Great Lakes Maritime Research Institute

A University of Wisconsin - Superior and University of Minnesota Duluth Consortium

Refinement of the Ballast-Free Ship Concept

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In this project, the Ballast-Free Ship concept (Kotinis et al. 2004), or the Variable Buoyancy Ship concept (Parsons 2010), has been further analyzed and refined to resolve outstanding issues related to its effectiveness, operational practicality and economics. Recent GLMRI sponsored testing has shown that the optimum use of the Ballast-Free Ship concept could result in a significant improvement in propulsion power requirement. This savings needed to be better understood, however, to ensure that this advantage could actually be realized. The remaining confounding issue was that in all laboratory experiments conducted previously it had been necessary to use stock propellers available in the hydrodynamic laboratory library. It was suspected that part of the indicated required power reduction might have been due to the stock propellers simply being more optimal for the Ballast-Free trunk flow case. An optimum propeller has been designed for the vessel at full load and a new model propeller has been manufactured using rapid prototyping. This propeller has been used in towing tank experiments to clarify this issue. The draft and trim control capability of the Ballast-Free bulk carrier has also been investigated to ensure the acceptable capability is available for ship operations. An unsuccessful attempt was made to assess the effect of the detailed design of the inlet and outlet plena and the use of butterfly bulkhead isolation valves on the timely initiation of the internal trunk flow. Finally, the economic analysis of the Ballast-Free bulk carrier has been updated to reflect current prices and the design changes introduced in this study.

1. Hydrodynamic Investigation

1.1 Background. A critical aspect regarding the viability of the Ballast-Free Ship (BFS) concept is the impact of the concept on the hydrodynamic performance of the vessel. The PI and the co-PI of this project have performed investigations (Kotinis et al. 2004, Kotinis 2005, Kotinis and Parsons 2007 and 2008/2010), both in the towing tank and numerically using Computational Fluid Dynamics (CFD), in order to understand the interaction between the water suction/discharge and the flow around a bulk carrier vessel, including the inflow to the propeller. The investigations performed prior to this project showed that discharging water at the stern at low speed, relative to the ship speed, did not have a negative effect on the propulsion requirements of the vessel and might result in a fuel savings of about 1.6% in the no load (ballast) condition (Kotinis and Parsons 2008/2010). These investigations were all performed in model scale using analysis procedures that are widely-accepted in experimental ship hydrodynamic investigations. These procedures are not physically able to scale the viscous flow in an accurate manner, thus, they cannot fully account for flow interactions that occur within the boundary layer region. For this reason, it was decided to follow a different course of action in order to quantify the effect of the BFS concept on the flow around the vessel. The first step was to analyze the wake of the un-appended vessel using CFD. This was done for both the bulk carrier model and full scale vessel operating in both full load and ballast drafts. The initial results of the CFD analysis were reported in (Kotinis and Parsons 2008/2010). As expected, these results revealed considerable differences in the wake distribution in the propeller plane between model and full scale hulls. This numerical investigation has been utilized in the current project.

1.2 Design of optimal propeller for the Ballast-Free bulk carrier model. The next task in the refinement of the hydrodynamic investigation of the BFS required the design of an optimal, wake-adapted propeller. The model-scale vessel operating at the full load draft was used as the design basis. The corresponding wake distribution in the propeller plane, which was previously computed using CFD, was utilized as input to the propeller design procedure. The resistance of the vessel in this condition was measured during towing tank experiments (Kotinis and Parsons 2008/2010). The co-PI performed a preliminary analysis using data from the Wageningen B-Series 5-bladed propellers in order to find the combination of rotational speed and expanded area ratio that provides high efficiency with minimal blade cavitation. This optimal value of the expanded area ratio ($A_e/A_o = 0.75$) was used to compute the chord lengths of the blade sections at different radii based on the Wageningen B-Series data. The blade sections were modeled using a parameter a = 0.8 camber distribution combined with a modified NACA 66 thickness distribution. The optimal circulation and pitch distributions were then obtained utilizing the open source propeller design and analysis program OpenProp (Epps et al. 2009). OpenProp's propeller design algorithm is based on a vortex lattice lifting line analysis with panels distributed along the propeller blade span. A helical wake model aligned with the flow at the lifting line is incorporated, enabling the design of a moderately loaded propeller. The optimization algorithm is based on Lerbs' criterion, which allows for a radially varying circumferential mean inflow. The propeller has a 15^o rake and a moderate 25^o (34.7%) quadratic skew distribution. A 3-D image of the resulting optimal propeller design is depicted on the left in Fig. 1. The corresponding open water performance diagrams are displayed in Fig. 2.

