Fabrication of a SWATH Vessel Scale Model for Seakeeping Tests using Rapid Prototyping Methods

by

John Robert DiMino

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Signature of Author:________________________________

Department of Mechanical and Ocean Engineering
May 10, 2013

Certified By:________________________________

Stefano Brizzolara
Research Scientist
Thesis Supervisor

Accepted By:________________________________

Annette Hosoi
Professor of Mechanical Engineering
Undergraduate Officer

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ABSTRACT

This paper describes the techniques used to fabricate a one meter long, 1/6 scale model of a Small Waterplane Area, Twin Hull (SWATH) Unmanned Surface Vehicle (USV) that will be used primarily for dynamic seakeeping testing in the MIT Tow Tank. The model represents a design conceived by Stefano Brizzolara, which will be used for launching, recovering, and servicing Unmanned Underwater Vehicles (UUV) at sea. Construction methods included a number of rapid prototyping methods rarely used for this kind of project, including 3D printing, lasercutting, and spraypainting. The benefits and disadvantages of each of these processes will be discussed. Although there was insufficient time to conduct any tow tank tests, several data-recording techniques are reviewed which may be used by future students continuing the research of this vessel.

Thesis Supervisor: Stefano Brizzolara

Title: Research Scientist

Acknowledgements

The author would like to thank the following people for their invaluable help throughout the research and progress of this project.

Stefano Brizzolara is the designer of the family of SWATH designs this thesis focuses on. He provided invaluable guidance and counsel in building the model for tow tank testing. His lectures in several classes, including Principals of Naval Architecture and Design of Ocean Systems contributed to the knowledge applied in this project.

Michael Soroka of MIT SeaGrant also provided help and insight regarding the fabrication techniques and topics of this paper.

The author's uncle, John Russel DiMino, and cousin, John Carmen DiMino who own and operate Black Horse Auto Body in Norristown, PA generously provided their facilities and expertise to paint the submerged bodies of the SWATH gratis.

Biographical Note

John DiMino is an MIT senior student in Mechanical and Ocean Engineering conducting research at MIT Sea Grant under the mentorship of Professor Stefano Brizzolara. He interned for two summers with the Office of Naval Research in Newport, RI and West Bethesda, MD studying marine robotics and ship design. Upon graduation, he will begin working for Lockheed Martin on underwater systems.

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1. Introduction

1.1 Characteristics of SWATH Vessels

SWATH ships are a relatively new form of vessel that have become popular for their superior stability in waves compared to equivalently sized monohulls or catamarans. SWATHs like catamarans have a twin hull arrangement. However, their peculiarity is derived from the cylindrical submerged bodies that constitute most of the ship's displacement. By carrying the majority of their underwater volume well below the free surface where wave action occurs, SWATHs are less sensitive to exciting forces due to incoming waves.

The large underwater surface area of SWATHs comes at a price. Frictional resistance is greatly increased, and thus most SWATHs have a relatively low cruising speed. The combination of excellent seakeeping characteristics and low speeds make them ideal platforms for research vessels. Applications of SWATH research ships include station keeping, sea floor mapping, unmanned vehicle carriers and more.

1.2 Current Design

Designs for a pair of unmanned SWATH vehicles have been proposed in (Brizzolara et al., 2011).

The first ship presented is intended for high speed military response applications. It is a high speed vessel that utilizes super-cavitating foils and turbo-jet engines to reach speeds of up to 120 knots. At low speeds, the ship operates as a typical SWATH, with the foils folded up against the struts and out of the water. When the ship must move swiftly, it increases its power and folds the foils to a 40 degree angle to lift the submerged bodies out of the water.

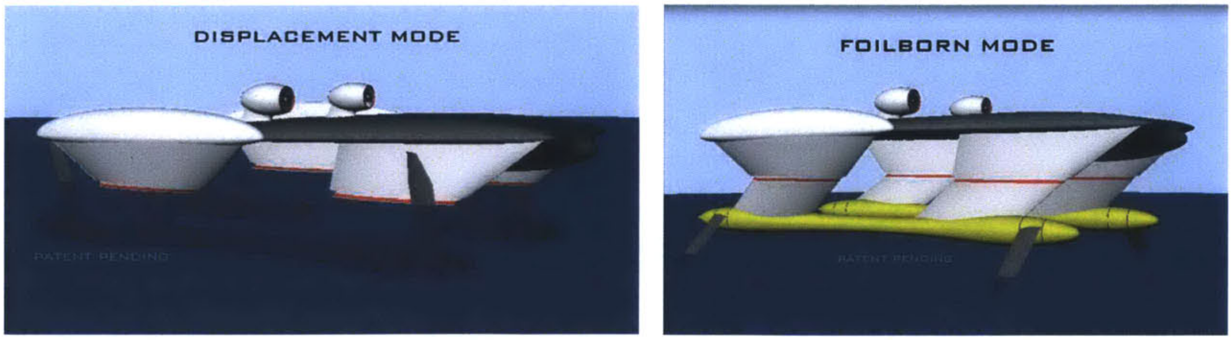

Figure 1: Renderings of the X meter SWATH USV in low speed displacement mode (left) and high speed foilborn mode (right)

The other design proposes a 6 meter long SWATH USV intended to move at average speeds and to service UUVs. The bridgedeck contains a retractable sling that can retrieve or deploy torpedo-shaped UUVs, and charge their batteries once they are onboard. This type of mission greatly benefits from the superior stability of a SWATH hullform, as retrieving payloads in high sea states would otherwise prove exceedingly difficult (Brizzolara & Chryssostomidis, 2013).

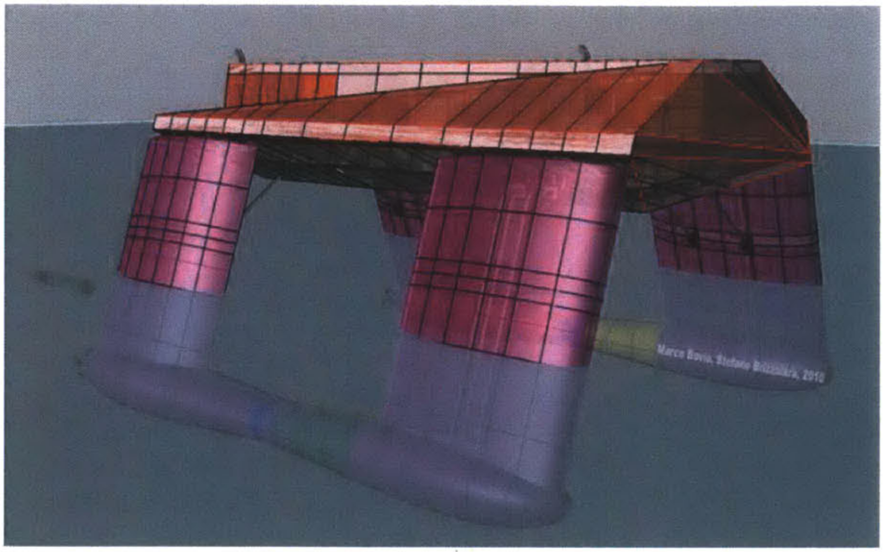

Figure 2: A rendering of the 6 meter SWATH USV about to recover a UUV

Some of the noticeably innovative features of the design shown in Figure 2 include the curved submerged bodies, the use of two struts per side as opposed to a single long one, and the outward swept angle of the struts. Each of these elements is intended to improve the stability of the vessel or reduce its wave-induced drag.

