Measurement of Propeller Lift Force

Lab 2 Final Report

VM495 Mechanical Engineering Laboratory II

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Abstract

The increasing use of Small Unmanned Aerial Vehicle (SUAV, such as quadrotor) has triggered the interest in analyzing the performance of the motor(s) mounted with the propeller(s) that power them. The objective of this experiment is to measure the lift force of a single propeller under static condition, find out its relation with the rotating speed (Test 1), and study the effect of wind shield located under the rotating propeller (Test 2) as well as the vibration of unbalanced propellers (Test 3). For Test 1, the experimental results show that when the propeller was rotating under static condition (zero flight speed), the lift force it generated was proportional to the square of its rotating speed. Furthermore, at the same rotating speed, the propeller with larger diameter, larger pitch, and more blades would generate larger lift force. For Test 2, the wind shield, with larger area and smaller distance under the propeller, would increase the propeller lift force. For Test 3, more unbalance of the propeller would result in larger vibration. However, it is difficult to well quantify the unbalance. Finally, with good repeatability, the data collected in this experiment and the self-made measuring device can be used to verify whether the SUAV is able to accomplish the proposed mission with the target motor(s) and propeller(s).

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1. INTRODUCTION

Quadrotor is a type of Small Unmanned Aerial Vehicle (SUAV). It has been becoming more and more popular all over the world due to its excellent motion performance. It can not only adapt to complex terrains but also accomplish difficult flight missions. With modules of various functions, quadrotor has great potential in many fields, such as search and rescue, prospection of zone of ignorance and monitor of public territory. The realization of the latest control algorithm allows the quadrotor to resist large excitation with high accuracy. Figure 1.1 shows the free body diagram of a typical quadrotor.

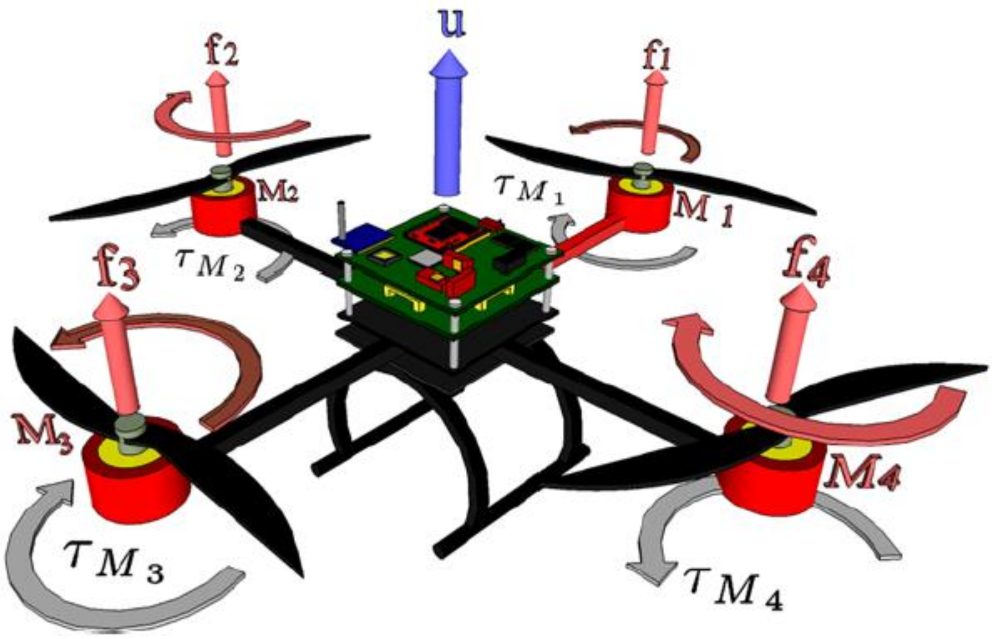


Figure 1.1: Free body diagram of the quadrotor. Retrieved from http://www.mathworks.com/matlabcentral/answers/109279-modelling-a-quadrotor-with-simmechanics.

Propellers provide the thrust force (also known as lift force under static condition) for many of these SUAVs and the magnitude of the thrust force is largely dependent on the propeller characteristics (such as diameter, pitch, blade number, etc.), the rotating speed of the propeller, and the flight speed (indicated as *u* in Figure 1.1).[1] Since the small-scale propellers have relatively small thrust coefficient and low efficiency, current research focuses on the improvement of these two parameters.

2. TEST OBJECTIVE

The objective of this experiment is to measure the lift force of a single propeller uner static condition, find out its relation with the rotating speed, and study the effect of the wind shield located under the rotating propeller as well as the vibration of unbalanced propellers. At the beginning, a particular measuring fixture was designed and fabricated. It combined a photo detector (to measure the motor speed), a load cell (to measure the force), a brushless motor mounted with the test propeller, and a detachable wind shield. Algorithm for the photo detector and calibration for the load cell were then carried out to obtain the final results, e.g., the rotating speed and corresponding lift force.

For Test 1, pitch is defined as the displacement a propeller makes in a complete spin of 360 °angle, shown in Figure 2.1.[3]

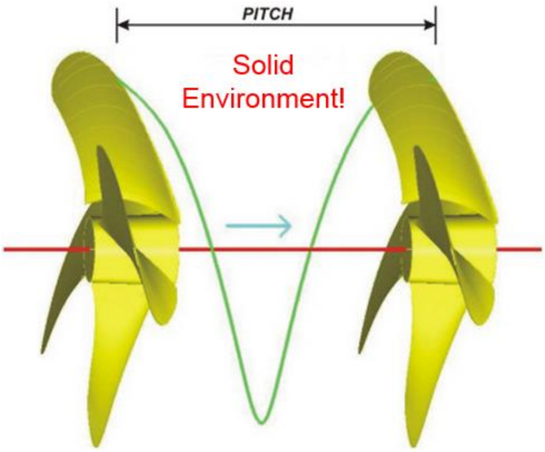


Figure 2.1: Pitch.[3]

For Test 2, Figure 2.2 shows the wind shield. Note that each block has an angle of 45 °.

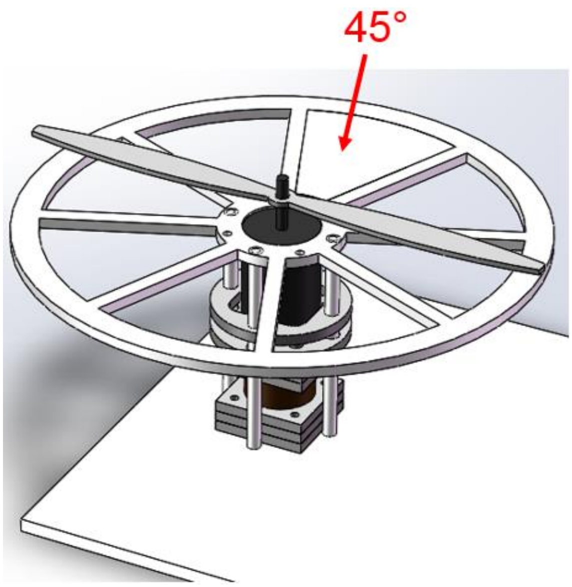


Figure 2.2: Wind shield.

For Test 3, Figure 2.3 shows a balanced propeller. Figure 2.4 shows an unbalanced propeller due to wear. Figure 2.5 shows an unbalanced propeller due to wear and cut.

Figure 2.3: Balanced propeller.

Figure 2.4: Unbalanced propeller due to wear.

Figure 2.5: Unbalanced propeller due to wear and cut.

2.1 Test 1 - Effect of Propeller Diameter, Pitch, and Blade Number

Step 1: Assemble the experimental setup and check whether the brushless motor work normally.

Step 2: Install the propeller and check whether the propeller is well assembled.

Step 3: Rotate the adjusting knob to 10 fixed values. For each value, record the data of photo detector and load cell through NI myDAQ. The number of data is 8192 (= 2^{13}) for each sensor and for each value.

Step 4: Change the propeller with different characteristics (diameter, pitch, and blade number) and redo step 3.

2.2 Test 2 - Effect of Wind Shield under Propeller

Step 1: Assemble the wind shield with no piece on it.

Step 2: Install the propeller and check whether the propeller is well assembled.

Step 3: Rotate the adjusting knob to a certain value and record the data of photo detector and load cell through NI myDAQ.

Step 4: Assemble one block on the wind shield and record the data of photo detector and load cell through NI myDAQ.

Step 5: Assemble another block on the wind shield and redo step 4 until all 8 blocks assembled on the wind shield.

Step 6: Change four different distances between the wind shield and propeller. For each time, record the data of photo detector and load cell through NI myDAQ.

2.3 Test 3 - Vibration of Unbalanced Propellers

Step 1: Assemble a balanced propeller and record the data of photo detector and load cell through NI myDAQ..

Step 2: Wear the propeller (Figure 2.4) and record the data of photo detector and load cell through NI myDAQ.

Step 3: Further cut a small part of the propeller (Figure 2.5) and record the data of photo detector and load cell through NI myDAQ.

3. EXPERIMENTAL SETUP

Figure 3.1 shows the entire experimental setup. In particular, it consists of two main parts. One is the mechanical setup and the other is the electrical setup.

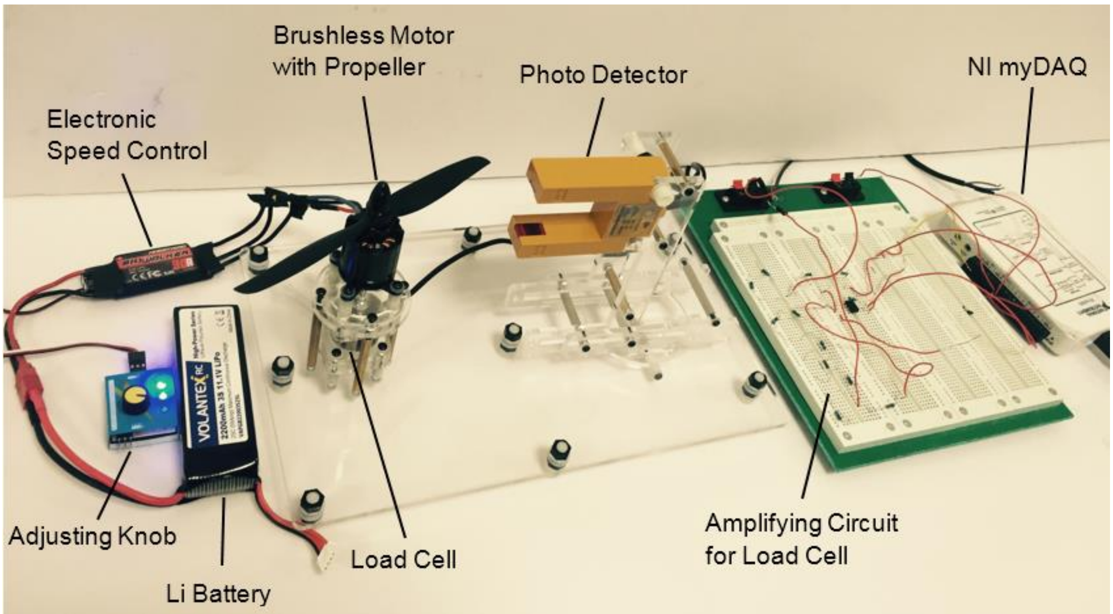


Figure 3.1: Experimental setup.

3.1 Mechanical Setup

Figure 3.2 shows the mechanical setup design. The yellow component is the photo detector (which we borrow from the Mechanical Lab), the black component is the brushless motor, and the brown component below is the load cell we bought. The design was carried out in *SolidWorks*, aiming to clearly demonstrate the design itself, as well as to verify that the dimensions of all the components could make the setup work for different motors and propellers. Note that the mobility is quite important for this experiment, shown in Figure 3.3.

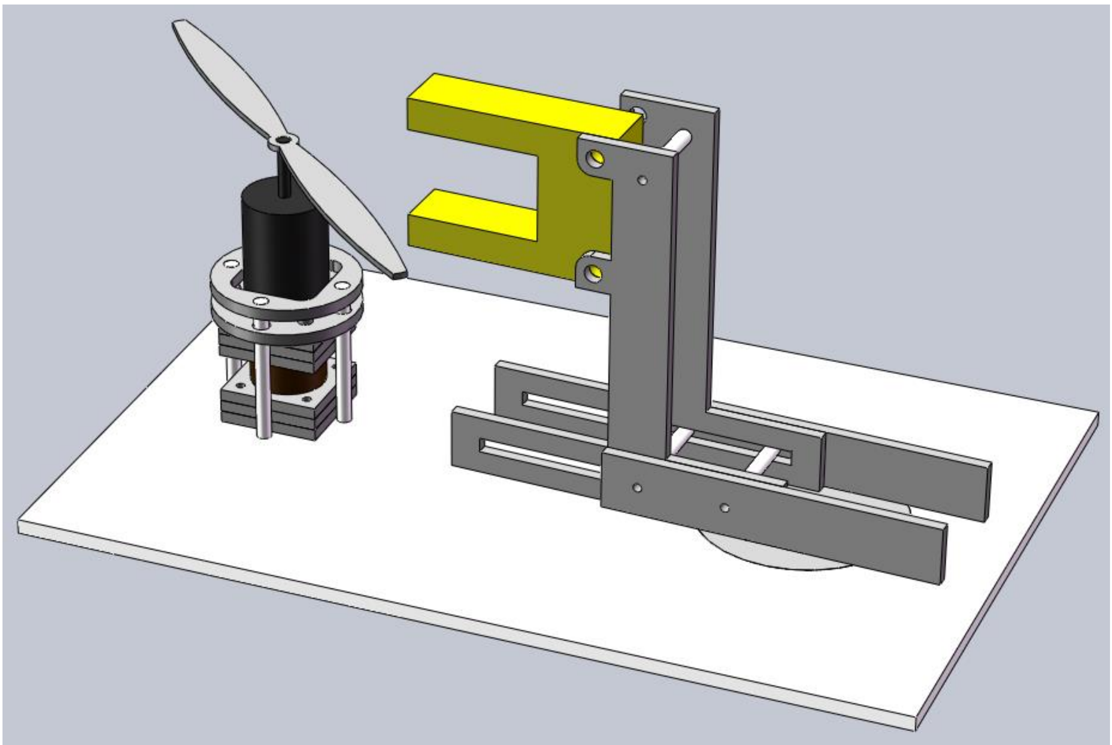


Figure 3.2: Experimental setup design.

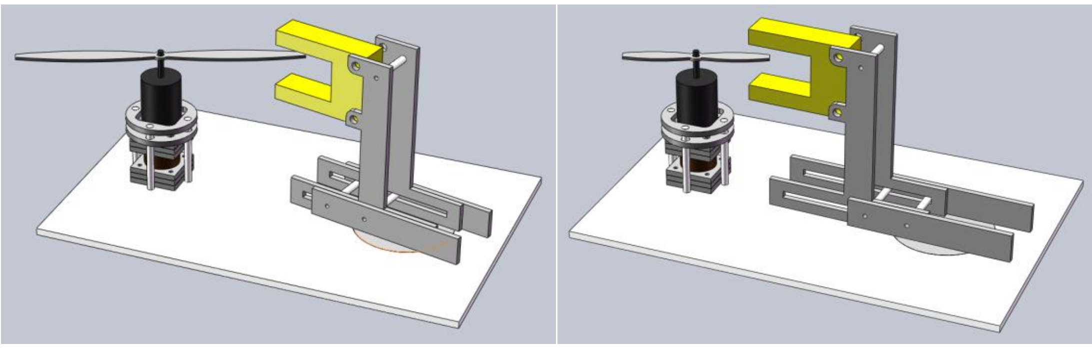


Figure 3.3: Experimental setup mobility.

