Literature Review for Design and Assessment of Directional Stability and Turning Performance of Naval Destroyers

Kevin McTaggart

Defence Research and Development Canada
Scientific Report
DRDC-RDDC-2016-R033
February 2016

Abstract

The maneuvering of naval monohull destroyers is considered, including directional stability and turning performance. Both strong turning performance and directional stability can be achieved for a naval destroyer. Adequate rudder size and placement of each rudder behind a propeller will contribute to maneuvering performance. Various methods are available for evaluating maneuvering performance of a proposed design. Accurate predictions of maneuvering motions require accurate hull maneuvering force coefficients, which are most commonly obtained from physical model tests. Computational fluid dynamics including viscous effects is still maturing as a technique for routine prediction of ship maneuvering performance.

Significance for defence and security

If the maneuvering performance of a new naval destroyer design needs to be assessed, then values for hull maneuvering forces should be based on physical model tests or computational fluid dynamics including viscous effects. Physical model tests are likely more reliable and cost effective at this point in time; however, computational fluid dynamics continues to evolve rapidly and is being used more commonly for evaluation of ship maneuvering characteristics.

Résumé

On étudie les manœuvres des destroyers monocoques, y compris leur stabilité de route et leur capacité de virage, lesquelles peuvent être grandes. La capacité de manœuvre repose notamment sur la taille du gouvernail et son emplacement derrière l'hélice. On peut évaluer la capacité de manœuvre d'un concept proposé selon diverses méthodes. Pour prévoir les mouvements de manœuvre avec exactitude, il faut également établir avec exactitude les coefficients de force de manœuvre, généralement par des essais sur des maquettes. La dynamique numérique des fluides, notamment les effets visqueux, ne constitue pas encore une technique totalement éprouvée de prévision courante de la capacité de manœuvre d'un navire.

Importance pour la défense et la sécurité

Pour évaluer la capacité de manœuvre d'un nouveau concept de destroyer, il faut habituellement établir les valeurs relatives aux forces de manœuvre de la coque par des essais sur des maquettes ou par la dynamique numérique des fluides, y compris les effets visqueux. Les essais effectués sur des maquettes demeurent probablement plus fiables et rentables actuellement, mais la dynamique numérique des fluides progresse rapidement et est plus souvent employée pour évaluer les caractéristiques de manœuvre des navires.

Table of contents

List of figures

List of tables

1 Introduction

Directional stability and turning performance are very important aspects of a naval destroyer. Directional stability is the ability to travel straight after an initial yaw disturbance [1]. Good directional stability is highly desirable for operations involving interactions with other entities, such as replenishment at sea and landing of helicopters. Furthermore, good directional stability reduces wear on steering gear and helps ensure safety in the event of a steering malfunction. Turning performance, including the ability to have a small turning circle, is very important for ship operations such as torpedo evasion. On first glance, directional stability and turning performance can appear to be opposing requirements; however, both are positively influenced by a well designed rudder. The present report considers maneuvering performance to be a combination of directional stability and turning performance.

This report reviews literature on design and assessment of maneuvering performance for a monohull naval destroyer. It is assumed that the destroyer would have a conventional steering configuration, with one or two propellers and one or two rudders. Section 2 discusses design aspects of naval ship maneuverability. Section 3 describes the forces that determine the resulting motions of a maneuvering ship. Evaluation of directional stability using simple linear methods is presented in Section 4. Physical modelling of ship maneuvering is discussed in Section 5. Sections 6, 7 and 8 discuss numerical modelling using coefficient-based methods, potential flow, and computational fluid dynamics. Example calculations for a naval destroyer are given in Section 9. Section 10 gives recommendations for design and assessment, followed by final conclusions in Section 11.

2 Design of Naval Ships for Maneuverability

Experience of Canada and partner navies during recent decades has indicated that maneuverability of naval ships is generally satisfactory. Consequently, Canada and its partner navies have not allocated significant resources toward investigation of ship maneuverability. For new naval vessels, the new NATO maneuvering standard [2] specifies many criteria that should be met. For turning of a naval destroyer, the most significant criterion is that the tactical diameter should satisfy the following:

$$\frac{y_{0180}}{L} \leq \begin{cases} 3.5 & \text{for } Fn_0 \leq 0.2 \\ 13\,Fn_0^2 - 3\,Fn_0 + 3.6 & \text{for } > 0.2 \end{cases} \tag{1}$$

where y_{0180} is tactical diameter, L is ship length between perpendiculars, and Fn_0 is ship Froude number based on initial speed entering turn. The NATO maneuvering standard indicates that the above criterion is applicable to a number of naval missions, including anti-submarine warfare, anti-air warfare, and replenishment at sea.

Given the generally satisfactory maneuvering performance of existing naval vessels, they can provide useful guidance toward the design of new vessels. The effectiveness of the ship rudder is a key aspect of maneuvering performance. Furthermore, the rudder is one of the few aspects of the ship that can be altered significantly to influence maneuvering performance. A well functioning rudder will contribute to ship stability when the vessel is going straight and will also provide strong turning performance when required. Obviously, the size of the rudder will have a large influence on maneuvering performance. Existing vessels that have known strong maneuvering performance can be examined to provide guidance regarding the size of the rudder. The location of the rudder and the hullform in its vicinity will influence rudder performance. Most naval vessels have rudders that extend significantly below the keel, leading to strong flow velocity past the rudder. Improved rudder performance can be obtained by placing the rudder in the propeller slipstream so that the rudder experiences increased incident flow velocity, as discussed by Söding [3].

Among the available literature, Crane, Eda, Landsburg provide [4] provide a comprehensive discussion of ship maneuvering oriented toward the ship designer. Tupper [1] gives a very readable and informative treatment of maneuvering and ship design, including mentioning that directional stability increases with trim by stern. Much of the other literature is more focussed on assessment of ship maneuvering for a given ship using model tests, sea trials, or numerical simulation.

3 Forces and Motions for a Maneuvering Ship

Several references give useful overviews of forces and motions acting on a maneuvering ship, including Inoue, Hirano, Kijima and Takashina [5], the Specialist Committee on Esso Osaka of the International Towing Tank Conference [6], Faltinsen [7], and Bertram [8]. The Manoeuvring Committee of the International Towing Tank Conference provided reports in 2011 and 2014 [9, 10] that summarize recent progress. Maneuvering forces are most commonly evaluated using a ship-based axis system, as shown in Figure 1. The x and y coordinates run in the longitudinal and lateral directions respectively. For the longitudinal x axis, the origin is usually located at either midships or the longitudinal centre of gravity. The ship has translational velocity components u and v, and a yaw velocity component r. Note that yaw velocity is expressed in units of rad/s. The ship is subjected to translational force components X and Y and a rotational moment N. The rotational deflection angle of the ship rudder is denoted δ.