The unique shape of the submerged bodies has been optimized to achieve the lowest drag at its intended cruise speed of 12 knots, according to the research conducted in (Brizzolara et al., 2004). The bulb-like shape at the forward and aft ends of the vessel will create wave patterns that positively interfere with each other, minimizing its overall wake and significantly reducing wave resistance.

The twin struts connecting the submerged bodies to the bridgedeck ensure sufficient hydrostatic longitudinal stability. Using two struts located at the extreme ends of the ship, as opposed to one long thin one going down the length of the body, pushes the concentration of waterplane area further from the axis of pitch rotation located near the middle of the ship. This increases the moment of inertia of the waterplane area in the direction of pitch and raises the longitudinal metacentric height, minimizing static attitude due to variation in loading conditions.

The canting on the struts is intended to increase the damping in heave, pitch, and roll motions, with respect to a conventional vertical arrangement, by generating eddies. This adds a significant viscous term to the radiation forces.

These features set this design apart as a new and innovative concept. In order to fully understand its behavioral characteristics, a scale model must be built to perform seakeeping tests.

2. Design of the Ship Model

Before a full-sized prototype can be constructed, hydrodynamic experimentation must be conducted on a scale model of the intended design. Plans were made for a scale model of the second, smaller SWATH USV to be fabricated and tested in the MIT Towing Tank. The results of the towing tank model testing would then be compared to the Computational Fluid Dynamics predictions being conducted in the Innovative Ship Design Lab at MIT Sea Grant, by the group of Dr. Brizzolara.

2.1 Froude Scaling

Froude scaling is a numerical method of comparing the relative speed of a full-sized ship to the hydrodynamically equivalent speed of a scale model. For these tests, the maximum speed of the carriage mounted above the MIT tow tank was a limiting factor, and thus the scale of the ship needed to be designed based off of this maximum tow speed as well as its designed cruising speed. The full-sized vessel is intended to be 6 meters long and have a cruising speed of 12 knots (6.2 m/s). Since the carriage can safely move at only a maximum speed of roughly 2.5 meters per second, the necessary length of a model can be calculated using

$$Fn = \frac{U_M}{\sqrt{g\,L_M}} = \frac{U_F}{\sqrt{g\,L_F}} \tag{1}$$

where Fn is the Froude number, U_M and U_F are the model and full-sized ship speeds respectively, and L_M and L_F are the model and full-sized lengths respectively.

Solving for equation (1) with the appropriate parameters gives a Froude number for the full sized ship of 0.81. Using this number for the model gives a necessary length of 0.97 meters. This was rounded up to a full meter for the sake of simplicity.

2.2 Computer Aided Design

Once the scale of the model was established, the next step was to develop a 3D CAD model of the entire vessel and all of its parts. The original design for the smaller SWATH was created as an IGES file as several conjoined bodies. In order to divide the ship into machinable parts, the model was imported into SolidWorks 2013 and edited. The decision was made to manufacture the struts and submerged bodies separately. To facilitate mating the two sections, the junction between submerged body and strut was included in the submerged body segments. The upper part of the struts can then easily attach to the lower parts of the struts which are manufactured with the submerged bodies. For reasons described in the next section, the maximum dimension of one submerged section could not exceed 8 inches (20 cm).

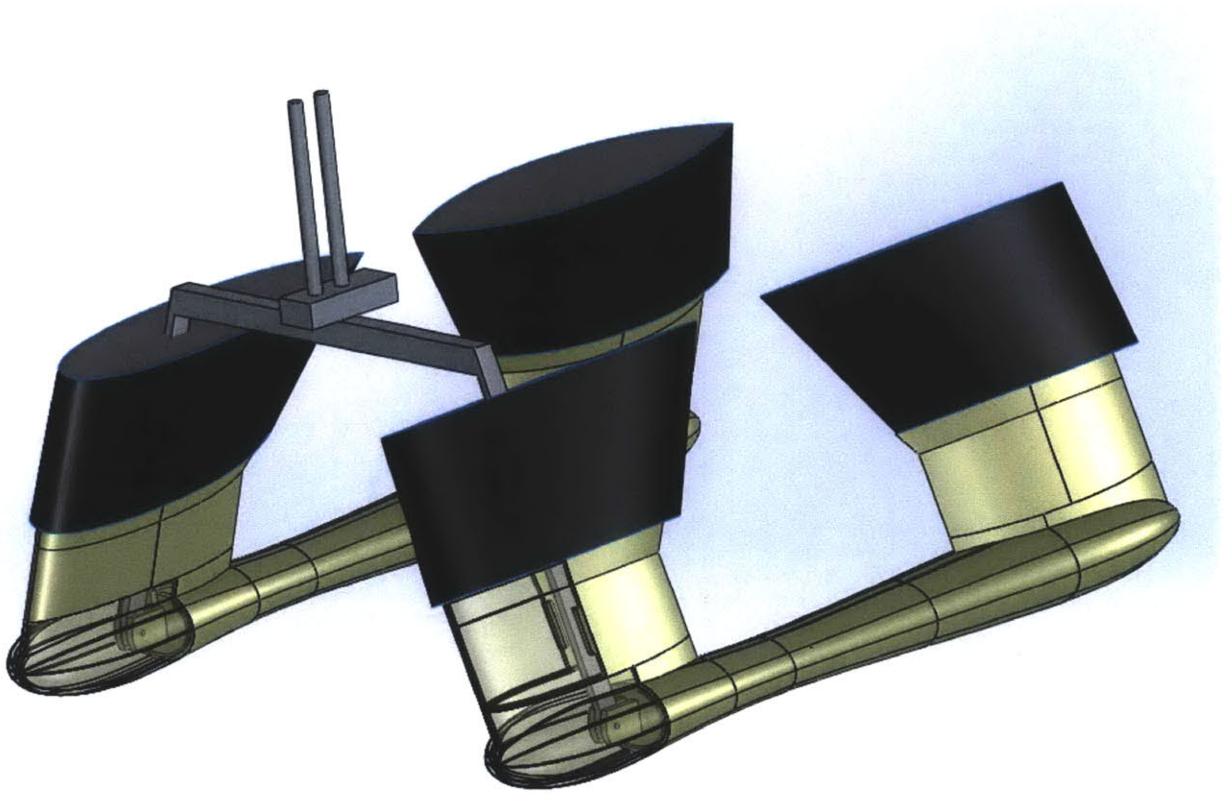

Figure 3: An isometric view of the SWATH model CAD assembly, including the towing wishbone spanning between the two demihulls

2.3 Internal Structure and Towing Hitches

Great care was taken to ensure that the hull would not flex or break during testing and transportation. A thickness of 5 mm was used for the entire outer shell. To further increase rigidity, as well as prevent flooding of multiple compartments, a bulkhead was added to one side of each submerged body segment. They also support a small ridge that runs around the edge of each part and is used to join the segments together. The bulkheads are 6 mm thick.