Figure 3.4 shows the mechanical setup we fabricated. The main material we used is acryl since it is easy to fabricate as well as has enough strength. We first translated the 3D *SolidWorks* file into 2D *AutoCAD* file. With the help of Mr. Chen Tianhua, we then used the laser cutting machine to obtain each component. Later, we assembled the entire mechanical setup with auxiliary materials, such as bolts, nuts, columns, etc. It turned out that the design met the experimental requirements.

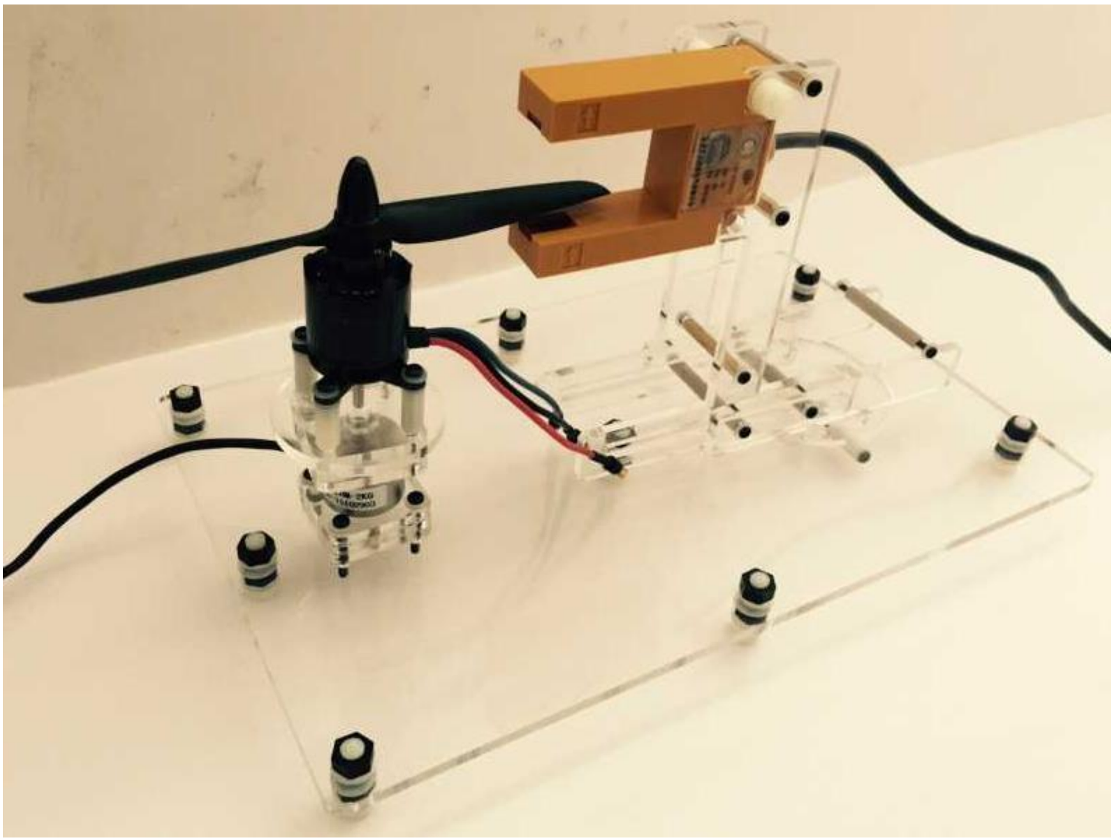


Figure 3.4: Mechanical setup.

3.1.1 Load Cell Fixture

As shown in Figure 3.5, the load cell we bought had thread at both ends. Therefore, we used three layers of acrylic boards, with the middle one left a space for an M5 nut, to fix the load cell, shown in Figure 3.6. The upper end was applied the same method.

Figure 3.5: Load cell with thread at both ends.

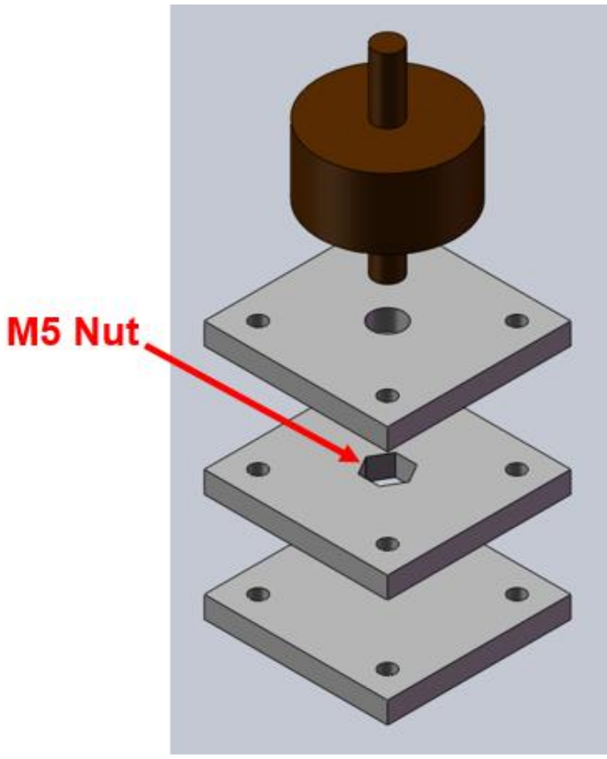


Figure 3.6: Load cell fixture.

3.1.2 Motor Fixture

The modified design was to connect the motor and the load cell with bolts and acrylic boards instead of a string. However, when the motor mounted with the propeller was rotating, it created a torque as well as a lift force. So in order to balance the torque, we used four columns to prevent the rotation of the motor, shown in Figure 3.7. The fixture only allowed vertical motion, which was exactly what we wanted.

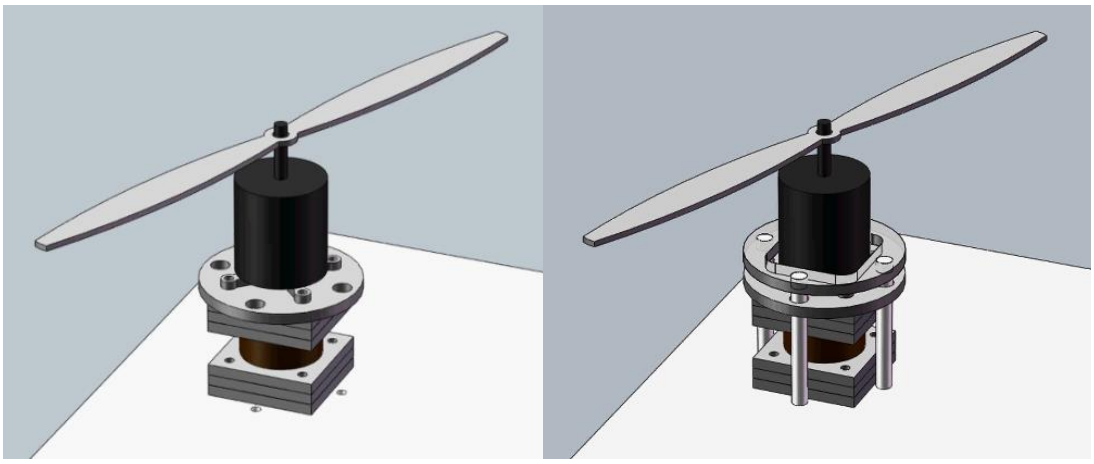


Figure 3.7: Motor fixture.

3.2 Electrical Setup

The electrical setup is shown in Figure 3.8. No.1 component is the Lithium battery which can provide 11.1V voltage. This Li battery could supply power for every electrical component. No.2 component is ESC (Electric Speed Control) which is used to control the rotating speed of the brushless motor by changing the voltage across it. No.3 component is the brushless motor which is used to drive the propeller. No.4 component is the adjusting knob which could send pulse signal to ESC and ESC would change the voltage across the motor accordingly.

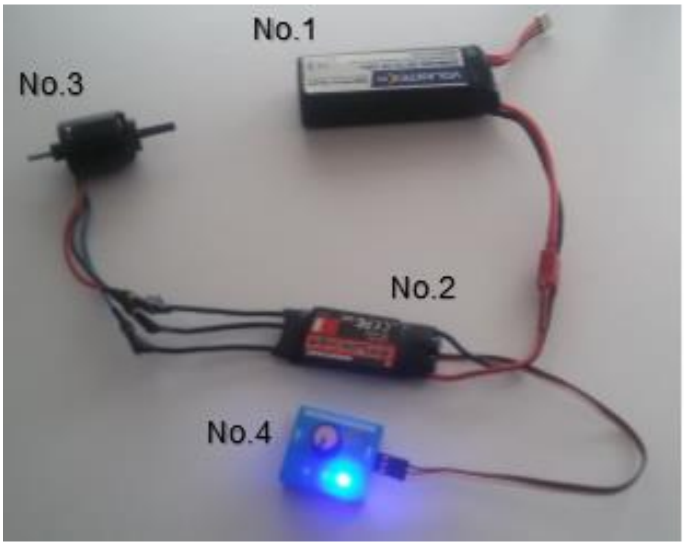


Figure 3.8: Electrical setup.

3.2.1 Motor Connection

The brushless motor was connected to ESC. Since the brushless motor worked on three-phase alternating current, it required three lines to connect with each other, as shown in Figure 3.9. The middle black wire of the brushless motor was connected with the middle wire of ESC. The other two wires of the motor were connected with the other two wires of ESC. If you want to change the direction of rotation, you can exchange the connection of these two wires.

Figure 3.9: Connection between the motor and ESC.

3.2.2 KV Value

Figure 3.10 shows the three types of motors we used in this experiment. Each of them had different KV values. KV value is defined as the theoretical RMP the motor can rotate per voltage input. Therefore, the theoretical RPM of a motor under certain voltage is determined by

$$\text{RPM} = \text{KV Value} \times \text{Input Voltage}. \tag{2.1}$$

Hence, under the same voltage, the higher KV value will result in higher RPM; however, higher RPM will lead to lower torque. Therefore, when we used the motor with large KV value, we chose small-size propeller; otherwise, no lift force would be expected.

KV 880 KV 1250 KV 2400

Figure 3.10: Three motors with different KV values.

4. SENSORS

4.1 Photo Detector

We used photo detector to measure the rotating speed of the propeller. Specifically, we recorded the output signal to monitor the passing of the propeller blade through the photo detector. In addition to the general introduction of the photo detector, this part includes the sensitivity of the photo detector and methodology to obtain the RPM. The detailed characteristics of the photo detector are listed in Table 4.1.

Table 4.1: Photo detector characteristics.

Type	E3S-GS3E4
Sensing Distance	30 mm
Voltage Supply	12 ~ 24 V
Response Time	1 ms

4.1.1 Sensitivity

Since we need to measure the RPM of the propeller, we require a relative high sensitivity of the photo detector to catch each resolution. Our photo detector can record signal one times per millisecond. Therefore, the theoretical maximum RPM it can measure is given by

$$\mathrm{RPM_{max}} = \frac{2\pi}{n} \times \frac{1}{10^{-3}} \times \frac{60}{2\pi} = \frac{60000}{n}, \tag{4.1}$$

where n donates the number of blades.

4.1.2 Data Processing

Initially, we wanted to calculate RPM in a simple and direct way, which was recording the times N that the propeller passed the photo detector in 1 second and the RPM is thus given by

$$\mathrm{RPM} = N \times 60. \tag{4.2}$$

Figure 4.1 shows the output signal of photo detector and we can see crowed voltage changes in a small time interval. We also see some overlap between the signal change and boundary line, which may cause errors of algorithm when LabVIEW makes judgments of whether the propeller passes the gate. We even found the data were not accurate or precious, so we tried another method.

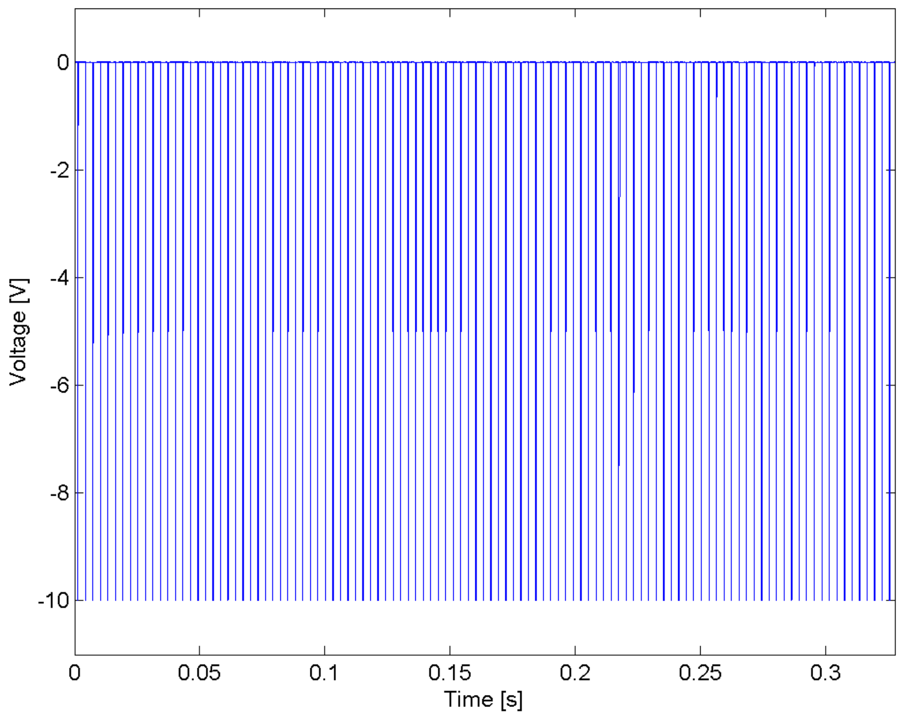


Figure 4.1: Output signal.

In the second method, in order to make sure of high accuracy, we recorded the time interval t between 2 voltage changes, shown in Figure 4.2. For an n-blade propeller, one signal change means the propeller goes through a semicircle. Then it takes $n\,t$ time to make a full circle and thus the rotating speed of the propeller can be calculated by

$$\text{RPM} = \frac{60}{n \cdot t}. \tag{4.3}$$

where n donates the number of blades.

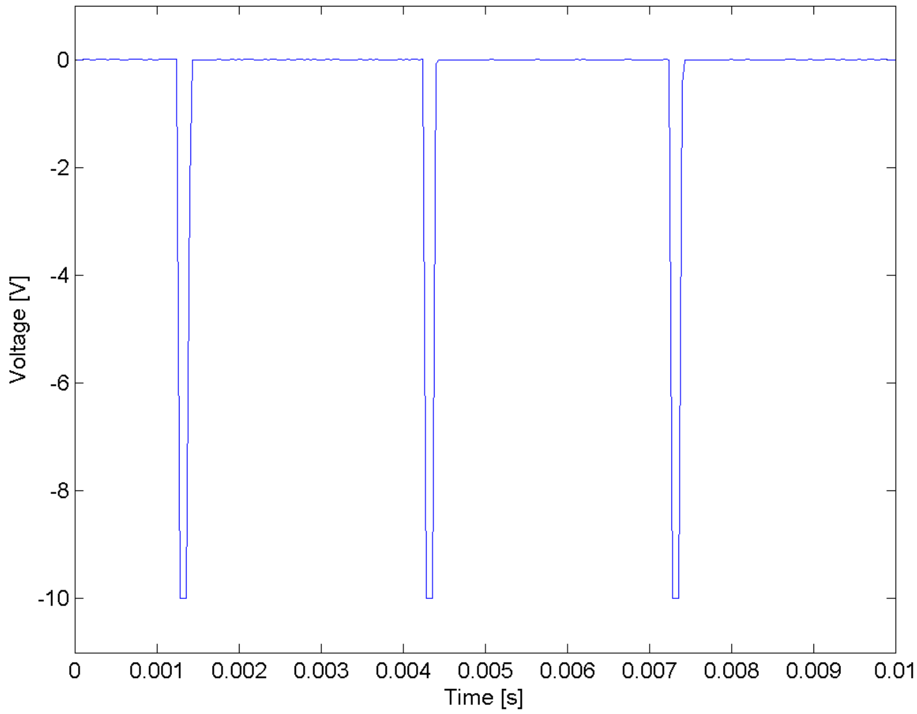


Figure 4.2: Output signal in time interval 2t.

