Stern End Bulb for Energy Enhancement and Speed Improvement

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Unlike the bow bulb, the stern end bulb (SEB) has been used on just a few ships to improve performance. In one of these rare, full-scale applications, a maximum resistance reduction in the 5% to 7% range is claimed. A few applications of SEBs are shown along with some model test data for a Naval Auxiliary ship. The rationale for SEB is discussed along with the hydrodynamic mechanism associated with a SEB. In addition to wave-making reduction, the SEB can reduce eddy-making and possibly improve course-keeping. The results of several fluid flow computations with initial SEB designs are shown for two ship classes: the T-AKE LEWIS and CLARK dry cargo ship and the DDG 51 ARLEIGH BURKE destroyer. The calculations use the Ship Wave Inviscid Flow Theory potential flow computer code and the FreeRans viscous flow free surface computer code. Several SEBs were designed and investigated analytically for the T-AKE class ships, and the best of these is predicted to reduce resistance by 4.5% at 20 knots. In addition, several initial SEB/Stern Flap configurations were designed for the DDG 51 Class Flight IIa destroyers and five configurations, some with just an SEB added to the hull and others with a combined SEB-Stern Flap configuration were model-tested. The examination of these initial efforts led to the design of several new-style combined SEB-Stern flap configurations, the best of which is predicted to save at least 745 Bbls of fuel per ship per year.

Keywords: resistance; powering; stern bulb; stern flap; wave-making

1. Introduction

It is acknowledged that a ship moving in the water generally creates a much higher bow wave than stern wave and thus the most logical location for a bulb is at the bow because the large energy content in the bow wave is a potential source of recoverable energy. Nevertheless, the stern end of the ship also makes waves, which are a source of "wasted" energy. Thus, the intent of the exploratory work herein was to provide some sample estimates of resistance reduction for stern end bulbs.

Bow bulb design has matured over the past several decades with many individual examples of very successful bow bulbs applied to both commercial and naval ships. Today, bow bulb design is assisted by the myriad of open literature bow bulb design examples, by model test-based systematic variations on bow bulb parameters, and by the continual development of better computational tools. In contrast to the plethora of technical reports on bow bulb design and effectiveness, there are only a few dozen technical reports on stern end bulbs.

Currently, stern end bulb (SEB) development is at its infancy stage, possibly in a situation that is somewhat analogous to bow bulb development as it existed at the time when the so-called "Taylor Bulb" was the only kind of bow bulb applied to ships. The "Taylor Bulb" concentrated the volume low in the bulb and did not project forward of the usually plumb stem and as a consequence, the resistance reduction was in the low single-digit percentages. The maturing of the bulbous bow theory and design has resulted in several bulbous bow designs. which reduce resistance by 10% or more. Similarly it is hoped that the SEB work reported here will spark the development of even more efficient SEBs.

2. Background

The basic effectiveness of bulbs relies on the beneficial wave interaction between the waves generated by the bulb and the waves resulting from the hull. With regard to the stern end of the ship, there are several ways to modify stern waves, including 1)

Manuscript received by JSPD Committee August 27, 2012; accepted October 22, 2012.

section area and after body shape variation; 2) transom extension (lengthening of the ship); 3) propulsion pods; 4) stern flap and/or wedge; and 5) SEB. As a strictly energy-saving or speed-improving item, the last two are the most practical for retrofit to an existing ship.

With regard to stern flaps, U.S. Navy experience (Cusanelli 2002) proves the stern flap to be effective on seven different ship classes as determined by full-scale trials with and without a stern flap. In addition, the U.S. navy has installed stern flaps on designs that did not have full-scale trials. All of these stern flaps were very effective in reducing power and as of 2011, approximately 200 stern flaps have been installed on various U.S. Navy ships. This experience shows that in fact there is a lot of energy in stern waves. Those ships that are not candidates for a stern flap (such as transom out of the water or high dead rise transoms) may very well be candidates for an SEB.

The U.S. Navy propulsion pod experience (Karafiath & Lyons 1999) shows that there is a beneficial resistance interaction between propulsion pods and the hull for speeds corresponding to hull length-based Froude numbers between 0.4 and 0.5. The conclusion is based on model tests with propulsion pods that are mounted under the after section of the hull generally between stations 18 and 20. This location is considered to be not the best from the wave interaction point of view. Nevertheless, the data support the concept of placing volume at the stern for the reduction of wave resistance.

Extending the transom of a ship in general tends to reduce the resistance because of the length effect and because the immersed transom area tends to be reduced. However, a transom extension in many cases is not economically feasible because of the impact of the extension on ship characteristics and naval architectural limits.

Early SEB research took place mostly in Japan (Inui & Miyata 1979, 1980; Miyata 1980; Miyata et al. 1981a, 1981b, 1981c; Okamoto & Yamano 1983; Okamoto et al. 1983). During these efforts, the SEB design developed from an initiative to improve rudder–hull interaction on single screw merchant ships.

Approximately 12 years ago, the Naval Surface Warfare Center Carderock Division (NSWCCD) took advantage of some of the Japanese early design work and used empirical and experience-based intuitive guidance to design and perform model resistance tests on a stern bulb fitted to an AOE 6 class hull form and later fitted the same design to a T-AO 187 class model. A photograph of this SEB design is shown in Fig. 1. Figure 2 shows a drawing with the dimensions applicable to the AOE 6. The model test-based resistance effect of the bulb as shown in Fig. 3 is for physically the same model bulb as fitted to both the AOE 6 and the T-AO 187 class models.

The resistance ratio shown in Fig. 3 is the resistance with the SEB/no SEB resistance for the case of the fully appended ship(s). The AOE is at light displacement and the T-AO is at design displacement. Both ships are twin screw with shaft and struts and twin rudders. At the highest speed, The AOE 6 showed nearly a

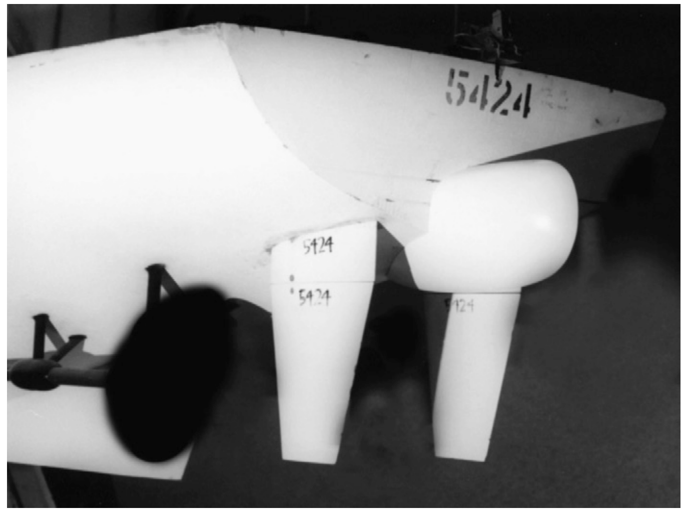


Fig. 1 Stern end bulb on the AOE model

4% reduction in total resistance at the light displacement. At the design displacement, the resistance with and without SEB was virtually the same. The light displacement resistance reduction was the result of an approximately 7.5% reduction in the residuary resistance coefficient. The SEB increased the wetted surface by ½%.

