FINAL REPORT

Marine Engine Testing and Emissions Laboratory (METEL)

Led by Maine Maritime Academy

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Project Title:

Efficiency Improvement of Workboats through Hull Form Optimization Project

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The Marine Engine Testing and Emissions Laboratory is a consortium of 2 Universities funded by the U.S. Department of Transportation - University Transportation Centers Program. Members of the consortium at the Maine Maritime Academy and the University of Maine System. Maine Maritime Academy is the Lead Institution.

Overview

Maine Maritime Academy (MMA), sponsored by Maine Center for Coastal Fisheries (MCCF), has developed a high efficiency, advanced hull form for application to the coastal fishing fleet. The design has undergone extensive model testing and exhibits improved performance in the typical cruising speed range of these vessels. Reductions in fuel consumption and emissions are in the range of 15% to 25% depending on loading condition and sea state. The design achieves these reductions using an optimized trimaran hull, allowing for the large required deck space without the large waterline beam and power requirements of current boats. It differs in proportion from larger ship-size designs and works in a different way, achieving low resistance through both wave-drag effects and reduction in wetted surface.

While the powering reductions are proven by model testing, much of the small craft and fishing community is not accustomed to relying on these methods. Similarly, though seakeeping and maneuvering tests at model scale suggest good performance, a demonstrator of sufficient size to carry people in real-world conditions is needed to provide sea-trial data and allow fishermen to try the concept first-hand. To that end, MMA applied for and received a grant from the Maine Economic Improvement Fund (MEIF) to continue concept development and construct an approximately 3/5-scale prototype. The 38 ft. concept developed in earlier research projects was scaled and re-designed as needed, resulting in a 22 ft. vessel. Construction started at The Landing School in August of 2017 and ended in October 2018. The vessel will be operated by MMA and will undergo extensive testing and sea-trials.

1. Summary of Project

The project achievements are broken into two main categories: prototype construction/workforce development and continued design development. Each category is summarized below, with select topics explained in further detail in the next section. Several items are interconnected, as the prototype development drove the overall design and vice-versa. The prototype, for example, has more difficult stability requirements since people do not scale down with the boat, driving up the relative center of gravity.

1.1 Prototype Construction and Workforce Development

The primary outcome of this project is the construction of a 3/5-scale technology demonstrator at The Landing School in Arundel, Maine. The construction grant includes funds for engineering, workforce development, labor, and material cost for a 22 ft. prototype. Development and construction milestones are summarized below:

- Completion of structural calculations and laminate schedule for the prototype.
- Employment and training of two full-time boatbuilding apprentices for one year.
- Scaling and lofting of the prototype lines from original 38 ft. fishing boat.
- Development of hybrid composite-wood construction technique to balance performance and carbon footprint of prototype hull.
- Design calculations for scaled prototype (stability, weight, power, structural loading, and scantlings).
- New design details allow for experimental variation at prototype scale.
- Design change to full inboard diesel engine in lieu of outboard gasoline engine.
- Documentation of prototype design and completion of CAD drawings

1.1.1 Construction Milestones

- Completion and joining of upper and lower hull sections.
- Installation of 37.5 hp 4-cylinder diesel engine, shafting, fuel system, electrical system, raw water cooling, wet exhaust, steering, throttle, and helm station.
- Application of coatings: epoxy sealer, epoxy primer, topcoat, bottom paint.
- First start of diesel engine October 29, 2018.
- Milling and glue-up of removable sidehulls.
- Current overall status of vessel construction: 95% complete.

1.2 Design Development and Engineering

In addition to the direct construction work, several additional design developments have occurred over the course of the project. These items are listed here and include important refinement to the design requirements, general stability improvements, and the ability to compute difficult hydrodynamic interactions using Computational Fluid Dynamics (CFD).

- A market survey resulting in more favorable design speed range
- New concept design applying the technology to coastal ferries.
- Further experimental analysis of maneuvering and seakeeping
- Completion of detailed structural calculations for the 38 ft. fishing boat.
- Redesign of sidehull geometry to meet CFR 46 stability criteria.
- Computational hydrodynamic analysis of propeller efficiency
- CFD analysis of high-speed flow for previously tested sidehull geometry

2. Selected Results

Several results discussed below highlight the design characteristics of the vessel and main progress over the period of performance. These results focus on the initial design description, revised speed requirements, design modifications, and documentation & status of prototype construction.

2.1 Initial Design, Market Survey, Change to Speed Requirements

The initial design was for a boat of about 38 feet in length, with a light displacement of about 12000 pounds, and cruise/top speed of 16/20 knots, respectively. Powering is by conventional diesel engine in the range 220 to 250 hp. The concept design is shown in Figure 2.1.

