CDI Business Solutions

THE QUARTERLY DIGEST

of CDI Marine Systems Development Division (SDD)
(formerly Band, Lavis & Associates)
900 Ritchie Highway, Severna Park, MD 21146

Volume 29 April 2005

FROM DAVE'S DESK

We have three articles in this issue of our newsletter dealing with our contributions to (1) marine waterjet technology, (2) fast Air Cushion Vehicles (ACVs), and (3) the Life-Cycle Cost (LCC) of fast ships. All three articles feature the significant innovations that we have created to improve the performance and reliability, combined with reduced cost, of fast vessels.

After 16 years of research and development into fast marine craft waterjet propulsion systems, using compact axial-flow pumps, we have at last gained serious interest from government and industry for the innovative work we have accomplished. Spearheaded initially at Band, Lavis & Associates by our Chief Engineer, John Allison, starting in 1988, we have performed many studies and have had our pumps tested in numerous facilities, including those of several of the world's leading pump manufacturers. Over the years, our pumps have been installed in several high-speed craft, including the U.S. Marine Corps Expeditionary Fighting Vehicle (EFV, formerly AAAV). We, and our government, now believe that this technology should be exploited to support the various emerging high-speed ships and craft that our military is now interested in pursuing. Our most recent endeavors are summarized, starting on this front page, in an article by John Purnell, our senior pump designer.

This article on waterjet propulsion is followed by a summary of a technical paper that Brian Forstell and I have written for delivery this June at the FAST 05 Conference in St. Petersburg, Russia. The article describes the significant progress made in the United States over the last 10 years for improving the operational capabilities of high-speed Air Cushion Vehicles (ACVs). Reviews are given of the breakthroughs achieved in improving vehicle seakeeping, maneuvering, powering, noise reduction and reliability. This has been achieved through the systematic development and testing of innovative systems for new Deep Skirts, new maneuvering devices, new lift-air supply fans, new air-screw

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ADVANCED COMPACT WATERJET PROPULSION FOR HIGH-SPEED SHIPS

By John Purnell, Senior Engineer

The necessity of delivering time-critical cargo, both commercial and military, has driven future sealift ships to require higher speeds. High ship speeds (of 35 knots and beyond) require the use of both slender hullforms (to reduce the ship's drag) and efficient but compact propulsion systems (to minimize the total installed power and installation space required). For this application, waterjets are the overwhelmingly preferred choice since:

- They have no appendage drag (with a flush-mounted waterjet inlet); and
- They have high efficiency (because they recover part of the ship's frictional drag by ingesting the low momentum boundary layer at the waterjet inlet).

Advanced Waterjet Development

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A Tradition of Excellence in Advanced Marine Technology

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propellers and aerodynamic shrouds. The article further describes how model and full-scale development testing has been utilized and how the most advanced Computational Fluid Dynamic (CFD) analysis and design software for rotating machinery has been exploited to improve the design of lift and propulsion systems. Numerous craft have already benefited significantly from these advances in technology as demonstrated in the paper and presentation, respectively, by photographs and video of full-scale vessels in operation.

The last article by Jeff Benson, our Programs Manager, summarizes the work we have been doing on the design of high-speed commercial RO/RO ships and in reducing the cost of short-sea shipping.

We are very proud of our innovations that are making a difference in this age of increasing interest in fast craft and ships.

ADVANCED COMPACT WATERJET PROPULSION FOR HIGH-SPEED SHIPS, Continued from page 1

However, today's commercially available large waterjets, above 10,000 horsepower, are mixed-flow pumps. For these pumps, the installation flange diameter is 70 to 85 percent larger than the diameter of the inlet flow duct, and this large flange diameter is often incompatible with the slender hulls required for high-speed ships. Increasing the hull's beam to accommodate the size and number of mixed-flow waterjets required could result in significant increases in drag, which leads to a spiraling increase in ship displacement and power that must be installed. Axial-flow waterjet pumps, however, have installation flange diameters that are only about 15 to 20 percent larger than the inlet duct and are therefore thought to be a potential solution to this problem. They are also much lighter in weight.