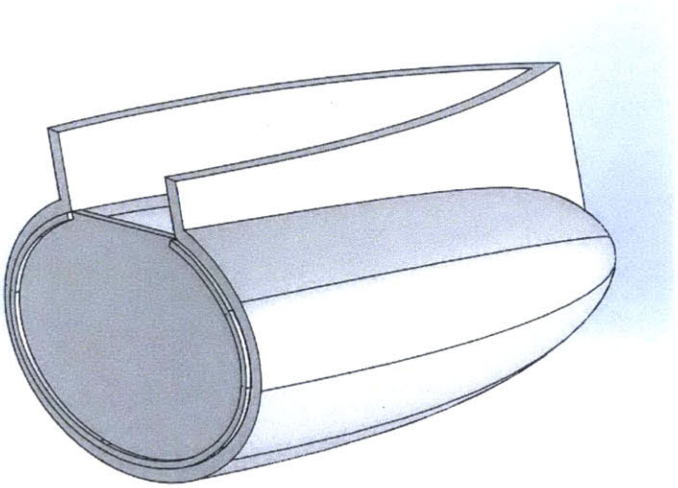

Figure 4: CAD model of the port stern segment, showing the bulkhead and connecting tabs.

The towing points are located in line with the main longitudinal axis of each submerged body in the first segment of each demihull. If the model was towed from any higher, it would cause a forward pitching moment, driving the bow into the water. The towing points consist of two thick tabs extending perpendicular to the second segment's bulkhead. A quarter inch hole allows a bolt to be passed through the tabs and towing apparatus to secure them in place while allowing for rotation between the components. The towing apparatus is shaped like a wishbone whose ends attach to the tabs in the submerged body and extend through the strut. It holds the two demihulls together at the correct angle and links the hull to the gantry above the tow tank.

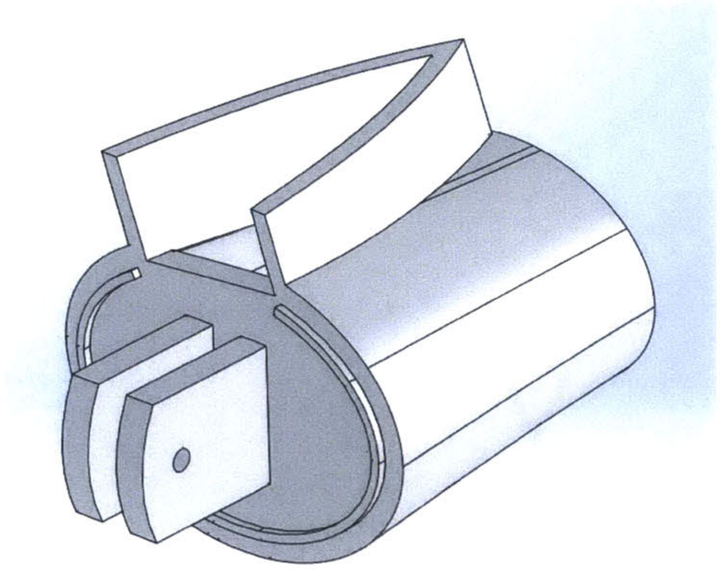

Figure 5: CAD model of the submerged body segment containing the towing points.

2.4 Mid Struts

A layer, referred to as the mid struts, was created to simplify the mating process between the upper struts and submerged body. These connected to the top of the strut stubs built onto the submerged bodies, and to the bottom of the upper struts. They also serve to create the canted angle between the submerged body and upper struts. Each mid strut was divided into two parts, for a total of eight. The parts included wider tabs on every side to make the connection to the submerged bodies, upper strut, and its corresponding half. In order to make room for the towing wishbone, the tabs to connect the two halves of each forward mid strut do not extend far into the internal space. This allows the mid strut to move back and forth as the model pitches. The aft mid struts have a connecting tab that is continuous across their length, since there is no towing wishbone to take up space.

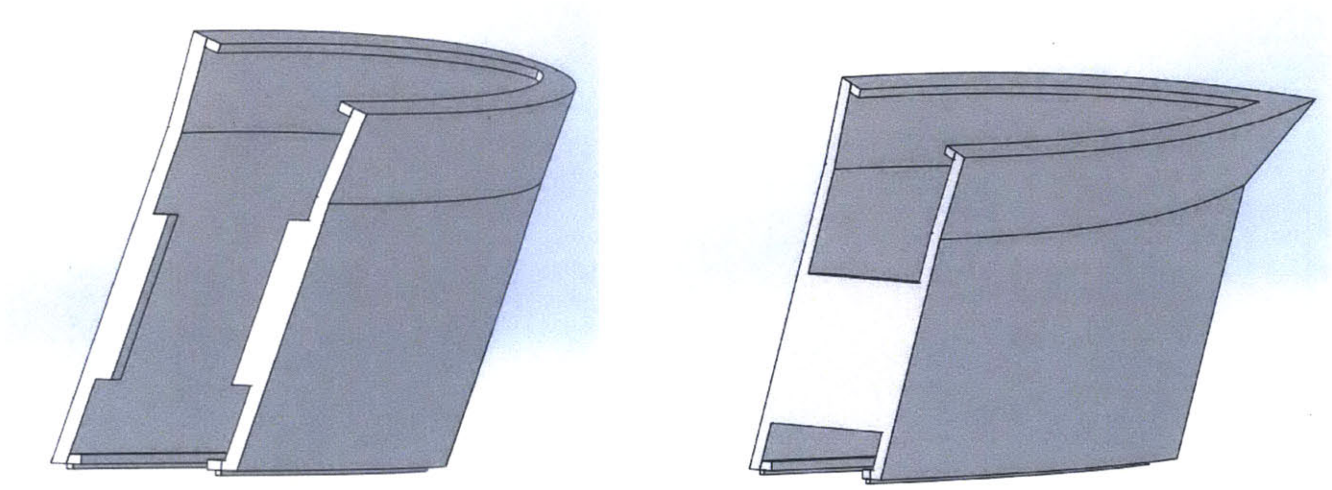

Figure 6: The leading edge of the forward mid strut (left) and the leading edge of the aft mid strut (right). Note the short connecting tabs, rounded front, and vertical edge of the forward piece, and the full length connecting tab, the pointed front, and angled edge of the aft piece.

2.5 Upper Struts

The four upper parts of the struts also posed a challenge to build. They each have the appearance of short, low aspect ratio airfoils. The forward struts have rounded leading edges and pointed trailing edges, while the leading and trailing edges for the aft struts are both pointed. Each strut's cross section also increases in size as the height increases. The edges at the bow and stern of the ship are vertical, but the edges of the struts at the interior are angled. These components are large and bulky, measuring roughly 19 x 8 x 4 inches. An important feature of the hulls is that the upper struts are not flush with the lower part of the hulls. The upper struts extend an extra 8 millimeters from the mid struts, giving it a stepped feature. This is intended to divert spray from reaching the upper parts of the ship, as well as to prevent the vessel from pitching excessively, introducing an additional source of damping.

2.6 Gantry Connection

The model needs to be attached to the gantry above the tow tank in such a way that restricts all yaw, roll, sway, and surge motion while allowing displacement of the vessel in pitch and heave. The towing wishbone mentioned above can be constructed in such a way as to prevent yaw and roll rotation, while confining the surge to only the motion of the gantry and eliminating all sway. A precise linkage must be made to ensure that no other forces interfere with the pitch and heave caused by wave motion. The rotation will be measured about the joint connecting the hitches inside the submerged bodies to the towing wishbone. For heave, the wishbone will be connected to the bottom of a vertical piston that can easily slide up and down. This setup allows the relevant displacements to be recorded without any influence from factors such as the weight of the model affecting the results.