Experimental performance measurements from several model tests are shown in Figure 2.2. Below about 22 knots, the trimaran performs better than a traditional monohull in all loading conditions and sea states. The best performance occurs between 10 and 15 knots. As with most multi-hull designs, the slender, high length-to-beam ratio hulls reduce the wave drag component of resistance. In non-dimensional terms, however, small working craft are heavier for their length than ships. Such hull proportions lend themselves to a reduction in wetted surface when compared to a traditional Maine lobster boat. As shown in the right side of Figure 2.2, the trimaran is more efficient at enclosing displaced volume with wetted surface, at least at low speed. As speed increases and dynamic effects drive up the wetted surface, the trimaran loses its advantage to the semi-planing traditional hull. The trends in wetted surface closely match the degradation of power reduction as the trimaran increases speed from 15 to 20 knots. Reducing design speed helps tremendously due to the cubic relationship between speed and power; slowing down from 20 to 16 knots cuts fuel consumption in half. Slowing down from 16 to 14 knots would reduce it

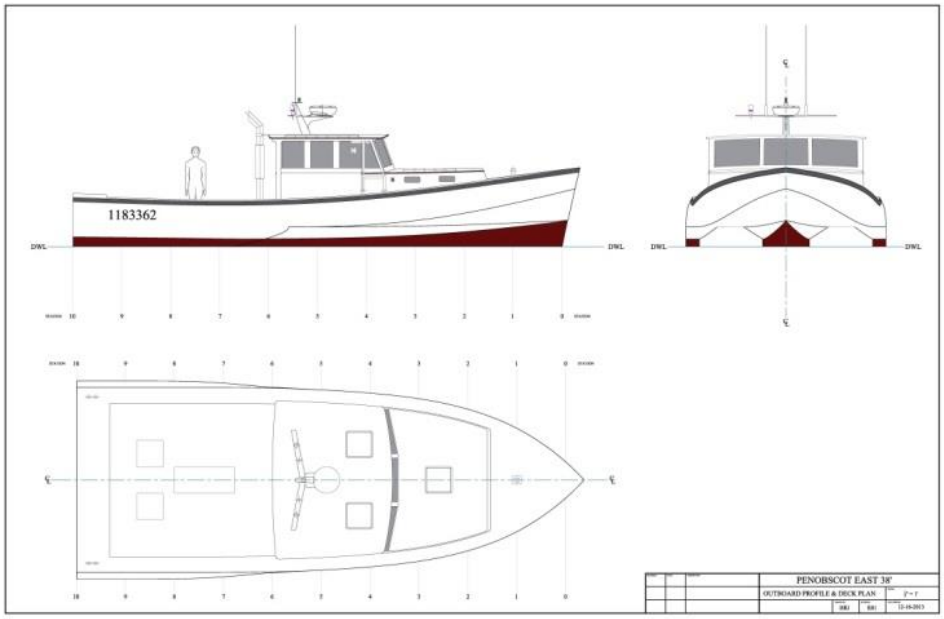

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Figure 2.1: Drawings of 38 ft. low-emissions coastal fishing vessel.

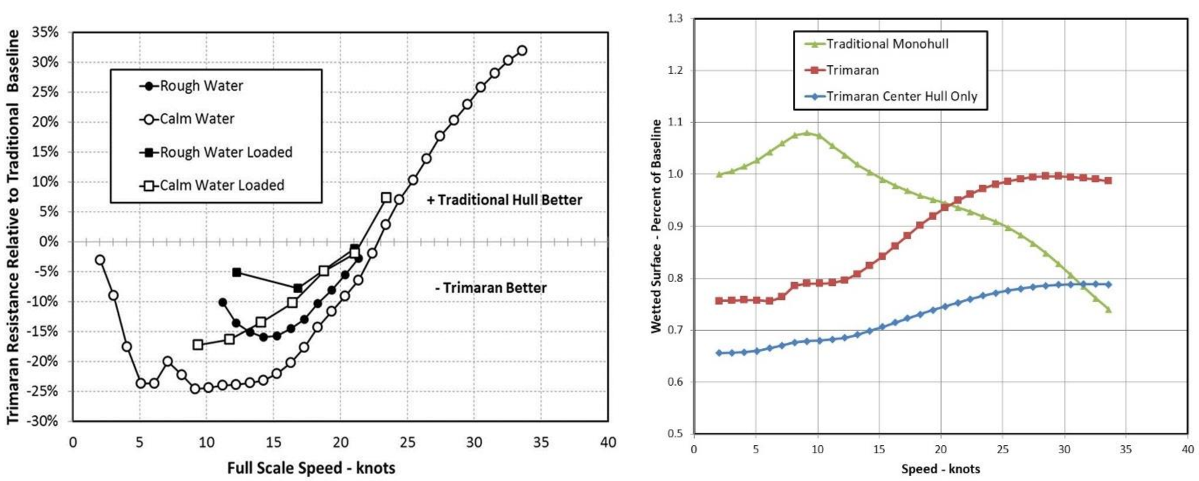

Figure 2.2: Design performance in various load conditions and sea states, trimaran compared to a traditional vessel (left) and dynamic wetted surface comparison (right)

