11th International Conference on Marine Technology
MARTEC 2018

FOUR QUADRANT WAKE AND THRUST DEDUCTION FRACTIONS FOR CRASH STOP MANOEUVRING

Sunarsih[1], Mohd Zamani Ahmad[1*], Adi Maimun Abdul Malik[2] and Nasrudin Ismail[1]

[1]School of Mechanical Engineering
[2]Marine Technology Centre
Faculty of Engineering,
Universiti Teknologi Malaysia,
81310 Skudai, Johor Bahru

ABSTRACT

Wake and thrust deduction fractions which represent propeller and ship hull interactions affecting ship manoeuvring performance. It is common and acceptable to assume the values as constant. However, a better approach for ship manoeuvring in four quadrant operations involving ahead, crashahead, crashback and backing is to take into consideration the various propeller functions and dynamic propeller-hull interactions. The research extensively established four quadrant wake and thrust deduction fractions in various speed and RPM combinations to the extent of extremely high propeller loadings. The values enrich the currently available data which are scarce and hard to find in previous works. The knowledge which also better exposes the behaviour of propeller and ship hull interactions in various manoeuvring conditions is advantageous for reliable crash stop manoeuvring predictions.

Keywords: *Propulsion factor, wake fraction, thrust deduction fraction, four quadrant operation, crash stop manoeuvring*

1.0 INTRODUCTION

A propeller fitted to a ship moving forward operates in water disturbed by the ship hull. A mutual interaction occurs between the ship hull and the propeller called as hull-propeller interaction. The behaviour of the propeller is affected by the ship, likewise propeller operation behind the ship affects the behaviour of the ship. The hull-on-propeller interaction is indicated by the wake fraction while the propeller-on-hull interaction is signified by the thrust deduction fraction, a decrease of thrust as an alteration of increase of the ship resistance due to propeller actions [1-4].

Voorde [5] and Hur *et al.* [6] highlighted that making reliable predictions in dynamic conditions during crash stopping manoeuvre where direction of propeller inflow varies with change of ship speed and propeller rotational rate is challenging due to the need of various wake and thrust deduction values which are scarce [5, 7]. The most common simplistic practice is taking both factors as constant values in any manoeuvring conditions [5, 7, 8] such as in Benvenuto *et al.* [9], Sung and Rhee [10] and Artyszuk [11]. In some investigations, it is frequently assumed as zero [8] or independent of either propeller loading, such as in Cimen [12], or in combination with ship speed and propeller pitch such as denoted by Voorde [5]. Despite justifiable due to the lack of data and nothing

*Corresponding author: drmohdzamani@gmail.com

better is known, Voorde [5] and Hur *et al.* [6] emphasised that such simplistic assumptions of constant values led to large errors. Various wake and thrust deductions values representing dynamic ship manoeuvring conditions are indispensable for accurate and satisfactory predictions. Wirz [13] indicated that any approach towards optimisation of ship stopping ability should focus on the astern manoeuvres.

This research established four quadrant wake and thrust deduction fraction properties in various operating conditions. The properties were obtained via extensive overload tests at various speed and RPM combinations to the extent of extremely high propeller loadings. The established properties enrich the work of Harvald [14, 15] who was recorded as the pioneer in the field.

2.0 FOUR QUADRANT WAKE AND THRUST DEDUCTION FRACTIONS

Being the ship hull-propeller interaction properties, both wake and thrust deduction fractions are closely related. An increase in the wake fraction normally associated with the increase of the thrust deduction fraction [2, 3]. Both wake and thrust deduction fractions are almost independent of the ship speed although it is often found that the wake fraction gradually decreases as the speed increases due to correlation between the viscous resistance coefficient and the viscous component of the effective wake fraction. On the dependency towards the propeller loading, both wake and thrust deduction fractions behave almost similarly. Both fractions decrease as propeller loading increases [1].

Regarding wake and thrust deduction fractions at various manoeuvring conditions, the knowledge and data are scarce [5, 7]. As a result, both factors are commonly assumed as a single value and being constant throughout any manoeuvring conditions. In contrast, reliable manoeuvring predictions involving dynamic conditions such as crash stopping manoeuvre requires the data in various manoeuvring conditions [5, 6] which is available only by extensive overload tank tests.

In attempts to obtain a reliable result with the absence of the various wake and thrust deduction data, Voorde [5] identified thrust deduction fraction in various manoeuvring conditions based on results of model tests for stopping manoeuvre. During the model tests, propeller thrusts and ship speeds are measured on the time basis. The thrust deductions are then identified by solving the longitudinal equation of motion at a speed u expressed by

$$(m + \Delta m)\frac{du}{dt} = A_2 u^2 + (1 - t)\, T \qquad (1)$$

where m, Δm and A_2 are respectively ship mass, apparent mass and total resistance coefficient for the given condition.

