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Manufacturing and Testing of a Small Scale Suspension Boat

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Manufacturing and Testing of a Small Scale Suspension Boat

By

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Abstract

To reduce the high vertical accelerations of the high speed boats, a “suspension boat” concept was developed and patented by Grenestedt [1,2]. A 1:6 subscale version of a two-seat high-speed manned suspension boat was manufactured and tested. The manufacturing of the hull, the sponsons, and the suspension components is described, followed by an outline of the driveline and controls. In general, the boat performed very well in water tests and the only major problem of the boat was its turning performance. Further work has been initiated to improve this.

1. Background and introduction

This project deals with high-speed boats, which typically are subjected to very high vertical accelerations when operating in waves. In order to reduce the high vertical accelerations of the high speed boats, a "suspension boat" concept was developed and patented by Grenestedt [1][2]. Research performed at Lehigh University indicates that vertical accelerations can be reduced an order of magnitude using this concept. This thesis deals with building and testing a small-scale version of a two-seat high-speed manned suspension boat. This boat consisted of a center hull that is not in contact with water during operation, four sponsons that ride in the water, and suspension links connecting the sponsons to the center hull. In the following sections the manufacturing of the hull, the sponsons, and the suspension components is described, followed by an outline of the driveline and controls. The thesis ends with a section describing water tests and results. In short, the water tests must be considered very successful.

2. Manufacturing of the center hull

The center hull is shown in yellow and the four sponsons in blue in Figure 1. A mold for the center hull was designed, CNC machined out of tooling board, surface coated, and mold released. This work was performed mainly by Chao Li. After the mold had been prepared, plies of prepreg were cut and placed in the mold and cured. The details were as follows:

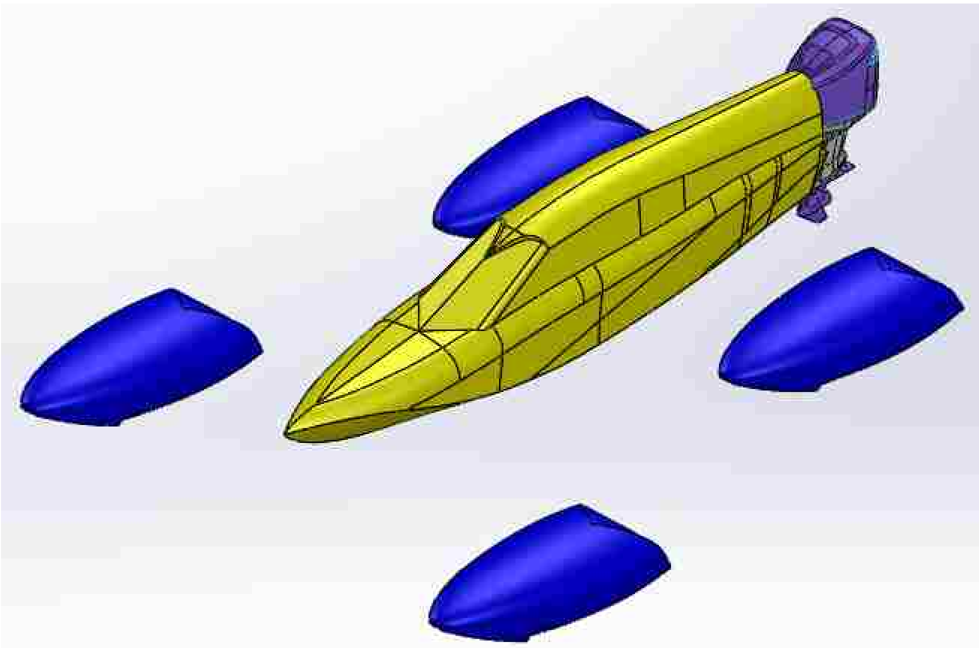


Figure 1:The center hull and suspensions of the suspension boat

2.1 Laying prepreg

Templates for the prepreg were made of thin plastic sheet. Using these template three plies of Gurit SE84LV/RC200T prepreg weave, weighing 200 grams per square meter (gsm) were cut.

The first ply was placed at 0/90 degrees relative to the length of the boat. The 0-degree fibers were used for the global hull bending load and the 90-degree fibers were used for the transverse strength and stiffness. A number of cuts had to be made in the prepreg in order to make it conform to the compound curvatures of the mold. These cuts were covered by narrow strips of the same prepreg. The first ply was then vacuum debulked.

The second and third plies were then laid in the mold. The second ply was placed at +45/-45 degrees relative to the length of the boat for torsional strength and stiffness. The edges of the second ply were 5mm higher and lower, respectively, than the edges of the two mold halves; see the right sketch in Fig. 3. This provided an overlap between the two halves of the hull. The third ply was placed at 0/90 degrees relative to the length of the boat, and its edges were 10 higher/lower (Fig. 3).

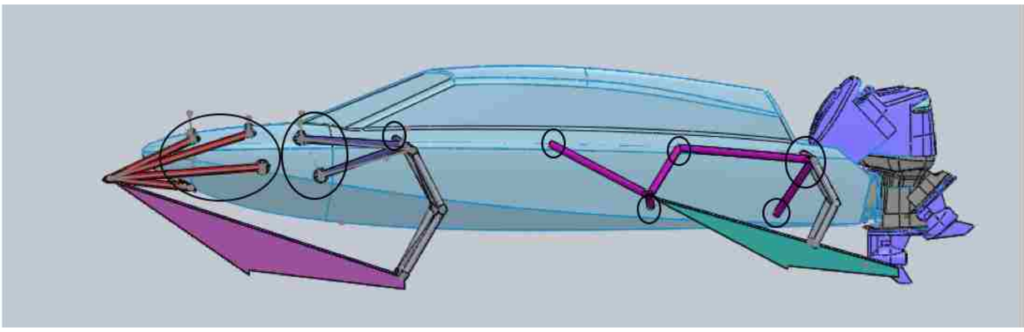


Figure 2: Locations of point forces on the center hull

Some reinforcement work should be done at the locations of force points. The joint points between the tubes and the hull were defined as the force points and theses points were determined from the 3D model of the initial design and then marked on the mold as shown in Figure 2. Several 50mm wide prepreg strips were cut and laid on these locations between the first layer and the second layer, as well as between the second layer and the third layer. These strips formed web frames after the mold was closed. The reinforcing strips on the second layercan be seen in Fig. 3.