1.3 Hydrodynamic Investigation. The optimal wake-adapted propeller was then manufactured using Fused Deposition Modeling (FDM); a rapid prototyping procedure. Acrylonitrile butadiene styrene (ABS) was used as the propeller material since it provides high mechanical strength and rigidity, but is also easy to process. The manufactured model-scale propeller is shown on the right in Fig. 1.

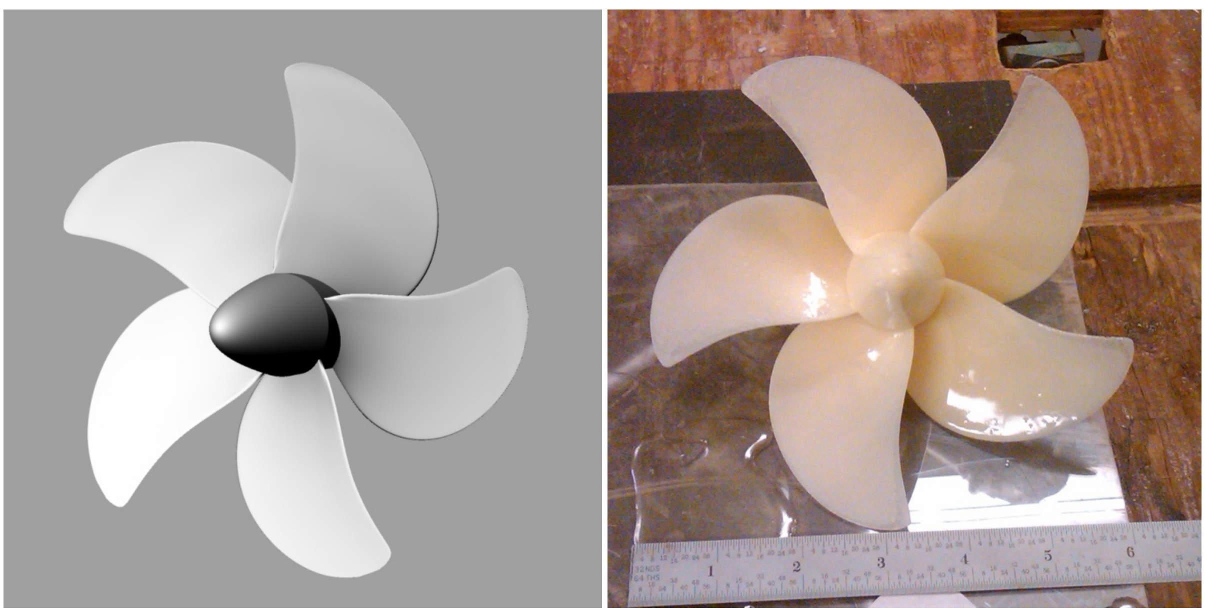

Figure 1. Optimum Propeller Design (left) and Rapid Prototyping Realization of Model Propeller (right)

The model-scale propulsion tests were then performed in the towing tank of the Marine Hydrodynamics Laboratories (MHL) at the University of Michigan. The results revealed that, as suspected, the utilization of an optimal propeller does diminish the gain in propulsive efficiency obtained with the non-optimal stock propellers. These gains in propulsive efficiency, however, are still capable of offsetting the 4.5% increase in resistance observed with the discharge of the trunk flow at the stern of the vessel. A comparison between the no-trunk-flow case and the case with a 90-min exchange time discharge at Station 17 (near the forward engine room bulkhead) is shown in Table 1. This confirms that the Ballast-Free Ship concept can be used in Seaway-sized bulk carriers without incurring a fuel use penalty.

