

A New Paradigm for High-Speed Monohulls: the Bow Lifting Body Ship

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ABSTRACT

Lifting body technology has been demonstrated—via computational fluid dynamics (CFD), scale-model tests, and full-scale at-sea trials—to provide reduced motions at zero and loiter speeds while providing dynamic lift at high speeds to reduce hull drag and to provide active ride control. Hypothesizing that incorporating a lifting body with the bow of a monohull may capture the positive effects of bulbous bows, preliminary CFD studies showed potentially significant benefits of such a configuration in reducing total hull resistance. This led to additional computational studies resulting in the design of a notional 91.4 m, 50-knot monohull with a patented bow lifting body. Scale-model tests, conducted with and without a lifting body, confirmed CFD predictions of improved resistance of the bow lifting body configuration over a wide speed band. Based on these results we developed a quarter-scale technology demonstration craft: a 21.3 m stabilized monohull with bow lifting body. This paper describes the conceptual design, computational analysis, and scale-model testing of the notional 91.4 m bow lifting body ship; the design, construction, and at-sea testing of the 21.3 m bow lifting body technology demonstration craft, including implementation of an active ride control system; and future opportunities and direction for this technology.

Keywords

Lifting bodies, bow lifting body, ride control.

1 INTRODUCTION

Increasing interest in high-speed, high-performance ships continues to spur development of alternative hull forms and non-traditional technologies to achieve the level of performance sought by end-users. Our approach to this challenge has been to combine the complementary technologies of innovative hull forms, lifting bodies, and active ride control systems. Lifting body technology has been demonstrated—via computational fluid dynamics (CFD), scale-model tests, and full-scale at-sea trials—to provide reduced motions at zero and loiter speeds while providing dynamic lift at high speeds to reduce hull drag and to provide active ride control. In the course of our research, we investigated a ship configuration

incorporating a lifting body at the bow of a conventional monohull, anticipating that there would be resistance improvements similar to those enjoyed by bulbous bow configurations. This paper describes the development of what has become the patented bow lifting body (Loui et al. 2007), from initial concept development to deployment of a 21.3 m proof-of-concept technology demonstration craft. We begin with a brief background on lifting body technology.

2 LIFTING BODY TECHNOLOGY BACKGROUND

Lifting bodies are underwater appendages with cambered foil cross sections that generate dynamic lift at speed. They are characterized by substantial volume, large planform areas, and low lift coefficients. Hybrid lifting body ships combine a parent hull form (monohull or multi-hull) with lifting bodies.

The potential benefits offered by innovative hull forms combined with lifting bodies and active control systems as integral components of a hybrid lifting body ship include the following (Peltzer 2007).

Improved seakindliness, or the quality of *behaving comfortably* at sea (Gillmer & Johnson 1982).

Improved seakeeping, or the ability to *maintain normal functions* at sea (Gillmer & Johnson 1982). This is accomplished through reduced added resistance, reduced slamming, and improved course keeping.

Higher speed, due to reduced total drag. This is accomplished through: hydrodynamic efficiency of the lifting body, which has a higher lift-to-drag ratio than the parent hull; reduced motions in a seaway, yielding lower added resistance, due to passive damping mechanisms (large added mass and viscous effects) and an active ride control system; reduced hull immersion due to the lift provided by the lifting body and complementary foils at speed; and wave cancellation effects in the case of a bow lifting body.

Higher payloads, since for a given parent hull lifting bodies provide added displacement and useable volume. An existing hull design retrofitted with lifting bodies will gain displacement compared to the original, and the volume in the lifting body can be used for fuel or

propulsion equipment. An integrated design, in which the ratio of displacement in the parent hull to that in the lifting bodies is a design variable, can result in a smaller, shorter parent hull. This in turn will reduce the powering requirements and could potentially result in a smaller structural weight fraction. The consequence of these effects is a larger payload fraction, which in turn translates to enhanced mission capabilities, extended range, or some combination of both.

The design space for lifting body ships is large, considering the number of possible combinations of parent hulls and lifting body types and configurations. Within this design space, our efforts have focused on a few specific configurations that fall naturally into two fairly broad categories, which we've designated as (1) Hybrid Small Waterplane Area Craft (HYSWAC), and (2) Hybrid Deep-V (HDV) (Peltzer 2007).



Figure 1 Lifting Body Technology Demonstrators

The HYSWAC configuration can be characterized as a multi-hull parent combined with a single large lifting body near midships, and some means of providing supplementary dynamic lift to balance longitudinal moments. The 19.8 m, 50.8 t *Midfoil* is one example of the HYSWAC configuration (Figure 1, top); the 48.8 m, 295 t technology demonstrator *Sea Flyer* is another (Figure 1, center). The Hybrid Deep-V configuration

uses, as the name suggests, a deep vee monohull as the parent hull; an example is the 28.8 m, 102 t technology demonstrator HDV-100 (Figure 1, bottom). An all-composite design, this 45-knot vessel employs lifting bodies aft and an incidence-controlled foil forward.