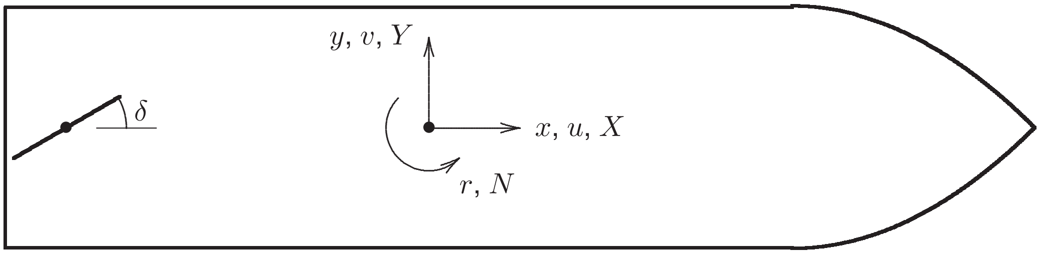

Figure 1: *Axis system for maneuvering motions and forces, including single rudder*

The equations of motion in body-fixed coordinates can be evaluated from the following based on Inoue, Hirano, Kijima and Takashina [5], who specify that the x origin is at the longitudinal centre of gravity:

$$(M + A_{11})\,\dot{u} - (M + A_{22})\;v\,r = X^{hull} + X^{prop} + X^{rudder} \tag{2}$$

$$(M + A_{22})\,\dot{v} + (M + A_{11})\;u\,r = Y^{hull} + Y^{rudder} \tag{3}$$

$$(I_{zz} + A_{66})\;\dot{r} = N^{hull} + N^{rudder} \tag{4}$$

where M is the ship mass, A_{11}, A_{22}, and A_{66} are the ship added mass coefficients in surge, sway, and yaw, $\dot{u}$, $\dot{v}$, and $\dot{r}$ are the ship accelerations in surge, sway, and yaw, X^{hull} is the hull surge force, X^{prop} is the propeller surge force, X^{rudder} is the rudder surge force, Y^{hull} is the hull sway force, Y^{rudder} is the rudder sway force, I_{zz} is the ship yaw inertia, N^{hull} is the hull yaw moment, and N^{rudder} is the rudder yaw moment.

Although the above equations of motion are relatively simple, accurate evaluation of the various force contributions is very challenging.

Non-dimensional terms are frequently used for both ship velocities and forces. When defining non-dimensional terms, total ship velocity is often used:

$$V = \sqrt{u^2 + v^2} \tag{5}$$

The non-dimensional surge, sway, and yaw velocities are then defined as:

$$u' = \frac{u}{V} \tag{6}$$

$$v' = \frac{v}{V} \tag{7}$$

$$r' = \frac{r\,L}{V} \tag{8}$$

where L is ship length between perpendiculars. The non-dimensional forces acting on the ship can be expressed as follows:

$$X' = \frac{X}{1/2\ \rho\ A_w\ V^2} \tag{9}$$

$$Y' = \frac{Y}{1/2\ \rho\ L\ T_{mid}\ V^2} \tag{10}$$

$$N' = \frac{N}{1/2\ \rho\ L^2\ T_{mid}\ V^2} \tag{11}$$

where A_w is ship wetted surface area, and T_{mid} is ship draft at midships. Note that superscripts for hull, propeller, and rudder have not been included in Equations 9 to 11 for simplicity. The above non-dimensional forces are expressed as functions of non-dimensional force coefficients. Two different approaches are commonly used in developing non-dimensional force coefficients. Non-dimensional force coefficients using absolute velocity terms have the benefit of modelling drag forces in a conventional manner; however, non-dimensional force coefficients represented by polynomials (i.e. no absolute velocity terms) are amenable to Fourier analysis. Inoue, Hirano, and Kijima [11] use absolute velocity terms to model sway and yaw non-dimensional forces as follows:

$$\begin{aligned} Y' &= v'\,Y'_v + r'\,Y'_r + v'\,|v'|\,Y'_{v|v|} \\ &\quad + v'\,|r'|\,Y'_{v|r|} + r'\,|r'|\,Y'_{r|r|} \end{aligned} \tag{12}$$

$$\begin{aligned} N' &= v'\,N'_v + r'\,N'_r + r'\,|r'|\,N'_{r|r|} \\ &\quad + v'\,v'\,r'\,N'_{vvr} + v'\,r'\,r'\,N'_{vrr} \end{aligned} \tag{13}$$

Alternatively, the ITTC Specialist Committee on Esso Osaka [6] uses the following polynomials to model sway and yaw non-dimensional forces:

$$Y' = v'\,Y'_v + r'\,Y'_r + v'\,v'\,v'\,Y'_{vvv}$$

$$+ v'\, v'\, r'\, Y'_{vvr} \;+\; v'\, r'\, r'\, Y'_{vrr} \;+\; r'\, r'\, r'\, Y'_{rrr} \tag{14}$$

$$\begin{aligned} N' &= v'\, N'_v \;+\; r'\, N'_r \;+\; v'\, v'\, v'\, N'_{vvv} \\ &\quad + v'\, v'\, r'\, N'_{vvr} \;+\; v'\, r'\, r'\, N'_{vrr} \;+\; r'\, r'\, r'\, N'_{rrr} \end{aligned} \tag{15}$$

When comparing the absolute value (Equations (12) and (13)) and polynomial (Equations (14) and (15)) formulations, some of the terms are identical, including the linear terms.

4 Simple Linear Methods for Evaluating Directional Stability and Handling

The equations for motions and forces presented in the previous section can form the basis for evaluating directional stability and handling. Fortunately, evaluation of ship directional stability and handling can consider small values for non-dimensional sway and yaw velocities v' and r', thus requiring only linear force coefficients.

4.1 Linear Hull Maneuvering Force Coefficients

Inoue, Hirano, and Kijima [11] present equations for ship maneuvering force coefficients developed using a combination of theoretical considerations and model test data. For a ship with even keel, the maneuvering force coefficients based on motions and forces at midships are given by:

$$k = \frac{2\,T_{mid}}{L} \tag{16}$$

$$^{mid}Y'_v = -\frac{\pi\,k}{2} - \frac{1.4\,C_B\,B}{L} \tag{17}$$

$$^{mid}Y'_r = \frac{\pi\,k}{4} \tag{18}$$

$$^{mid}N'_v = -k \tag{19}$$

$$^{mid}N'_r = -0.54\,k + k^2 \tag{20}$$

where k is effective aspect ratio, C_B is ship block coefficient, and B is beam. The preceeding subscript ^{mid} for force terms indicates that the axis system has its origin at midships. In deriving the above equations, the ship is considered to be a foil with low effective aspect ratio as given by k. The first term in each of the above equations is based on the analytical solution for a thin foil. Equations (17) and (20) each have an additional term to account for observations from physical model tests for ship geometries.