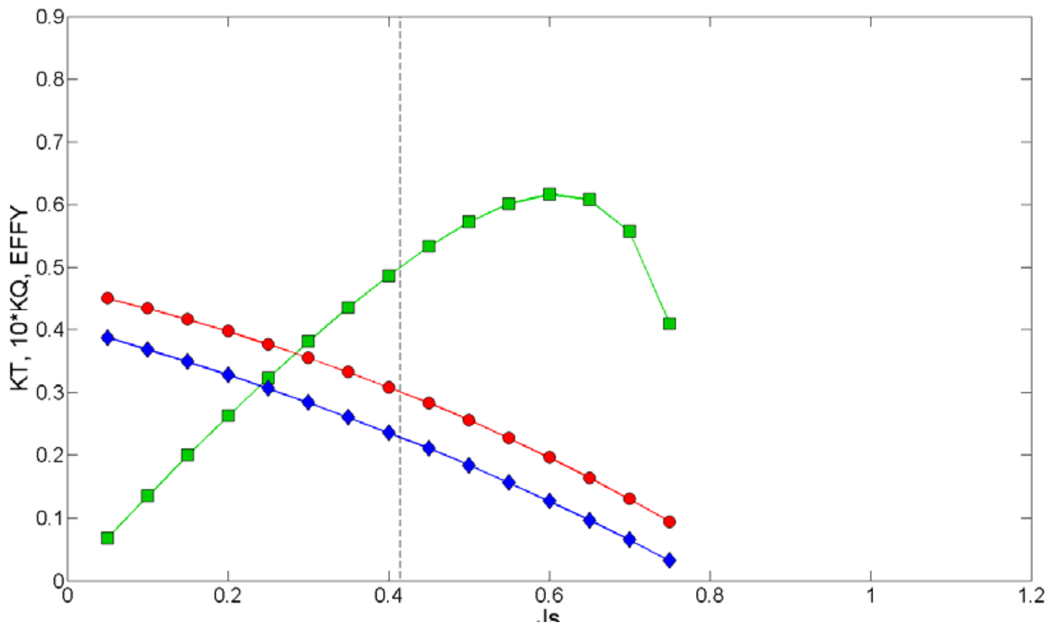

Figure 2. Open Water Performance Characteristics of Optimal Propeller

Table 1 Propulsion Test Results - Ballast Condition at 15.5 knots

	Baseline - No Trunk Flow	Discharge at Station 17 - 90-min Exchange Time
Open water efficiency η_O	0.437	0.423
Effective wake fraction w	0.458	0.468
Thrust deduction t	0.343	0.366
Hull efficiency $\eta_H = (1 - t)/(1 - w)$	1.211	1.193
Relative rotative efficiency η_R	1.078	1.183
Behind propeller efficiency $\eta_P = \eta_O\ \eta_R$	0.471	0.500
Advance coefficient J = V(1-w)/(nD)	0.399	0.383
Propulsive efficiency $\eta_D = \eta_O\ \eta_H\ \eta_R$	0.571	0.597
Change in propulsive efficiency $\Delta\eta_D$	base	+4.55%
Delivered power P_D (hp)	12,336 ± 64	12,343 ± 107

2. Trim and Draft Control

The control of the vessel's trim and draft when adopting the BFS concept is more 'discrete' when compared to a conventional bulk carrier. A conventional vessel can fill any ballast tank to any level, up to its capacity, to achieve a continuous array of trim and draft conditions as might be required by the crew. The initial BFS design concept omitted fill/empty lines to each isolatable section of the outboard trunks that extend beneath the cargo region of the ship and included no subdivision capability within the two longitudinal trunks next to the keel (Kotinis et al. 2004). The BFS or Variable Buoyancy ship as configured in the initial conceptual design can, therefore, only achieve a discrete number of conditions. The trunks nearest the keel must either be flooded or empty. The two outer trunks on each side have isolation valves at each of the cargo hold bulkheads and thus adjacent segments of these trunks can be flooded from either the bow or the stern, or both, provided a pump out capability is provided just inside the bow and stern isolation valves. This creates many options, but the potential is limited. This needed to be evaluated further to ensure that these vessels will have adequate control of their draft and trim.