Initial design requirements for speed were determined anecdotally from several regional meetings with Maine fishermen. Since speed places such high pressure on the design, a more scientific market survey was completed under a separate funding source (a Maine Technology Institute grant). The results of the survey, shown in Figure 2.3, indicate that the cruise speed fits exactly in the best performance range of the current design. The survey suggests that a cruise speed of 16 knots or less is sufficient for 92% of fishermen, and a cruise speed of 14 knots or less is enough for 57%. If the adoption of a new hull design could be accompanied by a small cultural shift in vessel speed, even more significant savings in fuel consumption and emissions could be achieved.

Note that Figure 2.3 compares the trimaran to a moderately beamy traditional vessel considered to have good efficiency for current designs. Performance vs. very wide boats following the recent design trend will be even more favorable.

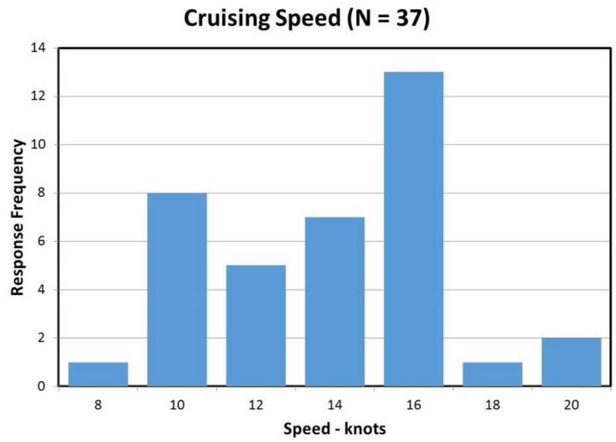

Figure 2.3: Fishermen response to survey for desired cruise speed.

2.2 Design Modifications to Meet Stability Criteria

The stability of the trimaran is largely dependent on the sidehull waterplane inertia and above-waterline shape. During the original design process, MMA did not have the tools to generate righting arm curves (GZ curves) for a multi-hull. Since the initial work was focused on resistance and power reduction, only initial stability was assessed using the waterplane inertias, areas, and sidehull spacing. Unfortunately, the wall-sided shape of the initial sidehulls did not make up lost buoyancy fast enough as the other sidehull came out of the water. This shape led to an unexpected drop-off in righting arm at small angles, resulting in unusual roll motions. The problem was exacerbated when scaling down to the 22 ft. prototype, as the relative location of the center of gravity, KG, increased.

To address the issue, a new sidehull geometry was created to improve the small-angle stability while maintaining the resistance characteristics measured in model tests of various sidehull size and position. The new geometry increases cumulative righting energy by up to 55% at small angles, allowing the vessel to meet the stability criteria for CFR 46 170.173, the weather criteria for vessels of unusual form.

The results of the change in geometry are shown in Figure 2.4. The left figure shows the sidehull geometry, which has non-linear increasing beam as roll angle increases. Such a cross-section increases low-angle righting arm and cumulative righting energy, but it must be balanced with a fine shape forward to maintain low drag as the main hull bow wave reaches the sidehulls.

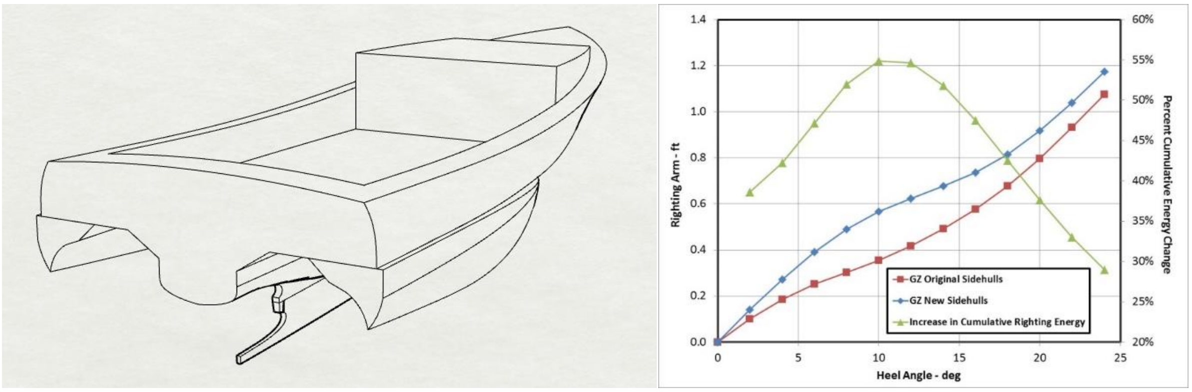

Figure 2.4: Improvement in righting energy due to new sidehull geometry, allowing vessel to meet CFR 46 170.173 weather stability criteria for vessels of unusual form.