Clarke, Gedling, and Hine [12] performed work on estimating hull maneuvering force coefficients. Using experimental data for a variety of ships, they proposed equations which have been modified here to use the non-dimensional force conventions given in Equations (10) and (11):

$$^{mid}Y'_v = -\frac{\pi\,T_{mid}}{L}\left(1.0 + \frac{0.40\,C_B\,B}{T_{mid}}\right) \tag{21}$$

$$^{mid}Y'_r = \frac{\pi\,T_{mid}}{L}\left(0.5 - \frac{2.2\,B}{L} + \frac{0.080B}{T_{mid}}\right) \tag{22}$$

$$^{mid}N'_v = -\frac{\pi\,T_{mid}}{L}\left(0.5 + \frac{2.4\,T_{mid}}{L}\right) \tag{23}$$

$$^{mid}N'_r \;=\; -\frac{\pi\, T_{mid}}{L}\left(0.25 \;+\; \frac{0.039\; B}{T_{mid}} \;-\; \frac{0.56\; B}{L}\right) \tag{24}$$

Clarke and Horne [13] developed updated equations based on a subsequent analysis of maneuvering force coefficients from model tests.

As noted previously, maneuvering force coefficients in Equations 17 to 24 are based on motions and forces at midships. The maneuvering force coefficients based on motions and forces at the longitudinal centre of gravity are:

$$x'_{mid} \;=\; \frac{x_{mid}}{L} \tag{25}$$

$$^{CG}Y'_v \;=\; {}^{mid}Y'_v \tag{26}$$

$$^{CG}Y'_r \;=\; {}^{mid}Y'_r \;+ x'_{mid}\;{}^{mid}Y'_v \tag{27}$$

$$^{CG}N'_v \;=\; {}^{mid}N'_v \;+\; x'_{mid}\;{}^{mid}Y'_v \tag{28}$$

$$^{CG}N'_r \;=\; {}^{mid}N'_r \;+\; x'_{mid}\, x'_{mid}\;{}^{mid}Y'_v \;+ x'_{mid}\;{}^{mid}Y'_r \;+ x'_{mid}\;{}^{mid}N'_v \tag{29}$$

where x_{mid} is the x coordinate of midships relative to the centre of gravity.

Equations 17 to 24 are based on a ship with even trim. Inoue, Hirano, and Kijima [11] presented additional terms to account for the influence of trim. As expected, trim by the stern will increase directional stability, and trim by the bow will decrease directional stability. In comparison with other ship types, the influence of trim on directional stability for a naval destroyer will typically be small because trim will be small.

When considering application of regression methods to determination of ship maneuvering force coefficients, it should be noted that regression methods are often based on a wide variety of ship geometries, leading to significant scatter of data. More accurate results can likely be obtained by applying regression analysis to model test data for ships similar to that being designed.

4.2 Linear Rudder Force Coefficients

The linearized forces resulting from rudder deflection can be expressed as:

$$Y \;=\; \delta\, Y_\delta \tag{30}$$

$$N \;=\; \delta\, N_\delta \tag{31}$$

These forces are typically non-dimensionalized according to Equations (10) and (11). The linearized sway force acting on a deflected rudder can be evaluated by:

$$Y \;=\; \frac{1}{2}\,\rho\, V^2\, A_{rudder}\,\frac{\partial C_{lift}}{\partial \alpha}\,\delta \tag{32}$$

where A_{rudder} is the rudder lateral area and $\partial C_{lift}/\partial\alpha$ is the lift curve slope, which will have a value of approximately 4 for typical ship rudders. The linearized yaw moment acting on the ship due to rudder deflection is then given by:

$$N = x_{rudder}\, Y \tag{33}$$

For a conventional ship with an aft rudder, the non-dimensional sway-rudder force coefficient Y'_δ will be greater than zero and the non-dimensional yaw-rudder force coefficient N'_δ will be less than zero.

When a rudder has zero deflection, it will still have significant influence on the ship maneuvering properties. The non-dimensional contributions will be as follows:

$$\begin{aligned}
Y'_v &= -\frac{A_{rudder}}{L\,T_{mid}}\,\frac{\partial C_{lift}}{\partial\alpha} && (34)\\
Y'_r &= -\frac{A_{rudder}\;x_{rudder}}{L^2\,T_{mid}}\,\frac{\partial C_{lift}}{\partial\alpha} && (35)\\
N'_v &= -\frac{A_{rudder}\;x_{rudder}}{L^2\,T_{mid}}\,\frac{\partial C_{lift}}{\partial\alpha} && (36)\\
N'_r &= -\frac{A_{rudder}\;x^2_{rudder}}{L^3\,T_{mid}}\,\frac{\partial C_{lift}}{\partial\alpha} && (37)
\end{aligned}$$

4.3 Evaluation of Directional Stability and Handling Using Linearized Force Coefficients

Using the linearized models presented above, methods are available for evaluating ship directional stability. Bertram [8] presents the steady yaw rate in a turn based on linearized force coefficients. The equation is adapted here with forces non-dimensionalized according to Equations (10) and (11):

$$\begin{aligned}
r' &= \frac{Y'_\delta\;N'_v\;-\;Y'_v\;N'_\delta}{Y'_v\;(Y'_r\;-\;M')\;C'}\,\delta && (38)\\
M' &= \frac{M}{1/2\,\rho\,T_{mid}\,L^2} && (39)\\
C' &= \frac{N'_r\;-\;M'\,x'_{CG}}{-M'}\;-\;\frac{N'_v}{Y'_v} && (40)
\end{aligned}$$

where M' is non-dimensional ship mass and x'_{CG} is the longitudinal location of the ship centre of gravity non-dimensionalized by ship length. The value of x'_{CG} depends on the selected origin used for the maneuvering force coefficients. The directional stability index C' is greater than zero if the ship has yaw stability. As noted by Bertram, application of Equation (40) to determine directional stability is problematic due to uncertainties in the input coefficients.

Bertram indicates that the slope of the spiral curve in the origin has become a popular indicator of good handling:

$$S' \;=\; \frac{N'_v\, Y'_\delta \;-\; Y'_v\, N'_\delta}{Y'_v\; (N'_r \;-\; M'\, x'_{CG}) \;-N'_v\; (Y'_r \;-\; M')} \tag{41}$$

For satisfactory handling, the spiral curve slope S' should be less than zero. Examining the terms in Equation (41), suitable sizing and placement of the rudder, which will determine Y'_δ and N'_δ, can be used to obtain a value for S' less than zero.

Section 9 of this report gives example computations of directional stability C' (Equation (40)) and spiral slope S' (Equation (41)) for a naval destroyer.

5 Physical Model Testing

Physical model testing has been used for decades for assessment of ship maneuvering performance, with the following three types of experiments being most commonly used:

- rotating arm experiments,
- planar-motion mechanism experiments,
- free running experiments.

Goodman [14] presents an excellent overview of rotating arm and planar motion mechanism (PMM) experiments, focussing on application to submerged bodies. Rotating arm and PMM experiments can be used to determine hull maneuvering force coefficients by imparting prescribed motions to a vessel and measuring the resultant forces. PMM experiments have become more commonly used than rotating arm experiments due to the availability of sophisticated control systems and the ability to complete model tests in a towing tank rather than a larger rotating arm facility. Within Canada, the National Research Council has a PMM capability in St. John's, Newfoundland but has no rotating arm facility. Free running experiments can be used to measure maneuvering performance directly; however, costs can be high, especially when simulating a large number of conditions. Consequently, PMM testing is likely the most commonly used physical modelling method for assessment of ship maneuvering.

