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Manufacturing and Preliminary Testing of a Subscale Suspension Boat

Chao Li
Lehigh University

Manufacturing and Preliminary Testing of a Subscale Suspension Boat

by

Chao Li

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Date

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Joachim L. Grenestedt, Advisor

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D. Gary Harlow, Chairperson

Department of Mechanical Engineering and Mechanics

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Abstract

Vertical accelerations have been a major problem for high speed boats for a long time. In order to fix that, a suspension boat concept was developed and patented by Professor Joachim L. Grenestedt. A number of small-scale suspension boats have been tested with very good result. A full-scale two-seat manned suspension boat is presently being manufactured at Lehigh. The goal of the present project was to manufacture and test a 1:6 scale model of this boat. This boat has a center fuselage to which four sponsons are mounted vie suspension links, springs and shock absorbers. Suspension boat center hull, or fuselage, was built of carbon fiber prepreg in a CNC machined cavity mold. It is essentially an exact scale model of the full-scale boat. However, the sponsons were much simplified and used only to quickly evaluate the ride and some basic parameters. The boat was equipped with an inboard brushless motor driving a fixed surface piecing propeller via a flex shaft. A rudder mounted in the slipstream behind the propeller was used for directional control. The power and rpm of the motor was logged, as well as GPS speed in later runs. The small-scale boat in general performed very well, although steering was quite poor. Improving steering is under way.

1. Background

A 1:6 scale model of a two-seat manned suspension boat, shown in Fig. 1, was built and tested. The length of the full-scale boat was 8.0 m and the width was 3.2 m, The suspension boat consists of a center hull that during operation is not in contact with water, and four sponsons connected via suspension links to the center fuselage. The sponsons are carrying the full weight of the boat when it operates at speed. The center fuselage is narrow to reduce water loads as well as aerodynamic drag. The small size also allows it to be strong yet lightweight. The bow has a quite steep deadrise angle to avoid high slamming loads in larger waves that the center hull could hit. The rear of the center hull is very narrow. A subscale model is an effective means to evaluate and to predict the character of full-scale boat.

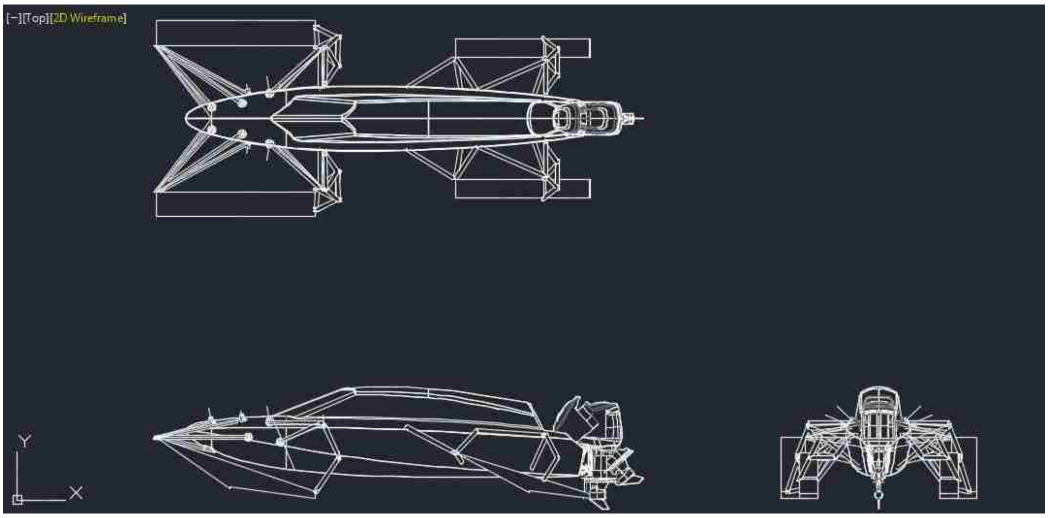

Fig 3.1 Full size suspension boat CAD model

2. Manufacturing of composite center hull

The center hull is a key part of the suspension boat. The full-scale hull had already been designed. Some small changes were made on the subscale model in order to adapt the power system and to simplify manufacturing of a composite subscale hull.

2.1 Manufacturing mold

A cavity mold was made in such a way that the center hull could be manufactured in one step. In this section, the manufacturing of the cavity molds is described.

2.1.1 CAD modeling of the molds

CAD models of the molds were generated from CAD models of the full-scale hull. An opening on the top of the mold was added to get access to an internal vacuum bag which necessary for the manufacturing. The opening was also essential for access to the inside the center hull so internal components could be installed. Several slots for locating pins were made in the parting plane of the molds.

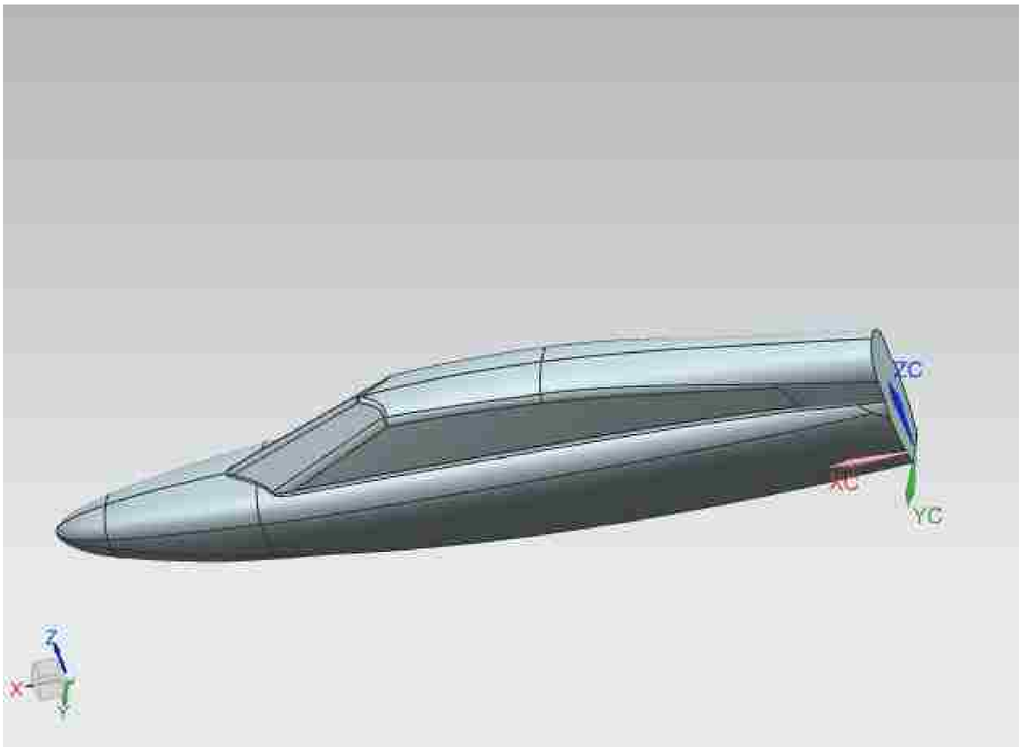

Fig 4.1 CAD model of the hull

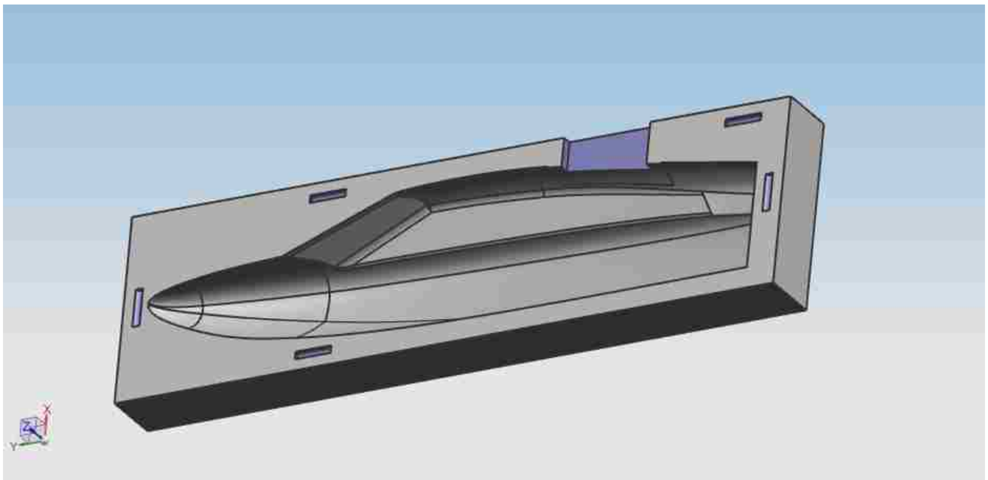

Fig 2.2 CAD model of the right half of the hull mold

2.1.2 Generating tool paths

Considering both the speed and accuracy of milling molds, a rough milling and a finish-milling were needed. In this case, a hull mold with 1166 mm in length, cavity mill with 1 inch diameter flat mill was used as rough milling. And contour milling with 1/4 inch diameter ball mill was used as finishing-milling.