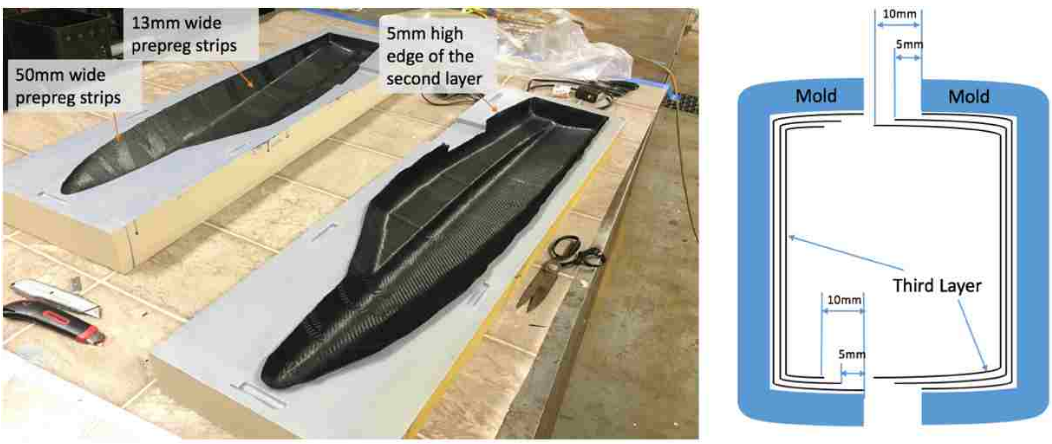


Figure 3: Hull mold (left) and sketch of overlap (right)

2.2 Vacuuming the mold and curing

Peel ply was attached on the third layer to ensure a nice and rough inner surface. Then the mold should be closed carefully so that the prepreg layers could be overlapped perfectly and no peel ply was inserted in to the split. A breather was then wrapped on the outer surface of the mold. A vacuum bag was placed both inside and outside of the mold and then sealed carefully. At the process of evacuation, the vacuum bag was pressed on both outside and inside due to the atmospheric pressure. To ensure a good inner surface, plenty of the vacuum bag was placed inside so that enough force could be applied on every corner of the inner surface.

The mold was placed in an oven and the temperature ramped to 85+/-5 °C after the airtightness was checked. Figure 4 shows the mold be evacuated and placed in the oven, ready for curing.

After 24 hours' curing, the oven was turned off. When the temperature decreased to the room temperature, the mold was then removed out of the oven and the composite hull was finally obtained after opening the mold.

At the process of closing the mold, the mold halves failed to close perfectly. For example, as the layers were not overlapped perfectly, some burrs from the connecting interface should be trimmed. Large amount of time and effort was spent on tearing down the peel ply. It was mainly because that the peel ply was inserted in the layers by mistake and the opening of the hull was small and located at the rear part of the hull. The peel ply couldn't be torn down from the inner surface of the hull easily especially for the bow of the hull.

Figure 4: The mold inside an envelope bag, placed in the oven, ready to be cured

3. Manufacturing of sponsons

Four sponsons were made and mounted via suspension links to the hull. Sponsons were made by cutting a block of Styrofoam to the shape of a sponson and covering it with thin plywood. The foam was first milled to the desired thickness using the large 5-axis CNC router at Lehigh's Composites Lab as shown in Figure 5. The foam cores of the front sponsons were 70 mm thick and the rear ones 50 mm.

Figure 5: The foam be milled by the large 5-axis CNC router

The foam sheet was cut to size using a hotwire cutting frame mounted to a waterjet cutter, thus turning the waterjet into a CNC hotwire cutter. The finished foam for two front sponsons are shown in Figure 6.

Hardpoints for mounting the sponsons to the suspension links were made of 6 mm thick solid wood. Cutouts for these hardpoints can be seen in Figure 6.

Figure 6: Foam block

The foam blocks of the sponsons were covered by 0.8 mm thick plywood, which greatly improve strength as well as provide a smooth surface. The plywood pieces were cut using an abrasive waterjet cutter, sanded and cleaned. Some of the plywood pieces are shown in Figure 7.

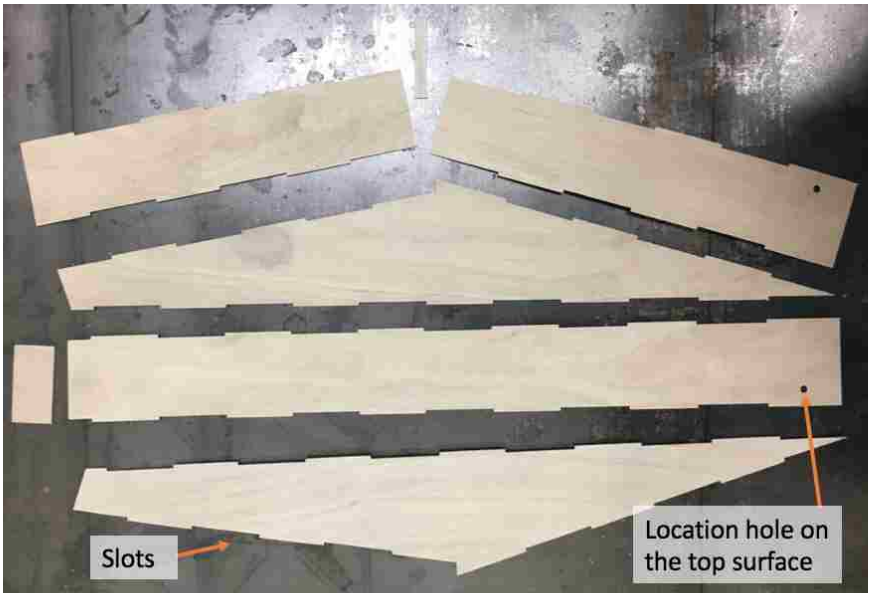


Figure 7: Ply wood skin

The wooden strips for hardpoints and the plywood pieces were bonded to the foam blocks by epoxy adhesive. West System 105 epoxy resin and 206 hardener were mixed thoroughly, then a low-density filler was added to get a uniform and reasonably thick consistency. This mixture was brushed onto each surface of the foam blocks. At the same time, pure 105/206 epoxy (without filler) was prepared and brushed onto all wood (hardpoints and plywood).