In discussing the SEB, one must also keep in mind that a stern flap is a much less expensive energy reducer; however, not all ship afterbodies are amenable to a stern flap. Both the AOE and the T-AO have very little transom immersion and at light and intermediate loads, their transoms are out of the water, thus making a mostly horizontally oriented stern flap be out of the water and be susceptible to wave slap and be totally ineffective in terms of energy-saving at these ship displacements.

3. Stern end bulb design: T-AKE and DDG 51 Ships

The motivation for exploring SEB performance is for fuel-saving. SEBs are seen as a potentially retrofittable item. At the same time an SEB can also enhance the maximum vessel speed. The selection of the T-AKE and DDG 51 class vessels for a potential SEB retrofit was made on practical considerations. In February 2011, the Navy has accepted delivery of the 11th T-AKE and 60th DDG class ships. More of each are still to be built. With such a large number of relatively new ships, the economics of a retrofit are enhanced because the energy-saving accrues over many future years and the nonrecurring design and testing costs can be spread out over a large number of ships.

With respect to hull form shape, the T-AKE is a single-screw merchant ship hull with the single shaft enclosed by a skeg. Except for the heaviest displacement conditions, the transom tends to be out of the water; thus, from the hydrodynamic viewpoint, it is not

Nomenclature

AOE → U.S. Navy Fast Combat Support Ship
Cr → Residuary Resistance Coefficient
Cw → Wave Resistance Coefficient
DDG → Guided Missile Destroyer
FreeRans → Viscous Flow Free Surface Solver
PR → Power Ratio
SEB → Stern End Bulb
SWIFT → Ship Wave Inviscid Flow Theory
T-AKE → U.S. Navy Dry Cargo/Ammunitions Ship
T-AO → U.S. Navy Fleet Oiler

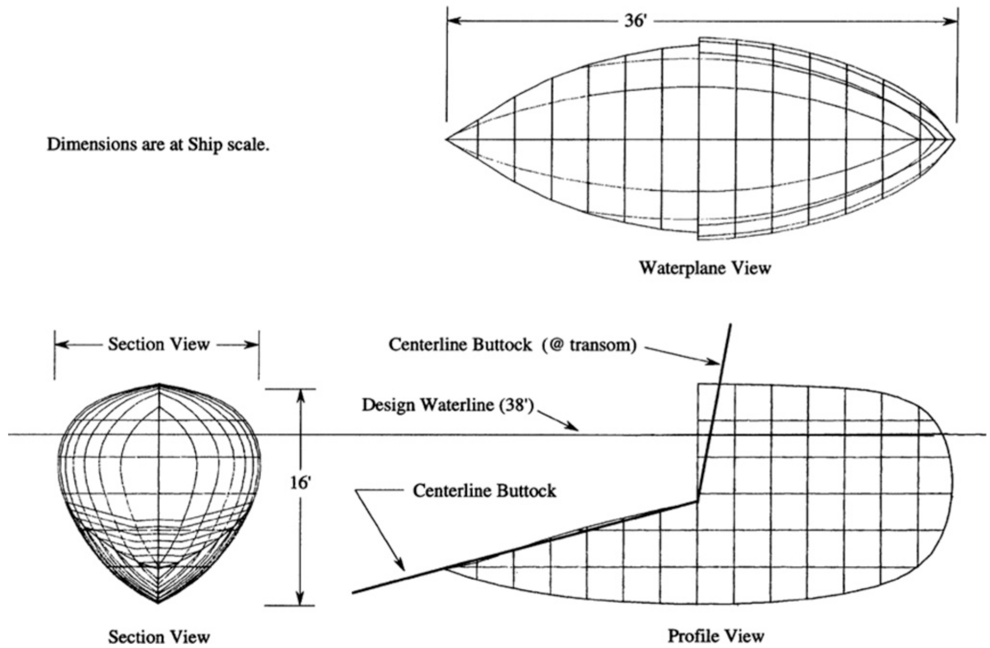


Fig. 2 Drawing of the AOE model stern end bulb

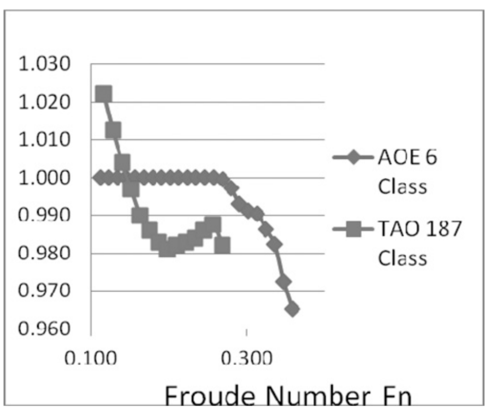


Fig. 3 Total resistance ratio for the bulb design of Fig. 2 model tested with the AOE 6 hull and with the T-AO 187 hull

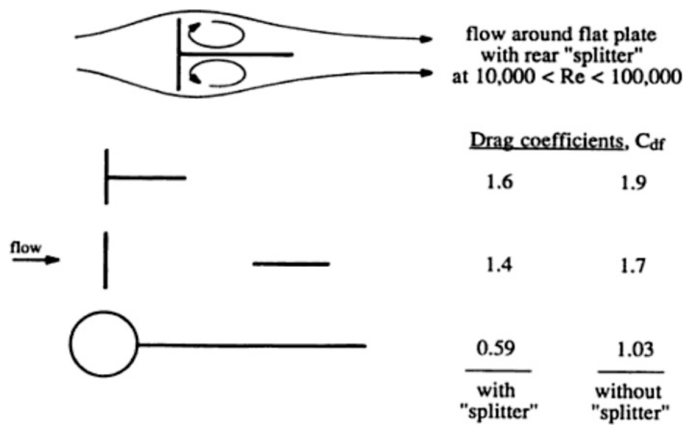


Fig. 4 Drag reduction resulting from a splitter plate behind bluff bodies

a good candidate hull form for a stern flap. It is however a possible candidate for an SEB with the reservation that the hull Froude number at the 20 knot design speed is only 0.230 and the residuary resistance is only 30% of the total resistance.

