deflection because the
SB’s roll equation Eq. (2.5) does not include the coupling terms related to sway acceleration or yaw angular acceleration which are not negligible just after large rudder deflection.

The errors of CFD and SB’s Z90 and EFD result are listed in Table 2.8. The criteria of the errors are the same as the aforesaid zigzag tests. Similarly to the Z20 zigzag simulations, CFD shows smaller errors with EFD results than SB in Table 2.8. Especially SB’s nonlinear steering index (N90) has huge error with that of EFD which indicates SB coefficients need some tuning to satisfy these large maneuvering cases. Trajectories of Z90 are shown in Fig.2.12c. Again CFD shows close agreement with EFD while the SB shows large error. The time series of the EFD, CFD and SB large angle zigzag test are shown in Fig.2.15. CFD and SB slightly over predict the surge velocity (Fig.2.15a). CFD shows good agreement with EFD for the other state variables. SB under predicts the sway velocity (Fig.2.15b) and overpredicts the yaw rate (Fig.2.15c) which is the main factor for the large error in the trajectory. SB overpredicts the roll angle (Fig.2.15d) just after the rudder deflection which is also similar as for the 20/20 zigzag.

Additionally, as shown in Table 2.9, most of the EFD maneuvering trials and predictions by both SB and CFD adequately meet IMO criteria (ABS, 2006) which show superior maneuverability of ONRT. This is mainly because its hull form is slender. Note that there is no criterion for large angle zigzag.

In these free running trials, CFD shows reliability to reproduce the EFD free running maneuvers in calm water, whereas SB shows fair ability to express the maneuvers which is inferior to the CFD. The SB errors could be reduced by tuning the hydrodynamic and rudder maneuvering coefficients using the SI or obtaining the rudder maneuvering coefficients using captive model tests.
2.7 SYSTEM IDENTIFICATION RESULTS

2.7.1 Maneuvering Coefficients Estimated by EKF

For EKF, the rudder motion and propeller RPM are inputs as control variables Eq. (2.30) and the state variables of SB, EFD and CFD free running results are inputs as measurement variables Eq. (2.30). The added masses and added moment of inertias go to the denominator of the right hand side of Eqs. (2.2)-(2.5) as shown in Eqs. (2.33)-(2.36). Therefore the added mass and added moment of inertia values should be known to use EKF because the error of the added mass and added moment of inertia have great influence on all the other coefficients. Moreover rudder coefficients values also should be known because the rudder forces/moments cannot be separated from the state variables. Here the initial maneuvering coefficients values are set to be 120% of the original SB coefficients.

\( u(k) = [\delta(k) \ n(k)]^T \)  
(2.30)

\( x(k) = [u(k) \ v(k) \ p(k) \ r(k) \ \phi(k)]^T \)  
(2.31)

\( f[x(k),u(k),\Theta] = [f_1 \ f_2 \ f_3 \ f_4] \)  
(2.32)

\( f_1 = \left[ (m + m_y) vr + T(u,n) - R(u) + X_w(u)v^2 + X_w(u)r^2 + X_w(\delta,u,v,r) \right] / (m + m_y) \)  
(2.33)

\( f_2 = \left[ Y_x(u) + Y_x(u) + Y_x(u) + Y_x(u) + Y_x(u) + Y_x(u) + Y_x(u) \right] / (m + m_y) \)  
(2.34)

\( f_3 = \left[ m_x x + K_x(u) + K_x(u) + K_x(u) + K_x(u) + K_x(u) + K_x(u) + K_x(u) \right] / (I_z + I_z) \)  
(2.35)

\( f_4 = \left[ N_x(u) + N_x(u) + N_x(u) + N_x(u) + N_x(u) + N_x(u) + N_x(u) \right] / (I_z + I_z) \)  
(2.36)

\( f_5 = p(k) \)  
(2.37)
Table 2.10 shows the ratio and difference between the original maneuvering coefficient values used in the original SB simulations and estimated coefficients values based on EKF. Here the ratio and difference are computed by Eqs. (2.38) and (2.39). In Table 2.10, “Linear Av. Δ%D” is average of the Δ%D of $Y_v$, $Y_r$, $K_p$, $N_v$, and $N_r$. “Nonlinear Av. Δ%D” is average of the Δ%D of maneuvering coefficients excluding $Y_v$, $Y_r$, $K_p$, $N_v$, and $N_r$. “Total Av. Δ%D” is averaging of all the maneuvering coefficients. In Table 2.10, the maneuvering coefficients estimated from the SB free running data gives small error from the original SB maneuvering coefficients which suggest that EKF has good ability to reconstruct the maneuvering coefficients from free running trial data. However the maneuvering coefficients estimated from EFD and CFD free running data shows large difference from the original coefficients. Especially the $Y_v$ coefficients estimated from EFD-Z90 and CFD-Z20, Z90 free running data have opposite sign compared to the original $Y_v$ which is not rational because the ONRT is course stable ship and the $Y_v$ is the damping term in sway. Meanwhile the maneuvering coefficients estimated from EFD-T25 and CFD-T25 seem to have smaller difference than the maneuvering coefficients estimated form the other EFD and CFD free running data. The global difference (Global Av. Δ%) of EFD and CFD shows similar values which is because the EFD and CFD state variables shows close agreement as shown in Figs.2.11-2.13.

\[
A_{\text{Est./Orig.}} = \frac{A_{\text{estimated}}}{A_{\text{original}}}
\]

\[
A_{\text{Δ%D}} = \left| \frac{A_{\text{estimated}} - A_{\text{original}}}{A_{\text{original}}} \right| \times 100
\]  

(2.38)  

(2.39)

2.7.2 Maneuvering Coefficients Estimated by CLS

The CLS requires not only state variables but also total hydrodynamic forces/moments and acceleration variables during free running trial which cannot be provided by EFD. Therefore only SB and CFD free running data are used for CLS. In the CFD and SB data, the rudder normal force can be separated from total hydrodynamic forces which make it possible to estimate rudder
maneuvering coefficients. By using the total hydrodynamic forces/moments, the added mass and added moment of inertia can be estimated which cannot be estimated in EKF. Moreover it is expected to estimate generalized maneuvering coefficients, which show reasonable results for wide range of maneuvering, by connecting the time series of several types of free running trials, which is referred to as parallel processing (Abkowitz 1980). Motion continuity is not necessary for CLS, while it is in EKF. Hereafter the connected data (T25, Z20, and Z90) are entitled as SUM.

The CLS attempts to minimize the square of the error between output total forces, rudder normal force Eqs. (2.40)-(2.45) and estimated forces Eqs. (2.46)-(2.50) by tuning coefficients Eqs. (2.51)-(2.55).

Optimize: \[ y(x) = \min \left[ \sum_{n=0}^{\infty} \left( X_{\text{out}} - X_{\text{est}}(x) \right)^2 \right] \]  

\[ X_{\text{out}} = F_{\text{rudder}} \]  

\[ X_{\text{out2}} = (X_{\text{out}} - T + R) \]  

\[ X_{\text{out3}} = Y_{\text{out}} \]  

\[ X_{\text{out4}} = (K_{\text{out}} - mgGZ) \]  

\[ X_{\text{out5}} = N_{\text{out}} \]  

\[ X_{\text{out6}}(x_i) = F_\theta = \frac{1}{2} \rho A_D U^2 f_\theta \sin \alpha_k \]  

\[ X_{\text{out7}}(x_i) = [X_{\text{in}}(u) + m_g] v + X_{\text{in}}(u) r^2 + X_{\text{in}}(u) v^3 - (1 - \tau_k) F_\phi \sin \delta - m_\delta \]  

\[ X_{\text{out8}}(x_i) = Y_\theta(u) v + [Y_\theta(u) - m_p u] r + Y_\theta(u) \phi + Y_{\text{in}}(u) v^3 + Y_{\text{in}}(u) r^2 + (1 + \alpha_f) F_\phi \cos \delta \cos \phi - m_\delta \]  

\[ X_{\text{out9}}(x_i) = m_z \frac{v}{2} + K_\phi(u) v + K_\phi(u) r + K_p(u) p + K_\phi(u) \phi + K_m(u) v^3 + K_m(u) r^2 + K_m(u) v^2 r \]  

\[ + K_m(u) r^2 v + K_m(u) r^3 + z_{\text{in}}(1 + \alpha_f) F_\phi \cos \delta - J_x \phi \]
\[
X_{\text{est}}(x) = N_1(u) v + N_2(u) r + N_3(u) \phi + N_4(u) v^2 + N_5(u) r^2 v + N_6(u) r^3 \nu + \left( x_\phi + a_{\phi} x_\phi \right) F_\phi \cos \delta \cdot \cos \phi - J_\phi \dot{\phi}
\]

(2.50)

\[
x_1 = \begin{bmatrix} \gamma_\phi & I_\phi & \varepsilon \end{bmatrix}
\]

(2.51)

\[
x_2 = \begin{bmatrix} (X_u + m_y) & X_u & X_v & I_u \end{bmatrix}
\]

(2.52)

\[
x_3 = \begin{bmatrix} Y_v (Y_u - m_y) & Y_u & Y_v & Y_u & Y_v & Y_u & a_{\phi} \end{bmatrix}
\]

(2.53)

\[
x_4 = \begin{bmatrix} z_H & K_{\phi} & z_{HR} \end{bmatrix}
\]

(2.54)

\[
x_5 = \begin{bmatrix} N_1 & N_2 & N_3 & N_4 & N_5 & N_6 & N_7 \end{bmatrix}
\]

(2.55)

Table 2.11 shows the ratio and difference between the original maneuvering coefficients including rudder maneuvering coefficients values used in the SB simulations and the maneuvering coefficients values estimated by CLS. Here the EFD free running data cannot be applied to the CLS method because the EFD acceleration terms are usually too noisy to use and this method requires rudder normal force during the free running test. However there is no interest to use EFD free running data since the CFD can reasonably well reproduce the EFD free running results as shown in Figs.2.12-2.15.

In Table 2.11, "Rudder Av. \( \Delta\% D \)" is average of the \( \Delta\% D \) of rudder maneuvering coefficients \( l_\phi \), \( \gamma_\phi \), \( c \), \( t_\phi \), \( a_{\phi} \), \( z_{HR} \), and \( x_\phi \). Here \( \Delta\% D \) of the maneuvering coefficients related to \( \phi \) (\( Y_\phi \), \( K_\phi \), and \( N_\phi \)) are excluded from the averaging \( \Delta\% D \). This is because the errors of \( \phi \) maneuvering coefficients are extremely large. In fact, the effect of the \( \phi \) maneuvering coefficients are too small to compute correctly in calm water maneuvers and the original values of \( \phi \) maneuvering coefficients values are also very small which causes the errors to be very large. Also it is impossible to distinguish the restoring term \( mgGZ(\phi) \) and \( K_\phi \phi \) term in this model which means the error of \( mgGZ(\phi) \) directly goes to the \( K_\phi \).

In Table 2.11, the estimated maneuvering coefficients using SB simulations shows less than 8%
error from the original SB maneuvering coefficients in total which suggest that the CLS has good ability to reconstruct the maneuvering coefficients from the CFD free running trial data. The constraints ensure that the sign of the estimated linear maneuvering coefficients are correct in Table 2.11.

2.8 DISCUSSIONS

By applying system EKF and CLS identification techniques, 10 sets of maneuvering coefficients are estimated from the several CFD and EFD free running data (T25, Z20, Z90, and SUM). However, by just examining Tables 2.10 and 2.11, it is difficult to conclude which set of maneuvering coefficients are the best ones which can cover the widest range of maneuvers. The SB simulation using the original coefficients have some errors with EFD and CFD free running results as shown in Figs.2.12-2.15. Therefore the set of original maneuvering coefficients are not optimum. Hence SB simulations using the estimated maneuvering coefficients are executed for clarifying which set of estimated maneuvering coefficients are the most generalized ones for the SB mathematical model. Here the 10 sets of coefficients are labeled to simplify the discussions. For example, a set of maneuvering coefficients named “CLS-CFD-Z90” indicates that these maneuvering coefficients are estimated by CLS using CFD-Z90 free running data.

First, 10 sets of T25 are computed by SB simulation using the 10 sets of estimated maneuvering coefficients. Table 2.12 shows the errors between EFD-T25 results and the SB simulations using estimated maneuvering coefficients. The error criteria are employed as in Table 2.6. Figure 2.16 shows “Total Av. E%D” errors shown in Table 2.12 sorted by the value of “Total Av. E%D”. In the Fig.2.16, the line shows “Total Av. E%D” of the original SB simulation shown in Table 2.6. As expected, the maneuvering coefficients estimated by T25 (CLS-CFD-T25, EKF-CFD-T25, CLS-CFD-SUM, and EKF-EFD-T25) gives smaller error than those of using other data (Z20 and
It seems reasonable that the coefficients estimated from T25 data show small error in the same T25 SB simulation. Most of the maneuvering coefficients using the Z20 and Z90 data give larger error than that of the original maneuvering coefficients.

Table 2.13 shows the errors between EFD-Z20 results and the SB-Z20 simulations using estimated maneuvering coefficients. The error criteria are employed as in Table 2.7. Figure 2.17 shows “Total Av. E%D” errors shown in Table 2.13 sorted by the value of “Total Av. E%D”. In the Fig.2.17, the line shows “Total Av. E%D” of the original SB simulation shown in Table 2.7. In Fig.2.17, most of the estimated maneuvering coefficients show better results than the original maneuvering coefficients. Especially CLS-CFD-Z20 shows small error. Table 2.14 shows the errors between EFD-Z90 results and the SB-Z90 simulations using estimated maneuvering coefficients. Figure 2.18 shows “Total Av. E%D” errors shown in Table 2.14 sorted by the value of “Total Av. E%D”. In the Fig.2.18, the line shows “Total Av. E%D” of the original SB simulation shown in Table 2.8. In Fig.2.16, the maneuvering coefficients estimated by Z90 (EKF-EFD-Z90, EKF-CFD-Z90, CLS-CFD-SUM, and CLS-CFD-Z90) show much smaller error than that of original maneuvering coefficients.