2.3 Prototype Construction

To reduce risk on a radical new hull design, MMA has pursued the construction of a 3/5-scale prototype with The Landing School. The collaboration has led to the investigation of not only the lifetime emission reduction of the vessel, but to reducing the carbon footprint of the hull itself. The Landing School recently built three 19-foot vessels with near-zero carbon footprint for hull construction. In addition, this opportunity provided significant opportunity for workforce development, as the hull required new construction techniques and structural arrangements. Two full-time boatbuilding apprentices were employed on the project.

Sketches of the technology demonstrator are shown in Figures 2.5 and 2.6. Figure 2.5 shows the prototype at scale with the original fishing vessel. Figure 2.6 shows the construction sub-assemblies built at The Landing School, demonstrating the critical composite horizontal hull panel joining the upper and lower hull components.

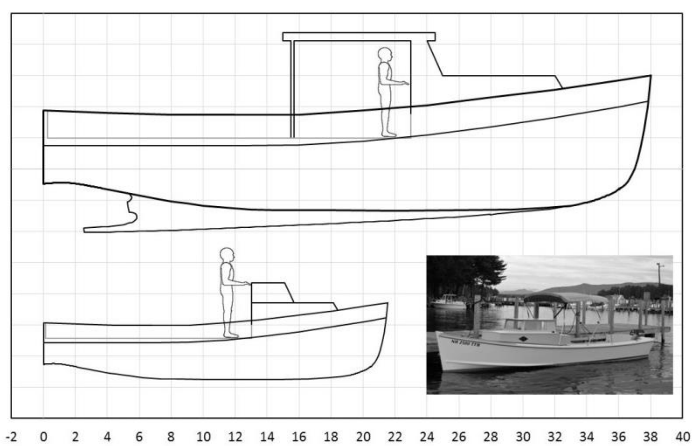

Figure 2.5: Comparison of fishing vessel design with technology demonstrator.

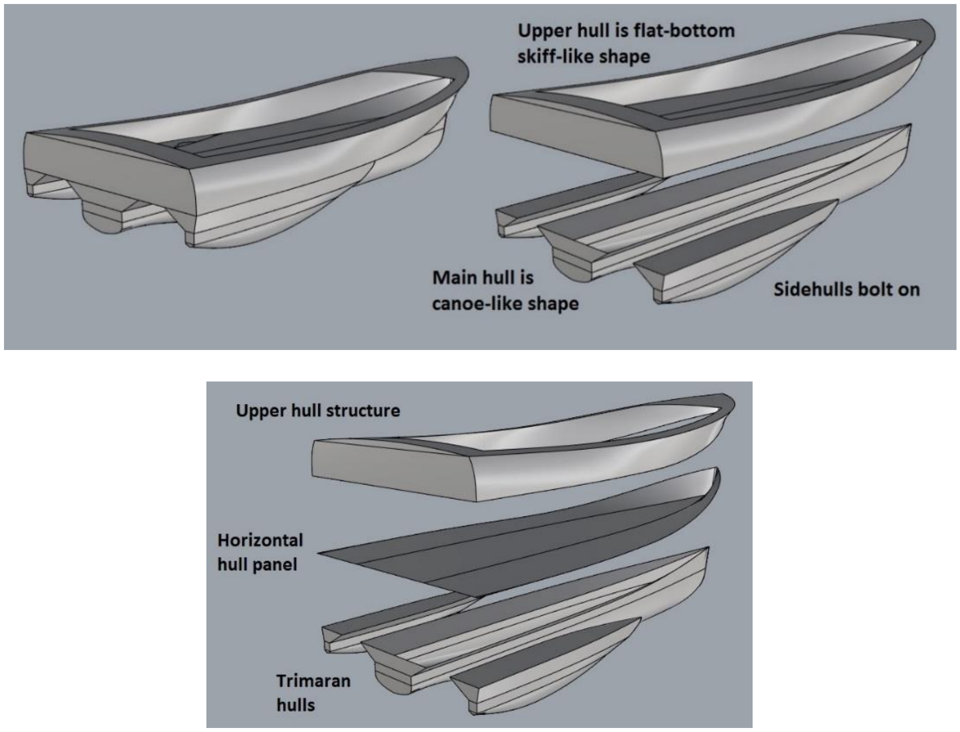

Figure 2.6: Construction breakdown of demonstrator to be built at The Landing School.

Note the upper hull portion, which looks like a flat-bottom skiff, attached to a long, narrow main hull underneath. Side hulls are about 45% of the length of the main hull and bolt on to the upper hull.

