Seaway-Sized Bulk Carrier Model for Hydrodynamic Optimization of Ballast-Free Ship Design

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October 2, 2006

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Great Lakes Maritime Research Institute
A University of Wisconsin - Superior and University of Minnesota Duluth Consortium

Research funded in part by the Great Lakes Maritime Research Institute

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Table of Contents

List of Tables

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List of Figures

1. Introduction

The Ballast-Free Ship Concept has been recently invented [US Patent #6694908 2004] and investigated [Kotinis et al. 2004, Kotinis 2005, *Ballast Water News* 2004] at the University of Michigan. Even though the feasibility of the concept was demonstrated, the aforementioned analysis was limited by its required comprehensive research scope and associated budget. Thus, it was only feasible to support model testing that utilized an existing model. Although the vessel type of greatest interest for the Great Lakes nonindigenous aquatic species introduction problem is the Seaway-sized bulk carrier, the best available model was of a relatively finer, higher-speed barge-carrying Lighter Aboard Ship (LASH) vessel. This existing model was modified to utilize a more conventional stern, but the model test results were not directly applicable to the Seaway-sized bulk carriers studied in detail in the rest of the research effort.

The current research focuses on the design of a typical Seaway-sized bulk carrier and the construction of a scaled model to be utilized in subsequent towing tank experiments. This model has already been procured and is expected to be delivered to the University of Michigan at the end of October, 2006.

A major part of the initial hydrodynamic analysis that was performed on the modified LASH vessel was based on the ship-specific Computational Fluid Dynamics (CFD) code SHIPFLOW® [Flowtech Int. 1998], which has been shown to have significant limitations regarding the prediction of the important viscous flow near the stern.

In the current research, the external flow around the Ballast-Free bulk carrier has been investigated numerically using FLUENT® [Fluent 2005]. These external flow results have been utilized to obtain the necessary boundary conditions for numerical simulation (also in FLUENT®) of the water flow in the longitudinal ballast trunks. The internal flow was simulated in order to estimate the flow rate scaling factor needed in preparation for the subsequent towing tank experiments.

In the next stage of this research, the model will be utilized for towing tank experiments in order to study, in more detail, the hydrodynamic impact of the Ballast-Free Ship Concept. The experimental and numerical hydrodynamic investigation, combined with an optimization procedure, is expected to lead to a design solution that could offer a net savings in Required Freight Rate (RFR) relative to alternate ballast water treatment methods and approaches. The numerical solution will be refined and validated through the scale model testing.

2. Background

The initial Sea Grant supported development of the Ballast-Free Ship Concept was reported in a paper before the Annual Meeting of the Society of Naval Architects and Marine Engineers in Washington, DC, on October 2004 [Kotinis et al. 2004]. Overall, the investigation of the Ballast-Free Ship Concept has shown that it provides a viable alternative to the addition of costly ballast water treatment systems in order to meet the evolving performance requirements for ballast water treatment. The concept essentially eliminates the transport of foreign ballast water. This should be more effective than current treatment methods in reducing the potential for the further introduction of nonindigenous aquatic species into the Great Lakes and coastal waters. Furthermore, it should be equally effective as international requirements extend below the 50 micron range [IMO 2004].

The traditional approach to ballast operations, since the introduction of steam machinery, has been the use of water ballast to increase the weight of the vessel in the light cargo condition. A paradigm shift in thinking would be to view the ballast condition as a change of buoyancy rather than an addition of weight in order to get the vessel to its safe ballast drafts. Such a shift in thinking led to the invention of the Ballast-Free Ship Concept [US Patent #6694908 2004].

In this concept, the traditional ballast tanks are replaced by longitudinal, structural ballast trunks that extend beneath the cargo region of the ship below the ballast draft. The arrangement of an equal capacity conventional Seaway-size bulk carrier is shown on the left in Fig. 2.1; the arrangement of a Ballast-Free Ship Concept Seaway-size bulk carrier is shown for comparison on the right. In this example, the three ballast trunks per side are connected to the sea through a plenum at the bow and a second plenum at the stern. Typical trunk and plenum arrangements at the bow and stern of the vessel are illustrated in Fig. 2.2 and 2.3, respectively. These trunks are flooded with seawater to reduce the buoyancy of the vessel in the ballast condition in order to get the vessel down to its ballast drafts. Since there is a natural hydrodynamic pressure differential created between the bow region and the stern region of a ship due to its motion through the water, a slow flow is induced in these open ballast trunks. This ensures that the ballast trunks are always filled with slowly-moving "local seawater." This will essentially ensure that there is no transport nonindigenous aquatic species across the globe. Therefore, the vessel becomes foreign "ballast-free" from the traditional viewpoint.

When the ballast voyage is completed, the ballast trunks can be isolated from the sea by valves and then pumped dry using conventional ballast pumps. The need for costly ballast water treatment equipment or ballast water treatment chemicals would, thus, be eliminated. This approach would also be equally effective for biota smaller than 50 microns. During the full load condition or any condition where ballast is not necessary, the double bottom ballast trunks can be segregated utilizing sluice gate valves. This is needed to provide the vessel adequate damage survivability.