3 BLB CONCEPT DEVELOPMENT

As early as 2001 we began investigating the potential benefits of fitting a lifting body to the bow of a large, conventional monohull, hypothesizing that such a configuration would enjoy similar reduced drag benefits as a bulbous bow with the added advantages of being able to effect trim control and provide motion damping. This preliminary work led to a grant by the National Defense Center of Excellence for Research in Ocean Sciences (CEROS) in 2003 to validate our preliminary results and to further study the concept of a bow lifting body (BLB) ship, focusing on a nominal 91 m design designated as BLB-300 that was notionally targeted to meet the Littoral Combat Ship mission.

Two candidate parent hull forms, both deep-vee monohulls with anti-slamming bows, were evaluated by means of CFD to determine their relative hydrodynamic performance over a range of displacements, speeds, and trim angles. One of the two hull designs was clearly superior, with lower drag across the speed range (30-50 knots) at all displacements and trim angles analyzed, and was selected for further study with the BLB; this baseline hull is shown in Figure 2.

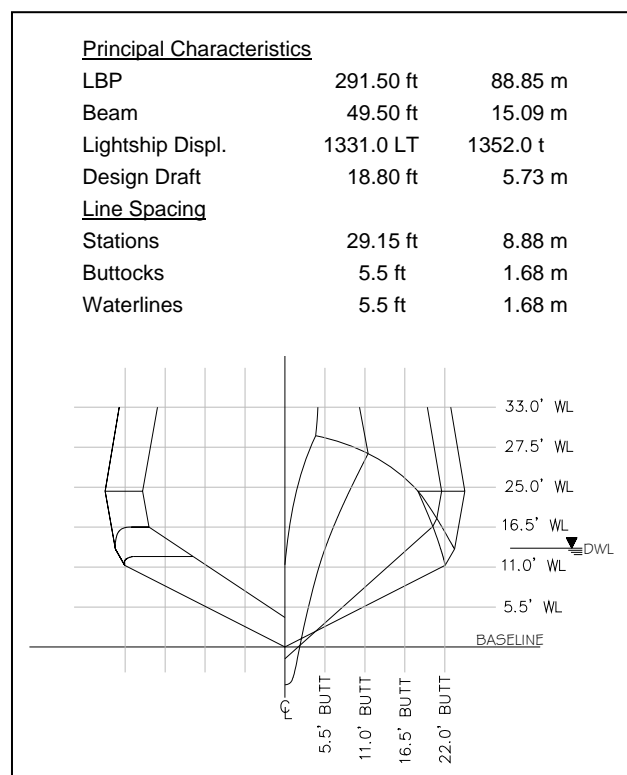


Figure 2 Baseline Parent Hull for CEROS Study

Several different lifting body section designs and planform shapes were evaluated for hydrodynamic performance, with particular attention paid to efficiency across the mid- to high-speed range and avoidance of cavitation at the higher end. The best candidate was then used in further CFD studies alone (Figure 3) and with the baseline parent hull to determine the best longitudinal location and angle of attack relative to the hull (Figure 4).

Comparison of CFD drag predictions of the hull with BLB to those of the bare hull alone pointed to the need to include a dynamic lift appendage near the stern to counteract the trimming moment from the BLB and to permit the ship to operate at a reduced parent hull immersion. The combination of trim control and reduced immersion resulted in a design that had significantly improved efficiency (represented by total ship lift-to-drag ratio) across the speed range, from about 30% higher at 30 knots to about 10% higher at 50 knots.