3. Rapid Prototyping for Hull Fabrication

Real world SWATH vessels are notoriously hard to build, due to their uncommon geometry and the lack of experience with this type of design in most shipyards. It turns out that this problem also scales, and creates a number of issues when trying to build even a small model of a SWATH. The submerged bodies are each a meter long and have an elliptical cross section that varies drastically down its length. Furthermore, two large, foil-shaped struts protrude from the top of each body and complicate the design.

The most common way to fabricate a typical monohull ship model is to use a CNC mill to carve out the upside-down shape of the hull. Most often the materials used are wood or plastic foam, which are then covered in a layer of fiberglass. For this particular SWATH, the complex continuous geometry of the submerged bodies means that even a 5 axis mill would most likely be unable to provide a satisfactory model. The submerged bodies could not be turned on a lathe either. The cross section is elliptical rather than circular, ruling out this method.

Instead of relying on traditional methods of manufacturing ship model hull, a new set of techniques were needed to build this intricate ship design.

3.1 3D Printing the Submerged Bodies

Since typical shop machines were proven to be ineffective for making these parts, the decision was made to 3D print the submerged bodies. The lab at Sea Grant is home to a uPrint Dimension 3D printer which builds models out of ABS plastic. However, the maximum part size that the printer can build is 8 x 6 x 6 inches. In order to build the 1 meter long parts, the bodies were divided into five 20 centimeter (just under 8 inches) segments in SolidWorks. The second of these segments was further divided in half, to allow room for the towing hitches to be printed attached to a bulkhead. As mentioned above, bulkheads and connecting tabs were added to facilitate assembly. The segments were exported as STL files and uploaded to the printer to be produced. After being printed, the model was soaked in an acid bath for several hours to melt off the supporting material from the printer.

Figure 7: The stern section of the submerged bodies being removed from the acid bath

Once all of the parts had finally been made, they were laid in order and joined using West System Marine Grade Epoxy. This resin is often used to repair and seal full-sized boats, and is extremely strong once dried. Small cracks between the joints of two parts were filled in using Tamiya modeling putty. This material is usually used on scale models, and served this purpose well. The gaps were liberally filled with the putty, allowed to dry, and then sanded smooth.

The mid strut pieces were also epoxied on top of the submerged body. The forward mid strut section was attached to the bow section of the submerged body; however these two sets of parts have not yet been fixed to the rest of the submerged body assemblies. The reason for this is that the towing hitches have not yet been connected to the towing wishbone or any sensors. If the bow section were put on, it would be virtually impossible to later access the towing points.

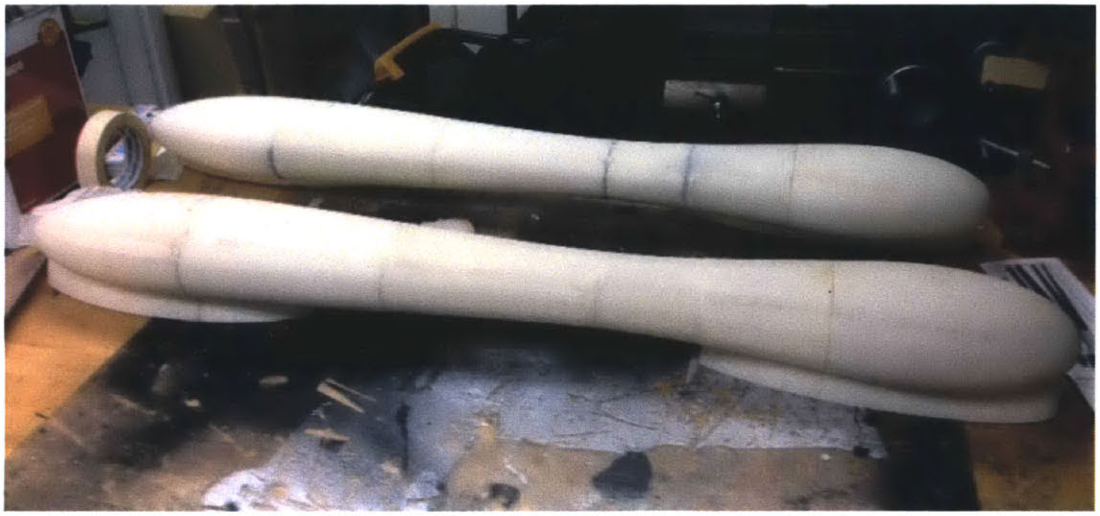

Figure 8: The assembled submerged bodies. Note the gray lines where modeling putty was used to fill in gaps.

Although 3D printing was seen as the only viable method for producing these parts, there were still a number of issues that were encountered. First of all, the segments were relatively large to be made by 3D printing, and thus the build times for each part were extremely long. An average piece from the submerged body assembly would take as long as 30 hours. This placed a huge time burden on the project, as most of the month of January, 2013 was spent waiting for parts to be built. Additional problems arose from the fact that on most segments one end was open and one was sealed off by a bulkhead. While a part is being made in a 3D printer, the inside of the machine heats up to about 50 degrees Celsius in order to help keep the plastic pliable. When the part is removed and exposed to the room's cooler temperature, it contracts considerably. The ends of the parts with bulkheads were unaffected, but the open ends would shrink, making the process of fitting the pieces together rather difficult. On the next iteration of this project, it would be prudent to include reinforcements on both ends of the part to keep their intended shape.

In order to obtain accurate results, scale ship models must have a very smooth exterior finish. The 3D printer posed another issue, because the parts displayed very small ridges between each layer of ABS. Both submerged bodies were rubbed down with acetone to soften the plastic and then sanded to minimize the stepping effect and make the surface smooth.

3.2 Spray Coating the Submerged Bodies

A model that is made from a 3D printer is assembled by stacking a series of two dimensional patterns on top of one another. Consequently, the model turns out to be extremely porous. If it were to be submerged without some kind of sealant, the part would leak and become saturated with water. In order to prevent this from happening, the assembled submerged bodies were given a coat of polyurethane paint.

Models built at the University of Genoa, where Dr. Brizzolara began his research, are painted with a type of polyurethane-based paint commonly used on automobiles. This paint leaves a smooth, shiny finish and is completely watertight. Unfortunately, MIT's campus possesses none of the necessary facilities and tools to apply automobile paint.

Figure 9: the submerged body pieces after being given a coat of primer in the automobile spraypaint booth

The author was able to utilize the facilities present in his relative's auto body business to spraypaint the parts. This permitted the submerged bodies to be given several coats of primer and polyurethane paint. First the parts were all machine sanded until they were sufficiently smooth. Next a coat of grey primer was applied and allowed to dry overnight. The primed parts were then given a light wet-sanding before they were sprayed with yellow polyurethane paint. This gave the bodies a very smooth finish. The color yellow is often used on experimental ship models because it is highly visible underwater. A few small cracks between some of the parts were later filled in with touch-up paint.