In order to provide adequate intact stability, equivalent damage survivability, equivalent cargo capacity, etc., the entire vessel design needs to be developed to support this concept of ballast operations as illustrated in Fig. 2.1. The ship requires a higher tank top in order to locate enough ballast trunk volume below the ballast draft and requires a greater hull depth in order to maintain the vessel's capacity to carry light cargos, such as grain. The Ballast-Free Ship Concept also includes features to minimize the buildup of sediment within the ballast trunks and facilitate their required cleaning; i.e., easier to clean 2.4 m high ballast trunks, elimination of the lower part of the floors next to the shell, etc.

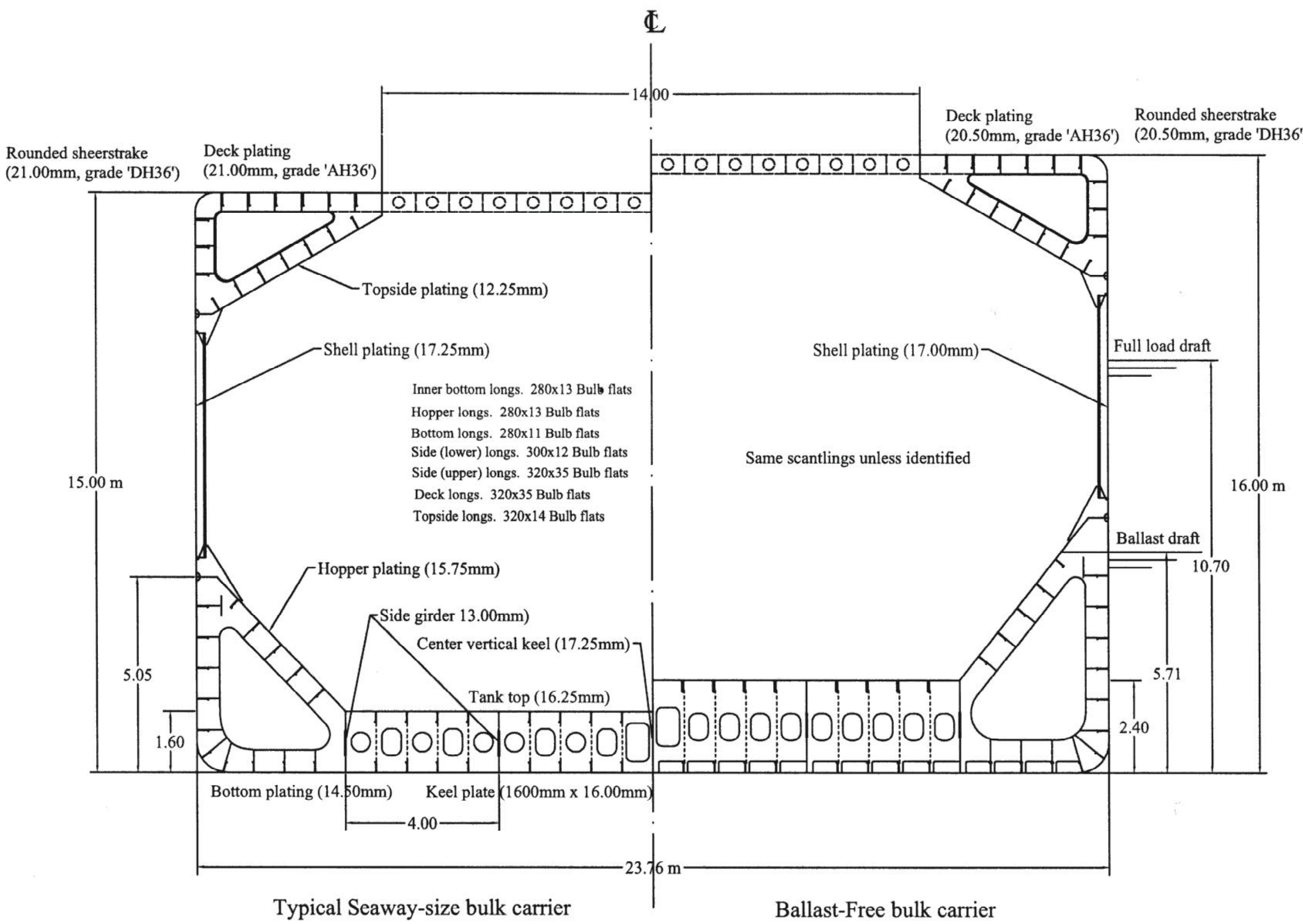

Figure 2.1: Typical Seaway-size Bulk Carrier (left) and Ballast-Free Concept Bulk Carrier (right)

As noted, the recent Sea Grant sponsored research on the development of the Ballast-Free Ship Concept was limited by its required comprehensive research scope and associated budget. For budgetary reasons, it was only feasible to support model testing that utilized an existing model. Although the vessel type of greatest interest for the Great Lakes nonindigenous aquatic species introduction problem is the Seaway-size bulk carrier, the best available model was of a relatively finer, higher-speed barge-carrying Lighter Aboard Ship (LASH) vessel. This existing model was modified to utilize a more conventional stern, but the model test results were not directly applicable to the Seaway-size bulk carriers studied in detail in the rest of the research effort.