Table 2.15 shows “Total Av. E%D” of T25, Z20, and Z90 and “Global Av. E%D” which are averages of T25, Z20, and Z90’s “Total Av. E%D”. Figure 2.19 shows “Global Av. E%D” of Table 2.15 sorted by the value of “Global Av. E%D”. In the Fig.2.19, the line shows “Global Av. E%D” of the SB simulations using the original maneuvering coefficients. In Fig.2.19, all the maneuvering coefficients show smaller error than that of original maneuvering coefficients. Especially CLS-CFD-SUM shows the best results overall. As shown in Table 2.15, although “CLS-CFD-SUM” does not show the smallest error in each case, it has small error in all cases which brings CLS-CFD-SUM as the best maneuvering coefficients in all. Some of the other maneuvering coefficients (CLS-CFD-Z90 and EKF-EFD-Z20) also show small errors.
In the original SB and EKF method, empirical values are used for the rudder model. Figure 2.20 shows the comparison of the rudder normal force between CFD and the SB simulations with the same imposed model and rudder motions. Herein EFD normal rudder forces are provided from NRIFE basin free running data. The SB simulation using “CLS-CFD-SUM” maneuvering coefficients and CFD shows close agreement with EFD while the original SB simulation using empirical rudder coefficients significantly overestimates the rudder force. Therefore, in EKF method using empirical rudder coefficients, the errors of the rudder forces affect the estimation of hull maneuvering coefficients for minimizing the sum error of ship motions. This could be a reason that some of the $Y_r$ maneuvering coefficients show opposite sign in the EKF estimations in Table 2.10. Hence, even the ship motion seems to be fair, the EKF maneuvering coefficients are not appropriate in physical meaning. The CLS seems to be fair to estimate reasonable maneuvering coefficients by treating the forces/moments directly. To predict reasonable maneuvering coefficients for a wide range of ship maneuvers, several trials should be combined as in parallel processing (CFD-SUM) or several kinds of motion should be taken into one trial such as the Z90 test.

The set of “CLS-CFD-SUM” coefficients, which show the best generalization in all 10 maneuvering coefficients sets, are applied for other types of free running trials: $\delta=35\text{deg}$ turning and $\psi_c/\delta=10/10$ zigzag with different model speed $Fr=0.10$. These trials were not included for the previous SI. Figure 2.21a shows the trajectories of $\delta=35\text{deg}$ turning with $Fr=0.10$. The trajectory of the SB simulation using “CLS-CFD-SUM” maneuvering coefficients shows better agreement with EFD than that of SB simulation using the original maneuvering coefficients (SB-Orig.). The simulation using “CLS-CFD-SUM” also shows better agreement in steady state variables and turning indices during the turning test except sway velocity as shown in Table 2.16. The error of sway velocity makes the gap between “EFD” and “CLS-CFD-SUM” in the trajectory in Fig.2.21a. Nevertheless “CLS-CFD-SUM” shows better agreement than “SB-Orig.” in total.
Figure 2.21b shows the trajectories of $\psi_c/\delta = 10/10$ zigzag with $Fr=0.10$. The trajectory of SB simulation using “CLS-CFD-SUM” maneuvering coefficients shows close agreement with EFD while trajectory of “SB-Orig.” shows some discrepancy with EFD. Figure 2.22 shows time series of state variables. The surge velocity in Fig.2.22a of “CLS-CFD-SUM” shows some error from EFD but it is negligibly small and does not influence the total model motion. “CLS-CFD-SUM” shows better agreement with EFD than that of “SB-Orig.” in the other state variables in Figs.2.22b, c and d. Especially “CLS-CFD-SUM” yaw rate shows nearly perfect agreement with EFD while “SB-Orig.” underestimates it. The errors of steering indices and overshoot angles are shown in Table 2.16. “CLS-CFD-SUM” shows better agreement in both steering indices and overshoot angles than “SB-Orig.” results.

The set of “CLS-CFD-SUM” maneuvering coefficients shows better ability to predict a wide range of maneuvers than that of “SB-Orig.” maneuvering coefficients. For these reasons, it could be possible to replace the numerous captive model tests with several CFD free running trials using the SI technique which brings more generalized maneuvering coefficients.

### 2.9 CONCLUDING REMARKS

System identification techniques using CFD free running trial data are accurate and efficient approach to estimate the maneuvering coefficients in the SB mathematical model. Hydrodynamic and rudder maneuvering coefficients included in a 4DOF SB model are estimated from only a few CFD free running simulations trial data employing EKF and CLS SI techniques.

Free running tests in calm water are executed in the IIHR wave basin and NRIFE seakeeping and maneuvering basin for the CFD and SB validations. CFD simulation results shows close agreement with the EFD, which suggests the CFD simulation can reproduce the EFD free running
results. SB simulations using 4DOF nonlinear maneuvering mathematical model, which include hull maneuvering coefficients obtained from numerous captive model experiments and empirical rudder maneuvering coefficients, show fair ability to predict calm water maneuvers within some errors.

With these several free running data, the maneuvering coefficients included in the SB model are estimated by EKF and CLS SI techniques. Both EKF and CLS show abilities to estimate the maneuvering coefficients from free running data. EKF is useful to estimate maneuvering coefficients from the EFD free running data because the EKF only needs state variables for the computation. However the EKF has a basic problem to estimate rudder parameters, if the rudder force data are missing, which disturbs to estimate the other maneuvering coefficients properly. On the other hand, CLS can estimate not only the maneuvering coefficients but also the rudder maneuvering coefficients which predicts the rudder force correctly and the constraints ensure that the maneuvering coefficients have reasonable values. For CLS, the CFD free running simulations are necessary because the CFD simulations can provide both total hydrodynamic forces/moments and local rudder normal forces. By parallel processing several free running data, the estimated maneuvering coefficients become more generalized than using just one free running data which indicates that the maneuvering coefficients are appropriate for a wide range of maneuvers. Especially the SB simulation using the set of “CLS-CFD-SUM” coefficients shows better agreement with EFD than using the original maneuvering coefficients even for other types of free running trials which are not included in the SI.

Hence, by using the present approach, several CFD free running simulations can replace the number of captive model experiments needed to estimate the maneuvering coefficients for the SB model. Furthermore reliable maneuvering simulations can be possible without any model experiments within short computation time. Note that similar approach is currently under development in aerospace, using CFD to replace captive model EFD tests (Morton, 2011).
The current SB model for wave conditions (Umeda et al., 2008 and Yasukawa, 2006) have some problems for quantitative agreement with EFD while CFD free running simulation in waves shows quantitative agreement. Therefore the SB wave model is going to be validated and modified by using CFD free running simulations in the next chapter.
### Table 2.1 Principal particulars of the ONRT vessel.

<table>
<thead>
<tr>
<th></th>
<th>Model scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length: $L$</td>
<td>3.147 m</td>
</tr>
<tr>
<td>Breadth: $B$</td>
<td>0.384 m</td>
</tr>
<tr>
<td>Depth: $D$</td>
<td>0.266 m</td>
</tr>
<tr>
<td>Draft: $d$</td>
<td>0.112 m</td>
</tr>
<tr>
<td>Displacement: $W$</td>
<td>72.6 kg</td>
</tr>
<tr>
<td>Metacentric height: $GM$</td>
<td>0.0424 m</td>
</tr>
<tr>
<td>Natural roll period: $T_0$</td>
<td>1.644 s</td>
</tr>
<tr>
<td>Rudder area: $A_R$</td>
<td>0.012 m$^2 \times 2$</td>
</tr>
<tr>
<td>Block coefficient: $C_b$</td>
<td>0.535</td>
</tr>
<tr>
<td>Vertical position of CG from waterline (downward positive): $OG$</td>
<td>$-0.392 \times d$</td>
</tr>
<tr>
<td>Radius of gyration in pitch: $k_{yy}$</td>
<td>$0.25 \times L$</td>
</tr>
<tr>
<td>Maximum rudder angle: $\delta_{\text{max}}$</td>
<td>$\pm 35^\circ$</td>
</tr>
</tbody>
</table>
Table 2.2 Values of maneuvering and rudder coefficients used in 4-DoF nonlinear SB model.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>value</th>
<th>source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon$</td>
<td>1.0</td>
<td>Empirical (Kose et al., 1981)</td>
</tr>
<tr>
<td>$\gamma_h$</td>
<td>0.70</td>
<td>Empirical (Kose et al., 1981)</td>
</tr>
<tr>
<td>$I_{R}/L$</td>
<td>-1.00</td>
<td>Empirical (Kose et al., 1981)</td>
</tr>
<tr>
<td>$t_{R}$</td>
<td>0.30</td>
<td>Empirical (Kose et al., 1981)</td>
</tr>
<tr>
<td>$a_{H}$</td>
<td>0.25</td>
<td>Empirical (Kose et al., 1981)</td>
</tr>
<tr>
<td>$z_{HR}/d$</td>
<td>0.854</td>
<td>Geometrical (center of rudder)</td>
</tr>
<tr>
<td>$x_{H}/L$</td>
<td>-0.45</td>
<td>Empirical (Kose et al., 1981)</td>
</tr>
<tr>
<td>$m_{x}$</td>
<td>0.0131</td>
<td>Empirical (Motora, 1960)</td>
</tr>
<tr>
<td>$X_{vr}$</td>
<td>-0.0858</td>
<td>Drift angle test (Umeda et al., 2008)</td>
</tr>
<tr>
<td>$X_{vr}$</td>
<td>0.0522</td>
<td>CMT (Umeda et al., 2008)</td>
</tr>
<tr>
<td>$X_{rr}$</td>
<td>-0.0212</td>
<td>CMT (Umeda et al., 2008)</td>
</tr>
<tr>
<td>$m_{z}$</td>
<td>0.109</td>
<td>Strip theory</td>
</tr>
<tr>
<td>$Y_{v}$</td>
<td>-0.300</td>
<td>Drift angle test (Umeda et al., 2008)</td>
</tr>
<tr>
<td>$Y_{v}$</td>
<td>-0.0832</td>
<td>CMT (Umeda et al., 2008)</td>
</tr>
<tr>
<td>$Y_{vv}$</td>
<td>-1.77</td>
<td>Drift angle test (Umeda et al., 2008)</td>
</tr>
<tr>
<td>$Y_{vr}$</td>
<td>0.262</td>
<td>CMT (Umeda et al., 2008)</td>
</tr>
<tr>
<td>$Y_{rr}$</td>
<td>-0.800</td>
<td>CMT (Umeda et al., 2008)</td>
</tr>
<tr>
<td>$Y_{\phi}$</td>
<td>0.174</td>
<td>CMT (Umeda et al., 2008)</td>
</tr>
<tr>
<td>$(I_{x}+J_{y})'$</td>
<td>4.13E-05</td>
<td>Free roll decay test (Umeda et al., 2008)</td>
</tr>
<tr>
<td>$z_{HR}/d$</td>
<td>0.852</td>
<td>Drift angle test (Umeda et al., 2008)</td>
</tr>
<tr>
<td>$K_{p}$</td>
<td>-0.243</td>
<td>Free roll decay test (Umeda et al., 2008)</td>
</tr>
<tr>
<td>$K_{\phi}$</td>
<td>6.26E-04</td>
<td>Heel angle test (Umeda et al., 2008)</td>
</tr>
<tr>
<td>$J_{z}$</td>
<td>0.00789</td>
<td>Strip theory</td>
</tr>
<tr>
<td>$N_{v}$</td>
<td>-0.0932</td>
<td>Drift angle test (Umeda et al., 2008)</td>
</tr>
<tr>
<td>$N_{r}$</td>
<td>-0.0549</td>
<td>CMT (Umeda et al., 2008)</td>
</tr>
<tr>
<td>$N_{\phi}$</td>
<td>-0.532</td>
<td>Drift angle test (Umeda et al., 2008)</td>
</tr>
<tr>
<td>$N_{\phi}$</td>
<td>-0.629</td>
<td>CMT (Umeda et al., 2008)</td>
</tr>
<tr>
<td>$N_{rr}$</td>
<td>-0.139</td>
<td>CMT (Umeda et al., 2008)</td>
</tr>
<tr>
<td>$N_{\phi}$</td>
<td>-0.00446</td>
<td>CMT (Umeda et al., 2008)</td>
</tr>
<tr>
<td>$N_{\phi}$</td>
<td>-0.00511</td>
<td>Heel angle test (Umeda et al., 2008)</td>
</tr>
</tbody>
</table>
Table 2.3 Grids for free model simulations.

<table>
<thead>
<tr>
<th>Name</th>
<th>Size (grid points)</th>
<th># of procs</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hull S/P*</td>
<td>199x61x104 (1.26 M x2)</td>
<td>12 (x2)</td>
<td>Double O</td>
</tr>
<tr>
<td>Skeg S/P</td>
<td>61x49x40 (0.12 M x2)</td>
<td>1 (x2)</td>
<td>O</td>
</tr>
<tr>
<td>Bilge Keel S/P</td>
<td>99x45x50 (0.23 M x2)</td>
<td>2 (x2)</td>
<td>H</td>
</tr>
<tr>
<td>Rudder Root Collar S/P</td>
<td>121x35x28 (0.12 M x2)</td>
<td>1 (x2)</td>
<td>O</td>
</tr>
<tr>
<td>Rudder Root Gap S/P</td>
<td>121x51x19 (0.12 M x2)</td>
<td>2 (x2)</td>
<td>Conformal to Collar</td>
</tr>
<tr>
<td>Rudder Outer S/P</td>
<td>61x36x55 (0.12 M x2)</td>
<td>1 (x2)</td>
<td>Double O</td>
</tr>
<tr>
<td>Rudder Inner S/P</td>
<td>61x36x55 (0.12 M x2)</td>
<td>1 (x2)</td>
<td>Double O</td>
</tr>
<tr>
<td>Rudder Gap S/P</td>
<td>121x51x19 (0.12 M x2)</td>
<td>2 (x2)</td>
<td>Conformal to Inner and Outer</td>
</tr>
<tr>
<td>Shaft Collar S/P</td>
<td>39x50x57 (0.11 M x2)</td>
<td>1 (x2)</td>
<td>O</td>
</tr>
<tr>
<td>Shaft Proper S/P</td>
<td>74x41x37 (0.11 M x2)</td>
<td>1 (x2)</td>
<td>O</td>
</tr>
<tr>
<td>Shaft Tip S/P</td>
<td>110x117x100 (1.29 M x2)</td>
<td>12 (x2)</td>
<td>O with end pole</td>
</tr>
<tr>
<td>Strut Outer S/P</td>
<td>69x34x50 (0.12 M x2)</td>
<td>1 (x2)</td>
<td>O</td>
</tr>
<tr>
<td>Strut Inner S/P</td>
<td>69x34x50 (0.12 M x2)</td>
<td>1 (x2)</td>
<td>O</td>
</tr>
<tr>
<td>Superstructure</td>
<td>165x61x85 (0.86 M)</td>
<td>8</td>
<td>Wrap</td>
</tr>
<tr>
<td>Refinement</td>
<td>145x81x113 (1.33 M)</td>
<td>12</td>
<td>Cartesian</td>
</tr>
<tr>
<td>Background</td>
<td>213x84x113 (2.02 M)</td>
<td>20</td>
<td>O</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>(12.1 M)</td>
<td>116</td>
<td></td>
</tr>
</tbody>
</table>

* S/P: Starboard/Port

Table 2.4 EFD, CFD and SB test matrices.