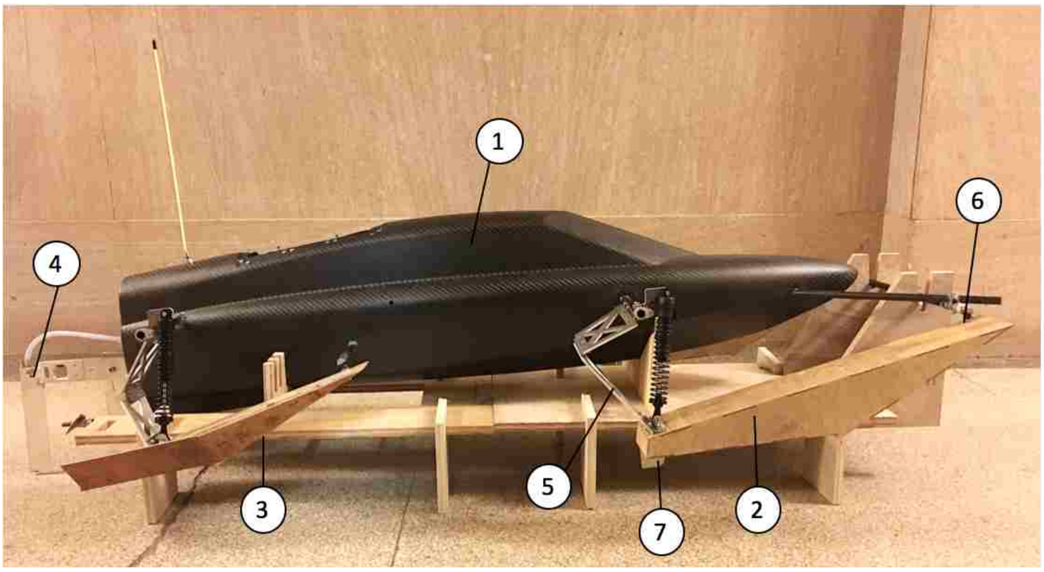
Figure 8: The setup of the vacuum bag for bonding plywood sheets on a sponson

All parts were then assembled and placed onto a release coated table, and vacuumed down (Fig. [8]). The vacuum ensured that all parts were firmly bonded together. After a 12 hour cure the sponsons were demolded, sanded, and brushed with a coat of 105/206 epoxy. Holes were drilled for threaded brass inserts for all hardpoints. These were also mounted in epoxy. Figure 9 shows the finished front sponsons.

Figure 9: The front sponsons

4. Suspension components

The four sponsons were mounted via suspension links to the center hull. In short, each sponson was attached via a spherical joint in the front to a carbon fiber tube that was rigidly mounted to the center hull. In the rear of each sponson was a double-hinge as shown in Figure 10. This hinge mechanism keeps the sponsons from changing deadrise angle (roll angle). A coil-over shock absorber (hydraulic shock absorber with a coil spring over the body) was also installed at the rear of each sponson.



1 – Hull 2 – Front sponson 3 –Modified rear sponson 4 – Rudder and strut set
5 – Suspension linkage & Shock absorber 6 – Carbon tube & Tapping insert & Rod end 7 – Fin

Figure 10: The assembly of the suspension boat

4.1 Installation of carbon tubes for sponsons mounting

Three parallel carbon fiber tubes and two single carbon tubes were used to connect the suspension links to the hull. Holes were drilled through the center hull and the carbon tubes were inserted and bonded onto the hull with epoxy adhesive (ProSet 176/276). A jig was designed to support the hull, locate the position of the carbon tubes, help the holes being drilled correctly and fixate the carbon tube during the bonding process. The jig was designed and cut by a waterjet cutter. Figure 11 shows the hull in the jig. Figure 12 shows the distribution of carbon tubes and sponsons.

Figure 11: The jig and the hull

Figure 12: Top view of the suspension boat

4.2 Installation of suspension linkages and shock absorbers

The suspension linkages connect the sponsons to the center hull and govern the motion of the sponson. In the original full-scale design, the suspension components consist of a number of welded round tubes. However, due to the low loads of the subscale boat, the suspension components could be manufactured much more easily from flat waterjet cut aluminum sheet. In an initial design, 2 mm thick 6061 aluminum was used. However, when testing the boat (as described in a later chapter) there was some permanent deformation in a few of the suspension components. New parts were then made using 3mm thick 6061 aluminum. Figure 13 shows a sketch of the suspension linkages. An MS20001P piano hinge with the knuckle length 6.35 mm was riveted to the aluminum plates and screwed to the carbon fiber tubes. An HPI-racing HPIC2365 coil-over shock was mounted at the rear of each sponson as shown in Fig. 10. The damping of the original shock was considered too high and the shock oil was changed to a lighter one (Mugen Super Silicone Shock oil #200). The springs were set up such that when the boat was supported on the four bottom surfaces of the sponsons, the pitch attitude would be horizontal and the center of the driveshaft would be at the level of the lowest points of the four sponsons. A static sag of around 30% of the stroke was desired.

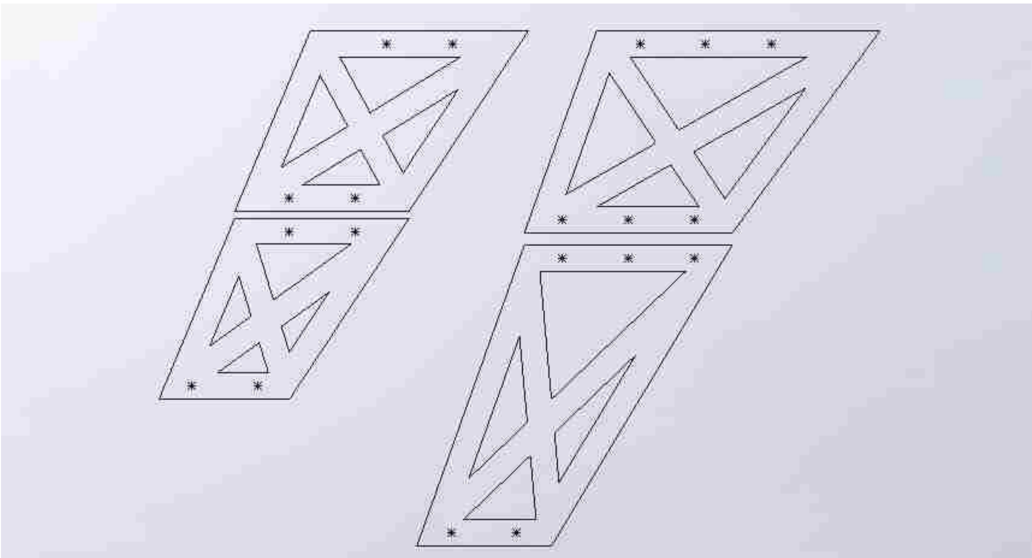


Figure 13: The sketch of the linkages

5. Overview of the electronic devices and propulsion system

5.1 Introduction of Electronic device

Figure 14 shows the layout of the drive train and the electronic devices.