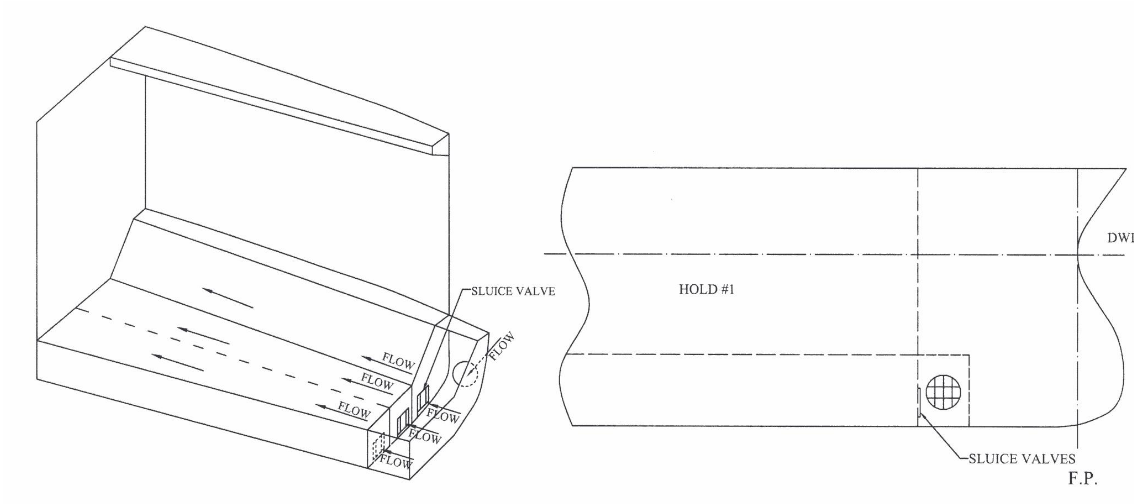

Figure 2.2: Typical Forward Plenum and Collision Bulkhead Arrangement

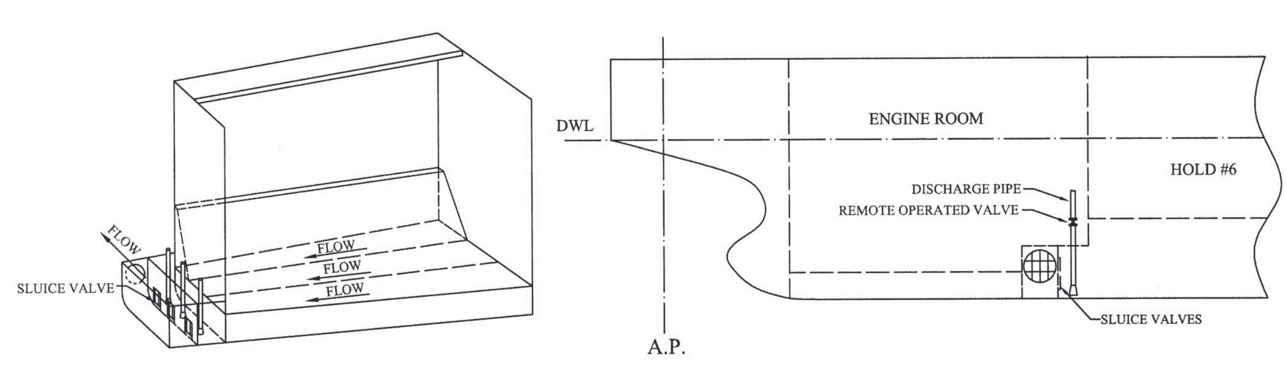

Figure 2.3: Typical Aft Plenum Arrangement

Budget restrictions in the initial investigation phase also required that the model tests be limited to a single system design for a single existing model. There was no opportunity to optimize the hydrodynamic design of the system to minimize the economic impact of the Ballast-Free Ship Concept design. Model tests and CFD simulations using a modified LASH vessel hull showed that the specific ballast intake and discharge locations and method tested in the initial investigation resulted in a modest 2.2% increase in resistance but a more significant 7.4% increase in the required propulsion power. This specific result assumed a change in the ballast water within the ballast trunks once every two hours, which would meet the environmental intent of the Ballast-Free Ship Concept. The large power increase could result in an undesirable engine size increase and would result in fuel cost penalties. In that investigation, it was concluded that further hydrodynamic optimization could eliminate most, if not all, of this significant added power requirement.

3. General Description of Design Procedure

A typical Seaway-sized bulk carrier was designed using data from similar vessels. The prototype vessels were the *Isa* bulk carrier owned by the Polish Steamship Company (PZM Polsteam) as shown in Figure 3.1 and a recent bulk carrier class designed by the Jiangnan shipyard in China.

Figure 3.1: Polsteam Seaway-sized Bulk Carrier *Isa*

The vessel hydrostatic data match the data of typical bulk carriers of the same size. The service speed was assumed to be 14.5 knots, which results in a Froude number of 0.175. The speed of the vessel when in ballast draft was assumed to be 15.5 knots, which results in a Froude number of 0.185. The stern region was designed to accommodate specific propeller-hull clearances. For this purpose, the Det Nordske Veritas (DNV) requirements were utilized. The main particulars of the Ballast-Free Bulk Carrier are presented in Table 3.1.

The model testing of interest will be performed with the vessel at the ballast draft. A conservative heavy weather ballast draft corresponds to a value of 40% of the summer load line at the forward perpendicular and 70% at the aft perpendicular. These values were utilized in the current study. The vessel particulars at this ballast condition are listed in Table 3.2.