The RPM calculated by this method was correct and accurate theoretically. The numerical value of t was around 10^{-3} s, which was extremely small. Therefore, a little error of t would lead to a large difference of RPM, which means a relative large uncertainty of RPM would occur in this method. To avoid this, we tried another method, which is FFT.

In the last method, we used FFT to get an accurate value of RPM with a relative small uncertainty compared to previous methods. As shown in Figure 4.3, the first peak represents the FFT constant C_0 and the second peak is the fundamental frequency f_0. Note that for a certain RPM, we take 8192 (= 2^{13}) data for calculation and the sampling rate is 20 kHz.

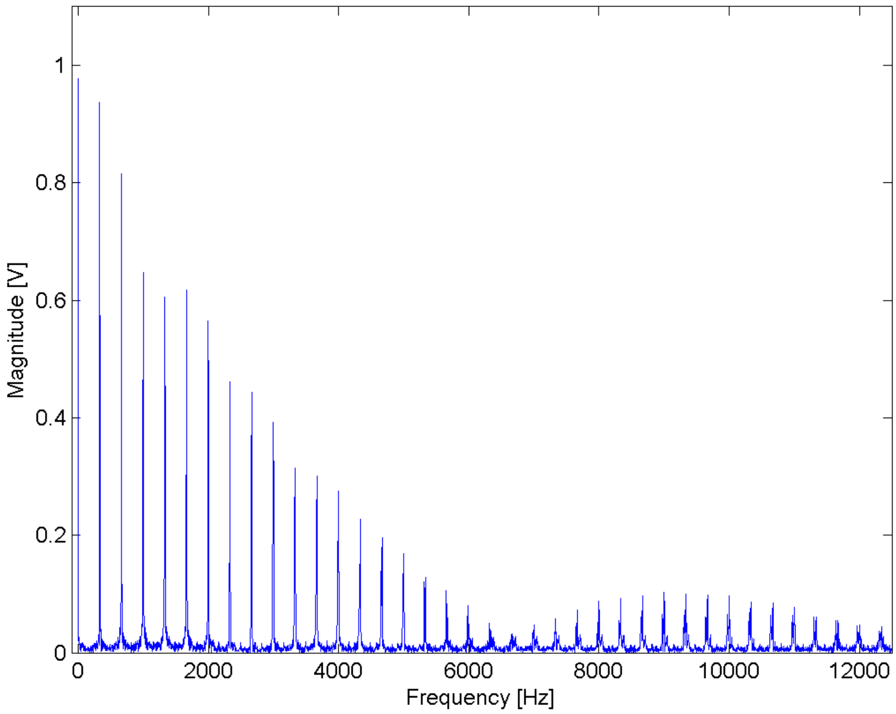


Figure 4.3: FFT of output signal.

Therefore, the rotating speed can be determined by

$$\mathrm{RPM} = f_0 \times \frac{60}{n}, \tag{4.4}$$

where n donates the number of blades.

4.2 Load Cell

Since our object is to find out the relationship between the lift force and the propeller rotating speed, we have a high requirement for the range and the resolution of the load cell. Overall, we want to find a load cell with the following characters: proper range, small size, high resolution, fine stability and easy installation.

After consulting the engineers in the lab and owner of TaoBao, we got the general data for a motor that, if mounted a 10'' propeller, the lift force would achieve 600 g when the rotating speed was around 8000 RPM. Considering the fact that in the experiment, the size of the propeller varied from 5'' to 10'', we decided to choose a load cell with capacity ±2 kg. The detailed parameters are listed in Table 4.2.

Table 4.2: Load cell characteristics.

Type	BSLM-3
Capacity	±2 kg

Rated Output	1.5 mV/V
Non-Linearity	±0.1% FS
Zero Balance	±0.1% FS
Hysteresis	±0.1% FS
Creep (in 30 minutes)	±0.05% FS
Repeatability	±0.1% FS

4.2.1 Test Experiment

The load cell could be easily installed into the fixture, and then we started to test the actual using condition. In the first trial, the results were horrible, shown in Figure 4.4. Noises greatly disturbed the normal output voltage, making us really difficult to tell what the exact output voltage was. The normal input voltage in the lab was around 10 V; hence the expected maximum output voltage was only around 15 mV. The output results were then greatly affected by the noises. Hence, we decided to design an amplifying circuit to increase the output voltage as well as to reduce the noise effect.

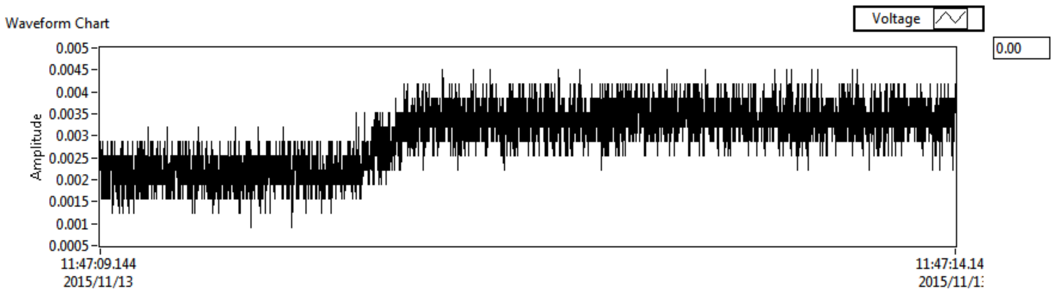


Figure 4.4: Load cell output without the amplifying circuit.

Figure 4.5 shows the designed amplifying circuit, with R_1 = 815 kΩ, R_2 = 217 Ω, R_3 = 803 kΩ, and R_4 = 218.3 Ω. By substituting them into Equation (4.5):

$$\frac{V_{out}}{V_{in}} \approx \frac{R_1}{R_2}, \tag{4.5}$$

we can derive that the output voltage of the load cell was increased by about 3755 times, which is exactly what we desired.

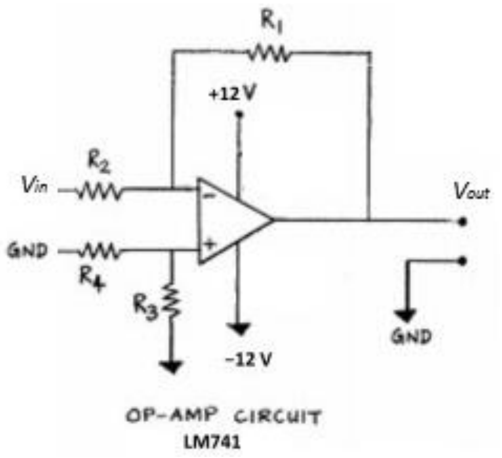


Figure 4.5: Designed amplifying circuit.[4]

After applying the amplifying circuit, although the noises still exists, its negative influence was greatly reduced, as shown in Figure 4.6.

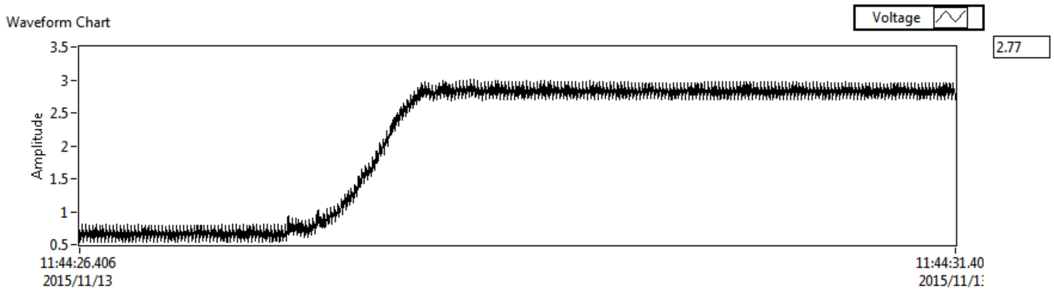
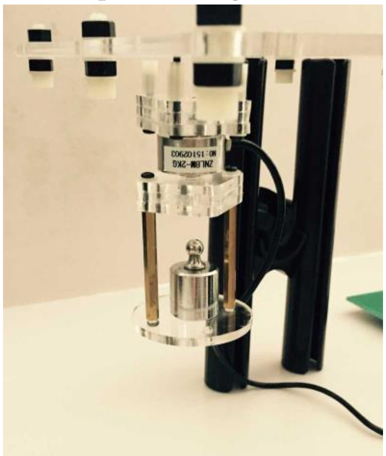


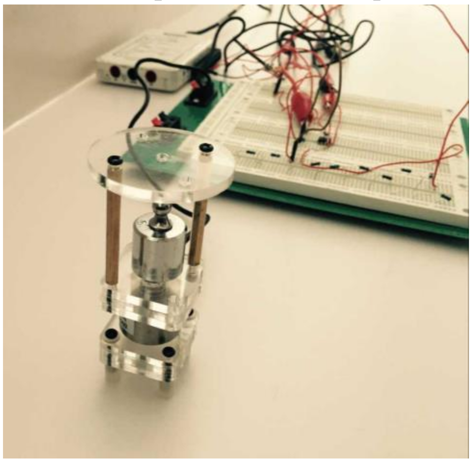
Figure 4.6: Load cell output with the amplifying circuit.

4.2.2 Calibration

We conducted a calibration test for our purchased load cell. Figure 4.7 (a) shows the tension test setup while Figure 4.7 (b) shows the compression test setup.



(a) Tension.



(b) Compression.

Figure 4.7: Calibration test setup.

The test methodology was that we recorded the output voltage of the load cell for every 50-gram increase in the weight, starting from the free-of-weight condition (but the shelf structure, used to place the weight, was still mounted) to the maximum weight our propellers can lift. Figure 4.8 shows the calibration result. As we can see, although we have already taken the weight of the shelf structure into consideration, there still exists a zero error, meaning that the output voltage of the load cell is not zero when it is free of any load. And this zero error depends on the direction of the load cell. Note that in Figure 4.7, the direction of the load cell in the tension test setup was opposite to that in the compression test setup. Besides, the calibration result was quite good. We can conclude that the output voltage of the load cell linearly depends on the load acted on it.

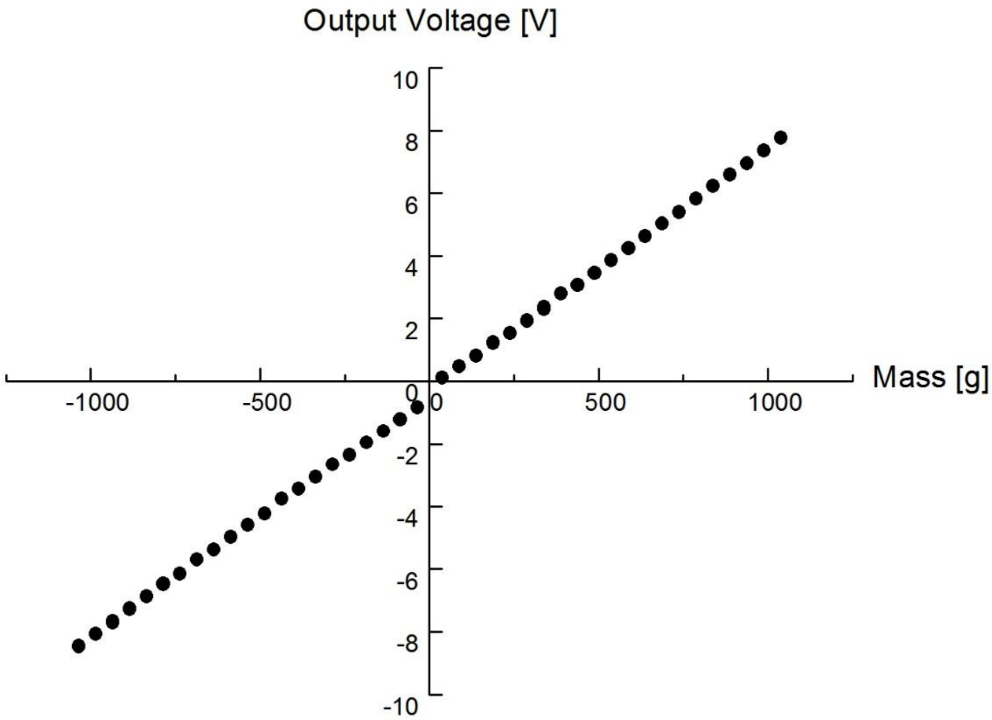


Figure 4.8: Calibration test result.

Note that for every data point shown in Figure 4.8, we actually recorded 20 times, shown in Figure 4.9. As we can see, the fluctuation was within 30 mV, indicating a 0.39% error for this data, which is quite acceptable.

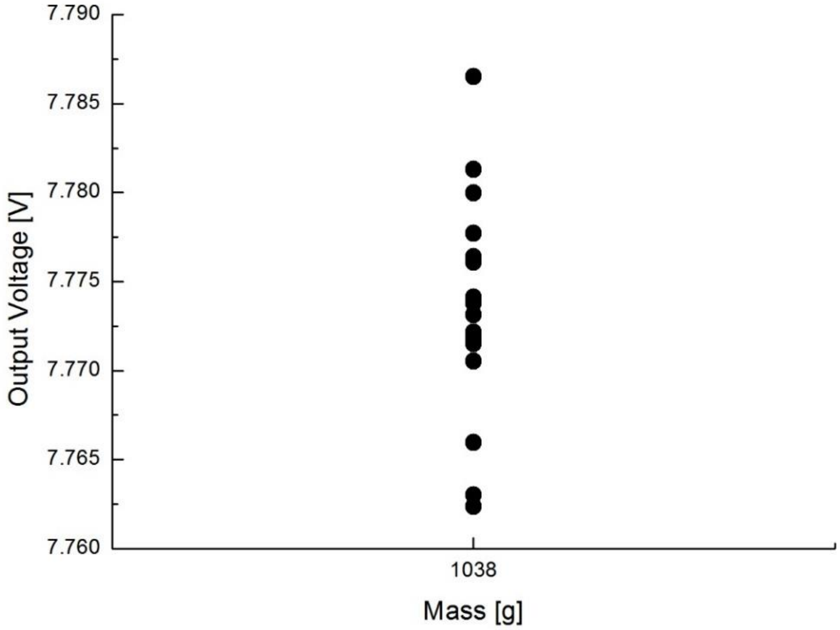


Figure 4.9: Output voltage for 1038-gram tension.

4.2.3 Data Processing

Figure 4.10 shows the transient step response of the load cell. Before the propeller was rotating, the fluctuation due to noise was only about ±10 mV. However, when the propeller was rotating, the fluctuation due to vibration was around ±200 mV, almost 20 times the initial value. Therefore, at a certain rotating speed, we recorded 8192 (= 2^{13}) voltage data, converted them into force according to the calibration, and finally treated the mean value as the corresponding lift force. For each propeller, lift force was measured at 10 different rotating speeds.