The DDG 51 hull form is a much more attractive candidate for an SEB from the speed point of view. However, the DDG 51 is already fitted with a very effective stern flap and thus any SEB would have to be either more effective than the DDG with stern flap or an SEB configuration that is combined with a stern flap would have to be developed.

3.1. Reduced turbulence

The principal mechanism for resistance reduction by the SEB is by reducing the wave resistance. In addition, it is hoped that the SEB will reduce the turbulence in the wake and the viscous drag of the afterbody though a splitter effect as shown in Fig. 4 (Vogl 1994).

4. Stern end bulb for T-AKE

A photograph of the T-AKE model afterbody is shown in Fig. 5. Notice the large rudder stool above the moveable part of the spade rudder. To enhance the feasibility of a retrofit SEB, a decision was made to limit the submergence depth of the SEB to that of the deepest portion of the rudder stool. Thus, there would be no need to modify any portion of the rudder blade and the SEB forward edge would be faired into the rudder stool.

For the purpose of expediting the calculations, the rudder, the rudder stool, and the bilge keels were not considered in the calculations.

Initially several SEB designs designated as SEB 1 through 5 were evaluated using the potential flow computer program Ship

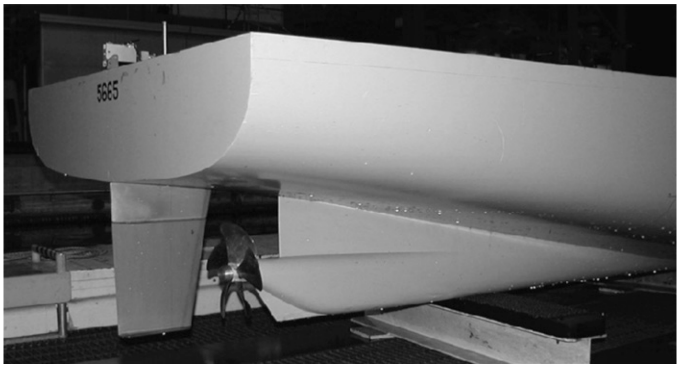


Fig. 5 T-AKE model afterbody

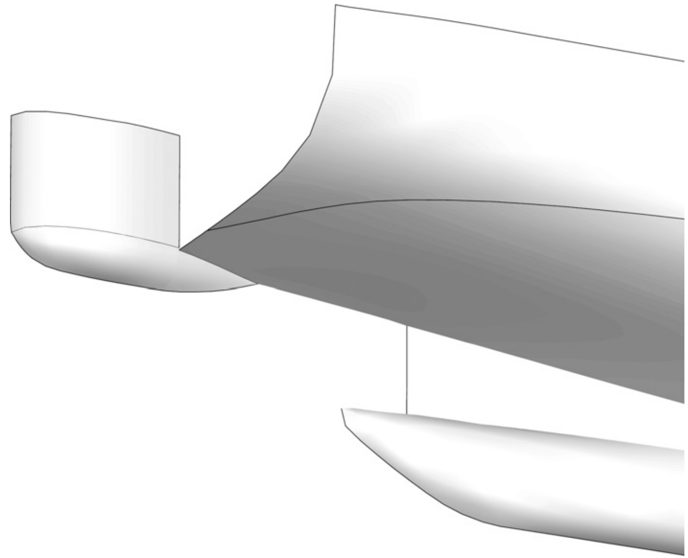


Fig. 6 T-AKE stern end bulb Design #2

Wave Inviscid Flow Theory (SWIFT). The SEBs are described in Table 1. Note that in Fig. 6 showing SEB #2, most of the transom is out of the water. Thus, a stern flap retrofit, which was first thought of before an SEB, is highly problematical in that only a small part of the flap would be in the water and at lighter drafts, the flap would be completely out of the water.

The SWIFT computer code has an option to very quickly evaluate hull forms in a specified fixed trim and heave condition. In this mode, the initial bulb #1 was evaluated and examination of the results suggested that the maximum bulb volume needed to be shifted further aft. Bulb #2 was then developed by longitudinally reversing bulb #1 and fairing it to the transom. These fixed trim and heave calculations showed that with bulb #2, there was a maximum 16% reduction in residuary resistance at a 25-knot ship speed. To quickly narrow the number of potential bulb configurations, the twin bulb configuration #3 was developed by simply moving bulb #2 outboard (both port and starboard directions) 21.77 ft from the ship centerline. The twin bulbs centerlines were aligned parallel to the ship centerline. This new twin bulb had a residuary resistance that was nearly the same as that with bulb #2 for speeds between 23 knots and 27 knots; however, at lower speeds, the twin bulb configuration had a residuary resistance that was more than double that of the single bulb configuration #2. Examination of the twin bulb free surface wave pattern suggested that the twin bulb should be flow-aligned and not necessarily parallel to the ship centerline. Nevertheless, given the very high low-speed residuary resistance, twin bulbs were dropped from further consideration. However, twin bulbs are an option if high-speed resistance reduction is the primary goal.

Bulb #4 was a lengthened version of bulb #2 and bulb #5 was a deeper version of bulb #2 and the residuary resistance coefficient as calculated by the SWIFT potential flow code is given in Table 1. The low residuary resistance with SEB #2 at 24 knots was judged to be a sufficient indication of promising performance and therefore additional calculations were undertaken with the FreeRans computer code to better predict the performance of SEB #2.The calculations were done in the free to heave and trim condition. The predicted total resistance reduction is presented in Table 2.

A comparison of the FreeRans predicted free surface elevations is shown in Fig. 7a –b.