<table>
<thead>
<tr>
<th>Test</th>
<th>Fr</th>
<th>$\delta$ (deg)</th>
<th>$\psi_c^*$ (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EFD</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turning Circle</td>
<td>0.1, 0.2</td>
<td>25, 35</td>
<td>N/A</td>
</tr>
<tr>
<td>Zigzag</td>
<td>0.1, 0.2</td>
<td>10, 20</td>
<td>10, 20</td>
</tr>
<tr>
<td>Large Angle Zigzag</td>
<td>0.2</td>
<td>35</td>
<td>90</td>
</tr>
<tr>
<td>CFD and SB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turning Circle</td>
<td>0.2</td>
<td>25</td>
<td>N/A</td>
</tr>
<tr>
<td>Zigzag</td>
<td>0.2</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Large Angle Zigzag</td>
<td>0.2</td>
<td>35</td>
<td>90</td>
</tr>
</tbody>
</table>

$\psi_c^*$: target yaw angle
Table 2.5 Constraints for the coefficients.

| \( (X_{vr} + m_y), t_R, a_H, Z_H, Z_{HR}, X_H, nix, m_y, J_{xx}, J_{zz}, 7_R, E \) | \( \geq 0 \) |
| \( X_{rr}, X_{rr}, Y_{v}, X_{v_0}, (Y_{r} - m_y), K_p, N_p, N_{rr}, t_R \) | \( \leq 0 \) |
| \( t_R, \gamma_R \) | \( \leq 1 \) |

Table 2.6 CFD and SB turning circle simulation errors from the EFD results \((Fr=0.20, \delta = 25\text{deg})\).

<table>
<thead>
<tr>
<th></th>
<th>( u )</th>
<th>( v )</th>
<th>( r )</th>
<th>( \phi )</th>
<th>( SSV )</th>
<th>( A )</th>
<th>( T )</th>
<th>( R )</th>
<th>( ATR \text{ Av.} )</th>
<th>Total Av.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E%D</td>
<td>E%D</td>
<td>E%D</td>
<td>E%D</td>
<td>Av. E%D</td>
<td>E%D</td>
<td>E%D</td>
<td>E%D</td>
<td></td>
<td>E%D</td>
</tr>
<tr>
<td>CFD</td>
<td>-1.68</td>
<td>5.93</td>
<td>-3.59</td>
<td>17.5</td>
<td>7.18</td>
<td>-1.23</td>
<td>-2.19</td>
<td>-1.34</td>
<td>1.59</td>
<td>4.38</td>
</tr>
<tr>
<td>SB</td>
<td>-2.62</td>
<td>-1.28</td>
<td>-5.95</td>
<td>20.5</td>
<td>10.5</td>
<td>-2.21</td>
<td>4.06</td>
<td>2.44</td>
<td>2.90</td>
<td>6.70</td>
</tr>
</tbody>
</table>

Table 2.7 CFD and SB zigzag simulation errors from the EFD results \((Fr=0.20, \psi_e/\delta=20/20)\).

<table>
<thead>
<tr>
<th></th>
<th>( K_{20} )</th>
<th>( T_{20} )</th>
<th>( N_{20} )</th>
<th>( K_{TN} )</th>
<th>( 1^{st} \text{ OS} )</th>
<th>( 2^{nd} \text{ OS} )</th>
<th>( OS )</th>
<th>Total Av.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E%D</td>
<td>E%D</td>
<td>E%D</td>
<td>Av. E%D</td>
<td>E%D</td>
<td>E%D</td>
<td>Av. E%D</td>
<td>E%D</td>
</tr>
<tr>
<td>CFD</td>
<td>0.88</td>
<td>-2.67</td>
<td>5.90</td>
<td>3.15</td>
<td>-1.54</td>
<td>-2.52</td>
<td>2.03</td>
<td>2.29</td>
</tr>
<tr>
<td>SB</td>
<td>-3.64</td>
<td>-45.7</td>
<td>-3.65</td>
<td>17.7</td>
<td>-6.92</td>
<td>6.30</td>
<td>6.61</td>
<td>12.2</td>
</tr>
</tbody>
</table>

Table 2.8 CFD and SB large angle zigzag simulation errors from the EFD results \((Fr=0.20, \psi_e/\delta=90/35)\).

<table>
<thead>
<tr>
<th></th>
<th>( K_{90} )</th>
<th>( T_{90} )</th>
<th>( N_{90} )</th>
<th>( K_{TN} )</th>
<th>( 1^{st} \text{ OS} )</th>
<th>( 2^{nd} \text{ OS} )</th>
<th>( OS )</th>
<th>Total Av.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E%D</td>
<td>E%D</td>
<td>E%D</td>
<td>Av. E%D</td>
<td>E%D</td>
<td>E%D</td>
<td>Av. E%D</td>
<td>E%D</td>
</tr>
<tr>
<td>CFD</td>
<td>4.32</td>
<td>-20.7</td>
<td>-1.61</td>
<td>8.88</td>
<td>-1.23</td>
<td>-1.60</td>
<td>1.42</td>
<td>5.15</td>
</tr>
<tr>
<td>SB</td>
<td>25.1</td>
<td>-47.7</td>
<td>100</td>
<td>57.6</td>
<td>-0.59</td>
<td>-0.72</td>
<td>0.65</td>
<td>29.1</td>
</tr>
</tbody>
</table>
Table 2.9 Summary of IMO criteria for all presented turning circle and zigzag cases

<table>
<thead>
<tr>
<th>Parameter/Parameter/Parameter/index</th>
<th>Turning circle</th>
<th>10/10 Zigzag</th>
<th>20/20 Zigzag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fr</td>
<td>EFD 0.2</td>
<td>CFD 0.1</td>
<td>Fr 0.1</td>
</tr>
<tr>
<td>δ (deg)</td>
<td>25 25</td>
<td>35 35</td>
<td>δ/ψ, (deg) 10/10</td>
</tr>
<tr>
<td>Advance (A/L)</td>
<td>2.82 2.86</td>
<td>2.89 2.26</td>
<td>- 2.59</td>
</tr>
<tr>
<td>Transfer (T/L)</td>
<td>1.81 1.85</td>
<td>1.72 1.30</td>
<td>1.45 - 1.56</td>
</tr>
<tr>
<td>Radius (R/L)</td>
<td>2.17 2.20</td>
<td>2.12 1.62</td>
<td>- 1.77</td>
</tr>
<tr>
<td>Diameter (TD/L)</td>
<td>4.35 4.42</td>
<td>4.20 3.12</td>
<td>- 3.55</td>
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</tbody>
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Criteria: $a_{101} < f_{101}(L/V)$ and $a_{102} < f_{102}(L/V)$

Criteria: $A < 4.5L$ and $TD < 5L$

Criteria: $a_{201} < 25$ deg

Criteria: $a_{202} < 25$ deg for ONRT geometry at $Fr = 0.1$
Table 2.10 Ratio of estimated coefficients using EKF and the original coefficients: “T25” δ=25deg turning with Fr=0.20; “Z20” ψ/δ=20/20 zigzag with Fr=0.20; “Z90” ψ/δ=90/35 large angle zigzag with Fr=0.20; “SUM” parallel processing T25, Z20 and Z90.

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<tr>
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<th>CFD</th>
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<tr>
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<td>X_{vv} Est./Orig.</td>
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<td>0.97</td>
<td>0.95</td>
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<td>0.98</td>
</tr>
<tr>
<td>Y_{r} Est./Orig.</td>
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<td>Y_{yrr} Est./Orig.</td>
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</tr>
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<td>Y_{rr} Est./Orig.</td>
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<td>\eta Est./Orig.</td>
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<td>\eta Est./Orig.</td>
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<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
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<tr>
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<td>N_{rrr} Est./Orig.</td>
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<tr>
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<td>8.34</td>
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</table>

Global Av. Δ%D 9.01 59.05 54.41
Table 2.11 Ratio of estimated coefficients using CLS and the original coefficients: “T25” $\delta=25^\circ$ turning with $Fr=0.20$; “Z20” $\psi_c/\delta=20/20$ zigzag with $Fr=0.20$; “Z90” $\psi_c/\delta=90/35$ large angle zigzag with $Fr=0.20$; “SUM” parallel processing T25, Z20 and Z90.

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<th>CFD</th>
</tr>
</thead>
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<td>$\epsilon$ Est./Orig.</td>
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<td>0.81</td>
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Table 2.12 Steady state variables and turning index errors between EFD $\delta=25\text{deg}$ turning circle results and SB simulations using estimated coefficients: “SSV Av. E\%D” average of the absolute E\%D values of $u$, $v$, $r$, and $\phi$ “ATR Av. E\%D” average of the absolute E\%D values of $A$, $T$, and $R$; “Total Av. E\%D” average of “SSV Av. E\%D” and “ATR Av. E\%D”.

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<th>$r$</th>
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<th>T</th>
<th>R</th>
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<td>E%D</td>
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Table 2.13 Steering indices and overshoot angle errors between EFD 20/20 zigzag results and SB simulations using estimated coefficients: “KTN Av. E%D” average of the absolute E%D values of K20, T20, and N20; “OS Av. E%D” average of the absolute E%D values of 1st OS and 2nd OS; “Total Av. E%D” average of “KTN Av. E%D” and “OS Av. E%D”.

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OS*; overshoot angle
Table 2.14 Steering indices and overshoot angle errors between EFD 90/35 large angle zigzag results and SB simulations using estimated coefficients: “KTN Av. E%D” average of the absolute E%D values of K90, T90, and N90; “OS Av. E%D” average of the absolute E%D values of 1st OS and 2nd OS; “Total Av. E%D” average of “KTN Av. E%D” and “OS Av. E%D”.

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Table 2.15 Average errors between EFD free running (T25, Z20, Z90) results and SB simulations using estimated coefficients: “T25 E%D” total average E%D of Table 2.12; “Z20 E%D” total average E%D of Table 2.13; “Z90 E%D” total average E%D of Table 2.14; “Global Av. E%D” average of “T25 Av. E%D”, “Z20 Av. E%D”, and “Z90 Av. E%D”.

<table>
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<th></th>
<th>T25 E%D</th>
<th>Z20 E%D</th>
<th>Z90 E%D</th>
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<td>EFD</td>
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<tr>
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<tr>
<td>CFD-SUM</td>
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<td>6.48</td>
<td>4.43</td>
<td>5.56</td>
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Table 2.16 Errors between blind EFD free running results (δ=35deg turning circle and \( \psi, \delta=10/10 \) zigzag tests with \( Fr=0.10 \)) and SB simulations using original and CLS-CFD-SUM coefficients: “T35Fr010 Av. E%Đ” average of “SSV Av. E%Đ” and “ATR Av. E%Đ”; “Z10Fr010 Av. E%Đ” average of “KTN Av. E%Đ” and “OS Av. E%Đ”; “Global Av. E%Đ” average of “T35Fr010 Av. E%Đ” and “Z10Fr010 Av. E%Đ”.

<table>
<thead>
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<th>( \delta=35\text{deg} )</th>
<th>( Fr=0.10 )</th>
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<th>CLS-CFD-SUM</th>
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<tr>
<td>( u \ E%Đ )</td>
<td>-11.81</td>
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<td></td>
</tr>
<tr>
<td>( v \ E%Đ )</td>
<td>-8.36</td>
<td>32.84</td>
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</tr>
<tr>
<td>( r \ E%Đ )</td>
<td>-15.41</td>
<td>9.67</td>
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</tr>
<tr>
<td>( \phi \ E%Đ )</td>
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<tr>
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<tr>
<td>A E%Đ</td>
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<td></td>
</tr>
<tr>
<td>T E%Đ</td>
<td>-12.29</td>
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<tr>
<td>ATR Av. E%Đ</td>
<td>12.02</td>
<td>5.11</td>
<td></td>
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<tr>
<td>T35Fr010 Av. E%Đ</td>
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<td>12.44</td>
<td></td>
</tr>
<tr>
<td>10/10 ( Fr=0.10 )</td>
<td>K10 E%Đ</td>
<td>-20.08</td>
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<tr>
<td>Zigzag</td>
<td>T10 E%Đ</td>
<td>-28.85</td>
<td>4.41</td>
</tr>
<tr>
<td>with ( Fr=0.10 )</td>
<td>N10 E%Đ</td>
<td>-30.13</td>
<td>-8.05</td>
</tr>
<tr>
<td></td>
<td>KTN Av. E%Đ</td>
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</tr>
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<td>1\text{st} OS E%Đ</td>
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<td>2\text{nd} OS E%Đ</td>
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<td>Global Av. E%Đ</td>
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Fig. 2.1 Photograph and drawing of IIHR wave basin.

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Fig. 2.14 Time series of zigzag test ($\psi_s/\delta$=20/20, $Fr$ =0.20): (a) surge velocity; (b) sway velocity; (c) yaw rate; (d) roll angle; (e) yaw angle; (f) rudder angle.
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Fig. 2.16 Total average errors of T25 SB simulations using estimated and original maneuvering coefficients.

Fig. 2.17 Total average errors of Z20 SB simulations using estimated and original maneuvering coefficients.
Fig. 2.18 Total average errors of Z90 SB simulations using estimated and original maneuvering coefficients.

Fig. 2.19 Global average errors of T25, Z20, and Z90 SB simulations using estimated and original maneuvering coefficients.
Fig. 2.20 Comparison of the rudder normal forces between CFD and SB simulations (EKF and CLS-CFD-SUM): (a) turning circle ($\delta = 35\text{deg}, Fr =0.10$); (b) zigzag ($\psi_c/\delta=90/35, Fr =0.10$).

Fig. 2.21 Trajectories of free running simulations: (a) turning circle ($\delta = 35\text{deg}, Fr =0.10$); (b) zigzag ($\psi_c/\delta=10/10, Fr =0.10$).
Fig. 2.22 Time series of zigzag test ($\psi/\delta=10/10$, $Fr=0.10$): (a) surge velocity; (b) sway velocity; (c) yaw rate; (d) roll angle; (e) yaw angle; (f) rudder angle.
3 MANEUVERING IN FOLLOWING AND QUATERING WAVES

3.1 INTRODUCTION

Ship stability and maneuverability in waves are one of the most important topics for ship safety. Especially, in following and quartering waves, it is necessary to discuss about maneuverability in waves to prevent dangerous phenomena like broaching.