Thus, in 2002, we embarked upon a four-year program, funded by CCDoTT (Center for the Commercial Deployment of Transportation Technologies), with recent oversight from ONR, to examine technology options and eventually to focus on the RDT&E to develop compact axial-flow pumps.

Project Objective and Approach

The objective of this four-phase project for CCDoTT is to develop and validate the attributes of a preferred compact waterjet propulsor suitable for high-speed sealift applications where waterjet propulsion is the only realistic choice. The four phases of the project are:

Phase 1, completed in August 2002, studied options for compact units, including the following: 1) pumps with contra-rotating blade rows, 2) pumps with inlet pre-swirl vanes, 3) ventilated pumps, 4) super-cavitating pumps, and 5) axial-flow pumps. The latter was chosen for further work.

Phase 2, completed in September 2003, developed the concept design of a waterjet-propelled, 50-knot, 600-ft long slender monohull RO/RO ship for commercial coastal short-sea shipping (see article by Jeff Benson). This design was developed with help from the CDI whole-ship design synthesis model PASS™, which helped to confirm the choice of axial waterjet pumps as having the most favorable ship impact to minimize ship fuel consumption and maximize overall ship economy of operation. A complete hydrodynamic design of a 57,300 hp axial-flow waterjet pump for this application was also developed using Computational Fluid Dynamics (CFD), which would form the basis for further model-scale analysis in Phase 3.

Phase 3, due to be completed in May 2005, involves additional CFD model-scale analysis, manufacture, and water tunnel testing of a model waterjet pump that was required to adequately define the pump's critical performance characteristics and cavitation limits. Testing utilizes a Laser Doppler Velocimeter (LDV) system to characterize and define the flow-fields and assure performance prediction accuracy.

Phase 4, due to be completed in April 2006, involves the construction and testing, in a towing tank, of a suitable high-speed ship model for, among other things, the critical interaction effects between the hull and the waterjet inlet. It determines the pump's powering characteristics at design-point and off-design operating conditions. Data developed covers the full range of ship operating conditions anticipated for the primary full-scale waterjet propulsor.

The whole-ship and ship interaction data, combined with pump model tests of Phase 3, will provide the critical information necessary to validate the design process and the CFD modeling results.

This will enable realization of the Overall Project Goal: To enable the realistic design and prediction of overall full-scale performance of large (>20 MW) axial-flow pumps in a high-speed ship application using the proper and appropriate model testing and data scaling procedures such as those defined by the International Towing Tank Conference (ITTC).

Project Participants

Assisting CDI Marine, in Severna Park, MD, on this project for CCDoTT has been the Naval Surface Warfare Center, Carderock, MD, Marine Propulsors Company, Berlin, MD, and the Office of Naval Research (ONR).

AIR CUSHION VEHICLE (ACV) DEVELOPMENTS IN THE U.S.

By David Lavis and Brian Forstell

We, as a company, have been involved continuously in the research and development of ACVs since 1977. Dave Lavis has been involved continuously since 1959, initially in the U.K. This long involvement in developing ACV technology has provided us with the opportunity to work on most every significant ACV program in the United States and many in Europe and the Far East. However, since the rapid developments that took place in the 1960s, it has only been during the last 10 years that additional significant technological advances have occurred. This has been primarily as a result of the continued evolution of more powerful computers and the recent advances in numerical analysis and design tools that have been used to evolve an impressive range of new-generation systems for:

- Air Cushion Skirts
- Lift Fans
- Ducted Air-Screw Propulsors
- Bow Thruster Maneuvering Devices

These advances have resulted in significant improvements in craft speed-power performance, seakeeping, maneuvering and reliability. Many of these new systems are currently in operation on the U.S. Navy LCAC and the Finnish Navy 70-knot T-2000 Combat Patrol ACV. New ACVs that will also leverage these new developments are currently in either the detailed design or the concept design phase.

1. SKIRT SYSTEMS

Most ACVs employ a conventional bag-finger skirt system. This skirt design originated in England in the early 1960s and has seen a modest evolution primarily directed at reliability improvements. This skirt design features a peripheral bag for air distribution, below which are suspended open fingers. Longitudinal and transverse cushion dividers are frequently incorporated into this skirt design to enhance pitch and roll static stability.