5. Computational fluid dynamics codes

5.1. Ship Wave Inviscid Flow Theory: potential flow code

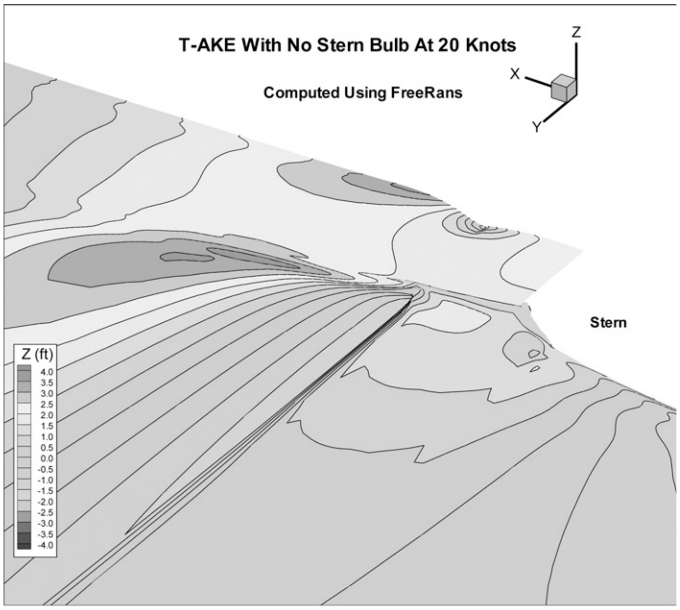
SWIFT uses higher-order curved panels to represent the ship surface instead of flat panels. The use of curved panels reduces the geometric discontinuity (leakage) experienced by the usual faceted flat panel approximations. The distribution of singularity strengths is assumed to be linear in the case of a source network and quadratic in the case of a doublet network. This gives the full power of the higher-order singularity panel method. These numerical

Table 2 FreeRans computed total resistance reduction for T-AKE with stern end bulb #2

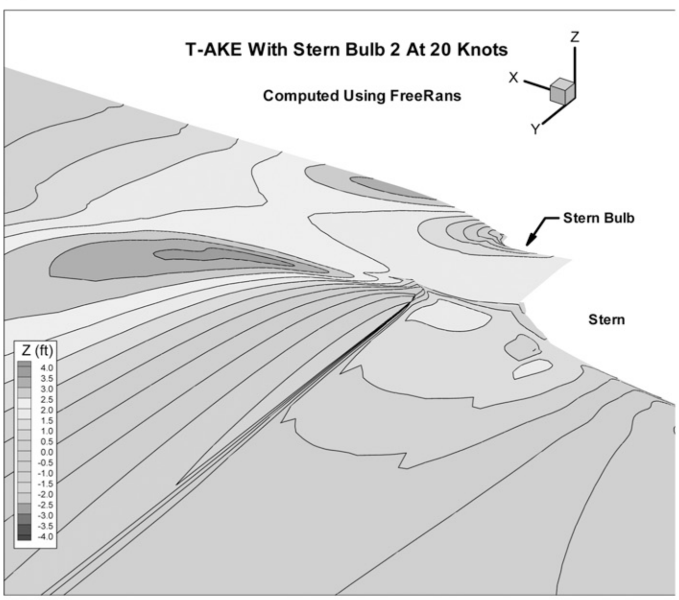
Speed knots	Total resistance reduction
20	4.5%
24	3.8%

Table 1 T-AKE stern end bulb (SEB) configurations

SEB	ALL bulbs 12.6 ft wide	Aft of transom ft	FWD of transom ft	1000 Cr 20 knots	1000 Cr 24 knots
	No bulb			0.5	2.5
2	NACA reversed longitudinally	24.02	12.6	0.55	1.08
3	Two #2 bulbs	24.02	12.6	1.0	1.9
4	#2 with longer trailing edge	30.77	12.6	0.5	2.0
5	#4 deeper	24.02	12.6	0.55	1.8



(a)



(b)

Fig. 7 (a) Predicted free surface for T-AKE with no bulb, 20 knots, (b) Predicted free surface with SEB #2, 20 knots

treatments adopted in SWIFT improve the computational accuracy and produce robust numerical results. A body-fitted free surface panel generation system is built into SWIFT, which does not require any user interaction. These body-fitted panels are created using a one-sided hyperbolic–tangent distribution.

5.2. FREERANS: combined viscous flow free surface computer code

FreeRans is a free surface viscous flow code developed for solving the three-dimensional Reynolds-averaged Navier-Stokes equations. It performs numerical calculation of viscous flow around a surface ship, which consists of two major physical mechanisms: computation of the water elevation at the free surface (wave pattern) and computation of the viscous boundary layer around the ship hull. The numerical algorithm adopted is based on the cell-centered, central difference, finite volume formula for spatial discretization with an explicit one-step Runge-Kutta time-stepping scheme. The pseudo-compressibility approach is also adopted. A combination of finite-volume discretization, Runge-Kutta time-stepping scheme, and pseudo-compressibility approach has provided an effective method for obtaining steady-state solutions for incompressible viscous flow. In addition, the FreeRans code has been developed to handle three-dimensional, multiple-block grids with Chimera overlapping capability.

The FreeRans code adopts a surface-fitting method to compute the free surface effect around a moving ship hull. This numerical scheme will satisfy both kinematic and dynamic boundary conditions required on the free surface. The kinematic boundary condition forces water particles on the free surface to remain in the boundary surface all the time. The dynamic condition satisfies constant atmospheric pressure on the free surface boundary. The free surface elevation is always updated and its current values are used as a boundary condition for the pressure on the bulk RANS flow computations. This numerical treatment provides a reliable and accurate solution of free surface flow calculation around a moving ship.

The FreeRans code can also compute the sinkage and trim for a moving ship hull. It computes the sinkage and trim simultaneously with the associated free surface RANS flow calculation. The forces and moments acting on the underwater geometry are used to compute the change in sinkage and trim through a simple hydrostatic calculation based on the ship's water plane geometry. The sinkage and trim is implemented by moving the hull relative to the global grid rather than trying to move the mean free surface reference. All the free surface elevations are then recalculated to fulfill both kinematic and dynamic boundary conditions in the new free surface locations. This methodology provides an effective and efficient approach to compute the associated sinkage and trim for a moving ship.

6. DDG 51 class stern end bulb design

6.1. Initial stern end bulb designs for DDG 51

The initial DDG 51 class SEB design took the shape of the T-AKE SEB design and adjusted the size, so that the DDG 51 SEB started 10.21 ft forward of the transom and extended 21.67 ft aft of the transom. The maximum bulb width was 8.76 ft.

The DDG 51 stern configuration alternatives of interest are shown in Fig. 8a–d.

The potential flow computed residuary resistance using the SWIFT code in a free to heave and trim mode is shown in Fig. 9 for the four geometries shown in Fig. 8.

At 25 knots and above, the best performance is achieved by the stern bulb alone and at 23 knots and below the best performance is indicated by the combined flap and SEB. The SWIFT calculated free surface elevation contours of these four configurations indicated several similarities in trend to the T-AKE FreeRans calculations. At 30 knots speed, the effect of just adding a bulb to the DDG bare transom is to lower the general free surface elevation in an area behind and to the side of the bulb.