System-based (SB) and recently computational fluid dynamic (CFD) methods are used to predict ship stability and maneuverability in calm water and waves. Since short computational time is required to sweep out dangerous maneuvering and wave conditions from huge number of suspect conditions, SB method shows a superior ability to CFD; SB needs less than a minute for one free running simulation using a personal computer, while CFD needs a few weeks or a month using a very expensive supercomputer. Meanwhile it is also very expensive and time consuming to predict maneuvering coefficients from captive model tests which is necessary for SB method, while CFD merely needs ship and rudder geometries, and propeller characteristics. The SB free running simulations in calm water shows that SB model is very sensitive to the accuracy of the maneuvering coefficients such that the scatter in SB predictions are substantial for a SB model with coefficients estimated from different captive tests (Stern et al., 2011). Also, SB shows only qualitative agreement with EFD free running results in following and quartering waves, while CFD shows quantitative agreement (Sadat-Hosseini et al., 2011). Since CFD free running simulation can provide not only ship motion but also total forces/moments acting on the ship which are unknown during EFD free running, it can give a chance to modify and tune the SB model to reduce the disagreement with EFD free running results in calm water and waves.

For calm water maneuvers, several researches showed SI techniques are available to predict maneuvering coefficients from free running results. In previous SI researches, EFD (Abkowitz, 1980) or SB simulation results (Rhee, 1999) were often used to reconstruct the coefficients. The
The author uses CFD outputs to improve the SB predictions in calm water in Chapter 2. Hull and rudder maneuvering coefficients included in a SB model are estimated from turning circle and zigzag CFD free running simulations data. SB simulations using the identified coefficients shows much better agreement with EFD free running than those using coefficients estimated from captive model experiments and empirical prediction. Hence, several CFD free running simulations could replace the many number of captive model experiments needed to estimate the maneuvering coefficients for SB model. For maneuvering in waves, the hydrodynamic maneuvering coefficients estimated from EFD captive test in calm water are often used in SB model. Also, the wave forces are considered as summation of Froude-Krylov and diffraction forces. These facts cause in discrepancy between SB prediction and EFD, as maneuvering coefficients variations due to waves (Son and Nomoto, 1982) and wave drift forces are important for SB prediction in waves (Yasukawa and Fizul, 2006).

The objective of this chapter is to employ the SI technique with CFD outputs to improve SB predictions in following and quartering waves by tuning the maneuvering coefficients and wave forces. The wave forces/effects are found from CFD simulations. First, CFD free running simulations in waves are executed. Second, CFD forced motion simulations in calm water are performed with imposing exactly the same motions as in the free running simulation. The wave forces/effects are estimated as the difference between the total force of the CFD free running and CFD forced simulations. The CFD wave forces/effects are compared with the conventional SB wave model based on slender body theory and used to tune SB wave forces/effects by SI technique. The SI technique along with CFD simulations are expected to improve SB simulation in waves and provide opportunity for SB to have quantitative broaching prediction in following and quartering waves. The improved SB and CFD free running simulation results are compared with that of EFD. Here it should be pointed out that SB and CFD simulations are done before EFD data are available.
3.2  SB WAVE MODEL

3.2.1  Original SB Wave Model

The wave-induced forces/moments are added to the calm water maneuvering model (Eqs. (2.3)-(2.6)) and modified into Eqs. (3.1)-(3.4).

\[
(m + m_c)\ddot{u} - (m + m_c)\dot{v} = T(u; n) - R(u; n) + X_w(u)u + X_w(u)v
\]
(3.1)

\[
(m + m_c)\dot{v} + (m + m_c)\dot{u} = Y_w(u)u + Y_w(u)v + Y_w(u)\dot{v}
\]
(3.2)

\[
(U + J_p)\dot{r} = m_zu + K_w(u)v + K_w(u)r + K_w(u)p + K_w(u)\phi
\]
(3.3)

\[
(U + J_p)\dot{r} = N_w(u)v + N_w(u)r + N_w(u)p + N_w(u)\phi + N_w(u)v^2 + N_w(u)r^2 + N_w(u)p^2 + K_w(u)v + K_w(u)r + K_w(u)p
\]
(3.4)

Herein Froude-Krylov force and diffraction force are taken into account for the original SB wave model (Umeda et al., 2008) as shown in Eqs. (3.5)-(3.19).

\[
X_w(\xi / \lambda, \psi) = X_{w, FK} + X_{w, Diff}
\]
(3.5)

\[
Y_w(\xi / \lambda, \psi) = Y_{w, FK} + Y_{w, Diff}
\]
(3.6)

\[
K_w(\xi / \lambda, \psi) = K_{w, FK} + K_{w, Diff} + OG \cdot Y_w
\]
(3.7)

\[
N_w(\xi / \lambda, \psi) = N_{w, FK} + N_{w, Diff}
\]
\[ K_{W}^{FE}(\xi_{0}/\lambda, \psi) = \rho \zeta_{W} \sin \psi \cdot \int_{AE}^{PE} C_{4}(x) \left\{ B(x)/2 \right\}^{3} e^{-kd(x)} x \sin k(\xi_{0} + x \cos \psi) \, dx \]

\[ = \rho \zeta_{W} \sin \psi / k \cdot \int_{AE}^{PE} C_{1}(x) B(x) \left\{ 1 - \left[ 1 + kd(x) \right] e^{-kd(x)} \right\} \sin k(\xi_{0} + x \cos \psi) \, dx \]

\[ = \rho \zeta_{W} \sin \psi \cdot \sqrt{Kc^{2} + Ks^{2}} \sin \left( k\xi_{0} + \epsilon_{K} \right) \]

\[ = A_{KFE} \sin \left( k\xi_{0} + \epsilon_{K} \right) \]

\[ N_{W}^{FE}(\xi_{0}/\lambda, \psi) = \rho \zeta_{W} \sin \psi \cdot \int_{AE}^{PE} C_{1}(x) S(x) e^{-kd(x)/2} x \sin k(\xi_{0} + x \cos \psi) \, dx \]

\[ = \rho \zeta_{W} \sin \psi \cdot \sqrt{Nc^{2} + Ns^{2}} \sin \left( k\xi_{0} + \epsilon_{N} \right) \]

\[ = A_{NFE} \sin \left( k\xi_{0} + \epsilon_{N} \right) \]

\[ \epsilon_{F} = \tan^{-1}(F_{S}/F_{C}) \]

\[ \epsilon_{K} = \tan^{-1}(K_{S}/K_{C}) \]

\[ \epsilon_{N} = -\tan^{-1}(N_{S}/N_{C}) \]

\[ C_{1} = \frac{\sin \left( kB(x)\sin \psi / 2 \right)}{kB(x)\sin \psi / 2} \]

\[ C_{4} = \begin{bmatrix} 2 \sin \left( k \sin \psi \cdot B(x)/2 \right) - \{ kB(x)\sin \psi \} \cos \left( k \sin \psi \cdot B(x)/2 \right) \end{bmatrix}^{3} \]

\[ F_{C} = \int_{L} e^{-kd(x)/2} S(x) C_{1} \left\{ \cos \left( kx \cos \psi \right) \right\} \sin \left( kx \cos \psi \right) \, dx \]

\[ F_{S} = \int_{L} e^{-kd(x)/2} S(x) C_{1} \left\{ \cos \left( kx \cos \psi \right) \right\} \sin \left( kx \cos \psi \right) \, dx \]

\[ K_{c} = \begin{bmatrix} K_{1c} - K_{2c} / k^{2} \\ K_{1S} - K_{2S} / k^{2} \end{bmatrix} \]

\[ K_{1c} = \int_{L} \begin{bmatrix} B(x) / 2 \end{bmatrix}^{3} e^{-kd(x)} C_{4} \left\{ \cos \left( kx \cos \psi \right) \right\} \sin \left( kx \cos \psi \right) \, dx \]

\[ K_{1S} = \int_{L} \begin{bmatrix} B(x) / 2 \end{bmatrix}^{3} e^{-kd(x)} C_{4} \left\{ \cos \left( kx \cos \psi \right) \right\} \sin \left( kx \cos \psi \right) \, dx \]

\[ K_{2c} = \int_{L} B(x) \left\{ 1 - \left[ 1 + kd(x) \right] e^{-kd(x)} \right\} C_{1} \left\{ \cos \left( kx \cos \psi \right) \right\} \sin \left( kx \cos \psi \right) \, dx \]

\[ K_{2S} = \int_{L} B(x) \left\{ 1 - \left[ 1 + kd(x) \right] e^{-kd(x)} \right\} C_{1} \left\{ \cos \left( kx \cos \psi \right) \right\} \sin \left( kx \cos \psi \right) \, dx \]

\[ N_{c} = \int_{L} e^{-kd(x)/2} x S(x) C_{1} \left\{ \cos \left( kx \cos \psi \right) \right\} \sin \left( kx \cos \psi \right) \, dx \]

\[ N_{s} = \int_{L} e^{-kd(x)/2} x S(x) C_{1} \left\{ \cos \left( kx \cos \psi \right) \right\} \sin \left( kx \cos \psi \right) \, dx \]

\[ Y_{W}^{Diff}(u, \xi_{0}/\lambda, \psi) = \zeta_{W} \omega_{w} \sin \psi \cdot \int_{AE}^{PE} \rho S_{y}(x) e^{-kd(x)/2} \sin k(\xi_{0} + x \cos \psi) \, dx \]

\[ -\zeta_{w} \omega_{w} \sin \psi \cdot \int_{AE}^{PE} \rho S_{y}(x) e^{-kd(x)/2} \cos k(\xi_{0} + x \cos \psi) \, dx \]

\[ K_{W}^{Diff}(u, \xi_{0}/\lambda, \psi) = -\zeta_{w} \omega_{w} \sin \psi \cdot \int_{AE}^{PE} \rho S_{y}(x) l_{y}(x) e^{-kd(x)/2} \sin k(\xi_{0} + x \cos \psi) \, dx \]

\[ -\zeta_{w} \omega_{w} \sin \psi \cdot \int_{AE}^{PE} \rho S_{y}(x) l_{y}(x) e^{-kd(x)/2} \cos k(\xi_{0} + x \cos \psi) \, dx \]

\[ N_{W}^{Diff}(u, \xi_{0}/\lambda, \psi) = \zeta_{W} \omega_{w} \sin \psi \cdot \int_{AE}^{PE} \rho S_{y}(x) e^{-kd(x)/2} x \sin k(\xi_{0} + x \cos \psi) \, dx \]

\[ -\zeta_{w} \omega_{w} \sin \psi \cdot \int_{AE}^{PE} \rho S_{y}(x) e^{-kd(x)/2} x \cos k(\xi_{0} + x \cos \psi) \, dx \]
Where the 2D added mass $S_y(x)$ is estimated by solving the Laplace equation under zero encounter frequency assumption.

It is known that wave particle velocity affects the rudder inflow velocity (e.g. Hashimoto et al., 2004). The wave particle velocity is taken into account on the rudder inflow velocity as in Eqs. (3.20)-(3.24). Moreover, during the maneuvering in waves, the roll motion would affect the rudder inflow angle and inflow velocity. Therefore the roll motion effect is taken into the rudder inflow velocity as shown in Eq. (3.25) modified from Eq. (2.24). Herein $L_R$ is sectional plane lever from the CG to the rudder center.

$$u_{rw} = u_R + u_w \quad (3.20)$$

$$v_{rw} = v_R + v_w \quad (3.21)$$

$$u_w = \zeta_\omega \cos \psi e^{-kz} \cos (kz_0 + kx \cos \psi) \quad (3.22)$$

$$v_w = -\zeta_\omega \cos \psi e^{-kz} \cos (kz_0 + kx \cos \psi) \quad (3.23)$$

$$U_R = \sqrt{u_{rw}^2 + v_{rw}^2} \quad (3.24)$$

$$\alpha_R = \delta - \gamma \frac{v_{rw}}{u_{rw}} \quad (3.25)$$

This wave model successfully reproduces the wave-induced force for some fishing vessels (Hashimoto et al., 2004). However it is also known the Froude-Krylov surge force has some discrepancy with actual wave-induced surge force for several conventional and unconventional vessels including ONRT (Ito et al., 2012). The surge, sway, roll, and yaw wave-induced forces were measured in stern quartering waves by Hashimoto et al. (2011) using 2m ONRT model. Fig.3.1 shows the comparisons between the measured wave-induced forces and computed ones using linear slender body theory (Umeda et al., 1995) with the amplitudes and phase lag. Herein the “ws” is wave steepness in short. As shown in Fig.3.1, there are some discrepancies between SB wave-induced forces and EFD forces in both amplitudes and phase lags. Therefore it is clear that
SB wave model needs to be modified to predict reasonable ship motions in waves.

### 3.2.2 Modified SB Wave Model

In Subsection 3.2.1, it is shown that the original SB wave model cannot reproduce the wave-induced force for the ONRT. Therefore some modifications are clearly requested. The SI techniques, similar to Chapter 2, are applied to modify the SB wave model to predict reasonable ship maneuver in waves. First modification should be started with the Froude-Krylov force which is dominant for the wave-induced force. As shown in the Fig. 3.1, there are discrepancies not just in the amplitudes but also in the phase lag. Therefore there need to have some tuning for the amplitudes and the phases of the Froude-Krylov force. The equations of the Froude-Krylov forces Eqs. (3.6)-(3.9) are modified into Eq. (3.26) adding tuning parameters for the amplitude \((a_f, b_f, c_f, d_f)\) and phase \((\varepsilon_{a_f}, \varepsilon_{b_f}, \varepsilon_{c_f}, \varepsilon_{d_f})\). These parameters are going to be tuned with the SI technique will be introduced in the next section.

\[
\begin{align*}
\dot{X}_w^{FK} &= a_f A_{XFK} \sin (k \xi_G + \xi_F + \varepsilon_{a_f}) \\
\dot{Y}_w^{FK} &= b_f A_{YFK} \sin (k \xi_G + \xi_F + \varepsilon_{b_f}) \\
\dot{K}_w^{FK} &= c_f A_{KFK} \sin (k \xi_G + \xi_F + \varepsilon_{c_f}) \\
\dot{N}_w^{FK} &= d_f A_{NFK} \sin (k \xi_G + \xi_F + \varepsilon_{d_f})
\end{align*}
\]

(3.26)

Next modification is done for the diffraction force. The diffraction force itself is relatively small compared with Froude-Krylov force, the amplitude and phase is tuned in Eq. (3.26). Therefore the tuning parameters for diffraction forces \((b_2, c_2, d_2)\) are given only for the amplitude as shown in Eq. (3.27).

\[
\begin{align*}
\dot{Y}_w^{diff} &= b_2 Y_w^{diff} \\
\dot{K}_w^{diff} &= c_2 K_w^{diff} \\
\dot{N}_w^{diff} &= d_2 N_w^{diff}
\end{align*}
\]

(3.27)
Meanwhile the variation of the maneuvering coefficients in waves could be one of the important factors to discuss the ship maneuver in waves. The course keeping stability in waves is examined with hydrodynamic derivatives with respect to wave heading angle by calculating the eigenvalue of the linearized sway-yaw model as shown in Eqs.(3.28) and (3.29) (Son and Nomoto, 1982). Here the symbol prime denotes non-dimensional quantities. Validation of $Y_r\prime$, $N_r\prime$, $Y_v\prime$ and $N_v\prime$ in wave were measured using captive tests with $Fr=0.35$ in $H/\lambda=0.05$, and $\lambda/L=1.25$ wave condition near to broaching condition (Araki et al., 2011). The wave-induced forces $Y_x\prime$ and $N_x\prime$ are calculated as the sum of the Froude-Krylov and diffraction forces. Here $m_y\prime$ and $J_z\prime$ are assumed to be constant.

$$As^3 + Bs^2 + Cs + D = 0$$  \hspace{1cm} (3.28)

where

$$A = (m'+ m_y')(I_y' + J_z')$$
$$B = -(m'+ m_y')N_r' - (I_z' + J_z')Y_v'$$
$$C = -(m'+ m_y')N_x' + N_v' Y_v' - (Y_r' - m')N_v'$$
$$D = Y_r' N_x' - Y_v' N_v'$$  \hspace{1cm} (3.29)

The maximum value of the real part of the solution of Eq. (3.28), $\sigma_{\text{max}}$, is shown in Fig.3.2. When it is positive, the sway-yaw motion is unstable and vice versa. According to Fig.3.2, the ship is directionally stable for most of the wave upslope and unstable in the wave downslope. This tendency is almost independent of the wave heading angle as pointed out by Wahab and Swaan (1964). According to the observations of free running experiment in stern quartering waves, most of the broaching and/or course deviation starts when the ship situates around the wave downslope which coincides with the results of Fig3.2.