In 1995, the U.S. Navy had an emerging requirement to perform a surf-zone mine countermeasures mission (MCM) with the LCAC. This specific MCM mission required that the LCAC have the ability to hover, at zero forward speed, in the surf zone with surf heights up to 2.4 m. This operational requirement lead to the design requirement for a new skirt that had a 2.1 m cushion depth rather than the 1.5 m cushion depth of the original bag-finger skirt system. The modified craft still had to be compatible with U.S. Navy well-deck ships, and there was a strong desire to reduce the demands of skirt maintenance through increased system reliability. The skirt design developed to meet these requirements, by CDIM-SDD under contract to NSWC Panama City, was the first-generation Deep Skirt that is currently being installed on all U.S. Navy LCACs. This skirt design features a double-bubble outer side bag to preserve well-deck compatibility, back-to-back side fingers along the sides of the skirt to provide enhanced roll static stability, and a transverse cushion divider to supplement pitch static stability and reduce leakage of cushion air when underway in waves. No form of longitudinal keel is used in the Deep Skirt design. Figure 1 provides a bottom view of the complete Deep Skirt design.

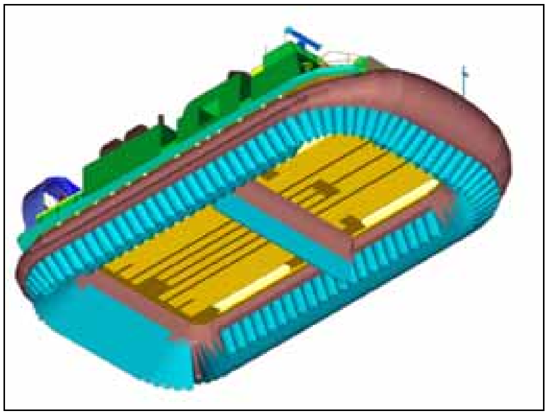

Figure 1. Bottom View of the Deep Skirt Concept

Note that the back-to-back fingers are used along the sides, while conventional open fingers are used at the bow and the corners of the Deep Skirt. Modern planing fingers are used at the stern.

Operational experience gained from fleet use of the first-generation Deep Skirt has shown that the design has significantly reduced the resistance of the craft in a seaway, improved the craft ride quality, increased the craft payload carrying capability, and significantly reduced skirt maintenance requirements.

The second-generation Deep Skirt was developed for the Finnish T-2000 Combat ACV. This design employed all of the lessons learned from the development of the first-generation design. Among these lessons was the use of more sophisticated modeling techniques to develop the inflated geometry and the subsequent flat patterns. This advanced modeling technique provided a skirt design that was relatively free from stress concentrations in the finger surfaces which tend to accelerate material failure. This is illustrated by comparing Figure 2 with Figure 3.

These two figures present the deflection, displacement, or stress that is predicted to occur in the face of a side finger during underway operations based on Finite Element Analysis (FEA).

A comparison of the analysis results indicated that CDIM-SDD was successful in significantly reducing high-stress concentrations of material in the second-generation design. Note that this particular design typically operates for over 400 hours without significant maintenance requirements.