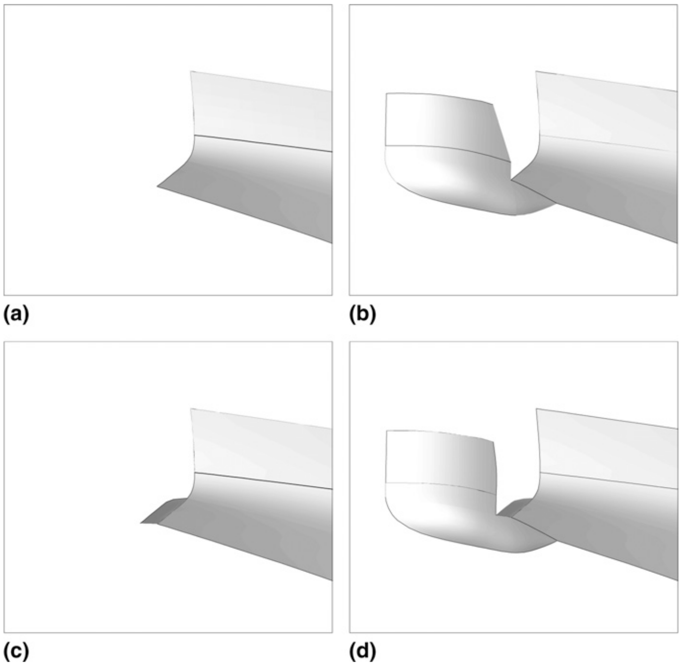


Fig. 8 (a) DDG bare hull, (b) DDG with stern end bulb, (c) DDG with 15° flap, (d) DDG with flap and stern end bulb

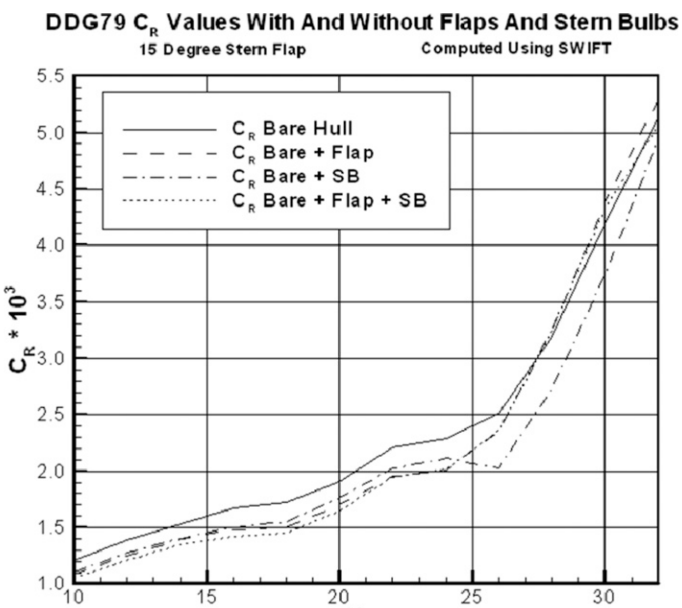


Fig. 9 DDG residuary resistance predictions with alternative stern devices

6.2. Model resistance test for initial designs

Fully appended model resistance tests were conducted for the configurations shown in Table 3. All tests were at even keel corresponding to the 9300 LT displacement.

Figure 10 shows stern end bulb #3. In Fig. 11 the resistance of the three SEB configurations and that of the currently existing 15° flap configuration are compared with the no transom device case as the baseline for comparison. All three SEBs performed very similarly throughout the speed range except that bulb #3 had the least low speed (8 kt. to 12 kt.) resistance penalty. All bulbs improved the performance at 18 knots with bulb #3 improving the resistance by nearly 4%. At high speed between 27 and 32 knots, bulb #3 had the lowest resistance with a nearly 4% reduction in resistance.

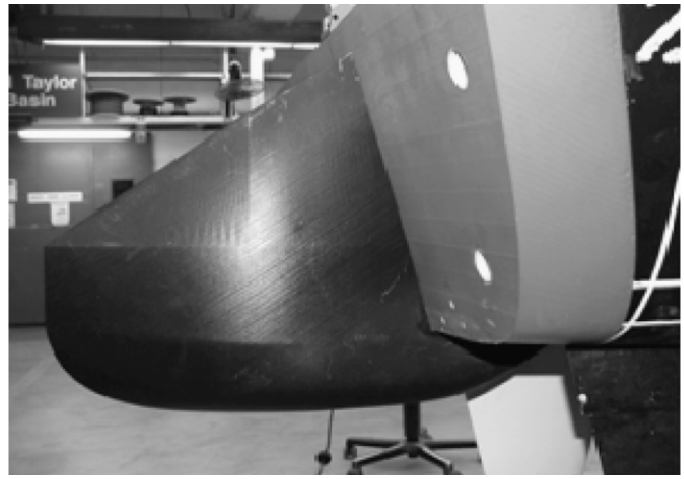


Fig. 10 DDG stern end bulb #3

Table 3 DDG Flt II A model test conditions

Test no.	SEB/flap configuration	Comment
98	None	23 knot model alignment
99	None	No transom Device
101	15° flap, no SEB	Baseline DDG Flt IIa
102	SEB #1	CFD selected SEB design
103	SEB #2	Reduced draft, −15% volume
104	SEB #3	Reduced width, −15% volume
105	SEB #3, 15° flap	Stern flap flanks SEB
106	SEB #3, 10° flap	Stern flap flanks SEB
107	10° flap, no SEB	Same flap chord as test 101

SEB = stern end bulb; CFD = computation fluid dynamic.

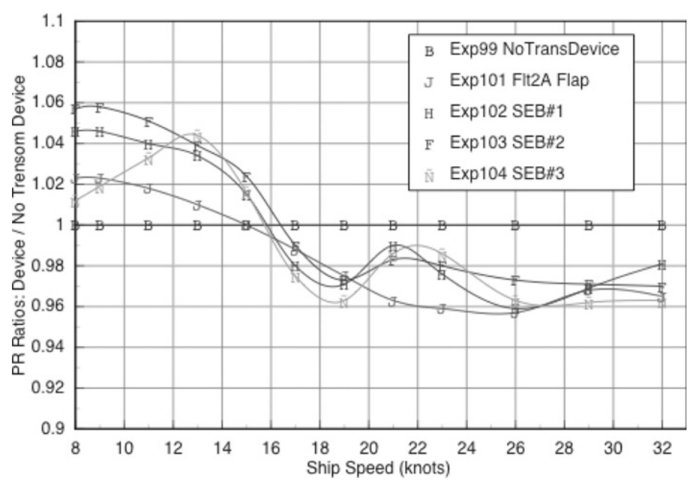


Fig. 11 Ratio of total effective power comparison between “with” and “without” transom device configurations

Figure 12 shows the same data as Fig. 12a, but the basis of comparison is the currently existing DDG configuration with the 15° stern flap.

