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Tow Forces in Waves for Canadian Navy Vessels

Kevin McTaggart and Eric Thornhill

Defence R&D Canada – Atlantic

Technical Memorandum
DRDC Atlantic TM 2009-139
December 2009

Canada

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Abstract

Towing operations are often conducted by the Canadian Navy. Evaluation of associated forces is required to determine whether towing can safely occur without breakage of rope. This report examines forces that can influence towing operations in a seaway. Ship hydrodynamic resistance and air resistance are evaluated using drag coefficients. For a vessel being towed, additional resistance arises from propeller parasitic drag, which will vary greatly depending on whether a propeller is freewheeling or locked. The presence of a seaway introduces added resistance, and also dynamic forces due to surge excitation acting on the two vessels in a towing operation. A frequency domain method has been developed for predicting dynamic forces during towing. Towing force predictions in sea state 5 show that the presence of a seaway can contribute greatly to total towing forces. It is recommended that propellers on a towed vessel be allowed to freewheel during towing operations, and that towing speeds be reduced in higher sea states.

Résumé

La Marine canadienne effectue souvent des opérations de remorquage. Il est nécessaire d'évaluer les forces en jeu afin d'établir si le remorquage peut se faire en toute sécurité sans rupture de la remorque. Le présent rapport examine les forces susceptibles d'influer sur les opérations de remorquage dans une voie maritime. On emploie des coefficients de traînée pour évaluer la résistance aérodynamique et la résistance hydrodynamique des navires. Dans le cas d'un navire remorqué, la traînée parasite des hélices, qui varie considérablement selon que les hélices tournent en roue libre ou sont bloquées, produit une résistance supplémentaire. La présence d'une voie maritime induit une résistance additionnelle ainsi que des forces dynamiques attribuables aux vagues agissant sur les deux navires pendant le remorquage. Une méthode de prévision dans le domaine fréquentiel a été mise au point pour évaluer les forces dynamiques agissant pendant le remorquage. Les prévisions des forces exercées pendant le remorquage dans une mer à l'état 5 montrent que la présence d'une voie maritime contribue grandement à l'ensemble des forces exercées. Pendant le remorquage, il est conseillé de laisser tourner en roue libre les hélices du navire remorqué et de réduire la vitesse de remorquage lorsque la mer est agitée (états élevés de la mer).

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Executive summary

Tow Forces in Waves for Canadian Navy Vessels

Kevin McTaggart and Eric Thornhill; DRDC Atlantic TM 2009-139; Defence R&D Canada – Atlantic; December 2009.

Introduction: Towing operations are often conducted by the Canadian Navy. Evaluation of associated forces is required to determine whether towing can safely occur without breakage of rope. This report examines forces that can influence towing operations in a seaway.

Principal Results: Ship hydrodynamic resistance and air resistance are evaluated using standard approaches based on drag coefficients. When a ship is being towed, additional resistance arises from propeller parasitic drag, which will vary greatly depending on whether a propeller is locked or freewheeling. The presence of a seaway causes added resistance, and also dynamic forces due to surge excitation of the two vessels involved in a towing operation. A frequency domain method has been developed to evaluate dynamic towing forces. Predictions of towing forces in sea state 5 indicate that added resistance and dynamic forces will contribute greatly to total towing forces.

Significance of Results: The presence of a seaway must be considered when determining whether towing can safely proceed. Due to the large magnitude of forces induced by a seaway, it is recommended that improved methods be developed for evaluating associated forces. The frequency domain method developed for predicting dynamic towing forces is based on conservative assumptions, and likely over-predicts towing forces. The strong dependence of towing forces on sea conditions, ship speed, and heading suggest that real-time operational guidance would be very useful for reducing the risk of tow rope breakage during towing operations. It is recommended that propellers on a towed vessel be allowed to freewheel during towing operations, and that towing speeds be reduced in higher sea states.

Future Plans: Added resistance computations will be implemented in ShipMo3D, and will likely give improved accuracy over the current strip theory predictions from SHIPMO7. Time domain simulations of towing operations will be developed, and will likely give more accurate predictions of dynamic forces. Sea trials are planned to validate numerical force predictions.

Sommaire

Tow Forces in Waves for Canadian Navy Vessels

Kevin McTaggart and Eric Thornhill ; DRDC Atlantic TM 2009-139 ; R & D pour la défense Canada – Atlantique ; décembre 2009.

Introduction : La Marine canadienne effectue souvent des opérations de remorquage. Il est nécessaire d'évaluer les forces en jeu afin d'établir si le remorquage peut se faire en toute sécurité sans rupture de la remorque. Le présent rapport examine les forces susceptibles d'influer sur les opérations de remorquage dans une voie maritime.

Résultats principaux : On emploie des méthodes normalisées axées sur les coefficients de traînée pour évaluer la résistance aérodynamique et la résistance hydrodynamique des navires. Lorsqu'un navire est remorqué, la traînée parasite des hélices, qui varie considérablement selon que les hélices tournent en roue libre ou sont bloquées, produit une résistance supplémentaire. La présence d'une voie maritime induit une résistance additionnelle ainsi que des forces dynamiques attribuables aux vagues agissant sur les deux navires pendant le remorquage. Une méthode de prévision dans le domaine fréquentiel a été mise au point pour évaluer les forces dynamiques agissant pendant le remorquage. Les prévisions des forces exercées pendant le remorquage dans une mer à l'état 5 montrent que les forces dynamiques et la résistance accrue contribuent grandement à l'ensemble des forces exercées.

Importance des résultats : Au moment de déterminer si le remorquage peut se dérouler en toute sécurité, il faut tenir compte de la présence d'une voie maritime. Comme les forces induites par une voie maritime sont très importantes, il est conseillé de mettre au point de meilleures méthodes d'évaluation des forces connexes. La méthode de prévision dans le domaine fréquentiel mise au point pour déterminer les forces dynamiques agissant pendant le remorquage se fonde sur des hypothèses prudentes et surévalue probablement les forces exercées. Le fait que les forces exercées pendant le remorquage dépendent fortement des conditions de la mer, de la vitesse des navires et du cap suivi, laisse à penser qu'il serait utile de disposer des données opérationnelles en temps réel afin de réduire les risques de rupture de la remorque pendant des opérations de remorquage. Pendant le remorquage, il est conseillé de laisser tourner en roue libre les hélices du navire remorqué et de réduire la vitesse de remorquage lorsque la mer est agitée (états élevés de la mer).

Travaux ultérieurs prévus : Des calculs de la résistance supplémentaire seront intégrés dans le logiciel ShipMo3D et fourniront probablement des données plus précises que celles découlant de la méthode actuelle de la théorie des bandes utilisée dans le logiciel SHIPMO7. Des simulations en domaine temporel des opérations de remorquage seront mises au point et permettront probablement de prédire les forces dynamiques avec plus de précision. Des essais en mer sont prévus afin de valider les valeurs numériques des forces prévues.