The measured data and thrust deduction obtained during the stopping test by Voorde [5] shows various values in irregular patterns. As such, difficulties were encountered in presenting the quantities as functions of propeller properties. It is believed that various thrust deduction values during the model test appear due to various factors such as inconsistency of the propeller thrust and ship speed measurements as well as calculation process involving time domain differentiation.

As proclaimed by Artyszuk [7], the work of Harvald [14, 15] is the pioneer in the field of four quadrant and various wake and thrust deduction fractions. Various wake and thrust deduction values identified from overload model tests at various manoeuvring conditions and water depths are presented as functions of apparent advance coefficient J_v ($J_v = V_s/nD$). As observed from the profiles obtained, both wake and thrust deduction fractions are scattering although it is more pronounced for the thrust deduction fraction. The values highly depend on the measurement's variable such as the ship speed and propeller rotational rate. Both wake and thrust deduction values normally increase as water depth decreases. A considerably higher uncertainty appears for crash quadrant of operations [14].

Artyszuk [7] denotes that taking wake fraction as constant value for crash stopping manoeuvre prediction is justified due to lack of data and onboard torque measurement is thereby recommended for more accurate values. Using some general analyses based on Harvald's work [14, 15], Artyszuk [7] deduces that the ship stopping ability prediction depends mostly on the various thrust deduction values on the basis of the propeller loading throughout the manoeuvring. Hence various thrust deduction values are necessitated while the constant wake values are justifiable.

Artyszuk [7] also proposes a new general approach for determination of the various thrust deduction values in the form of differential equation (t_d) hence as function of the manoeuvring time ($t_d(t)$) formulated as

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

where:

v_x, v_y, ω_z – surge, sway (positive to starboard) and angular velocities,
m, m_{11}, m_{22} – ship mass, surge and sway added mass,
F_{xH} – hull resistance force,
c_m – constant represents hull positive thrust.

3.0 EXPERIMENTAL ARRANGEMENT AND PROCEDURE

The research has been carried out a series of overload tests by mixed loading method to extremely high propeller loadings using an LNG carrier ship model fitted with a Wageningen B-series propeller model. The experiment was performed in the towing tank of Marine Technology Centre, Universiti Teknologi Malaysia (MTC-UTM) facilities as depicted in Figure 1. The four quadrant wake and thrust deduction profiles have been established for headway movement based on the four quadrant operations portrayed in Figure 2.

Figure 1: Towing tank facilities at MTC UTM

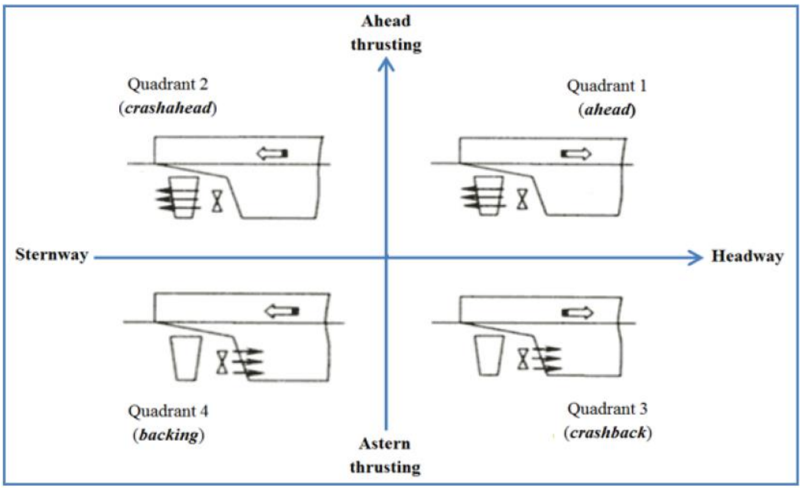

Figure 2: Four quadrant operations

3.1 Parameters definition

Figure 3 illustrates the positive direction of the propeller and ship parameters involved in the measurement adopted from Harvald [14]. *n*, *Q*, *T*, *F*, *R* and *V* are respectively represent the rate of propeller rotation, the shaft torque, propeller thrust, tow-rope pull/force for acceleration or retardation, ship resistance and ship speed.

