# CHAPTER 1 INTRODUCTION

Predictions of ship-maneuvering performance have been one of the most challenging topics in ship hydrodynamics research because of its highly complex unsteady and non-linear nature. Due to the lack of analytical methods for ship maneuverability, maneuvering predictions have traditionally relied on either empirical methods using database or experimental model tests. The empirical database methods usually use mathematical model and maneuvering coefficients based on either empiricism or mixed semi-theoretical and semi-empirical methods. The methods include such as the cross flow drag model (Hooft, 1994), database regression methods (such as, Wagner Smitt, 1971, Norrbin, 1971, Inoue et al. 1981, Clarke et al., 1983, and Oltmann, 1992), the Kijima method (Kijima et al., 2003), and more recently the combined slender body and the cross flow drag theories (Martinussen et al., 2008, and Toxopeus et al., 2008). The empirical database methods are relatively simple and quick to use, however, typically these methods are only effective when main dimensions of the ship of interest are in the database and the accuracy of predictions is often limited by the sensitivity of the parameters used in the regressions. Experimental model test method includes free and captive model tests. Free model test (e.g., Martinussen and Linnerrud, 1987) is using a scaled model that is self-propelled and –steered. For the test, the model performs definitive maneuvers such as spiral, zigzag, or turning maneuvers. Free model test is usually conceived as the closest to reality (except for scale effect) as no mathematic model or assumption is made. However, usually free model test yields only the final results/information, thus the test results may be less insightful to the individual maneuvering factors. Recent studies to extract more information from the free model test results, so-called the system identification method, show progresses by using either mathematical models (Oltmann, 2000, Depascale et al., 2002, Viviani et al., 2003, Aryszuk, 2003, and Yoon et al., 2003) or a Neural Network logic (Hess and Faller, 2000, Moreira and Soares, 2003, and Hess et al., 2008). On the other hand, captive model test may comprise of oblique towing test, rotating arm test (or circular motion mechanism, CMT), and planar motion mechanism (PMM) test (Gertler, 1966, Strøm-Tejsen, J. and Chislett, M.S., 1966). Captive model test is based on mathematical modeling of the ship motion equations, from which hydrodynamic derivatives (or maneuvering coefficients) of the mathematic model are determined experimentally.

Recently, computational fluid dynamics (CFD) based methods have shown promise for computing complex hydrodynamic forces for steady and unsteady maneuvers. Significant progress has been made toward this goal by applying Reynolds-averaged Navier-Stokes (RANS)-based CFD codes to static maneuvers (Tahara et al., 2002, Simonsen and Stern, 2003a, b and c, Cura Hochbaum and Vogt, 2003, Toxopeus, 2006, Simonsen et al., 2006, Simonsen and Stern, 2006, Carrica et al., 2006, Xing et al., 2007, Bhushan et al., 2007), to dynamic maneuvers (Kim and Rhee, 2002, Burg and Marcum, 2003, Di Mascio and Broglia, 2003, Di Mascio et al., 2004, Broglia et al., 2006, Cura-Hochbaum, 2006, Dimascio et al., 2007, Wilson et al., 2007, Sakamoto et al., 2009), and to trajectories (Pankajakshan et al., 2002, Jensen et al. 2004) or more direct six-degree-of-freedom (6DOF) maneuvering predictions (Carrica and Stern, 2008), with generally good agreements with experimental data. The CFD simulations provide more insight to the entire flow structure around the hull, and the simulation results can be used to compute the forces and moment acting on the hull and to determine hydrodynamic derivatives. Although RANS methods are considered promising, they are still challenged by difficulties associated with time-accurate schemes, 6DOF ship motions, the implementations of complex hull appendages and propulsors, and environmental effects such as wind, waves, and shallow water. Furthermore, to be accepted as a credible simulation tool by end-users such as industry or navy, and ultimately to be used for simulation-based design (SBD), they are required to be verified and validated (V&V, Stern et al., 2001) for practical ship geometries and conditions. V&V and benchmarking of unsteady RANS for ship hydrodynamics, however, as well remains a challenge due in part to lack of available experimental fluid dynamics (EFD) validation data, especially for ship motions and maneuvering.

To meet the demands on EFD validation data, procurement of detailed global and local flow benchmark EFD data for fluid physics, model development, and validation of RANS ship hydrodynamics CFD codes has been an ongoing effort since 1970's. Recent efforts have focused on modern tanker (KVLCC1 and KVLCC2), container (KCS), and surface combatant (DTMB 5415) hull forms, as per the Gothenburg 2000 Workshop (Larsson et al., 2003) and Tokyo 2005 Workshop (Hino et al., 2005). Kim et al. (2001) and Lee et al. (2003) provided steady-flow data for KVLCC2 and KCS. For DTMB 5415, data procurement has been part of an international collaboration between IIHR[1], INSEAN[2], and DTMB[3], more than 10 years. Initially steady-flow data were procured, including rigorous uncertainty analysis (Longo et al., 2005), identification of facility biases (Stern et al., 2000, and Stern et al., 2005), mean flow map (Olivieri et al, 2001), steady nominal wake PIV (Gui et al, 2001a), and propeller-hull interaction (Ratcliffe et al., 2001). Subsequently, unsteady-flow data was procured, including wave breaking (Olivieri et al., 2004), forward-speed diffraction forces, moment, and wave pattern (Gui et al., 2001b and 2002) and phase-averaged PIV nominal wake (Longo et al., 2007) and pitch and heave tests (Irvine et al., 2008) in regular head waves. More recent effort has been made at the SMMAN 2008 Workshop (Stern et al., 2008). The purpose of the workshop was to benchmark the prediction capabilities of different ship maneuvering simulation methods including the systems- and CFD based methods through comparisons with results. For SIMMAN 2008, the same tanker (KVLCC), container ship (KCS), and