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1 Introduction

Canadian naval vessels are often required to tow other vessels [1, 2]. DRDC Atlantic has been tasked by Directorate Maritime Systems Support 2 (DMSS 2) to examine forces associated with towing vessels. The objective of this work is to provide guidance to ship operators to reduce the risk of towline breakage during towing.

DRDC Atlantic previously studied towing forces on Canadian naval vessels operating in calm water [3]. The present study considers forces in both calm water and in waves. Operating in a seaway introduces quasi-steady added resistance forces [4] and dynamic forces caused by the relative surge motions between the vessels [5]. The present study also considers the parasitic drag arising for the propeller(s) of a towed vessel, which can be significant.

Table 1 shows combinations of vessels considered for towing operations of Canadian naval vessels. Section 2 describes approaches for predicting towing forces. Section 3 gives properties of towing rope, and is followed by results for Canadian naval vessels presented in Section 4. General discussion and conclusions are given in Sections 5 and 6.

Table 1: *Towing Combinations for Canadian Naval Vessels*

	Towing vessel				
Towed vessel	Protecteur	Iroquois	Halifax	Kingston	Victoria
Protecteur	X	X	X		
Iroquois	X	X	X	X	
Halifax	X	X	X	X	
Kingston	X	X	X	X	
Victoria	X	X	X	X	X
Commercial	X	X	X	X	

2 Prediction of Towing Forces

Towing forces will depend primarily on the effective resistance of the vessel being towed; however, the present study considers dynamic towing forces in waves, which will depend on the properties of both vessels involved. The total towing force is expressed as follows:

$$F_{tow} = F_{resist} + F_{air} + F_{propeller} + F_{seaway} \tag{1}$$

where F_{resist} is the ship hydrodynamic resistance excluding the influence of the propeller, F_{air} is the ship air resistance, $F_{propeller}$ is the contribution due to propeller drag, and F_{seaway} is the contribution from the seaway. The seaway contribution includes added resistance and dynamic effects as follows:

$$F_{seaway} \quad = \quad F_{RAW} \; + \; F_{dynamic} \tag{2}$$

where F_{RAW} is added resistance in waves and $F_{dynamic}$ arises from the relative longitudinal motions between the two vessels. Added resistance F_{RAW} tends to be greatest in head seas, while dynamic force $F_{dynamic}$ tends to be greatest in following seas. The combination of these two terms into a single term F_{seaway} is beneficial for determining the worst case heading for towing.

2.1 Hydrodynamic Resistance

The ship hydrodynamic resistance F_{resist} can be determined using a variety of approaches, including regression methods based on general hull parameters [6], towing tank tests, or computational fluid dynamics (CFD) [7]. Hydrodynamic resistance can be expressed as follows:

$$F_{resist} \quad = \quad \frac{1}{2} \, \rho_w \, U^2 \, A_w \, C_{resist} \tag{3}$$

where ρ_w is water density, U is forward ship speed, A_w is wetted hull surface area, and C_{resist} is resistance coefficient. Hydrodynamic resistance for Canadian naval vessels can be predicted to high accuracy due to the availability of model test data. The resistance coefficient C_{resist} based on wetted hull surface area is typically of the order of 0.003.

2.2 Air Resistance

Air resistance in a head wind can be expressed as follows:

$$F_{air} \quad = \quad \frac{1}{2} \, \rho_a \, V_{ar}^2 \, A_a \, C_{air} \tag{4}$$

where ρ_a is air density, V_{ar} is relative wind speed, A_a is projected frontal area of the ship in air, and C_{air} is air drag coefficient. The air drag coefficient C_{air} based on projected frontal area is typically of the order of 0.6. When evaluating ship air resistance, one of the biggest challenges is selecting an appropriate value for the wind speed, which contributes to the relative wind speed. Blendermann [8] discusses prediction of ship wind forces in detail, including wind forces at oblique headings.

2.3 Propeller Parasitic Drag

The parasitic drag from the propeller will depend on whether the propeller is locked or free to rotate. Larsson and Eliasson [9] and MacKenzie and Forrester [10] examine parasitic drag on sailboats with inboard engines; however, there is little published work on parasitic propeller drag for large vessels.

Larsson and Eliasson propose the following equation for parasitic drag acting on a single propeller:

$$F_{propeller} = \frac{1}{2} C_{propeller} \, \rho_w \, U^2 \, A_{frontal} \tag{5}$$

where $C_{propeller}$ is the propeller parasitic drag coefficient, and $A_{frontal}$ is the projected frontal area of the propeller, which can be of the order of 0.6 times the nominal disk area of the propeller $\pi/4 D^2_{propeller}$, with $D_{propeller}$ being the propeller diameter. MacKenzie and Forrester suggest that the drag coefficient $C_{propeller}$ can range from 0.3 for a propeller free to rotate to 1.2 for a propeller with a locked shaft. Preliminary estimates for DND vessels suggest that parasitic drag for a locked propeller can be of the order of 8 times the hull resistance, which might be too conservative.

As an alternative to directly using a drag coefficient to estimate parasitic drag, MacKenzie and Forrester developed an alternative approach for estimating parasitic drag from propellers that are rotating due to forward ship speed but are under the influence of a constant braking torque due to mechanical friction from the shaft, bearings, and other possible sources. MacKenzie and Forrester's approach utilizes extrapolation of thrust and torsion coefficient curves to high values of advance coefficient, defined by:

$$J_{advance} = \frac{V_{advance}}{n_{propeller} \, D_{propeller}} \tag{6}$$

where $V_{advance}$ is propeller inflow velocity, $n_{propeller}$ is the propeller rotational velocity (rotations per second), and $D_{propeller}$ is propeller diameter. Sample computations using this approach for a DND vessel suggest that the effective drag coefficient $C_{propeller}$ can range from 0.1 for a freewheeling propeller to 2.35 for a locked propeller.

2.4 Added Resistance in Waves

Added resistance in waves is the time-averaged value of the wave-induced forces acting on a ship. Added resistance is a second-order effect, with magnitude being proportional to the square of the wave height. Reference 4 describes the prediction of added resistance with SHIPMO7 [11], a strip theory program for predicting ship motions in waves. For most ships, the primary contributor to added resistance is the time-averaged hydrodynamic pressure due to relative vertical motion in the vicinity of the waterline.

2.5 Dynamic Wave-induced Towing Forces

When a vessel is towing another vessel in waves, additional loading on the tow rope is caused by the wave excitation of the two vessels. These forces could be analysed using time domain simulation; however, a large number of simulations would need to be evaluated because of the random nature of seaways. As an alternative, a frequency domain approach has been developed which uses conservative assumptions. This approach provides nominal upper limits for dynamic towing forces.

Figure 1 gives a schematic of ship towing used for frequency domain analysis. Wave-induced forces cause surge motions of the fore and aft ships. The surge motions of the ships cause dynamic loading of the tow rope, which modifies the surge motions of the ships. It is assumed that the surge motions are uncoupled from the other motion modes for the ships. For the most common case of a ship with lateral symmetry, vertical plane motions (surge, heave, and pitch) are uncoupled from lateral plane motions (sway, roll, and yaw). Furthermore, surge motions have minimal coupling with heave and pitch for most ship geometries, which have relatively large length to beam ratios.

