International Journal of Technology 14(3) 561-575 (2023)
Received January 2022 / Revised February 2022 / Accepted May 2022

International Journal of Technology

http://ijtech.eng.ui.ac.id

Enhancing A Reliable Ship Performance Evaluation in Dynamic Maneuvering Conditions – A Gap Analysis

Sunarsih[1*], Edi Jadmiko[1], Muhammad Badrus Zaman[1], Adi Maimun Abdul Malik[2], Arifah Ali[3]

[1]*Department of Marine Engineering, Faculty of Marine Technology, Institut Teknologi Sepuluh Nopember, Surabaya 60111, Indonesia*
[2]*Marine Technology Centre, Universiti Teknologi Malaysia, 81310 Skudai, Johor Bahru, Malaysia*
[3]*Department of Aeronautical, Automotive and Offshore Engineering, School of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor Bahru, Malaysia*

Abstract. Ship and propeller interaction greatly affect ship maneuvering performance and behavior. In steady ahead operation, the interaction properties remain unchanged due to steady ship-propeller operations. In dynamic operations, such as stopping, the properties vary considerably based on the ship and propeller speed combinations. Past researches and practices use a simplistic assumption of single and constant value resembling steady ahead operation due to the lack of knowledge and data on the properties. Up to very recently, researchers in the field and related areas refer to the one and only work from more than five decades ago. The current research presents an insight to disclose the properties features, efforts, and progressions made in the field to the extent of challenges bottlenecking the development. The work broadens the analysis of the implication and inadequacy of the current circumstance toward appropriateness, accuracy, and validity of the research and related studies in the field.

Keywords: Crash stopping; Dynamic operation; Hull-propeller interaction; IMO maneuvering; Propulsion factor

1. Introduction

The quality of ship maneuvering is exceptionally important from both technical and operational points of view. Ship maneuverability is of great interest to ship owners, operators, ports, and state authorities. In addition to collision avoidance, ship maneuverability should be prioritized in further studies due to the criticalness and impact on ship safety and operability (Vanem *et al.*, 2008). From a practical point of view, there is an evolution of needs from day-to-day operations involving ship maneuverability to computer-aided simulation modeling (Cimen, 2009; Pérez and Clemente, 2007; Benvenuto, Brizzolara, and Figari, 2001) under various operating conditions (Paroka, Muhammad, and Asri, 2017; Prabowo *et al.*, 2016; Priadi and Tjahjono, 2015). The method which averts the necessity of conducting costly and time-consuming full-scale trials and allows a wider range of operations without jeopardizing the ship, such as in the case of crash-stopping maneuver, is the most promising tool to investigate and assess the ship maneuvering behavior and maneuverability compliance to IMO Manoeuvring Standards (IMO, 2002b).

---

[*]Corresponding author's email: sunarsih@its.ac.id, Tel.: +62315994251; Fax.: +62315994754

doi: 10.14716/ijtech.v14i3.5489

However, an appropriate mathematical model and precise knowledge of various coefficients used in the modeling are required to produce accurate and satisfactory results (Cimen, 2009).

In contrast to the inherent design and most of the daily operations in forward movement indicating ahead operation, dynamic ship maneuvering such as during crash stopping requires propeller function in four-quadrant operation comprising ahead, crash-ahead, crash-back, and backing. Unlike traditional maneuvering modeling, the mathematical model and coefficients employed in such dynamic operation hence demand to be in the similar mode of four quadrant operation. To be precise, realistic knowledge of various ship hull and propeller interactions represented by wake and thrust deduction fractions is indispensable for satisfactory maneuvering prediction (Voorde, 1974).

However, knowledge and data on the hull-propeller interaction properties in various maneuvering conditions are very limited (Ye *et al.*, 2012; Sutulo and Soares, 2011; Artyszuk, 2003; Harvald, 1976). The work of Harvald (1977, 1967) as the pioneer (Artyszuk, 2003) since more than a half-century ago is still referred to by various researchers in the field and related areas up to now (Illes *et al.*, 2021, 2020; Sunarsih, 2018; Trodden and Haroutunian, 2018; Sutulo and Soares, 2011). Only recently, Sunarsih (2018) was recorded to execute similar research and took advantage of the properties developed to evaluate ship-stopping ability based on the Standards framework.

Reference of nowadays researches to outdated works, such as Harvald (1977, 1967), due to the absence of further studies afterward bearing the consequence that there is an enormous knowledge gap in the field and the current situation remains the same as decades ago. Despite the fact and the urgency to take any proper actions, no investigation has been performed to unveil the core and the aftermath problems. Addressing the issue, this paper carried out an in-depth analysis to expose the challenges in the advancement by profoundly observing related research thus far and rooted the analysis to the pioneering work. Implications of the existing limitations were outlined accordingly to encourage further studies in the field and related areas.

2. Identification of Knowledge Gap

The current research carried out a systematic review to identify the knowledge gap in the field of dynamic maneuvering involves various hull-propeller interactions indicated by various wake and thrust deduction fractions based on Artyszuk's claim (Artyszuk, 2003) that Harvald (1977, 1967) is the pioneering work and solid evidence declared by Sunarsih (2018) that nothing has been progressed afterward up to years ago. Figure 1 illustrates the research framework employed as the basis of the systematic review performed.

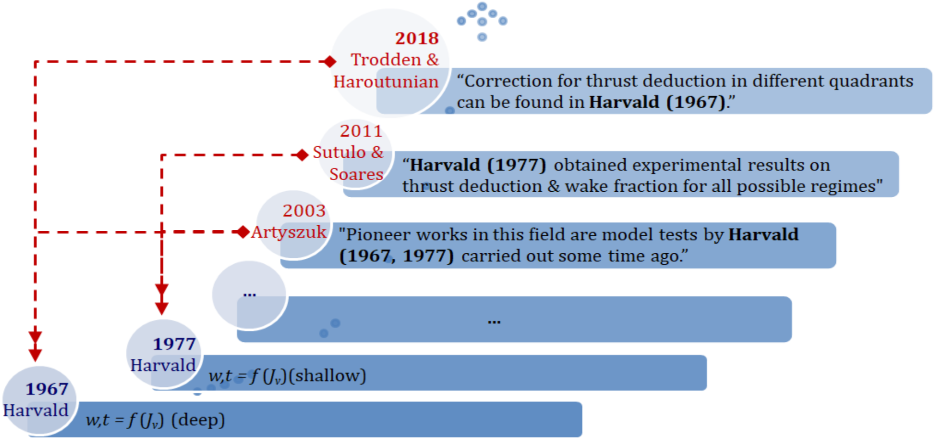


Figure 1 Evidence-based framework for a systematic review of the current research

As evidenced, the work of Harvald (1977, 1967) was referred to by Trodden and Haroutunian (2018) who studied the sensitivity of ship maneuvering motion on NO_x formation years ago for further reference and analysis. Formerly, Sutulo and Soares (2011) who reviewed various selected topics related to mathematical models mainly for simulation of ship maneuvering purposes acknowledged that not much data on the properties were available aside from the work hence encouraging the collection of new data. Recently, both Illes *et al.* (2021) and Illes *et al.* (2020) also listed the work despite unclear contributions to the studies.