In the original SB wave model, the variations of maneuvering coefficients are out of their scope. Therefore the variations of maneuvering coefficients are taken into account in the new modified SB wave model and the modified maneuvering coefficients are as shown in Eqs. (3.30)-(3.33). In this study, only major coefficients are modified. The variations of the amplitudes and the phase lags are
tuned with the SI technique. Where \((a_2, a_3, a_4, b_3, b_4, c_3, c_4, d_3, d_4)\) are tuning parameters for the variation amplitude and \((\varepsilon_a, \varepsilon_b, \varepsilon_c, \varepsilon_d, \varepsilon_e, \varepsilon_f, \varepsilon_g, \varepsilon_h, \varepsilon_i)\) are for phase.

\[
\begin{align*}
\dot{X}_w &= \left(1 + k\xi_a a_2 \sin(k\xi_0 + \varepsilon_a_2)\right) X_w \\
\dot{X}_w &= \left(1 + k\xi_a a_3 \sin(k\xi_0 + \varepsilon_a_3)\right) X_w \\
\dot{X}_w &= \left(1 + k\xi_a a_4 \sin(k\xi_0 + \varepsilon_a_4)\right) X_w \\
\dot{Y}_v &= \left(1 + k\xi_a b_2 \sin(k\xi_0 + \varepsilon_b_2)\right) Y_v \\
\dot{Y}_v &= \left(1 + k\xi_a b_3 \sin(k\xi_0 + \varepsilon_b_3)\right) Y_v \\
\dot{K}_v &= \left(1 + k\xi_a c_3 \sin(k\xi_0 + \varepsilon_c_3)\right) K_v \\
\dot{K}_v &= \left(1 + k\xi_a c_4 \sin(k\xi_0 + \varepsilon_c_4)\right) K_v \\
\dot{N}_v &= \left(1 + k\xi_a d_3 \sin(k\xi_0 + \varepsilon_d_3)\right) N_v \\
\dot{N}_v &= \left(1 + k\xi_a d_4 \sin(k\xi_0 + \varepsilon_d_4)\right) N_v
\end{align*}
\]  

Moreover wave drift force would cause the course deviation during the ship maneuvering in waves. The wave drift forces are expressed with Eq. (3.34). For the simplification, the wave drift coefficients \(C_X, C_Y\) and, \(C_N\) shown in Eq. (3.35) are expressed as the Weibull distribution respect to ship to wave length ratio \(\lambda/L\). The shape and scale parameters \(\mu, \eta\) in Eq. (3.35) are determined from the Yasukawa’s experiment (2008) as shown in Fig.3.3. In the Fig.3.3, “EFD-” markers indicate the experimental results (Yasukawa and Fizul, 2006) and “Fit-” lines fitted with the Weibull distribution using Table 3.1 values. The EFD result in Fig.3.3 indicates the heading angle dependency is relatively small especially in surge drift force following with Eq. (3.34) expression. The parameters \(\alpha_{x,y,n}\) in Eq. (3.35) are estimated with the SI technique.

\[
\begin{align*}
W_{C_X} &= \rho g \xi_2^2 B^2 / L \cdot C_X(\lambda/L) \\
W_{C_Y} &= \rho g \xi_2^2 B^2 / L \cdot \sin \psi \cdot C_Y(\lambda/L) \\
W_{C_X} &= OG \cdot W_{C_Y} \\
W_{C_N} &= \rho g \xi_2^2 B^2 \cdot \sin \psi \cdot C_N(\lambda/L) \\
C_{x,y,n}(\lambda/L; x,y,n) &= \alpha_{x,y,n} \left[ \frac{\lambda/L; x,y,n}{\eta_{x,y,n}} \right]^{\eta_{x,y,n} - 1} \exp \left( \frac{\lambda/L; x,y,n}{\eta_{x,y,n}} \right) \left[ \frac{\lambda/L; x,y,n}{\eta_{x,y,n}} \right]^{\eta_{x,y,n}}
\end{align*}
\]  

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It is obvious the wave particle velocity affects the rudder inflow velocity. However, the wave particle velocity itself cannot be simply calculated because the wave particle would be disturbed by the ship hull. Fig. 3.4 shows the EFD and SB rudder normal force, including rudder particle effect Eq. (3.22), during the captive rudder force test with $F_r=0.35$, $\delta=10$deg in following wave $H/\lambda=0.02$, 0.05, and $\lambda/L=1.20$. "EFD-calm" indicates EFD rudder normal force in calm water condition. "EFD-" indicates EFD result and "SB-" are calculation results estimated with original SB model. The "WS002" stands wave steepness 0.02 and "WS005" is wave steepness 0.05. From Fig. 3.4, the rudder normal forces slightly increase around the wave upslope and decrease around the downslope, which is effective for the outbreak of the broaching. Comparing EFD and SB results, it can be said the original SB fluctuation due to the wave is reasonable with EFD results, though the original SB results overestimate its amplitudes. Therefore the wave particle velocities related with the rudder inflow velocity and angle need to be tuned with the parameters $\beta_{1,2}$ shown in Eq. (3.37) by the SI technique.

$$\begin{align*}
\dot{u}_w &= \beta_u \cdot u_w \\
\dot{v}_w &= \beta_v \cdot v_w
\end{align*}$$

$$\lambda/L, \lambda/L_{y,w} = \begin{pmatrix} \lambda/L \\ \lambda/L_{y,w} \end{pmatrix} = \begin{pmatrix} \frac{\lambda/L}{10} \\ \frac{\lambda/L}{3(10/10)} \end{pmatrix}$$  (3.36)

3.3 SYSTEM IDENTIFICATION

Here the several tuning parameters and wave effect factors are pointed out in the previous section. Those factors are added to the original SB wave model and parameters are going to be tuned in this section.

In low frequency condition, such as running in following and stern quartering wave conditions, the total hydrodynamic force can be roughly decomposed into two parts. One is the hydrodynamic
force due to the ship motion. The other is the wave-induced force including Froude-Krylov force, diffraction force, wave drift force, wave particle effect to the rudder, effect due to variation of maneuvering coefficients, as mention in the previous section. It is true that it surely has other effects such as ship-wave interaction forces (e.g. restoring variation, roll damping variation, etc.) and radiation forces. However, on the ONRT, the restoring variations could be small due to the tumblehome topside. And radiation effects would be small in low encounter frequency conditions.

Meanwhile it is already shown in Chapter 2 that CFD simulations are powerful tool for the SI because the total hydrodynamic force during free running can be provided. However, even with the CFD simulation, it is hard to distinguish hydrodynamic force due to ship motion and wave-induced force from total hydrodynamic force. However, to predict and tune the SB wave model, it is necessary to extract the wave-induced force from total hydrodynamic forces. First, to achieve this purpose, 6DOF CFD free running simulations in waves are executed, providing total hydrodynamic forces. Second, CFD forced motion simulations in calm water are performed with imposing exactly the same motions as the first free running simulation, providing hydrodynamic force due to the ship motions. Thus the wave-induced force can be estimated as the difference between the total force of the first and second CFD simulations.

Figure 3.5 shows the extracted CFD wave-induced forces and SB wave-induced forces using the original SB wave model in \( H/\lambda=0.02, \lambda/L=1.2 \) following and stern quartering conditions. In range (1), the model is towed with \( Fr=0.20 \) and heading angle \( \chi=20\deg \). In range (2), it is free with nominal \( Fr=0.20 \) and \( \chi_e=20\deg \) course keeping with proportional rudder controlling with gain \( P=1.0 \). In range (3), free running 20/20 zigzag maneuver with nominal \( Fr=0.20 \). In range (4), it is straight free running in following wave with nominal \( Fr=0.20 \). In the figure "-CFD" solid lines indicate extracted CFD wave-induced forces and "-Orig" dashed lines are SB wave-induced forces computed with original SB wave model. Comparing CFD and original SB wave-induced forces, there are large discrepancies in the all wave force amplitudes. The SB original forces overestimate surge
force and underestimate sway, roll, and yaw forces compared with those estimated by CFD. Slight phase lags are also seen in sway, roll, and yaw forces. Moreover, in range (3), the original SB wave model fails to predict the wave force during zigzag maneuver, relatively large maneuver compared with the course keeping. Herein it is necessary to modify and tune the SB wave model as shown in Section 3.2. The CLS with parallel processing is used for the SI combining course keeping, zigzag, and straight running, which shows reasonable results in calm water cases. The SB wave model is tuned and optimized in the following manners as shown in Eqs. (3.38)-(3.53).

\[ \text{Optimize: } y(x_i) = \min \left[ \sum_{i=1}^{5} \left( X_{\text{est}} - X_{\text{env}}(x_i) \right)^2 \right] \]

\[ X_{\text{env}} = F_{\text{new}} \]

\[ X_{\text{est}} = X_{w-CFD} \]

\[ X_{\text{env}} = Y_{w-CFD} \]

\[ X_{\text{est}} = K_{w-CFD} \]

\[ X_{\text{est}} = N_{w-CFD} \]

\[ X_{\text{est}}(x_i) = F_{w} = \frac{1}{2} \rho A \hat{U}^2 \cdot f \cdot \sin \alpha \]

\[ X_{\text{est}}(x_2) = \hat{X}_{\text{CFD}}(a_1, e_1) + k_{w}(a_2 \sin(k_{w} + e_2) \cdot X_{w} \cdot Y_{w} + a_3 \sin(k_{w} + e_3) \cdot X_{w} \cdot Y_{w}) \]

\[ X_{\text{est}}(x_3) = \hat{X}_{\text{CFD}}(a_1, e_1) + k_{w}(a_2 \sin(k_{w} + e_2) \cdot X_{w} \cdot Y_{w} + a_3 \sin(k_{w} + e_3) \cdot X_{w} \cdot Y_{w}) \]

\[ X_{\text{est}}(x_4) = K_{w}(c_1, e_1) + c_2 k_{w}(c_2 \sin(k_{w} + e_2) \cdot K_{w} \cdot \nu + c_3 \sin(k_{w} + e_3) \cdot K_{w} \cdot \nu) + \Omega_{w}(t) \]

\[ X_{\text{est}}(x_5) = \hat{N}_{w}(d_1, e_1) + d_2 N_{w}(d_2 \sin(k_{w} + e_2) \cdot N_{w} \cdot \nu + d_3 \sin(k_{w} + e_3) \cdot N_{w} \cdot \nu) + \Omega_{w}(t) \]

\[ x = [\beta \ \beta] \]
First, the tuning parameters for the wave particle velocity $\beta_1$ and $\beta_2$ are estimated. Figure 3.6 shows rudder normal forces during the simulations. Here “SB-calm” dotted line indicates the SB computational result using SB rudder model for calm water case which is shown in Eq. (2.13). The dashed line “SB-wave” is using original SB result including wave particle effect with $\beta_1 = \beta_2 = 1.0$. "SB-SI-wave" is using optimized tuning parameters listed on the Table 3.2. In Fig.3.6, “SB-wave” seems to overestimate the wave particle effect on the rudder normal force, as same as Fig.3.4, while “SB-calm” and “SB-SI-wave” are close to “CFD”. From these results, the wave particle velocity is weakened by the wake generated by the hull.

To verify the influence of new proposed wave effects: variation of maneuvering coefficients and wave drift force, the wave forces are compared with three methods: the wave forces are computed with Froude-Krylov and diffraction forces in Fig.3.7; Froude-Krylov force, diffraction force, and variation of maneuvering coefficients due to wave in Fig.3.8; Froude-Krylov force, diffraction force, variation of maneuvering coefficients, and wave drift force in Fig.3.9.

The tuning parameters related to Froude-Krylov and diffraction forces are tuned and shown in Table 3.3 and Fig.3.7, where “-SI” dashed lines indicate SB simulation with tuned SB wave model. Except in range (3), most of the SI wave forces show good agreements with “CFD”. However, in range (3), Froude-Krylov and diffraction SI model mostly and especially in sway, roll, and yaw, fails to reproduce the complicated wave forces during the zigzag maneuver.
Figure 3.8 shows the SI results with tuning the parameters related to the Froude-Krylov, diffraction forces, and variation of maneuvering coefficients. The tuned parameters are listed in Table 3.4. As shown in Fig.3.8, in range (1), (2), and (4), "-SI" agreements with "CFD" wave-induced forces have little difference with previous results shown in Fig.3.7. Moreover, in the Table 3.4, the Froude-Krylov and diffraction related parameters show small difference with Table 3.3. However, in range (3), "-SI" dramatically improve the agreement with "CFD". This result indicates the variation of the maneuvering coefficients in waves should be taken into account in the SB wave model for the quantitative prediction.