2.1.3 Milling

After tool paths were generated, they were first evaluated on soft and low-cost EPS (Expanded Polystyrene) to observe the quality and check the tool paths. After considered qualified, milling was done on general plastic blocks to manufacture the molds.

Fig 2.3 EPS mold where rough milling has been completed and finish milling has just begun.

Fig 2.4 EPS mold with offset error. The error was fixed before the final molds were machined.

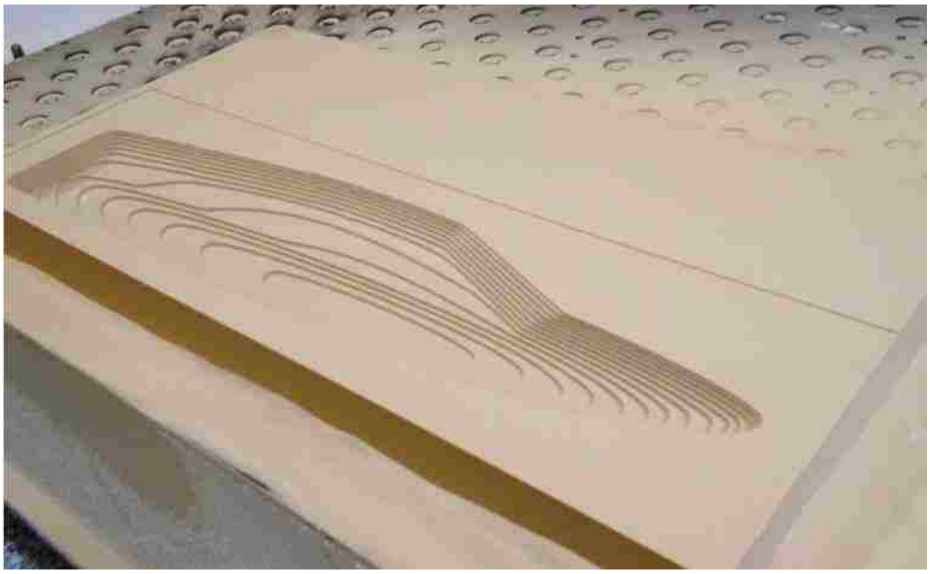

Fig 2.5 Rough milling completed on General Plastic tooling board

Fig 2.6 Finishing-milling completed on General Plastic tooling board

2.1.4 Surface finish of the molds

After the molds were milled, more steps needed to be done to make the mold surface harder and prepared for laying up the prepreg in the mold.

2.1.4.1 Sanding the molds

Sanding was necessary to remove the scallops to make the inner surfaces of the molds smooth. Sand paper (600 grit) was used during sanding. The presently used General Plastic tooling board is relatively soft, so sanding had to be done carefully.

2.1.4.2 Brushing epoxy

Epoxy was brushed onto the molds in order to get a strong and stiff surface. Before brushing, cleaning the mold is necessary in case contaminant roughs the mold. The mold was thoroughly wiped by acetone. Epoxy (MGS L285 and H287) was mixed properly and then a small amount of blue chalk was added. The blue chalk helps gauging the thickness of the epoxy coat. The epoxy was gently spread with a squeegee and the redundant resin was wiped off with paper towels to make sure there was a uniform thin layer of epoxy on the mold surfaces. The epoxy was left to cure for 8 hours. After it cured, the surfaces were sanded with 1000 grit sand paper and cleaned with acetone. The same procedure was repeated twice to make a good mold surface.

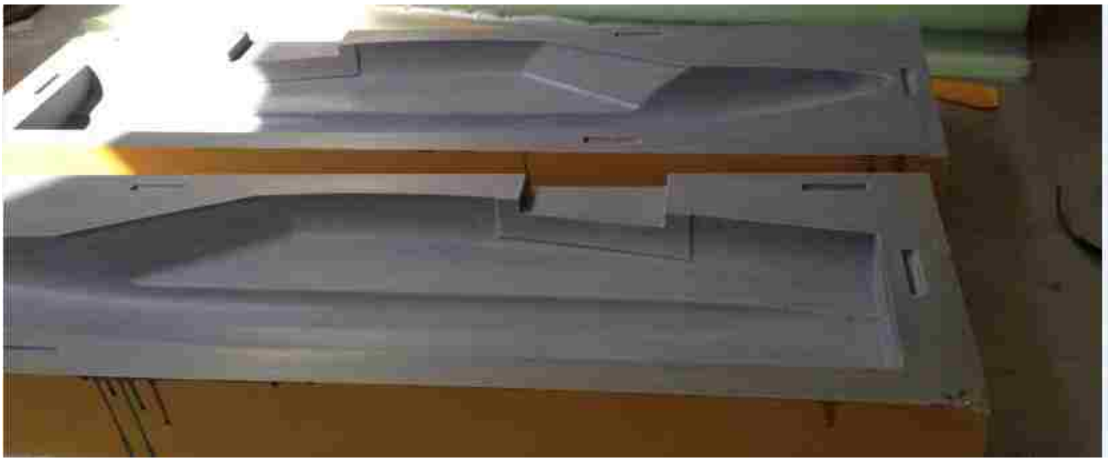

Fig 2.7 Finished molds.

Fig 2.8 Epoxy used

2.1.4.3 Release agent

Chemlease Mold Cleaner EZ was used to remove dirt. After it had evaporated, mold primer Chemlease MPP-2180 was painted inside the mold. After about 20 minutes, release agent Chemlease 15 Sealer EZ was applied. After it had cured for 20 minutes, release agent Chemlease 41-90 EZ was finally applied.

2.2 Laying prepreg

The center hull was made using carbon fiber prepreg (pre-impregnated reinforcements). The particular reinforcement used was Gurit SE84LV/RC200T prepreg weave, weighing 200 grams per square meter (gsm)

2.2.1 Layup

The layup consisted of three plies of weave [0/90, ±45, 0/90]. The 0-degree fibers were used for global hull bending load, the 90-degree fibers for transverse strength and stiffness (to retain the cross section of the hull), and the +/-45-degree fibers were needed for torsional strength and stiffness.

2.2.2 Laying prepreg

Three main layers of prepreg were laid in each mold to build the shell structure of the hull. The outline of the shape of the prepreg needed to be cut was drawn on clear plastic sheets as templates. The prepreg was cut according to the templates.

The first layer of prepreg was laid into the mold. The prepreg must be laid down carefully in the mold without any wrinkles. After laying the first layer, the mold with prepreg was vacuum debulked in order to get rid of any bubbles formed between so that the surface of the hull will be exactly as the shape as designed. After debulking, local reinforcements were added. The local reinforcements consisted of 13 mm wide strips that covered slits that had to be cut in the prepreg to allow it to conform to the compound curvature. All the connecting points on the hull were applied reinforcement. The method was to stick additional 50.8mm wide prepreg strips through the hardpoints between layers. Hardpoints were needed where suspension components attach to the center fuselage. See Fig 2.9.

After the mold was closed, the symmetric strips on both molds formed a web frame that strengthened all the hard points of the structure.

Then the second ply, more local reinforcements, and finally the third ply were laid into the molds.