Figure 10: A close up view of the finish on the submerged bodies after several coats of polyurethane paint

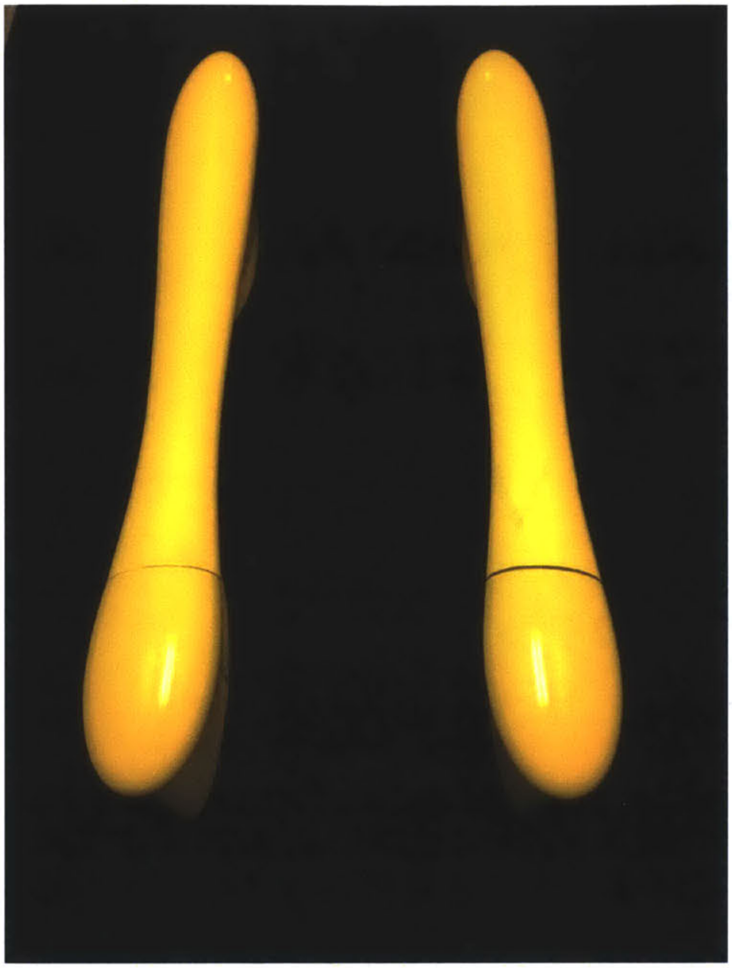

Figure 11: The completed submerged bodies. Note that the bow sections are not yet permanently attached.

3.3 Lasercutting the Strut Frames

The four struts of the SWATH design posed a challenge to construct because of their size and shape. These pieces were roughly 40 x 20 x 10 cm at their widest end. An attempt was made to fabricate them using a large piece of PVC foam on a 3 axis mill. However, the finish was unacceptably rough and there were difficulties in aligning the two faces of each part on the machine.

The next plan was to build a sort of skeleton consisting of consecutive cross sections of the strut and wrap the assembly in some kind of coating. A similar technique is used to construct lightweight model airplane wings. Cross sectional shapes of the struts were taken at two inch intervals from the CAD model. This meant that each strut skeleton would consist of five cross sectional plates held together by one bracket. Each shape was given slots to fit into place on the holding brackets. They were also all given a large rectangular hole in the middle as access points to the submerged bodies. In order to achieve the step effect with the lower part of the hull mentioned earlier, the bottom plate was made to be 8 millimeters wider all around than the top of the mid strut. A DXF file for each section and bracket was uploaded onto a lasercutter and cut out on 1/8th inch (3cm) acrylic. Next, the cross sectional plates were fit into place on the brackets and epoxied together using the same epoxy as on the submerged bodies.

Figure 12: The assembled frames for the forward struts

3.4 Wrapping the Struts

Once the frame was built, it needed to be given a skin to complete the geometry of the struts. One type of material considered was a sheet of thermoplastic, which could be wrapped around the skeleton and heated to shrink fit it into place. However, this method often produces a scalloping effect between each rib, and also does not provide enough strength and stiffness. Eventually a sheet of light canvas was chosen to wrap the struts with.

The next attempt was to wrap the frame in fabric. Four pieces of canvas was cut out for each of the four struts, which would fold over the straight edge of every strut while the cut ends would meet at the angled edge. Using a hot glue gun, the canvas sheets were first attached at the middle to the straight edge of the struts and then glued to the edges of the cross sectional plates a few inches at a time. It was very important to ensure that the canvas was held taught over the frame. Any slack causes indentations in the final shape of the struts. For the most part, this was avoided. There were a few buckles in the canvas, but these were all located at the top of the struts, and thus will not affect the seakeeping dynamics of the model.

Figure 13: One of the forward struts hanging up to dry after its epoxy coat

Once the canvas had been secured around the frame, they were given a generous coat of marine epoxy. This adds a great deal more rigidity to the assembly, minimizing any flexing that could occur during testing, and also helps to smooth out the finish of the parts. After being allowed to dry overnight, the struts were given two coats of white acrylic spray paint.

This method did show decent results, but it is possible to achieve even more accurate geometry. Another attempt is currently being planned. This time, the frame will again be lasercut, but this time there will be transverse brackets included that will prevent any scalloping between the plates. Although the extra brackets will add more weight, the superior rigidity and geometry provided by this layout will be worth the extra displacement.

Additionally, new materials will need to be chosen to replace the canvas, which had a very rough finish even after being coated in epoxy and paint. The current plan is to use a very thin sheet of balsa wood. In the next iteration, the frame itself will also likely be lasercut from a sheet of balsa wood. This allows certain kinds of fast-drying wood superglue to be used to quickly secure the parts together. Similar methods to this are used to build wooden remote-controlled airplanes, meaning it should be relatively easy to find guidance on this sort of procedure. The extra rigidity of the balsa wood compared to canvas should give a far superior finish. Once completed, the struts will be epoxied to the top of the mid struts.

3.5 Towing Apparatus

Although there was insufficient time to fabricate the towing wishbone, making this part should be a relatively straightforward procedure. A thin strip of aluminum can be bent to form the correct angles and dimensions to hold the demihulls in the correct orientation with respect to each other and link them to the tow tank gantry. A set of ball bearings should be mounted on an axle going through the towing connectors in order to minimize the friction between the towing wishbone and axle. The necessary dimensions for the towing wishbone are given in the drawing below.

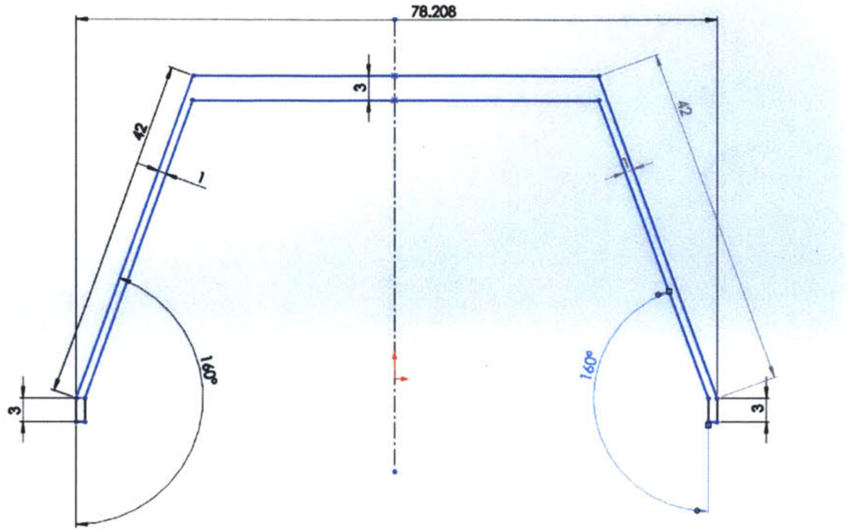

Figure 14: Drawing of the dimensions for the towing wishbone. Lengths are in centimeters and angles are in degrees.

A similar strip of metal should be used to join the demihulls together from the aft struts. This will prevent torsion felt by wave action from twisting the hulls with respect to each other.