It is interesting to note that the model test data in Fig. 13 shows just a very small but consistent difference in the DDG 51 trim angle associated with either of the bulbs or the flap. At 30 knots speed, the maximum trim effect resulting from any of the transom devices is approximately a 0.1° decrease in trim. This small amount of trim difference does not account for the resistance effects of the transom devices.

The DDG 51 SEB design challenge is to improve the already enhanced performance with a flap as evidenced in Fig. 11. The initial SEB design model test performance, although impressive by itself, was not able to significantly improve on the performance of the ship with a stern flap. Even more importantly, with the bulb, there was a low-speed resistance penalty. Stern flaps also show a low-speed resistance penalty at model scale. However, as supported by six different model comparisons to full-scale trial data, this low-speed model resistance penalty does not exist or is ameliorated at full scale for the stern flap. This is a beneficial viscous phenomena associated with flow separation from the stern flap.

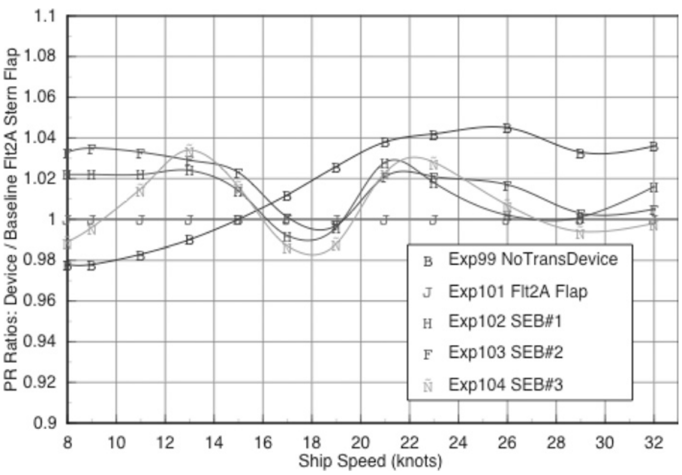


Fig. 12 Ratio of total effective power comparison between "stern end bulb (SEB) only" and "SEB + stern flap"

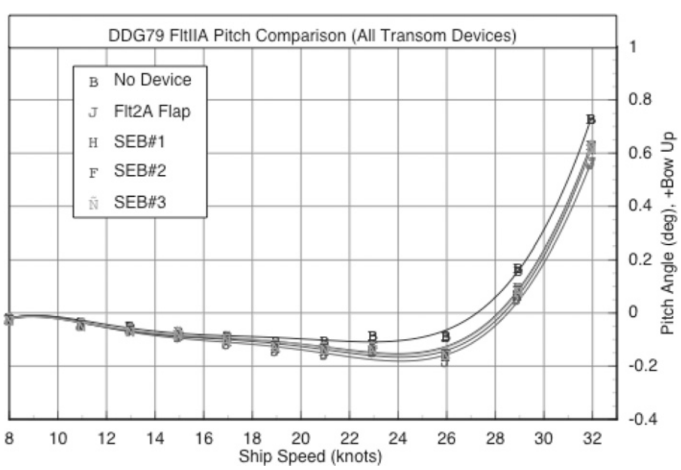


Fig. 13 Model test DDG-51 trim angle (bow up is +)

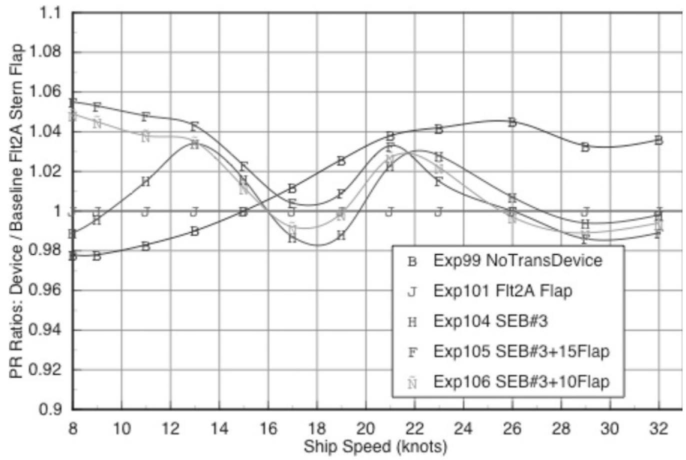


Fig. 14 Model test resistance ratio with the stern end bulb and stern flap combination

For the SEB, scale effect is much more difficult to judge. We are dealing mostly with a potential flow wave-making phenomena, which in the course of model testing is assumed to be free of scale effect. However, an SEB survey paper (Ward & Sedat 1984) shows that the SEB was more effective on a 10-m long model than on its 2.5-m geosym model. This result may be more of a comment on the inadequacy of the 2.5-m model test than on a general scale effect between model and ship.

The initial design SEB was also model-tested in conjunction with a stern flap on each side of the SEB. Figure 14 shows the experimental data for SEB #3 as flanked by the stern flap set to 10° and also as set to 15°.

The initial SEBs that were designed and model-tested in conjunction with a flap most likely compromised the stern flap effectiveness in the center region where the SEB masked the underside of the flap. In addition, this portion of the bulb that reaches under the flap may have been experiencing a high drag.

6.3. Second iteration designs

Figure 15 shows the forward projection of the initial design SEB. The goal of the second iteration designs here labeled as configurations A through H shown in Fig. 16a–h was to develop an integrated SEB-stern flap configuration with better fuel-saving performance than with just the flap alone.