The research recalled the pioneering work of Harvald (1977, 1967) and associated researches dealing with the development, modeling, and application of the properties towards knowledge advancement and development of reliable maneuvering prediction in dynamic operating conditions. Four key points set as structured issues to develop an insightful analysis and gain the knowledge about the topic are defined based on the following research questions: What has been investigated in the past? What advancement has taken place? What bottlenecks the development? And; what does the limitation suggest?

3. The Gap Key Points

The outcomes of the in-depth analysis of the four key points set for the systematic review performed were outlined as follows.

3.1. Pioneer Studies in the Field

Records have shown that pioneer studies of various propulsion factors of wake and thrust deduction fractions implying dynamic maneuvering are dominated by experimental-based works. As seen in Figure 2, some studies were purposely carried out to identify the properties while others defined the properties through investigation of the involved test parameters throughout dynamic maneuvering.

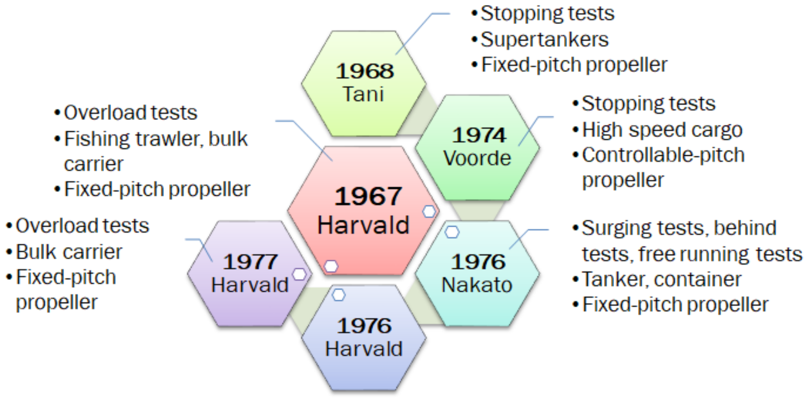


Figure 2 Experimental-based studies in the field of dynamic propulsion factors

As the pioneer of the work, Harvald (1967) was recorded to identify various propulsion factors of wake and thrust deduction fraction properties via overload tests of a fishing trawler and bulk carrier models at several different speeds and propeller revolutions in four quadrant operation. The models correspond to full-scale ships of about 59,450 t and 60,000 t DWT, respectively. For variation, the trawler model was tested using two different propellers while the bulk carrier model was examined in combination with four blades fixed pitch propeller. In the work, the wake and thrust deduction values were determined from the test data of thrust coefficient K_T in open water and behind ship conditions by performing point-by-point calculations using both thrust and torque identities. The values were then presented as functions of apparent advance coefficient J'.

A decade later, investigation on the bulk carrier model was extended to operation in infinite and restricted water depth conditions (Harvald, 1977). Two water depths of 1.5 and 1.25 times draft of the model were selected to represent shallow water operation with the distribution of ship speeds and propeller revolutions varied in three and four settings ranges from 1.0 m/s to 1.8 m/s and 3 rps to 12 rps respectively for both ahead and astern operations. Analyses of the test results for the determination of wake and thrust deduction values and ship-stopping ability were carried out as in previous research.

Despite the fact of being the pioneering work in the field, the early work of Harvald (1967) was not mentioned in later works by Voorde (1974) and Tani (1968). It is uncertain whether both researchers deserted the work or not knowing that such a study once was performed and generated some properties. Unknowingly forsaking the established properties, Tani (1968) who investigated the stopping ability of supertankers straightforwardly declared that no thrust deduction data for stopping maneuvers exist at the time and the knowledge hence must depend upon further study. During the analysis, the properties were assumed to be neglectable despite some attempts to establish a simple calculation method while preparing a set of calculation diagrams for the targeted ship.

In the case of Voorde (1974), the work proclaimed that there was limited knowledge and data regarding wake and thrust deduction properties in various conditions during a stopping maneuver and related studies typically took the values as constant. The study carried out an experimental test of stopping maneuvers employing a high-speed cargo fitted with a controllable pitch propeller. During the stopping test, propeller thrust T and ship speed u were measured on a time basis.

In various attempts to model the dynamic thrust deduction properties using the measured data, Voorde (1974) solved the longitudinal equation of motion at the speed u expressed by Equation 1 where inputs are the measured thrust and ship speed, and plotted the thrust deduction values of (1-t) as functions of thrust loading C_T^* formulated in Equation 2 and apparent advance ratio u/nD for constant pitch angle.

$$(m + \Delta m)\frac{du}{dt} = -A_2u^2 + (1 - t)\,T \tag{1}$$

$$C_T^* = \frac{T}{\frac{1}{2}Q\frac{\pi}{4}D^2u^2} \tag{2}$$

However, Voorde (1974) encountered difficulties in plotting the properties against the thrust coefficient C_T and parameter u/nD for constant pitch angles. The work denoted that it seems to be impossible to present the properties as functions of propeller parameters due to too much data scattering and uncertainties of the properties' behavior as redrawn in Figure 3. It was believed that the problem was rooted in inaccuracies of both test data comprising propeller thrust and ship speed, and mathematical computation in the process of differentiation. The work indeed acknowledged that the thrust measurements were not very accurate and justified that the model tests performed were intended to develop a new technique for stopping tests in a towing tank.

Later, Nakato *et al.* (1976) carried out experimental tests employing tanker and container models respectively identified as Ship T and Ship C to estimate accelerating and decelerating ship motions. Differently, the work acknowledged the thrust deduction properties established by Harvald (1967) and confirmed that propeller operation affects ship accelerating and decelerating motions. The tests carried out revealed that propeller thrust and its deduction factor which was almost independent of the ship's acceleration and deceleration were affected by the apparent advance ratio J_s (or J',$J_v = V_s/nD$). Figure 4 depicts the thrust deduction properties (1–t) identified for both ship models.