Notable milestones during the initial construction phase include lofting the lines full-scale, calculation of load cases and required section modulus, and selection of laminate schedule for the important composite horizontal hull panel.

Figures 2.7 shows the new hull panel and upper structure scaled at a different ratio in height than in length and beam. The vertical scaling is different to accommodate the geometry requirements of operators, which don't change between full- and prototype-scale. Finally, the hull construction is shown to be underway in Figure 2.8.

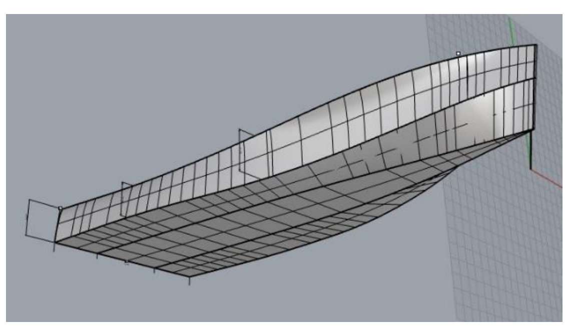

Figure 2.7: Upper hull structure and horizontal panel scaled to prototype dimensions.

Figure 2.8: Construction jig for upper hull structure in place at The Landing School.

Additional photos of construction are shown in Figures 2.9 and 2.10. In Figure 2.9, the upper hull is to the left, with the lower main hull to the right. The inboard diesel engine can be seen in the main hull. Figure 2.10 shows the main hull test fit to the upper hull.

Several details have been changed to allow experimental variation of the hull geometry at prototype scale. These features will allow further optimization of the design for both fishing vessels and coastal transportation:

- A removable bow section to test forefoot depth and bow bulbs for resistance and maneuvering characteristics
- Removable side hulls to test different stability configurations. Prototype scale stability required new geometry since people do not also scale down.
- The built-in stern wedge was removed to simplify strip-plank construction. A stern wedge/flap will be bolted on to the transom to test different angles.

The design was originally proposed with a small outboard engine to reduce cost. After further consideration, propulsion was changed to a full inboard diesel engine. This arrangement will allow the prototype to much more closely match the maneuvering characteristics of the full-scale vessel. A low-cost, four-cylinder diesel of about 38 hp. (a marinized Kubota engine by Nanni) allowed the change with minimal impact on budget. The engine can be seen in Figures 2.9 and 2.12.

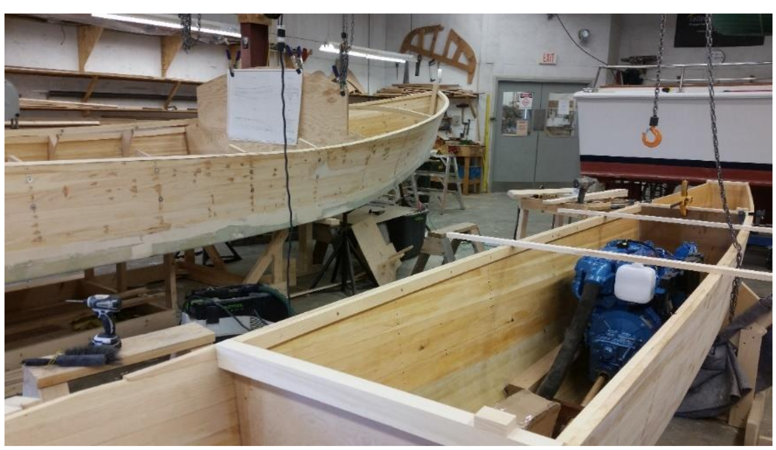

Figure 2.9: Construction progress showing diesel engine in main hull.

Figure 2.10: Test fit of upper hull to main hull. Note removable bow section.

The state of the vessel as of November 2018 is shown in Figure 2.11. All coatings, including bottom paint, are now complete. Note the missing bow section, which will be constructed at MMA. As noted, the boat will be able to bolt on different bow shapes to test the effect on resistance, powering, maneuverability, and seakeeping. The sidehulls are also not attached in the photo and will be similarly bolted on to test different geometry and the impact upon the static and dynamic stability. The engine and working deck are shown in Figure 2.12. Not the helm, throttle, and instrument panel, as well as the traditional deck. From this vantage point there is no indication that the vessel is a multi-hull. Figure 2.13 shows the propeller installation and shafting arrangement.