The SI results tuning all components, Froude-Krylov, diffraction, maneuvering coefficients variations, and wave drift forces, are shown in Table 3.5 and Fig.3.9. In Fig.3.9, there are some minor difference from Fig.3.8 especially in surge and yaw. Focusing in the surge force at range (4), straight running in following waves, the surge wave force is slightly shifted down and fit with CFD compared with that in Fig.3.8 which seems to be the effect of the wave drift force tuning. Watching the yaw moment at range (2), course keeping maneuver in stern quartering waves, it is slightly shifted up and fit with CFD compared with that in Fig.3.8. Although the improvements caused by adding the wave drift are small, these minor differences could help quantitative prediction for ship motion in waves. Using these tuned parameters the ship motions in waves are predicted in the next section.

3.4 COMPARISONS AND DISCUSSIONS

3.4.1 Maneuvering Prediction in Moderate Waves

First, the free running in $H/\lambda=0.02$, $\lambda/L=1.2$ following waves are simulated and comparison between EFD, CFD, and SB results are shown in Fig.3.10. Herein "SB-SIcalm" dashed blue line
indicates the SB simulation result using original wave model shown in Subsection 3.2.1 with system identified coefficients shown in Table 2.11 Chapter 2. “SB-SIwave” black solid line shows the SB simulation using modified wave model, shown in Subsection 3.2.2, with using tuning parameters listed in Table 3.5 and Table 2.11. The surging amplitude errors and mean velocity errors compared with EFD are shown in Table 3.6. In Fig.3.10 and Table 3.6, CFD simulation shows remarkable agreements with EFD result. “SB-SIwave” using tuned modified wave model also shows good agreements with EFD while “SB-SIcalm” gives some error. The error of “SB-SIcalm” surging amplitudes is +25% while “SB-SIwave” merely shows -6% error. As shown in Fig.3.1, the original SB wave model overestimates the wave-induced force in surge. By adding wave drift component “SB-SIwave” successfully reproduces the normal speed loss within high degree of accuracy. Moreover the oscillating amplitude becomes reasonable with the tuning parameters for the Froude-Krylov force.

The simulation procedure for maneuvering (course keeping and zigzag) is as follows. First the model is accelerated to the target ship speed with 2DOF (heave and pitch). After the model reaches to the speed, the model is towed with constant speed for a while and released when the bow is located on the wave crest. The rudder control starts just after the model is released. In EFD, it should be noted that the towing time was very short because of the limitation of the facility’s size. Moreover it is 3DOF (heave, pitch and roll) during towing in EFD. The trajectories and time series comparisons during course keeping with $\chi_c=20\text{deg}$, nominal $Fr=0.20$ in $H/\lambda=0.02$, $\lambda/L=1.2$ are shown in Fig.3.11. Here the $r'$ and $p'$ is nondimensionalized with wave celerity $C_w$ and ship length. During the free running, the model is imposed with constant forward speed $Fr=0.20$ until 8.02 seconds then released to start course keeping maneuvers. In the trajectories in Fig.3.11, CFD and “SB-SIwave” show large course deviations from the target heading angle similar to EFD results while “SB-SIcalm” merely shows small deviation. From the time series comparisons, although the CFD and “SB-SIwave” show some discrepancy with EFD in roll rate, it is clear that “SB-SIcalm”
has larger discrepancy on the wave forces and wave drift effects compared to CFD and EFD. "SB-SI-calm" wave model overestimates the surge wave force and underestimates the sway, roll, and yaw wave forces. The SB-SI-wave shows better agreement with CFD than SB-SI-calm for both state variables and the trajectory. The wave drift effects can be seen in sway motion prediction which improves the prediction of the course deviation.

Figure 3.12 shows the comparison between EFD, CFD and SB 20/20 zigzag in following and quartering waves with nominal $Fr=0.20$, $H/\lambda=0.02$, $\lambda/L=1.2$. CFD results show good agreement with EFD for trajectory, surge, sway, and yaw motions. In roll motion, CFD seems overestimating the wave force compared to EFD as same as course keeping case. "SB-SI-calm" shows qualitative agreement with EFD maneuver but not quantitative. "SB-SI-calm" overestimates surge wave force and underestimates sway, and yaw wave forces. "SB-SI-calm" prediction of the zigzag trajectory is very close to the one predicted in calm water shown in Fig.2.12b. This is due to the fact that the maneuvering coefficients variations and drift forces induced by waves are neglected in "SB-SI-calm".

Overall CFD simulations shows reasonable results with EFD in the moderate wave condition ($H/\lambda=0.02$, $\lambda/L=1.2$). By using modified and tuned wave model, the new SB simulation provides better prediction compare to SB simulation using the original wave model. However the author's final target is to predict broaching using SB model and the wave conditions likely for broaching is more severe than this condition. In the next subsection SB model is applied for the broaching prediction in sever wave condition and higher ship speed.

3.4.2 Broaching Prediction

To avoid maneuvering instability including broaching, it is important to specify dangerous operational conditions such as dangerous auto pilot course and ship speed. Using the SB model, the
numerical simulation was executed for 4900 combinations of 70 auto pilot courses and 70 specified propeller revolutions represented as the nominal Fr, which is realized in calm water with the specified propeller revolutions. The modes of ship motions are categorized into 6 groups: "Harmonic motion", "Stable surf-riding", "Capsizing without broaching", "Capsizing due to broaching", "Broaching without capsizing", and "Not identified" as these modes. Elements for this classification are defined as follows (Umeda et al., 2006).

"Harmonic motion" can be identified if a value of $\tau$ exists which satisfies the following relationship within computational error.

$$\cos(x_i(t)) = \cos(x_i(t + \tau))$$

and

$$x_i(t) = x_i(t + \tau), i = 2, \ldots, 8$$

when

$$x = (x_1, x_2, \ldots, x_8)^T = (\xi_0, \lambda, u, v, p, r, \phi, \psi, \delta)^T$$

"Stable surf-riding" can be identified if all state variables tend to be constant. That is,

$$\dot{x}_i(t) = 0, i = 1, \ldots, 8$$

(3.55)

As shown in Fig.3.13, since the restoring vanishing angle of ONRT is 180deg because of the huge superstructure, capsizing cannot be occurred. However the serious roll angle should damage the crew and the ship herself. Therefore the case which satisfies the following condition is regarded as practical "capsizing" in this simulation study.

$$|\phi| > 100\degree$$

(3.56)

"Broaching" is defined as the phenomenon whereby a ship cannot maintain her course despite maximum steering effort. Therefore, if the following relationship is realized, we can regard it as broaching:

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The ship motion that does not satisfy all the above criteria within the calculated duration of 400 seconds in model scale is categorized as "not identified". Herein the simulated "Harmonic motion" is colored in green, "Stable surf-riding" in blue, "Capsize without broaching" in black, "Broaching without capsizing" in orange, "Capsize due to broaching" in red, and "Not identified" is shown with white blank in the instability maps. The experimental "Harmonic motion-EFD" is shown with circle blanked marker, "Surf-riding-EFD" with diamond, and "Broaching" with triangle. The initial condition for the SB simulation are computed based on sudden change concept (SCC) proposed by Umeda et al. (2002). Herein the course keeping maneuver starts when the ship situates at a wave trough during straight free running with nominal \( Fr=0.20 \) in pure following wave.

Figure 3.14 shows comparison between EFD free running results (Umeda et al., 2008) and SB simulation using identified maneuvering coefficients, shown in Table 2.11, and original wave model. Although the SB simulation results match with EFD results around small auto pilot course, there are large discrepancies in other area. There are large "Not identified" area, white area, can be seen around high speed and large auto pilot course conditions. For investigating "Not identified" area, Fig.3.15 shows SB time series with nominal \( Fr=0.45 \) and 30deg auto pilot course "A" and nominal \( Fr=0.37 \) and 25deg auto pilot course "B" conditions. In "A" solid line on Fig.3.15, the rudder reaches to its maximum rudder angle and roll angle almost reaches to 100deg. Focusing in the relation between rudder angle and yaw rate, the situation is very close to "Broaching" criteria shown in Eq. (3.56). Moreover due to the sharp turning, roll angle nearly reach to -100deg, the threshold of "Capsize" criteria Eq. (3.55). Even in another operational condition, nominal \( Fr=0.37 \) and 25deg auto pilot course, shown in dashed line "B" on Fig.3.15 shows similar time history with line "A". Thus "Not identified" white area should be recognized as dangerous situation.

\[
\begin{align*}
    r < 0, \dot{r} < 0 & \text{ at } \delta = \delta_{\text{max}} \\
    \text{or} & \\
    r > 0, \dot{r} > 0 & \text{ at } \delta = -\delta_{\text{max}}
\end{align*}
\]
Figure 3.16 shows a comparison between EFD free running results and SB simulation using identified maneuvering coefficients, shown in Table 2.11, and modified wave model using tuned parameters listed in Table 3.5. The instability area, “Capsize” black area, suddenly increases showing large discrepancy with EFD. Figure 3.17 shows SB time series with nominal $Fr=0.29$ and 5deg auto pilot course “A” and nominal $Fr=0.40$ and 5deg auto pilot course “B”. On line “A” of Fig.3.17, the condition categorized “Not identified” in Fig.3.16, seem to show “Harmonic motion”. However, with careful observation, it can be found that the all motion include sub-harmonic motion in which period is twice the wave encounter period. Spyrou (1997) explained this kind of yaw instability by transforming his SB model into the Mathieu equation. Moreover the peak of the motions seems slightly different in every encounter period which could be chaotic behavior described by Maki (2008). However these sub-harmonic motion and chaotic motion cannot be categorized as “Harmonic motion” with Eq. (3.54) criteria. On line “B” of Fig.3.17, although the roll angle exceeds 100deg in first period, the ship motion converge into “Stable surf-riding” after a while. This could be one of the reasons the SB simulation fails to predict the surf-riding threshold. However the ship maneuverability seems too unstable even in small auto pilot course. Going back to Eqs. (3.30)-(3.33), these equations indicates the variation will increase linearly with wave height. This assumption may cause this unnecessary instability; Son and Nomoto (1982) mentions the variation of the maneuvering coefficients is caused by the variation of the form of the wetted area due to wave. However the wetted area do not varied linearly with wave height.

The variation of the maneuvering coefficients modified to be constant with wave height. Figure 3.18 is renewed from Fig.3.16 with fixing maneuvering coefficient variation into same variation in $H/\lambda=0.02$ the same wave steepness when the parameters are identified. The SB simulation results dramatically changed from Fig.3.16 and most of instability part disappears and replaced by “Stable surf-riding” area. In Fig.3.8, variations of maneuvering coefficients are 2.5 (=0.05/0.02) times larger than those in Fig.3.16, and this fact causes such large difference in ship
motion which indicates the broaching prediction is very sensitive with the maneuvering coefficients variations.

In Fig.3.19 the SB simulation is using system identified maneuvering coefficients, shown in Table 2.11, and modified wave model using tuned parameters but excluding wave drift components listed in Table 3.4. Comparing with Fig.3.16 and Fig.3.19, the tendencies of mapping are quite similar. This result indicates the wave drift components are not so important to determine the ship motion mode although it has some benefit for estimating quantitative prediction as shown in Fig.3.11.

In Figure 3.20, the SB wave model excluding wave drift and variation of maneuvering coefficients components, tuned coefficients values are shown in Table3.3, is used for SB simulation. Although these tuning parameters show some discrepancies during the SI part in Fig.3.7, this simplest model well predicts both surf-riding and broaching thresholds.

The EFD captive model test results are applied to the SB simulation in Fig.3.21. Herein the rudder normal force variations are modified as Eq. (3.58) with Table 3.7, so that the variation fits with the captive model test results as show in Fig.3.22. The second term in Eq. (3.58) is added because the mean value of the rudder force seems to be smaller than that in calm water. During the captive model test, the rudder slightly emerged from water when ship CG situates in wave downslope in severe wave $H/\lambda=0.05$ as shown in Fig.3.23. This rudder emergence may cause the rudder force reduction.

$$\hat{F}_N = F_N \left(1 + \alpha_{FN} \xi w k \sin \left(k \xi_G + \epsilon_{FN}\right) \cdot \cos \psi \right) - \beta_{FN} \rho g \xi_w^2 A_{w} U^2 \cos \psi \cdot \sin \delta$$

Moreover the tuning parameters for the Froude-Krylov forces are estimated as shown in Fig.3.1 and the tuning values are listed on Table 3.8. However even using these tuning parameters estimated with the captive model tests, the broaching prediction fails in Fig.3.21.
3.5 CONCLUDING REMARKS

System identification technique using CFD free running data is shown to be an efficient approach for estimating maneuvering, rudder, and wave correction parameters in the SB model. In Chapter 2, it is shown the reasonable maneuvering coefficients can be obtained from a few set of CFD free running data in calm water. However the SB model still shows some error predicting the ship motion in waves. The original SB model clearly fails to predict the ship motions in waves which including the Froude-Krylov and diffraction forces as the wave forces and wave particle velocity as the wave effect on the propeller and rudder. Therefore the SB wave model is improved by adding correction parameters for Froude-Krylov, diffraction forces, and wave particle velocity. Moreover effects of wave drift forces and maneuvering coefficient variations due to waves are taken into account and these correction parameters are predicted by CLS using the extracted CFD wave forces/effects data. The extracted CFD wave forces/effects data are generated from the CFD free running data in waves and CFD forced motion data in calm water.

During the SI, it becomes clear that Froude-Krylov forces are dominant in the wave forces while the variation of maneuvering coefficients also plays important roles to predict large maneuver such as zigzag maneuvers in astern waves. Moreover the wave drift force itself is relatively small but has a certain role for the quantitative agreements with CFD extract wave forces.

In the moderate waves, the SB simulations using the new wave model and estimated wave correction parameters show better agreement with CFD than the SB simulations using the original wave model. The CFD simulations are validated with EFD free running results; CFD mostly shows quantitative agreement with EFD which shows possibility of replacing EFD free running trial with CFD simulations.
Although the SB simulations using the new wave mode show good agreement in moderate waves, broaching prediction has some difficulties. The correction parameters are estimated within moderate wave and operational conditions \( \frac{H}{\lambda}=0.02 \) and \( \frac{\lambda}{L}=1.0 \) with nominal \( Fr=0.20 \). However, the broaching happens in more severe wave and higher speed conditions. This gap could cause the difficulty of the broaching predictions. Meanwhile, during broaching prediction, there are several experiments found. First, the wave drift force component seems to be not so essential to determine the ship motion mode. Second, EFD Froude-Krylov and rudder correction parameters failed to predict broaching. Third, the maneuvering coefficients variation components show a crucial role to determine the ship motions mode and the linear assumptions respect to wave height seems to be inappropriate. Fourth, the simplest modified wave model, just tuning Froude-Krylov force and diffraction force, provides most reasonable prediction. However, in future, the CFD simulations, using for the SI, need to be conducted and validated for different ship speeds and wave conditions, including more severe condition with higher ship speed and severe wave condition near to broaching conditions so that more appropriate parameters for broaching prediction could be estimated.
TABLES AND FIGURES FOR CHAPTER 3

Table 3.1 shape and scale parameters for the weibull distribution on wave drift forces.