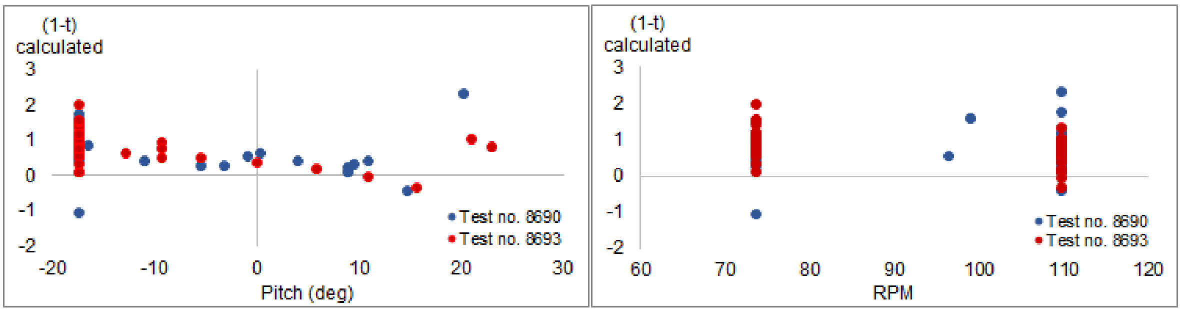


Figure 3 Thrust deduction fraction properties as a function of propeller parameters

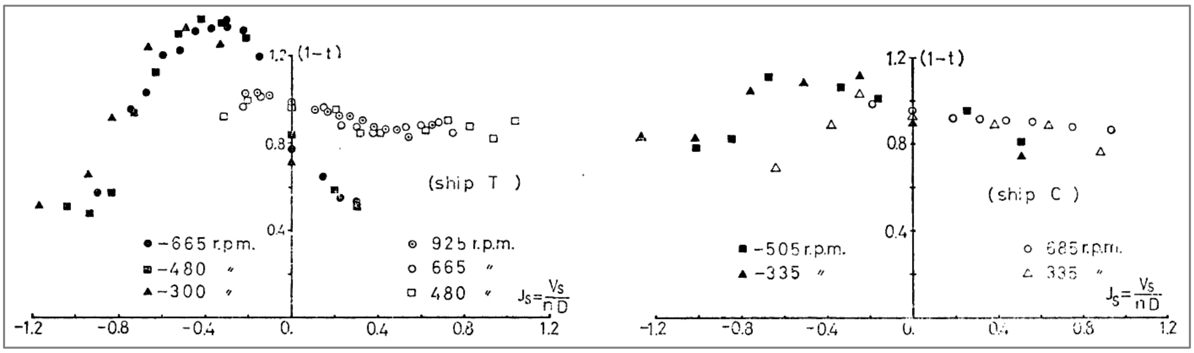


Figure 4 Thrust deduction factors obtained by behind tests (Nakato *et al.*, 1976)

Based on the finding, the work correspondingly regarded both the thrust and the deduction factor as a function of the ship's speed V_s and propeller revolution n. The work further determined the ship accelerating and decelerating motions $\dot{V}_s$ from behind tests at constant speeds by examining the force module of the longitudinal equation of motion comprises effective thrust T_e made up of both variables and the ship resistance. Following the equation formulated in Equation 3, the speeds of the motions were derived from the numerical integration of the accelerating and decelerating motions. It was claimed that the results obtained were close to free-running test data.

$$(m + m_x)\,\dot{V}_s = T(1 - t) - R \qquad (3)$$

3.2. Progression in the Field and Related Areas

Research associated with various wake and thrust deduction fractions representing dynamic maneuvering is not limited to crash-stop modeling and analysis. As evidenced, research interest has emerged in related areas such as thrust generation modeling and green shipping involving such maneuvering conditions. Figure 5 chronologically captures past research progressing the four quadrant wake and thrust deduction fraction properties and modeling rooted in the work of Harvald (1977, 1967).

Harvald (1967) led studies in the field by carrying out overload tests in four-quadrant operations to identify various wake and thrust deduction values. Two ship models of a fishing trawler and a bulk carrier were employed in the tests. The test results including the wake and thrust deduction properties obtained were modeled and presented as maneuver nomograms depicting ship, machinery, and propeller interactions. Further, Harvald (1976) took advantage of the results and properties to analyze the sensitivity of various ship and propeller parameters to ship-stopping ability from a hydrodynamics point of view. Finally, the establishment of the wake and thrust deduction properties was continued to shallow water operation using the bulk carrier model (Harvald, 1977) where test results were analyzed and shown in the similar way.

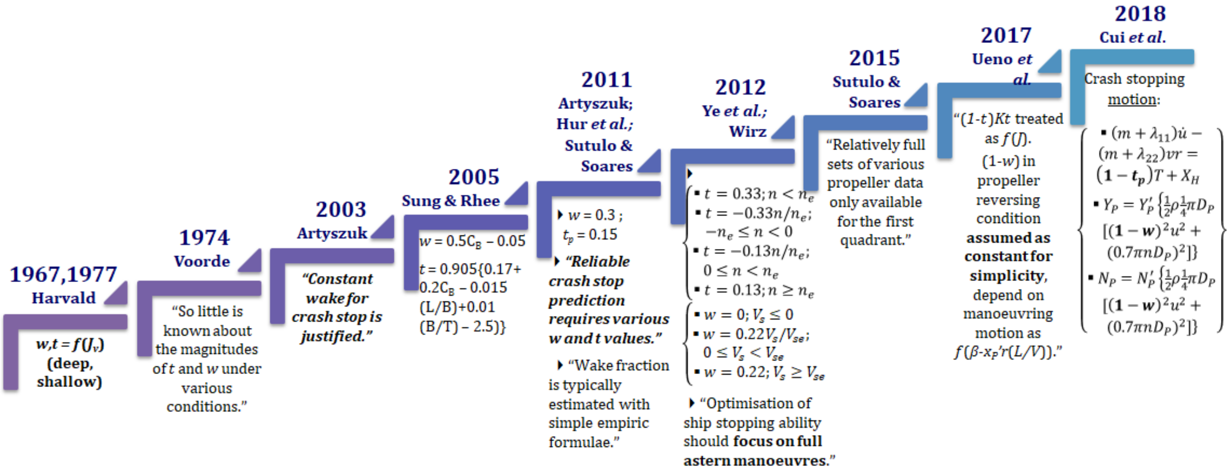


Figure 5 Past studies on various hull-propeller interactions for dynamic maneuvering

Early research progressing various wake and thrust deduction fractions properties in dynamic maneuvering was recorded by Voorde (1974). The study which assessed ship-stopping behavior and hull-propeller-interaction properties throughout the maneuver based on measurement data revealed that data and knowledge pertaining to the properties during crash stopping were scarce and difficult to obtain without even considering the work of Harvald (1967) previously. However, agreement with such postulation was still found in many later studies up to nowadays (Sunarsih, 2018; Sutulo and Soares, 2015; Artyszuk, 2011; Sutulo and Soares, 2011; Sung and Rhee, 2005, Artyszuk, 2003).