Table 3.1: Ballast-Free Bulk Carrier Main Particulars

Waterline length (m)	195.5
Length between perpendiculars (m)	192.0
Maximum beam (m)	23.76
Depth to main deck (m)	16.0
Full-load draft (m)	10.70
Block coefficient	0.835
Prismatic coefficient	0.837
Waterplane area coefficient	0.909
Midship section coefficient	0.998
Full-load displacement (metric tons)	42,546
Wetted surface area (m^2)	7673

Table 3.2: Ballast-Free Bulk Carrier Ballast Condition

Waterline length (m)	189.5
Maximum beam (m)	23.76
Draft at F.P. (m)	4.28
Draft at A.P. (m)	7.49
Speed (knots)	15.5
Reynolds number (fresh water)	$1.35*10^9$

The hull of the Ballast-Free Bulk Carrier has been designed in Maxsurf [Formation Design Systems 2003]. The vessel lines are illustrated in Figures 3.2 through 3.4.

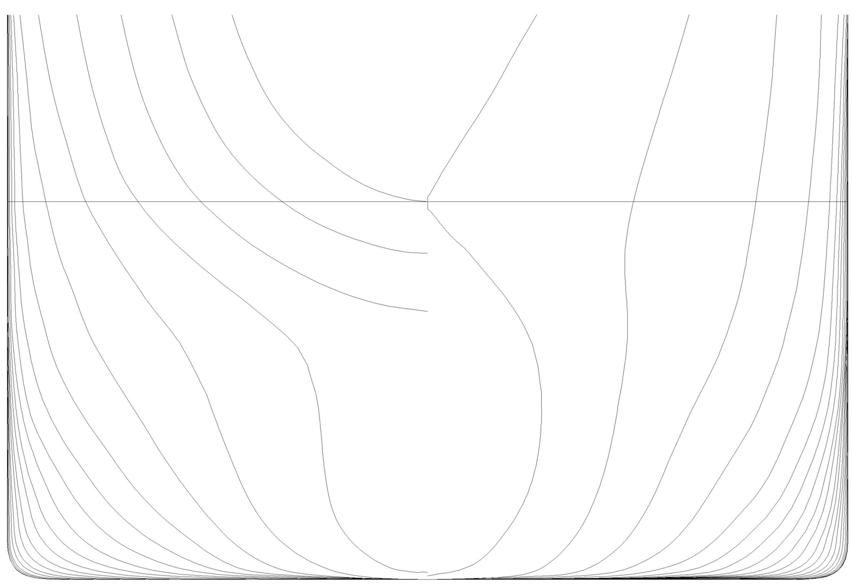

Figure 3.2: Ballast-Free Bulk Carrier Body Plan

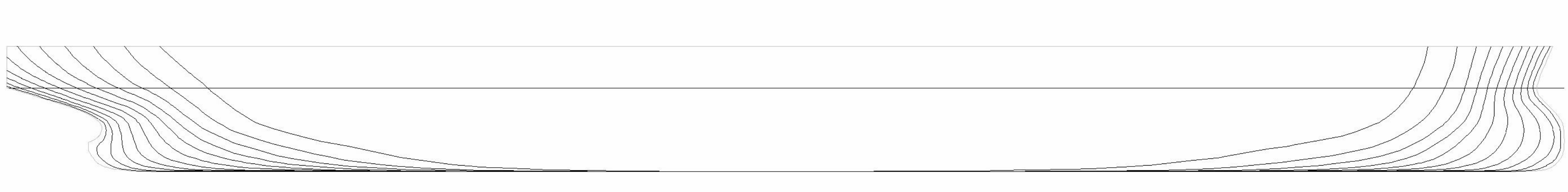

Figure 3.3: Ballast-Free Bulk Carrier Profile View

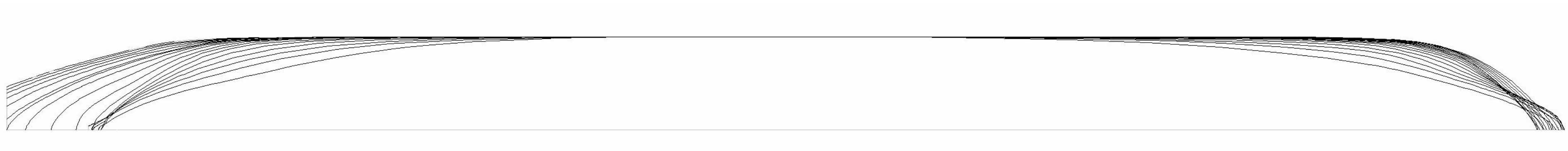

Figure 3.4: Ballast-Free Bulk Carrier Plan View

4. Model Construction Constraints

The construction of a ship model to be tested in a towing tank needs to comply with certain requirements that stem from the experimental procedure and the available testing equipment. The models tests will be performed at the towing tank of the University of Michigan Marine Hydrodynamic Laboratory (MHL). The towing tank dimensions are shown in Table 4.1.