- The Scorpion HK-5035/760 motor was installed on the inclined bulkhead as described in a later chapter. A 6.35 mm diameter flex shaft going through a brass tube was connected to the motor by a coupler. Substantial effort was made to ensure that the motor was aligned with the driveshaft.
- A Swordfish plus 300A electronic speed control (ESC) was used to operate the motor.
- Two Lithium-polymer batteries of 6200 mAh 5S 18.5V 34C were used to provide power.
- A battery eliminator circuit (BEC) was used to drop the batteries' voltage for the receiver, servo and eLogger.
- An Eagle Tree eLogger V4 with GPS was used to log the throttle signal and the speed of the boat. The GPS was placed on the plastic cover to get the signal.
- The receiver was put on the top of the carbon tube and remained a distance to the ESC to prevent any signal disturbance generated by ESC.
- A Hitec HS-5646WP servo was used to control the movement of the rudder.

Data sheets for the components are included in Appendix A.

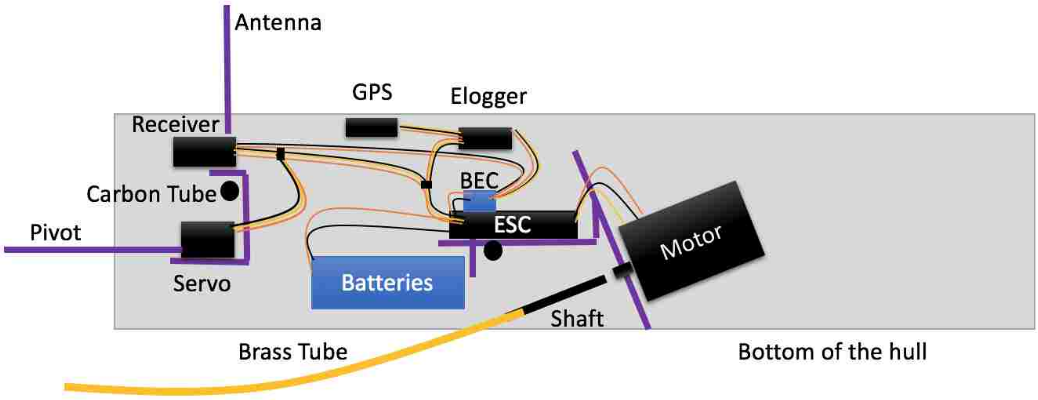


Figure 14: The layout of the electronic devices

5.2 Installation of the motor mount and flex shaft

Figure 15: The wooden test sample of the motor mount

The motor, motor mount, flex shaft, brass tube and propeller were laid out in the 3D CAD model. Mounting the propeller in the desired location, and making a nice even curvature of the flex shaft that would join the motor and be perfectly aligned with the motor shaft, were the most important considerations. The brass tube was bent, inserted into the hull and bonded using an epoxy adhesive. Jig were used to locate the position and the angle of the motor mount. In Fig. 15 a test jig for the motor bulkhead is shown. A motor mount consisting of a 6.35 mm thick G-10 board and a 3 mm 6061 aluminum plate were cut and installed. The G-10 motor mount was installed in the hull using an epoxy adhesive.

5.3 Assembly of rudder, strut and propeller

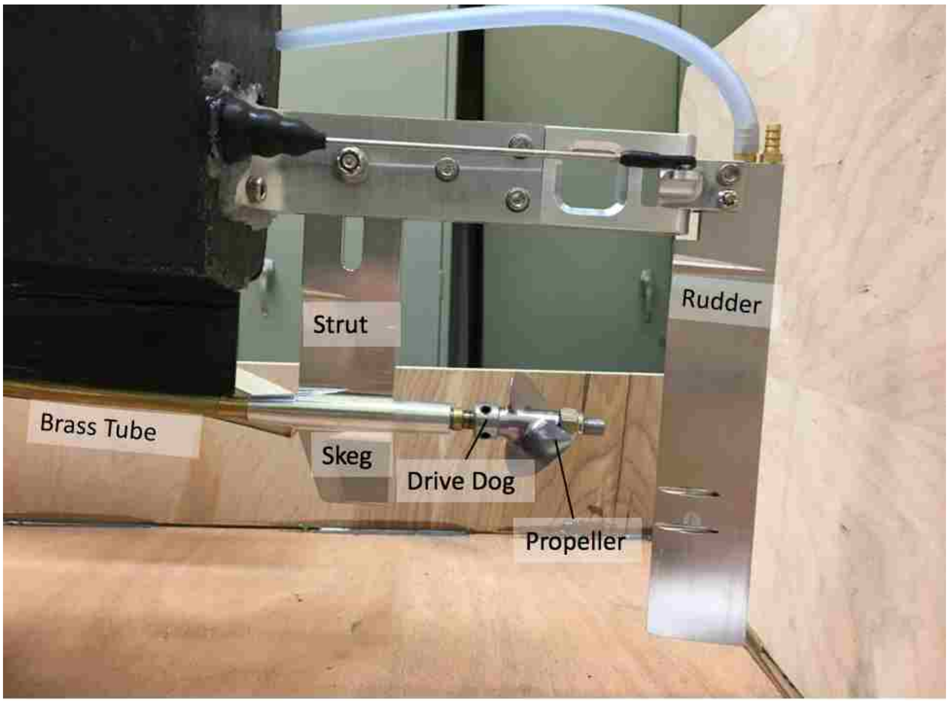


Figure 16: The stern of the boat

Figure 16 shows the stern of the suspension boat.

- Large inline Strut and Rudder assembly was screwed on the back surface of the boat. The assembly consists of a SPDR-012-DU dual rudder and a SPDS-013-SK skeg strut from Speedmaster Marine Model Products. A skeg was attached at the bottom of the strut. A G-10 back plate was bonded to the inner surface of the transom to support the assembly.
- A sealant was used to seal the gap between bolts and bolt-holes.
- The pickup for the cooling water is in the rudder. The ESC and the motor are water cooled.
- The center of the propeller is about 26mm below the bottom of the center hull. The brass tube continued from the motor, through the bottom of the center hull, and through the strut barrel to end just before the drive dog.
- A propeller shaft bushing was pushed into the brass tube from the rear of the strut.
- The drive dog was placed on the flex shaft and a minimum of 6 mm gap should be maintained between the drive dog and the bushing. This is needed since the flex shaft shortens under torque.
- Two different propellers were used. The first one was a two blade Alu Hydropropeller from MODELLBAU ZVARSKY. The size was 56 mm and the pitch was 78.4. The CNC milled ceramic coated propeller was well balanced and sharpened. The second one was a CNC high quality Aluminum propeller, the size was 58 mm and pitch was 80.

Figure 17 shows details of the strut assembly.