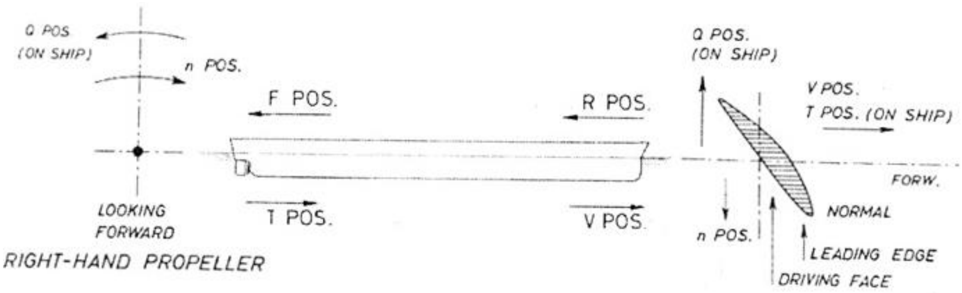

Figure 3: Positive direction of propeller and ship parameters

3.2 Ship and Propeller Model Particulars

Table 2 provides the ship and propeller particulars employed in the experimental tests.

Table 2: Ship and propeller particulars

Item	Dimension	
	Ship	**Model**
Hull		
Length between perpendiculars (*L*) in meters	266.00	3.325
Breadth (*B*) in meters	41.60	0.520
Draft [m]	11.13	0.139
Block coefficient	0.746	
Propeller		
Propeller diameter [m]	7.7	0.096
Blade number	5	
Blade area ratio	0.88	
Pitch ratio	1.4	

4.0 RESULTS AND DISCUSSIONS

The research had extended the work of Harvald [14] in regards with wake and thrust deduction properties in ahead and crashback operations. The properties had been identified from extensive overload test results by mixed loading method at four test speeds comprise 0.45 m/s, 0.72 m/s, 0.86 m/s and 0.98 m/s in combinations with various RPMs to extremely high.

Figure 4 and Figure 5 respectively depict the wake and thrust deduction fractions obtained at various RPM and speed combinations in ahead and crashback operations identified via thrust identity. Take note that wake and thrust deduction properties represent ship-propeller interactions hence given as functions of apparent advance ratio J_v derived as $J_v = V_s/nD$.

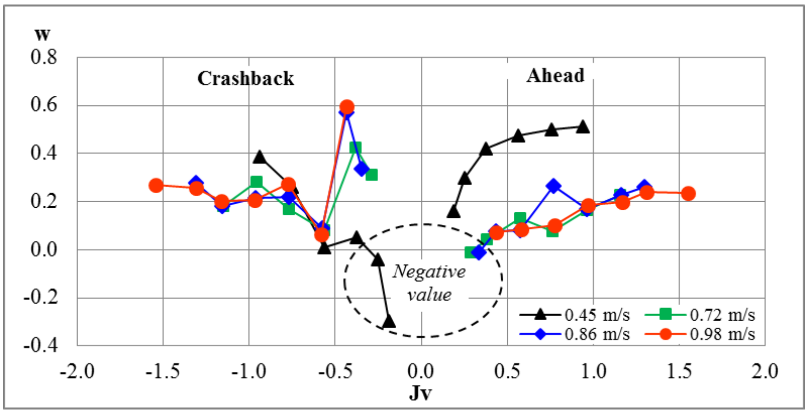

Figure 4: Thrust deduction fraction at various speed and RPM combinations

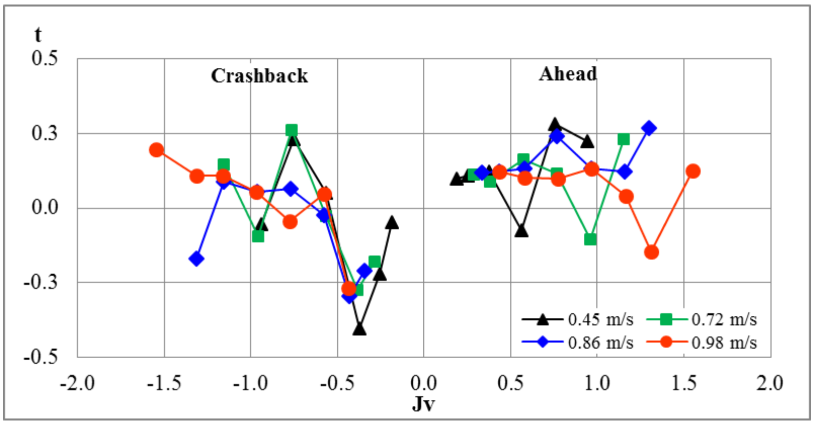

Figure 5: Thrust deduction fraction at various speeds and RPM combinations

As seen in the figure, wake properties at 0.45 m/s demonstrate a separate profile and become negative at low J_v of crashback operation. The profiles show similarity to the shallow water characteristic by Harvald [14]. Some negative values at lower J_v representing extremely high RPM operations in ahead and crashback operations indicated in the figure signify the propeller advancing at a higher speed relative to the water. In crashback operation, the extremely high RPM operations at $J_v \in [-0.5,0)$ generate different profile from $J_v < -0.5$ properties which conform to Ueda *et al.* [16] and Black and Swithenbank [17] possess the similarity to backing operation properties.