An investigation was undertaken to assess the trim and draft control capability of the conventional and BFS or Variable Buoyancy Seaway-sized bulk carrier to ensure that comparable capability would be provided. The hydrostatic analyses were performed in Hydromax® (Formation Design Systems 2006), assuming that the conventional and the Variable Buoyancy bulk carrier carry no cargo and 2/3 of the amount of fuel and fresh water carried at the ballast departure condition. To better visualize this issue, the equilibrium polygon used in early submarine design (Arentzen and Mandel 1960, Goldberg 1988, Burcher and Rydill 1994) was adapted to provide an effective way to characterize the trim and draft control capability of surface vessels as shown in Fig. 3. These trim and draft control authority diagrams were used to study and visualize the trim and draft control capability of a Seaway-sized Variable Buoyancy bulk carrier in comparison to that available of a conventional bulk carrier (Fig. 3).

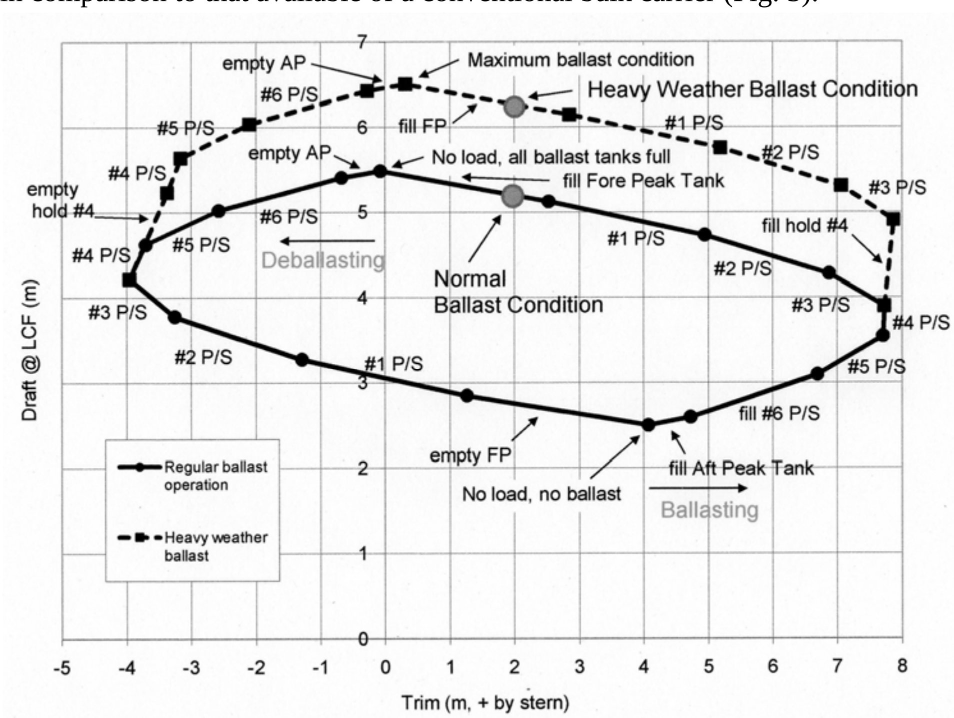

Figure 3. Trim and Draft Control Authority Diagram for Conventional Seaway-sized Bulk Carrier

With the addition of a closed Fore Peak tank/Aft Peak tank trim control system and trunk fill/empty lines to each end of the outer four ballast trunks, it appears that although it is a discrete capability the Variable Buoyancy bulk carrier would have adequate capability to control trim and draft. This capability is summarized in Fig. 4 where any condition on the horizontal "error bound" bars is achievable. Additional capability could also be realized by filling portions on some trunks before filling the remaining trunks in order to reach additional internal areas of the trim and draft control envelope. The complete results of this study have been reported in a paper (Parsons and Kotinis 2011) that was submitted for publication in the *Journal of Ship Production and Design* on April 2, 2011. A copy of this draft paper was provided to the GLMRI office at the time of submittal.