Table 4.1: MHL Towing Tank Dimensions

Length (m)	109.7
Width (m)	6.70
Depth (m)	3.20
Tank cross-sectional area (m^2)	21.44

A significant constraint in the experimental procedure is the interference between the side walls and bottom of the tank and the pressure field and wave system generated by the motion of the model. This is usually termed "blockage effect" and results in total resistance measurement errors (artificial increase). A general guideline is that the model cross-sectional area be at most 1/200 of the tank cross-sectional area (in terms of the tank beam and water depth). Nevertheless, if the operating Froude number is relatively low (less than 0.20), the wave resistance is not a large proportion of the total resistance, and thus correction factors can be introduced in the calculation procedure when large models are utilized.

If the vessel under investigation normally operates in deep water, a similar situation needs to be simulated in the towing tank experiments. Operation in shallow water is generally considered to increase the resistance. A general guideline is that the ratio of the square root of the model cross-sectional area over the tank water depth should not exceed a value of 0.25.

5. Model Propeller Selection and Geometric Scale Factor

A very significant parameter in determining the geometric scale factor of the model is the size of the available stock propellers. Two propellers from the MHL stock (No.10 and No.23) were investigated during the propulsion analysis. The thrust requirements were based on Holtrop's resistance and propulsive coefficients estimates [Holtrop 1984]. The total resistance of the Ballast-Free bulk carrier at the full-load condition was estimated at 573 kN. The propulsive coefficients were also estimated using Holtrop's empirical formulas. These were utilized as input to the propeller analysis.

The corresponding non-dimensional thrust and torque versus coefficient of advance (Kt, Kq – J) charts of the propellers were utilized for the analysis. The results showed that the model propeller No.23 provides a higher propulsive efficiency (0.55) assuming a full-scale propeller diameter of 6.0 m. The corresponding value of the geometric scale ratio is $\lambda = 37.92$, which is within the acceptable range, based on the design constraints. This will result in a model waterline length of approximately 5 m. The amount of back cavitation is expected to be well below the upper limit for merchant ships. A summary of the stock propeller No. 23 characteristics is presented in Table 5.1. The model characteristics are demonstrated in Table 5.2.

Table 5.1: MHL No. 23 Stock Propeller Characteristics

Diameter (in.)	6.229
Pitch/Diameter (P/D) ratio	1.08
Number of blades	4
Expanded area ratio (A_E/A_O)	0.55
Hub diameter (in.)	1.226
Hub length (in.)	1.355
Material	Brass

Table 5.2: Ballast-Free Bulk Carrier Model Characteristics

Geometric scale factor λ	37.92
Waterline length (m)	5.00
Maximum beam (m)	0.627
Average draft (m)	0.155
F.P. draft (40% F.L.)	0.113
A.P. draft (70% F.L.)	0.198
Wetted surface area (m^2)	5.34
Speed (m/s)	1.295
Reynolds number (fresh water)	$5.78*10^6$

The extent of laminar flow along the model length that corresponds to the aforementioned scale factor value and model speed is 9% (of the model length). The attachment of trip-wires or sand-strips to the model bow will be used to stimulate turbulence at a point closer to the forward stagnation point as expected at full scale.

6. Computational Fluid Dynamics (CFD) Analysis of the External Flow

The commercial CFD code FLUENT® was utilized to study the external flow around the model of the Ballast-Free Bulk Carrier in the ballast condition. The model scale speed is 1.295 m/s, which is calculated assuming Froude scaling. The obtained solution has been demonstrated to be grid–independent. The Realizable κ-ε turbulence model was utilized in the calculations. The flow close to the hull was approximated with wall functions. The computational grid consists of a hybrid mesh with 1,507,546 cells. The investigated flow corresponds to a double-model solution; the free-surface is ignored and the waterplane is considered to be a plane of symmetry.

The converged CFD solution can be utilized to obtain the hull resistance, which consists of the friction drag and the pressure (form) drag for this configuration. The friction drag around a ship hull is usually estimated through a semi-empirical formula adopted by the International Towing Tank Conference (ITTC). The computed value is extremely close to the semi-empirical one. The form drag corresponds to only a small fraction of the total drag. The utilization of a double-model flow allows for the computation of the form factor, which is calculated as the ratio of the total drag (excluding the wave drag) to the ITTC friction drag estimate. The computed value is reasonable for the ship in the ballast condition. A summary of the results is presented in Table 6.1.

Table 6.1: Ballast-Free Bulk Carrier Model Resistance Calculations

Friction drag coefficient (FLUENT)	$3.32*10^{-3}$
Friction drag coefficient (ITTC)	$3.31*10^{-3}$
Pressure (form) drag coefficient (FLUENT)	$0.45*10^{-3}$
Total drag coefficient (FLUENT)	$3.77*10^{-3}$
Form factor k	0.139

An important aspect of the Ballast-Free Ship Concept is the location of the water inlet and discharge plena. The steady pressure differential between the two locations will generate a slow water flow in the longitudinal ballast trunks. The volume flow rate is proportional to the square root of the pressure differential. It was demonstrated [Kotinis 2005] that the higher the flow rate the more effective (less time required) the flushing of the trunks. The computed pressure contours in the bow and stern region of the Ballast-Free Bulk Carrier are shown in Figs. 6.1 and 6.2, respectively.

The pressure contours in the bow region reveal that the pressure is high in a small region near the bulbous bow. However, starting at the forward perpendicular, the flow is relatively smooth with low pressure and pressure gradient values. This is also observed in Fig. 6.3, where the velocity vectors in the bow region are plotted. The downward flow direction reduces the height of the bow wave. The only significant drawback is with respect to the location of the bow plenum, as the positive pressure is limited to a small area starting at the stagnation point and extending aft to about 6% of the waterline length.