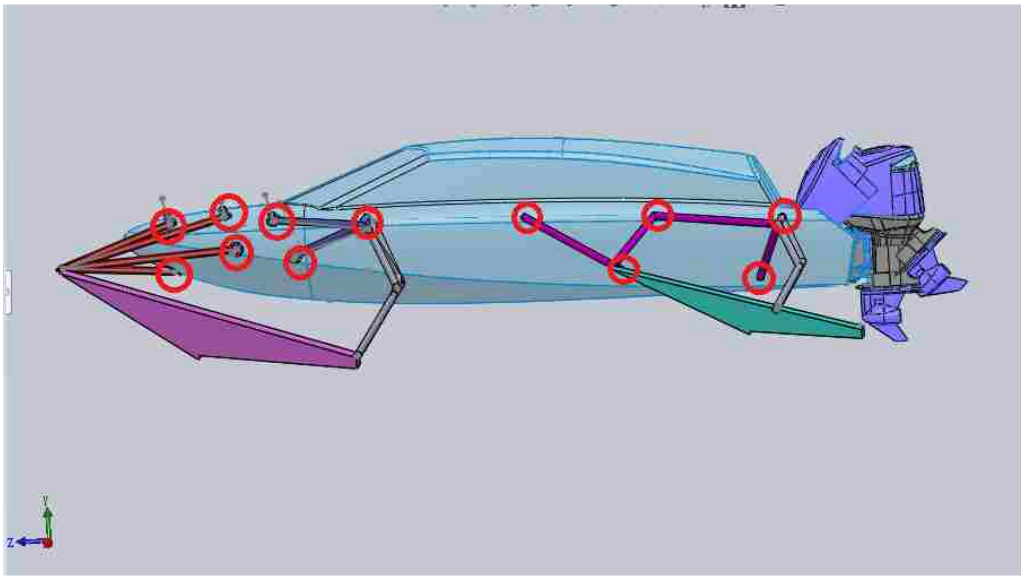

Fig 2.9 Hardpoints in the center fuselage

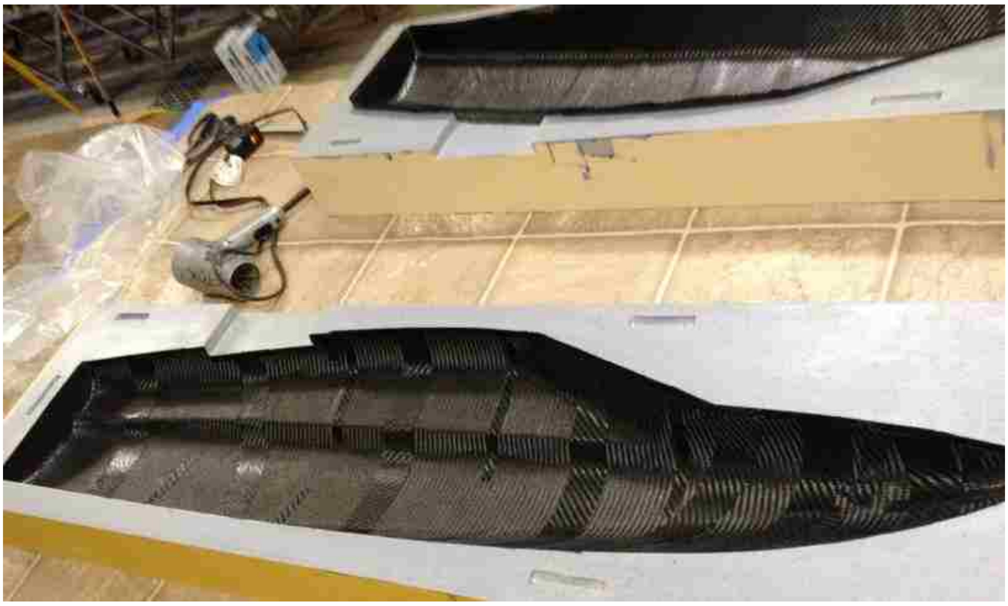

Fig 2.10 First layer laid as well as local reinforcements

Fig 2.10 shows the local reinforcements between layer one and layer two. The wide strips were the reinforcement strips which formed a strong web frame. The narrow strips were used to prevent cover slots cut to fit curvature surfaces.

Prepreg was laid in the 0/90 direction on the transom. More trips were laid in ±45 direction along the transom edge of both molds.

The edges of different layers were shown as Fig 2.11, in which way the hull can be formed into an intact shell structure after being closed.

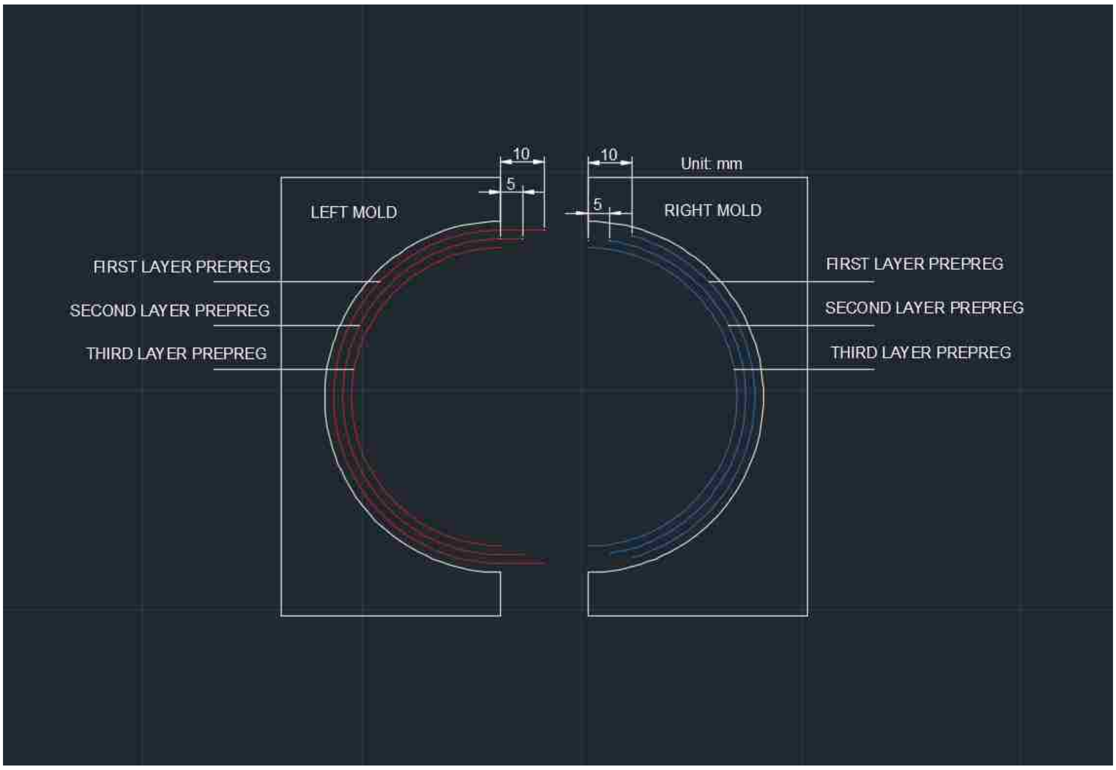

Fig 2.11 Sketch of the edges of different layers

2.3 Closing molds

Before closing the mold, peelply was added to the inner surface. The aim was to have a nice internal surface after the peelply is peeled off after curing. This kind of surface was helpful to bond other structures firmly into the hull. No breather was used. Plenty of the vacuum bag was used for the inside of the mold in order to avoid "hammocking" (the area of the vacuum bag being not enough to cover the surfaces).

When closing the molds, layers of prepreg were overlapped to each other. Care must be taken to prevent the peelply from getting caught between the prepreg layers, which will weaken the structure.

2.4 Vacuuming the molds before curing

After closing the molds, the outside of the mold was wrapped with breather and envelope bagged. The envelope vacuum bag was sealed to the internal bag to allow atmospheric pressure into the latter. The sealed mold is shown in Fig. 2.12.

Fig 2.12 Vacuumed molds inside the oven, ready to be cured

2.5 Curing the composite hull

The envelope bag was checked to be sealed perfectly before going into the oven. Because the pump was continuously working throughout the heating procedure, a high-temperature Teflon vacuum hose was used inside the oven. Outside the oven a less expensive nylon tube was used. The part was cured at 85+/-5 C for 24 hours.

2.6 Demolding the center hull

After completed cure of the prepreg, the oven was turned off the temperature allowed to slowly decrease to room temperature. The molds were then opened and the hull removed. The vacuum bag was stuck fairly hard inside the hull. A long flat metal bar was used to split the vacuum bag from the surface, and the vacuum bag was pulled and tore at the same time.