The ship model DTMB 5415, based on a preliminary design of the US Navy DDG 51, has been the subject of two sets of extensive PMM experiments that have been published in the public domain [15, 16]. Maneuvering force data from these reports can be considered representative of a modern naval destroyer, and can be used for validation of other methods for predicting hull maneuvering force coefficients.

It should be noted that results from physical model tests will be influenced by scale effects. Although Froude number is matched during a maneuvering model test, the Reynolds number during a maneuvering model test is typically much lower than the full-scale value. Computational fluid dynamics predictions for destroyer maneuvering indicate that rudders will be slightly less effective at model scale than at full scale [17].

6 Numerical Simulation of Ship Motions Using Coefficient-Based Methods

Discussion thus far has focussed mostly on forces on a ship hull arising from maneuvering. If these forces are known with sufficient accuracy, then ship motions can be evaluated in the time domain using numerical integration of ship accelerations given by Equations 2, 3, and 4. Inoue, Hirano, Kijima, Takashina [5], Barr [18], and the ITTC Specialist Committee on Esso Osaka [6] describe coefficient-based simulation methods in detail. Hull forces are evaluated using equations described in Section 3 of the current report. Similar coefficient-based equations are used for evaluating forces acting on propellers and rudders. Interactions between propellers and rudders are important and are modelled in most maneuvering simulations.

DRDC has two software suites available that use coefficient-based methods to model maneuvering forces for ships in calm water or waves. ShipMo3D [19, 20, 21] computes ship motions in both the frequency and time domains, with time domain simulations being used to model maneuvers such as turning circles. McTaggart [22] describes modelling of maneuvering forces within ShipMo3D. FREDYN [23, 24] simulates motions in the time domain for intact and damaged ships in waves, including maneuvering.

PMM model test facilities described in Section 5 typically include software that is capable of simulating maneuvers using force coefficients obtained from model tests. This combination of PMM tests and simulation software is an alternative to performing free running model tests.

Coefficient-based simulation methods run very fast on modern computers, with 100 times faster than real time being a typical computational speed. ShipMo3D validation with the Esso Osaka [6] shows predicted tactical diameters within 12 percent of results from sea trials when hull force coefficients from PMM experiments are used as input to ShipMo3D.

7 Numerical Evaluation of Maneuvering Forces Using Potential Flow Methods

Potential flow methods, which assume zero water viscosity, are widely used for predicting ship motions in waves. Numerical predictions using strip theory [25, 26] and three-dimensional theory [27] are easy to obtain, computationally efficient, and generally of sufficient accuracy [28, 29]. In contrast to seakeeping predictions, accurate maneuvering predictions are difficult to obtain using potential flow methods due to the large influence of flow separation on hull maneuvering forces.

Some appreciation of flow separation can be gained by considering the panelled representation of a generic frigate shown in Figure 2, with the wet hull in yellow, dry hull in green, propellers in blue, and other appendages in red. When the ship is present in an incident flow field, such as that due to ship forward speed and/or ocean waves, the zero normal flow boundary condition on the wet hull can be satisfied by placing a distribution of hull sources on the ship wet panels. This approach is used in ship seakeeping analysis. If the ship in Figure 2 is travelling with steady forward speed, then flow separation will occur at the transom. Significant flow separation will occur at the edges of appendages if the ship has sway and yaw velocity components.

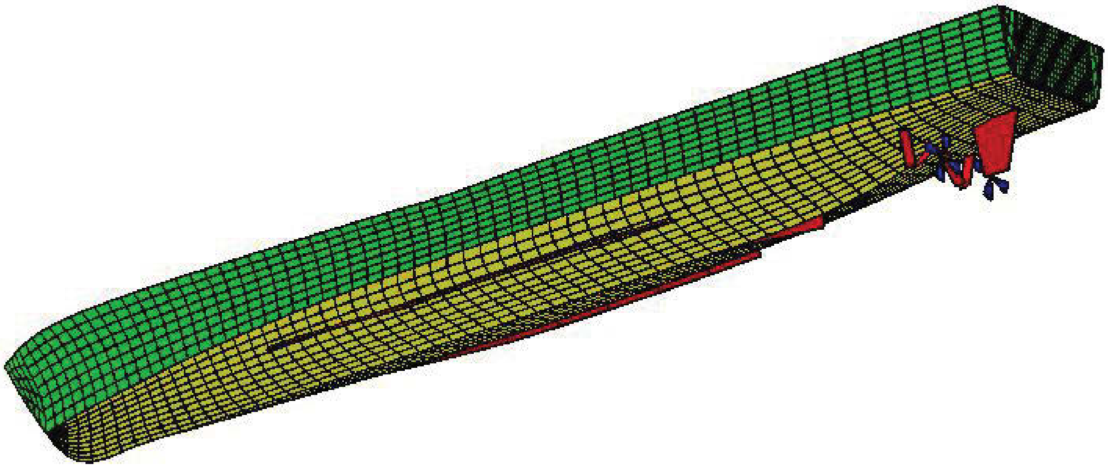

Figure 2: *Panelled representation of generic frigate for potential flow modelling*

Two main approaches are used for applying potential flow methods to prediction of maneuvering forces. In the first approach, as described by Beukelman and Journé [30], potential flow methods are combined with cross-flow drag evaluated using a cross-flow drag coefficient. In the second approach, as described by Nonaka [31], Bertram [8], and Greeley and Willemann [32], flow separation is considered by modelling of vortices. Fujino [33] offers insightful commentary of results from Nonaka's method, indicating underprediction of tactical diameters by approximately 20 to 30 percent. Note that Nonaka used slender body theory, which is less accurate than fully three-dimensional approaches. Although Bertram [8] and Greeley and Willemann [32] describe three-dimensional approaches, they do not indicate expected accuracy for predicted maneuvers, such as turning circles.

A maneuvering ship will induce waves at the free surface due its presence in the surrounding flow. Such waves should be included when evaluating forces on a maneuvering ship. A three-dimensional potential flow method including numerical modelling of horseshoe vortices [8] could model both free surface waves and flow separation, and would likely have greater accuracy than the slender body approach of Nonaka [31].

8 Numerical Evaluation of Maneuvering Forces Using Reynolds-Averaged Navier-Stokes Computational Fluid Dynamics

Computational fluid dynamics (CFD) is emerging as a method for predicting ship maneuvering forces. Although CFD can refer to a broad range of methods, including potential flow, the present report uses the common convention of CFD referring to methods that include detailed modelling of viscous effects. Zikanov [34] gives an overview of CFD. Various CFD methods are used in practice, ranging from moderately high computational requirements to extremely high computational requirements. The present discussion focusses on the Reynolds-Averaged Navier-Stokes (RANS) methods, which have lower computational requirements than some other CFD methods and are the most commonly applied to evaluation of ship maneuvering forces.

CFD is used for flow analysis in a broad range of engineering fields; however, application of CFD to analysis of ship maneuvering forces is challenging for several reasons:

- a large computational domain is required, with length and width equal to several ship lengths, and depth equal to several ship drafts,
- the interface between air and water must be solved,
- the radiation of waves away from the ship presents challenges for CFD,
- user interfaces for CFD software are generally not well suited to ship hydrodynamic analysis.