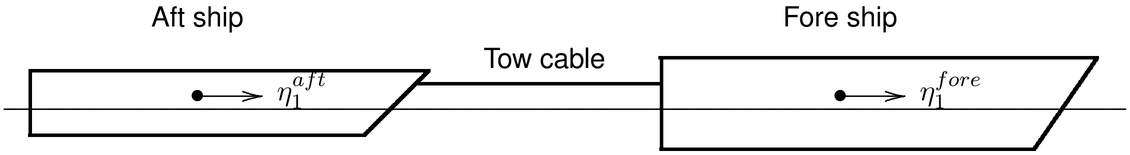

Figure 1: *Schematic of Fore Ship Towing Aft Ship*

It is conservatively assumed that the wave excitation force on the forward ship is 180 degrees out of phase with the wave excitation force on the aft ship. This assumption implies the worst case with respect to the longitudinal distance between the vessels in terms of excitation phasing. The distance between two vessels during towing operations is typically greater than the characteristic ship length; thus, hydrodynamic interactions are assumed to be negligible between the two vessels. The mass and damping of the tow rope are assumed to be small relative to the contributions from the two vessels. It is assumed that the tow rope will always be in tension, and that the oscillatory stiffness will be linear. The assumption of the tow rope being in tension is likely reasonable because the mean speed during towing will induce tension on the rope.

Using the assumptions described above, the equations of surge motions for the two vessels are given by:

$$\left(M^{fore} + A_{11}^{fore}\right) \ddot{\eta}_1^{fore} \ + \ B_{11}^{fore} \dot{\eta}_1^{fore} \ + \ \left(\eta_1^{fore} - \eta_1^{aft}\right) k_t \ = \ \left|F_1^{fore}\right| \tag{7}$$

$$\left(M^{aft} + A_{11}^{aft}\right) \ddot{\eta}_1^{aft} \ + \ B_{11}^{aft} \dot{\eta}_1^{aft} \ + \ \left(\eta_1^{aft} - \eta_1^{fore}\right) k_t \ = \ -\left|F_1^{aft}\right| \tag{8}$$

where M is ship mass, A_{11} is surge added mass, $\ddot{\eta}_1$ is surge acceleration, B_{11} is surge damping, $\dot{\eta}_1$ is surge velocity, η_1 is surge displacement, k_t is towing rope stiffness, and F_1 is wave excitation force. The superscripts $fore$ and aft denote the fore and aft ships respectively. If time-varying terms are related to complex terms using $g(t) = \text{Real}\{Ge^{i\omega_e t}\}$, where ω_e is wave encounter frequency, then the complex equations of motion can be written as:

$$\begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix} \left\{ \begin{array}{c} \eta_1^{fore} \\ \eta_1^{aft} \end{array} \right\} = \left\{ \begin{array}{c} \left|F_1^{fore}\right| \\ -\left|F_1^{aft}\right| \end{array} \right\} \tag{9}$$

The matrix terms in the above equation are given by:

$$H_{11} \ = \ -\omega_e^2 \left(M^{fore} + A_{11}^{fore}\right) \ + \ i \, \omega_e \, B_{11}^{fore} \ + \ k_t \tag{10}$$

$$H_{12} \ = \ -k_t \tag{11}$$

$$H_{21} \ = \ -k_t \tag{12}$$

$$H_{22} \ = \ -\omega_e^2 \left(M^{aft} + A_{11}^{aft}\right) \ + \ i \, \omega_e \, B_{11}^{aft} \ + \ k_t \tag{13}$$

$$\tag{14}$$

The terms in the above equations can be evaluated using ShipMo3D [12, 13]. The added mass terms A_{11} are computed using potential flow theory, and are typically less than 5 percent of the ship mass M. The damping terms B_{11} include contributions from wave radiation damping and ship drag. The linear ship drag damping for oscillatory motion is given by $\rho_w U A_w C_{resist}$. The tow rope stiffness k_t is given by $A_t E_t / l_t$, where A_t is the cross-sectional area of the tow rope, E_t is the elastic modulus, and l_t is the length. The dynamic component of rope tension is given by:

$$F_{dynamic} \ = \ k_t \left(\eta_1^{fore} \ - \ \eta_1^{aft}\right) \tag{15}$$

The equations given above can be used to evaluate the magnitude of dynamic towing forces in a regular seaway. For ships in a random seaway, the RMS dynamic towing force and zero-crossing period can be evaluated using linear superposition and evaluation of spectral moments. The nominal extreme dynamic force with exceedence probability α for a specified duration D in a given seaway can be evaluated using:

$$F_{dynamic}^{max} \ = \ \sigma(F_{dynamic}) \sqrt{2 \ \ln\left(\frac{D}{\alpha T_z}\right)} \tag{16}$$

where σ is RMS dynamic force and T_z is mean zero-crossing period.

Eigenvalue analysis [14] can be used to determine the natural frequency of a system with a tow rope and two ships:

$$\omega_t^2 = \frac{k_t \left[\left(M^{fore} + A_{11}^{fore}\right) + \left(M^{aft} + A_{11}^{aft}\right)\right]}{\left(M^{fore} + A_{11}^{fore}\right) \left(M^{aft} + A_{11}^{aft}\right)} \tag{17}$$

The above equation is useful for checking if resonance can occur with the wave encounter frequency.

3 Tow Rope Properties

When evaluating whether rope breakage might occur during towing operations, data are required for rope strength and stiffness. Table 2 gives properties for ropes that could be used by the Canadian Navy. The values are based on data in Reference 15 for ropes of 3-strand twisted and 8-strand plaited constructions. Rope of 12-strand braid construction would have somewhat greater strength. The nominal elongation at breaking values in Table 2 have been used to evaluate nominal rope stiffnesses.

Table 2: *Tow Rope Strength and Elastic Properties*

	64 mm polyester	64 mm nylon
Minimum breaking strength	540 kN	640 kN
Rope elongation at breaking	12-35%	30-50%
Nominal elongation at breaking	20%	40%

When considering towing forces in a seaway, it is likely that polyester rope will be subjected to higher dynamic forces than nylon rope because polyester rope has higher stiffness.

4 Predicted Towing Forces for Canadian Naval Vessels

Towing forces have been predicted for Canadian naval vessels operating in sea state 5, with conditions as given in Table 3. Using the assumption of head wind, the relative wind speed is given by:

$$V_{ar} = U + V_a \tag{18}$$

Table 3: *Environmental Conditions for Towing Predictions*

Sea state	5
Wave spectrum	Bretschneider
Significant wave height, H_s	3.25 m
Peak wave period, T_p	9.7 s
Absolute wind speed, V_a	25 knots
Wind direction	Head wind

Table 4 shows drag parameters used for the present study. The hydrodynamic and air resistance coefficients are the same as used in a previous towing study [3]. The propeller parasitic drag coefficient is assigned a value of 0.3 to model free-wheeling propellers.