Peelply was stuck to the surface even tighter. It was started from the edge of the opening to tear off peelply. This procedure was quite time consuming.

After getting rid of all the redundant materials, a carbon fiber hull was successfully made, Fig. 2.13.

Fig 2.13 Hull still in one of the mold halves.

3. Installing sponson structures

The sponsons and the suspension were key parts of the suspension boat. All the structures were simplified from the full scale boat.

3.1 Fixed tubes for suspension mounting

Five carbon fiber tubes were used to connect the sponsons to the center fuselage. Three of them went throughout the center hull. Two individual tubes were inserted into the hull with one end attached to the internal surface of the hull.

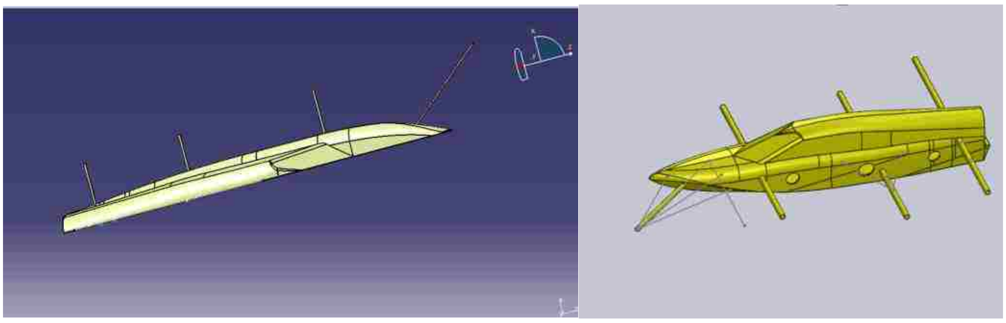

Fig 3.1 Tubes

3.1.1 Calculation

The section of the carbon fiber tubes chosen was 10mm outer-diameter (D) and 6.8mm inner-diameter (d). The moment of inertia of section was:

$$\mathrm{I} = \frac{\pi(D^4 - d^4)}{64} = 4 \times 10^{-10}(m^4)$$

All the loads were transferred by the shock onto the end of the tubes. The distance from the end to the fixed point on the hull was:

$$\mathrm{L} = 112(\mathrm{mm})$$

If the load on the end is F. The maximum moment in the tube is

$$\mathrm{M} = \mathrm{FL} = 0.112 \times \mathrm{F}(\mathrm{Nm})$$

The permissible stress was

$$\sigma_s = \frac{MC}{I}$$

In this case, C was D/2=0.005m

The compression strength of the carbon fiber tube was estimated to 800 MPa, the maximum permissible load on each tube would be

$$F_{max} = \frac{\sigma_s I}{CL} = 571N$$

For a boat less than 10kg, these tubes were strong enough.

3.1.2 Tube installation

Holes were drilled in the hull. In order to drill the holes accurately, a jig was made. Carbon tubes were inserted and bonded onto the hull with epoxy adhesive (ProSet 176/276). A fillet (Fig 3.2) was made both internally and externally between the tubes and the hull, which made the connection stronger.

Fig 3.2 The connection between the hull and the tube

3.2 Manufacturing of sponsons

Sponsons were made with a foam core, 6 mm thick plywood inserts for hardpoints, and 0.8 mm thick ply wood skin. The wood inserts were designed for connections, such as tapping inserts and self-drill screws that were used to connect the sponsons to the shocks and tubes. The foam core of the front sponsons were 70 mm wide and the rear ones were 50 mm. The foam was milled to the required thickness and then cut by hot wire frame attached to a waterjet cutting machine.

The finished foam for a rear sponson is shown in Fig 3.3. After the foam sponsons were cut, epoxy with filler was spread on them to bond the plywood skins. All plywood was glued to the foam and then the sponson was vacuum bagged to a release coated table. The vacuum procedure made the skins stick firmly to the foam. After the sponsons had cured overnight, they were demolded, sanded and cleaned by acetone three times and then brushed with a thin layer of epoxy to make them water proof . A finished sponson is shown in Fig.3.4.

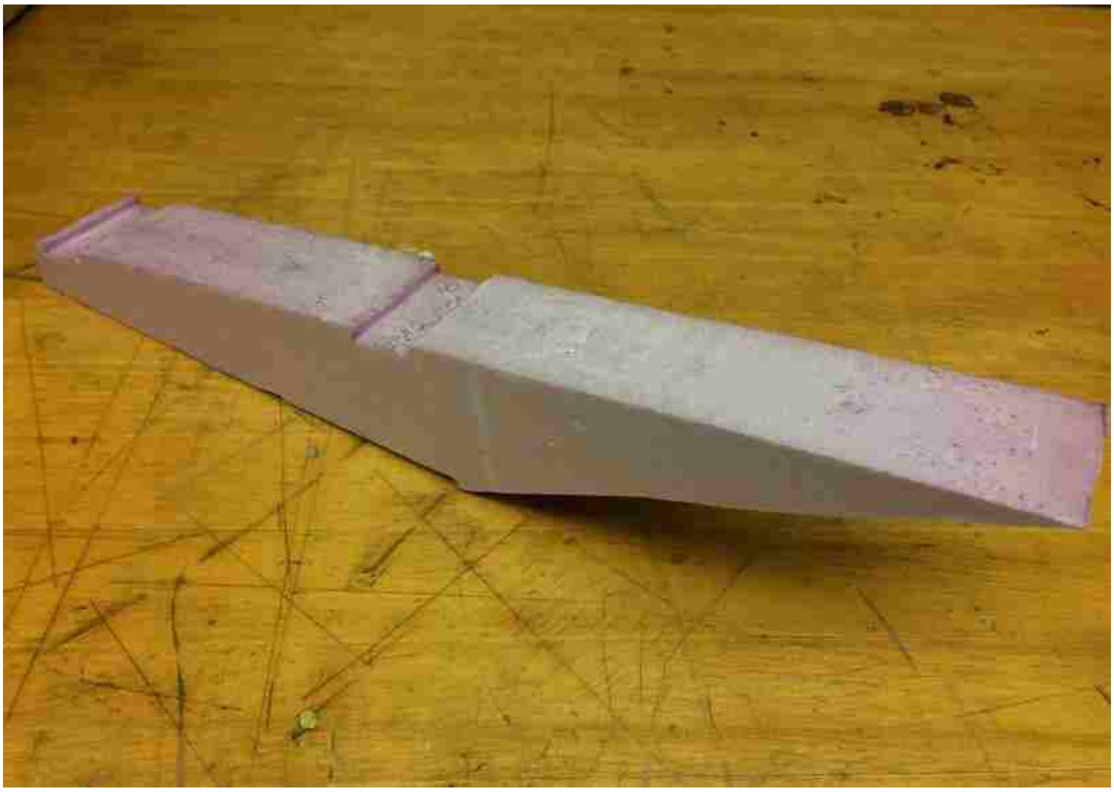

Fig 3.3 Foam core

Fig 3.4 The finished rear sponson

3.3 Manufacturing of suspension linkages

The suspension linkages were made of 6061 aluminum. The linkages were designed as two aluminum plates with lightening holes, whereas the full-scale suspension links will be welded tubular structures. The links were connected to the sponsons, the tubes and each other by hinges. Rivets and screws were used as fasteners. The first suspension links were made from 2.0 mm thick aluminum, but water tests proved these to be too weak. The first version design was shown in Fig 3.5.

Later versions were made of 3mm thickness with less lightening hole area which eliminated plastic deformation in future tests The shapes of the latest front linkages were shown in Fig 3.6

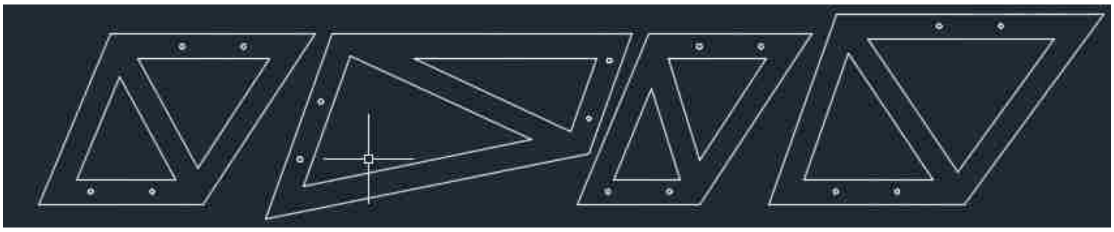

Fig 3.5 First version of linkages (from left to right: rear upper linkage, front lower linkage, rear lower linkage, front upper linkage)

Fig 3.6 Shock assembly

3.4 Shocks and springs

The shocks were connected onto the sponsons and the center fuselage, Fig. 3.6. The springs used were chosen to provide the designed attitude of the boat when running.