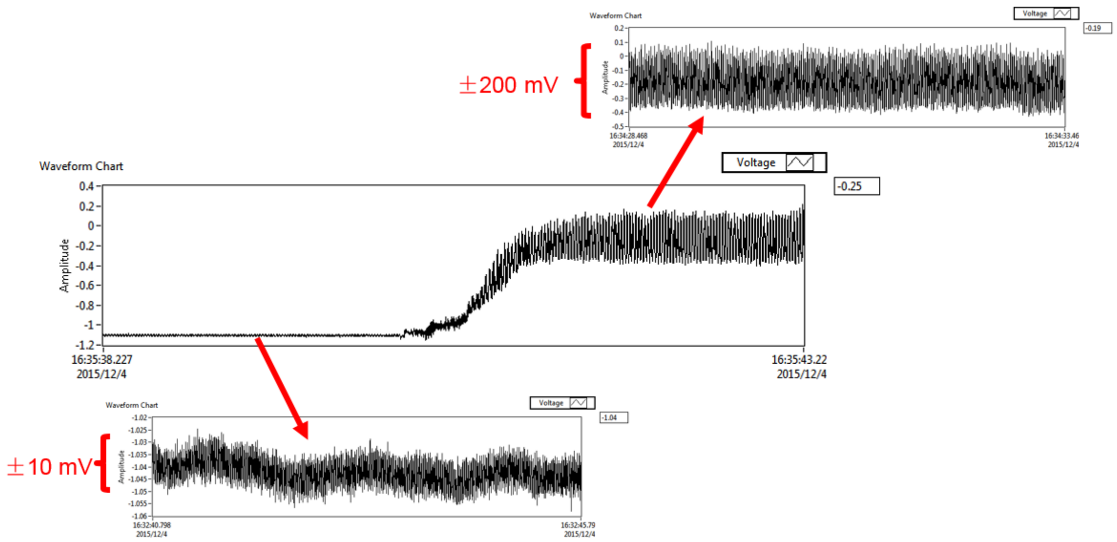


Figure 4.10: Transient step response.

5. RESULTS & DICUSSION

The nomenclature of the propeller is important for understanding the results. For a 2-9×6E, the blade number is 2, the diameter is 9 inches, and the pitch is 6 inches. Pitch is defined as the displacement a propeller makes in a complete spin of 360° angle in a solid environment.[3] Note that in a liquid environment, the propeller will slide with less displacement. Figure 5.1 shows the relationship between the rotating speed and corresponding lift force for the 2-9×6E propeller, with a quadratic polynomial fitting. As we can see, the fitting result is quite good, which indicates that the propeller lift force is proportional to the square of the rotating speed at zero flight speed.

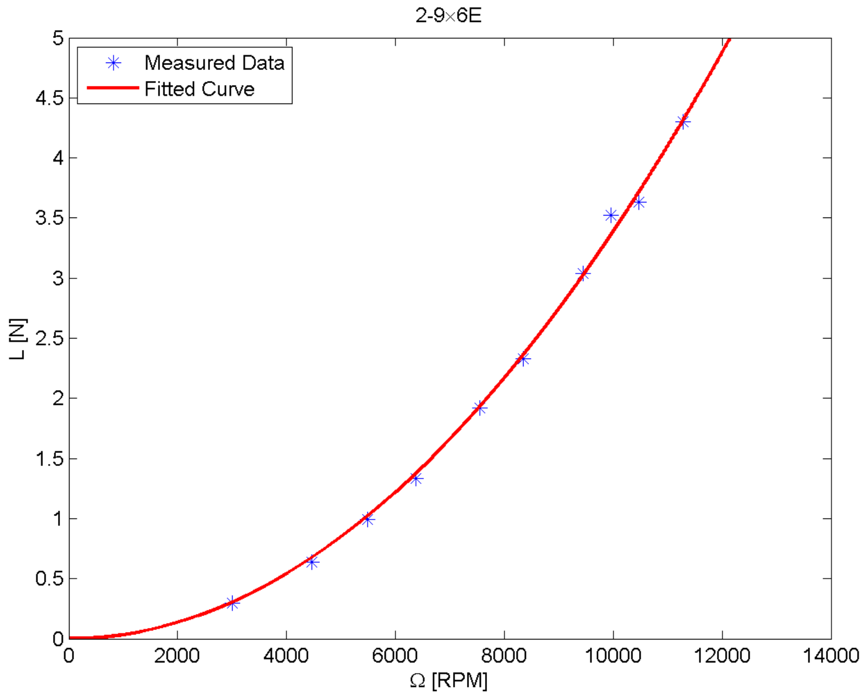


Figure 5.1: Lift force vs. rotating speed.

To verify the confidence in the measurement, a repeatability test were carried out. In particular, we conducted three tests for each of the propeller on three different days, as shown in Figure 5.2. As we can see, the three curves almost overlap with each other, which indicates that the measurement is repeatable. Other propeller repeatability test results are shown in Appendix A.

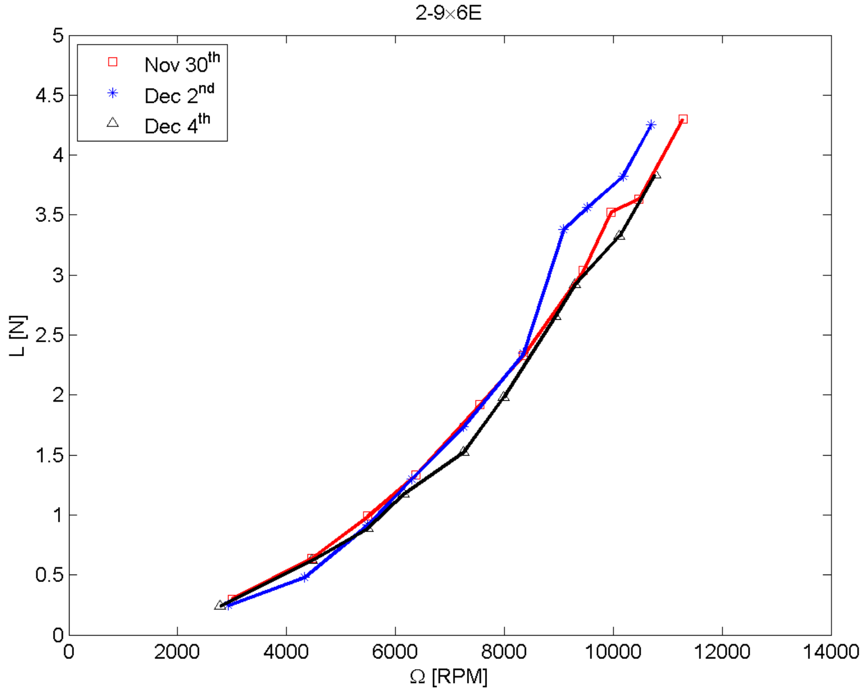


Figure 5.2: Repeatability test results.

For a more general perspective, the performance of a propeller is given in term of the lift coefficient, defined as

$$C_L = \frac{L}{\rho n^2 D^4}, \tag{5.1}$$

where L is the lift force, ρ is the air density, n is the rotating speed, and D is the propeller diameter[1]. Figure 5.3 shows the relationship between the rotating speed and corresponding lift coefficient for the 2-9×6E propeller. We can see that the lift coefficient is almost independent of the rotating speed, which makes sense. We have previously verified that there is a quadratic relationship between the rotating speed and corresponding lift force. With Equation (5.1), the lift coefficient is thus a constant for a certain propeller.

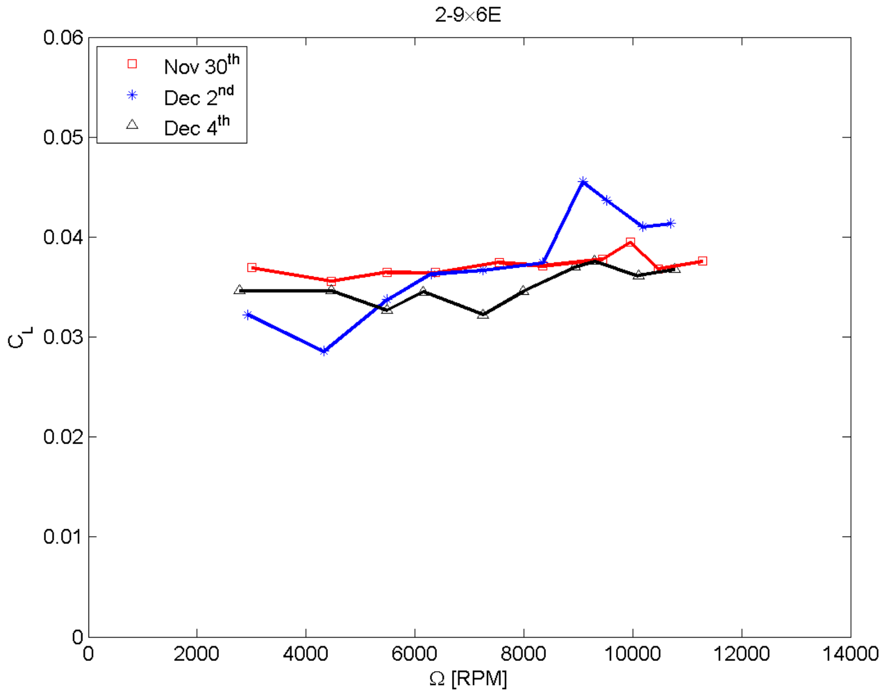


Figure 5.3: Lift coefficient vs. rotating speed.

5.1 Test 1 - Effect of Propeller Diameter, Pitch, and Blade Number

Figure 5.4 shows the effect of propeller diameter, pitch, and blade number on lift force. The experimental results show that when the propeller was rotating at the same rotating speed, the propeller with larger diameter, larger pitch, and more blades would generate larger lift force.

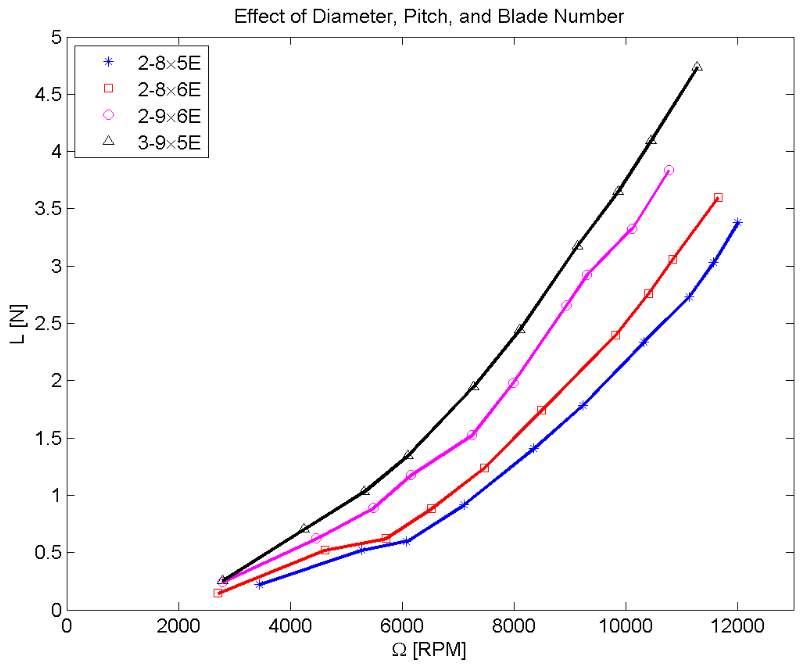


Figure 5.4: Effect of propeller diameter, pitch, and blade number on lift force.

Figure 5.5 shows the effect of propeller diameter, pitch, and blade number on lift coefficient. As we can see, the propeller with larger pitch, and more blades would have larger lift coefficient. However, the difference in the propeller diameter did not result in too much change in the lift coefficient. More detailed figures are presented in Appendix A.

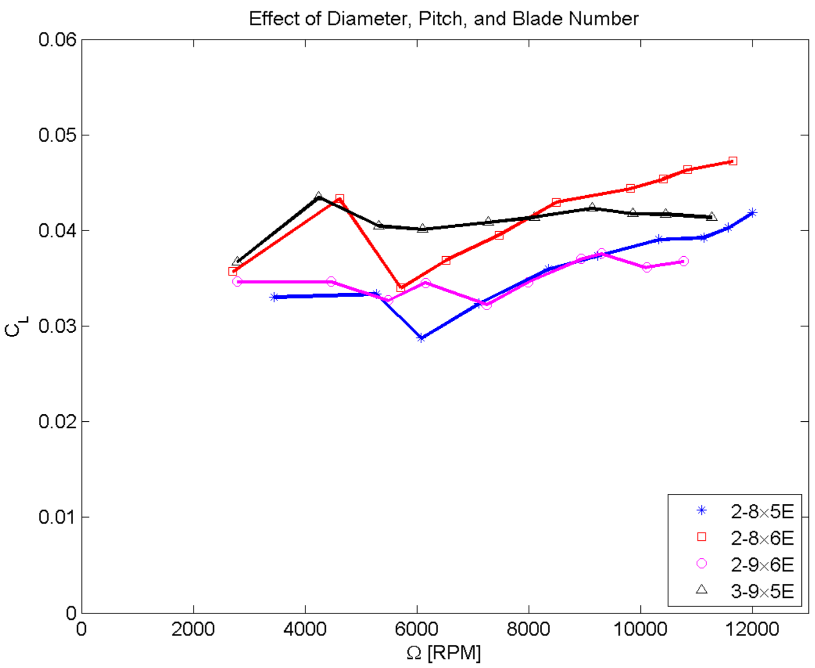


Figure 5.5: Effect of propeller diameter, pitch, and blade number on lift coefficient.

5.2 Test 2 - Effect of Wind Shield under Propeller

Figure 5.6 shows the effect of wind shield angle on lift force. For this test, the test propeller was 2-9×6E. The rotating speed was around 9000 RPM. The distance between the wind shield and the propeller was fixed at 9 mm. As we can see, when the angle was smaller than 180°, the lift force did not change too much. However, when the angle was larger than 180°, the lift force would increase monotonously. The reason lies in the fact that a propeller works under Newton's Third Law and a solid base would typically generate a larger reaction force than air. Air would just diffuse it.

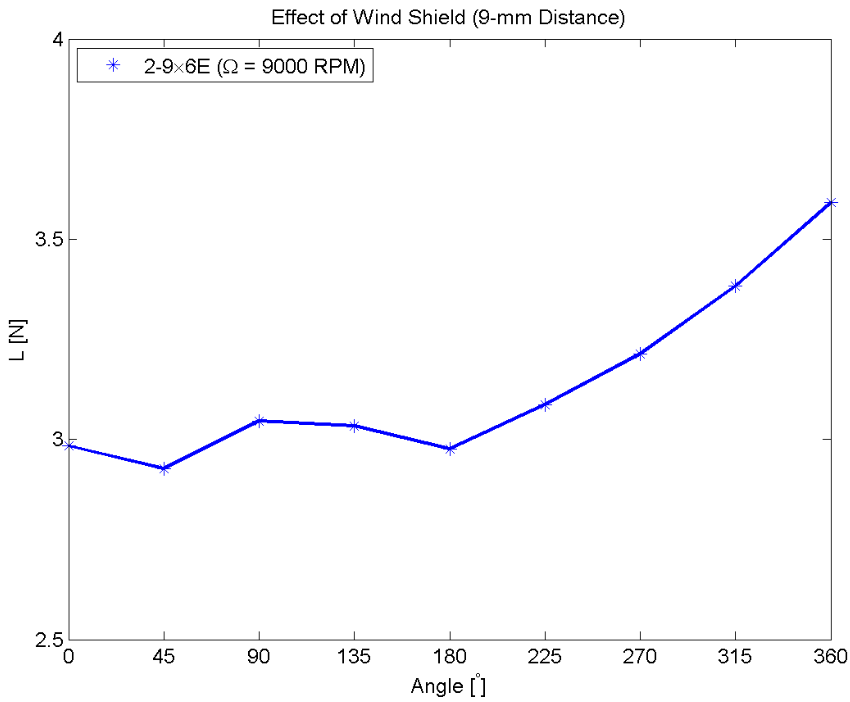


Figure 5.6: Effect of wind shield angle on lift force.

Figure 5.7 shows the effect of distance between the wind shield and the propeller. For this test, the test propeller was still 2-9×6E. The rotating speed was also around 9000 RPM while the wind shield angle was fixed at 360°. Due to the limitation of the mechanical setup, we could only obtained 4 data points. However, the trend is obvious. With larger distance between the wind shield and the propeller, the lift force would decrease.