<table>
<thead>
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<th>Coef.</th>
<th>X</th>
<th>Y</th>
<th>N</th>
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</thead>
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<td>$\eta$</td>
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<td>9.44</td>
<td>7.22</td>
</tr>
<tr>
<td>$\mu$</td>
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</tr>
<tr>
<td>$\alpha$</td>
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<td>324.05</td>
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</table>

Table 3.2 SI tuning result for SB wave model with rudder inflow component.

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<thead>
<tr>
<th>Coef.</th>
<th>Orig</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_1$</td>
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<td>0.643</td>
</tr>
<tr>
<td>$\beta_2$</td>
<td>1.0</td>
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</table>

Table 3.3 SI tuning result for SB wave model with Froude-Krylov and diffraction components.

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<tr>
<td>$b_1$</td>
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<td>1.53</td>
</tr>
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</table>

<table>
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<tr>
<td>$c_2$</td>
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<td>$\varepsilon_c1$</td>
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<td>$d_1$</td>
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<td>$d_2$</td>
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<tr>
<td>$\varepsilon_d1$</td>
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</table>
Table 3.4 SI tuning result for SB wave model with Froude-Krylov, diffraction, and maneuvering coefficients variation components.

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<th>SI</th>
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<td>$d_1$</td>
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<tr>
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Table 3.5 SI tuning result for SB wave model with Froude-Krylov, diffraction, maneuvering coefficients variation, and wave drift components.

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<th>Coef.</th>
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<th>SI</th>
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<tbody>
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<td>$c_1$</td>
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<td>1.51</td>
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<tr>
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<td>$\alpha_Y$</td>
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Table 3.6 Comparisons of surging amplitude and mean velocity normalized with EFD values during straight free running in $H/\lambda=0.02$, $\lambda/L=1.2$ following wave with nominal $Fr=0.20$.

<table>
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<tr>
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<th>Surging amplitude</th>
<th>Mean velocity</th>
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<tr>
<td>CFD</td>
<td>0.97</td>
<td>1.00</td>
</tr>
<tr>
<td>SB-SICalm</td>
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</tr>
<tr>
<td>SB-SIwave</td>
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Table 3.7 Tuning parameters for Eq.3.56 rudder model estimated with captive model tests

<table>
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<tr>
<td>( \alpha_{FN} )</td>
<td>0.0</td>
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</tr>
<tr>
<td>( \beta_{FN} )</td>
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</tr>
<tr>
<td>( \epsilon_{FN} )</td>
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</table>

Table 3.8 Tuning parameter for Froude-Krylov and diffraction forces estimated with captive model tests.

<table>
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<tr>
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<th>EFD</th>
<th>Coef.</th>
<th>Orig</th>
<th>EFD</th>
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<td>( c_1 )</td>
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<td>0.657</td>
</tr>
<tr>
<td>( \varepsilon_{a1} )</td>
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<td>-0.171</td>
<td>( c_2 )</td>
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<td>0.0</td>
</tr>
<tr>
<td>( b_1 )</td>
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<td>( \varepsilon_{c1} )</td>
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<td>( b_2 )</td>
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<td>( d_1 )</td>
<td>1.0</td>
<td>1.21</td>
</tr>
<tr>
<td>( \varepsilon_{b1} )</td>
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<td>-0.383</td>
<td>( d_2 )</td>
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<td>0.0</td>
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<tr>
<td>( \varepsilon_{d1} )</td>
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<td>-0.246</td>
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<td></td>
<td></td>
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</table>
Fig. 3.1 Comparison between EFD wave-induced forces and Froude-Krylov forces with $\chi=30\text{deg}$ in $H/\lambda=0.025$, 0.05 and $\lambda/L=1.25$. 

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Fig. 3.2 Maximum value of the real part of the solution of equation (3.27) with a $H/\lambda=0.05$, and $\lambda/L=1.25$.

Fig. 3.3 Drift force in regular following wave aspect to ship wave ratio and heading angle with $Fr=0.15$ in $H/\lambda=0.02$.

Fig. 3.4 Variation of rudder normal force during captive rudder force test with $Fr=0.35$, $\delta=10$deg in following wave $H/\lambda=0.02$, 0.05, and $\lambda/L=1.20$. 
Fig. 3.5 Wave force comparison between CFD and SB-Orig with Froude-Krylov and diffraction component with $H/\lambda=0.02, \lambda/L=1.2$; (1) captive running with $\chi=20$deg, $Fr=0.20$; (2) course keeping free running with $\chi_c=20$deg, nominal $Fr=0.20$; (3) 20/20 zigzag free running with nominal $Fr=0.20$; (4) free running in following waves with nominal $Fr=0.20$. 

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Fig. 3.6 Rudder normal force comparison between CFD, SB original wave inflow effect and SB-SI with and without wave inflow component with $H/\lambda=0.02$, $\lambda/L=1.2$; (1) captive running with $\chi=20$deg, $Fr=0.20$; (2) course keeping free running with $\chi_c=20$deg, nominal $Fr=0.20$ (3) 20/20 zigzag free running with nominal $Fr=0.20$; (4) free running in following waves with nominal $Fr=0.20$. 
Fig. 3.7 Wave force comparison between CFD and SB-SI with Froude-Krylov and diffraction components with $H/\lambda=0.02$, $\lambda/L=1.2$; (1) captive running in $\chi=20\text{deg}$, $Fr=0.20$; (2) course keeping free running with $\chi_c=20\text{deg}$, nominal $Fr=0.20$ (3) 20/20 zigzag free running with nominal $Fr=0.20$; (4) free running in following waves with nominal $Fr=0.20$. 
Fig. 3.8 Wave force comparison between CFD and SB-SI with Froude-Krylov, diffraction, and maneuvering coefficients variation components in $H/\lambda=0.02$, $\lambda/L=1.2$; (1) captive running with $\chi=20\deg$, $Fr=0.20$; (2) course keeping free running with $\chi=20\deg$, nominal $Fr=0.20$; (3) 20/20 zigzag free running with nominal $Fr=0.20$; (4) free running in following waves with nominal $Fr=0.20$. 
Fig.3.9 Wave force comparison between CFD and SB-SI with Froude-Krylov, diffraction, maneuvering coefficients variation, and wave drift components in $H/\lambda=0.02$, $\lambda/L=1.2$; (1) captive running with $\chi=20\text{deg}$, $Fr=0.20$; (2) course keeping free running with $\chi_c=20\text{deg}$, nominal $Fr=0.20$; (3) 20/20 zigzag free running with nominal $Fr=0.20$; (4) free running in following waves with nominal $Fr=0.20$. 
Fig. 3.10 Comparisons of surge velocity between EFD, CFD, SB simulation with original wave model, and SB simulation with modified wave model using tuning parameters during straight free running in $H/\lambda=0.02$, $\lambda/L=1.2$ following wave with nominal $Fr=0.20$. 
Fig. 3.11 Trajectory and time series during course keeping free running with $\chi_c=20\text{deg}$, nominal $Fr=0.20$ in $H/\lambda=0.02$, $\lambda/L=1.2$. 
Fig. 3.12 Trajectory and time series during 20/20 zigzag free running with nominal $Fr=0.20$ in $H/\lambda=0.02$, $\lambda/L=1.2$. 
Fig. 3.13 Restoring arm of ONRT in calm water with GM=0.0424m

Fig. 3.14 Ship motion comparison between free running experiments and SB using original wave model in $H/\lambda=0.05, \lambda/L=1.25$. 
Fig. 3.15 Time series of SB simulations using original wave model in $H/\lambda=0.05$, $\lambda/L=1.25$; (A): nominal $Fr=0.45$, 30deg auto pilot course, (B): nominal $Fr=0.37$, 25deg auto pilot course.
Fig. 3.16 Ship motion comparison between free running experiments and SB using modified and tuned wave model in $H/\lambda = 0.05$, $\lambda/L = 1.25$. 
Fig. 3.17 Time series of SB simulations using modified and tuned wave model in $H/\lambda=0.05$, $\lambda/L=1.25$; (A): nominal $Fr=0.40$, 5deg auto pilot course, (B): nominal $Fr=0.29$, 5deg auto pilot course.
Fig.3.18 Ship motion comparison between free running experiments and SB using modified and tuned wave model with constant maneuvering coefficients variation in $H/\lambda=0.05$, $\lambda/L=1.25$. 
Fig. 3.19 Ship motion comparison between free running experiments and SB using modified and tuned wave model excluding wave drift component in $H/\lambda = 0.05$, $\lambda/L = 1.25$. 
Fig. 3.20 Ship motion comparison between free running experiments and SB using modified and tuned wave model excluding wave drift and maneuvering coefficients variations components in $H/\lambda=0.05$, $\lambda/L=1.25$. 


Fig. 3.21 Ship motion comparison between free running experiments and SB using modified and tuned wave model using captive model experimental results in $H/\lambda=0.05$, $\lambda/L=1.25$.

Fig. 3.22 Comparison between captive rudder tests result and curve fitted with Eq. 3.56 with $Fr=0.35$, $\delta=10\text{deg}$ in following wave $H/\lambda=0.02$, 0.05, and $\lambda/L=1.20$. 
Fig. 3.23 Rudder emergence during captive rudder force test with $Fr=0.35$, in $H/\lambda=0.05$ and $\lambda/L=1.2$ following wave.
CONCLUDING REMARKS

In this thesis, SI technique, well known in control engineering, were applied into ship maneuvers in calm water, following and quartering waves with using CFD free running data. The CFD simulation could provide attractive and fruitful data. The one the author focuses on was the hydrodynamic force acting on the ship during the free running simulation. By comparing the hydrodynamic force directly, better and advanced results were expected than previous SI researches using the free running ship motions in calm water.

In Chapter 2, EFD free running in model scale was executed in IIHR wave basin and NRIFE seakeeping and maneuvering basin. In the IIHR basin, the ship motion was tracked with 6DOF visual motion capture system. The rudder normal force was measured with strain gage pasted on the rudder shaft during the free running in the NRIFE basin. The CFD free running simulation was realized using CFD-Ship-Iowa v4, single-phase level set with dynamic overset grids. The turning circle, zigzag, and large angle zigzag free running maneuvers in calm water were executed in both EFD and CFD. The CFD free running simulation showed remarkable agreement with EFD free running motions and the rudder normal force. These results indicate the possibility that the CFD free running simulation could replace the experiments. Meanwhile the original SB free running simulation using a 4DOF mathematical model, with the maneuvering coefficients estimated from captive tests or empirically, showed certain errors with EFD results. Therefore SI using EKF and CLS was proposed to provide reasonable SB simulation by tuning the maneuvering coefficients. However the coefficients estimated from EKF showed large discrepancy from the ones estimated from captive model test while the coefficients estimated from CLS gave reasonable results. Moreover the SB free running simulation using CLS identified maneuvering coefficients showed much closer result to the EFD than the simulations using EKF maneuvering coefficients. In CLS, by parallel processing the several CFD free running results, the estimated coefficients became robuster than using one free running data. Summarizing the SI results in calm water, the SB free
running simulations, using maneuvering coefficients estimated with CLS using CFD parallel processed free running data, provided best agreement with several EFD results and also showed better agreement than SB simulation using the hull maneuvering coefficients estimated from captive model tests and empirically obtained rudder coefficients.

In Chapter 3, the same SI technique, using CLS and CFD free running data, was applied into following and quartering wave cases to modify the wave force modeling. To extract the wave force from the total hydrodynamic force during free running in the waves, two types of CFD free running were required. One was usual free running simulation in moderate waves and the other was the forced motion test with imposing exactly the same motion as the free running. The wave forces were estimated as the difference between the total force of the first and second simulations. Meanwhile the original SB wave model, taking the Froude-Krylov, diffraction forces and the wave particle effect on rudder into accounts, showed some disagreements with the captive model experiments and CFD extracted wave force. Therefore the SB wave model was modified by adding some wave effects, maneuvering coefficients variations and wave drift forces, and tuning parameters for the each wave components. Those tuning parameters were identified using CLS and CFD extracted wave forces. The free running simulations, straight running, course keeping, and zigzag in moderate following and quartering waves were executed with EFD, CFD, SB using original wave model, and SB using modified wave model with identified parameters. First the CFD simulations were well validated with EFD. The SB simulation using modified wave model provided better agreements with EFD than SB using original wave model. For a further step, the SB simulations were executed to predict broaching threshold with 4900 operational condition (combination of auto pilot course and nominal $Fr$) in severe wave conditions. Here the both original SB model and identified SB model had some difficulties predicting the broaching thresholds. However the identified SB model showed unstable maneuvering behaviors, which were not exactly defined as broaching, and indicated the amplitudes of maneuvering coefficients variations were very sensitive to
predict such unstable behavior. Moreover the SB wave model just tuned in Froude-Krylov and
diffraction forces gave reasonable surf-riding and broaching thresholds comparable to EFD free
running results. The CFD simulation data in severe wave conditions to be used for the SI could
facilitate to provide more suitable parameters for broaching prediction.

There were several SI researches for calm water maneuvers. However most of them using
EFD free running ship motion and none of them use CFD free running results. Moreover few
researches can be found applying SI into wave cases. Although, there are some difficulties
remaining to predict broaching in severe waves, this thesis might give a first handhold for predicting
ship maneuvers without any experiments. Thus this research topic is still in the infancy, many
discussions are received for the development.

Future tasks to be investigated can be suggested below

- Executing CFD free running simulations in severe waves close to broaching condition for
  estimating suitable parameters for broaching prediction;

- Applying the proposed SI technique into many other ships, including commercial and
  unconventional ships for the validation;

- Investigating more sophisticated SI process (e.g. combining CFD captive and free running
  simulation to extract wave-induced force).
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I would like to express my deep gratitude to Associate Professor Naoya Umeda for his patient guidance, enthusiastic encouragement and useful critiques of this research work. Moreover I appreciate Prof. Umeda providing valuable opportunities to attend international conferences and worthwhile stay at the University of Iowa.

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Finally, I wish to thank my family for their support and encouragement throughout my study.
APPENDIX A: EXTENDED KALMAN FILTERING (Raol et al., 2004)

The nonlinear system can be expressed with the following set of equations

\[ x(k) = f[x(k), u(k), \Theta] + w(k) \]  (A.1)

where \( x(k) \) is true state variables, \( u(k) \) is control variables and \( w(k) \) is process noise. \( \Theta \) is the vector of unknown parameters given by

\[ \Theta = [x_0, \beta] \]  (A.2)

where \( x_0 \) represents state variables at time \( k=0 \) and \( \beta \) represents parameters in the mathematical model defining the system characteristics.