Table 4: *Drag Parameters for Towing Predictions*

Hydrodynamic resistance, C_{resist}	0.003
Air resistance, C_{air}	0.6
Propeller parasitic drag, $C_{propeller}$	0.3
Ratio of propeller frontal area to disk area, $A_f/(\pi/4D^2_{propeller})$	0.6

Dynamic towing forces are dependent on both the vessel being towed and the towing vessel. For towing of a given vessel, it was found that dynamic forces could increase as the size of the towing vessel decreased because a smaller towing vessel would be more prone to surge motion, thus causing higher restraining forces exerted on a tow rope. Consequently, dynamic towing forces are presented for vessels being towed by both HALIFAX and KINGSTON (where applicable). Dynamic towing forces are also dependent on towing rope properties. Values presented here are for

64 mm polyester rope with properties as given in Table 2. Presented dynamic forces are extreme values with a 1 percent exceedence probability during 1 hour. When computing dynamic forces, wave frequencies have been shifted when required to avoid encounter frequencies below 0.2 rad/s, for which ship force surge predictions become unrealistically large.

4.1 Towing of PROTECTEUR

Table 5 gives parameters for PROTECTEUR for a deep departure condition. Predicted forces are given in Table 6, with seaway forces given for the worst heading at each speed. The seaway forces contribute greatly to the total towing forces.

Figures 2 and 3 show the variation of added resistance and dynamic forces with heading. Added resistance forces are greatest in head seas and increase with ship speed, as expected. Dynamic forces are smallest in beam seas, for which surge excitation forces are small. For towing of PROTECTEUR, added resistance is a dominant force.

Table 5: *PROTECTEUR Towing Parameters, Deep Departure Condition*

Length between perpendiculars, L_{pp}	162.5 m
Draft at midships, T_{mid}	10.09 m
Trim by stern, t_{stern}	-0.21 m
Displacement, $\triangle$	25025 tonnes
Wetted area, A_w	5228 m^2
Frontal wind area, A_a	380 m^2
Number of propellers	1
Propeller diameter, $D_{propeller}$	6.31 m

Table 6: *Forces (kN) for Towing of PROTECTEUR by HALIFAX*

	Towing speed (knots)		
	2	4	6
Seaway	132	163	198
Resistance	8	34	76
Propeller	3	12	28
Air	28	32	36
Total	171	241	338

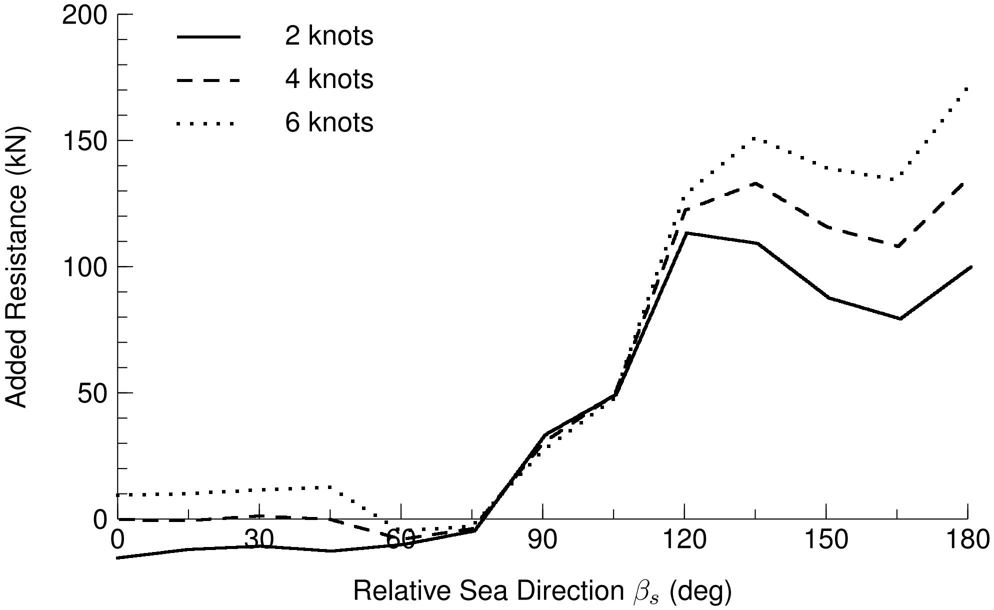

Figure 2: *Added Resistance Versus Relative Sea Direction for PROTECTEUR in Sea State 5*

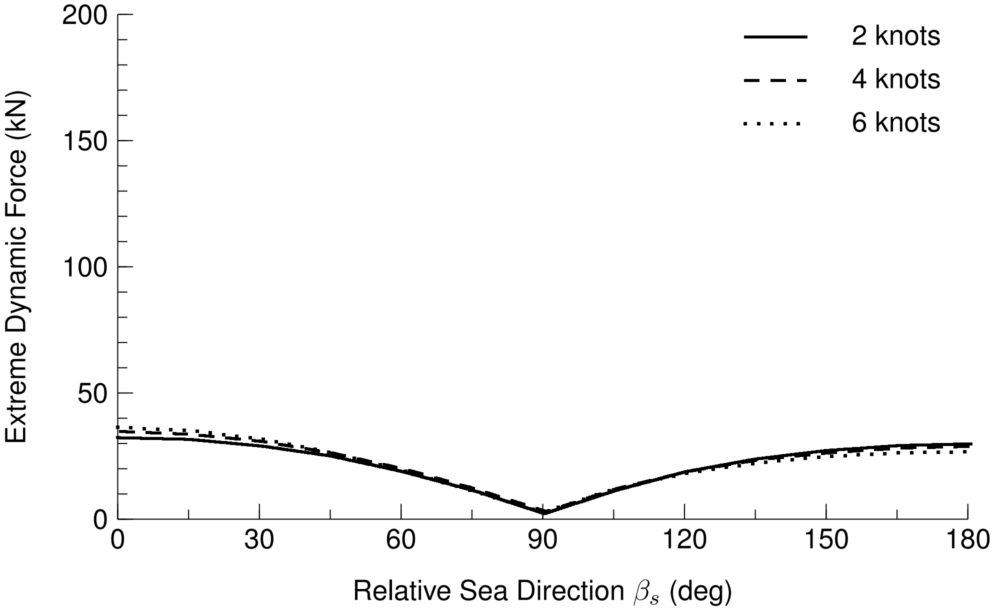

Figure 3: *Extreme Dynamic Force for PROTECTEUR Towed by HALIFAX with Polyester Rope in Sea State 5*

4.2 Towing of IROQUOIS

Table 7 gives parameters for IROQUOIS for a deep departure condition. Predicted forces are given in Tables 8 and 9, with seaway forces given for the worst heading at each speed.

Figures 4 and 5 show the variation of added resistance and dynamic forces with heading when towed by HALIFAX. Added resistance forces are greatest in head seas and increase with ship speed, as expected. Dynamic forces are greatest in following seas due to high surge excitation forces and low encounter periods. Dynamic forces are somewhat larger when towed by KINGSTON than when towed by HALIFAX.