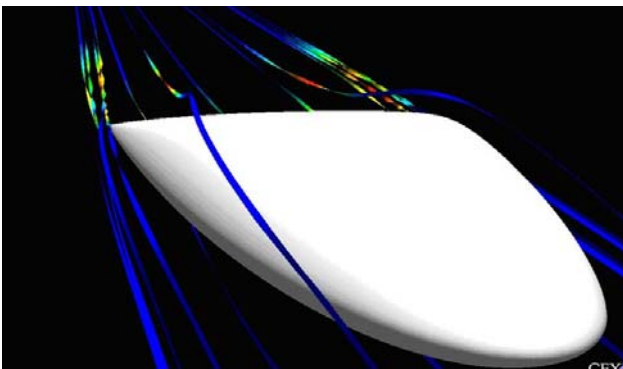


Figure 3 Lifting Body Selected for CEROS Study

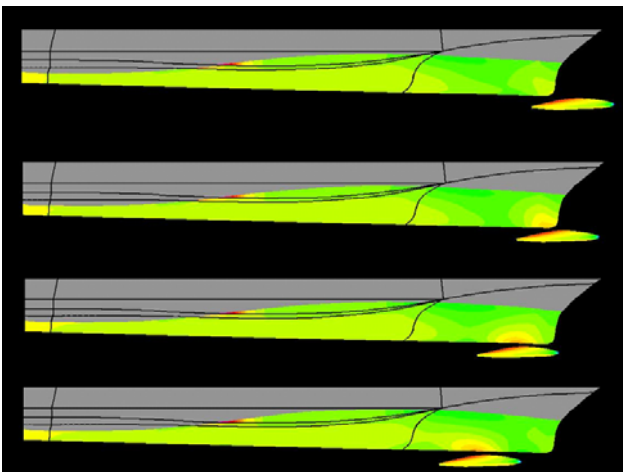


Figure 4 Lifting Body Longitudinal Position Study

4 COMPUTATIONAL STUDIES

Encouraged by these early results, we continued developing the BLB concept as part of a lifting body research project funded by the Office of Naval Research (ONR). Further computational studies, using CFD tools,

were conducted so that we might better understand the interactions between the BLB and the parent hull.

A parametric study investigating the optimal displacement value for the ship (Figure 5) determined the total combined dynamic lift we needed to produce from the BLB and an aft lifting device.

Once the optimum displacement at cruise speed was determined for the hull, the BLB design could be tailored to produce the required lift. We analyzed a number of BLB shapes, in conjunction with the hull, to determine the most efficient shape that produced the needed amount of lift (Figure 6).

Additionally, a detailed set of RANS-based CFD analyses were conducted to focus on the forward portion of the ship to investigate the wave cancellation provided by the BLB. The bare hull and a BLB-appended hull were run in the exact same conditions (draft, speed, trim) and the height of the bow wave was investigated. As shown in Figure 7, the bow wave was effectively cancelled out by the presence of the BLB.

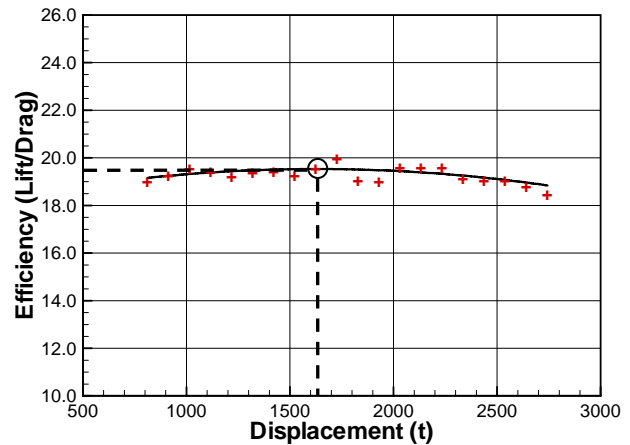


Figure 5 Optimum Displacement of Hull

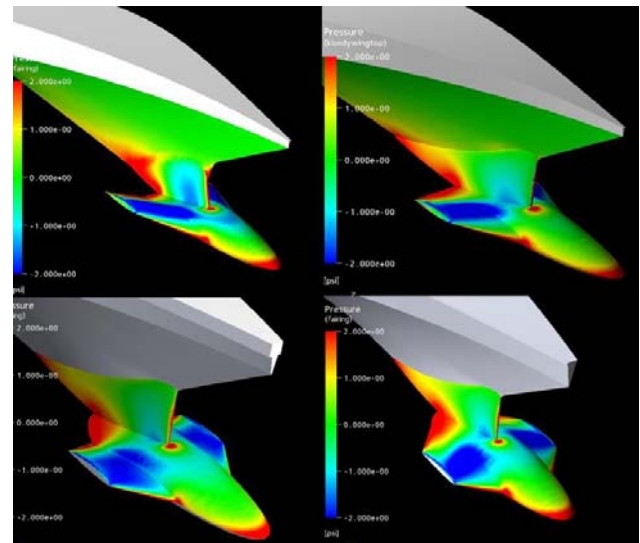


Figure 6 Examples of BLB Shapes Investigated

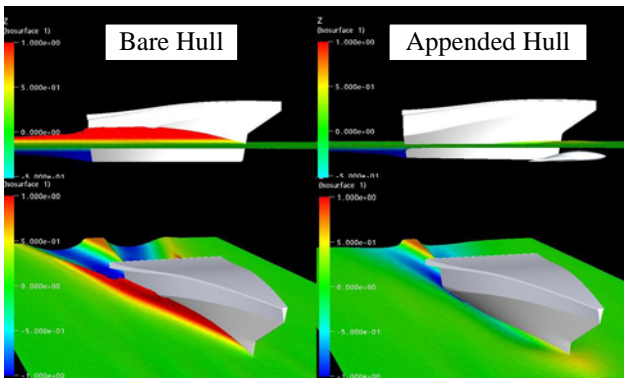


Figure 7 BLB Wave Cancellation Analysis

This analysis provided further evidence that the BLB is providing wave cancellation benefits across a broad speed range, thereby reducing overall resistance, and with a notable reduction in the so-called ‘hump’ speed resistance.