8.1 CFD Ship Maneuvering Work Completed to Date

CFD application to ship maneuvering has been developing at a rapid rate in recent years. Application of CFD to ship maneuvering is still largely confined to research studies due to the high degrees of knowledge, personnel effort, and computational power required.

The are two main approaches for application of CFD to ship maneuvering:

- simulation of captive model tests (rotating arm tests and planar-motion mechanism tests) to determine ship maneuvering force coefficients,
- simulation of motions for a freely maneuvering ship.

The ITTC Manoeuvring Committee [9, 10] notes that CFD simulation of captive model tests is more commonly used than simulations of motions for a freely maneuvering ship due to computational requirements.

Oldfield, Moradi, Larmaei, Kendrick and McTaggart [35] predicted ship maneuvering force coefficients using simulations of planar-motion mechanism and rotating arm tests. Their paper is one of the few to give details regarding the high computational requirements for CFD simulations. A typical unsteady simulation of a planar-motion mechanism test required approximately 17 hours using 60 computational cores (1020 core-hours). For a typical simulation of a rotating arm test, 5 hours were required using 80 computational cores (400 core-hours).

Carrica, Ismail, Hyman, Bhushan and Stern [36] showed excellent results for simulations of turning circles and zigzags for destroyer model DTMB 5415. The vast majority of their predicted turning circle parameters were well within 10 percent of experimental values. The paper does not give detail regarding required computing resources, but the ITTC Manoeuvring Committee [9] suggests that several months of CPU and wall clock time would be required for such simulations. The success of the numerical predictions in Reference 36 is due to many factors, which likely include the following:

- extensive research experience by the authors in application of CFD to ship maneuvering,
- software that has been developed specifically for ship hydrodynamics,
- large funding support over many years for the development of software,
- highly capable computer hardware,
- availability of time for producing meshes and running simulations,
- availability of model test results when refining simulations.

Stern, Agdrup, Kim, Hochbaum, Rhee, Quadvlieg, Perdon, Hino, Broglia and Gorski [37] gave an overview of results of the SIMMAN 2008 workshop, which focussed on verification and validation of CFD predicitons of ship maneuvering. This paper included comparisons of tactical diameter for destroyer model DTMB 5415, showing very good accuracy from CFD predictions.

Practical application of CFD to ship maneuvering most likely will require that accurate predictions be obtained in a timely manner from widely available software. DRDC sponsored the simulations described by Oldfield, Moradi, Larmaei, Kendrick and McTaggart [35] to investigate what was practically possible using the commercial software Star-CCM+. The available budget was sufficient for several person-months of effort and computations using a desktop computer. This effort produced very encouraging results, and highlighted the importance of skilled users when applying CFD software to ship maneuvering force prediction.

8.2 CFD Software for Evaluation of Ship Maneuvering

It is anticipated that CFD software will be used by DND and its contractors for ship maneuvering analysis. Such software should be validated for purpose and should be available to an adequate number of users to support DND efforts.

OpenFOAM [38] is freely available CFD software. It is widely used by academic researchers because of its free cost and availability of source code, which is often modified by researchers. DRDC has performed some work evaluating OpenFOAM and has found the documentation and ease of use to be inferior to commercially available CFD software. DRDC is not aware of any organizations routinely using OpenFOAM for ship maneuvering analysis.

Among commercial CFD software, Star-CCM+ from CD-adapco [39] is likely the most widely used for ship hydrodynamics. Simonsen, Otzen, Klimt, Larsen, Stern [40] and Oldfield, Moradi, Larmaei, Kendrick and McTaggart [35] describe its application for simulating PMM experiments to determine ship maneuvering coefficients. DRDC has licenses for Star-CMM+, and staff have taken the introductory (three days) and Virtual Towing Tank (two days) training courses. DRDC is aware of four commercial companies in Canada actively using Star-CMM+ for ship hydrodynamics. Due to the wide range of capabilities of Star-CCM+, the introductory course is quite challenging. The Virtual Towing Tank course is more focussed and generally easier to follow. The wide range of capabilities of Star-CMM+ contributes to the user interface being difficult to use. To circumvent this problem, users in specific engineering domains often develop their own user interfaces written in Java to call the Star-CCM+ application programmer interface (API).

NUMECA FINE™/Marine [41] is one of several domain-specific CFD suites offered by NUMECA. It appears to be gaining in popularity within the marine industry. Due to it being tailored for marine applications, training and navigation of the user interface are simpler than for more general purpose CFD suites. Unfortunately, a literature search revealed no significant publications on application of NUMECA FINE™/Marine to ship maneuvering.

9 Example Calculations for a Naval Destroyer

The section presents example calculations for a full-scale ship based on model DTMB 5415 in Reference 42, with dimensions given in Table 1. Interestingly, the ratio of lateral rudder area to nominal hull lateral area is 0.035, much greater than a typical value of 0.015 indicated by Bertram [8].

Table 1: *Full-scale ship dimensions for DTMB 5415*

Length between perpendiculars, L	142.00 m
Beam at waterline, B	19.06 m
Draft at midships, T_{mid}	6.15 m
Block coefficient	0.51
Number of rudders	2
Lateral area of each rudder	15.4 m^2
Total lateral rudder area/$(L\ T_{mid})$	0.035
Number of propellers	2

The present calculations assume that the rudders are located 65 m aft of midships and that the ratio of the span to chord length of each rudder is 3.0. It is also assumed that the ship longitudinal centre of gravity is located at midships.

Table 2 gives hull maneuvering force coefficients based on Equations 17 to 20 from Inoue, Hirano, and Kijima [11] and Equations Equations 21 to 24 from Clarke, Gedling, and Hine [12]. The linear hull force coefficients from the two different methods have very good agreement.

Table 2: *Linear maneuvering force coefficients for DTMB 5415*

	Inoue et al. [11]	Clarke et al. [12]
Y'_v	-0.2286	-0.2188
Y'_r	0.0664	0.0609
N'_v	-0.0845	-0.0798
N'_r	-0.0385	-0.0397

Table 3 gives directional stability as evaluated using Equation (40). The positive directional stability for the hull is expected due to its relatively fine block coefficient. Not surprisingly, the presence of the rudders has a large influence on directional stability.

Table 3: *Directional stability C' for DTMB 5415*

	C' for hull only	C' for hull and rudders
Inoue et al. [11] hull force coefficients	0.193	0.984
Clarke et al. [12] hull force coefficients	0.214	1.012

Table 4 gives spiral curve slopes evaluated using Equation (41). Both sets of hull coefficients give spiral curve slopes less than zero, indicating good maneuvering performance.

Table 4: *Spiral curve slope S' for DTMB 5415*

	Spiral curve slope S'
Inoue et al. [11] hull force coefficients	-3.312
Clarke et al. [12] hull force coefficients	-3.366

The calculations presented above demonstrate the evaluation of maneuvering performance using simple methods; however, the results from these calculations would be more useful if there were a better understanding of how values for directional stability C' and spiral curve slope S' are relative to maneuvering performance. For example, what values of directional stability and spiral curve slope are recommended so that a naval destroyer can meet NATO criteria for maneuvering?