In contrast to Artyszuk (2003), Voorde (1974) who analyzed the sensitivity of ship-stopping maneuver and steady-state astern movement on the coefficients, Sutulo and Soares (2011) who reviewed various mathematical models mainly for simulation of ship maneuvering then developed one, (Sutulo and Soares, 2015) acknowledged the properties of Harvald (1977, 1967) and irregularities in the behavior. Despite the values, Artyszuk (2003) declared that assuming the wake fraction for the prediction of crash-stopping maneuver as a constant is justified whereas Sutulo and Soares (2011) disclosed that the fraction is typically estimated using simple empiric formulae. In later reports, Artyszuk (2011) and Sung and Rhee (2005) who developed generic methods for the evaluation of ship-stopping ability took different approaches to treat the properties. The earlier employed wake and thrust deduction values estimated based on ship particulars as widely applied during the preliminary design stage whilst the latter defined constant values for any maneuvering conditions. As evidenced, discrepancies in handling the properties were existed. However, Hur, Lee, and Chang (2011) and Voorde (1974) who analyzed propeller loads during crash-stop maneuvering emphasized that reliable predictions in dynamic conditions during crash-stopping maneuver require various values whilst simplistic assumptions of constant values throughout any manoeuvring conditions, despite justifiable due to the lack of data and nothing better is known, led to large errors in the predictions.

A relatively good alternative approach in taking various wake and thrust deduction fractions into account for dynamic maneuvering was presented by Ye *et al.* (2012) who developed a thrust estimation scheme for various ship operating conditions. The work assumed the fractions to vary in values based on ship speed and propeller RPM combinations. A better approach was shown by Ueno, Suzuki, and Tsukada (2017) who performed an estimation of full-scale ship-stopping ability using a free-running model. The work assumed wake fraction $(1–w)$ as a function of maneuvering motion represented by β-x_P'$r(L/V)$ whilst thrust deduction fraction treated as a whole factor of propeller properties $(1–t)K_T$ assumed as a function of advance ratio J. In contrast to both works, a recent study by Cui, Wu, and Chen (2018) who developed a simulation program for the evaluation of ship maneuverability seemed to be neglectful of this issue. Nothing was disclosed concerning dynamic wake and thrust deduction fractions despite the prediction of crash-stopping ability performed.

3.3. Challenges in the Progression

Fundamentally, limited knowledge of some research areas was due to no continuation nor further research in the field. Concerning the four quadrant wake and thrust deduction fractions, the one and only work referred to nowadays research is the results of model tests by Harvald (1977, 1967) from decades ago. Albeit could not be assumed as completely true, the phenomenon could be read as negligence of responsibility towards science society since emphases on the exigencies of the properties and invaluable consequences for taking invalid and inaccurate approaches in handling the properties have been simultaneously proclaimed by past studies.

Harvald (1977, 1967), Voorde (1974) and Tani (1968) have called for new property development. However, no significant progression in the field appeared thereafter. The very recent work of Trodden and Haroutunian (2018) who studied the sensitivity of ship maneuvering motion on NO_x formation still highlights the work of Harvald (1967) for the correction of thrust deduction fraction in various quadrants. Evidently, knowledge and data of various wake and thrust deduction fractions nowadays are still scarce and remain the same as those of more than five decades ago.

Considering the circumstances, the problem in aggregating new and more data and knowledge on the properties might lie in the following three facts. Firstly, ships are basically designed to move in one, forward direction at a specific design speed. Correspondingly, treating the wake and thrust deduction fractions representing the hull-propeller interaction in a similar way to only one ahead operation might seem reasonable. Secondly, derivations and investigations of the properties in four-quadrant operation either via experimental tests, mathematical modeling, or numerical analyses are laborious, costly, and time-consuming thus burdensome to be executed. Thirdly, it was widely known to researchers in the field that simplistic postulations and practices to handle the data and knowledge limitations on the properties were considered justifiable. Hence, simply following such consent could be regarded as acceptable.

According to Voorde (1974), various wake and thrust deduction fraction properties are derivable only by extensive tank tests of a fully fitted ship model at overload conditions. It refers to propulsion tests at extremely high propeller loadings hence enabling the model to create negative towing forces F and being self-propelled at particular thrust values (MARIN, 1996). Indeed, laborious works were indicated by Harvald (1967) where in some cases tests were executed at lower than the desired speed whilst some others were left out due to time consideration.

Artyszuk (2003) denoted that a more accurate relationship of the wake and thrust deduction factors to propeller thrust and torque could be drawn by utilizing onboard propeller measurement. However, propeller operation at extremely high loadings could possibly jeopardize the ship and its related systems. While the computation method could be set as an alternative to extensive tank tests which are laborious, costly, and time-consuming, Hur, Lee, and Chang (2011) disclosed that the cost of investigation of hydrodynamic loads involving various operating conditions during crash stop operation accurately was also considerably expensive. As a matter of fact, research cost has always been the dominant factor bottlenecking further research for the cultivation of novel and deeper knowledge in the field.

3.4. Implications of the Current Status

As proven, knowledge and data of various wake and thrust deduction fractions in four-quadrant operations representing various maneuvering conditions are scarce and hard to find in previous works. Past to current research made various assumptions in values and mathematical models of the properties with justifications to treat the limitation while trying to create better results. However, the accumulation of new properties and modification of related mathematical models are significantly required since invalid assumptions and improper mathematical modeling of the properties bottleneck the realization of accurate hence reliable, and satisfactory ship performance evaluation in dynamic maneuvering conditions.

3.4.1. Invalid practices in handling knowledge and data limitation

As a result of limited knowledge and data of various wake and thrust deduction fractions, studies concerning maneuvering in various and dynamic operating conditions such as stopping-maneuvers assumed the properties variously. The postulations take the form of certain values constantly, zero, or as a function of certain parameters to the extent of neglectable. Artyszuk (2003), Harvald (1976), and Voorde (1974), confirmed that the most common and thus simplest practices are assuming the properties as a single value and remaining constant throughout any maneuvering conditions. Voorde (1974) supposed such assumptions were due to no better knowledge which was proven by Tani (1968) who proclaimed that the data were unavailable at the time and hence neglected during his assessment of large tanker stopping ability. Due to failure in expressing the thrust deduction properties as function of propeller parameters, Voorde (1974) then took constant thrust deduction factor value (1-*t*) by 0.824 for estimation of the model ship stopping ability.

Among other past studies employing single and constant wake and thrust deduction values were Cui, Wu, and Chen (2018), Sutulo and Soares (2015), Artyszuk (2011), Sung and Rhee (2005), Benvenuto, Brizzolara, and Figari (2001). For the mathematical model of ship standard maneuvers including crash stopping, Benvenuto Brizzolara, and Figari (2001) suggested the propulsion factors of wake and thrust deduction to be estimated from the Holtrop method (Holtrop, 1984; Holtrop and Mennen, 1982) as formulated in Equation 4 and Equation 5 respectively if no tank test result available.

$$w = c_9 c_{20} C_V \frac{L}{T_A}\left(0.050776 + 0.93405 c_{11} \frac{C_V}{(1-C_{P1})}\right) + 0.27915 c_{20}\sqrt{\frac{B}{L(1-C_{P1})}} + c_{19} c_{20} \quad (4)$$

$$t = 0.25014(B/L)^{0.28956}(\sqrt{BT}/D)^{0.2624}/(1-C_P+0.0225lcb)^{0.01762} + 0.0015C_{stern} \quad (5)$$

Sung and Rhee (2005) who proposed a new prediction method for ship stopping ability of diesel ships fitted with FPP employed constant wake and thrust deduction fractions based on Taylor (1910) as expressed in Equation 6 and Hideo and Oh (1971) formula given by

$$t = 0.905 \times \{0.17 + 0.2C_B - 0.015(L/B) + 0.01(B/T - 2.5)\} \quad (6)$$

Artyszuk (2011) who previously proposed the determination of various thrust deduction fractions as a function of maneuvering time while assuming the wake fraction as constant (Artyszuk, 2003) employed default constant wake and thrust deduction fraction values respectively by 0.3 and 0.15 to evaluate propulsive and stopping performance of cellular container carriers.