The final shape of the BLB is shown in Figure 8 (inset). Additionally, an aft foil was designed to complement the dynamic lift produced by the BLB, dynamically balancing the entire system at speed about the center of gravity of the vessel (Figure 8).

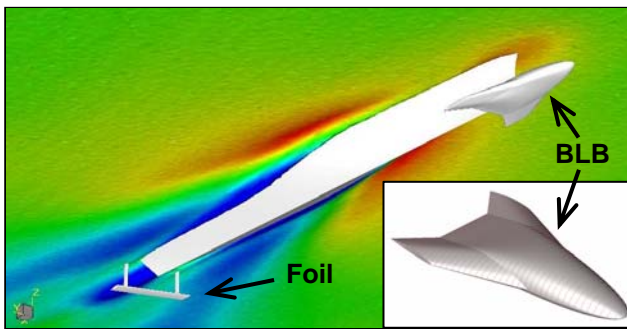


Figure 8 Revised BLB Ship Configuration

5 MODEL TESTING VALIDATION

The next logical step in the development and validation of the bow lifting body concept was to conduct a series of model tests.

The objectives of these model tests were to:

1. Verify the near-field wave pattern that is observed in CFD, particularly the reduction in the bow wave and unwetting of the hull with the presence of the BLB,
2. Validate the forces and wave profiles predicted by CFD, particularly the increased performance of the appended BLB-300 vs. the bare hull, and
3. Verify spray and wave characteristics to ensure proper tunnel height design for and sizing of amas (outrigger hulls for low-speed stability) for a planned

70-foot technology demonstrator based on the BLB-300 configuration.

We designed and built a 1/30th scale-model test of the BLB-300, originally developed under the CEROS grant and further refined as part of the ONR project. The model testing was conducted at Offshore Model Basin in California; Figure 9 shows a computer rendering (top) and a photo of the physical model (bottom). The model was constructed in such a fashion that the BLB and the aft foil could be removed, allowing separate tests of the bare hull model and the fully appended model. The model tests were conducted in October, 2004; prior to testing, a complete series of RANS-based CFD predictions was performed using CFX, a commercially-available CFD software package.

The results of the model tests compared nicely with the experimental data, for both free surface wave predictions and forces. Figure 10 shows an example of the former, comparing bare hull vs. appended hull and CFD predictions vs. model test photos. Note the excellent correlation between the predicted and actual wetted surface of the bow waves for both cases. Note also the reduced bow wave of the appended hull. Figure 11 shows the correlation between predicted and measured drag. Two series of CFX predictions are shown, using natural transition and fully turbulent transition models; note that the latter better predicts the drag at higher speeds.