The full stroke was 45 mm, 30% stroke was 13.5 mm. The spring rate of the spring was 1570 N/m. During operation of the suspension boat, the weight is carried near the transoms of the four sponsons. The weight on each sponson in this configuration is approximately 2.5kg. So the spring will shrink 15.6mm, which is acceptable.

When the boat was tested, it was found that the damping factor of the shocks were too large. The solution was to reduce the amount of shock oil inside the shock and to use a lighter (lower viscosity) shock oil (Mugen super silicone shock oil #200).

4 Propulsion and steering system

The propulsion system includes a motor, ESC (Electric Speed Controller), shafting, propellers, etc. The steering system includes a rudder and a servo.

4.1 Strut and rudder

A strut and rudder assembly was purchased from a hobby shop (Fig 4.1). A skeg was attached at the bottom of the strut. The strut is attached to the transom of the hull by four screws. In order to strengthen the transom, a piece of G-10 board was bonded on the inside of the transom as shown in Fig 4.2. The screw holes were sealed with silicon. The rudder is rectangular (32mm×125mm). In water tests, the boat displayed poor maneuverability, which will be discussed in later sections.

Fig 4.1 Strut and rudder

Fig 4.2 G-10 reinforcement

4.2 Motor and ESC

The motor and the ESC are the main propulsion components that drive the propeller.

4.2.1 Motor

The motor provides propulsion power. It is controlled by ESC.

The motor used on the boat was Scorpion 5035-760kv.

For specifications see Appendix A.

4.2.2 ESC

The ESC takes power from the batteries and receives a throttle signal from the receiver. The ESC then transfers the power to the motor and controls power output.

The ESC used on the boat was Swordfish 300 Pro ESC

For specifications see Appendix B.

4.2.3 Tubing and water cooling

While moving, due to dynamic pressure, water flowed into the hole drilled on the rudder. A silicon tube transported the water from the rudder (Fig 4.1) and sent it into ESC. From there, he water exiting the ESC was then sent into the motor through another silicon tube. A third silicon tube drains off the water coming out of the motor through a hole on the side wall of the main hull. This is necessary so that the motor and ESC can be continuously operated without overheating.

4.3 Shafting and engine mount

A 6.35 mm diameter flex shaft connects the propeller to the motor. Curvature, internal space and the arrangement of the electronic devices have all been taken into consideration when doing shafting. The final shafting and engine mount position is shown as Fig 4.3. The shaft tube is a bent brass tube, in which the flex shaft operates. The outer tube was bonded in the hull. Furthermore, another piece of carbon fiber deadwood fills in the vertical space between the brass tube and the base line.

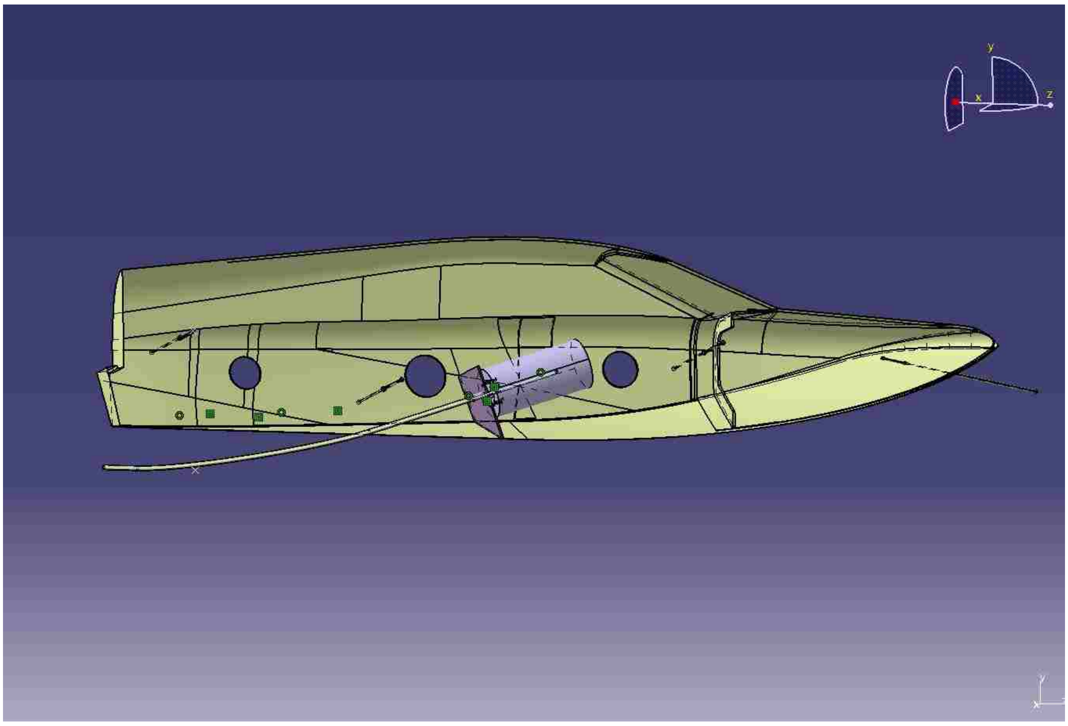

Fig 4.3 Shafting

The engine mount consisted of a 6.35mm thick G-10 board and a 3mm 6061 aluminum panel. The left and right edges of the bulkhead were extended as high as possible to increase the bond area between the hull and the bulkhead, a curved top edge was designed for convenience when changing motors and performing maintaining. Different holes were drilled to adapt different motors. Hence the shape was shown as Fig 4.4.

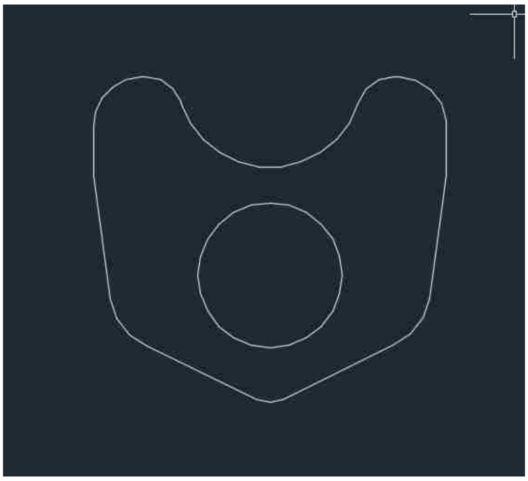

Fig 4.4a G-10 Engine mount

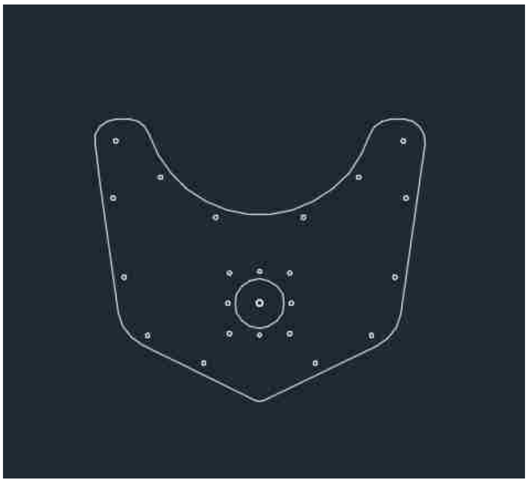

Fig 4.4b Aluminum reinforcement

In order to align the shaft with the motor on the engine mount, the brass tube was fixed first. After the epoxy cured, the engine mount with motor installed was put into the hull. A metal cylinder was inserted into the coupler and the brass tube in both ends, so that the motor axis was aligned to the brass tube. Finally the engine mount was bonded to the hull with the shaft aligned.

4.4 Propeller

Two propellers have been used.

Propeller 1 was 5678 (56 mm diameter, 78 mm pitch) 2-blade propeller (R) made of T7075 aluminum.