Table 7: *IROQUOIS Towing Parameters, Deep Departure Condition*

Length between perpendiculars, L_{pp}	121.3 m
Draft at midships, T_{mid}	5.04 m
Trim by stern, t_{stern}	0.21 m
Displacement, $\triangle$	5116 tonnes
Wetted area, A_w	2042 m^2
Frontal wind area, A_a	210 m^2
Number of propellers	2
Propeller diameter, $D_{propeller}$	4.4 m

Table 8: *Forces (kN) for Towing of IROQUOIS by HALIFAX*

	Towing speed (knots)		
	2	4	6
Seaway	67	76	89
Resistance	3	13	30
Propeller	3	12	27
Air	15	18	20
Total	88	119	165

Table 9: *Forces (kN) for Towing of IROQUOIS by KINGSTON*

	Towing speed (knots)		
	2	4	6
Seaway	74	83	96
Resistance	3	13	30
Propeller	3	12	27
Air	15	18	20
Total	96	126	173

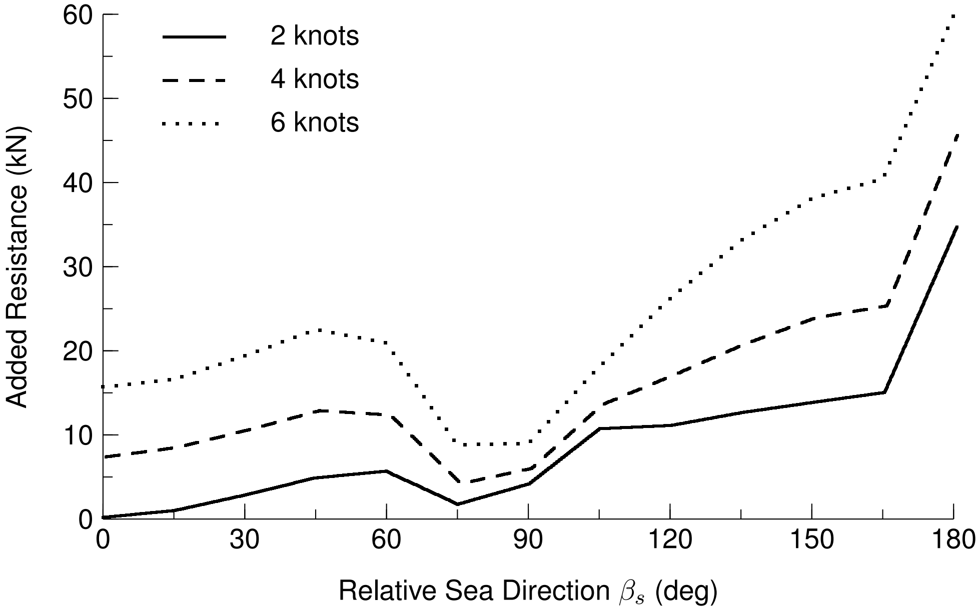

Figure 4: *Added Resistance Versus Relative Sea Direction for IROQUOIS in Sea State 5*

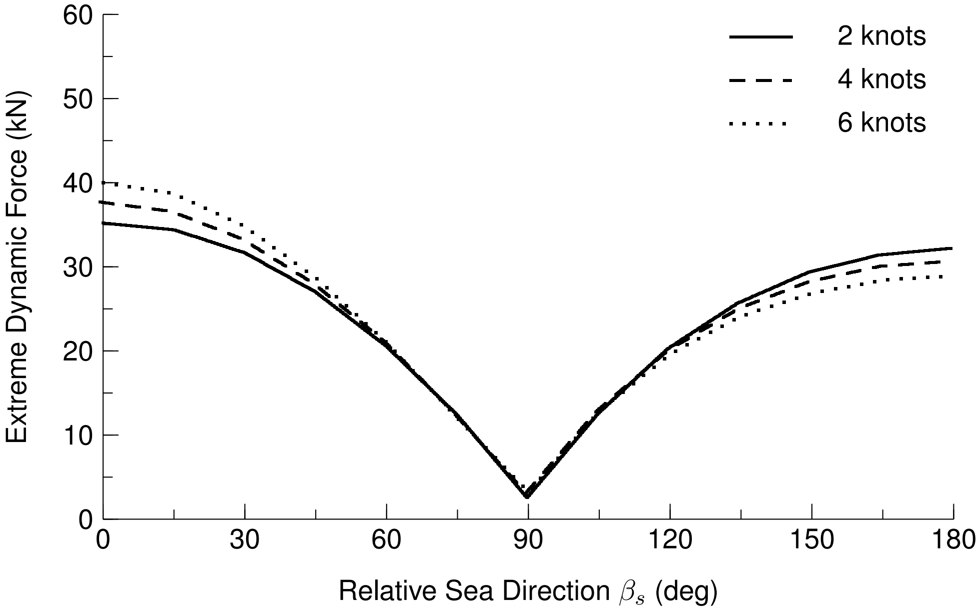

Figure 5: *Extreme Dynamic Force for IROQUOIS Towed by HALIFAX with Polyester Rope in Sea State 5*

4.3 Towing of HALIFAX

Table 10 gives parameters for HALIFAX for a deep departure condition. Predicted forces are given in Tables 11 and 12, with seaway forces given for the worst heading at each speed.

Figures 6 and 7 show the variation of added resistance and dynamic forces with heading. Added resistance forces are greatest in head seas and increase with ship speed, as expected. Dynamic forces are greatest in following seas due to high surge excitation forces and low encounter periods. Dynamic forces are somewhat larger when towed by KINGSTON than when towed by HALIFAX.

Table 10: *HALIFAX Towing Parameters, Deep Departure Condition*

Length between perpendiculars, L_{pp}	121.3 m
Draft at midships, T_{mid}	5.16 m
Trim by stern, t_{stern}	-0.1 m
Displacement, $\triangle$	4914 tonnes
Wetted area, A_w	2036 m^2
Frontal wind area, A_a	210 m^2
Number of propellers	2
Propeller diameter, $D_{propeller}$	4.34 m

Table 11: *Forces (kN) for Towing of HALIFAX by HALIFAX*

	Towing speed (knots)		
	2	4	6
Seaway	68	75	87
Resistance	3	13	29
Propeller	3	12	26
Air	15	18	20
Total	89	117	162

Table 12: *Forces (kN) for Towing of HALIFAX by KINGSTON*

	Towing speed (knots)		
	2	4	6
Seaway	75	83	94
Resistance	3	13	29
Propeller	3	12	26
Air	15	18	20
Total	97	125	170