Table 5 gives tactical diameters from model tests and computational fluid dynamics for the MARIN 7967 variant of DTMB 5415 [36]. The initial speed before commencing the turn is given by Fn_0, which has values of 0.25 and 0.41. Propeller RPMs were kept constant during each turning circle maneuver. The equilibrium rudder deflection during each turn was 35 degrees. For the model tests, tactical diameters differed between turns to starboard and port, with average values given in Table 5. The CFD predictions and model test values in Table 5 have excellent agreement, with differences of 5 percent or less. The obtained tactical diameters are slightly greater than specified NATO criteria for naval destroyers in open water [2].

Table 5: *Tactical diameter for DTMB 5415 variant MARIN 7967*

	Tactical diameter y_{0180}/L	
	$Fn_0 = 0.25$	$Fn_0 = 0.41$
Physical model tests [36]	4.07	4.70
Computational fluid dynamics [36]	3.87	4.62
NATO open water criterion [2]	3.66	4.56

10 Recommendations

The information presented above can form the basis for recommendations regarding maneuvering design and assessment for naval destroyers.

10.1 Recommendations for General Design

Ship maneuvering performance is challenging to predict and is also challenging to modify after a ship has been built. Fortunately, maneuvering performance for existing naval destroyers is generally good, and they can provide insight for construction of new vessels.

A ship configuration with two rudders and two propellers has benefits of redundancy and has the advantage of each rudder being in a propeller slipstream, increasing rudder performance. It is recommended that naval destroyers with conventional propulsion have two rudders and two propellers.

It is recommended that naval destroyers be designed to have strong maneuvering performance with level trim. This approach allows for unexpected maneuvering performance to be somewhat addressed by inducing trim, thus altering directional stability.

It is recommended that maneuvering criteria for a given ship be assessed and satisfied for a range of loading conditions, including the anticipated heaviest loading condition during the life of the ship. Inclusion of the heaviest loading condition is important because the rudder area relative to the hull lateral area will be smallest at this condition.

Experience with destroyer model DTMB 5415 suggests that the total lateral rudder area of a naval destroyer should be at least three percent of the hull lateral area. It is recommended that this ratio be examined during preliminary ship design. Note that the recommended rudder area ratio is merely intended as a guideline, and will not guaranty satisfactory maneuvering performance.

As ship design progresses from preliminary design to final design, increasingly sophisticated methods should be used to assess maneuvering performance. The progression of assessment methods could proceed in the following sequence:

- preliminary rudder area determined based on hull lateral area,
- directional stability and spiral curve slope using hull force coefficients from regression methods and Equations (40) and (41),
- full experimental or numerical modelling of turning and zigzag maneuvers, most likely using numerical simulation with input force coefficients from restrained model tests or computational fluid dynamics.

10.2 Recommendations for Physical Model Testing

Physical model tests continue to be important for assessment of ship maneuvering performance and validation of numerical predictions. Physical model tests compare favourably with other methods when accurate determination of maneuvering forces and resulting motions are required.

It is recommended that physical model testing be conducted for new destroyer designs. A PMM experimental facility combined with accompanying validated software for simulating motions can provide accurate prediction of ship maneuvering performance. Further experiments with a freely maneuvering model can provide additional confidence in maneuvering performance.

Physical model tests of ship maneuvering require both specialized facilities and specialized technical expertise. Care should be taken to ensure that both are available when considering a model test program.

10.3 Recommendations for Simulation of Maneuvering Using Coefficient-Based Numerical Methods

Coefficient-based numerical methods have very fast computational speed, making them very useful for applications such as examining the influence of proposed design changes. When using these methods, effort should be made to obtain the best possible input force coefficients. It is recommended that these input force coefficients should be obtained from physical model tests or detailed CFD studies.

ShipMo3D and FREDYN can both simulate maneuvers using input hull force coefficients. These programs should be validated against experimental maneuvering data for destroyer model DTMB 5415.

10.4 Recommendations for Potential Flow Modelling

The importance of flow separation during ship maneuvering presents a great challenge to potential flow methods. To date, maneuvering simulations based most on potential flow modelling have required input maneuvering force coefficients, which have been obtained from physical model tests or computational fluid dynamics.

It’s possible that accurate modelling of the free surface using source panels and modelling of flow separation using horseshoe vortices could lead to reasonable estimates of maneuvering forces using potential flow methods. Given the high computational speed and modest required implementation effort, it is recommended that these improvements to existing potential flow methods be investigated.

In the long term, potential flow methods could be used to determine boundary conditions for CFD methods. This coupled approach could eliminate problems with large fluid domains and wave reflections, which are currently two of the greatest challenges in the application of CFD to ship maneuvering.

10.5 Recommendations for Computational Fluid Dynamics

Computational fluid dynamics continues to advance at a tremendous pace; however, it has not yet been widely adopted for prediction of ship maneuvering performance. Barriers to routine application include high software license costs, high memory requirements, high CPU time requirements, high real time requirements, high personnel requirements, and lack of robustness of results due to challenges such as wave reflection.

It is recommended that progress in application of CFD to ship maneuvering continue to be monitored. In the short term, efforts should focus on prediction of hull maneuvering force coefficients using numerical simulation of PMM tests and rotating arm tests. In the longer term, simulation of complete maneuvers should be examined. Coupling of CFD with potential flow methods should be explored for improvements in computational speed and robustness of results.

11 Conclusions

Experience with naval destroyers and example computations suggest that a naval destroyer can have both good turning performance and good directional stability. The maneuvering performance of a ship will be strongly influenced by its rudder(s). For a modern destroyer with conventional propellers, it is recommended that the ship have two rudders and two propellers so that the performance of each rudder can be enhanced by a propeller slip stream. It is also recommended that the total lateral rudder area should be at least three percent of the lateral area of the ship hull when at its deepest loading condition.

Prior to ship construction, ship maneuvering performance can be predicted using free-running model experiments or using simulations with accurate input hull force coefficients. Due to the complexity of flow separation influencing ship maneuvering forces, physical model tests or detailed CFD modelling should be performed to determine hull maneuvering forces during maneuvers. These accurate force values can be used as input to coefficient-based methods for evaluating motions of a maneuvering ship. Application of CFD to ship maneuvering is still evolving, and is not yet routinely used in ship design.

References

[1] Tupper, E. (1996), Introduction to Naval Architecture, Jersey City, New Jersey: Society of Naval Architects and Marine Engineers.

[2] North Atlantic Treaty Organization (2011), Common Framework for Naval Surface Ship Manoeuvring Performance and Requirements. Pending Ratification – Submitted to NATO Staffing November 2011.

[3] Söding, H. (1998), Limits of Potential Theory in Rudder Flow Predictions, In *22nd Symposium on Naval Hydrodynamics*, Washington.

[4] Crane, C., Eda, H., and Landsburg, A. (1989), Principles of Naval Architecture, Volume III, Ch. 9, Controllability, Society of Naval Architects and Marine Engineers.