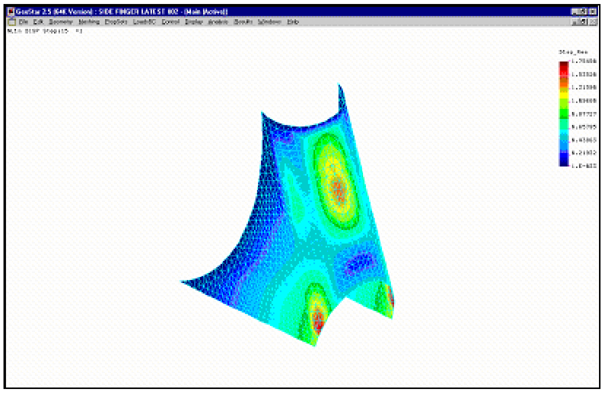

Figure 2. Stress Levels for First-Generation Skirt

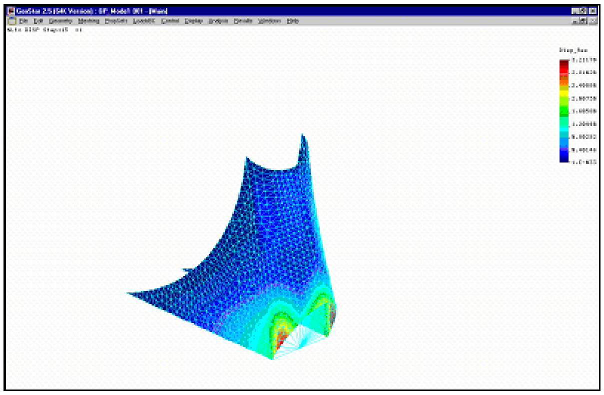

Figure 3. Stress Levels for Second-Generation Skirt

The third-generation Deep Skirt design is currently entering the fabrication phase and will undergo operational testing, in 2007, on a craft similar to the U.S. Navy LCAC. This skirt design has also leveraged the lessons learned from the prior two designs, with the primary emphasis being placed on reducing skirt drag in a seaway and further improving ride quality. Sub-scale model testing of the third-generation Deep Skirt design was completed at the David Taylor Model Basin at Carderock, Maryland in 2003. Model test data indicated that the design objectives were met.

Figure 4 compares the resistance associated with the ACV skirt for the three generations of Deep Skirt designs. This data has been derived from model test results and represents craft operation into a head sea having a 1.4 m to 1.5 m significant wave height.

As the data in Figure 4 represents three different craft designs that are all operating at different design weights, the model test data has been normalized by dividing the skirt drag by the design craft weight. The results of Figure 4 indicate that design experience, and the application of the lessons learned from the previous Deep Skirt designs, has resulted in a steady decrease in the craft resistance component attributed to the skirt. There is some inevitable variation in the actual significant wave height and wave modal period in the data of Figure 4 which does influence the data comparison somewhat. Nevertheless, the information presented in Figure 4 indicates that the application of careful design practices that recognize prior lessons learned, combined with the use of modern design tools, has resulted in roughly a 25% reduction in the drag associated with ACV skirt systems.

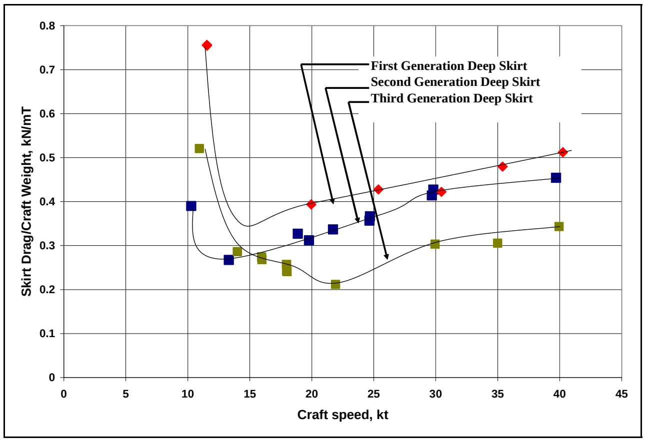

Figure 4. Comparison of Skirt Drag

2. LIFT FAN DESIGN

ACVs have demanding pressure-and-flow requirements placed on the lift fans which provide the cushion air flow. ACV fan designers desire a relatively flat characteristic supply curve in the area of the fan design operating point to enhance the ride quality of the craft when operating at high speed at sea. Additionally, designers seek the most efficient fan possible to minimize the power required by the lift system. Several good aerodynamic fan designs, such as the HEBA-A and HEBA-B, have been used by ACV designers for 40 years or more. However, as military ACV designs have tended toward smaller planforms, combined with increasing craft weights and operational speeds, the performance demands placed on the lift fans have increased to a point where existing fan designs can no longer efficiently meet the performance requirements without exceeding safe structural design practices.

CDIM-SDD has been developing custom fan designs for heavily laden ACV and SES for over 16 years. The Norwegian Navy's SKJOLD and OKSOY classes of SES, for example, use fans designed by CDIM-SDD. Much of our early fan development relied on engineering analysis, combined with sub-scale model testing, to verify and, if required, modify the design fan performance. While this approach has been very successful in producing more efficient and more quiet fans, it is quite time consuming and can be very costly. Recently, CDIM-SDD has been using advanced CFD RANS tools to develop new ACV lift fans. CDIM-SDD has recently completed the aerodynamic design of concept fans for a heavy-lift ACV. A sample output from this analysis is shown in Figure 5. The advent of sophisticated design tools such as CFD can allow for rapid convergence on unique design parameters. This approach to fan design and analysis has had the added advantage of showing that volute sizes can be much smaller than previously thought without significantly sacrificing fan performance.