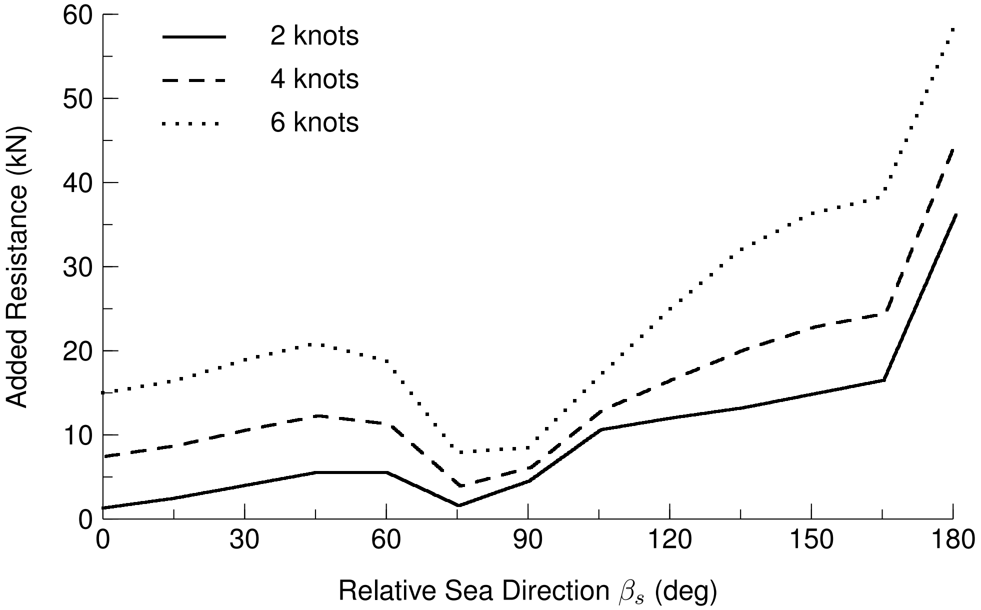

Figure 6: *Added Resistance Versus Relative Sea Direction for HALIFAX in Sea State 5*

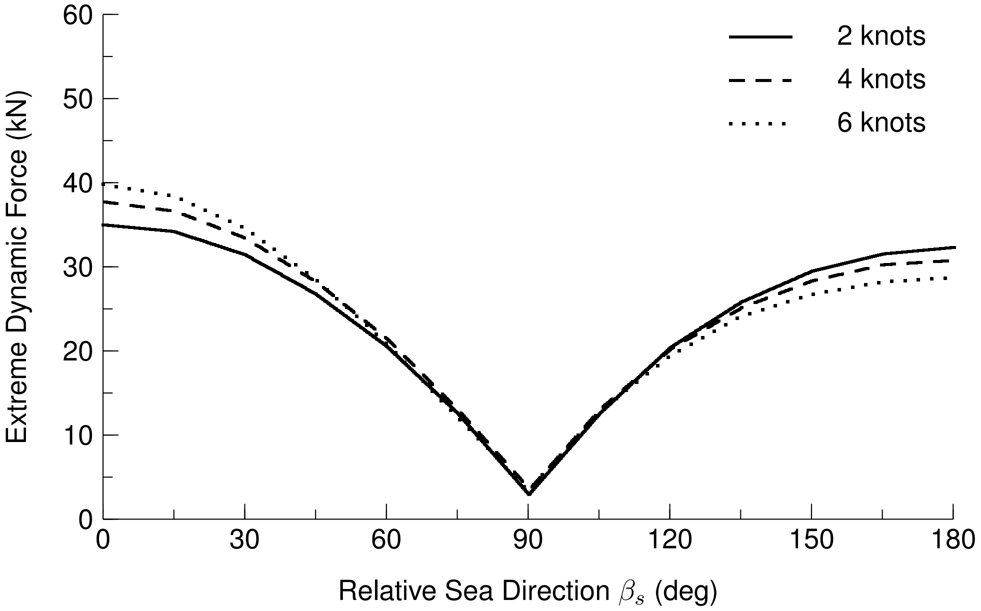

Figure 7: *Extreme Dynamic Force for HALIFAX Towed by HALIFAX with Polyester Rope in Sea State 5*

4.4 Towing of KINGSTON

Table 13 gives parameters for KINGSTON for an intermediate loading condition. Predicted forces are given in Tables 14 and 15, with seaway forces given for the worst heading at each speed.

Figures 8 and 9 show the variation of added resistance and dynamic forces with heading. Added resistance forces are greatest in head seas and increase with ship speed, as expected. Dynamic forces are greatest in following seas due to high surge excitation forces and low encounter periods. Dynamic forces are somewhat larger when towed by KINGSTON than when towed by HALIFAX.

Table 13: *KINGSTON Towing Parameters, Intermediate Loading Condition*

Length between perpendiculars, L_{pp}	52.0 m
Draft at midships, T_{mid}	2.956 m
Trim by stern, t_{stern}	0.506 m
Displacement, $\triangle$	896 tonnes
Wetted area, A_w	449 m^2
Frontal wind area, A_a	110 m^2
Number of propellers	2
Propeller diameter, $D_{propeller}$	2.14 m

Table 14: *Forces (kN) for Towing of KINGSTON by HALIFAX*

	Towing speed (knots)		
	2	4	6
Seaway	53	60	66
Resistance	1	4	9
Propeller	1	3	6
Air	8	9	11
Total	63	76	92

Table 15: *Forces (kN) for Towing of KINGSTON by KINGSTON*

	Towing speed (knots)		
	2	4	6
Seaway	63	69	75
Resistance	1	4	9
Propeller	1	3	6
Air	8	9	11
Total	73	85	101

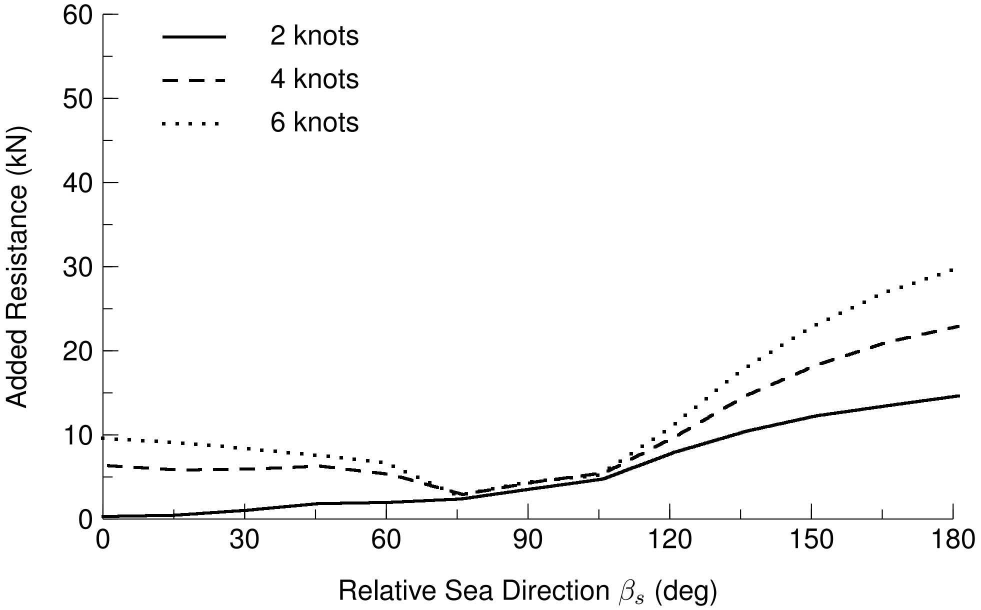

Figure 8: *Added Resistance Versus Relative Sea Direction for KINGSTON in Sea State 5*