Shown also the thrust deduction properties obtained scatter in both ahead and crashback operation which conform with Harvald [14]. The scattering profiles may appear due to various thrusts produced by the propeller which can be smaller, equal to or larger than the ship resistance [1]. At 0.45 m/s, the thrust deduction properties resemble the shallow water characteristic by Harvald [14]. At $J_v \in [-0.5,0)$ representing extremely high RPM in crashback operation, different profiles are observed due to 'similar to backing' operation.

The wake and thrust deduction profiles obtained are generally similar to Harvald's [14] wake and thrust deduction profiles in deep water. Observed from the profiles that there is resemblance between wake and thrust deduction profiles obtained by the research at 0.45 m/s and the wake and thrust deduction profiles in shallow water by Harvald [14] although the test was carried out in deep water. The phenomenon may occur due to the slow speed of 0.45 m/s equals to 8.3 kn in full scale possesses similarities to shallow water operations. As evidenced, it is invisible for wake properties obtained at 0.72 m/s, 0.86 m/s and 0.98 m/s respectively equal to 13.0 kn, 15.4 kn and 17.5 kn full scale speeds representing deep water operations. The effect which is encountered by the wake properties only is believed due to their inherent characteristics as functions of ship speed. Thrust deduction properties which are functions of propeller thrust demonstrate resistance to such influence.

Peculiarities also appear for wake and thrust deduction properties obtained at 'similar to backing' interval at $J_v \in [-0.5,0)$ in crashback operation highlighted by Ueda *et al.* [18] and Black and Swithenbank [17] as clarified in earlier section. At such interval originating from execution of extremely high RPMs, the 'similar to backing' phenomenon previously indicated for propeller properties becomes more pronounced for wake and thrust deduction properties as shown in Figure 6.

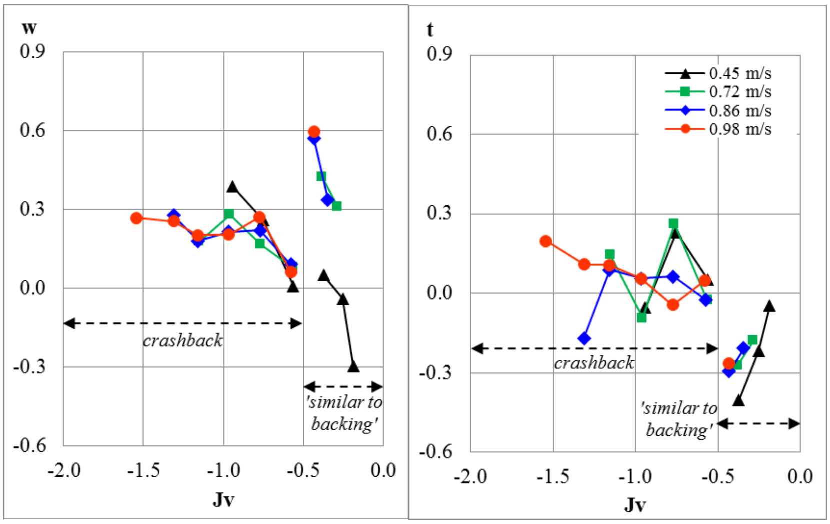

Figure 6: Wake and thrust deduction at crashback and 'similar to backing'

As observed from the figure, both wake and thrust deduction properties behave differently as compared to similar properties merely representing crashback operation at $J_v \in [-\infty,-0.5)$. For gradual reduction of the properties as RPM increases indicated by lower J_v in crashback operation, wake properties at the 'similar to backing' operation significantly rise while thrust deduction properties quickly decrease approaching zero afterwards. Shown also in the figure, wake and thrust deduction properties for 0.45 m/s previously signified as shallow water properties deviate from wake and thrust deduction profiles obtained at 0.72 m/s, 0.86 m/s and 0.98 m/s indicating deep water operations.