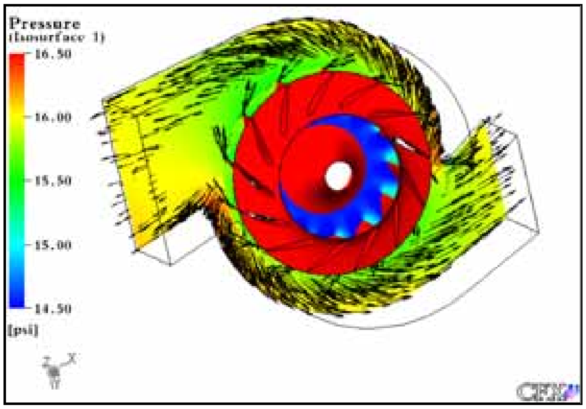

Figure 5. Sample Output from CFD Analysis

After completing the aerodynamic design of the heavy-lift LCAC fan using the CFD tools, a sub-scale model was constructed and tested to verify the design approach and anticipated fan performance. Figure 6 shows that the characteristic fan pressure and flow was accurately predicted by the CFD analysis. The CFD analysis did, however, tend to slightly over-predict the power absorbed by the fan.

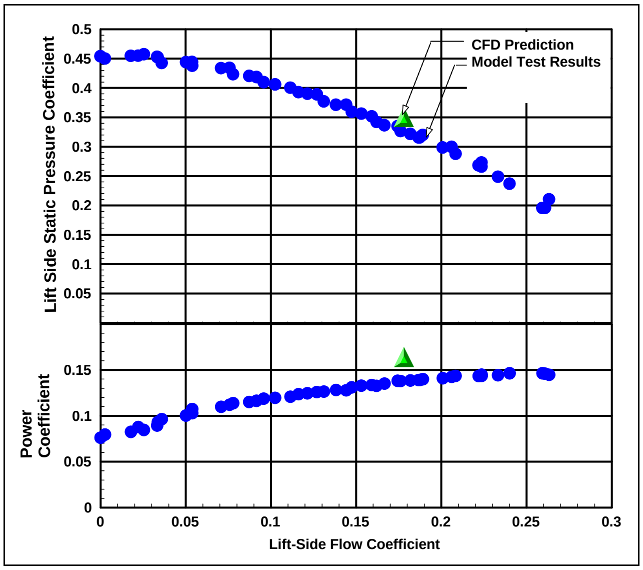

Figure 6. CFD Predictions vs. Model Test Results

3. DUCTED PROPULSOR DESIGN

Modern amphibious ACVs typically rely on ducted air-screw propellers to provide the majority of the required forward thrust. While this provides for a fully amphibious capability, it generally leads to a low propulsive efficiency compared with a comparable marine propulsor. Frequently, the designers of ACV propulsion machinery collaborate with air-screw manufacturers and adapt an existing air-screw originally developed for an aircraft application. This practice has generally been successful for the ACVs developed to date.

CDIM-SDD recently completed a design exercise directed at developing a custom ducted air-screw propeller capable of efficiently absorbing power levels that are approximately fifty percent higher than the power absorbed by the U.S. Navy LCAC propeller. This was accomplished using advanced CFD and inverse CFD tools to optimize the aerodynamic cross-section of the air-screw propeller, the propeller duct, and the stators that are downstream of the propeller. In the programming, the propeller and shroud geometries, along with all of the upstream craft structure, were modeled for inclusion in the analysis. This provided the full impact of all upstream blockage on the propulsor performance to be predicted. The various aerodynamic sections were parametrically varied to identify the properties that would meet the desired thrust levels while also minimizing the power absorbed by the propulsor.

The preferred propulsor design was found to be a six-bladed air-screw installed in a duct that has seven aerodynamic stators, as shown in Figure 7.