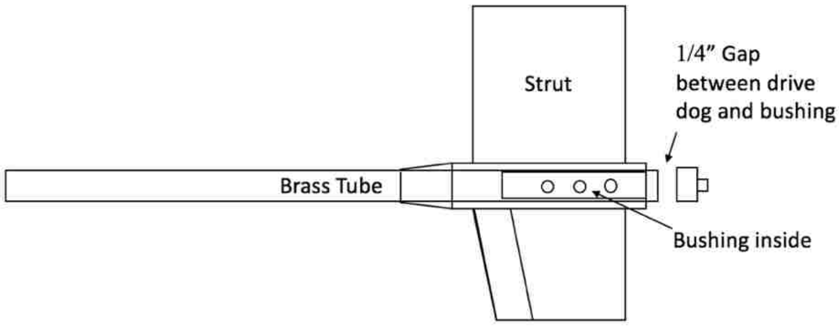


Figure 17: The way the brass tube and bushing be assembled

6. Test & Analysis

6.1 Test 1

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 while planing even when encountering waves. The speed was judged to be quite good (no GPS was used for the first tests). There were no structural issues except with a suspension link (described further in the next paragraph). All electronic devices worked within their designed operating limitations. The data obtained from the ESC showed that the motor was running at acceptable power and rpm and that the ESC and the batteries were operating at acceptable currents.

6.1.1 Problems and improvements

When the boat was riding in the water, water leaked into the hull. This changed the mass and the draught line. Before the next test more sealant was used on the hull to deal with this problem.

An aluminum suspension link deformed during the test, Figure 18.

To deal with it, new suspension links were manufactured from thicker aluminum.

Extra bolts were also used to improve strength.

Figure 18: The linkage after test 1

6.2 Test 2

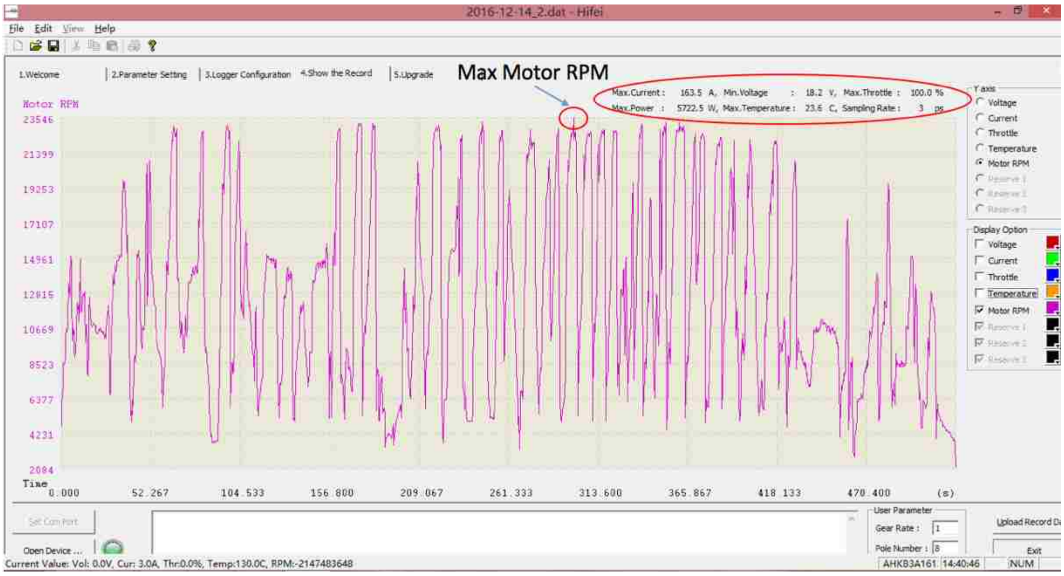


Figure 19: The Motor RPM vs Time for test 2

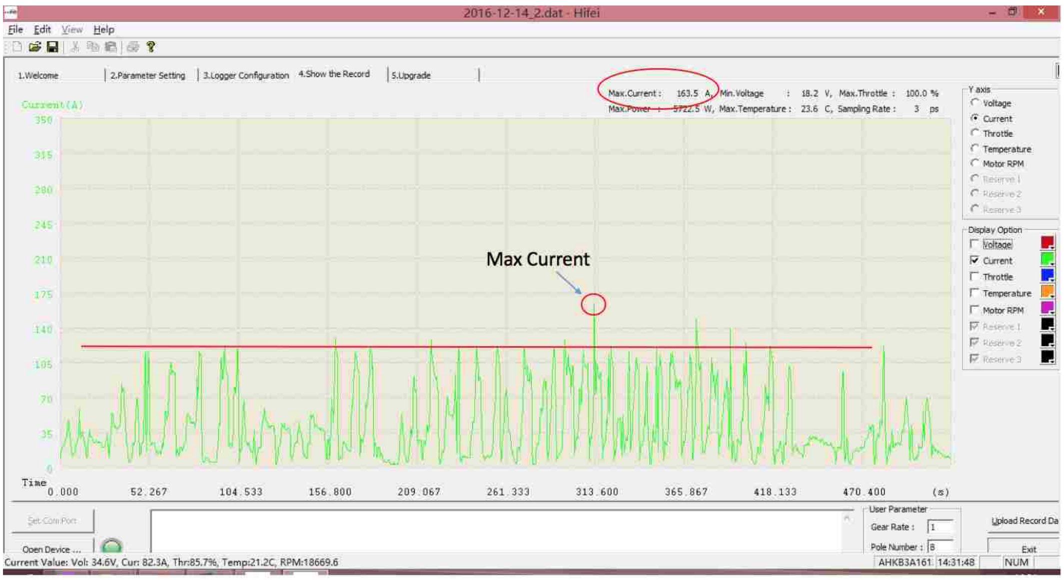


Figure 20: The Current vs Time for Test 2

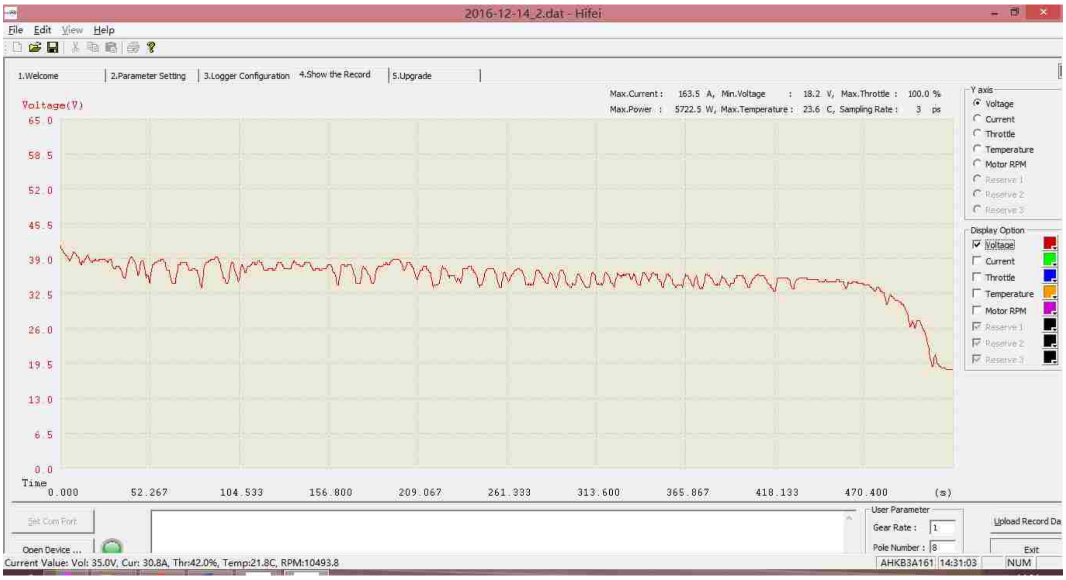


Figure 21: The Voltage vs Time for test 2

The second test concentrated more on maneuverability. 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.