Zero propulsion factors ($w,t = 0$) which according to Harvald (1976) were also frequently used in some studies were partially applied by Sunarsih, Izzuddin, and Priyanto (2015) and Ye *et al.* (2012). Both works assumed the wake fraction as a function of the ship's speed V_s while the thrust deduction fraction was the function of propeller loading n, although constant values were given for both properties as accordingly listed in Equation 7 and Equation 8. In the equation, V_{se} and n_e correspond to ship-rated speed and engine rotational speed.

$$w = \begin{cases} 0 & V_s \leq 0 \\ 0.22V_s/V_{se} & 0 \leq V_s < V_{se} \\ 0.22 & V_s \geq V_{se} \end{cases} \tag{7}$$

$$t = \begin{cases} 0.33 & n < n_e \\ -0.33n/n_e & -n_e \leq n < 0 \\ 0.13n/n_e & 0 \leq n < n_e \\ 0.13 & n \geq n_e \end{cases} \tag{8}$$

As propulsion factors of wake and thrust deduction fractions denote the ship and propeller interactions, employment of constant values for one or both fractions indicates that there is no change in the interaction which implies that the ship and propeller operate at a specific speed and RPM combination constantly. Meanwhile, the use of zero value signifies the absence of the ship and propeller interaction. Definitely, the assumption and use of constant and zero wake and thrust deduction values for four quadrant ship maneuvering modeling are invalid since the values fail to account for the dynamic behavior of ship and propeller interactions at various operating conditions involving various ship speed and propeller rotational rate combinations which vary considerably particularly during transition operation in crash stop maneuver (Sunarsih, 2018).

The use of wake and thrust deduction fractions determined based on ship parameters as executed by Sung and Rhee (2005) and Benvenuto, Brizzolara, and Figari (2001) are also invalid since such expressions are usually derived from various model tests as typical values and generally applicable for design condition hence for a particular ship design speed and propeller rotational rate only. In fact, according to Lewis (1988), wake and thrust deduction fractions proposed by Holtrop (Holtrop, 1984; Holtrop and Mennen, 1982) which were used by Benvenuto Brizzolara, and Figari (2001) were derived from more than 200 model propulsion tests vary in types statistically. Furthermore, as ship design is by default considers ahead operation only, taking such typical values/expressions for four quadrant ship maneuvering mathematical modeling includes crash stopping operation as in Cui, Wu, and Chen (2018), Oneto *et al.* (2018), and Sutulo and Soares (2015), are considered as an invalid approach.

3.4.2. Improper modeling of dynamic hull-propeller interaction

Several efforts toward modeling various wake and thrust deduction fraction properties representing dynamic hull-propeller interaction and taking them into account in four quadrant ship maneuvering mathematical modeling, particularly for evaluation of ship-stopping ability have been devoted to previous research. The attempts were mainly based on experimental test results from overload tests to the extent of free-running and stopping tests. Most approaches in the modeling were done by employing propeller-based parameters including propeller loading and advance ratio.

As dynamic ship maneuvering in four-quadrant operation involves various ship speeds and propeller rotational rates, the most suitable parameter to represent both variables is the apparent advance ratio J_v ($J_v = V_s/nD$). As such, it is only precise to depict the ship and propeller interaction properties of wake and thrust deduction fractions as functions of J_v. Being the pioneer in the field, Harvald (1977, 1967) has properly plotted both wake and thrust deduction values obtained as functions of similar parameters denoted by J' though no mathematical model was introduced to express the properties. For further use in the maneuvering analysis (Harvald, 1977, 1976, 1967), the work assumed both fractions vary with the propeller loading indicated in the maneuver nomogram containing ship, machinery, and propeller interactions.

In the work of Voorde (1974), it was stated that both wake and thrust deduction fractions are primarily dependent on the ship geometry mainly of the after body, propeller arrangement, loading condition, and so forth. The work further denoted that it seems acceptable to assume both fractions only as functions of the ship speed and propeller thrust magnitudes while independent of the ship speed and propeller loading combinations the thrust achieved. Such a presumption has been proven to be erroneous based on the findings of Harvald (1977, 1967) and experience at Marin (1996). Variation of wake and thrust deduction fraction values plotted as a function of apparent advance ratio J' in the work of Harvald (1977, 1967) have clarified that both fractions are significantly dependent on the ship's speed and the rate of propeller revolution in four quadrant operation. Marin (1996) disclosed that despite both fractions being almost independent of the ship's speed, the wake fraction often gradually decreases as the speed increases due to the correlation between the viscous resistance coefficient and the wake fraction viscous component. On the dependency on the propeller loading, it was claimed that both fractions most commonly gradually decrease as propeller loading increases.

In a later work by Artyszuk (2003), the identification of both wake and thrust deduction properties from the full-scale astern maneuvering trials failed due to some limitations. The work then proposed a new general approach for determining thrust deduction properties in the form of a differential equation (t_d) as a function of the maneuvering time (t) by assuming the wake fraction as constant. It is formulated as

$$t_d(t) = 1 - \frac{dv_x/dt\ .\ (m+m_{11}) - F_{xH} - (m+c_m m_{22})\, v_y\, \omega_z}{\rho n^2 D^4 K_T} \tag{9}$$

Where v_x, v_y, ω_z and m, m_{11}, m_{22} correspond to surge, sway (positive to starboard), angular velocities, and ship mass, surge, and sway added mass while F_{xH} and c_m are hull resistance force and constant representing the hull positive thrust, respectively. However, modeling the thrust deduction fraction as a function of maneuvering time seems to be improper since the value is uncertain. As for comparison, Figure 6 depicts irregularities of the properties redrawn from stopping test results by Voorde (1974).