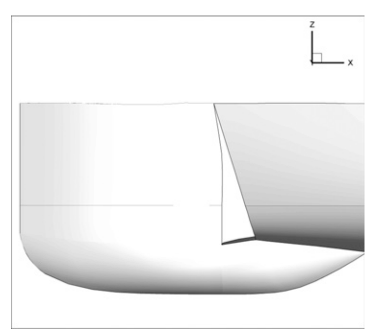


Fig. 15 Initial design stern end bulb (SEB) #5 for DDG 51 showing the forward extent of the SEB

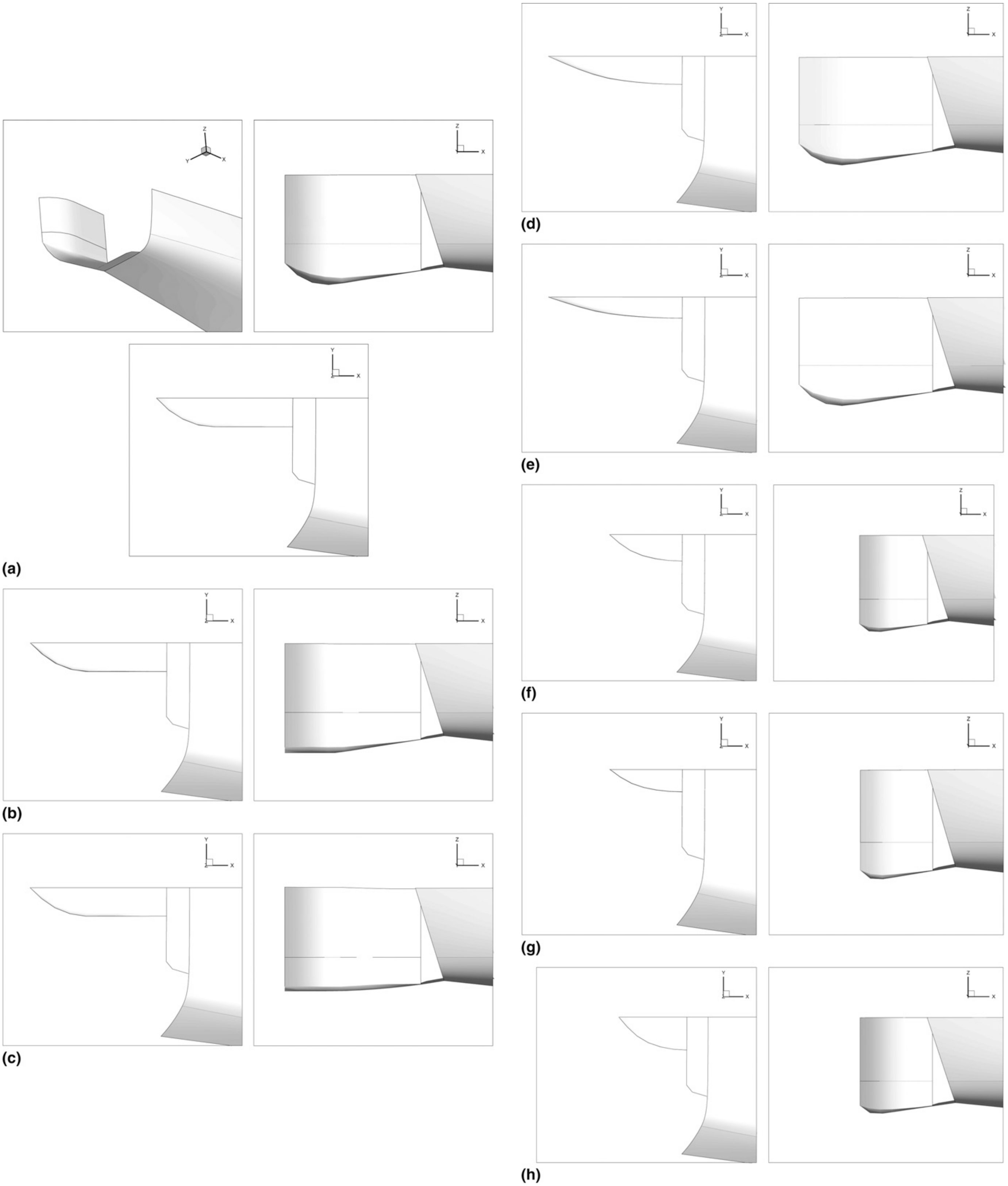


Fig. 16 (a) DDG-51 stern end bulb (SEB) design "A" with the forward extent eliminated, (b) DDG 51 SEB design "B" with lower draft tail, (c) DDG SEB design "C" (even greater tail draft reduction), (d) DDG SEB design "D" with fine water plane, (e) DDG SEB Design "E" (with −25% width), (f) DDG SEB design "F" with length reduction, (g) DDG SEB design "G" with −25% width, (h) DDG SEB design "H" with + 25% width

Designs A through E were prepared and evaluated first. The maximum length of the SEB, extending 18.3 ft aft of the flap trailing edge, was kept the same. The stern flap chord is 3.2 ft. All designs kept the integrated SEB-stern flap length within a space that would allow the ship to be positioned next to a pier at a 45° angle so that the aft most tip of the SEB would not touch the pier.

Designs A, B, and C were a miniseries to explore the effect of the downward-projecting tip of the SEB. The maximum SEB width was kept at 8 ft. Design D has a much finer water plane shape than the ABC designs. Design E reduced the width to 6 ft.

6.4. Estimated performance of the second iteration designs

The SWIFT calculated wave resistance for all the second iteration designs is shown in Fig. 17 as a ratio of wave resistance with the combined flap and bulb to the wave resistance with just the flap. The flap angles are held constant at 15°.

SEB configurations D and E show great reductions in wave resistance at high speeds peaking at 28 and 30 knots, respectively. However, because the DDG 51 class spends the bulk of operations between 9 and 23 knots, these bulbs were not candidates for a fuel-saving SEB. Thus, designs F, G, and H were developed and evaluated. The expectation was that shortening the SEB would enhance their performance in the moderate speed range under 23 knots.

The wave resistance of SEB design H is shown in Fig. 17 with wave resistance reduction starting at approximately 14 knots and improving as speed is increased.

The change in effective power for the A through H designs is shown in Fig. 18. In this figure the resistance associated with the shafts, struts, rudders, and bilge keels is neglected because these appendages were not included in the SWIFT calculations. The sonar dome was included. Most notably, bulb design E shows a very large resistance reduction at 30 knots, and this finding should be taken into account in the design of future high-speed ships. However, for fuel use reduction, bulb H is the most promising candidate. The fuel saved by the use of bulb H was estimated with the following procedure

- Adjusted for the shafting, drag according to model appendage striping data;
- Assume that a fuel saved is 70% that of a decrease in estimated total power (rule of thumb for gas turbine engine);
- Use official speed time profile (9 knots to full power speed) and officially reported DDG fuel use data; and
- The SEB does not affect propulsive efficiency.