The data was obtained from the model ESC.

The tests of the boat consisted of a large number of fairly short high-power sprints, followed by 180 degree turns. As shown in the Figures 19, 20 and 21, the max current was just over 160 A whereas most current peaks were around 130 A. This is less than the maximum allowed continuous current of the motor (150 A). The voltage was in the range 32 V ~ 40 V. The maximum power during this test was 5700W which is considerably lower than the maximum peak power of the motor

(8100 W). The peak rpm of the motor was 23,500, which is lower than the specified maximum rpm of the motor (28,120). The motor, ESC and batteries were once again operating well within their ideal ranges. Table 1 shows the data of test 2 and 3 and the specification of the motor.

6.2.1 Problems and improvements

A few changes were made after this test.

The center of gravity was moved 30 mm forward by mounting the two batteries about 100 mm forward in the center hull. The new center of gravity was 410 mm in front of the transom. 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 turnability, 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 the narrower track width of the rear sponsons. The front sponsons were re-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" as schematically depicted in Fig. 22. This may be beneficial for both yaw stability and turning.

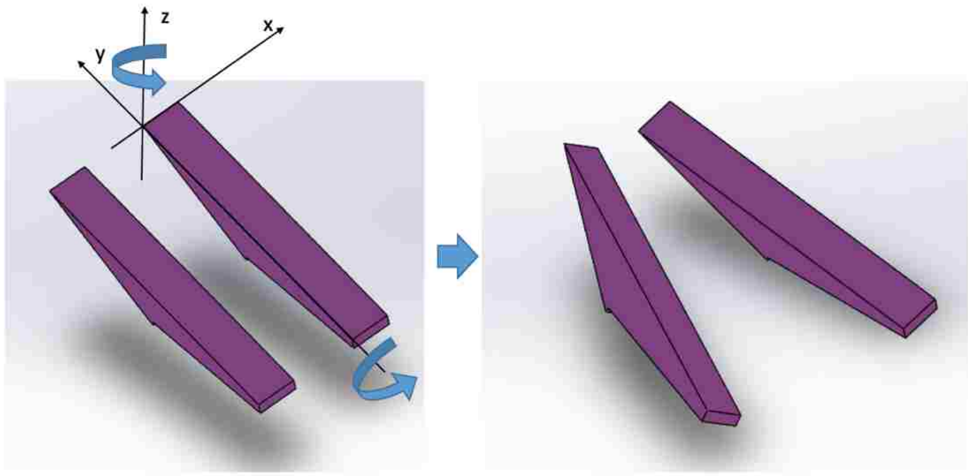


Figure 22: The schematic of the sponsons be adjusted

6.3 Test 3

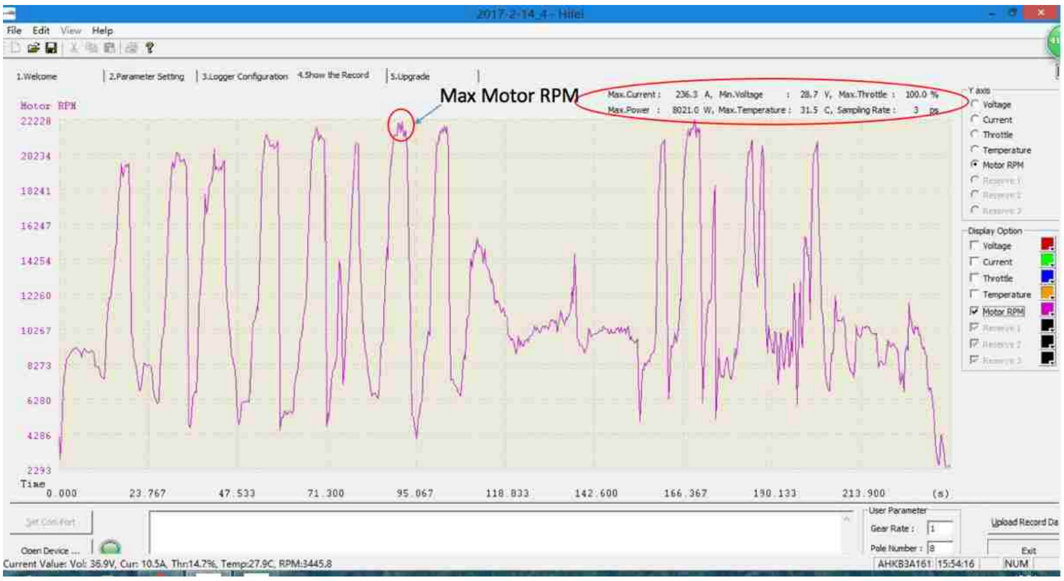


Figure 23: The Motor RPM vs Time for test 3

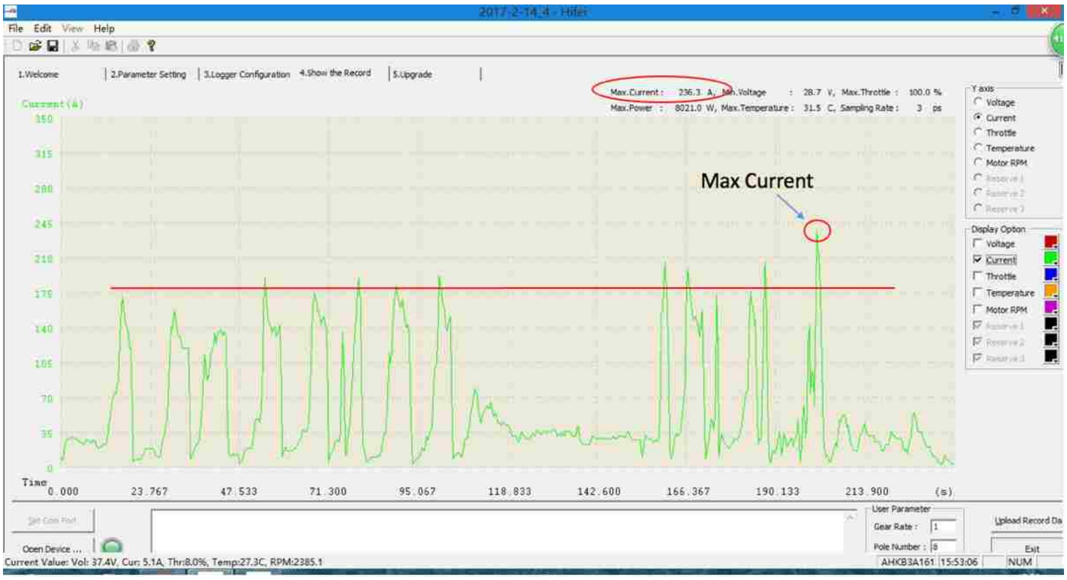


Figure 24: The Current vs Time for test 3

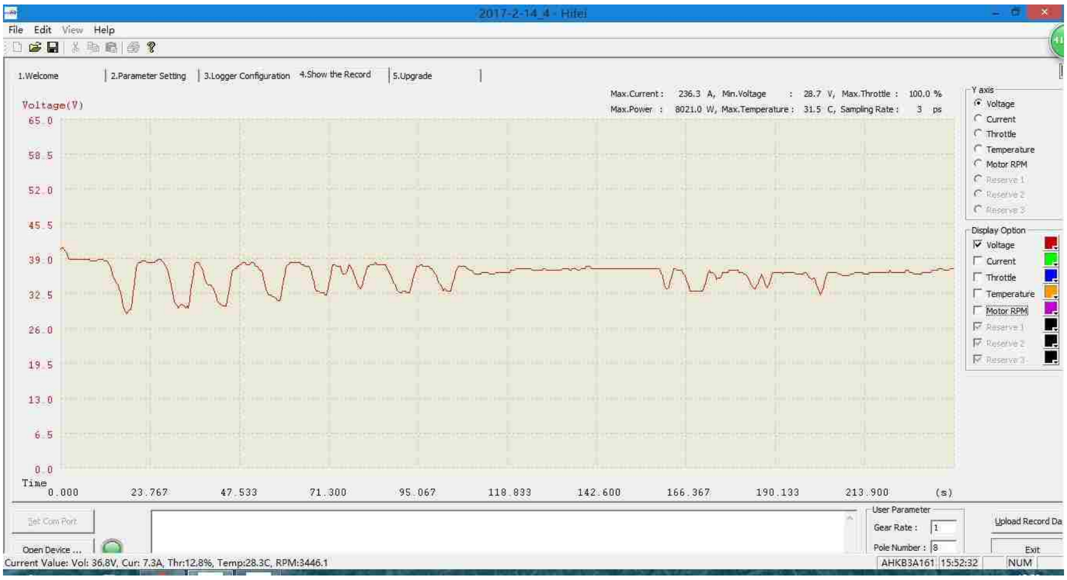


Figure 25: The Voltage vs Time for Test 3

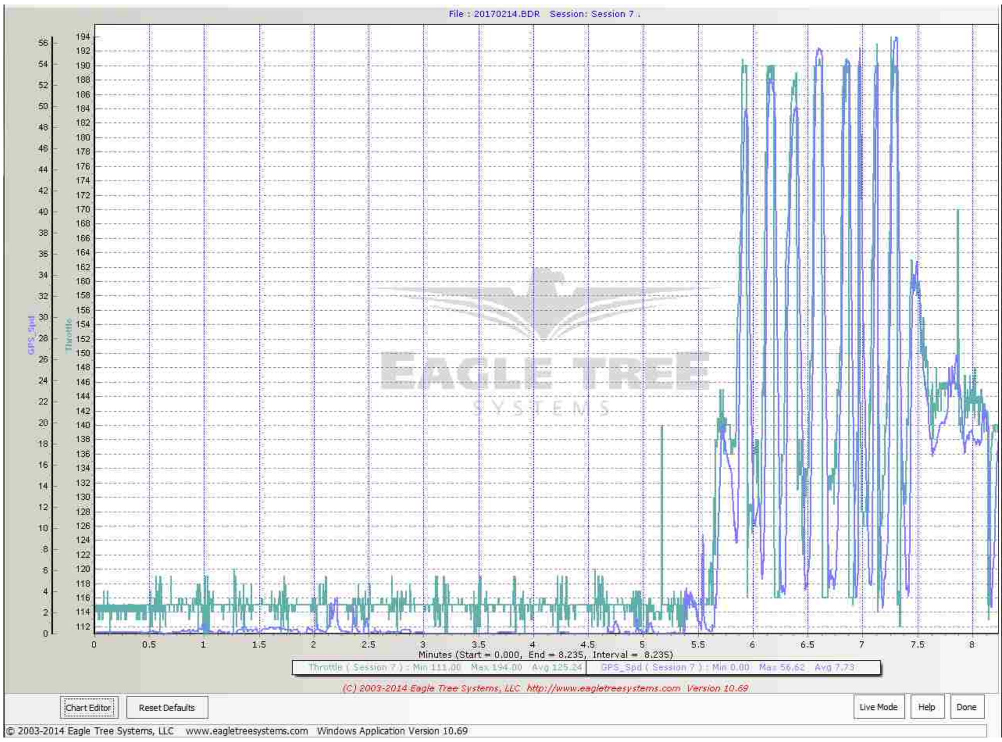


Figure 26: The GPS_Speed vs Time & Throttle vs Time 1

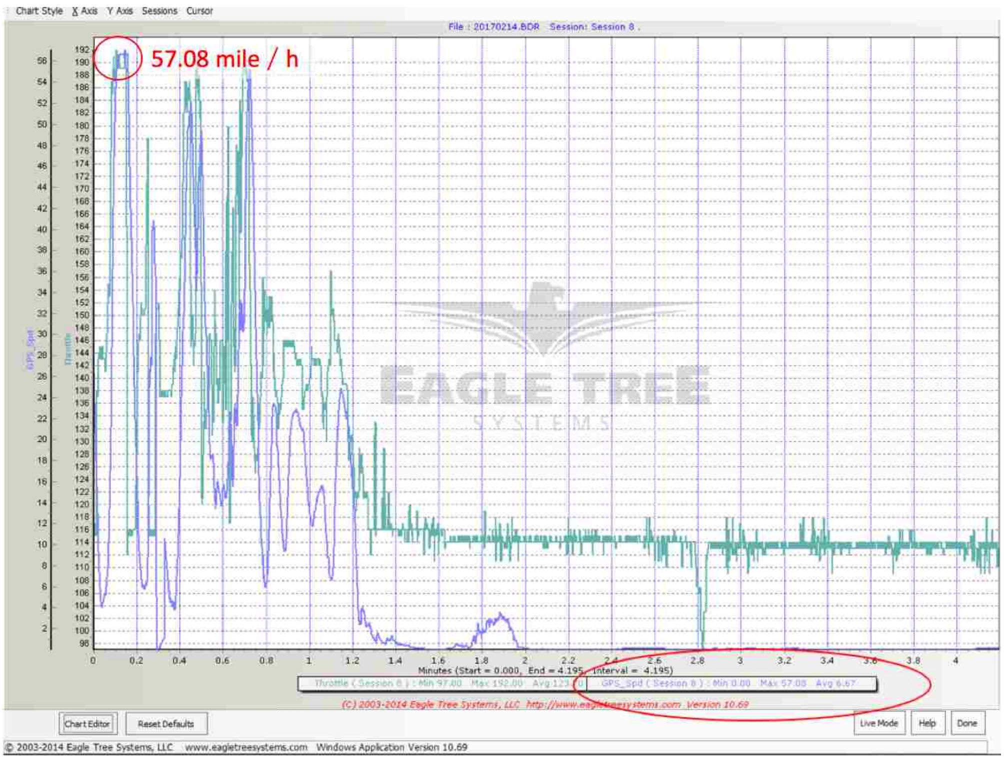


Figure 27: The GPS_Speed vs Time & Throttle vs Time 2

In the third test, the boat still had very good straight-line stability. 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 (Fig. 28). The toe-in did not appear to have any effect, neither positive nor negative. At one point during the test, throttle was applied too quickly and the boat flipped over backwards. At the end of the test one of the carbon fiber tubes for the sponson mount was broken, which is believed to have happened during this flip.