4. Model Verification

Once the majority of the model had been constructed, the final steps were to trim it with ballast to sit evenly in the water when at rest and predict its dynamic behavior.

4.1 Hydrostatics

Based on the known weight and volumetric values of the model, its hydrostatics can accurately be predicted. First, based on the CAD model used in this project, the total submerged volume can be obtained. This can then be used to calculate the buoyancy force with

$$\vec{B} = \rho \, g \, \nabla \tag{2}$$

where ρ is the density of water (fresh water in this case), g is the acceleration due to gravity, and ∇ is the underwater volume. Solving for equation (2) gives a buoyancy force of 96.31 Newtons (equivalent to 9.81 kg).

A precise weight of the model can be achieved by measuring the components. Although the model is not completely assembled, the largest components are already built and the weight of the whole model should only be slightly heavier than what is currently measured. Adding all of the weights of each part gives a total mass of 4.43 kg (43.44 N).

The weight of the model had already been estimated using the volume of the CAD parts and the density of the ABS plastic used, so the low weight was expected. Since the buoyancy force at the correct waterline is so much greater than the weight of the components, the model will easily float. In fact, it will need to be weighed down with ballast such as lead fishing weights equivalent to the difference between the two forces. Each strut has an opening in the middle that extends all the way down into the submerged bodies just for this purpose. Weights can be placed in any segment of the submerged body except for the middle one, which is sealed off on both ends. This allows a high degree of precision to be used in trimming the model to be perfectly level at the correct draft. The longitudinal center of gravity must be equal to the longitudinal center of buoyancy in order for the vessel to sit level in the water. The LCB is given at different drafts in the hydrostatics tables below.

Draft Amidsh. M	0.008	0.017	0.025	0.033	0.042	0.050	0.058	0.067	0.075	0.083	0.092	0.100	0.108	0.117	0.125	0.133	0.142	0.150
Displacement (dm^3)	6.10	7.72	9.26	10.63	11.68	12.33	12.81	13.30	13.78	14.26	14.74	15.23	15.71	16.19	16.68	17.16	17.64	18.12
Heel to Starboard degrees	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Draft at FP m	0	0.008	0.017	0.025	0.033	0.042	0.050	0.058	0.067	0.075	0.083	0.092	0.100	0.108	0.117	0.125	0.133	0.142
Draft at AP m	0	0.008	0.017	0.025	0.033	0.042	0.050	0.058	0.067	0.075	0.083	0.092	0.100	0.108	0.117	0.125	0.133	0.142
Draft at LCF m	0	0.008	0.017	0.025	0.033	0.042	0.050	0.058	0.067	0.075	0.083	0.092	0.100	0.108	0.117	0.125	0.133	0.142
Trim (+ve by stern) m	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WL Length m	1.000	0.995	0.983	0.983	0.983	0.983	0.983	0.983	0.983	0.983	0.983	0.983	0.983	0.983	0.983	0.983	0.983	0.983
WL Beam m	0.891	0.889	0.884	0.874	0.857	0.825	0.817	0.811	0.805	0.799	0.793	0.787	0.781	0.775	0.769	0.763	0.757	0.751
Wetted Area m^2	0.276	0.310	0.345	0.388	0.376	0.307	0.330	0.352	0.373	0.394	0.415	0.436	0.458	0.479	0.500	0.521	0.543	0.564
Waterpl. Area m^2	0.196	0.191	0.177	0.149	0.099	0.060	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058
Prismatic Coeff.	0.73	0.755	0.777	0.78	0.774	0.755	0.736	0.718	0.703	0.689	0.677	0.665	0.655	0.646	0.637	0.629	0.622	0.615
Block Coeff.	0.583	0.636	0.702	0.783	0.93	1.064	1.017	0.971	0.931	0.897	0.867	0.841	0.818	0.798	0.779	0.762	0.747	0.734
Midship Area Coeff.	0.799	0.842	0.904	1.004	1.202	1.413	1.4	1.359	1.332	1.309	1.289	1.271	1.256	1.242	1.229	1.214	1.204	1.195
Waterpl. Area Coeff.	0.85	0.846	0.83	0.775	0.621	0.451	0.438	0.438	0.438	0.438	0.438	0.438	0.438	0.438	0.438	0.438	0.438	0.438
LCB from Amidsh. (+ve fwd) m	0	-0.001	0	0.001	0.004	0.008	0.011	0.014	0.016	0.019	0.021	0.003833	0.004167	0.0045	0.004667	0.005	0.005333	0.0055
LCF from Amidsh. (+ve fwd) m	-0.002	-0.001	0.001	0.018	0.064	0.101	0.086	0.086	0.086	0.086	0.086	0.014333	0.014333	0.014333	0.014333	0.014333	0.014333	0.014333
KB m	-0.103	-0.076	-0.051	-0.028	-0.01	0.002	0.012	0.024	0.036	0.049	0.063	0.013	0.0155	0.018167	0.020833	0.023667	0.0265	0.0295
BMt m	29.161	22.486	17.279	12.726	7.643	4.208	3.822	3.624	3.441	3.27	3.111	0.493667	0.4705	0.448833	0.428333	0.409167	0.391	0.374
BML m	15.135	11.639	8.855	6.588	4.801	3.599	3.396	3.273	3.158	3.051	2.951	0.476333	0.461667	0.447833	0.435	0.422667	0.411167	0.400167
KMt m	29.058	22.41	17.228	12.698	7.633	4.21	3.835	3.648	3.477	3.319	3.174	0.506667	0.486	0.466833	0.449167	0.432833	0.417667	0.4035
KML m	15.033	11.563	8.804	6.559	4.791	3.601	3.408	3.296	3.194	3.1	3.014	0.489167	0.477167	0.466	0.455833	0.446333	0.437667	0.429667
Immersion (TPc) tonne/cm	0.072	0.071	0.065	0.055	0.037	0.022	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021
MTc tonne.m	0.03	0.028	0.024	0.019	0.013	0.008	0.007	0.007	0.007	0.006	0.006	0.006	0.006	0.005	0.005	0.005	0.005	0.005