Observation equation can be expressed with Eqs. (A.3) and (A.4).

\[ y(k) = h[x(k), u(k), \Theta] \]  (A.3)

\[ z(k) = y(k) + v(k) \]  (A.4)

where \( z(k) \) is observation variables affected by \( h \): the observation model which maps the true state space into the observation space, and observation noise \( v(k) \).

The following assumptions are made on the process noise \( w(k) \) and observation noise \( v(k) \):

\[ E[w(k)] = 0; \quad \text{Cov}[w(k)] = Q \]  (A.5)

\[ E[v(k)] = 0; \quad \text{Cov}[v(k)] = R \]  (A.6).

These mean that the noises are zero-mean and white Gaussian with \( Q \) and \( R \) as the covariance matrix of these noises.

The new augmented state vector is defined by

\[ x^r = [x^T \quad \Theta^T] \]  (A.7)

so that
\[ \dot{x} = \begin{bmatrix} f(x, u, t) \\ 0 \end{bmatrix} + \begin{bmatrix} G \\ 0 \end{bmatrix} w(k) \]  

(A.8)

\[ \dot{x} = f_u(x, u, t) + G_u w(k) \]  

(A.9)

\[ y(k) = h_u(x, u, t) \]  

(A.10)

\[ z_u(k) = y(k) + v(k), \ k = 1, \ldots, N \]  

(A.11)

where

\[ f_u'(t) = \begin{bmatrix} f' \\ 0' \end{bmatrix}; \]  

(A.12)

\[ h_u'(t) = \begin{bmatrix} h' \\ 0' \end{bmatrix}; \]  

(A.13)

\[ G_u' = \begin{bmatrix} G' \\ 0' \end{bmatrix}; \]  

(A.14).

The estimation algorithm is obtained by linearizing Eqs. (A.1) and (A.2) around the prior/current best estimate of the state at each time and then applying the Kalman filtering algorithm to the linearized model. The linearized system matrices are defined as

\[ A(k) = \left. \frac{\partial f_u}{\partial x} \right|_{x=x(k), u=u(k)} \]  

(A.15)

\[ H(k) = \left. \frac{\partial h_u}{\partial x} \right|_{x=x(k), u=u(k)} \]  

(A.16).

And the state transition matrix is given by

\[ \phi(k) = \exp[-A(k) \Delta t] \]  

(A.17)

where

\[ \Delta t = t(k+1) - t(k) \]  

(A.18).

The filtering algorithm is given in two parts: (i) time propagation and (ii) measurement update. In the above equations, we notice the time-varying nature of $A$, $H$ and $\phi$, since they are evaluated at the current state estimate, which varies with time $k$. 
(i) **Time propagation**

The states are propagated from the present state to the next time instant.

The predicted state is given by

$$\tilde{x}(k+1) = \tilde{x}(k) + \int_{k}^{k+1} f(\tilde{x}(k), u(k), t(k)) \, dt$$  \hspace{1cm} (A.19)

In the absence of knowledge of process noise, Eq. (A.19) gives the predicted estimate of the state based on the initial/current estimate. The Runge-Kutta integrations are used in Eq. (A.19). The covariance matrix for state error (here state is $x_a$) propagate from instant $k$ to $k+1$ as

$$\bar{P}(k+1) = \phi(k)\bar{P}(k)\phi^T(k) + G_a(k)QG_a^T(k)$$  \hspace{1cm} (A.20)

Here $\bar{P}(k+1)$ is the predicted covariance matrix for the instant $k+1$, $G_a$ is the process noise related coefficient matrix, and $Q$ is the process noise covariance matrix.

(ii) **Measurement update**

The EKF updates the predicted estimates by incorporating the measurement as and when they become available as follow:

$$\tilde{x}(k+1) = \tilde{x}(k+1) + K(k+1)[z_{a}(k+1) - h_a(\tilde{x}(k+1), u(k+1), t(k))]$$  \hspace{1cm} (A.21)

where $K$ is the Kalman gain matrix.

The covariance matrix is updated using the Kalman gain and the linearized measurement matrix from the predicted covariance matrix $\bar{P}(k+1)$.

The Kalman gain expression is given as

$$K(k+1) = \bar{P}(k+1)H^T(k+1)[H(k+1)\bar{P}(k+1)H^T(k+1) + R]^{-1}$$  \hspace{1cm} (A.22)

A posteriori covariance matrix expression is given as
\[ \hat{P}(k+1) = [I - K(k+1)H(k+1)]\hat{P}(k+1) \]  

(A.23).

Here the UD factorization can also be conveniently used in the EKF, since Eqs. (A.22) and (A.23) can be put in the factorization form and processed.
APPENDIX B: GENERALIZED REDUCED GRADIENT ARGORITHM (Pike, 2001)

Optimize: \( y(x) \)
Subject to: \( f_i(x) = 0 \) for \( i = 1, 2, ..., m \) \hfill (B.1).

The subject equations are modified to equality equations by adding slack variables.

To develop this method the independent variables are separated into basic and nonbasic ones. There are \( m \) basic variables \( x_b \), and \(( n - m )\) nonbasic variables \( x_{nb} \), i.e.:

\[ f_i(x) = f_i(x_b, x_{nb}) = 0 \quad \text{for} \quad i = 1, 2, ..., m \] \hfill (B.2).

Indicating the solution of \( x_b \) in terms of \( x_{nb} \) from Eq. (B.2) gives:

\[ x_i = \tilde{f}_i(x_{nb}) \quad \text{for} \quad i = 1, 2, ..., m \] \hfill (B.3).

In nonlinear programming, the nonbasic variables are used to compute the values of the basic variable and are manipulated to obtain the optimum of the model. The model can be thought of as a function of the nonbasic variables only, if the constraint Eq. (B.3) are used to eliminate the basic variables, i.e.:

\[ y(x) = y(x_b, x_{nb}) = y[\tilde{f}_i(x_{nb}), x_{nb}] = Y(x_{nb}) \] \hfill (B.4).

Expanding the above equation in a Taylor series about \( x_k \) and including only the first order terms give:

\[ \sum_{j=1}^{n} \frac{\partial y(x_k)}{\partial x_{j,b}} dx_{j,b} + \sum_{j=m+1}^{n} \frac{\partial y(x_k)}{\partial x_{j,ne}} dx_{j,ne} = \sum_{j=m+1}^{n} \frac{\partial Y(x_k)}{\partial x_{j,ne}} dx_{j,ne} \] \hfill (B.5).

In matrix notation Eq. (B.5) can be written as:

\[ \nabla' Y(x_k) dx_{ne} = \nabla' y_b(x_k) dx_{b} + \nabla' y_{nb}(x_k) dx_{nb} \] \hfill (B.6).

A Taylor series expansion of the constraint Eq. (B.2) gives an equation that can be substitute into Eq. (B.6) to eliminate the basic variables.
\[
\sum_{j=1}^{n} \frac{\partial f_j(x)}{\partial x_j} \, dx_{j,i} + \sum_{j=1}^{n} \frac{\partial f_j(x)}{\partial x_j} \, dx_{j,0} = 0 \quad \text{for } i = 1, 2, \ldots, m
\]  
\hspace{1cm} (B.7).

Or in matrix for Eq. (B.7) is:
\[
\begin{bmatrix}
\frac{\partial f_1(x)}{\partial x_1} & \cdots & \frac{\partial f_n(x)}{\partial x_n} \\
\vdots & \ddots & \vdots \\
\frac{\partial f_m(x)}{\partial x_1} & \cdots & \frac{\partial f_m(x)}{\partial x_m}
\end{bmatrix}
\begin{bmatrix}
dx_{1,0} \\
\vdots \\
dx_{n,0}
\end{bmatrix}
+ \begin{bmatrix}
\frac{\partial f_1(x)}{\partial x_1} & \cdots & \frac{\partial f_n(x)}{\partial x_n} \\
\vdots & \ddots & \vdots \\
\frac{\partial f_m(x)}{\partial x_1} & \cdots & \frac{\partial f_m(x)}{\partial x_m}
\end{bmatrix}
\begin{bmatrix}
dx_{M+1,0} \\
\vdots \\
dx_{n,0}
\end{bmatrix}
= 0
\hspace{1cm} (B.8).
\]

The following equation defines \( B_b \) as the matrix of \( f_i \) associated with the basic variables and \( B_{nb} \) as the matrix associated with the nonbasic variables, i.e.:
\[
B_b dx_b + B_{nb} dx_{nb} = 0
\hspace{1cm} (B.9).
\]

This is a convenient form of Eq. (B.8) which can be used to eliminate \( dx_b \) from Eq. (B.6). Solving Eq. (B.9) for \( dx_b \) gives:
\[
dx_b = -B_b^{-1} B_{nb} dx_{nb}
\hspace{1cm} (B.10).
\]

Substituting Eq. (B.10) into (B.6) gives:
\[
\nabla^T y(x_k) dx_{nb} = -\nabla^T y_b(x_k) B_b^{-1} B_{nb} dx_{nb} + \nabla^T y_{nb}(x_k) dx_{nb}
\hspace{1cm} (B.11).
\]

Eliminating \( dx_{nb} \) from Eq. (B.11), the equation for the reduced gradient \( y(x_k) \) is obtained.
\[
\nabla^T y(x_k) = -\nabla^T y_b(x_k) B_b^{-1} B_{nb} + \nabla^T y_{nb}(x_k)
\hspace{1cm} (B.12).
\]

Knowing the value of the first partial derivatives of the dynamical model and constraint equations at a feasible point, the reduced gradient can be computed by Eq. (B.12). This shall satisfy the model and the constraint equations. The generalized reduced gradient method use the reduced gradient to locate better value of the model in the same way as unstrained gradient search using Lagrange multipliers, i.e.:
There is the parameter of the line along the reduced gradient. A line search is used to locate the optimum of $Y(x_{nb})$ along the reduced gradient line from $x_k$.

In taking trial step as $a$ is varied along the generalized reduced gradient line, the matrices $B_b$ and $B_{nb}$ must be evaluated along with the gradients $\nabla y_b(x_b)$ and $\nabla y_{nb}(x_b)$. This requires knowing both $x_{nb}$ and $x_b$ at each step. The values of $x_{nb}$ are obtained from (B.13). However, Eq. (B.2) must be solved for $x_b$; and frequency, this must be done numerically using the Newton-Raphson method. The Newton-Raphson algorithm in terms of the nomenclature for this procedure is given by the following equation.

$$x_{a+1,b} = x_{a,b} - B_b^{-1}f(x_{a,b})$$

(B.14)

Here the value of the root of the constraint Eq. (B.2) are being sought for $x_b$, having computed $x_{nb}$ from Eq. (B.13). Thus, the derivatives computed for the generalized reduced gradient’s $B_b$ matrix can be used in the Newton-Raphson root seeking procedure also.
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NOMENCLATURE

$a_{1-4}$ Tuning parameters for wave force amplitude in surge

$AE$ Aft end

$A/L$ Advance for turning circle trial

$a_H$ Interaction factor between hull and rudder

$A_R$ Rudder area

$b_{1-4}$ Tuning parameters for wave force amplitude in sway

$B(x)$ Sectional breadth

$c_{1-4}$ Tuning parameters for wave moment amplitude in roll

$C_b$ Brock coefficient

$c_w$ Wave celerity

$C_{XYN}$ Wave drift coefficients

$D$ EFD result value

$d_{1-4}$ Tuning parameters for wave moment amplitude in yaw

$d(x)$ Sectional draft

$D_{max}$ Maximum EFD result value

$D_{min}$ Minimum EFD result value

$D_p$ Propeller diameter

$f_{i01}$ IMO criteria function for 1st overshoot angle of 10/10 zigzag trial

$f_{i02}$ IMO criteria function for 2nd overshoot angle of 10/10 zigzag trial

$FE$ Fore end

$F_N$ Rudder normal force

$Fr$ Froude number

$g$ Gravitational acceleration

$GM$ Metacentric height

$GZ$ Righting arm

$H$ Wave height

$I_x$ Moment of inertia in roll
\( I_{xy} \)  
Moment of inertia in roll and pitch  
\( I_{xz} \)  
Moment of inertia in roll and yaw  
\( I_y \)  
Moment of inertia in pitch  
\( I_{yz} \)  
Moment of inertia in pitch and yaw  
\( I_z \)  
Moment of inertia in yaw  
\( J \)  
Advanced coefficient  
\( J_x \)  
Added moment of inertia in roll  
\( J_z \)  
Added moment of inertia in yaw  
\( k \)  
Wave number  
\( K \)  
Roll moment on body  
\( K_P \)  
Derivative of roll moment with respect to roll rate  
\( K_Q \)  
Torque coefficient  
\( K_R \)  
Rudder moment in roll  
\( K_r \)  
Derivative of roll moment with respect to yaw rate  
\( K_{rrr} \)  
Derivative of roll moment with respect to cubed yaw rate  
\( K_s \)  
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\( K_{FK}^{w} \)  
Froude-Krylov moment in roll  
\( K_\phi \)  
Derivative of roll moment with respect to roll angle  
\( L \)  
Ship length  
\( L_R \)  
Lever of rudder center from center of gravity  
\( l_R \)  
Longitudinal position of rudder center from center of ship gravity  
\( m \)  
Ship mass  
\( M \)  
Pitch moment on body
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\( t_R \)  
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\( u_R \)  
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\( u_T \)  
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\( u_w \)  
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Derivative of surge force with respect to squared sway velocity

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Diffraction force in surge

\( X_{FK_w} \)  
Froude-Krylov force in surge

\( Y \)  
Sway force on body

\( y^+ \)  
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\( y_{CG} \)  
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\( \varepsilon_{FN} \)  Tuning parameter for phase of rudder force variation

\( \phi \)  Roll angle

\( \gamma_R \)  Flow straightening coefficient

\( \eta \)  Shape parameter for the Weibull distribution

\( \kappa_{yy} \)  Radius of gyration in pitch

\( \lambda \)  Wave length

\( A_R \)  Rudder aspect ratio

\( \mu \)  Scale parameter for the Weibull distribution

\( \nu \)  Kinematic viscosity

\( \rho \)  Water density

\( \omega \)  Wave frequency

\( \omega_e \)  Wave encounter frequency

\( \psi_c \)  Desired course

\( \xi_0 \)  Longitudinal position of center of ship gravity from a wave trough

\( \xi_w \)  Wave amplitude
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