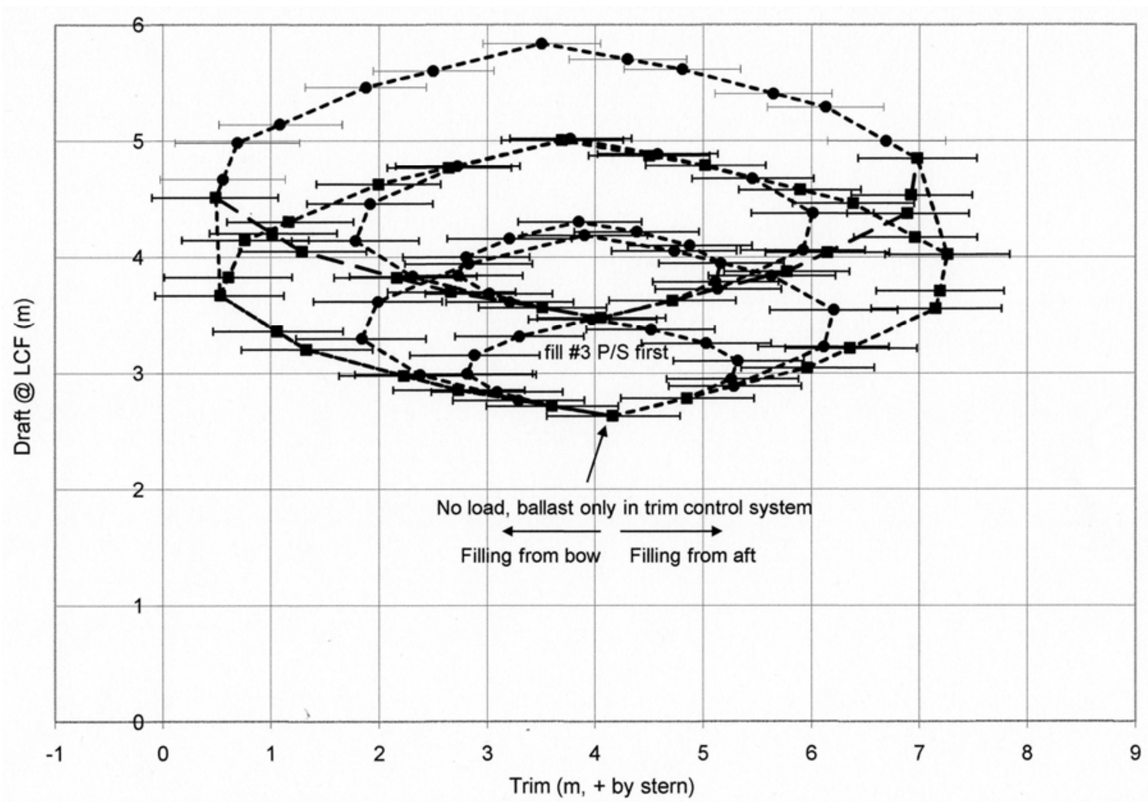

Figure 4. Composite Trim and Draft Control Capability using all Three Trunks on each Side, in any Combination, with the Closed Trim Control System on the Variable Buoyancy Seaway-sized Bulk Carrier

The full range of Variable Buoyancy bulk carrier trim and draft operations would require the assistance of a crew advisory system that could be incorporated into the onboard load computer that would propose operations and check the draft, trim, shear, and bending moment for each desired operation.

The trim and draft control authority diagram adapted from the equilibrium diagram used in early submarine design and introduced in this study provides a useful design tool for the visualization and assessment of the trim and draft control capabilities of all surface vessels. It is particularly valuable for the visualization of operational trim and draft constraints as shown in Fig. 5.