Figure 28: The attitude of the boat riding in the water

A 5880 propeller was used and an Eagle Tree eLogger V4 with GPS was installed in the hull before the test. Data are shown in Figures 23-27 and Table 1. Table 2 shows the specification of the propellers. The max current was 236 A whereas most current peaks were around 200 A. This is larger than the maximum allowed continuous current of the motor (150 A). The voltage was in the range 30 V ~ 39 V. The maximum power during this test was 8021 W which is close to the specified maximum peak power of the motor (8100 W). The max rpm of the moter was 22228, which is lower than the specified maximum rpm of the motor (28120). The maximum GPS speed was 91.86 km/h. The motor, ESC and batteries appeared to operate normally in spite of the high currents. The 5880 propeller was clearly too big and a smaller should be used to reduce the current.

	MHZ - Scorpion Motor HK-5035/760	Test 2	Test 3
Max Continuous Current (A)	150 A	130 A	200 A
Maximal peak power (W)	8100 W	5700 W	8021 W
Maximum rpm	28120	23546	22228

Table 1: Data of test 2 & 3 & specification of the motor

	Size (mm)	Pitch
Propeller 1417.56	56	78.4
Propeller 5880	58	80

Table 2: Specification of the propellers

6.3.1 Problems and improvements

As shown in Table 1 and 2, the diameter and pitch of the 5880 propeller were larger than of the 1417.56 propeller. The maximum rpm in test 3 was a little lower than that in test 2 but the current and power increased considerably. The boat appeared to run as in previous tests, although no GPS had been used before so there may have been a difference in speed. As the max continuous current in test 3 (~200 A) exceeded the max continuous current of the motor (150 A) the 5880 propeller was removed and the 14171.56 propeller reinstalled.

To further improve the turnabilit, after test 3 the rear sponsons were modified (Fig. 29) and fins were attached on the front sponsons (Fig. 30). Deflectors were installed on the outside of the rear sponsons at the angle of 45 degrees, with the intent to help the rear of the boat to slide sideways when the boat is making a turn.

Figure 29: New rear sponson