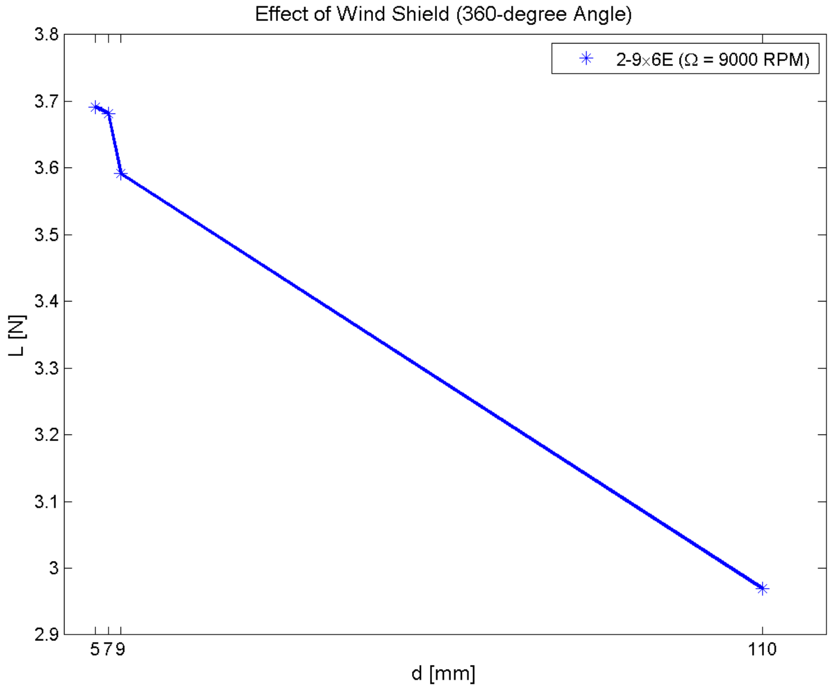


Figure 5.7: Effect of distance between the wind shield and the propeller on lift force.

5.3 Test 3 - Vibration of Unbalanced Propellers

Propellers, after long-time service, may experience damage due to both wear and cut. For this test, we tested the same 2-9×6E propeller at the same rotating speed (around 9000 RPM) but under different conditions. The first was the balanced condition. The second was unbalanced due to wear. The third was unbalanced additionally due to cut. Figure 5.8 shows the three propeller vibrations.

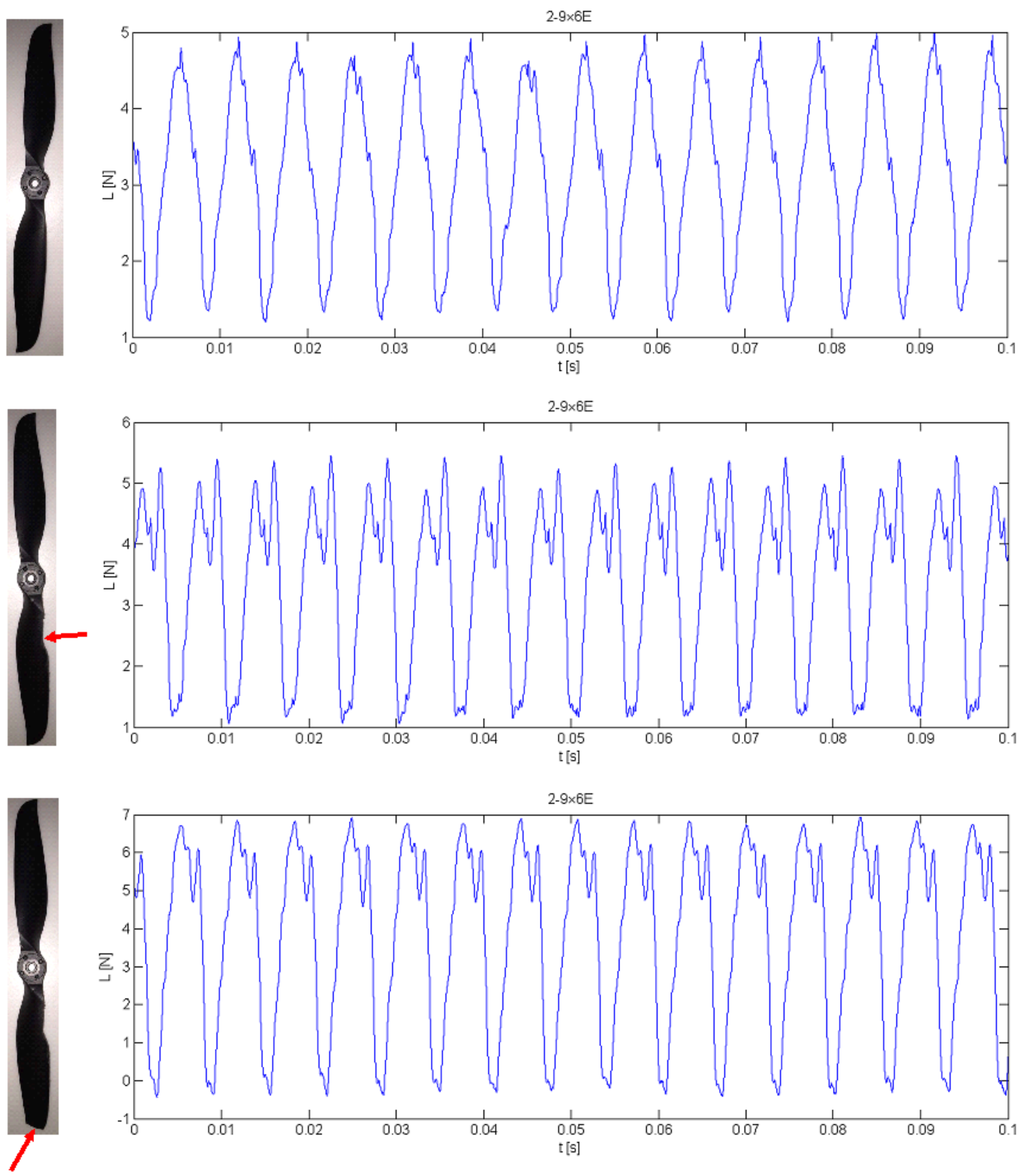


Figure 5.8: Vibration of unbalanced propellers.

Table 5.1 shows the statistics of the three propeller vibrations. As we can see, the more unbalance of the propeller, the larger vibration of the propeller would experience. However, it is difficult to well quantify the unbalance.

Table 5.1: Statistics of the three conditions.

	Mean [N]	Sample Standard Deviation [N]
Balanced	3.3283	1.1731
Unbalanced – wear	3.3401	1.3457
Unbalanced – wear + cut	3.3803	2.4534

6. COST & SCHEDULE

6.1 Bill of Materials

Table 6.1 shows the bill of materials in the end. Note that we are a little over budget, which is acceptable.

Table 6.1: Bill of materials.

#	Material	Specification	Number	Retail Price [RMB]
1	2-Blade Propeller	10×6E	1	7
2	2-Blade Propeller	10×5E	1	7
3	2-Blade Propeller	9×6E	1	6
4	2-Blade Propeller	9×4.7E	1	6
5	2-Blade Propeller	8×6E	1	5.5
6	2-Blade Propeller	8×5E	1	5.5
7	2-Blade Propeller	8×4E	1	5.5
8	2-Blade Propeller	7×4E	1	4.5
9	2-Blade Propeller	7×6E	1	4.5
10	2-Blade Propeller	7×5E	1	4.5
11	2-Blade Propeller	7×3E	1	4.5
12	2-Blade Propeller	6×5E	1	4
13	2-Blade Propeller	6×4E	1	4
14	2-Blade Propeller	6×3E	1	4
15	3-Blade Propeller	5030N	1	5.5
16	3-Blade Propeller	8040P	1	6.5
17	3-Blade Propeller	1060P	1	8
18	3-Blade Propeller	9050P	1	7
19	Brushless Motor	Kv1250	1	108
20	Brushless Motor	Kv2400	1	108
21	ESC	30 A	1	50
22	Lithium Battery	11.1V, 2200 mAh	1	90
23	Force Sensor	Capacity: ±2 kg	1	500
24	Battery Charger	11.1 V	1	25.9
25	Bolts & Nuts	Including copper columns, etc.	1	61.3
26	Acrylic Boards	200 mm×300 mm×5 mm	2	11.9
27	Acrylic Boards	200 mm×300 mm×4 mm	2	11
28	Acrylic Boards	201 mm×300 mm×3 mm	2	7.9
Total	/	/	/	**1104.3**

6.2 Final Schedule

Table 6.2 shows the final schedule of Lab 2. To be honest, we were working well on schedule.

Table 6.2: Lab 2 final schedule.

Week	Task
7	Sensor Test & Fixture Design & Purchase
8	Sensor Test & Fixture Design
9	Fixture Assembly & Calibration
10	Test
11	Test
12	Data Analysis & Report & Presentation
13	Data Analysis & Report & Presentation
14	Review

7. CONCLUSION

In the experiment, we all applied control variable to seek the experiment results.

For Test 1:
- The lift force was larger as the blade number of the propeller was larger.
- The lift force was larger as the diameter of the propeller was larger.
- The lift force was larger as the pitch of the propeller was larger.
- The experiment was repeatable.

For Test 2:
- The lift force was larger as the distance between wind shield and the propeller was smaller.
- The lift force was larger as the area of the wind shield was larger.

For Test 3:
- The average lift force provided by a scratched or a propeller cut a small piece was almost the same.
- The worse the damage condition of a propeller, the larger vibration the propeller would experience when working.

After we finished the experiment, we found several aspects that could improve our experiment. In the review process, we had to admit that although we tried hard before the experiment to eliminate all the errors and noises, some noises still affected the experimental results.

First, more stable fixture for motor. In the experiment, we used weights and supports to fix the whole structure. Therefore, when the motor was working, the structure wouldn’t move. However, we could still feel the vibration in the structure. In the later data review, we found out that the vibration didn’t cause too much error in the experimental results. But we still want to increase the accuracy of the experiment. We think if a second experiment setup is needed, we will design a special structure to cover the motor. The aim of the structure is to make sure the motor can only move vertically, and no horizontal movement.

Second, more accurate input current for motor. In the experiment, we used an adjusting knob and ESC (Electronic Speed Control) to control the current going through the motor. However, we just adjusted the knob by human eyes and hands. Although we tried our best to make sure the knob was at the same position each time, manual behavior would always has random error. Next time an electronic device that can output current directly will be a better choice (or just use another power supply). In that way, we can make sure the input current is exactly the same each time.

Third, more data points. In Test 2, we just found out the ambiguous relationship between the lift force and the distance between the wind shield and propeller. However, due to the limited raw data, we could only draw a straight line rather a smooth curve to find out the real situation. The main reason lies in the fact that the distance variation is constrained to the mechanical setup. In the design process, we did not consider studying the effect of a wind shield. Therefore, in order to acquire more data points, a new experimental setup should be designed.

Fourth, higher-performance DAQ system. The sampling rate we used was 20 kHz. When we tried to increase the sampling rate to 30 kHz, the LabVIEW program would break down immediately. After discussion, we think the program we wrote was correct, while the limitation of hardware support was the main reason why we could not exceed 20 kHz. In order to improve this aspect, we should write a more efficient program as well as do the experiment in a computer with more advanced CPU to finally increase the accuracy of the experimental results.

Last but not least, more protective structure. During the experiment, we wore goggles to protect our eyes, and we further covered ourselves with some boards when the propeller was working. Luckily, all the tests went on smoothly and no accident happened. However, a set of protective structures is still required for the future experiment. Only in this way can we have real safety.

REFERENCES

[1] R. W. Deters, G. K. Ananda, M. S. Selig, “Reynolds Number Effects on the Performance of Small-Scale Propellers,” *AIAA Applied Aerodynamics Conference*, 2014.

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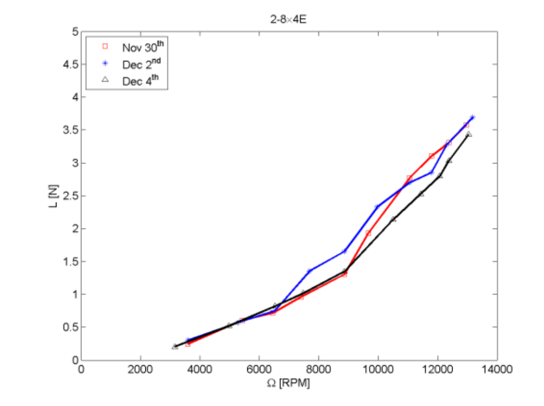
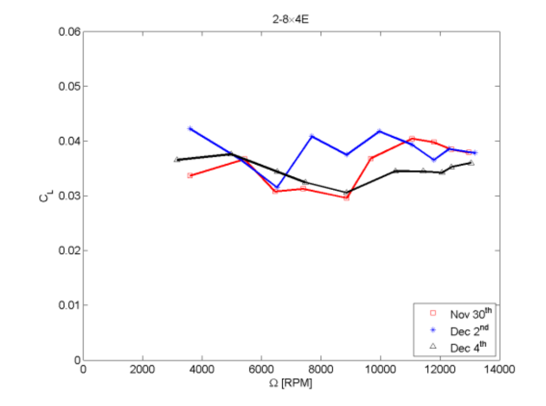
[3] E. Reyes, “What is Propeller Pitch,” *Propeller Pages* [online], URL: http://www.propellerpages.com/?c=articles&f=2006-03-08_what_is_propeller_pitch [cited 6 December 2015].

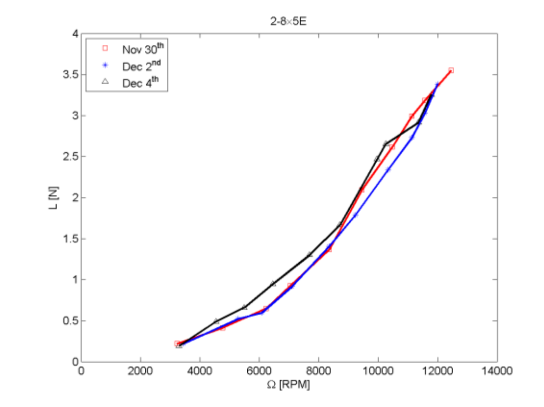
[4] “Vm495_Fall Semester 2015_Lab 1 Assignemt Handout,” *Sakai* [online], URL: http://sakai.umji.sjtu.edu.cn/access/content/group/cef4c218-e730-4a9f-89ae-ea505c78e939/Lab%201%20Assignment/Vm495_Fall%20Semester%202015_Lab%201%20Assignemt%20Handout.pdf [cited 15 November 2015].

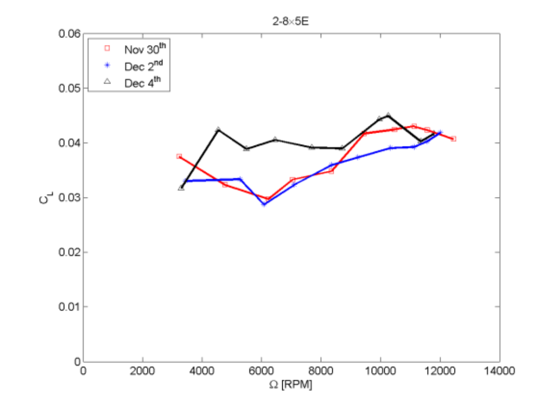
APPENDIX A: TEST RESULTS

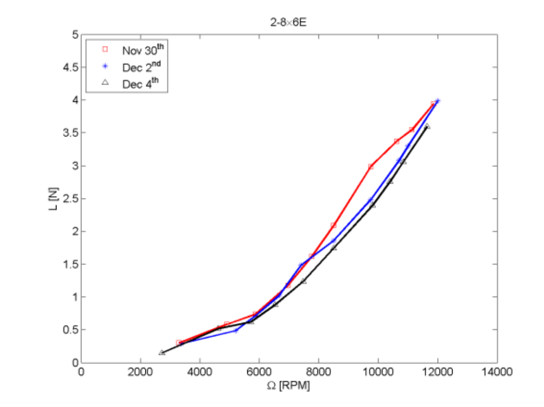
Table A-1: Repeatability test results.