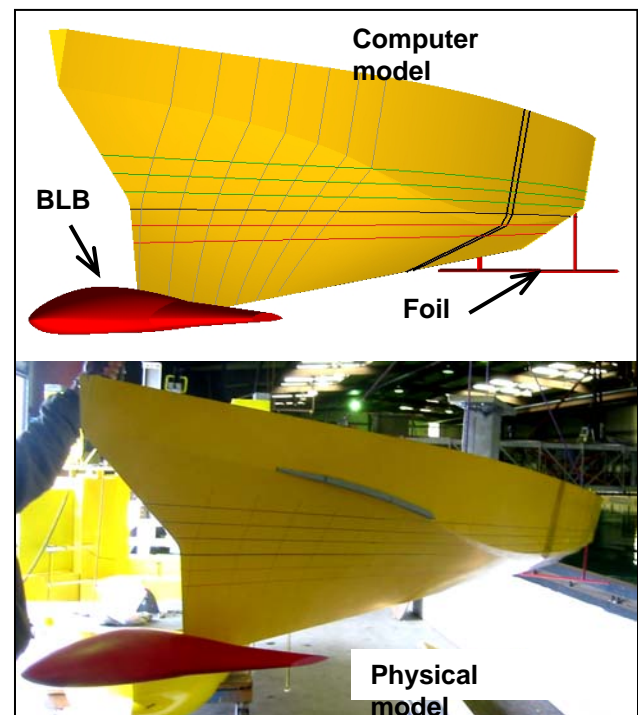


Figure 9 BLB-300 Computer & Physical Models

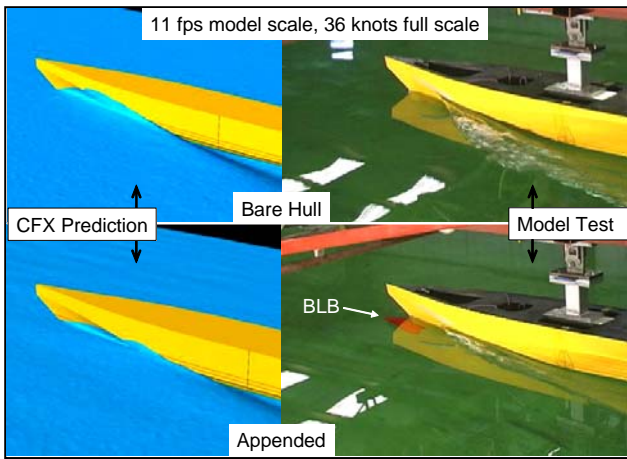


Figure 10 BLB-300 CFD and Testing Images

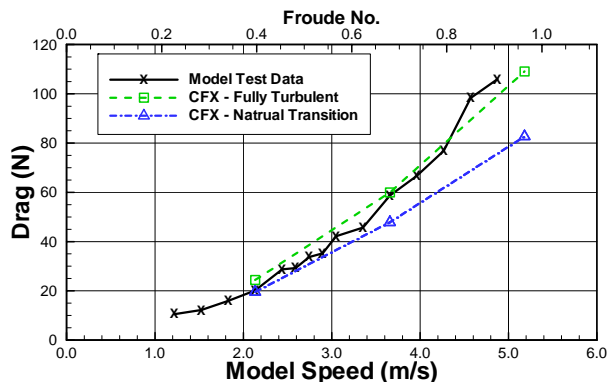


Figure 11 Drag: CFD vs. Model Test

In order to obtain wave profile data, height sensors were placed in the tank in order to record wave height data at two locations outboard of the hull; Figure 12 shows the measured height at one of those locations as the model passed the height sensor and also the computer prediction of the surface elevation at the same location; note the excellent correlation between the two.

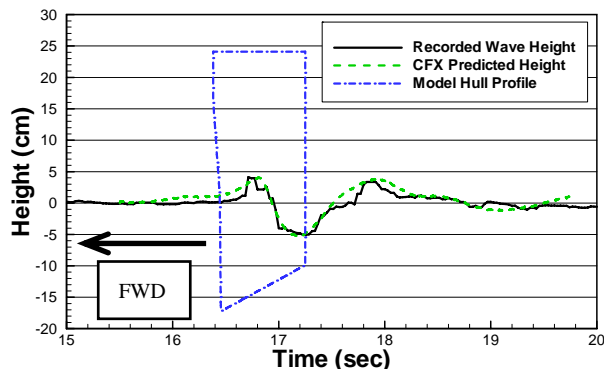


Figure 12 CFD and Wave Probe Data Comparison

As predicted in previous CFD studies, the hump speed was validated as being significantly reduced due to the wave cancellation provided by the BLB. A comparison between the bare hull drag and the fully appended hull drag from the model tests is shown in Figure 13; the

appended hull is significantly more efficient than the bare hull at Froude numbers above 0.40.

As expected, the data obtained from the model tests confirmed the findings of the earlier CEROS study showing improved efficiency (15% to 30% higher lift-to-drag ratio) of the BLB configuration as compared to the bare hull across the speed range tested in the model basin (18 to 50+ knots full-scale equivalent).

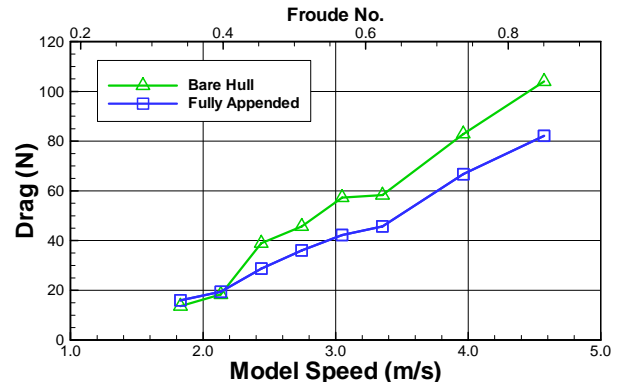


Figure 13 Reduction in Hump Speed Drag Validated

6 BLB-70 TECHNOLOGY DEMONSTRATOR

Following the successful model tests, the next step in developing BLB technology was to build a demonstration vessel to prove that the concept works in practice. We selected an approximately quarter-scale version of the BLB-300 design, designated BLB-70, which we concluded would give us a meaningfully-sized demonstrator at a reasonable cost.