Draft Amidsh. M	0.158	0.167	0.175	0.183	0.192	0.200	0.208	0.217	0.225	0.233	0.242	0.250	0.258	0.267	0.275	0.283	0.292	0.300	0.308	0.317
Displacement (dm^3)	18.60	19.09	19.57	20.05	20.54	21.02	21.50	21.98	22.47	22.95	23.43	23.92	24.39	24.89	25.64	26.78	28.33	30.28	32.65	35.45
Heel to Starboard degrees	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Draft at FP m	0.150	0.158	0.167	0.175	0.183	0.192	0.200	0.208	0.217	0.225	0.233	0.242	0.250	0.258	0.267	0.275	0.283	0.292	0.300	0.308
Draft at AP m	0.150	0.158	0.167	0.175	0.183	0.192	0.200	0.208	0.217	0.225	0.233	0.242	0.250	0.258	0.267	0.275	0.283	0.292	0.300	0.308
Draft at LCF m	0.150	0.158	0.167	0.175	0.183	0.192	0.200	0.208	0.217	0.225	0.233	0.242	0.250	0.258	0.267	0.275	0.283	0.292	0.300	0.308
Trim (+ve by stern) m	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WL Length m	0.983	0.983	0.983	0.983	0.983	0.983	0.983	0.983	0.983	0.983	0.983	0.983	0.983	1.113	1.108	1.104	1.099	1.095	1.096	1.117
WL Beam m	0.745	0.739	0.733	0.726	0.720	0.714	0.708	0.702	0.696	0.690	0.684	0.678	0.672	0.666	0.660	0.654	0.648	0.641	0.635	0.629
Wetted Area m^2	0.585	0.606	0.628	0.649	0.670	0.692	0.713	0.734	0.755	0.777	0.798	0.819	0.840	1.072	1.143	1.215	1.288	1.364	1.440	1.517
Waterpl. Area m^2	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.067	0.114	0.161	0.210	0.259	0.310	0.361
Prismatic Coeff.	0.609	0.603	0.597	0.592	0.587	0.583	0.579	0.575	0.571	0.567	0.564	0.561	0.558	0.49	0.492	0.497	0.505	0.517	0.528	0.531
Block Coeff.	0.721	0.709	0.699	0.689	0.68	0.671	0.663	0.656	0.649	0.642	0.637	0.631	0.625	0.513	0.39	0.32	0.277	0.249	0.229	0.212
Midship Area Coeff.	1.186	1.179	1.172	1.165	1.159	1.154	1.148	1.144	1.139	1.135	1.131	1.127	1.123	1.047	0.793	0.643	0.547	0.481	0.434	0.4
Waterpl. Area Coeff.	0.438	0.438	0.438	0.438	0.438	0.438	0.438	0.438	0.438	0.438	0.438	0.438	0.438	0.42	0.539	0.616	0.673	0.717	0.751	0.764
LCB from Amidsh. (+ve fwd) m	0.005667	0.006	0.006167	0.006333	0.0065	0.006667	0.006833	0.007	0.007167	0.007333	0.0075	0.007667	0.007833	0.007833	0.006667	0.004	0.0005	-0.00317	-0.00667	-0.00933
LCF from Amidsh. (+ve fwd) m	0.014333	0.014333	0.014333	0.014333	0.014333	0.014333	0.014333	0.014333	0.014333	0.014333	0.014333	0.014333	0.014333	-0.00533	-0.04867	-0.05933	-0.05917	-0.05433	-0.0465	-0.03733
KB m	0.0325	0.035667	0.038667	0.041833	0.045167	0.048333	0.051667	0.055	0.0585	0.061833	0.065333	0.068833	0.072333	0.075833	0.081333	0.0895	0.099833	0.112	0.125333	0.139333
BMt m	0.357833	0.342667	0.328167	0.3145	0.3015	0.289167	0.277333	0.266167	0.2555	0.245333	0.235667	0.226333	0.2175	0.209	0.199333	0.189667	0.182333	0.178833	0.180333	0.187
BML m	0.389833	0.38	0.3705	0.361667	0.353167	0.345	0.337333	0.329833	0.322833	0.316	0.3095	0.303333	0.297333	0.328	0.480833	0.614833	0.734	0.8385	0.926667	0.999667
KMt m	0.390333	0.378167	0.366833	0.356333	0.346667	0.3375	0.329	0.321167	0.314	0.307167	0.301	0.295167	0.289833	0.284833	0.280667	0.279167	0.282167	0.290833	0.3055	0.3265
KML m	0.422333	0.4155	0.409333	0.4035	0.398333	0.3935	0.389	0.385	0.381167	0.377833	0.374833	0.372	0.3695	0.403833	0.562167	0.704333	0.833833	0.950333	1.052	1.139
Immersion (TPc) tonne/cm	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.025	0.042	0.059	0.077	0.096	0.114	0.133
MTc tonne.m	0.004	0.004	0.004	0.004	0.004	0.004	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.005	0.014	0.023	0.033	0.043	0.054	0.065

Figure 15: The hydrostatic tables for the scale model SWATH

4.2 Predictions of Behavior in Waves

Before real-world ship model tests are conducted, the behavior of the vessel is usually predicted using computer simulations. For this project, WAMIT was used to estimate some of the quantitative characteristics. The calculations compare the added mass, damping coefficient, response amplitude operator, and more with respect to changing wave period.

The CAD model of the scaled down ship design was converted into a GDF file, which consists of a mesh of the ship's geometry. Next the vertical center of gravity was recorded, and the radii of gyration were calculated. The results were input into the program files, and WAMIT was run to find the added mass and damping coefficients in every direction at wave periods from 1 to 3 seconds. Since the scope of this project only focuses on pitch and heave, the 3-3 and 5-5 directions were the values of interest. The results for these valued are graphed below against the wave period.

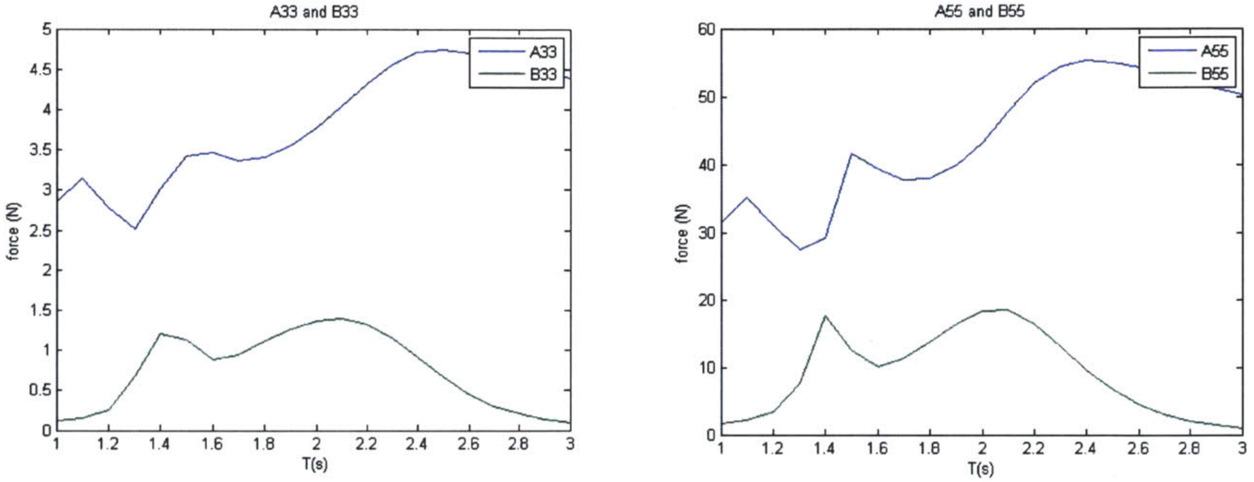

Figure 16: Graphs for the added mass and damping coefficients of heave (left) and pitch (right) with varying wave periods

The response amplitude operators were also analyzed. These values describe how the vessel responds to wave action. The RAOs for pitch and heave are graphed below against wave period.