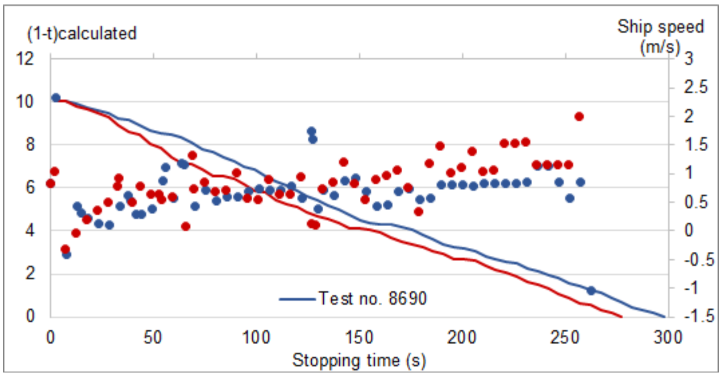


Figure 6 Thrust deduction fraction properties throughout stopping maneuvers

Avoiding further inaccuracies in the modeling, Voorde (1974) then assumed the factor to be constant and employed a value of (1-t) = 0.824 for determining the targeted ship stopping ability and expressed the wake fraction from propeller thrust and torque using Equation 10 and Equation 11 respectively whilst neglecting Reynolds and Froude number effects.

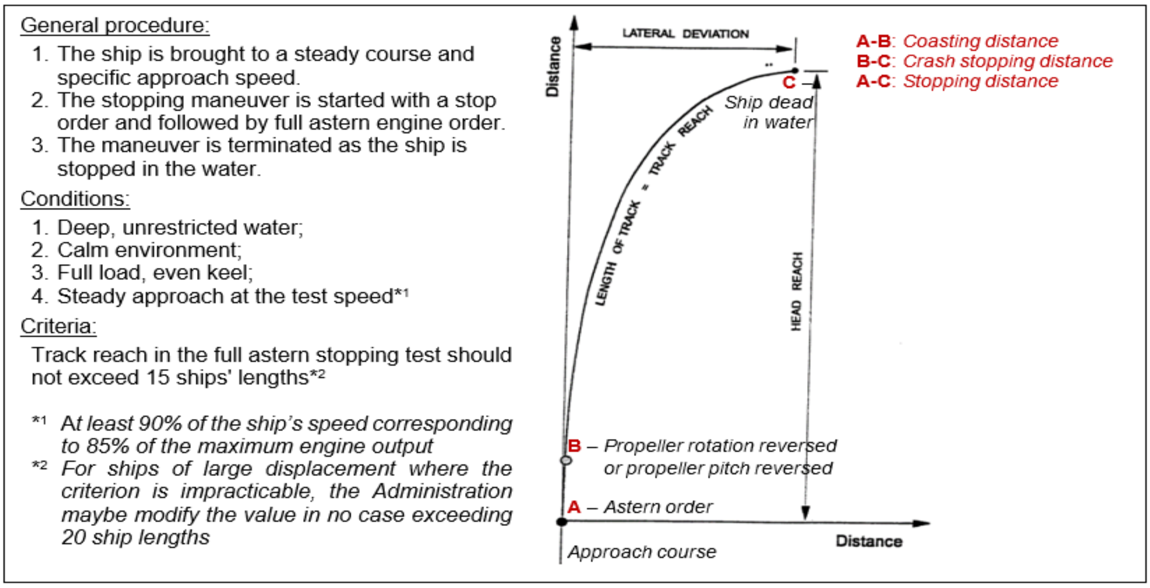
$$T = C_T \frac{1}{2} \rho \frac{\pi}{4} D^2 (1-w)^2 u^2 \tag{10}$$

$$Q = C_Q \frac{1}{2}\rho\frac{\pi}{4}D^3(1-w)^2u^2 \tag{11}$$

In a recent work of estimation of full-scale ship-stopping ability via a free-running model test equipped with an auxiliary thruster, Ueno, Suzuki, and Tsukada (2017) assumed wake factor (1-w) in astern maneuver as a constant value as in conventional maneuvering of straight course for simplicity. Meanwhile, the thrust deduction factor t is treated as a whole function of the coefficient of longitudinal force induced by reversing propeller denoted by $(1-t)\ K_T$. The coefficient is given as a function of advance ratio J to trade off the scale effect on the stopping maneuver since J which represents flow around the propeller is common for both model and full-scale ships. However, the work failed to solve the mathematical modeling employed and realize the full-scale stopping maneuver using the test configuration due to limited knowledge of the $(1-t)\ K_T$ factor. Seeking the possibility for evaluation of ship-stopping ability from a practical point of view, the work insisted to proceed further using such improper modeling.

3.4.3. Inaccuracy of dynamic ship maneuvering performance prediction

IMO Manoeuvring Standards (IMO, 2002a; 2002b) has developed the framework for the evaluation of ship maneuvering performance ability as summarised in Figure 7. In contrast to other maneuverability assessments including inertial stopping ability, evaluation of ship (crash) stopping ability via stopping test is of a dynamic type and involves four quadrant propeller operation. The process encompasses acceleration to a test speed, deceleration to a designated reverse speed, and re-acceleration in an astern maneuver to zero speed (stop) condition.



General procedure:

1. The ship is brought to a steady course and specific approach speed.
2. The stopping maneuver is started with a stop order and followed by full astern engine order.
3. The maneuver is terminated as the ship is stopped in the water.

Conditions:

1. Deep, unrestricted water;
2. Calm environment;
3. Full load, even keel;
4. Steady approach at the test speed*1

Criteria:

Track reach in the full astern stopping test should not exceed 15 ships' lengths*2

*1 *At least 90% of the ship's speed corresponding to 85% of the maximum engine output*

*2 *For ships of large displacement where the criterion is impracticable, the Administration maybe modify the value in no case exceeding 20 ship lengths*

Figure 7 IMO Manoeuvring Standards framework for stopping test (Sunarsih, 2018)

Despite the complexity, the Standards allow prediction of ship-stopping ability and demonstration of the behavior using calculation and/or computer simulation programs based on a fairly simple mathematical model representing the important aspects outlined in the framework. However, reliable predictions in such a dynamic environment require proper modeling of the propeller forces for the four quadrants of operations including the transition operations between the quadrants and various wake and thrust deduction fractions (Hur, Lee, and Chang, 2011; Hwang *et al.*, 2003; Voorde, 1974). Failure to meet such a requirement which lead to improper modeling of dynamic hull-propeller interaction displayed by past researchers seemed to have caused inaccuracies in the evaluations. As evidenced, several predictions underestimated or overestimated the measured experimental or trial data while some others underestimated and overestimated the values simultaneously. On top of those, there existed some predictions which violated the criteria of ship-stopping ability defined by the Standards.

Table 1 contrasts the full-scale measurement against the calculated stopping distance S and time t obtained via two stopping tests extracted from the work of Voorde (1974).