6.1 Hull Design

The parent hull we selected was a scaled version of the original hull developed in the CEROS study. Figure 14 shows a computer rendering of the construction design; Table 1 lists the boat's principal characteristics.

At this scale, the main hull alone does not provide the required static stability to carry the desired passenger payload (70 total), so we added two very narrow amas that provided the extra stability needed at zero and low speeds. These amas were designed to be clear of the water at normal operating speeds due to the dynamic lift from the BLB and the aft T-foils. Figure 15 shows the distribution of lift at design speed (23.6 knots) between the BLB, hull, and T-foils.



Figure 14 BLB Technology Demonstrator: BLB-70

Table 1 BLB-70 Principal Characteristics

Parameter	Value	
Length Overall	69.90 ft	21.30 m
Beam Overall	19.00 ft	5.79 m
Length _{WL} , Main Hull	67.80 ft	20.67 m
Beam _{WL} , Main Hull	10.42 ft	3.18 m
Draft, Maximum	5.42 ft	1.65 m
Displacement, Design	22.0 LT	22.4 t
Installed Power	2 x 704 hp	2 x 525 kW
Speed, Design	23.6 knots	
Speed, Maximum	30+ knots	

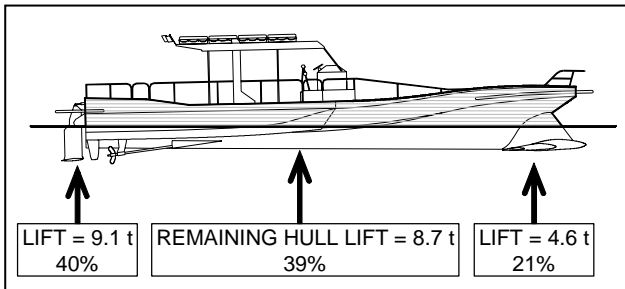


Figure 15 BLB-70 Lift Distribution

As noted earlier, the BLB design selected for the BLB-300 incorporated ‘winglets’ (Figure 8). For the BLB-70, these are articulated on a common shaft and actuated by hydraulic rams to provide movable control surfaces. CFD analysis was used to determine the forces and moments acting on these winglets at various speeds and angles of attack in order to properly size the shaft and the actuating hydraulics. The winglet lift characteristics as a function of angle of attack, used in developing the ride control algorithms, were also evaluated using CFD analysis.

For the purposes of model testing, we were not concerned with the structural interface between the bow lifting body and the hull and so the BLB was essentially ‘grafted’ onto the keel of the parent hull with no modification to the stem (Figure 9). However, for the BLB-70 we needed to ensure sufficient structure was provided to: (1) transfer loads from the BLB to the hull, and (2) provide adequate internal volume for the control surface actuation mechanism. Given these constraints, our goal was to design a structural interface that would not introduce a significant drag penalty and thereby negate the hydrodynamic advantage we expected from the BLB.

Our approach to solving this problem was to employ a commercial potential-flow CFD program (USAERO) coupled to a commercial optimization software package to find a geometry that would simultaneously satisfy the structural and hydrodynamic goals. The starting point was to model the structural interface as a constant-section strut with a sufficiently thick section to meet the structural strength and volume requirements. Through an optimization process, in which the geometry of that strut

was allowed to vary systematically, a suitable configuration was found that resulted in a negligible change in the overall lift-to-drag ratio (efficiency) of the boat. Figure 16 shows CFD pressure distribution plots of the starting and ending points of the optimization sequence.

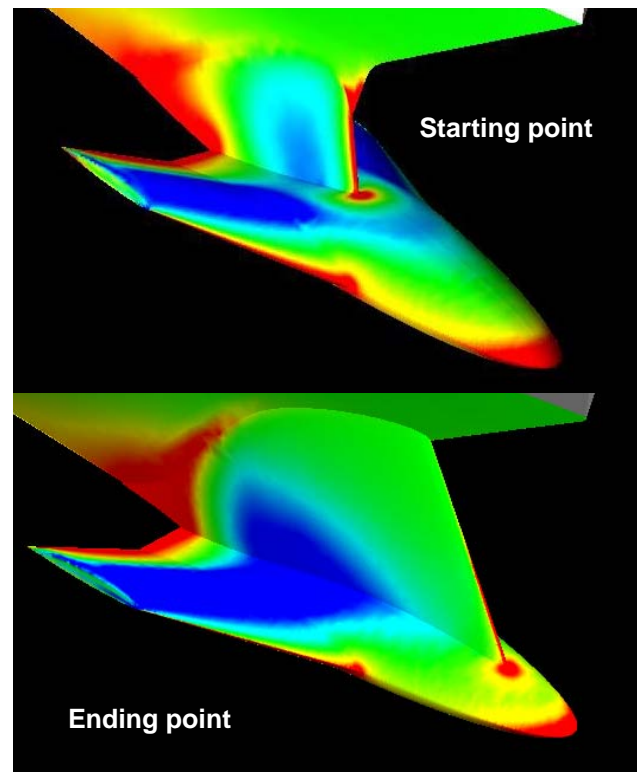


Figure 16 BLB Interface Optimization Sequence

The aft foil used in the BLB-300 model tests was a single high aspect ratio hydrofoil attached to the transom by means of two vertical struts as shown in Figure 17. For the actual BLB-70 demonstrator, this was replaced with a pair of incidence-control T-foils mounted one each on the transoms of the amas as shown in Figure 18, thereby providing control authority for both pitch and roll.