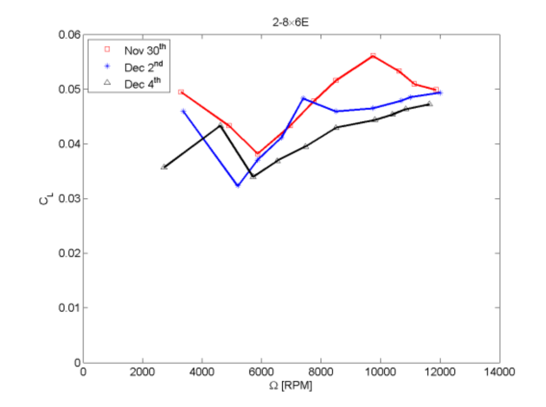












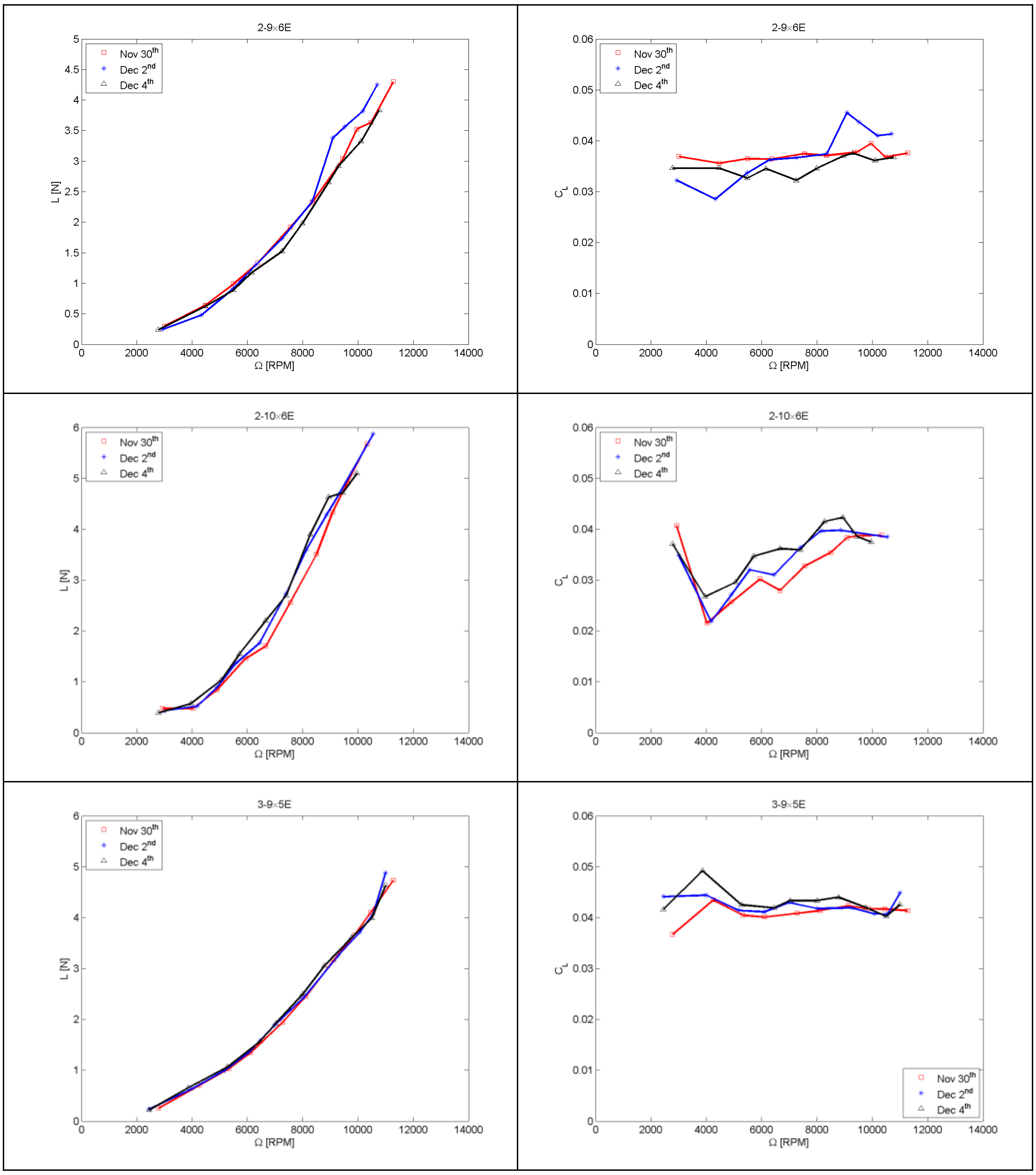
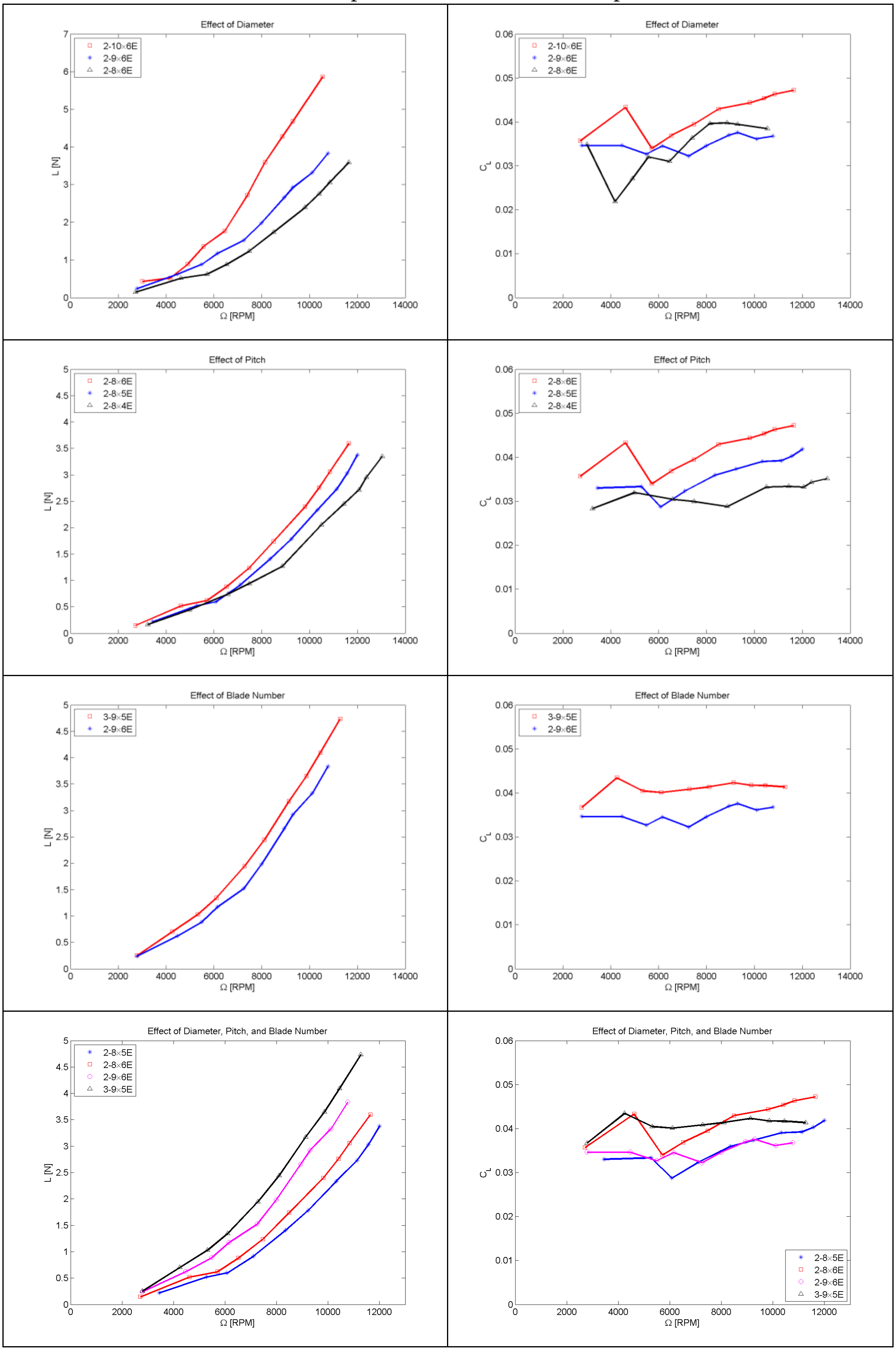

2-9×6E
2-10×6E
3-9×5E
Nov 30th
Dec 2nd
Dec 4th
L [N]
C_L
Ω [RPM]

Table A-2: Propeller characteristics comparison.



APPENDIX B: CALIBRATION DATA

Table B-1: Load cell calibration raw data.

	Compression [g]	Compression Output [V]	Tension [g]	Tension Output [V]
1	0	-0.841595	0	0.112877
2	0	-0.835393	0	0.113529
3	0	-0.83474	0	0.117446
4	0	-0.838657	0	0.117446
5	0	-0.83474	0	0.117773
6	0	-0.838005	0	0.116141
7	0	-0.837025	0	0.112224
8	0	-0.83474	0	0.119079
9	0	-0.836699	0	0.117773
10	0	-0.837678	0	0.111571
11	0	-0.84029	0	0.120058
12	0	-0.846818	0	0.117446
13	0	-0.831802	0	0.115162
14	0	-0.836046	0	0.118099
15	0	-0.837352	0	0.119079
16	0	-0.833108	0	0.118099
17	0	-0.840942	0	0.120711
18	0	-0.836372	0	0.125934
19	0	-0.833761	0	0.124954
20	0	-0.837352	0	0.121364
21	50	-1.215354	50	0.482718
22	50	-1.214048	50	0.484677
23	50	-1.219597	50	0.47978
24	50	-1.21568	50	0.47978
25	50	-1.211763	50	0.482718
26	50	-1.214375	50	0.480433
27	50	-1.218618	50	0.475537
28	50	-1.217639	50	0.483697
29	50	-1.223515	50	0.481412
30	50	-1.217639	50	0.478148
31	50	-1.218618	50	0.481412
32	50	-1.22123	50	0.477169
33	50	-1.214375	50	0.477169
34	50	-1.219597	50	0.481739
35	50	-1.216986	50	0.485003
36	50	-1.215354	50	0.472599
37	50	-1.224167	50	0.483371
38	50	-1.211763	50	0.47978
39	50	-1.218945	50	0.477495
40	50	-1.218618	50	0.477822
41	100	-1.585195	100	0.809145
42	100	-1.589112	100	0.80588
43	100	-1.58748	100	0.808818
44	100	-1.585195	100	0.804248
45	100	-1.593356	100	0.811756
46	100	-1.589439	100	0.807513
47	100	-1.589112	100	0.800658
48	100	-1.588786	100	0.810777
49	100	-1.593356	100	0.815673
50	100	-1.587807	100	0.808492
51	100	-1.59205	100	0.812735
52	100	-1.585522	100	0.814368
53	100	-1.584542	100	0.805554
54	100	-1.588786	100	0.818611
55	100	-1.594662	100	0.813715

56	100	-1.586175	100	0.81143
57	100	-1.591397	100	0.807186
58	100	-1.586175	100	0.815347
59	100	-1.58846	100	0.805228
60	100	-1.588786	100	0.809798
61	150	-1.957322	150	1.200204
62	150	-1.956016	150	1.24623
63	150	-1.958628	150	1.209344
64	150	-1.958954	150	1.236764
65	150	-1.95112	150	1.227297
66	150	-1.95471	150	1.223707
67	150	-1.95112	150	1.231867
68	150	-1.951446	150	1.223707
69	150	-1.952752	150	1.23252
70	150	-1.951446	150	1.222727
71	150	-1.957975	150	1.22436
72	150	-1.953078	150	1.23709
73	150	-1.954058	150	1.218157
74	150	-1.952752	150	1.242313
75	150	-1.950467	150	1.213587
76	150	-1.955363	150	1.233826
77	150	-1.952099	150	1.213261
78	150	-1.95569	150	1.241007
79	150	-1.95928	150	1.209017
80	150	-1.949814	150	1.236764
81	200	-2.34577	200	1.526957
82	200	-2.349687	200	1.541646
83	200	-2.34577	200	1.534138
84	200	-2.346096	200	1.536423
85	200	-2.351645	200	1.537076
86	200	-2.340547	200	1.538056
87	200	-2.341526	200	1.539361
88	200	-2.350992	200	1.531201
90	200	-2.358827	200	1.537076
91	200	-2.350013	200	1.546216
92	200	-2.346749	200	1.535118
93	200	-2.350666	200	1.532506
94	200	-2.352625	200	1.545237
95	200	-2.346096	200	1.534465
96	200	-2.348055	200	1.540993
97	200	-2.351645	200	1.530874
98	200	-2.346422	200	1.528589
99	200	-2.34936	200	1.544584
100	200	-2.349687	200	1.524672
101	250	-2.655549	250	1.926503
102	250	-2.654896	250	1.945763
103	250	-2.655222	250	1.931726
104	250	-2.652611	250	1.946415
105	250	-2.661098	250	1.946415
106	250	-2.659792	250	1.937602
107	250	-2.654243	250	1.940213
108	250	-2.661098	250	1.93956
109	250	-2.654896	250	1.932706
110	250	-2.652284	250	1.931073
111	250	-2.658813	250	1.946089
112	250	-2.651958	250	1.921607
113	250	-2.659792	250	1.952618
114	250	-2.655222	250	1.927483
115	250	-2.65816	250	1.935643
116	250	-2.660771	250	1.938581
117	250	-2.660119	250	1.920301

118	250	-2.660119	250	1.933685
119	250	-2.654243	250	1.926177
120	250	-2.659792	250	1.928462
121	300	-3.054116	300	2.33062
122	300	-3.054442	300	2.351837
123	300	-3.05281	300	2.351185
124	300	-3.047913	300	2.341392
125	300	-3.054768	300	2.345309
126	300	-3.058359	300	2.354775
127	300	-3.051178	300	2.336169
128	300	-3.050525	300	2.350205
129	300	-3.056401	300	2.350858
130	300	-3.048893	300	2.341392
131	300	-3.056401	300	2.359019
132	300	-3.051831	300	2.342698
133	300	-3.059338	300	2.341392
134	300	-3.045955	300	2.348247
135	300	-3.045302	300	2.342371
136	300	-3.045629	300	2.34792
137	300	-3.045955	300	2.351837
138	300	-3.052157	300	2.338454
139	300	-3.060971	300	2.347594
140	300	-3.049219	300	2.348247
141	350	-3.434403	350	2.794472
142	350	-3.429506	350	2.791534
143	350	-3.418734	350	2.800674
144	350	-3.430159	350	2.795778
145	350	-3.421672	350	2.793166
146	350	-3.426242	350	2.794146
147	350	-3.430159	350	2.793166
148	350	-3.431465	350	2.789576
149	350	-3.430812	350	2.794799
150	350	-3.426569	350	2.792514
151	350	-3.421999	350	2.795451
152	350	-3.422978	350	2.792514
153	350	-3.426895	350	2.797084
154	350	-3.426569	350	2.797084
155	350	-3.433423	350	2.793493
156	350	-3.424284	350	2.794799
157	350	-3.430486	350	2.794472
158	350	-3.428527	350	2.793166
159	350	-3.426895	350	2.794799
160	350	-3.422651	350	2.796104
161	400	-3.75626	400	3.068344
162	400	-3.758544	400	3.069976
163	400	-3.754954	400	3.064101
164	400	-3.753648	400	3.068018
165	400	-3.746467	400	3.073241
166	400	-3.755607	400	3.072914
167	400	-3.75169	400	3.063774
168	400	-3.750057	400	3.069976
169	400	-3.75626	400	3.062468
170	400	-3.770622	400	3.073567
171	400	-3.747772	400	3.059531
172	400	-3.765073	400	3.071935
173	400	-3.748425	400	3.073241
174	400	-3.74712	400	3.077484
175	400	-3.747446	400	3.069976
176	400	-3.758871	400	3.073567
177	400	-3.752669	400	3.068344
178	400	-3.754301	400	3.068018