Propeller 2 was 5880 (58 mm diameter, 80 mm pitch) 2-blade propeller (R) made of T7075 aluminum.

4.5 Other electrical devices

Other electrical devices include BEC, servo and receiver.

4.5.1 Battery eliminator circuit (BEC)

The BEC gains power from the battery and reduces the voltage in order to supply energy to the low-voltage electronic devices on the boat, such as receiver and servo. Input in this case was 42V and output was 5V.

The BEC used on the boat was a Castle Creations V2 CC BEC Pro 20A 12S Switching Regulator.

For specifications see Appendix C.

4.5.2 Servo

The servo controls the deflection angle of the rudder.

The servo used on the boat was a Hitec HS-5646WP.

For specifications see Appendix D.

The servo was installed on an aluminum shelf which was attached to the rear carbon fiber tube and the transom (Fig 4.5). The servo arm was connected to the rudder by a steel rod with a ball linkage (Fig 4.6). A rubber bellow was bonded on transom to make the hole where the rod goes out water-proof.

Fig 4.5 Servo installation

Fig 4.6 Servo linkage

4.5.3 Receiver

The receiver was used to receive signals from the transmitter and deliver them to the ESC and the rudder. It delivers pulse width modulated (PWM) signals to the servo and the ESC to control the direction and speed of the boat. The receiver was installed on the roof of the boat and the antenna went out of the roof in a plastic tube (Fig 4.7).

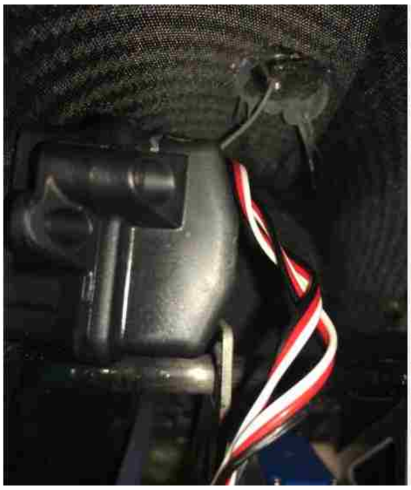

Fig 4.7a Receiver

Fig 4.7b Antenna

5 Testing on water

5.1 First test

The first test was performed on Nov. 11, 2016 using a 5678 propeller. The center of gravity was 380 mm in front of the transom.

The first test of the boat was in general quite successful.

The boat was floating in a very stable fashion, although the transom sat quite low.

The boat had no problem getting up on plane. Straight line stability was excellent. The boat ran over smaller waves and the suspension absorbed them very well. The center hull did not appear to touch the water. The speed was judged to be quite good (no GPS was used for the first test). There were no structural issues except with a suspension link (described further in the next paragraph).

5.1.1 Data and analysis

The data collected by the ESC are shown in Fig 5.1. In which the data were represented in different colors (Red – Voltage, Green – Current, Blue – Throttle, Yellow – Temperature, Pink – Motor RPM). General data are shown as Table 5.1

Fig 5.1 Comprehensive data

Max Current (A)	116
Max Power (W)	3030
Min Voltage (V)	34.6
Max Temperature (C)	27
Max Throttle (%)	100
Max Motor RPM	22300

Table 5.1

Current, power and RPM were the key data which told if the boat was overloaded.

a) Electric current and battery capacity

Two batteries (5S 6200mAh 35C Lipo) were connected in series. The maximum current provided by the batteries which was safe shall not exceed:

$$I_{max}^{battery} = Capacity \times C\ value = 6.2 \times 35 = 210(A)$$

The maximum current detected was 116A, which was safe for the batteries.

b) Electric current and ESC capacity

The maximum current capacity of the ESC was 300A so it was safe.

c) Motor capacity

According to the motor specification shown in Appendix A, the maximum continuous power and the maximum peak power was 5800W and 8100W. The peak power detected was 3030 W with 116 A which was safe.

d) RPM of the motor

The no-load RPM of the motor is:

$$RPM_{no-load} = Voltage\ input \times KV\ value = 37 \times 760 = 28120$$

However, when it is under load the RPM will drop due to voltage drop. The maximum RPM detected was 22300, which was acceptable.

5.1.2 Conclusion of the first test

It can be concluded that the power system matched the boat well.

Vertical accelerations were well controlled by sponsons which was the primary mission of the suspension boat. This was judged from watching the boat. There were very small pitch and heave excursions.

During the test some water entered the hull which indicated that there was some problem with the water-tight seals.

The boat was poor in steering.

5.2 Second test

The test was done on Dec. 9, 2016 using a 5678 propeller. The center of gravity was 410 mm in front of the transom.

The second test concentrated more on maneuverability. The tests of the boat consisted of a large number of fairly short high-power sprints, followed by 180 degree turns.

5.2.1 Changes done on the boat after the first test

It was found that slight plastic deformations had taken place in some of the suspension linkages. For this reason, the suspension linkages were re-designed and new ones manufactured as outlined in section 3.3. All the electrical devices were taken out and dried up before reinstalled. The sealing in the transom was redone to fix leaks.

5.2.2 Data and analysis

The data collected by the ESC are shown in Fig 5.2.

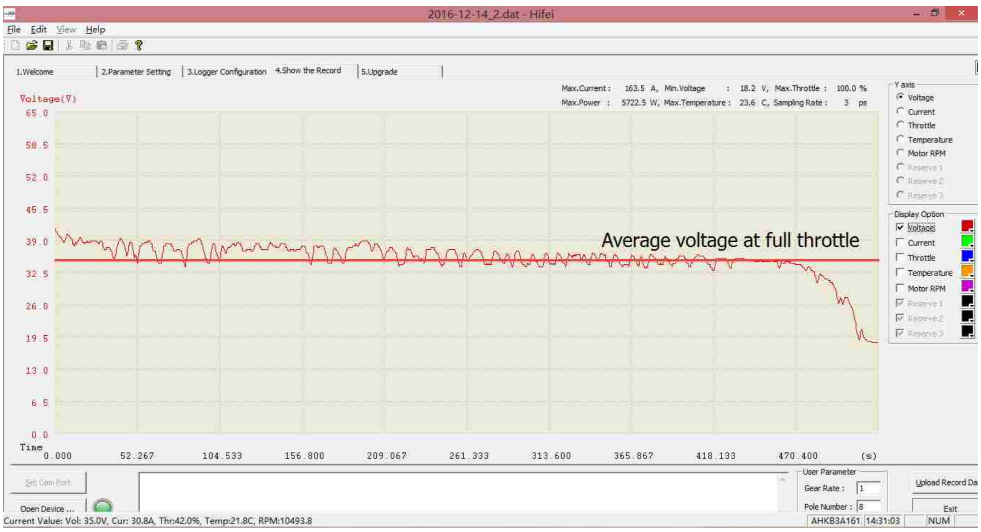

Fig 5.2a Voltage

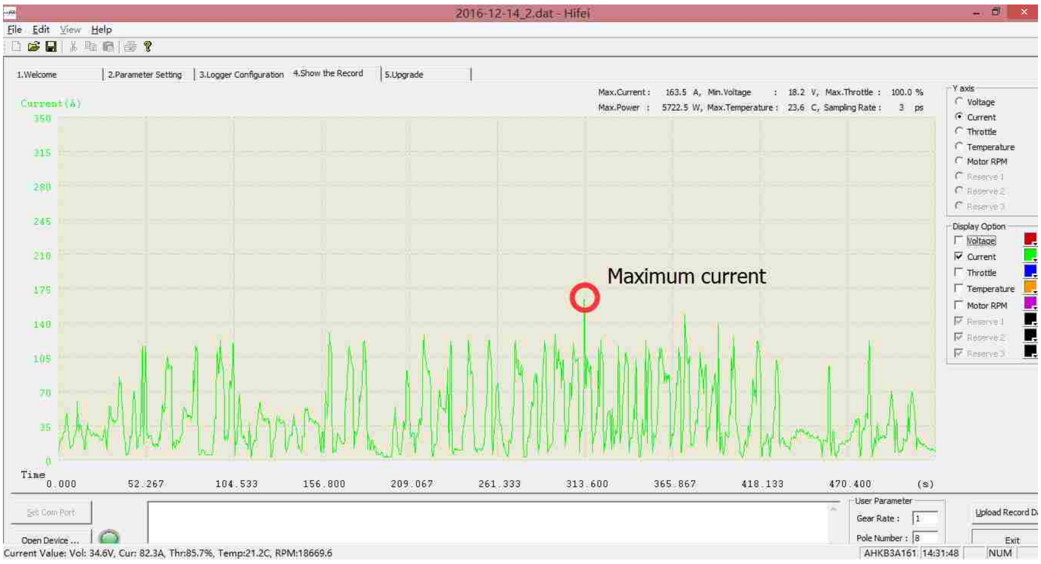

Fig 5.2b Current

Fig 5.2c Throttle

Fig 5.2d Motor RPM

Max Current (A)	163
Max Power (W)	5720
Min Voltage (V)	18.2
Max Temperature (C)	24
Max Throttle (%)	100
Max Motor RPM	23550

Table 5.2

The data of the electronic devices showed the boat was not over loaded during the short full-power sprints.

a) Electric current and battery capacity

The maximum current detected was 163A, which was lower than 210A. The batteries were safe.

b) Electric current and ESC capacity

The maximum current capacity of the ESC was 300A and it was safe.

c) Motor capacity

The peak power detected was 5720W, lower than 8100W, which was safe for the motor.

d) RPM of the motor

The maximum RPM detected was 23550, which was acceptable.