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surface combatant (DTMB 5415) hull forms are used as for the earlier Gothenburg 2000 and Tokyo 2005 Workshops, however, the focus has been on benchmarking the maneuvering prediction capability. The international collaboration for captive and free model EFD validation data involves 11 International Towing Tank Conference (ITTC) institutions and ten countries from Europe, Asia, and America. The benchmark EFD data included PMM and free model tests for KVLCC, PMM/CMT and free model tests for KCS, and free mode test with an appended model and PMM test with bare model for DTMB 5415. Particularly, the PMM test for DTMB bare model (the present work) was in collaboration between IIHR, FORCE[4], and INSEAN including uncertainty analysis. The SIMMAN 2008 Workshop results demonstrated the potential of RANS simulations to provide data fully equivalent to PMM/CMT model test data and a possibility of direct 6DOF maneuvering simulations. However, the workshop has also concluded that more EFD benchmark data is needed including uncertainty analysis for more quantitative verification and validation.

PIV studies for ship velocity fields have been conducted for various specialized purposes, may or may not be directly intended as benchmark data for RANS simulations (mainly as per reviewed by Longo et al., 2004). Dong et al. (1997) measured the bow flow of a 3.05 m ship model in a towing tank, from which the authors investigated the cross plane vector fields and considerable vorticity entrained into the toe of the bow wave. Roth et al. (1999) studied the mean and turbulent bow flow of a 7.01 m ship model including convergence test. Paik et al. (2004) conducted PIV analysis of flow around a container ship model with a rotating propeller. PIV studies have also been made for submarine applications. Fu et al. (2002) studied dominant cross-flow separation induced by a 5.18 m submarine model in a turn. Atsavapranee et al. (2004) presented stereo PIV

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measurements performed on a submarine towed with steady drift angle. Many of PIV studies as well have been performed for propeller wake flow. Di Felice and De Gregorio (2000) investigated the turbulent wake of a 5.41 m ship model equipped with two, four-bladed propellers in a circulating water channel, at a range of phase angles. Calcagno et al. (2002) used stereoscopic PIV in a circulating water tunnel to investigate the phase-averaged turbulent propeller wake flow of a 6.096 m ship model equipped with a 0.222 m diameter, 5-bladed propeller. Contron et al. (2000) and Di Felice et al. (2000) investigated the phase-averaged wake flow of two, four-bladed propellers in a cavitation tunnel. Judge et al. (2001) measured tip leakage vortices from a 0.8506 m diameter, three-bladed, ducted rotor with PIV. Lee et al. (2004) measured three-component velocity field of propeller wake using stereo PIV.

The present study is to provide benchmark EFD data and UA for DTMB model 5512, a geosym ($L$ = 3.048 m) of DTMB model 5415 for the US Navy DDG51. The EFD data includes time histories of global forces and moment and motion measurements and phase-averaged SPIV local flow velocity and turbulent Reynolds stress field measurements together with their UA. The measurement system features a custom design comprised of a PMM for captive model testing with an integrated stereoscopic particle image velocimetry (SPIV) for procuring instantaneous and phase-averaged flow maps. The PMM consists of a PMM sway/yaw motion mechanism unit, an integrated SPIV system with an automated traverse, roll/pitch/heave free/fixed mounts, and a six-component load cell, and a Krypton contactless motion tracker. The approach is complementary CFD, EFD, and uncertainty assessment. CFD is used to guide EFD, EFD is used for validation and model development, and lastly CFD is validated and fills in sparse data for complete documentation and diagnostics of the flow. Forces and moment and motions are measured for several towing speeds and mounting conditions for static drift and dynamic maneuvering tests. Several drift angles, frequencies, amplitudes, and yaw rates are investigated. The forces and moment measurements and UA are conducted in collaboration with FORCE, INSEAN, and the 24th-25th ITTC Maneuvering Committee, including overlapping tests using the same model geometry for validation of procedures and identification of facility biases and scale effects.  Results will be presented for both static and dynamic PMM, in the latter case including pure sway, pure yaw, and yaw and drift tests. The current project builds on previous work including forward-speed diffraction problem (Gui et al. 2001a; Gui et al. 2002; Longo et al. 2005), pitch and heave motions (Irvine et al., 2008), and investigations of roll motions with and without bilge keels (Bishop et al. 2004; Felli et al. 2004; Irvine et al. 2004) and is part of a collaborative effort between IIHR, DTMB, and INSEAN which has been ongoing as part of an international project for 6DOF ship hydrodynamics research.  The overall focus is on benchmark CFD validation data for surface combatant DTMB model 5415 (Stern et al., 2000).