A short list of things remains to be done:

- Finish and bolt-on sidehulls
- Machine and bolt-on bow section
- Fabricate rudder and skeg
- Fabricate and install companionway door
- Order and install deck fittings and rub rail
- Transport and/or acquire appropriate boat trailer

Figure 2.11: Nearly complete vessel at The Landing School

Figure 2.12: First diesel engine start-up October 29, 2018

Figure 2.13: Propeller installation

2.4 Documentation and CAD Drawings

The design of the prototype evolved during the construction process. The chine at the lower-to-upper hull joint was raised at the bow to accommodate more structure, and a significant portion of the sheer line was changed to increase freeboard and gunwale height at the helm station. Updated and finalized CAD drawings were needed to document all these changes and provide geometry for trailer construction. These drawings are complete, with a sample shown in Figure 2.14.

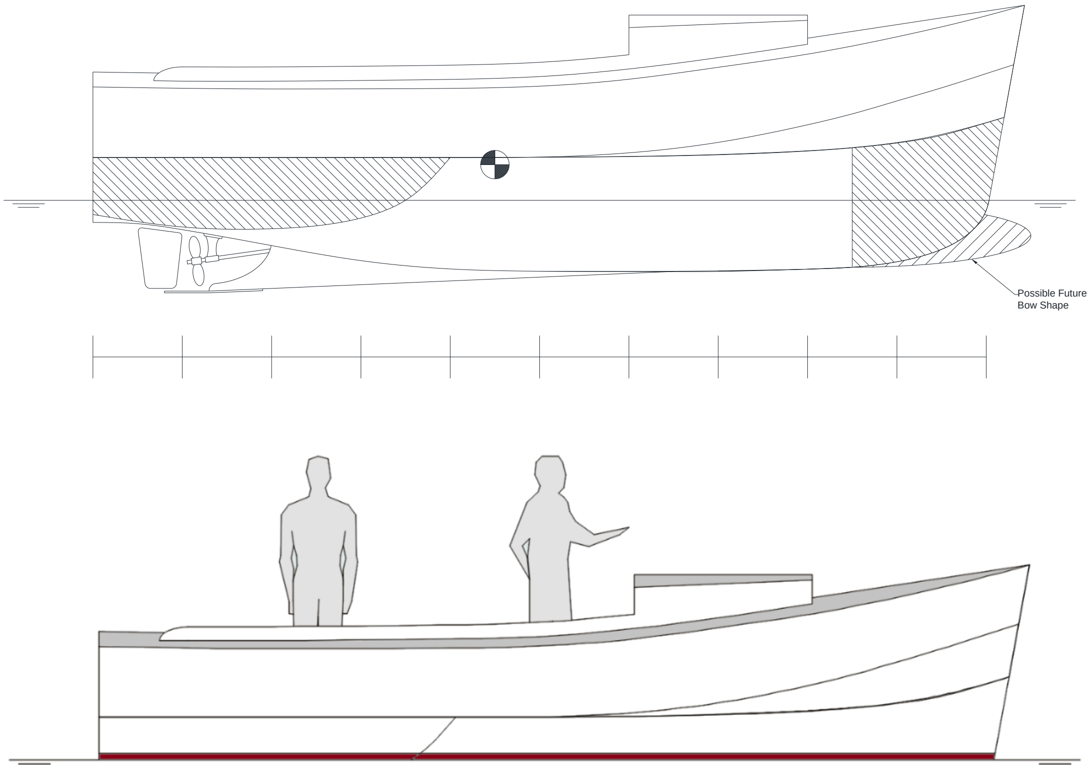

Figure 2.14: Sample of CAD drawings for final design

3. Conclusions and Future Work

The prototype hull is 95% complete and will be prepared for sea trials during Summer 2019. MMA will be able to extensively test the vessel powering, fuel consumption, emissions, maneuvering, and seakeeping. The boat has been designed to be easily modified with bolt-on components. A pot-hauler can be installed with the existing electrical system, so that suitability to such fishing methods can be qualified. The trimaran is well-suited to an electric drive, which could be installed in place of the traditional direct-drive diesel engine.

Sea trials will include direct fuel consumption measurement. Seakeeping and maneuvering characteristics will be quantified using an Inertial Measurement Unit (IMU) coupled with a GPS system. This unit was used on previous model tests and can be simply moved over to the boat for trials.

The prototype can be used to investigate the suitability of the trimaran design to a coastal ferry or offshore wind supply vessel.

3.1 Further Refinement of Sidehull Geometry

While the hydrodynamic optimization of the center hull is relatively easy, the sidehulls present a challenging engineering balance. The sidehulls must provide sufficient waterplane area and inertia for stability while having high slenderness and low wetted surface. The above-waterline geometry must give a good righting arm curve while being fine enough to sit in the main hull bow wave crest at high speed. Nonlinear effects such as keel vorticity and tunnel spray erode performance at the top of the speed range. Over the course of five model test series, these effects have been observed and measured experimentally at three different facilities. The trial-and-error of model construction and experimentation is quite time consuming, especially on the academic schedule.