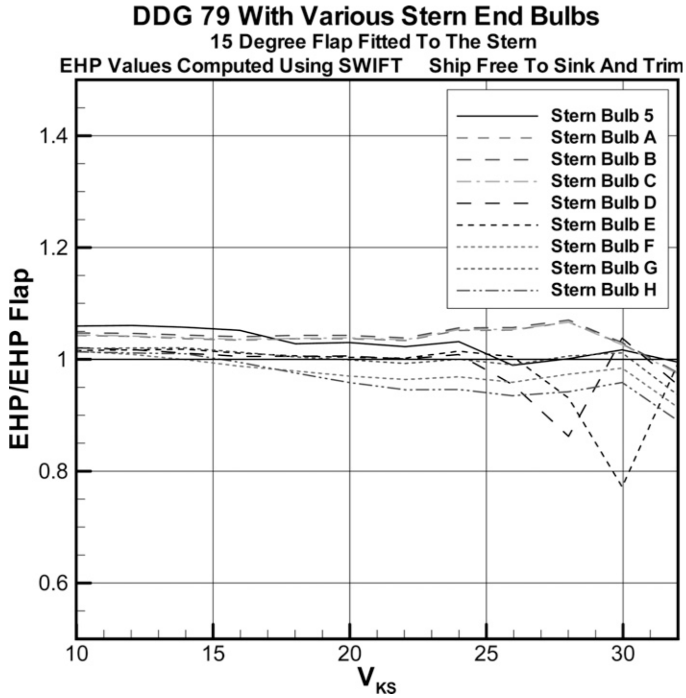


Fig. 18 DDG 51 effective power reduction (shafts, struts, rudders, and bilge keels are not included)

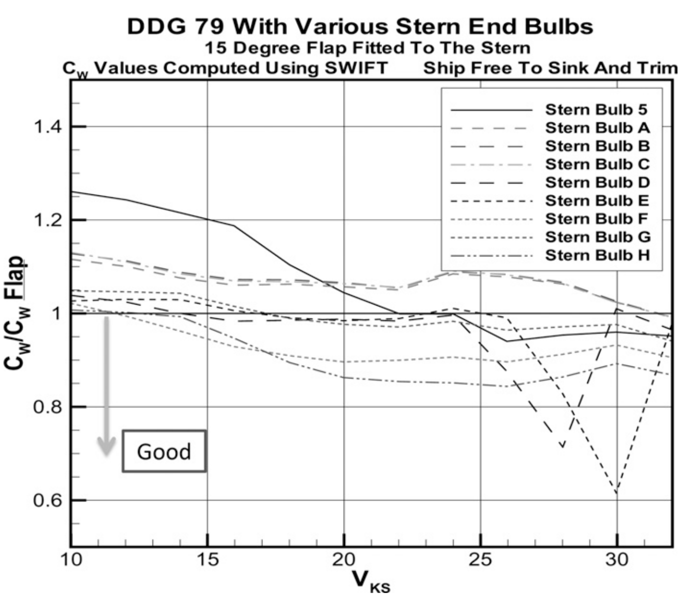


Fig. 17 DDG 51 stern end bulb wave resistance coefficient

The SEB design "H" retrofitted to the DDG will save 743 Bbls. per year per ship currently corresponding to approximately $130,000 at U.S. Navy burdened fuel costs. This is slightly more than 1% of the fuel used for propulsion. This estimate will be updated as the DDG 51 SEB project comes to completion.

6.5. Other hydrodynamic issues

6.5.1. Stern end bulb topside design. The work reported here concentrated on the evaluation of the SEB underwater hull form performance, and for the sake of convenience, the SEB was designed with vertical sides that extend upward and with a top that slopes forward. These topside design features will have to be integrated with the ship.

6.5.2. Course-keeping. The SEB will enhance the ship's course-keeping ability. Currently the ship frequently operates in the trail shafting mode with only one shaft line driving and there is significant rudder angle bias needed to maintain straight ahead course. The SEB should allow a reduction in this angle and thus save a bit more fuel. This beneficial effect has not been taken into account in this article.

6.5.3. Beneficial stern flap scaling. There is a vast amount of literature documenting improved performance with a stern flap at full scale relative to the model test performance. This has been documented elsewhere. The SEB design "H" is starting to look like an extension to the existing stern flap because the underside of design "H" is a continuation of the stern flap underside. Thus, it is reasonable to expect some beneficial scaling with SEB design "H"; however, none has been applied in this article.

6.5.4. Larger stern flap. The current DDG 51 Flight IIa ships have a 3.2-ft chord stern flap with a bottom wetted area of 71 sq ft sq SEB design "H" adds another 55 sq ft to the bottom area. Thus, it is reasonable to ask if instead of an SEB, we should just increase the stern flap size.

At the time of the DDG 51 Flight IIa original stern flap design, both the existing flap and a larger flap with a 4.8 ft chord and a 100 sq ft bottom area were model-tested, each at five different angles and throughout the speed range. Based on these resistance test results, the smaller flap was selected as optimal. A brief look at the original test data shows that except for the zero angle case, the larger flap had greater resistance than the smaller flap at all speeds below 24 knots.

The large 0° flap lacked high-speed performance enhancement. Thus, assuming that the computational fluid dynamic (CFD) predictions hold up in the still to be done model tests, the SEB design "H" will a better selection than a larger flap. Design "H" will also have better low-speed performance and better high-speed performance than the larger flap.

6.6. Future DDG 51 stern end bulb work

Current plans for this fiscal year are to complete FreeRans calculations for SEB "H" and then conduct model resistance tests with the "H" design and possibly with two other variations. Future work may involve the application of some generalized CFD optimization tools under development at NSWCCD and to possibly conduct model powering tests on configuration "H" or some other more promising configuration as developed by the computer optimization.

7. Conclusion

The calculations and model tests reported here show that a SEB can have a major beneficial impact on a vessels performance. For the T-AKE class U.S. Navy ships, the FreeRans calculations estimate a 4.5% resistance reduction at 20 knots ship speed. For the DDG 51, the SEB design can be tailored for performance improvement for maximum speed increase or for energy enhancement. For the DDG 51, the SEB is projected to save slightly more than 1% of the fuel used for propulsion and save $130,000 per ship per year. At current fuel costs, additional design work is planned to confirm/improve the energy saving as a result of a DDG SEB configuration.

Acknowledgments

The work was sponsored by the Naval Surface Warfare Center Independent Applied Research Program administered by Dr. John Barkyoumb. The hydrodynamic calculations were performed by Dr. Chen Wen Lin and Mr. Steven Fisher off code 5700. The model SEBs were manufactured using the Synthetic Lithography Apparatus (SLA), rapid prototyping machine, which uses computer-guided laser beams that solidify a liquid epoxy resin at specified locations. Mr. David Schwarzenberg and Mr Bryson Metcalf performed the SLA computer programming and were in charge of the model manufacturing. Mr. Dominic Cusanelli conducted the model tests and analysis. I am grateful for all these efforts.

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