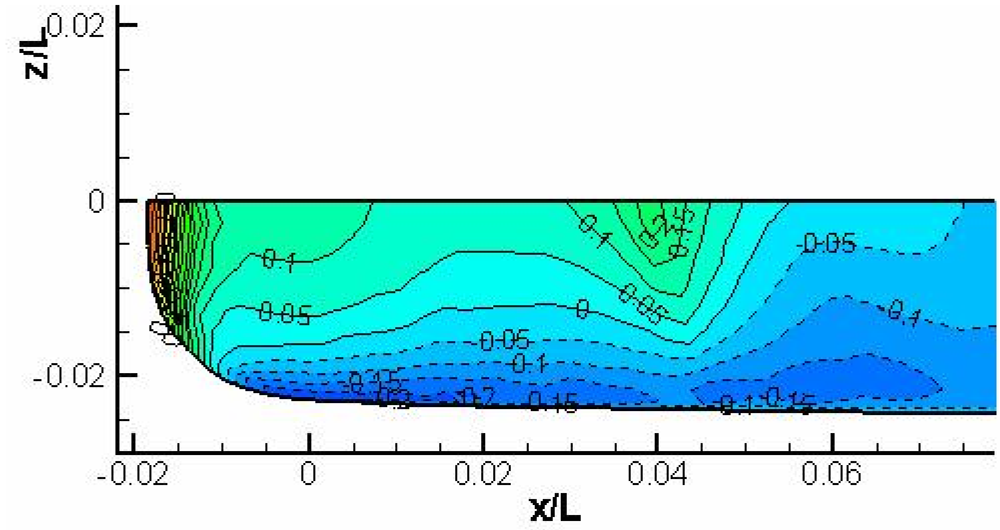

Figure 6.1: Pressure Contours Velocity Vectors at the Bow of the Ballast-Free Bulk Carrier Model

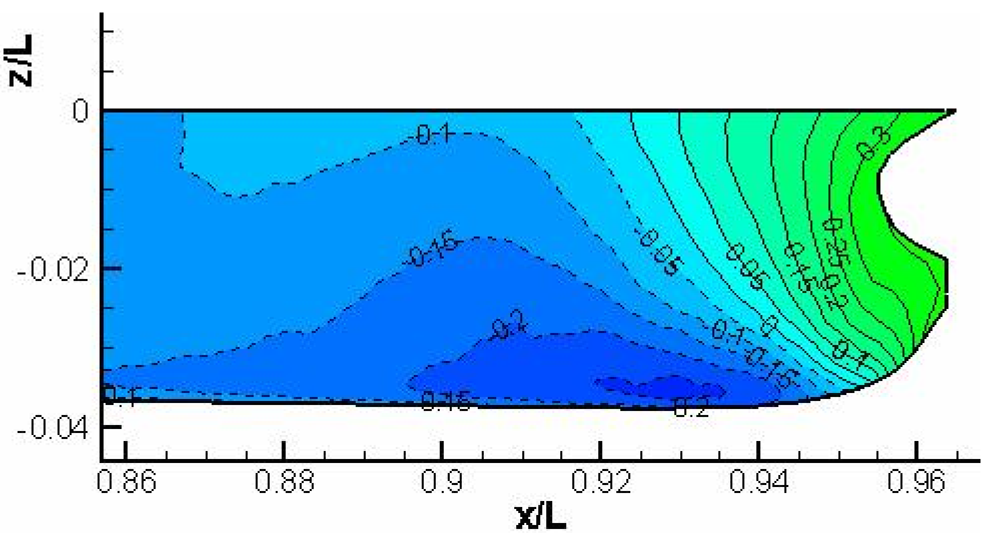

Figure 6.2: Pressure Contours at the Stern of the Ballast-Free Bulk Carrier Model

The stern region is governed by suction pressure, which has a peak near the bilge just ahead of the stern bulb. A significant positive pressure region exists above the stern bulb. No separation is observed in the velocity vector plot in Fig. 6.4. The location of the stern plenum will be close to the aft end of the engine room (around x/L = 0.92) and above the inner bottom (2.4 m from the keel).