5.2.3 Comparing with the first test.

Compared to Table 5.1, maximum current increased from 116 to 163 A, and maximum power increased from 3030 W to 5720 W. This high power is believed to be due to a very quick application of full throttle. Looking to the continuous current and power, it can be found that in both tests the continuous current in full throttle condition was around 110 to 120A which means there were no big differences in peak load between the two tests.

5.2.4 Conclusion of the second test

The peak power (5720W) was far from the max peak power (8100W) of the motor, and even didn't exceed the maximum continuous power (5800W) of the motor. Thus, a larger propeller could be used on the boat.

The boat handled very well in a straight line but it did not turn very well, as will be further discussed in the next paragraph. The suspension links did not have any issues during this test. The hull leaked less but there was still water inside the center hull at the end of the test.

From the video it appears that when the boat was running at full throttle the front sponsons were up in the air, which indicates that it may be beneficial to move the center of gravity forward (Fig 5.3).

Fig 5.3 A screenshot from testing video. Note lack of spray and wake from the left front sponson.

5.3 Third test

The test was performed on Feb. 14, 2017 with the larger 5880 propeller. The center of gravity was 410 mm in front of the transom.

The third test was similar to the second test in that it concentrated on maneuverability. The tests of the boat consisted of a large number of fairly short high-power sprints, followed by 180 degree turns.

5.3.1 Changes done on the boat after the second test

The batteries were moved forward about 100mm in order to move the center of gravity forward. This resulted in a center of gravity closer to what is expected in the full-scale suspension boat. A larger distance between the rudder and the center of gravity could help improve turnability. The skeg under the propeller strut was reduced in size in order to improve turn ability, although this would be expected to reduce high-speed yaw stability. The front sponsons create wakes as well as spray which sometimes hit the rear sponsons, in spite of their narrower track width. The front sponsons were mounted with some positive deadrise in order for the water to spray only to the outside and clear the rear sponsons. Further, the sponsons were mounted with some "toe-in". This may be beneficial for both yaw stability and turning.

A larger 5880 propeller was used since there was excess power available from the motor.

5.3.2 Data and analysis

The data collected by the ESC are shown as Fig 5.4. In which the data were represented in different colors (Red – Voltage, Green – Current, Blue – Throttle, Yellow – Temperature, Pink – Motor RPM). General data are shown in Table 5.3

Fig 5.4 Comprehensive data

The data collected by GPS is shown in Fig 5.5.

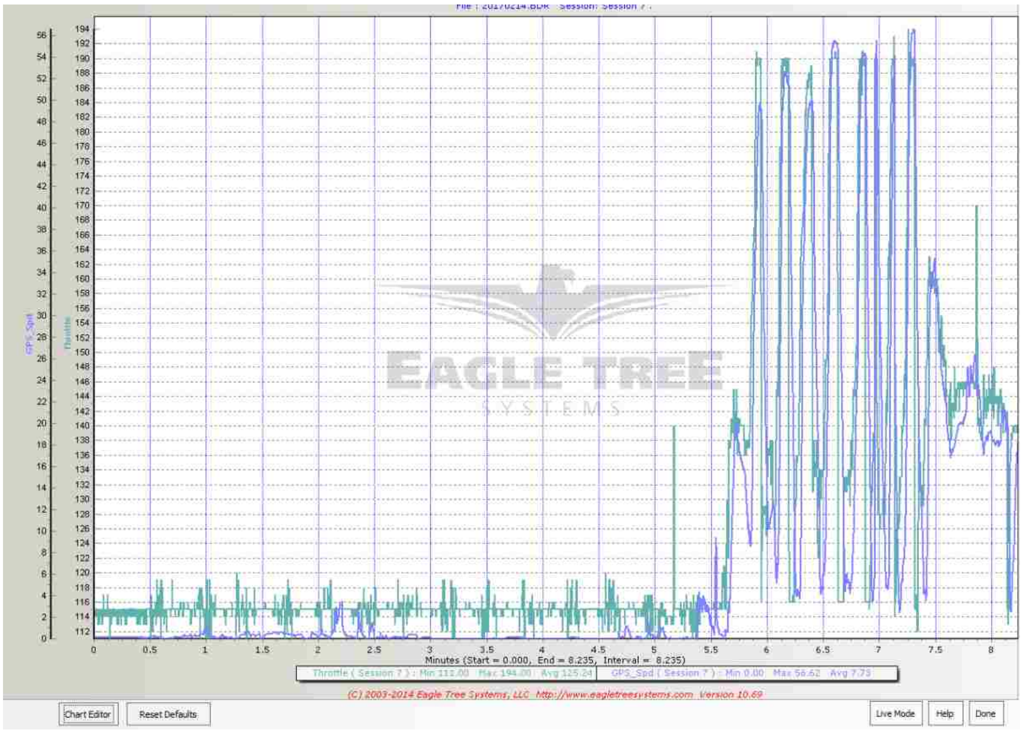

Fig 5.5a GPS data (Part1)

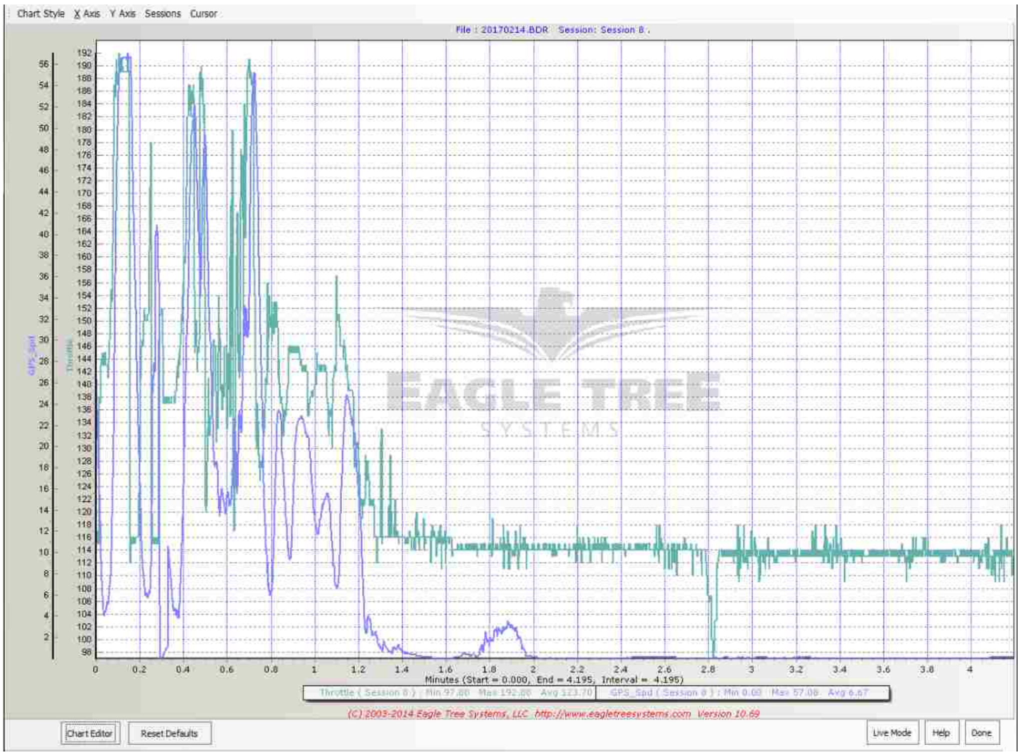

Fig 5.5b GPS data (Part2)

Max Current (A)	263
Max Power (W)	8020
Min Voltage (V)	28.7
Max Temperature (C)	31.5
Max Throttle (%)	100
Max Motor RPM	22230
Max Speed (km/h)	91.86

Table 5.3

The data of the electronic devices showed that the power system was approaching the limit due to a larger propeller.

a) Current status of the batteries

The maximum current detected was 263A, which was higher than 210A. Batteries were overloaded.

b) Current status of the ESC

The maximum current capacity of the ESC was 300A and it was safe.

c) Power status of the motor

The peak power detected was 8020W, which was very close to 8100W. The motor was close to peak power.

d) RPM of the motor

The maximum RPM detected was 22230, which was acceptable.