[5] Inoue, S., Hirano, M., Kijima, K., and Takashina, J. (1981), A Practical Calculation Method of Ship Manoeuvring Motion, *International Shipbuilding Progress*, 28(325), 207–222.

[6] The Specialist Committee on Esso Osaka (2002), Final Recommendations to the 23rd ITTC, In *23rd International Towing Tank Conference*, Vol. II, pp. 573–609, The Hague.

[7] Faltinsen, O. (2005), Hydrodynamics of High-Speed Marine Vehicles, Cambridge, England: Cambridge University Press.

[8] Bertram, V. (2012), Practical Ship Hydrodynamics, 2nd ed, Oxford: Butterworth-Heinemann.

[9] Manoeuvring Committee (2011), Final Report and Recommendations to the 26th ITTC, In *26th International Towing Tank Conference*, Rio de Janeiro.

[10] Manoeuvring Committee (2014), Final Report and Recommendations to the 27th ITTC, In *27th International Towing Tank Conference*, Copenhagen.

[11] Inoue, S., Hirano, M., and Kijima, K. (1981), Hydrodynamic Derivatives on Ship Manoeuvring, *International Shipbuilding Progress*, 28(321), 112–125.

[12] Clarke, D., Gedling, P., and Hine, G. (1983), The Application of Manoeuvring Criteria in Hull Design Using Linear Theory, *Transactions, Royal Institution of Naval Architects*, 125, 45–68.

[13] Clarke, D. and Horne, J. (1997), Estimation of Hydrodynamic Derivatives, In *Eleventh Ship Control Systems Symposium*, Vol. 2, pp. 275–290, Southampton, England.

[14] Goodman, A. (1960), Experimental Techniques and Methods of Analysis used in Submerged Body Research, In *Third Symposium on Naval Hydrodynamics*, Scheveningen, Netherlands.

[15] Simonsen, C. D. (2004), PMM Model Test with DDG51 including Uncertainty Assessment, (Report) FORCE Technology, Lyngby, Denmark.

[16] Benedetti, L., Bouscasse, B., Broglia, R., Fabbri, L., La Gala, F., and Lugni, C. (2007), PMM Model Test with DDG51 Including Uncertainty Assessment, (Report) Istituto Nazionale Per Studi Ed Esperienze Di Architettura Navale (INSEAN).

[17] Bhushan, S., Xing, T., Carrica, P., and Stern, F. (2009), Model- and Full-Scale URANS Simulations of Athena Resistance, Powering, Seakeeping, and 5415 Maneuvering, *Journal of Ship Research*, 53(4), 179–198.

[18] Barr, R. (1993), A Review and Comparison of Ship Maneuvering Simulation Methods, *Transactions, Society of Naval Architects and Marine Engineers*, 101, 609–635.

[19] McTaggart, K. (2012), ShipMo3D Version 3.0 User Manual for Creating Ship Models, (DRDC Atlantic TM 2011-307) Defence Research and Development Canada – Atlantic.

[20] McTaggart, K. (2012), ShipMo3D Version 3.0 User Manual for Computing Ship Motions in the Time and Frequency Domains, (DRDC Atlantic TM 2011-308) Defence Research and Development Canada – Atlantic.

[21] McTaggart, K. (2012), Validation of ShipMo3D Version 3.0 User Applications for Simulation of Ship Motions, (DRDC Atlantic TM 2011-306) Defence Research and Development Canada – Atlantic.

[22] McTaggart, K. (2008), Improved Maneuvering Forces and Autopilot Modelling for the ShipMo3D Ship Motion Library, (DRDC Atlantic TM 2008-162) Defence Research and Development Canada – Atlantic.

[23] de Kat, J., Pinkster, D.-J., and McTaggart, K. (2002), Random Waves and Capsize Probability Based on Large Amplitude Motion Analysis, In *21st International Conference on Offshore Mechanics and Arctic Engineering*, Oslo.

[24] van Walree, F. and Carette, N. (2011), Validation of Time Domain Seakeeping Codes for a Destroyer Hull Form Operating in Steep Stern-Quartering Seas, *International Journal of Naval Architecture and Ocean Engineering*, 3(1), 9–19.

[25] Salvesen, N., Tuck, E., and Faltinsen, O. (1970), Ship Motions and Sea Loads, *Transactions, Society of Naval Architects and Marine Engineers*, 78, 250–287.

[26] Schmitke, R. (1978), Ship Sway, Roll, and Yaw Motions in Oblique Seas, *Transactions, Society of Naval Architects and Marine Engineers*, 86, 26–46.

[27] Papanikolaou, A. and Schellin, T. (1992), A Three-Dimensional Panel Method for Motions and Loads of Ships with Forward Speed, *Schiffstechnik (Ship Technology Research)*, 39(4), 147–156.

[28] McTaggart, K., Datta, I., Stirling, A., Gibson, S., and Glen, I. (1997), Motions and Loads of a Hydroelastic Frigate Model in Severe Seas, *Transactions, Society of Naval Architects and Marine Engineers*, Vol. 105.

[29] McTaggart, K. (2010), Verification and Validation of ShipMo3D Ship Motion Predictions in the Time and Frequency Domains, In *International Towing Tank Conference Workshop on Seakeeping: Verification and Validation for Non-linear Seakeeping Analysis*, Seoul, Korea.

[30] Beukelman, W. and Journée, J. (2001), Hydrodynamic Transverse Loads on Ship in Deep and Shallow Water, In *HADMAR 2001, Twenty-second International Conference on Hydrodynamics and Aerdynamics in Marine Engineering*, Varna, Bulgaria.

[31] Nonaka, K. (1993), Estimation of Hydrodynamic Forces Acting on a Ship in Manoeuvring Motion, In *MARSIM '93, International Conference on Marine Simulation and Ship Manoeuvrability*, St. John's, Newfoundland.

[32] Greeley, D. and Willemann, S. (2013), Surface Ship Maneuvering Forces in Calm Water and Waves, *International Shipbuilding Progress*, 60, 613–631.

[33] Fujino, M. (1996), Prediction of Manoeuvrability: State of the Art, In *Marine Simulation and Ship Manoeuvrability*, Rotterdam.

[34] Zikanov, O. (2010), Essential Computational Fluid Dynamics, Hoboken, New Jersey: John Wiley & Sons.

[35] Oldfield, C., Larmaei, M. M., Kendrick, A., and McTaggart, K. (2015), Prediction of Warship Manoeuvring Coefficients using CFD, In *World Maritime Technology Conference*, Providence, Rhode Island.

[36] Carrica, P., Ismail, F., Hyman, M., Bhushan, S., and Stern, F. (2013), Turn and Zigzag Maneuvers of a Surface Combatant using a URANS Approach with Dynamic Overset Grids, *Journal of Marine Science and Technology*, 18, 166–181.

[37] Stern, F., Agdrup, K., Kim, S., Hochbaum, A., Rhee, K., Quadvlieg, F., Perdon, P., Hino, T., Broglia, R., and Gorski, J. (2011), Experience from SIMMAN 2008—The First Workshop on Verification and Validation of Ship Maneuvering Simulation Methods, *Journal of Ship Research*, 55(2), 135–147.