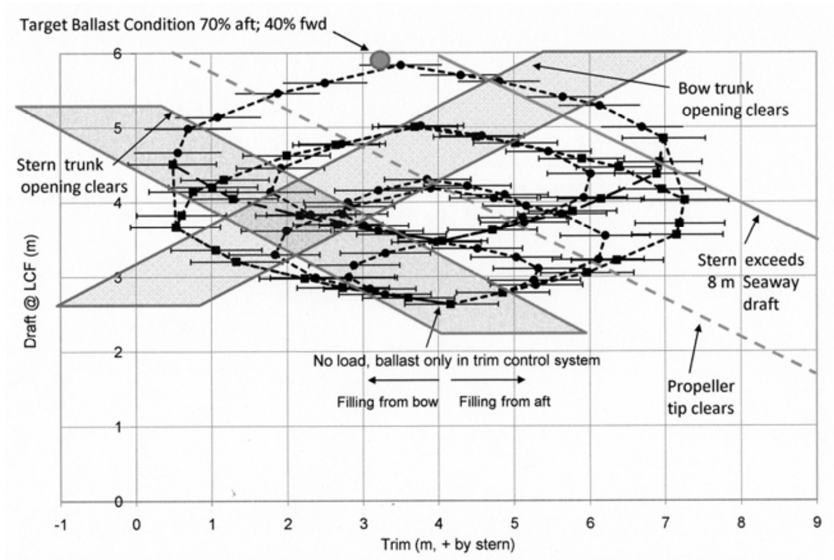

Figure 5. Operational Constraints Visualized on Trim and Draft Control Authority Diagram

3. Internal Flow Study

An attempt was made to revisit the initiation of the internal trunk flow in the Ballast-Free bulk carrier by utilizing the commercial Computational Fluid Dynamics (CFD) code ANSYS® FLUENT®. The mesh of the domain was generated in GAMBIT®, a general-purpose preprocessor for CFD analysis. The objective of this particular task was to update the required time to replace the existing ballast water in the double bottom trunks after flow initiation. This was desired because of the many changes in the geometry and design since the initial conceptualization of the Ballast-Free ship. Compared to the initial FLUENT® study in (Kotinis 2005), there now a single inlet at the bow and the isolation of the trunks is now achieved with butterfly valves instead of the sluice gates that were initially proposed. A representative example of the modeling of these valves is shown in Fig. 6.

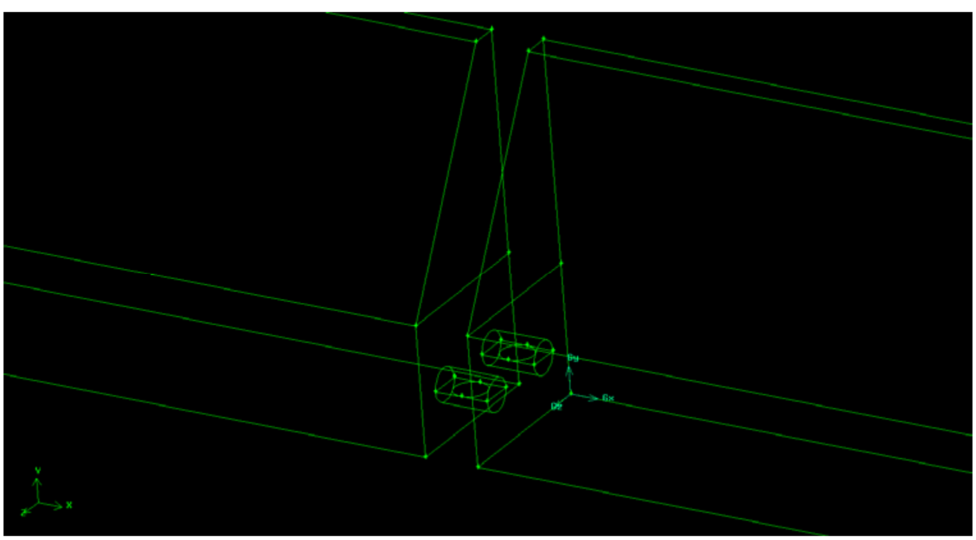

Figure 6. Modeling of Butterfly Isolation Valves in Bulkhead of Outer Trunks

In order to quantify the effect (head loss) of the butterfly valves on the trunk flow, the generation of a relatively fine mesh in the interior of the valve is required, as shown in Fig. 7. Despite our efforts, the size of the computational model, which is currently in excess of four million cells even with only half of the actual domain modeled (symmetry), has made it impossible to run the simulations successfully using available computer resources.

This effort will continue in the next few months. A computer hardware upgrade in addition to the utilization of different preprocessing software is anticipated to allow us to run the desired trunk flow initiation simulations successfully. This effort must now be considered beyond the feasible scope of the present project.