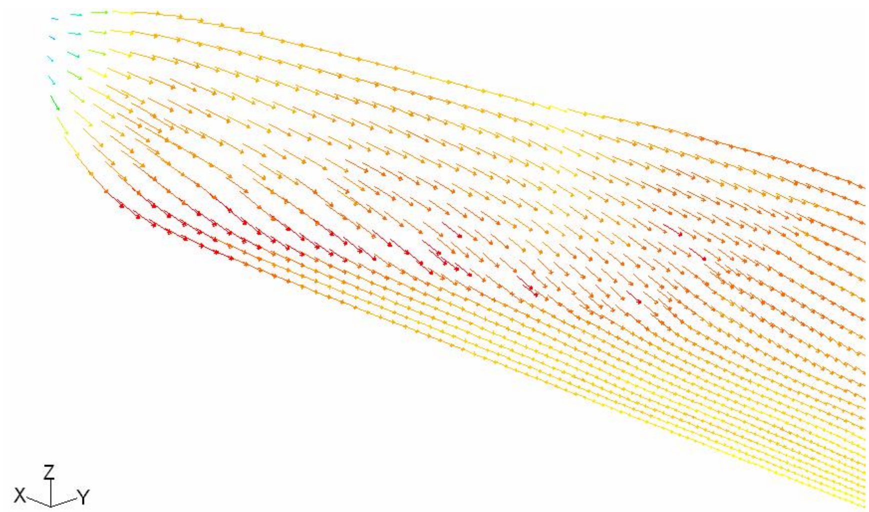

Figure 6.3: Velocity Vectors at the Bow of the Ballast-Free Bulk Carrier Model

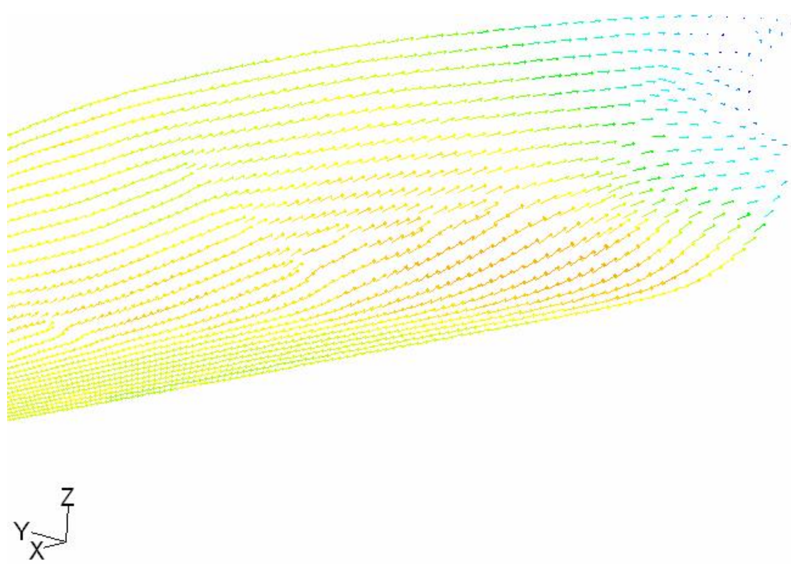

Figure 6.4: Velocity Vectors at the Stern of the Ballast-Free Bulk Carrier Model

7. Computational Fluid Dynamics (CFD) Analysis of the Internal Ballast Trunk Flow

The internal trunk flow was investigated in both full and model scale. A typical trunk configuration [Kotinis 2005] was generated and the corresponding pressure boundary conditions, as calculated from the external flow simulations, were imposed on the inlet/outlet plena. The forward plenum was located at a point about x/L = 0.04 between the 0.2 and 0.35 design waterlines. The aft plenum was located at a point near x/L = 0.925 between the 0.3 and 0.45 design waterlines.

The pressure distribution was assumed to be the same in both full and model scale. This assumption is justified by the fact that the Reynolds number is relatively high in both cases and the body at ballast draft is relatively streamlined (low form drag). The computational grid consists of a hybrid mesh with 705,915 cells. The trunks were assumed to be filled with ballast water and the natural trunk flushing was initiated by new ballast water entering the system through the inlet plenum. The volume flow rate at the inlet and outlet plena was monitored until convergence to a constant value was observed. The unsteady flow solver in FLUENT was utilized with a time step size of one second (1s). The solution at each time step was considered to have converged when the residuals dropped by four orders of magnitude. The computational model geometry of the double bottom structure is shown in Fig. 7.1.

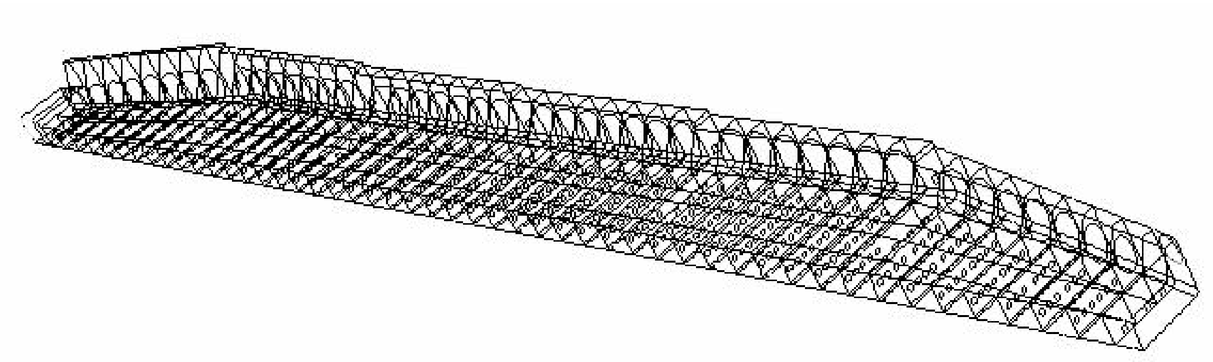

Figure 7.1: Computational Model Geometry of Double Bottom Structure

The average volume flow rate at full scale is 0.969 m^3/s. The model scale solution has an average flow rate of $1.02*10^{-4}$ m^3/s. The corresponding ratio is approximately 9,500. This result is in agreement with the scaling factor between the ship scale flow rate and the model scale flow rate, $Q_s = Q_m \lambda^{5/2}$, theoretically derived in the initial investigation of the Ballast-Free Ship Concept based on Froude scaling. This scaling assumed that the flow rate scaling should be proportional to the scale factor λ raised to the 2.5 power. The corresponding exponent of the geometric scaling factor based on the numerical CFD results was approximately 2.52.