Table 1 Calculated and measured ship-stopping ability

Crash stop no. 2					Crash stop no. 3				
Measured	***Calculation 1***		***Calculation 2***		***Measured***	***Calculation 1***		***Calculation 2***	
	Δm = 0.06 m	Error	Δm = 0.10 m	Error		Δm = 0.06 m	Error	Δm = 0.10 m	Error
S = 1260 m	S = 1173.3 m	6.9 %	S = 1218.6 m	3.3 %	S = 1300 m	S = 1226 m	5.7 %	S = 1270 m	2.3 %
t = 278 s	t = 270 s	2.9 %	t = 280 s	0.7 %	t = 246 s	t = 265 s	7.7 %	t = 272 s	10.6 %

As summarised in the table, variation of added mass Δm by 6 % and 10 % of ship mass m held a small effect in the prediction of ship-stopping ability. Employing both values, the calculated ship-stopping abilities consistently underestimated the measured stopping distance while causing discrepancies in the prediction of the stopping time. In Crash stop no. 2, the stopping time was underestimated for 8 s by 6 % added mass while overestimated for only 2 s by 10 % added mass. In contrast, both 6 % and 10 % added mass overestimated the stopping time of Crash stop no. 3 for as long as 19 s and 26 s respectively. Voorde (1974) highlighted that despite inaccuracies in the measurement of the stopping tests, large errors in the prediction may arise from the assumption of thrust deduction fraction being constant throughout the stopping maneuver.

Inaccurate predictions also appeared in the work of Sung and Rhee (2005) and Artyszuk (2011) who employed constant propulsion factors in the proposed generic analytical model for the determination of ship-stopping ability based on the Standards framework (2002b, 2002a). In the work of Sung and Rhee (2005), the proposed model was unstably underestimated or overestimated the stopping distance of particular ship types despite showing better agreement with the sea trial data as compared to IMO (2002a) method qualitatively. Meanwhile, in the work of Artyszuk (2011), the non-dimensional stopping distance s'_{total} obtained reached 20 L which signifies a violation of the Standards criteria by 15 L. Similar to Sung and Rhee (2005), Artyszuk (2011) expected the error to arise from the prediction of crash stopping distance since the prediction of the coasting distance seems to be fine. Both works highlighted that the proposed model requires further improvement with regards to the crash-stopping model where the emphasis was given on the hydrodynamic forces due to propeller reversal during the crash-stop maneuver and propeller characteristic in crash-back operation.

In the work of Sutulo and Soares (2015), the simulation of a crash-stopping maneuver using the model developed yielded a considerably large error of up to 39.1 % as displayed in Table 2. On the other hand, the recorded surge velocity displayed a good agreement with the trial data. Such revelation is a bit odd since both parameters are closely related such that the distance the ship traveled is an integration product of the ship's velocity. The work stated that the error appeared due to rough modeling of the so-called Hovgaard force, a force caused by the influence of the tangential induced velocities in the slipstream of a heavily loaded propeller which occurs such as during the operation of crash-stop maneuver. Despite the claim, there is a strong possibility that design-based wake and thrust deduction fractions employed in the model contributed to the error in the prediction as found in other works detailed earlier.

Table 2 Measured and simulated ship-stopping ability

Stopping parameter	Trial data	Simulation	Error
Final transfer	1150 m	700 m	39.1 %
Head reach	2400 m	2600 m	8.3 %

Later work by Ueno, Suzuki, and Tsukada (2017) revealed that similarity in the propeller reversing condition defined in the modular mathematical model employed could not be ensured by the thruster fitted in the ship model. After some modification to J and speed parameters, the simulation of the Full Astern stopping test from Slow Ahead (SAH) of the target ship of KVLCC1 using the model developed underestimated the head reach of the same ship as ITTC (2011) benchmark data by 15.95 %. Surprisingly, the result of the experimental test using a similar full-scale stopping maneuver free-running model test configuration carried out obtained a better result whose error accounts for only 1.45 %. Table 3 evaluates the accuracy of the simulation and experimental results yielded by the work against the benchmark data supplemented by Transas Marine (2006).

Table 3 Accuracy of the crash stop maneuvering simulation model and experimental result

Full Astern from SAH	Benchmark data	Simulation	Error	Experiment	Error
Head reach	6.9 L	5.8 L	15.95 %	6.8 L	1.45 %
Initial speed	9.9 knot	10 knot		10 knot	

Inevitably, improper modeling of the dynamic ship and propeller interactions in the form of single and constant or ship parameter-based values led to large errors in the prediction of ship-stopping ability as indicated by Hur, Lee, and Chang (2011) and Voorde (1974) despite justifiable due to the lack of knowledge and data in the field. Hur, Lee, and Chang (2011) who evaluated propeller loads during crash stop emphasized that wake fraction has to change according to ship speed to obtain more accurate results in the prediction of ship stopping ability. Correspondingly, Wirz (2012) who performed optimization of the crash stop maneuver claimed that any approach in the optimization of the stopping maneuver should focus on the reversing speed as hull-propeller interaction becomes more intense during such period. As a guideline for a valid prediction as par to the benchmark data recommended by ITTC (2011) and comply with the Standards (IMO, 2002a) criteria of ship stopping ability, the mathematical modeling and assumption of the components employed should be able to capture all ship behavior during a stopping maneuver.

4. Conclusions

Highlights have been given on the scarcity of knowledge and data of the four quadrant wake and thrust deduction fraction properties depicting various maneuvering conditions and current simplistic approaches in handling the limitations. The inaccuracy of the current ship maneuvering predictions employing invalid values and improper models for the sake of such simplicity has been disclosed thoroughly. There exists the urgency of the accumulation of new knowledge and data on the properties to the extent of remodeling the current mathematical model to enable the representation of the real ship maneuvering behavior in various operating conditions.

References

Artyszuk, J., 2003. Wake Fraction and Thrust Deduction During Ship Astern Manoeuvres. *In*: Marine Technology V: Fifth International Conference on Marine Technology and Transportation, Volume 2003, pp. 125–134

Artyszuk, J., 2011. Propulsive and Stopping Performance Analysis of Cellular Container Carriers. In: *Miscellaneous Problems in Maritime Navigation, Transport and Shipping: Marine Navigation and Safety of Sea Transportation*. 1st Edition. London: CRC Press

Benvenuo, G., Brizzolara, S., Figari, M., 2001. Simulation of the Propulsion System Behavior during Ship Standard Maneuvers. *In*: Proceedings of the Eighth International Symposium on Practical Design of Ships and Other Floating Structures, Volume 2001, pp. 657–663

Cimen, T., 2009. Development and Validation of a Mathematical Model For Control of Constrained Non-Linear Oil Tanker Motion*. Mathematical and Computer Modelling of Dynamical Systems,* Volume 15(1), pp. 17–49

Cui, J., Wu, Z., Chen, W., 2018. Research on Prediction of Ship Manoeuvrability. *Journal of Shipping and Ocean Engineering,* Volume 8, pp. 30–35

Harvald, S.A., 1967. Wake and Thrust Deduction at Extreme Propeller Loadings. Stevens Institute of Technology, Volume 61

Harvald, S.A., 1976. Factors affecting the stopping ability of ships. International Shipbuilding Progress, Volume 23, pp. 106–121

Harvald, S.A., 1977. Wake and Thrust Deduction at Extreme Propeller Loadings For a Ship Running in Shallow Water. *Transactions of the Royal Institution of Naval Architects,* Volume 119, pp. 213–236