5.3.3 Comparing with the second test.

Because of installing a larger propeller, the current and power increased. The boat didn't show much difference in running. The reduced area of the skeg did not seem to affect the boat much. The spray from the front sponsons appeared to clear the rear sponsons, as desired. The toe-in did not appear to have any effect.

5.3.4 Conclusion of the third test

The maximum current detected was larger than the rated max output of the batteries. The maximum power was close to the maximum peak power of the motor.

During the third test, when the boat was launching with a full throttle, the high pitch moment flipped the boat upside down (Fig 5.6), smashed on to the water, and broke the front reinforcing rod. However, the boat flipped back and still finished two full throttle dashes.

Fig5.6 (a) Fig5.6 (b)

Fig5.6 (c) Fig5.6 (d)

Fig5.6 (e) Fig5.6 (f)

Fig5.6 (g) Fig5.6 (h)

Fig5.6 (i) Fig5.6 (j)

Fig 5.6(a-h) The flipping and recover process of the suspension boat

6 Conclusions

6.1 Structure strength

The boat did not have many structural issues during the test runs. In early tests some suspension links deformed plastically, but these were quickly re-designed.

The boat rolled over quite a few times without damage. However, during the last run it flipped over backwards and broke a suspension strut. Everything else has held up well on the boat.

6.2 Buoyancy and large angle stability

In the tests, the buoyancy and large angle stability were satisfactory. The boat even recovered after having flipped over and rolled over a few times.

6.3 Maneuverability

In the three tests, the boat did not have very good turn ability.

Although good turn ability was not designed as a key feature of the suspension boat, it will be taken into consideration in future improvements.

Several improvements have already been implemented on the suspension boat:

1) Vertical fins were installed on front sponsons (Fig. 6.1).

Fig 6.1 The vertical fin installed on one of the front sponsons

2）Installing deflectors on the side of the rear sponsons. When the boat is making a turn, the intent is that the deflectors will help the rear of the boat to slide sideways (Fig 6.2).

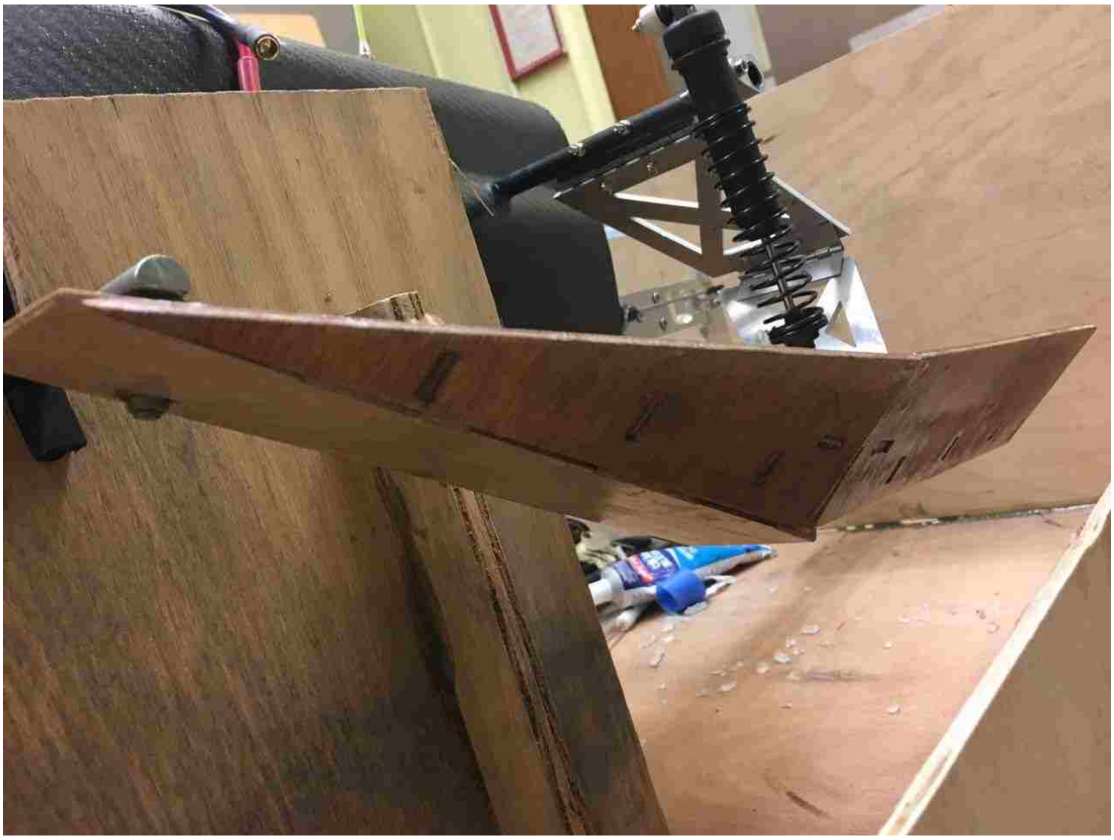

Fig 6.2 Deflectors on the rear sponsons

6.4 Propulsive performance

According to the data, the maximum speed in the third test detected by the GPS was 91.86km/h. This corresponds to a speed of

$$V_s = \sqrt{6} \times 91.86 = 225.01(km/h)$$

for a full-scale suspension boat that is six times larger than the present subscale model.

6.5 General conclusion

A 1:6 subscale suspension boat was manufactured and tested. In general the boat performed very well in water tests. The ride was very stable and waves were absorbed very well, even at scaled speed over 200 km/h. A good combination of motor, ESC, batteries and propeller was found. The only major problem of the boat was its turning performance. Further tests are planned, using modified rear sponsons and fins on the front sponsons.

Appendix A

Motor specifications

Outside Diameter	61.0 mm (2,4 in)
Stator Diameter	50 mm (1.96 in)
Stator Thickness	35 mm (1.37 in)
Magnet Poles	8
Motor Kv	760KV RPM / Volt
Max Continuous Power	5800 Watts
Max Continuous Current	150 Amps
Weight	729 Grams (23.43 oz)
Shaft Diameter	9.98 mm (0.393 in)
Body Length	75.0 mm (2.91 in)
Overall Shaft Length	100.7 mm (3.97 in)
Max Lipo Cell	10 S
Maximal peak power	8100 Watts

Appendix B

ESC specifications

Voltage	4-15s Lipos
Current / Max	300 Amps/380 Amps
BEC	OPTO
Size (mm)	119×72×27
Weight (incl. wires)	495g

Appendix C

BEC specifications

Max Input	12S LiPo (50.4V)	
Max Output Current	20 Amps peak	
Adjustable Output Voltage	4.8V-12.5V	
Max Continuous Current	Input Voltage	Max Continuous Output Current
	16V	15A
	24V	13A
	32V	11A
	40V	9A
	48V	8A
Length	1.69" (43mm)	
Width	1.3" (33mm)	
Height	0.94" (24mm)	
Weight (w/o wires)	1 oz (29 g)	

Appendix D

Servo specifications

Magnet Poles	3
Bearing	Dual ball bearings
Speed sec/60°(6.0V/7.4V)	0.20/0.18
Torque kg./cm. (6.0V/7.4V)	11.3 /12.9
Size (mm)	41.8×21.0×40.0
Weight (g)	61