MMA has recently acquired a CFD program capable of capturing these hydrodynamic phenomena. During the Spring 2019 semester, a student compared past capstone project model tests with output from this CFD program. The results are qualitatively compared to model test data in Figures 3.1 to 3.3, at 10, 16, and 20 knots respectively. The CFD captures high-speed dynamic wetted surface, onset of tunnel spray, and wave trough air entrainment forward of the stern wedge. These results show promise that the sidehull geometry could be further optimized without the need for a model test and experiment cycle.

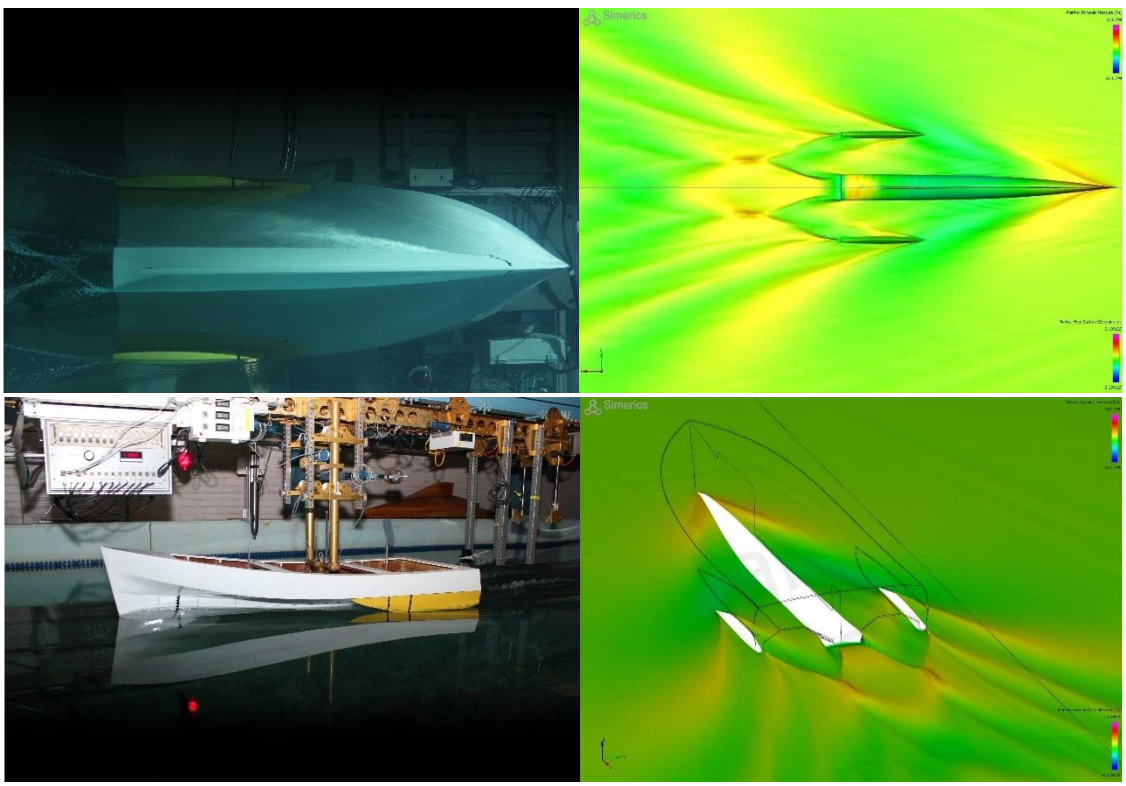

Figure 3.1: Comparison of experiment to CFD for 10 knots

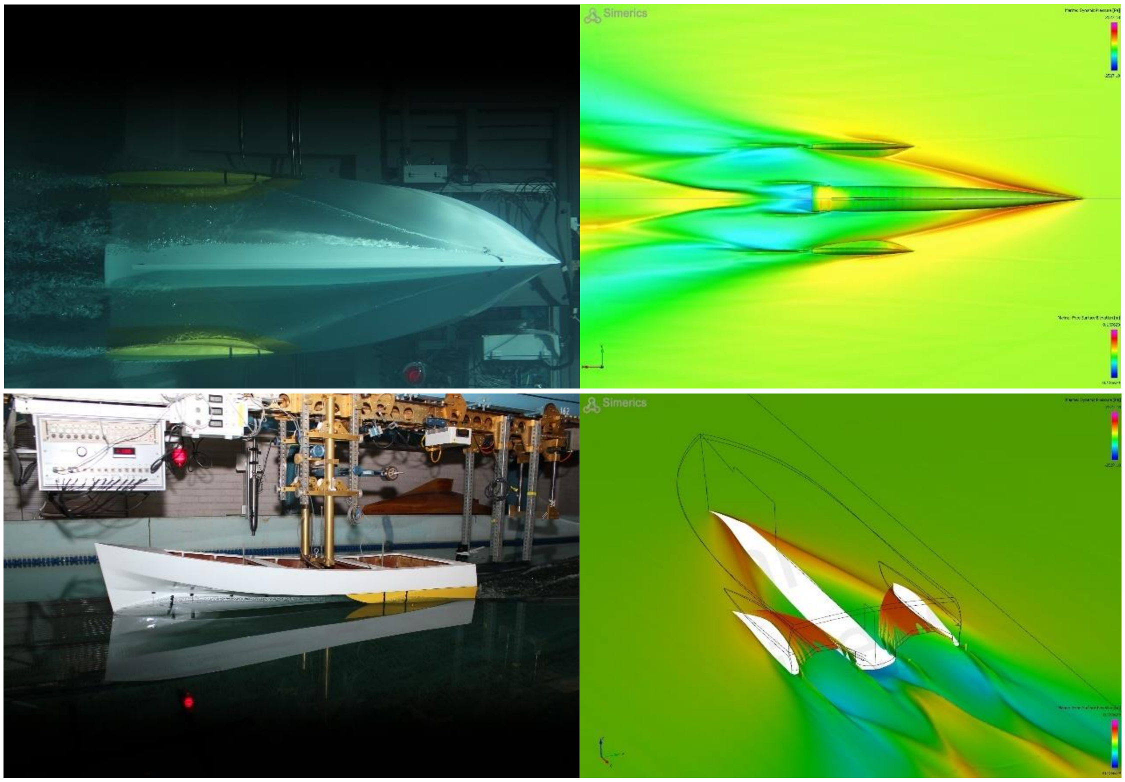

Figure 3.2: Comparison of experiment to CFD for 16 knots

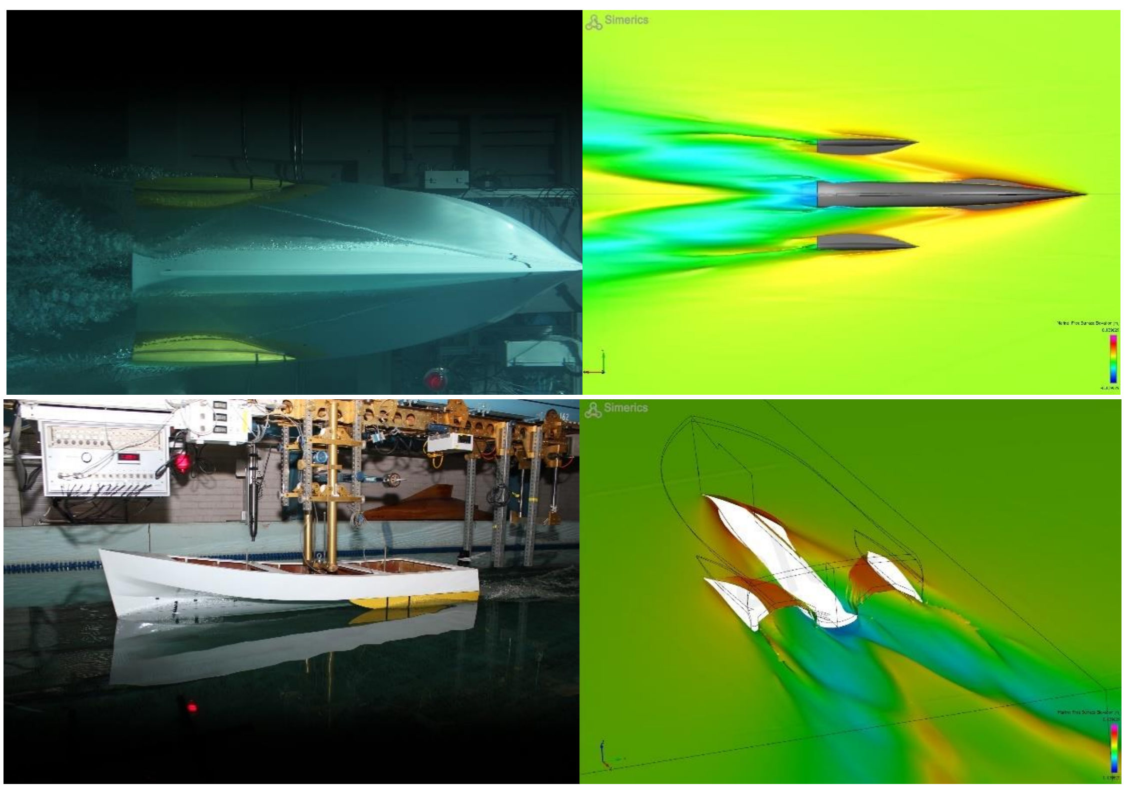

Figure 3.3: Comparison of experiment to CFD for 20 knots

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