Figure 17 Aft Foil Used in Model Test



Figure 18 BLB-70 Stern View Showing T-Foils

6.2 Ride Control System

Dynamic control of the BLB-70 is provided by an advanced ride control system based on our custom-designed microcontroller-based electronics. Bow height is measured with a microwave-radar; this height is controlled by the two large winglets on the outside of the bow lifting body. The winglets, mounted on a common shaft, change their angle of attack to produce variable lift; they are moved in unison by a pair of large hydraulic rams that are fed by a hydraulic servo-valve, which is controlled by one of the two custom single-board controllers that comprise the heart of the control system. Pitch and roll are measured with a motion reference unit, mounted in the aft portion of the boat, and are controlled via the pair of T-foils mounted on the transom. The T-foil incidence angles are adjusted by hydraulic rams driven by servo-valves, which are controlled by the second of the two custom single-board controllers. The two single board controllers share all environmental and feedback inputs so that both controllers have a complete set of information to use for control, eliminating the need for duplicate sensors. Algorithms for controlling the vessel were first designed in a full six degree-of-freedom nonlinear computer simulation, and were then fine-tuned on the boat during sea trials. Hydraulic power for the control system is provided by a pair of piston pumps driven by mechanical power take-offs on the main engines. The hydraulic system is also used to power a bow thruster and a power-assist helm pump for steering. Rudder position is electronically fed back through the ride control system for operator display and also to bank the boat to facilitate turning. Information about ship attitude, speed, and control surface deflections are available to the operator through a pair of LCD screens.

6.3 Construction

The aluminum hull components (main hull and two amas) for the BLB-70 were fabricated at Derecktor Shipyard in

Connecticut (Figure 19) and then shipped to Honolulu where we completed construction and outfitting.



Figure 19 BLB-70 Hull Fabrication in Connecticut



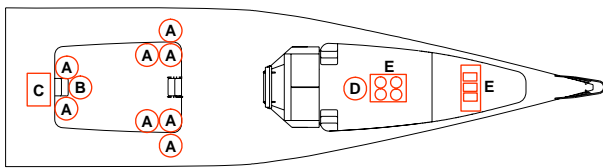
Figure 20 BLB-70 Lifting Body Fabrication in Honolulu

Once the hull components arrived in Honolulu, the amas were joined with the main hull, and machinery, piping and all auxiliary systems were installed. We fabricated the bow lifting body and foil in Honolulu, where they were integrated into the final vessel (Figure 20).

6.4 At-Sea Testing

The BLB-70 was the subject of extensive at-sea testing, including a series of tests that characterized the speed-power performance of the boat. Although the speed-power data alone were of interest, the comparison of that data with our CFD predictions was of equal or possibly greater interest from our perspective. Instrumentation was installed to capture engine performance data, propeller

shaft thrust and torque, boat motions, GPS position, and control surface activity. All together approximately 60 channels of data were collected at a rate of 20 Hz. Of specific interest for the speed-power data were the engine data, which included shaft speed, engine load, fuel consumption rate, and boost pressure for both engines. Speed data was obtained from the GPS receiver so this reflected speed over ground and not necessarily speed through the water. To compensate for possible currents, reciprocal runs were usually made for each test condition. Tests were conducted at two load conditions: 22.4 t, which represents the design condition, and 28.4 t, which represents the maximum full-load condition. To achieve the higher displacement, ballast weights were distributed around the boat as shown in Figure 21.



A: 226.8 kg B: 113.4 kg C: 1157 kg D: 235.9 kg E: 453.6 kg

Figure 21 Weights for 28.4 t Testing Condition

The control surfaces on the boat allow the operator to command trim angle and bow height above the water. A matrix of cases was established to find the best operating conditions for the boat. Trim ranged from 0 degrees to 2 degrees and bow height ranged from 1.98 m to 2.29 m. Most of the test runs were made in sea conditions where the significant wave height was approximately 0.91 m, which is typical for the test area off the leeward coast of Oahu. Figure 22 shows the comparison between test data and CFD predictions.