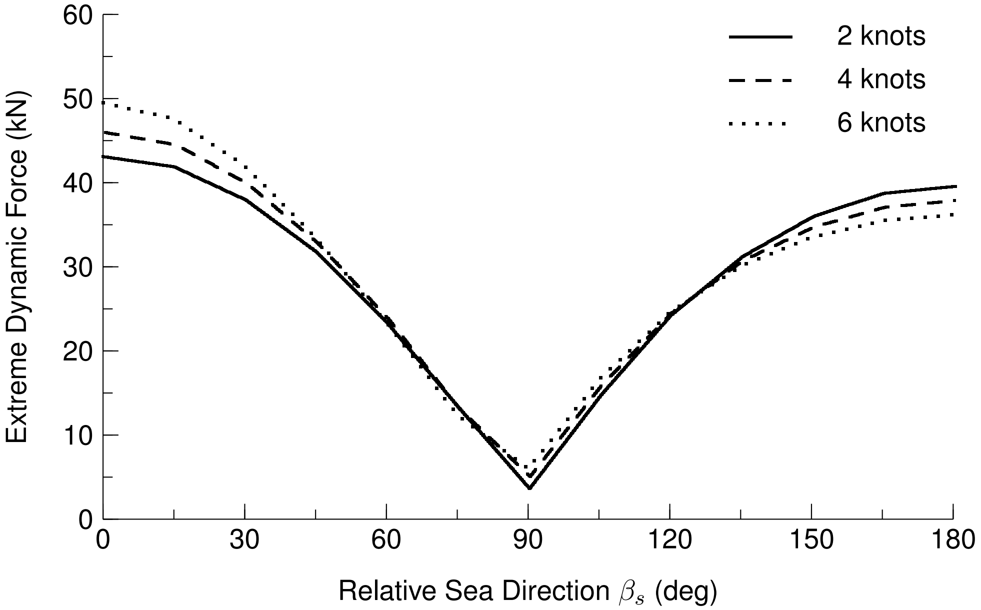

Figure 9: *Extreme Dynamic Force for KINGSTON Towed by KINGSTON with Polyester Rope in Sea State 5*

4.5 Towing of VICTORIA

Table 16 gives parameters for VICTORIA for a surfaced condition. Predicted forces are given in Tables 17 and 18, with seaway forces given for the worst heading at each speed. The predicted seaway forces for VICTORIA do not include added resistance, in part because there is currently no SHIPMO7 model of VICTORIA available for evaluating added resistance in waves; however, added resistance in waves for VICTORIA is likely small due to its narrow beam in the vicinity of the waterline.

Figure 10 shows the variation of dynamic forces with heading. Dynamic forces are greatest in following seas due to high surge excitation forces and low encounter periods. Dynamic forces are somewhat larger when towed by KINGSTON than when towed by HALIFAX.

Table 16: *VICTORIA Towing Parameters, Surfaced Condition*

Length between perpendiculars, L_{pp}	70.25 m
Draft at midships, T_{mid}	7.349 m
Trim by stern, t_{stern}	0.978 m
Displacement, $\triangle$	2533 tonnes
Wetted area, A_w	1175 m^2
Frontal wind area, A_a	16 m^2
Number of propellers	1
Propeller diameter, $D_{propeller}$	3.6 m

Table 17: *Forces (kN) for Towing of VICTORIA by HALIFAX*

	Towing speed (knots)		
	2	4	6
Seaway	41	44	48
Resistance	2	8	17
Propeller	1	4	9
Air	1	1	2
Total	45	57	76

Table 18: *Forces (kN) for Towing of VICTORIA by KINGSTON*

	Towing speed (knots)		
	2	4	6
Seaway	50	54	60
Resistance	2	8	17
Propeller	1	4	9
Air	1	1	2
Total	54	67	88

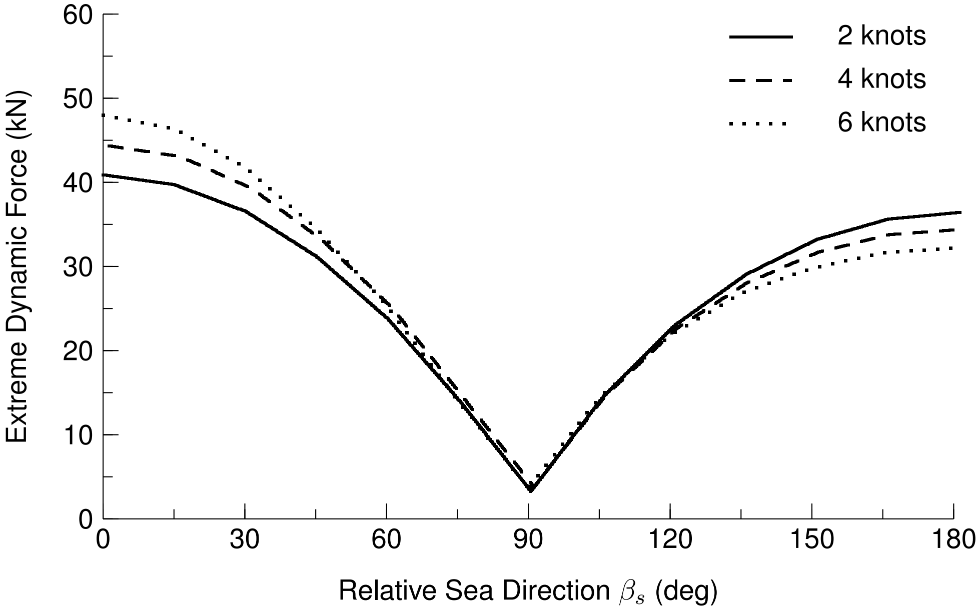

Figure 10: *Extreme Dynamic Force for VICTORIA Towed by HALIFAX with Polyester Rope in Sea State 5*

5 Discussion

The current results show that high seaway forces arise when performing towing operations in sea state 5. Preliminary estimates of seaway forces in other sea states can be obtained by assuming that added resistance is proportional to the square of wave height and dynamic forces are proportional to wave height.

This report considers propeller parasitic drag, which was not included in an earlier study examining towing forces [3]. Parasitic drag can be greatly reduced by allowing propellers to freewheel during towing. Data in the literature [9, 10] indicate there is significant uncertainty regarding predictions of parasitic drag.

Added resistance can contribute greatly to towing forces in a seaway. Because added resistance is a second-order effect, it is somewhat difficult to predict accurately. It is recommended that added resistance computations be implemented in ShipMo3D, which will provide improved accuracy over SHIPMO7 predictions.