[38] OpenFOAM - The Open Source Computational Fluid Dynamics (CFD) Toolbox (online), `http://www.openfoam.com/` (Access Date: 29 October 2014).

[39] STAR-CCM+ — CD-adapco (online), `http://www.cd-adapco.com/products/star-ccm%C2%AE` (Access Date: 29 October 2014).

[40] Simonsen, C., Otzen, J., Klimt, C., Larsen, N., and Stern, F. (2012), Maneuvering Predictions in the Early Design Phase Using CFD Generated PMM Data, In *Twenty-Ninth Symposium on Naval Hydrodynamics*, Gothenburg, Sweden.

[41] FINE$^{\text{TM}}$/Marine — Numeca (online), `http://www.numeca.com/en/products/finetmmarine` (Access Date: 30 October 2014).

[42] US Navy Combatant, DTMB 5415 Geometry and Conditions, SIMMAN 2008, FORCE Technology (online), `http://www.simman2008.dk/5415/5415_geometry.htm` (Access Date: 30 October 2014).

Symbols and Abbreviations

A_w	ship wetted surface area
A_{ij}	ship added mass
B	ship beam
C_B	ship block coefficient
C_{lift}	lift coefficient
C'	directional stability index
Fn_0	forward speed Froude number at beginning of maneuver
I_{zz}	ship yaw inertia
k	effective aspect ratio of ship hull
L	ship length between perpendiculars
M	ship mass
M'	non-dimensional ship mass
N	ship yaw moment
N'	non-dimensional yaw moment $N/(\rho L^2 T_{mid} V^2/2)$
N'_r	linear yaw-yaw force coefficient
$N'_{r\|r\|}$	nonlinear yaw force coefficient for yaw motion
N'_{rrr}	nonlinear yaw force coefficient for yaw-yaw-yaw motion
N'_v	linear yaw-sway force coefficient
N'_{vrr}	nonlinear yaw force coefficient for sway-yaw-yaw motion
N'_{vvr}	nonlinear yaw force coefficient for sway-sway-yaw motion
N'_{vvv}	nonlinear yaw force coefficient for sway-sway-sway motion
PMM	planar-motion mechanism
r	ship yaw velocity
r'	non-dimensional yaw velocity rL/V
$\dot{r}$	ship yaw acceleration
S'	slope of spiral curve
T_{mid}	draft at midships
u	ship surge velocity
u'	non-dimensional surge velocity u/V
$\dot{u}$	ship surge acceleration
V	ship horizontal plane velocity
v	ship sway velocity
v'	non-dimensional sway velocity v/V
$\dot{v}$	ship sway acceleration

X	force along ship longitudinal axis
X'	non-dimensional force along ship longitudinal axis $X/(\rho A_w V^2/2)$
x'_{CG}	non-dimensional location of ship centre of gravity
x_{rudder}	longitudinal location of rudder
Y	force along ship lateral axis
Y'	non-dimensional force along ship lateral axis $Y/(\rho L T_{mid} V^2/2)$
Y'_r	linear sway-yaw force coefficient
$Y'_{r\|r\|}$	nonlinear sway force coefficient for yaw-yaw motion
Y'_{rrr}	nonlinear sway force coefficient for yaw-yaw-yaw motion
Y'_v	linear sway-sway force coefficient
$Y'_{v\|r\|}$	nonlinear sway force coefficient for sway-yaw motion
Y'_{vrr}	nonlinear sway force coefficient for sway-yaw-yaw motion
$Y'_{v\|v\|}$	nonlinear sway force coefficient for sway-sway motion
Y'_{vvr}	nonlinear sway force coefficient for sway-sway-yaw motion
Y'_{vvv}	nonlinear sway force coefficient for sway-sway-sway motion
y_{0180}	tactical diameter
α	flow angle of attack
δ	rudder deflection angle

DOCUMENT CONTROL DATA

(Security markings for the title, abstract and indexing annotation must be entered when the document is Classified or Protected.)

1. ORIGINATOR (The name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Centre sponsoring a contractor's report, or tasking agency, are entered in section 8.)

DRDC – Atlantic Research Centre
PO Box 1012, Dartmouth NS B2Y 3Z7, Canada

2a. SECURITY MARKING (Overall security marking of the document, including supplemental markings if applicable.)

UNCLASSIFIED

2b. CONTROLLED GOODS

(NON-CONTROLLED GOODS)
DMC A
REVIEW: GCEC DECEMBER 2013

3. TITLE (The complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S, C or U) in parentheses after the title.)

Literature Review for Design and Assessment of Directional Stability and Turning Performance of Naval Destroyers

4. AUTHORS (Last name, followed by initials – ranks, titles, etc. not to be used.)

McTaggart, K.

5. DATE OF PUBLICATION (Month and year of publication of document.)

February 2016

6a. NO. OF PAGES (Total containing information. Include Annexes, Appendices, etc.)

40

6b. NO. OF REFS (Total cited in document.)

42

7. DESCRIPTIVE NOTES (The category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

Scientific Report

8. SPONSORING ACTIVITY (The name of the department project office or laboratory sponsoring the research and development – include address.)

DRDC – Atlantic Research Centre
PO Box 1012, Dartmouth NS B2Y 3Z7, Canada

9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant.)

01ea1.2

9b. CONTRACT NO. (If appropriate, the applicable number under which the document was written.)

10a. ORIGINATOR'S DOCUMENT NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document.)

DRDC-RDDC-2016-R033

10b. OTHER DOCUMENT NO(s). (Any other numbers which may be assigned this document either by the originator or by the sponsor.)

11. DOCUMENT AVAILABILITY (Any limitations on further dissemination of the document, other than those imposed by security classification.)

Unlimited

12. DOCUMENT ANNOUNCEMENT (Any limitation to the bibliographic announcement of this document. This will normally correspond to the Document Availability (11). However, where further distribution (beyond the audience specified in (11)) is possible, a wider announcement audience may be selected.)

Unlimited

13. ABSTRACT (A brief and factual summary of the document. It may also appear elsewhere in the body of the document itself. It is highly desirable that the abstract of classified documents be unclassified. Each paragraph of the abstract shall begin with an indication of the security classification of the information in the paragraph (unless the document itself is unclassified) represented as (S), (C), or (U). It is not necessary to include here abstracts in both official languages unless the text is bilingual.)

The maneuvering of naval monohull destroyers is considered, including directional stability and turning performance. Both strong turning performance and directional stability can be achieved for a naval destroyer. Adequate rudder size and placement of each rudder behind a propeller will contribute to maneuvering performance. Various methods are available for evaluating maneuvering performance of a proposed design. Accurate predictions of maneuvering motions require accurate hull maneuvering force coefficients, which are most commonly obtained from physical model tests. Computational fluid dynamics including viscous effects is still maturing as a technique for routine prediction of ship maneuvering performance.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (Technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus. e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus identified. If it is not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title.)

directional stability
maneuvering
ship motions
turning