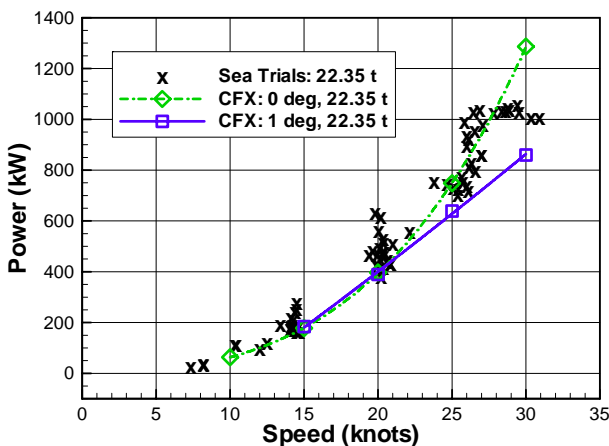


Figure 22 Measured and Predicted Speed-Power Data

Using CFX, resistance was predicted for a displacement of 22.4 t at 0 and 1 degree trim. These values were transformed to engine brake horsepower (BHP) by assuming a propulsive coefficient of 0.65 for

the propeller and a gearbox efficiency of 0.95. Similarly, the power computed from the shaft torque was converted to BHP by assuming the same gearbox efficiency. Using BHP as the common denominator allows direct comparison of engine load data provided by the engine computer with power as computed from shaft torque. In general, the two methods were in good agreement, but power computed from shaft torque data appeared to be more reliable (fewer dropouts and anomalous readings) and was therefore used in preparing Figure 22.

Figure 22 shows that the CFD predictions for 0 and 1 degree trim conditions bounded the results of the at-sea tests. Note that the CFD analyses reflect perfectly calm conditions and fixed control surfaces. Actual tests were generally in waves and the control surfaces were active. To account for these, as well as appendage drag, a 10% drag margin was added to the CFD results. This is a margin that we have typically added based on past experience. There are points in Figure 22 where significantly more power is indicated than the predictions. Generally, these resulted from a choice of less favorable operating conditions in which the boat was commanded to operate at a relatively deep immersion or the control surfaces were at their maximum deflections while attempting to achieve the commanded trim and height. For the best performance, care must be taken to operate the boat at the appropriate trim and height. In general, test results and CFD predictions agreed quite well. In an exercise where the average measured conditions were modeled in a steady CFD analysis the results agreed very well. These results give us confidence that the BLB concept indeed yields the benefits indicated by earlier analysis and model tests.

7 FUTURE DIRECTION

Expanding on the success of the BLB-70, we have been developing a roughly half-scale demonstrator (relative to our original 91 m design), the 49 m BLB-160 'Sea-Frame.' Intended for use as a multi-role technology demonstrator with a possible follow-on application as a fast offshore supply vessel, the BLB-160 is being designed to demonstrate the benefits of a BLB system by providing a comfortable ride to its passengers and crew while maintaining its ability to rapidly and efficiently deliver supplies to offshore facilities. The stabilized monohull arrangement provides a large deck area while the patented bow lifting body and an aft foil, in concert with our advanced ride control system, will significantly reduce motions underway. The BLB-160 is currently entering preliminary design phase and could begin construction as early as 2008. Table 2 provides the principal characteristics of the BLB-160; Figure 23 shows a rendering of the concept design.

Table 2 BLB-160 Principal Characteristics

Parameter	Value	
Length Overall	161.0 ft	49.07 m
Beam Overall	40.0 ft	12.19 m
Length _{WL}	152.0 ft	46.33 m
Draft, Maximum	10.0 ft	3.05 m
Displacement, Design	240 LT	244 t
Displacement, Maximum	300 LT	305 t
Deadweight	120 LT	122 t
Classification	ABS A1 HSC CREWBOAT	

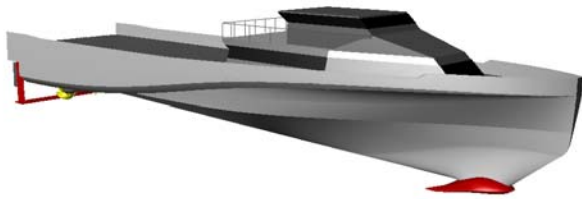


Figure 23 BLB-160 'Sea-Frame' Concept Design

8 CONCLUSIONS

Our development of the bow lifting body ship concept has progressed rationally from initial concept to CFD predictions to model tests to quarter-scale demonstrator, meeting or exceeding performance expectations at each stage and with excellent correlation between computer performance predictions, model test data, and at-sea trials data. This correlation gives us great confidence in the scalability of the concept and is allowing us to move forward with a much larger demonstrator. The result of this development effort truly reflects a new paradigm for high-speed monohulls.

ACKNOWLEDGEMENTS

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