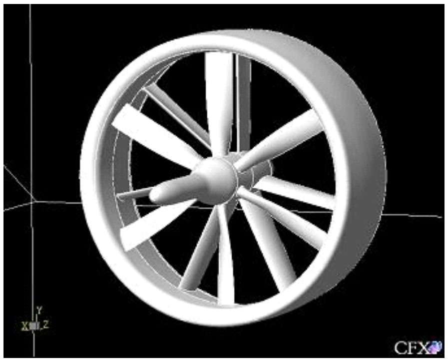

Figure 7. View of the Six-Bladed Propeller

Once the preferred design was obtained from the CFD analysis, a sub-scale model wind tunnel test program was planned to confirm the performance predicted from the CFD analysis. These tests were conducted at the Glenn L. Martin wind tunnel at the University of Maryland. The size of the wind tunnel test section, combined with the available size of electric drive motors, limited the size of the model propulsor to 1/6th scale. This relatively small scale ratio posed several significant challenges to the model designers and testers. The most notable of these challenges was how to adequately address the Reynolds Number effects that would obviously be present in the test data. It was decided that the best approach to addressing the model scale effects was to use the CFD tools to predict the performance of the sub-scale ducted propulsor in the wind tunnel environment. Thus, rather than actually verifying the performance of the full-scale propulsor, the wind tunnel test was being used to validate the CFD tools and analysis approach that was used to develop the aerodynamic design of the full-scale ducted air-screw.

In the CFD programming, the propeller and shroud geometries, along with the cabin structure in front of the propeller and shroud, and the wind tunnel geometry were modeled for inclusion in the analysis. Different propeller rotational angles were evaluated, and the model could be yawed at different settings relative to the tunnel air flow. Figure 8 shows the CFD wireframe of the model in the wind tunnel at +10 degrees craft yaw setting.

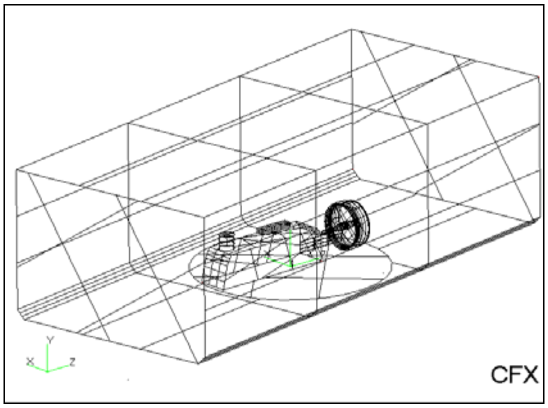

Figure 8. Model Wireframe Looking into the Wind Tunnel with the Model Yawed at +10 Degrees

The 1/6th-scale model propeller has adjustable blades and can be tested at different blade settings. Stator blade settings are fixed and thus do not change with changes in the propeller blade pitch setting. Figure 9 shows the model propulsor installed in the wind tunnel.

Figure 9. 1/6th-Scale Ducted Propulsor

After the CFD code arrived at a solution, the post processing of the data allowed streamlines to be plotted showing where specified flow comes and goes. Of interest was a determination of (i) from where did air flow into the propeller come, and (ii) its path around the cabin. CFD can trace the path of the flow particles that flow into the propeller disk area back to their source location at the inlet of the wind tunnel (Figure 10).

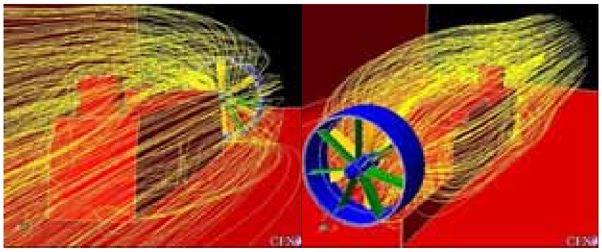

Figure 10. Fore and Aft Views of Propeller Inflow

Figure 11 provides an indication of the correlation obtained when the CFD predictions of the wind tunnel tests were compared with the actual wind tunnel test results. Note that the data have been reduced to non-dimensional form so the CFD predictions can be compared to the wind tunnel test results even though the propeller rotational speed for the CFD predictions is different from that actually used for the wind tunnel testing.