179	400	-3.760177	400	3.064753
180	400	-3.767358	400	3.058878
181	450	-4.224682	450	3.464953
182	450	-4.217827	450	3.466911
183	450	-4.227293	450	3.469849
184	450	-4.22207	450	3.463973
185	450	-4.229252	450	3.467564
186	450	-4.222397	450	3.46887
187	450	-4.241003	450	3.465605
188	450	-4.222397	450	3.465279
189	450	-4.229578	450	3.466911
190	450	-4.223376	450	3.46789
191	450	-4.220765	450	3.470502
192	450	-4.234148	450	3.462015
193	450	-4.230558	450	3.4643
194	450	-4.222397	450	3.460709
195	450	-4.23219	450	3.456792
196	450	-4.229905	450	3.454507
197	450	-4.227293	450	3.454181
198	450	-4.233495	450	3.459077
199	450	-4.219785	450	3.456792
200	450	-4.225661	450	3.453854
201	500	-4.57657	500	3.862867
202	500	-4.581466	500	3.87168
203	500	-4.583751	500	3.866457
204	500	-4.572	500	3.868416
205	500	-4.585057	500	3.869395
206	500	-4.587668	500	3.869069
207	500	-4.590606	500	3.856012
208	500	-4.575591	500	3.8534
209	500	-4.579508	500	3.860582
210	500	-4.572653	500	3.844913
211	500	-4.586036	500	3.852421
212	500	-4.573306	500	3.863846
213	500	-4.581466	500	3.845893
214	500	-4.584078	500	3.855033
215	500	-4.584731	500	3.860582
216	500	-4.58114	500	3.842628
217	500	-4.583098	500	3.858623
218	500	-4.568409	500	3.86352
219	500	-4.577549	500	3.843934
220	500	-4.582119	500	3.856338
221	550	-4.961753	550	4.24348
222	550	-4.966976	550	4.251967
223	550	-4.965997	550	4.25262
224	550	-4.969261	550	4.249356
225	550	-4.970567	550	4.248703
226	550	-4.970241	550	4.256864
227	550	-4.967956	550	4.251315
228	550	-4.968282	550	4.253273
229	550	-4.96208	550	4.2536
230	550	-4.968608	550	4.247397
231	550	-4.967629	550	4.249356
232	550	-4.965671	550	4.258496
233	550	-4.97579	550	4.250988
234	550	-4.972199	550	4.2536
235	550	-4.963059	550	4.25817
236	550	-4.969914	550	4.251315
237	550	-4.972525	550	4.250009
238	550	-4.969261	550	4.251315
239	550	-4.972199	550	4.253273

240	550	-4.965997	550	4.250335
241	600	-5.364564	600	4.629317
242	600	-5.364564	600	4.622135
243	600	-5.36946	600	4.623441
244	600	-5.363585	600	4.632581
245	600	-5.362279	600	4.632255
246	600	-5.374683	600	4.627032
247	600	-5.359994	600	4.624747
248	600	-5.370766	600	4.626705
249	600	-5.368808	600	4.632581
250	600	-5.369134	600	4.626379
251	600	-5.365543	600	4.633887
252	600	-5.371745	600	4.639436
253	600	-5.366523	600	4.621482
254	600	-5.368155	600	4.630949
255	600	-5.374683	600	4.635192
256	600	-5.3613	600	4.635519
257	600	-5.37501	600	4.635519
258	600	-5.368155	600	4.624094
259	600	-5.36587	600	4.617239
260	600	-5.363911	600	4.62997
261	650	-5.683483	650	5.035392
262	650	-5.680545	650	5.031801
263	650	-5.677607	650	5.040941
264	650	-5.686421	650	5.028863
265	650	-5.69197	650	5.033759
266	650	-5.688053	650	5.02821
267	650	-5.680871	650	5.033433
268	650	-5.688706	650	5.024293
269	650	-5.685441	650	5.022008
270	650	-5.674343	650	5.018744
271	650	-5.688379	650	5.027231
272	650	-5.689032	650	5.024946
273	650	-5.6874	650	5.027884
274	650	-5.690011	650	5.031801
275	650	-5.684136	650	5.026578
276	650	-5.683156	650	5.026578
277	650	-5.681524	650	5.033433
278	650	-5.679566	650	5.028863
279	650	-5.694908	650	5.026252
280	650	-5.685115	650	5.021682
281	700	-6.129055	700	5.408497
282	700	-6.133952	700	5.408824
283	700	-6.134605	700	5.407192
284	700	-6.124812	700	5.409803
285	700	-6.138522	700	5.394461
286	700	-6.138848	700	5.41372
287	700	-6.130035	700	5.408171
288	700	-6.147335	700	5.415026
289	700	-6.127097	700	5.416005
290	700	-6.13134	700	5.412414
291	700	-6.13134	700	5.407192
292	700	-6.131993	700	5.410129
293	700	-6.139501	700	5.40915
294	700	-6.151905	700	5.401316
295	700	-6.131993	700	5.405886
296	700	-6.136563	700	5.411435
297	700	-6.139175	700	5.409803
298	700	-6.12677	700	5.40915
299	700	-6.127423	700	5.41372
300	700	-6.13232	700	5.403927

301	750	-6.466907	750	5.822733
302	750	-6.466581	750	5.821101
303	750	-6.477679	750	5.815878
304	750	-6.467886	750	5.81751
305	750	-6.473436	750	5.83122
306	750	-6.475721	750	5.823386
307	750	-6.456135	750	5.829914
308	750	-6.471151	750	5.831546
309	750	-6.460052	750	5.825997
310	750	-6.467233	750	5.829261
311	750	-6.472783	750	5.830241
312	750	-6.478985	750	5.826324
313	750	-6.468866	750	5.835137
314	750	-6.480943	750	5.832852
315	750	-6.466581	750	5.834484
316	750	-6.476373	750	5.830241
317	750	-6.463969	750	5.837096
318	750	-6.476047	750	5.83122
319	750	-6.466907	750	5.837096
320	750	-6.48127	750	5.831873
321	800	-6.873961	800	6.232725
322	800	-6.874614	800	6.233051
323	800	-6.875267	800	6.231093
324	800	-6.867759	800	6.231746
325	800	-6.863842	800	6.226523
326	800	-6.87135	800	6.231093
327	800	-6.856008	800	6.22587
328	800	-6.867759	800	6.228481
329	800	-6.864495	800	6.237948
330	800	-6.872982	800	6.233378
331	800	-6.862536	800	6.226196
332	800	-6.872329	800	6.236642
333	800	-6.863516	800	6.237295
334	800	-6.861883	800	6.230113
335	800	-6.87037	800	6.240233
336	800	-6.866127	800	6.234357
337	800	-6.873308	800	6.233378
338	800	-6.863516	800	6.229787
339	800	-6.867433	800	6.231419
340	800	-6.863516	800	6.232398
341	850	-7.266	850	6.58853
342	850	-7.256533	850	6.591141
343	850	-7.263388	850	6.601913
344	850	-7.259471	850	6.591794
345	850	-7.260777	850	6.588856
346	850	-7.26143	850	6.600934
347	850	-7.254901	850	6.598323
348	850	-7.258492	850	6.591141
349	850	-7.251637	850	6.600934
350	850	-7.26143	850	6.580369
351	850	-7.262409	850	6.586571
352	850	-7.259798	850	6.598323
353	850	-7.266326	850	6.587551
354	850	-7.257839	850	6.593426
355	850	-7.257186	850	6.602893
356	850	-7.258165	850	6.589836
357	850	-7.253269	850	6.590815
358	850	-7.261103	850	6.604198
359	850	-7.261756	850	6.600934
360	850	-7.256533	850	6.598649
361	900	-7.67795	900	6.951516

362	900	-7.647593	900	6.949884
363	900	-7.706023	900	6.950211
364	900	-7.695251	900	6.953149
365	900	-7.686111	900	6.955107
366	900	-7.680235	900	6.950864
367	900	-7.689049	900	6.946947
368	900	-7.673707	900	6.94662
369	900	-7.698189	900	6.95119
370	900	-7.672075	900	6.948579
371	900	-7.684805	900	6.950864
372	900	-7.68252	900	6.951516
373	900	-7.688069	900	6.949231
374	900	-7.687743	900	6.952822
375	900	-7.687743	900	6.950864
376	900	-7.685784	900	6.955107
377	900	-7.680888	900	6.958371
378	900	-7.684152	900	6.95576
379	900	-7.675665	900	6.957392
380	900	-7.67795	900	6.953475
381	950	-8.067704	950	7.356612
382	950	-8.051056	950	7.35041
383	950	-8.055952	950	7.363467
384	950	-8.059217	950	7.357265
385	950	-8.067051	950	7.358244
386	950	-8.046812	950	7.366731
387	950	-8.0726	950	7.356938
388	950	-8.050077	950	7.361508
389	950	-8.062481	950	7.364773
390	950	-8.04975	950	7.355633
391	950	-8.068683	950	7.356938
392	950	-8.050403	950	7.358571
393	950	-8.069336	950	7.360529
394	950	-8.061828	950	7.360529
395	950	-8.064766	950	7.358244
396	950	-8.05432	950	7.356286
397	950	-8.05889	950	7.358897
398	950	-8.050077	950	7.365752
399	950	-8.067377	950	7.361835
400	950	-8.052035	950	7.362814
401	1000	-8.455825	1000	7.781293
402	1000	-8.457131	1000	7.786516
403	1000	-8.464965	1000	7.7715
404	1000	-8.469209	1000	7.7715
405	1000	-8.444074	1000	7.774112
406	1000	-8.474431	1000	7.771827
407	1000	-8.447012	1000	7.776397
408	1000	-8.449297	1000	7.77607
409	1000	-8.454519	1000	7.772153
410	1000	-8.460069	1000	7.770521
411	1000	-8.449949	1000	7.765951
412	1000	-8.465944	1000	7.77607
413	1000	-8.446359	1000	7.773133
414	1000	-8.445379	1000	7.773785
415	1000	-8.445379	1000	7.779988
416	1000	-8.445706	1000	7.751262
417	1000	-8.449297	1000	7.763013
418	1000	-8.457131	1000	7.777703
419	1000	-8.448317	1000	7.76236
420	1000	-8.452887	1000	7.786516

APPENDIX C: MATLAB CODE

MATLAB code to get lift force vs. rotating speed for each propeller:

```
clear all;

rpm = importdata('rpm_296_1.txt'); % raw data in voltage [V]
force = importdata('force_296_1.txt'); % raw data in voltage [V]
M = 113 + 12.7; % total mass (including the motor, the propeller, and
the top fixture of the load cell) [g]
g = 9.81; % gravity [m/s^2]
fs = 20000; % sampling rate
N = 8192; % sample number
D = 0.2032; % diameter of the propeller (0.2032 for 8'', 0.2286 for
9'', 0.254 for 10'') [m]
P = 992.5 * 10^2; % atmospheric pressure [Pa]
T = 18.5 + 273.15; % ambiant temperature [K]
rho = P / T / 287; % air density [kg/m^3]

for (i = 1: 81920);

    if force(i) > 0;

        force(i) = (68.622865 + 131.406045 * force(i) + M) * g / 1000;

    else

        force(i) = (32.095052 + 130.208333 * force(i) + M) * g / 1000;

    end

end


for (j = 1: 10);

    % average force
    lift(j, 1) = mean(force(N * (j - 1) + 1: N * j));
    lift_std(j, 1) = std(force(N * (j - 1) + 1: N * j));

    % fft
```

```
    S = rpm(N * (j - 1) + 1: N * j);
    Y = fft(S, N);
    mag = abs(Y) / (N / 2);
    mag(1) = 0;
    f = ([1: N] - 1) * fs / N;

    for (k = 1: 500)

        if mag(k) > 0.5;

            break;

        end

    end

    n(j, 1) = (k - 1) * fs / N * 30; % 30 for 2-Blade and 20 for 3-
Blade

    % lift coefficient
    c_l(j, 1) = lift(j, 1) / rho / (n(j, 1) / 60)^2 / D^4;

end

figure (11);
plot(n, lift, '*r')
axis([0 14000 0 5])
xlabel('\Omega [RPM]')
ylabel('L [N]')
legend('2-9\times6E Trial1')

figure (12);
plot(n, c_l, '*r')
%axis([0 14000 0 0.1])
xlabel('\Omega [RPM]')
ylabel('C_L')
legend('2-9\times6E Trial1')

%dlmwrite('r296_1.txt', n, 'newline','pc');
%dlmwrite('l296_1.txt', lift, 'newline','pc');
%dlmwrite('c296_1.txt', c_l, 'newline','pc');
%dlmwrite('ls296_1.txt', lift_std, 'newline','pc');
```

MATLAB code to get repeatability test results:

```
clear all;

r296_1 = importdata('r296_1.txt');
l296_1 = importdata('l296_1.txt');
c296_1 = importdata('c296_1.txt');

r296_2 = importdata('r296_2.txt');
l296_2 = importdata('l296_2.txt');
c296_2 = importdata('c296_2.txt');

r296_3 = importdata('r296_3.txt');
l296_3 = importdata('l296_3.txt');
c296_3 = importdata('c296_3.txt');

% repetability
figure (1);
plot(r296_1, l296_1, 'rs', r296_2, l296_2, 'b*', r296_3, l296_3,
'k^')
hold on;
plot(r296_1, l296_1, 'r', r296_2, l296_2, 'b', r296_3, l296_3,
'k','LineWidth', 2)
axis([0 14000 0 5])
xlabel('\Omega [RPM]','Fontsize',12)
ylabel('L [N]','Fontsize',12)
legend('Nov 30^{th}','Dec 2^{nd}','Dec 4^{th}',2)
title('2-9\times6E','FontSize',12)
set(gca,'FontSize',12)
%saveas(gcf,'repeat_296_l','png')

figure (2);
plot(r296_1, c296_1, 'rs', r296_2, c296_2, 'b*', r296_3, c296_3,
'k^')
hold on;
plot(r296_1, c296_1, 'r', r296_2, c296_2, 'b', r296_3, c296_3,
'k','LineWidth', 2)
axis([0 14000 0 0.06])
xlabel('\Omega [RPM]','Fontsize',12)
ylabel('C_L','Fontsize',12)
legend('Nov 30^{th}','Dec 2^{nd}','Dec 4^{th}',4)
title('2-9\times6E','FontSize',12)
set(gca,'FontSize',12)
%saveas(gcf,'repeat_296_c','png')
```