For towing of a given ship, dynamic forces are larger when towed by KINGSTON than for HALIFAX. The larger forces when towed by KINGSTON are likely due to its larger wave-induced response in surge, and subsequently higher restraining forces applied by the tow rope. The dynamic force predictions presented here are based on frequency domain computations with underlying assumptions. It is conservatively assumed that surge excitation forces on the fore and aft ship are 180 degrees out of phase. Furthermore, the towing rope is assumed to have linear elastic response. Time domain simulation could provide improved estimates of dynamic towing forces.

For towing in realistic seaways, added resistance and dynamic towing forces will be highly dependent upon seaway conditions, ship speed, and ship heading. Active operator guidance based on real-time monitoring of wave conditions could be very useful for providing towing force predictions and recommendations regarding safe speed and heading.

To maximize safety during towing operations, it is recommended that propellers on a towed vessel be allowed to freewheel so that parasitic drag will be minimized. It is also recommended that towing speeds be reduced in higher sea states to counteract increased added resistance and dynamic wave-induced forces.

To improve accuracy of predicted towing forces, it is recommended that time domain simulations of towing operations be developed. Time domain simulations could model additional physical phenomena, including nonlinear response of tow ropes to applied forces. It is also recommended that towing sea trials be conducted to improve understanding of towing forces and to provide validation data for numerical predictions.

6 Conclusions

Tow forces have been predicted for Canadian Navy vessels operating in waves. Hydrodynamic resistance and air resistance are commonly considered factors that influence tow forces. Parasitic propeller drag from a vessel being towed contributes significantly to tow forces. Propeller drag is much less for a freewheeling propeller than for a locked propeller; however, there is significant uncertainty in propeller drag predictions. The presence of waves causes added resistance and dynamic forces arising from surge excitation acting on vessels. Predictions in sea state 5 show that these forces vary greatly with ship speed and heading, and can be very large. Time domain simulations and sea trials are recommended to improve understanding of towing forces in seaways.

References

[1] Department of National Defence (Canada), Chief of Maritime Staff (1997). Seamanship Rigging and Procedures Manual Version 1.0. B-GN-181-105/FP-E00 CFCD 105.

[2] NATO (2001). Ship-to-Ship Towing. Standardization Agreement ATP-43(B)/MTP-43B.

[3] McTaggart, K.A. (2002). Wind and Current Forces on Canadian Forces Ships During Tug Operations. (DRDC Atlantic TM 2002-192). Defence Research and Development Canada - Atlantic.

[4] McTaggart, K.A. (1997). Added Resistance Prediction in SHIPMO7 Using a Near-Field Method. (TM 97/207). Defence Research Establishment Atlantic.

[5] McTaggart, K.A. (2009). Frequency Domain Analysis of Dynamic Wave-Induced Forces During Ship Towing. In *Twenty-Second Canadian Congress of Applied Mechanics*, Halifax, Canada.

[6] Holtrop, J. (1984). A Statistical Re-analysis of Resistance and Propuslion Data. *International Shipbuilding Progress*, **31**(363), 272–276.

[7] Thornhill, E. (2008). Stern Flap Resistance Reduction for Displacement Hulls. In *Twenty-Seventh Symposium on Naval Hydrodynamics*, Seoul, Korea.

[8] Blendermann, W. (1994). Parameter Identification of Wind Loads on Ships. *Journal of Wind Engineering and Industrial Aerodynamics*, **51**, 339–351.

[9] Larsson, L. and Eliasson, R. (1994). Principles of Yacht Design, London: Adlard Coles Nautical.

[10] MacKenzie, P.M. and Forrester, M.A (2008). Sailboat Propeller Drag. *Ocean Engineering*, **25**, 28–40.

[11] McTaggart, K.A. (1997). SHIPMO7: An Updated Strip Theory Program for Predicting Ship Motions and Sea Loads in Waves. (DREA TM 96/243). Defence Research Establishment Atlantic.

[12] McTaggart, K.A. (2007). ShipMo3D Version 1.0 User Manual for Frequency Domain Analysis of Ship Seakeeping in a Seaway. (DRDC Atlantic TM 2007-171). Defence Research and Development Canada - Atlantic.

[13] McTaggart, K.A. (2007). ShipMo3D Version 1.0 User Manual for Simulating Motions of a Freely Maneuvering Ship in a Seaway. (DRDC Atlantic TM 2007-172). Defence Research and Development Canada - Atlantic.

[14] Cook, R.D. (1981). Concepts and Applications of Finite Element Analysis, New York: John Wiley & Sons.

[15] Driscoll, Alan (2001). Handbook Of Oceanographic Winch, Wire And Cable Technology, Third ed, Ch. 12, Useful Information. United States: National Science Foundation.

Symbols and Abbreviations

A_a	ship air frontal area
$A_{frontal}$	propeller frontal area
A_w	hull wetted surface area
A_{11}	surge added mass
B_{11}	surge damping
C_{air}	air drag coefficient
$C_{propeller}$	propeller parasitic drag coefficient
C_{resist}	hydrodynamic resistance coefficient
D	duration for evaluating extreme forces
$D_{propeller}$	propeller diameter
E_t	elastic modulus of tow rope
F_{air}	ship air resistance
$F_{dynamic}$	dynamic force in seaway
$F_{dynamic}^{max}$	maximum dynamic force in seaway
$F_{propeller}$	propeller parasitic drag
F_{RAW}	added resistance in waves
F_{resist}	ship hydrodynamic resistance
F_{seaway}	seaway force from added resistance and dynamic force
F_{tow}	towing force
F_1	surge excitation force
H_{ij}	matrix term for evaluating surge motions of two ships
H_s	significant wave height
$J_{advance}$	propeller advance coefficient
k_t	tow rope stiffness
L_{pp}	ship length between perpendiculars
l_t	tow rope length
M	ship mass
$n_{propeller}$	propeller rotations per second
RMS	root-mean-square
T_{mid}	draft at midships
T_p	peak wave period
T_z	zero-crossing period
t	time

t_{stern}	trim by stern
U	forward ship speed
V_a	absolute wind speed
V_{ar}	relative wind speed
α	exceedence probability for extreme forces
β_s	relative sea direction (180 degrees for head seas)
η_1	surge displacement
ρ_a	air density
ρ_w	water density
$\sigma(F_{dynamic})$	RMS dynamic force
ω_e	wave encounter frequency
ω_t	surge natural frequency for two ships and towing rope
$\triangle$	ship mass displacement

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Towing operations are often conducted by the Canadian Navy. Evaluation of associated forces is required to determine whether towing can safely occur without breakage of rope. This report examines forces that can influence towing operations in a seaway. Ship hydrodynamic resistance and air resistance are evaluated using drag coefficients. For a vessel being towed, additional resistance arises from propeller parasitic drag, which will vary greatly depending on whether a propeller is freewheeling or locked. The presence of a seaway introduces added resistance, and also dynamic forces due to surge excitation acting on the two vessels in a towing operation. A frequency domain method has been developed for predicting dynamic forces during towing. Towing force predictions in sea state 5 show that the presence of a seaway can contribute greatly to total towing forces. It is recommended that propellers on a towed vessel be allowed to freewheel during towing operations, and that towing speeds be reduced in higher sea states.

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