Figure 30: Fin on the front sponson

7. Conclusions

A 1:6 subscale suspension boat was manufactured and tested. In general the boat performed very well in water tests. The ride was stable and waves were absorbed very well. A good combination of motor, ESC, batteries and propeller were 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.

References

[1] GRENESTEDT, J.L., "Suspension Boat Dynamics," Transactions of the Royal Institution of Naval Architects (RINA), vol. 155 Part B1, pp. 43-49, 2013.

[2] GRENESTEDT,J.L., “Boat Suspension,” US Patent 20100000454.

APPENDEX A

The specification of the electronic devices

A. Motor

Motor	MHZ - Scorpion Motor HK-5035/760
Shaft Diameter	9.98mm
Water cooling	Y
Outside Diameter	61.0mm
Stator Diameter	50.0mm
Stator Thickness Magnet Poles	35.0mm 8
Motor Kv	760 KV RPM / Volt
Max Continuous Power	5800 Watts
Max Continuous Current	150 Amps
Weight	729 Grams
Body Length	75.0mm
Overall Shaft Length	100.7mm
Max Lipo Cell	8 ~ 10 S
Maximal peak power	8100 Watts
Motor Timing	5° max. 7,5

Table 3: The specification of motor

B. ESC

ESC	Voltage	Current/max	Size(mm)	Weight (incl. wires)
Swordfish Pro+ 300A-SHV	4-15S Lipo	300amp/380amp	119*72*27	495g

Table 4: The specification of ESC

C. BEC

BEC	CC BEC PRO
Max volts	Surface: 8S (33.6V) Air (w/Brake): 10S (42.0V) Air (No Brake): 12S (50.4V)
Adjustable output voltage	4.8 to 12.5V
Default setting	5.1V
Peak current	20A
Continuous current	2S-4S: 15A 5S-6S: 13A 7S-8S: 11A 9S-10S: 9A 11S-12S: 8A
Size(mm)	47*33*22
Weight	40g

Table 5: The specification of BEC

D. Servo

Servo	Voltage	Stall Current Draw	Maximum torque Range kg./cm.	Dimensions (mm)	Weight(Gram)
HS-5646WP	6.0V~7.4V	2100mA	11.3~12.9	41.8*21.0*40.0	61.0

Table 6: The specification of Servo

E. eLogger

	Voltage Measurement	Current Measurement	Current Draw	Dimensions (mm)	Weight (gram)	Capture rate
eLogger V4	5V~80V	up to 100 Amps peak	approx 30 mA with no sensors	57*28*13	22	10 samples per second

Table 7: The specification of eLogger

VITA

Zhangning Wang, born in Shanghai, China in 1992. She received the degree of Bachelors of Engineering in Tongji University, Shanghai, China in June 2015. After that, she attended Lehigh University pursuing a Master of Science degree supervised by Professor Joachim L. Grenestedt.