8. Model Construction

The model of the Seaway-Sized Bulk Carrier for use in subsequent hydrodynamic optimization testing has been contracted for construction by F.M. Pattern Works of North Vancouver, BC. This is the primary deliverable of the project and its procurement represents approximately half of the project funding. The model is under construction at the time of this writing and delivery of the completed 5 m scale model is expected near the end of October 2006. Progress photographs of the glue up of the aft portion of the hull are shown in Figs. 8.1 and 8.2.

Figure 8.1: Aft Portion of the Scale Model Seaway-Sized Bulk Carrier – Inverted Stern Quarter View

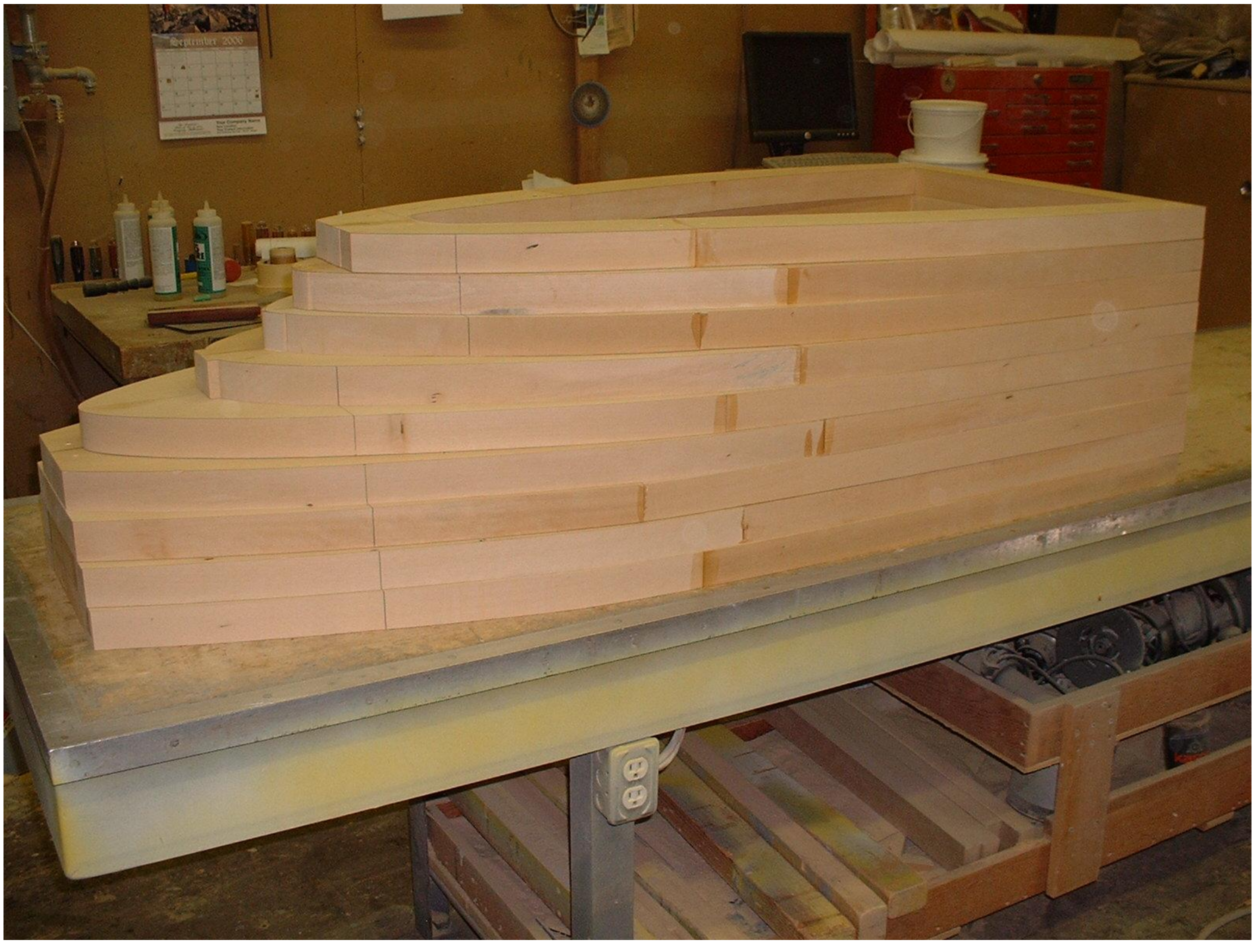

Figure 8.2: Aft Portion of the Scale Model Seaway-sized Bulk Carrier – Inverted Side View

9. Potential Economic Impacts of the Research Results

The hydrodynamic optimization of the Ballast-Free Ship Concept is expected to demonstrate that there is only a small, if any; propulsion power penalty associated with the concept. In that case, it should result in a net Required Freight Rate savings relative to alternate ballast water treatment methods such as filtration and UV treatment of about 0.20 $/ton of cargo. The concept should also provide superior protection from the further introduction of nonindigenous aquatic species into the Great Lakes and coastal waters.

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