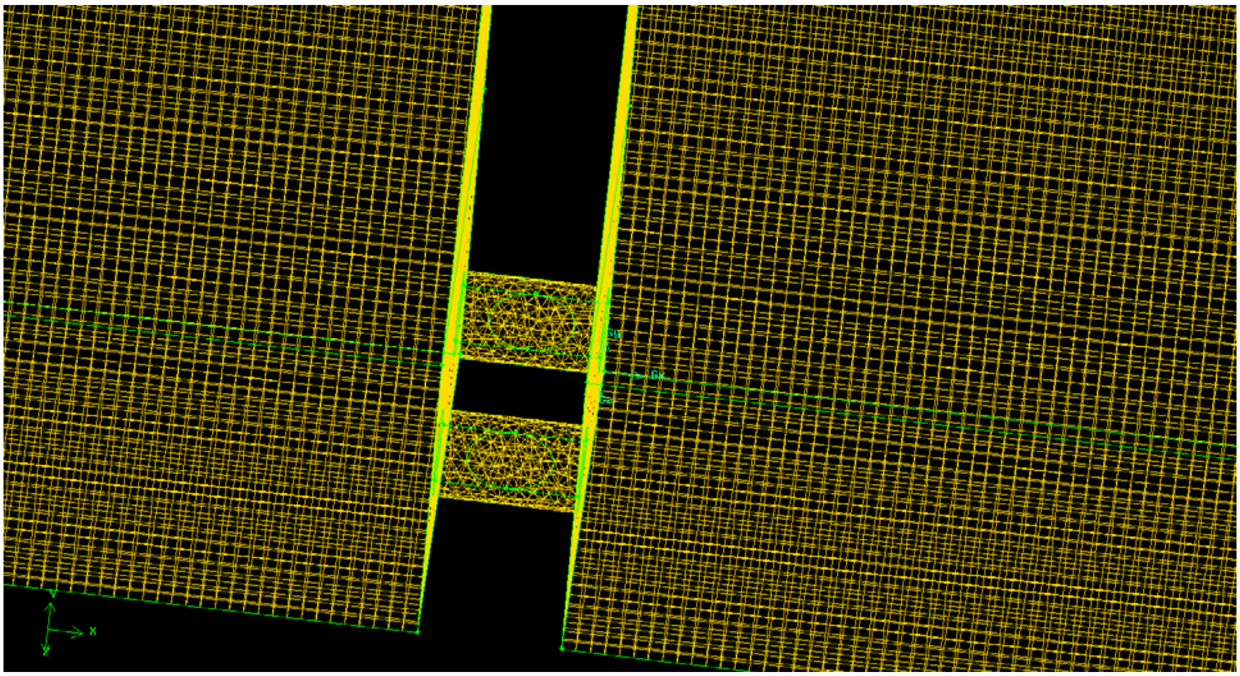

Figure 7. Mesh Detail in Way of Butterfly Isolation Valve

4. Order of Magnitude Economics Comparison

The order of magnitude economics comparison of a Ballast-Free and a conventional Seaway-sized bulk carrier was updated from our most recent work (Kotinis and Parsons 2008/2010). Because the Ballast-Free bulk carrier was designed to maintain the same grain capacity, its annual cargo capacity (ACC) would be unchanged. Thus, an appropriate measure of merit is the change in the Required Freight Rate (ΔRFR) using the equation (Mackey et al. 2000):

$$\Delta RFR = (CRF(i, n)\ \Delta P + \Delta A)/ACC \qquad (1)$$

where ΔP is the change in the capital cost, ΔA is the change in the annual operating cost, ACC is the constant annual cargo capacity, and CRF(i, n) is the Capital Recovery Factor for an i return on investment over a ship life of n years. The comparison assumes that ballast water exchange is no longer permitted and the conventional bulk carrier is required to have a ballast water treatment systems consisting of an automatic backwash filter followed by UV treatment to meet IMO requirements (IMO 2004). In this system the UV would be utilized during both intake and discharge.

The summary of this comparison is shown in Fig. 8. The trade is assumed to be a ballast voyage from Rotterdam to Duluth, MN at the head of the Great Lakes to load grain for an 8 m Seaway draft return voyage. The greater hull depth, fullness, and hull steel weight of the Ballast-Free bulk carrier are included. Foreign new construction, typical of South Korea, was assumed for the calculation of the construction costs. The comparison uses current shipbuilding steel and fuel prices. Because this study has shown no significant change in the required propulsion power, no change in the required propulsion fuel has been shown. An updated cost estimate for the capital cost and operating costs associated with the eliminated filtration/UV treatment system has also been included. This estimate is based on a fairly recent Finnish study (Sassi et al. 2005), with inflation. The estimate includes the closed Fore Peak tank/Aft Peak tank trim control system and the additional trunk fill and empty lines added as a result of this study.