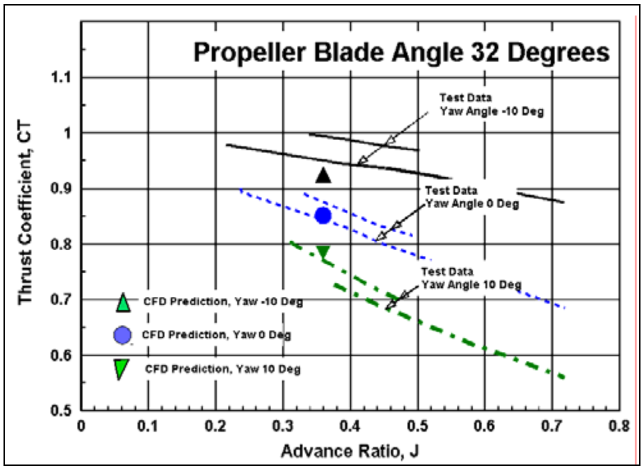

Figure 11. Measured Thrust vs. CFD Predictions

In reviewing Figure 11, it is seen that the thrust coefficient predicted by the CFD analysis agrees quite well with the measured data. The reader should note that the ordinate of Figure 11 is an expanded scale that tends to amplify differences between the measured results and the CFD analysis. From close examination of the data in this figure, it can be seen that the CFD prediction generally agrees with the measured data within ± 4%. The test data did, however, show that the CFD analysis generally tended to over-predict the required torque by approximately 8% on average.

4. BOW THRUSTER NOZZLES

Several modern ACVs, such as the U.S. Navy LCAC and the Westland Aerospace AP.1-88, employ bow thrusters to augment craft thrust and to provide a maneuvering device forward on the craft to enhance the craft turning performance. A typical bow thruster installation is shown in Figure 12, which features the Canadian Coast Guard AP.1-88.

Figure 12. Bow Thrusters on the AP.1-88

These nozzles expel high-velocity air, typically supplied by a dedicated fan, to produce thrust. As the bow thruster nozzle can usually be rotated about the vertical axis, it is capable of producing longitudinal thrust and/or side force depending on the angle of rotation. When multiple fans are used to provide air to a single bow thruster nozzle, some form of combining manifold is typically employed in the system design, albeit with an associated loss in potential bow thruster thrust that results from the turning losses experienced in the manifold. Another feature of typical bow thruster nozzles that can be seen in Figure 12 is their height, which can be up to two meters or more from the fan discharge to the top of the nozzle.

When CDIM-SDD became involved in the design development of the Finnish T-2000 Combat ACV, they were faced with the challenge of reducing the height of any system or component that was installed on the exterior of the craft. This requirement lead to the development of the low-profile bow thruster pictured in Figure 13.

Figure 13. Low-Profile Thruster on the T-2000

These bow thruster nozzles represent a substantial step towards reducing the height of the nozzles. As can be seen in Figure 13, the low-profile bow thruster consists of a rotatable nozzle that sits on top of an air collection plenum that, in turn, is mounted on top of an air-supply fan. The top of the T-2000 low-profile bow thruster nozzle is only 780 mm above the level of the superstructure deck.

As seen in Figure 13, the low-profile bow thruster nozzle comprises a series, or cascade, of small two-dimensional nozzles. The low-profile bow thruster concept was initially developed by CDIM-SDD for use on the Finnish Navy's T-2000 ACV. This design is much different than the conventional bow thrusters used on the LCAC and AP.1-88. The new design employs a series of miniature nozzles at staggered heights, closely resembling a cascade of airfoils. This novel design has the advantage of a much smaller radar cross-section. The compact design of the miniature nozzles has the added benefit of reducing the shock and friction losses that are characteristic of flow through bends. Figure 14 diagrammatically depicts the geometry of a high and low-loss bend, from <u>Fan Engineering</u>, 8th Edition, Buffalo Forge Company, 1983.