Based on the revelations, it is obvious that both wake and thrust deduction properties are dependent of the ship speed and RPM combinations hence refutes previous postulation by Voorde [5] which states otherwise. More importantly, it provides evidence that the current most common and simplest practices to assume both factors as constant values or zero in all kinds of manoeuvring operations as highlighted by Harvald [8] and Artyszuk [7] and implemented such as in Sung and Rhee [10], Artyszuk [11] and Ye *et al.* [19] are invalid and irrelevant. The identified properties henceforth can be used to supersede such simplistic practises to avoid large errors hence obtain more accurate results in the prediction of ship manoeuvring performance in dynamic environment of four quadrant operations as emphasised by Voorde [5], Artyszuk [7] and Hur *et al.* [6].

5.0 CONCLUSIONS

As evidenced, the research had successfully identified four quadrant wake and thrust deduction properties in various speed and RPM combinations in ahead and crashback operations. Dependency of the properties to the ship speed and RPM combinations lead to revelation of the 'similar to shallow water' and 'similar to backing' characteristics. Such results and findings are advantageous for realisation of a realistic and accurate hence reliable ship manoeuvring performance assessment during dynamic operating conditions in four quadrant operations.

i) The wake fraction w and thrust deduction fraction t are normally independent of speed V_s and RPM combination. However, at low speed similar to shallow water operation, both properties resembles the shallow water characteristic despite measurement in deep water operation.
ii) The wake fraction w and thrust deduction fraction t are normally decrease as RPM increases. However, at extremely high RPM in crashback operation referred to as 'similar to backing', wake fraction w decreases while thrust deduction fraction t increases significantly as RPM increases.
iii) The phenomenon of 'similar to backing' operation due extremely high RPM in crashback operation affects thrust and torque coefficients K_T and K_Q, wake fraction w and thrust deduction fraction t.

REFERENCES

[1] Artyszuk, J. (2003). *Wake fraction and thrust deduction during ship astern manoeuvres.* Paper presented at the Marine Technology V: Fifth International Conference on Marine Technology and Transportation.

[2] Artyszuk, J. (2011). Propulsive and Stopping Performance Analysis of Cellular Container Carriers. *Miscellaneous Problems in Maritime Navigation, Transport and Shipping: Marine Navigation and Safety of Sea Transportation,* 107.

[3] Benvenuto, G., Brizzolara, S., & Figari, M. (2001). *SIMULATION OF THE PROPULSION SYSTEM BEHAVIOR DURING SHIP STANDARD MANEUVERS.* Paper presented at the Practical Design of Ships and Other Floating Structures. Proceedings of the Eighth International Symposium on Practical Design of Ships and Other Floating Structures.

[4] Bertram, V. (2012). *Practical Ship Hydrodynamics* (Second ed.): Elsevier.

[5] Black, S., & Swithenbank, S. (2009). *Analysis of crashback forces compared with experimental results.* Paper presented at the First International Symposium on Marine Propulsors, Trondheim, Norway.

[6] 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, 15*(1), 17-49.

[7] Ghose, J., & Gokarn, R. (2004). *Basic ship propulsion*: Allied publishers.

[8] Harvald, S. A. (1967). Wake and thrust deduction at extreme propeller loadings.
[9] Harvald, S. A. (1976). Factors affecting the stopping ability of ships. *International shipbuilding progress, 23*(260).
[10] Harvald, S. A. (1977). Wake and thrust deduction at extreme propeller loadings for a ship running in shallow water. *RINA Supplementary Papers, 119*.
[11] Hur, J., Lee, H., & Chang, B. (2011). *Propeller Loads of Large Commercial Vessels at Crash Stop.* Paper presented at the Second International Symposium on Marine Propulsors smp.
[12] MAN. (2011). Basic Principles of Ship Propulsion.
[13] MARIN. (1996). Resistance and Propulsion. *Teaching Notes*.
[14] Sung, Y. J., & Rhee, K.-P. (2005). New prediction method on the stopping ability of diesel ships with fixied pitch propeller. *International shipbuilding progress, 52*(2), 113-128.
[15] Ueda, T., Sasaki, N., Sugai, N., & Yokoo, N. (1981). Experimental Study on Torque Fluctuation During the Crash Stop Maneuver of the Large Tanker with Ducted Propeller. *船舶技術研究所報告, 18*(1), 35-49.
[16] Ueda, T., Sasaki, N., Sugai, N., & Yokoo, N. (1981). Survey of torque fluctuation at the time of rapid stop and reverse. *Report of Ship Technical Research Institute, 18*(1), 35-49.
[17] 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 Ship Research Centre TNO*.
[18] 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, 11*(1), 35-43.
[19] 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, 6*(2), 148-154.