Hideo, S., Oh, C.D., 1971. A Method of Analyzing Propulsive Test Results of Full Ship Models. *Journal of the Kansai Society of Naval Architects of Japan,* Volume 139, pp. 25–42

Holtrop, J., 1984. A Statistical Re-Analysis of Resistance and Propulsion Data*. International Shipbuilding Progress,* Volume 31, pp. 272–276

Holtrop, J., Mennen, G.G.J., 1982. An Approximate Power Prediction Method. *International Shipbuilding Progress,* Volume 29(335), pp. 166–170

Hur, J.W., Lee, H., Chang, B.J., 2011. Propeller Loads Of Large Commercial Vessels at Crash Stop. *Second International Symposium on Marine Propulsors smp,* Volume 11

Hwang, W., Jakobsen, B., Barr, R., Ankudinov, V., Fuller, N., Vest, L., Morris, M., Mcgovern, A., Landsburg, A., 2003. An Exploratory Study to Characterize Ship Manoeuvring Performance at Slow Speed. *In*: International Conference of Manoeuvring and Control–MCMC2003. Kanazawa, Japan

Illes, L., Jurkovic, M., Kalina, T., Gorzelanczyk, P., Luptak, V., 2021. Methodology for Optimising The Hull Shape of a Vessel With Restricted Draft. *Scientific Journal of Silesian University of Technology,* Series Transport, Volume 110, pp. 59–71

Illes, L., Kalina, T., Jurkovic, M., Luptak, V., 2020. Distributed Propulsion Systems for Shallow Draft Vessels. *Journal of Marine Science and Engineering,* Volume 8, pp. 1–17

International Maritime Organization (IMO), 2002a. Explanatory Notes to the Standards for Ship Manoeuvrability, Annex 2.1. 2, 2.1. 5 (MSC/Circ. 1053)

International Maritime Organization (IMO), 2002b. Standards for Ship Manoeuvrability. Resolution MSC.137(76)

International Towing Tank Conference (ITTC), 2011. Recommended Procedures and Guidelines 7.5-02/06-03: Validation of Manoeuvring Simulation Models. *In*: 26th ITTC Manoeuvring Committee, pp. 1–11

Lewis, E.V., 1988. Principles of Naval Architecture Second Revision. *Jersey: Sname,* Volume 2, pp. 152–157

MARIN, 1996. *Resistance and Propulsion.* Maritime Research Institute Netherlands

Nakato, M., Kose, K., Terarnoto, S., Simamune, S., 1976. Experimental Study on Accelerating and Decelerating Ship Motions. *Journal of the Society of Naval Architects of Japan*, Volume 1976, pp. 77–84

Oneto, L., Coraddu, A., Cipollini, F., Karpenko, O., Xepapa, K., Sanetti, P., Anguita, D., 2018. Crash Stop Maneuvering Performance Prediction: a Data-Driven Solution for Safety and Collision Avoidance. *Data-Enabled Discovery and Applications,* Volume 2, pp. 1–11

Paroka, D., Muhammad, A.H., Asri, S., 2017. Prediction of Ship Turning Maneuvers in Constant Wind and Regular Waves. *International Journal of Technology,* Volume 8(3), pp. 387–397

Pérez, F.L., Clemente, J.A., 2007. The Influence of Some Ship Parameters on Manoeuvrability Studied at The Design Stage. *Ocean Engineering,* Volume 34, pp. 518–525

Prabowo, A.R., Bae, D.M., Sohn, .J.M., Zakki, A.F., 2016. Evaluating the Parameter Influence in the Event of a Ship Collision based on the Finite Element Method Approach. *International Journal of Technology*, Volume 7(4), pp. 592–602

Priadi, A.A., Tjahjono, T., 2015. Implementation of Traffic Separation Scheme For Preventing Accidents on The Sunda Strait. *International Journal of Technology,* Volume 6, pp. 990–997

Sunarsih, 2018. *Four Quadrant Thrust Generation Model with Bounded Dynamic Wake and Thrust Deduction Fractions*. Universiti Teknologi Malaysia

Sunarsih, Izzuddin, N., Priyanto, A., 2015. Thrust and Torque Estimation Scheme Based on Chebyshev Polynomial for Ship Manoeuvring Simulation. *Procedia Manufacturing,* Volume 2, pp. 359–363

Sung, Y.J., Rhee, K.-P. 2005. New Prediction Method On The Stopping Ability Of Diesel Ships With Fixied Pitch Propeller. *International Shipbuilding Progress,* Volume 52, pp. 113–128

Sutulo, S., Soares, C.G., 2011. Mathematical Models For Simulation of Manoeuvring Performance of Ships. *Marine Technology and Engineering,* Soares, G., Garbatov, C., Fonseca, Y., Teixeira, A.P., (ed.), Taylor & Francis Group, London, pp. 661–698

Sutulo, S., Soares, C.G., 2015. Development of a Core Mathematical Model for Arbitrary Manoeuvres of a Shuttle Tanker. *Applied Ocean Research,* Volume 51, pp. 293–308

Tani, H., 1968. The Reverse Stopping Ability of Supertankers. *The Journal of Navigation,* Volume 21, pp. 119–154

Taylor, D.W., 1910. *The Speed and Power of Ships. A Manual of Marine Propulsion.* New York, USA: John Wiley & Sons

Transas Marine, 2006. *Manoeuvring Booklet V1.06: Mathematical Model of VLCC 2 (Dis.127691t) b*l. UK: TRANSAS Marine Ltd

Trodden, D., Haroutunian, M., 2018. Effects of Ship Manœuvring Motion on No X Formation. *Ocean Engineering,* Volume 150, pp. 234–242

Ueno, M., Suzuki, R., Tsukada, Y., 2017. Estimation of Stopping Ability of Full-Scale Ship Using Free-Running Model. *Ocean Engineering,* Volume 130, pp. 260–273

Vanem, E., Antão, P., Østvik, I., De Comas, F.D.C., 2008. Analysing The Risk of LNG Carrier Operations. *Reliability Engineering & System Safety,* Volume 93, pp. 1328–1344

Voorde, V.D., 1974. Calculations and Experiments with Regard to The Stopping of a Ship With Diesel Propulsion and Fitted With a Controllable Pitch Propeller. Netherlands: Netherlands Ship Research Centre TNO

Wirz, D.-I.F., 2012. Optimisation of The Crash-Stop Manoeuvre of Vessels Employing Slow-Speed Two-Stroke Engines and Fixed Pitch Propellers*. Journal of Marine Engineering & Technology,* Volume 11, pp. 35–43

Ye, B., Wang, Q., Wan, J., Peng, Y., Xiong, J., 2012. A Four-Quadrant Thrust Estimation Scheme Based on Chebyshev Fit and Experiment of Ship Model. *Open Mechanical Engineering Journal,* Volume 6, pp. 148–154