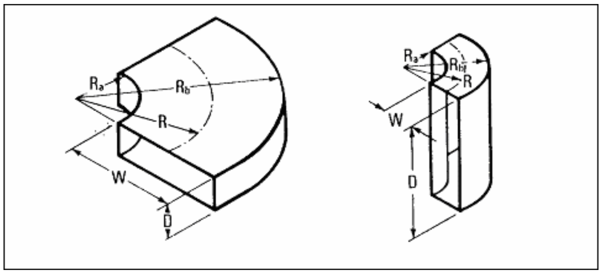

Figure 14. Diagram Defining Hard and Easy Bends

Parameters such as the curve ratio (R_a/R_b) and radius ratio (R/W) greatly affect the losses induced in the nozzle bend. In general, a large curve ratio and a large radius ratio are desired to minimize the losses in the bend. The low-profile bow thruster offers a larger curve ratio and larger radius ratio than a conventional bow thruster, thereby reducing the losses induced by the bent nozzle. This can be seen in Table 1, which presents a simple comparison of the conventional and T-2000 bow thrusters.

Table 1

Comparison of Nozzle Geometry

	Conventional Nozzle	**T-2000 Low-Profile Nozzle**
Curve Ratio (R_a/R_b)	0.09	0.22
Radius Ratio (R/W)	0.73	0.85

Although only a minor increase (~16%) in the radius ratio was realized, there was a significant increase (~144%) in the curve ratio. In addition, the low-profile bow thruster employs a rectangular section with a large aspect ratio, which is also desirable to minimize losses.

The low-profile bow thruster design was model tested in our laboratory to assess the potential performance from such a system. The model test results indicated that the low-profile bow thruster would meet or exceed the T-2000 bow thruster requirements, so the design was developed further.

Full-scale bollard pull trials, conducted in 2001, provided the data necessary to confirm the engineering predictions. The full-scale trials data indicated that the thrust developed by the low-profile bow thruster was in general agreement with the original predictions.

Thus, CDIM-SDD (formerly Band, Lavis & Associates) has had the pleasure of being able to work at the forefront of ACV technology research and development for over 28 years. This has resulted in significant exposure to emerging technology that is either currently in use or potentially available for use in new craft.

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A Tradition of Excellence in Advanced Marine Technology

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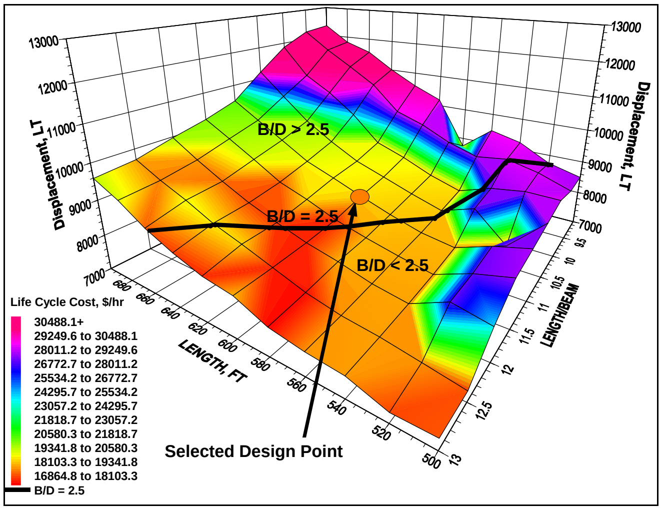
THE QUARTERLY DIGEST

of CDI Marine Systems Development Division

SHIPS THAT GO FAST

By Jeff Benson, Programs Manager

The Navy's long-term force structure plan submitted to Congress this month identifies a burgeoning interest in *ships that go fast.* In addition to the large MPF(F) ships, the Navy's emerging Sea Basing concepts include "HSS" (High Speed Ships) and nearer-term "High Speed Connector" ships. In conjunction with CCDoTT, CDIM-SDD used its advanced ship design software, PASS™, to examine the efficacy of a broad range of *ships that go fast* to respond to commercial and MarAd interest in Short-Sea Shipping. PASS™ is a first-principles, physics-based, advanced design synthesis tool capable of handling a full range of monohulls, multi-hulls (including catamarans, trimarans, SES and hybrids). Life-cycle cost, also generated by PASS™, was analyzed for variations of feasible hullform types, sizes, speeds, and payload capacities. The 8,400-LT, 600'-long slender monohull (L/B=10.9) proved the most cost-effective (see figure).



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