The net savings for the Ballast-Free bulk carrier with the ballast trunk water discharge close to Station 17 is estimated to be about $0.50 per tonne of cargo. So in addition to essentially eliminating all risk of the transport of nonindigenous aquatic species, the Ballast-Free ship concept would also provide a modest cost savings for a Seaway-sized bulk carrier.

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Vessel data and trip scenario	Conventional bulk carrier	Ballast-Free bulk carrier	Comments
Round trip distance to Montreal (nautical miles)	6,580		Round trip Montreal (CAN) to Rotterdam (NL)
Service speed (kts)	15.0		Typical data for an ocean-going Handymax bulk carrier transporting grain cargo from the Great Lakes (Duluth, Thunder Bay) to ports in Northern Europe and occasionally transporting steel into the Great Lakes.
Speed in ballast condition (kts)	15.5		
Proportion of miles in ballast (%)	50		
Average Seaway loaded cargo / maximum cargo (%)	75		
Whole Voyage Load factor (%)	37.5		
Days of navigation through the Great Lakes	9.33		Passage Montreal to Duluth and return (www.great lakes-seaway.com)
Port days per round trip	14		Includes loading/unloading time, bunkering time, and time waiting for berth
Round trips per annum	7.0		Assuming a 276 day Seaway shipping season
Maximum payload (metric tons)	32,000		
Cargo carried per annum (metric tons)	84,000		
Engine nominal MCR (kW)	8,580		Data for the MAN B&W 6S50MC two-stroke engine
Block coefficient	0.835	0.842	
Hull steel weight (metric tons)	5,550	5,800	
Hull steel cost ($)	4,773,000	4,988,000	Assuming a Chinese steel price of $860/metric ton (www.steelorbis.com 3/29/11)
Changes in capital cost with discharge at Station 17 near forward engine room bulkhead			
Additional hull steel cost ($)	215,000		
Butterfly valve cost ($)	468,000		Addition of 78 24" trunk isolation butterfly valves @ $6,000 each (materials plus labor)
Inlet and outlet plena ($)	150,000		Addition of plena (materials plus labor)
Elimination of ballast tank valves ($)	-36,000		Elimination of 12 @ $3,000 each (materials plus labor)
Eliminaton of ballast tank connection trunks	-72,000		Elimination of 12 pairs connecting doublebottom tanks to upper wing tanks
Reduction in ballast piping cost ($)	-220,000		Removal of 2 main ballast headers (materials plus labor)
Addition of trunk fill/empty lines ($)	440,000		Addition of 4 fill/empty headers for trunks (materials plus labor)
Addition of trunk fill/empty valves ($)	30,000		Addition of 10 @ $3,000 each (materials plus labor)
Reduction in bottom floor welding cost ($)	-11,684		Reduced welding at the bottom of solid floors (materials plus labor)
Addition of trim control system ($)	260,000		Addition of pump, valves and piping (materials plus labor)
Additional welding cost ($)	6,395		Additional welding due to raising of inner bottom/greater depth (materials plus labor)
Elimination of ballast water treatment ($)	-757,626		Assuming automatic backwash filtration combined with UV radiation
Net capital cost change ($)	472,085		
Changes in operating cost with discharge at Station 17 near forward engine room bulkhead			
Elimination of ballast water treatment operating cost ($)		-91,465	Assuming MDO price of $1023/metric ton (Rotterdam MGO, www.bunkerfuel.com 4/26/11)
Net operating cost change per annum ($)		-91,465	
Capital recovery factor	0.1019		i = 8%, n = 20 years
Change in required freight rate ($/metric ton)		-0.52	savings

Figure 8. Order of Magnitude Economics Comparison between a Conventional Bulk Carrier with Automatic Backwash Filtration and UV Ballast Water Treatment and a Ballast-Free Bulk Carrier