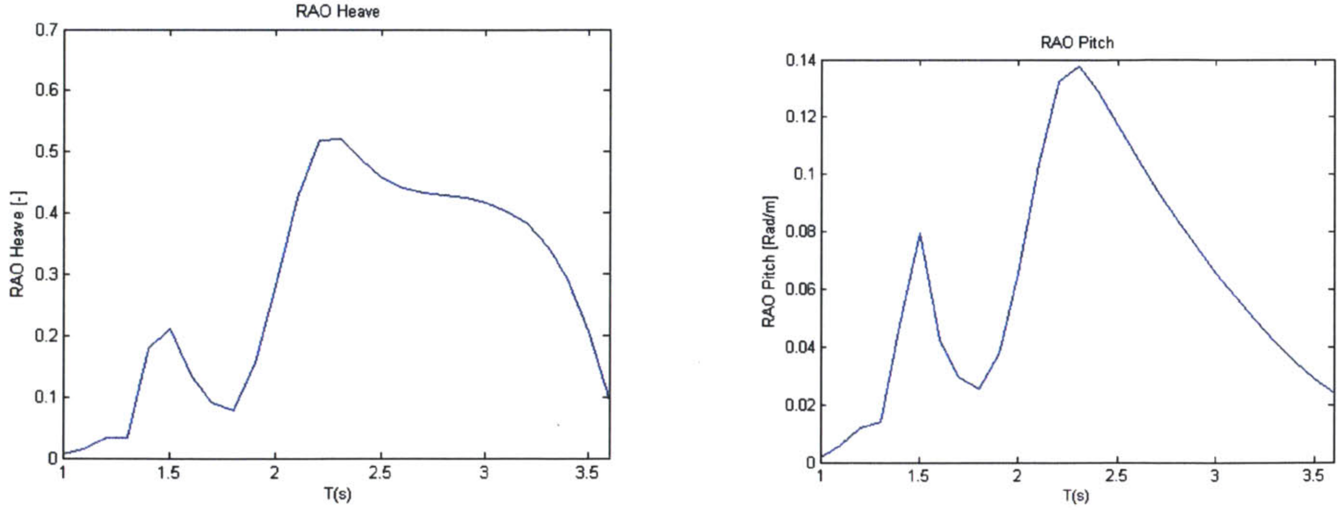

Figure 17: The response amplitude operators for pitch and heave

5. Movement Measurement Techniques

This last section will outline a number of techniques for measuring the pitch and heave of the SWATH model as it is tested in the MIT tow tank. Unfortunately, time did not permit any tests to be conducted this year. Future members of the Brizzolara research team should consider all of these options when the tests are eventually run.

5.1 Potentiometers

Perhaps the cheapest and simplest way of measuring the movement of the model would be to fix rotational or string potentiometers to strategic locations on the model and towing gantry. For example, a standard rotational potentiometer could be installed on the joint between the towing wishbone and the model's tow hitches, while a string potentiometer could be run from the top of the model to the bottom of the gantry, in order to measure pitch and heave respectively. Potentiometers are inexpensive and easy to connect to a small processer to record data; however, they experience a great deal of electronic noise and would most likely not provide the accuracy that is necessary for this kind of experiment.

5.2 Inertial Measurement Unit

An inertial measurement unit, or IMU, is another sensor that would be useful for this set of experiments. This device includes gyroscopes and accelerometers which can accurately calculate the precise movements and orientation of a body. Fixing an IMU on the top of the model would allow motion in all directions, including pitch and heave, to be measured and recorded onto a computer. It is a relatively simple technique that is very accurate, but a detailed circuit board would need to be created in order to read the data.

5.3 Hall Effect Sensors

The Hall Effect is a measurable response that occurs when two objects with magnetic fields change orientation with respect to each other. Sensors that measure this effect are commonly used in brushless motors, and are relatively inexpensive. The system consists of a sensor with a built in electro-magnet and feedback loop, and a permanent magnet. A number of these sensors can be placed in a similar manner to the potentiometers described above. Ideally, the sensor for pitch would be mounted on the towing wishbone inside the submerged body in line with the axis of rotation of the joint. The corresponding magnet would mount onto the model itself to record the rotation between the model and towing wishbone. As the vessel rotates around the towing wishbone, the change in magnetic fields is measured by the sensor and recorded.

5.4 Video Recording

The last method considered was to use a standard video camera to graphically analyze the motions of the model. First a pair of high-visibility markers would need to be placed on the fore and aft end of the model. Then the test would be conducted on the model while the camera records the model's behavior. The recording can then be analyzed on a computer using a number of different programs to measure the displacement of the markers, and relate this motion to the whole model. This technique is best suited to tests where the model is held stationary in a wave field, so the camera can be mounted in a fixed position. However, provisions can be made for it to work with a moving model if the camera itself is fixed to the gantry via a boom or other structure.

6. Conclusions

6.1 On Construction Methods

The methods described above are all relatively novel ways of constructing an experimental scale ship model. Some techniques were quite effective, while others did not turn out as initially planned. Some of the above methods are recommended for future researchers attempting to fabricate similar models, while some should be avoided.

Although the concept of 3D printing segments of the hulls caused some problems as described earlier, it still proved to be a useful technique that gave adequate results. Future researchers building peculiar ship models should consider this option, but alter it slightly. In order to avoid the issue of the open end of the part contracting during cooling, both ends of the hull should be sealed off with bulkheads to hold the desired shape. Of course, at least a small opening must be left to allow the support material from the 3D printer to be melted out in the acid bath.

The automobile paint also worked very well for giving a smooth finish to the submerged parts of the model. The coating is completely waterproof and quite smooth. A higher level of smoothness could be obtained by giving the parts an extra coating of glossy clear-coat.

The technique of making large parts, such as the struts of the SWATH with a frame of two-dimensional parts also had some merit to it. A skeleton of the intended shape can easily be constructed and filled with foam or wrapped in a thin layer of material to complete the part. However, the choice of using canvas was not ideal. The canvas had a relatively rough finish, and coating it with epoxy and paint did little to alter this. After the upper struts were completed, they appeared rough and would introduce a considerable added friction drag while running experiments on the model. In the future, a smoother material, such as thin plastic or wooden sheets, would likely provide a more ideal finish.

6.2 On Ship Performance

The predictions show that the innovative SWATH design should be very stable compared to similarly sized vessels of other hullforms. Once the physical tow tank tests have been run, the results can be compared to the predictions to judge their accuracy.

7. Future Work

There are many steps in the experimentation of the SWATH vessel that unfortunately were not reached this year. Time did not permit for any tests to be conducted before the submission of this paper. Therefore, it is important that future members of Dr. Brizzolara's research team continue to progress beyond the point where this report leaves off.

During the first few weeks of summer, another attempt will be made to build the upper struts more precisely. As described earlier, the next method will involve using balsa wood as both the structural frame and the wrapping. This assembly will then be epoxied and painted before being permanently fixed to the submerged bodies.

Another important step is to build the towing wishbone and link it to the model. Making the wishbone itself should be straightforward, as it only requires bending a thin strip of metal to the correct dimensions. The ends of the wishbone will be attached to a pair of ball bearings, which in turn will be aligned with the submerged body towing hitches with a ¼ inch bolt.

After the struts and towing wishbone are in place, the bow sections of each submerged body will be epoxied into place to complete the model.

Testing the model in a wave-generating tow tank is the main goal of this project. The model will need to be attached to the gantry above the tow tank so it can be pulled along at the desired speed. Alternatively, the model can be fixed to the gantry and held in place while the waves are sent down the length of the tank. Either way, a secure connection that only allows the model to move in the pitch and heave directions is necessary for these seakeeping tests.

Next, researchers will need to choose one of the aforementioned measurement methods, or come up with a new and more effective one. Data will likely be sent to the computer controlling the tow tank systems, but can also be logged on an SD card or similar device mounted on the model. The sensors will need to be ideally located to measure the relevant ship motions without interference.

If the results of the seakeeping tests prove to be favorable, then the next step would likely be to build an even larger model to test in a larger tank. Ideally at some point in the future, a working prototype of this SWATH vessel will be built to demonstrate its innovative concept.

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