MATLAB code to get propeller characteristics comparison:

```
clear all;

r286 = importdata('r286_3.txt');
l286 = importdata('l286_3.txt');
c286 = importdata('c286_3.txt');

r285 = importdata('r285_3.txt');
l285 = importdata('l285_3.txt');
c285 = importdata('c285_3.txt');

r284 = importdata('r284_2.txt');
l284 = importdata('l284_2.txt');
c284 = importdata('c284_2.txt');

r384 = importdata('r384_3.txt');
l384 = importdata('l384_3.txt');
c384 = importdata('c384_3.txt');

r296 = importdata('r296_3.txt');
l296 = importdata('l296_3.txt');
c296 = importdata('c296_3.txt');

r395 = importdata('r395_1.txt');
l395 = importdata('l395_1.txt');
c395 = importdata('c395_1.txt');

r2106 = importdata('r2106_2.txt');
l2106 = importdata('l2106_2.txt');
c2106 = importdata('c2106_2.txt');

% compare effect of pitch
figure (1);
plot(r286, l286, 'rs', r285, l285, 'b*', r284, l284, 'k^')
hold on;
plot(r286, l286, 'r', r285, l285, 'b', r284, l284, 'k','LineWidth',
2)
axis([0 14000 0 5])
xlabel('\Omega [RPM]','Fontsize',12)
ylabel('L [N]','Fontsize',12)
legend('2-8\times6E','2-8\times5E','2-8\times4E',2)
title('Effect of Pitch','FontSize',12)
```

```
set(gca,'FontSize',12)
%saveas(gcf,'pitch_l','png')

figure (2);
plot(r286, c286, 'rs', r284, c284, 'b*', r285, c285, 'k^')
hold on;
plot(r286, c286, 'r', r284, c284, 'b', r285, c285, 'k','LineWidth',
2)
axis([0 14000 0 0.06])
xlabel('\Omega [RPM]','Fontsize',12)
ylabel('C_L','Fontsize',12)
legend('2-8\times6E','2-8\times5E','2-8\times4E',2)
title('Effect of Pitch','FontSize',12)
set(gca,'FontSize',12)
%saveas(gcf,'pitch_c','png')

% compare effect of diameter
figure (3);
plot(r2106, l2106, 'rs', r296, l296, 'b*', r286, l286, 'k^')
hold on;
plot(r2106, l2106, 'r', r296, l296, 'b', r286, l286, 'k','LineWidth',
2)
axis([0 14000 0 7])
xlabel('\Omega [RPM]','Fontsize',12)
ylabel('L [N]','Fontsize',12)
legend('2-10\times6E','2-9\times6E','2-8\times6E',2)
title('Effect of Diameter','FontSize',12)
set(gca,'FontSize',12)
%saveas(gcf,'diameter_l','png')

figure (4);
plot(r286, c286, 'rs', r296, c296, 'b*', r2106, c2106, 'k^')
hold on;
plot(r286, c286, 'r', r296, c296, 'b', r2106, c2106, 'k','LineWidth',
2)
axis([0 14000 0 0.06])
xlabel('\Omega [RPM]','Fontsize',12)
ylabel('C_L','Fontsize',12)
legend('2-10\times6E','2-9\times6E','2-8\times6E',2)
title('Effect of Diameter','FontSize',12)
set(gca,'FontSize',12)
%saveas(gcf,'diameter_c','png')
```

```
% compare effect of number of blades
figure (5);
plot(r395, l395, 'rs', r296, l296, 'b*')
hold on;
plot(r395, l395, 'r', r296, l296, 'b','LineWidth', 2)
axis([0 14000 0 5])
xlabel('\Omega [RPM]','Fontsize',12)
ylabel('L [N]','Fontsize',12)
legend('3-9\times5E','2-9\times6E',2)
title('Effect of Blade Number','FontSize',12)
set(gca,'FontSize',12)
%saveas(gcf,'blade_l','png')

figure (6);
plot(r395, c395, 'rs', r296, c296, 'b*')
hold on;
plot(r395, c395, 'r', r296, c296, 'b','LineWidth', 2)
axis([0 14000 0 0.06])
xlabel('\Omega [RPM]','Fontsize',12)
ylabel('C_L','Fontsize',12)
legend('3-9\times5E','2-9\times6E',2)
title('Effect of Blade Number','FontSize',12)
set(gca,'FontSize',12)
%saveas(gcf,'blade_c','png')

% compare together
figure (7);
plot(r284, l284, 'b*', r286, l286, 'rs', r296, l296, 'mo', r395,
l395, 'k^')
hold on;
plot(r284, l284, 'b', r286, l286, 'r', r296, l296, 'm',r395, l395,
'k', 'LineWidth', 2)
axis([0 13000 0 5])
xlabel('\Omega [RPM]','Fontsize',12)
ylabel('L [N]','Fontsize',12)
legend('2-8\times5E','2-8\times6E', '2-9\times6E','3-9\times5E',2)
title('Effect of Diameter, Pitch, and Blade Number','FontSize',12)
set(gca,'FontSize',12)
saveas(gcf,'together_l','png')

figure (8);
plot(r284, c284, 'b*', r286, c286, 'rs', r296, c296, 'mo', r395,
c395, 'k^')
```

```
hold on;
plot(r284, c284, 'b', r286, c286, 'r', r296, c296, 'm', r395, c395,
'k','LineWidth', 2)
axis([0 13000 0 0.06])
xlabel('\Omega [RPM]','Fontsize',12)
ylabel('C_L','Fontsize',12)
legend('2-8\times5E','2-8\times6E', '2-9\times6E','3-9\times5E',4)
title('Effect of Diameter, Pitch, and Blade Number','FontSize',12)
set(gca,'FontSize',12)
saveas(gcf,'together_c','png')
```

APPENDIX D: LABVIEW PROGRAM

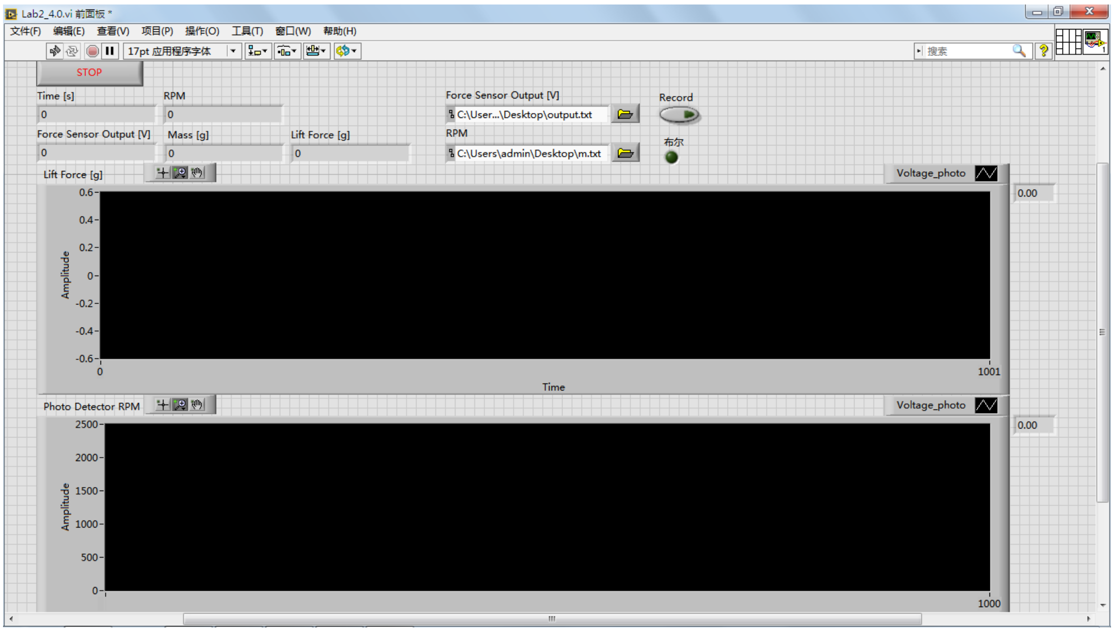


Figure D-1: LabVIEW front panel.

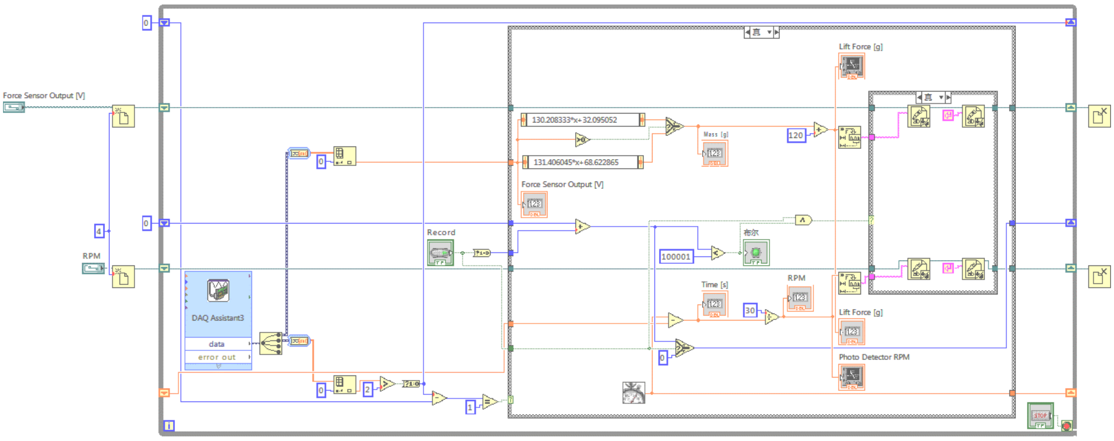
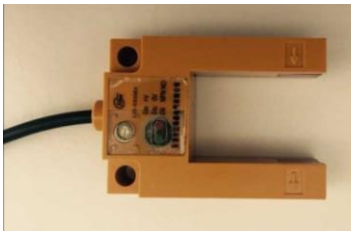
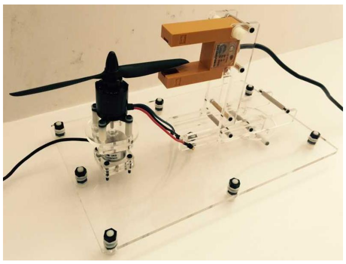


Figure D-2: LabVIEW block diagram.

APPENDIX E: EQUIPMENT AND MATERIALS

Table E-1: Equipment and materials.

 Figure E-1: Load cell.	 Figure E-2: Photo detector.	 Figure E-3: cDAQ-9171.
 Figure E-4: Li Battery.	 Figure E-5: ESC.	 Figure E-6: Adjusting knob.
 Figure E-7: Power supply.	 Figure E-8: Brushless motor.	 Figure E-9: Propeller.
 Figure E-10: Wires.	 Figure E-11: Circuit board.	 Figure E-12: Experimental setup.

APPENDIX F: AUTOCAD DRAWING

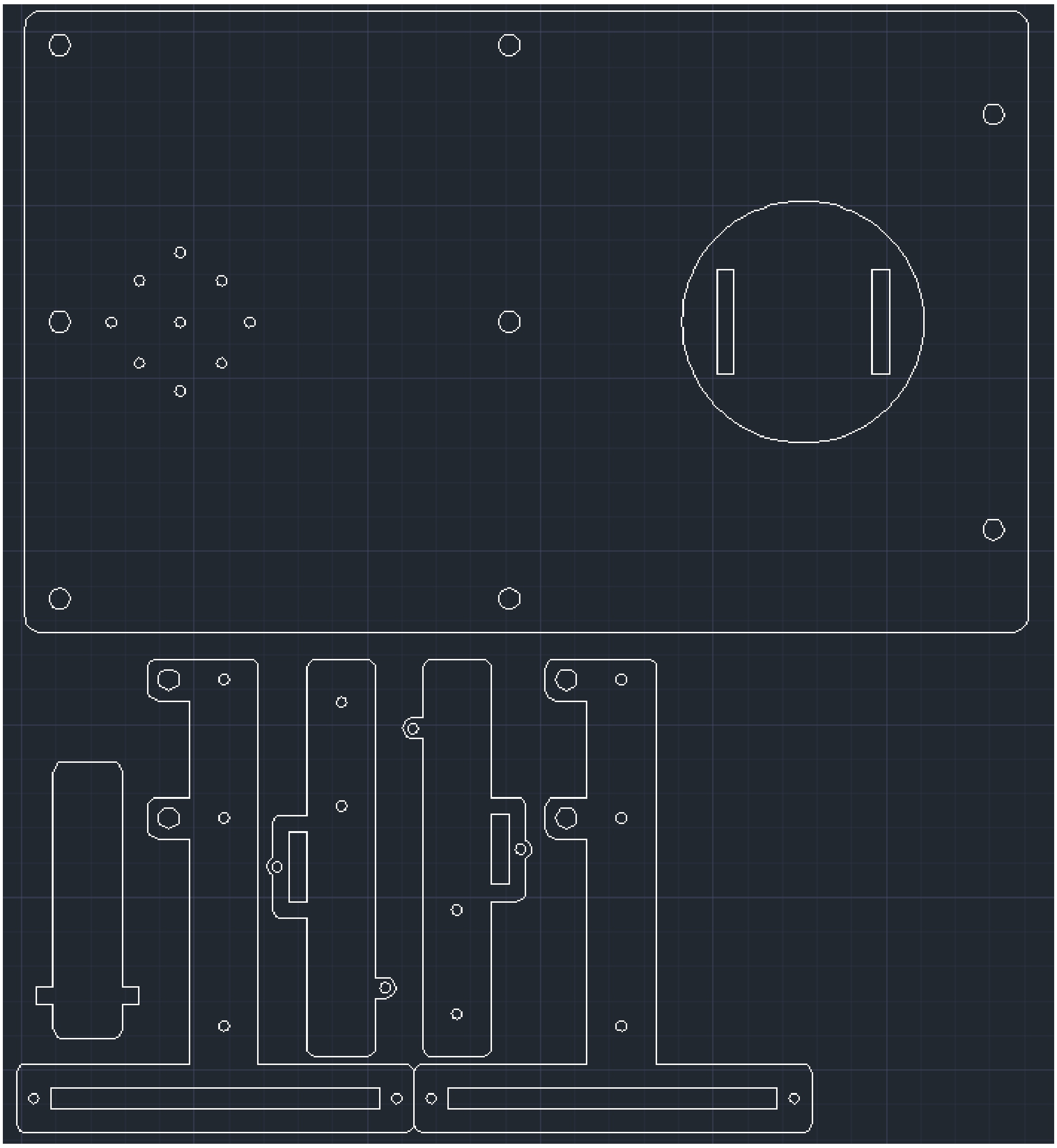


Figure F-1: AutoCAD of the base.

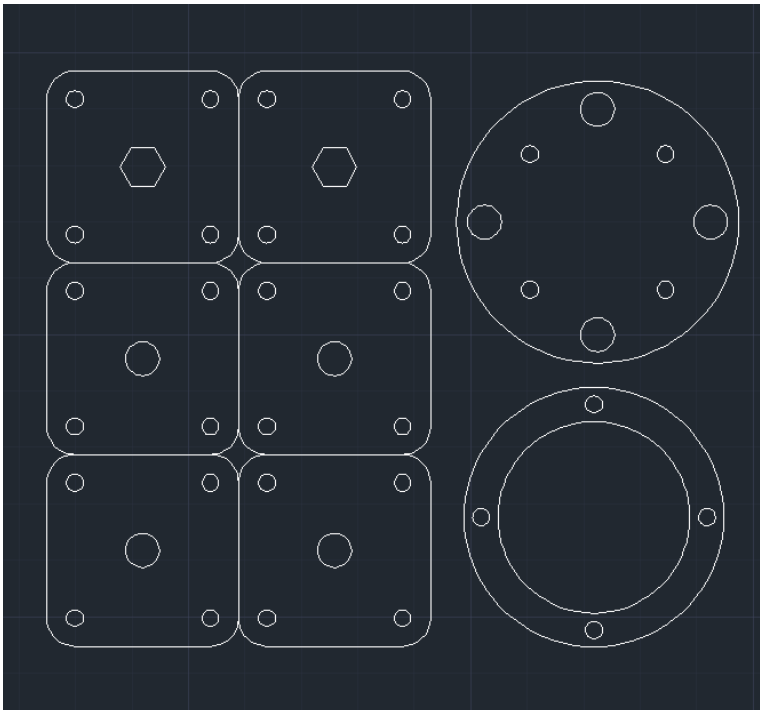


Figure F-2: AutoCAD of the load cell fixture.

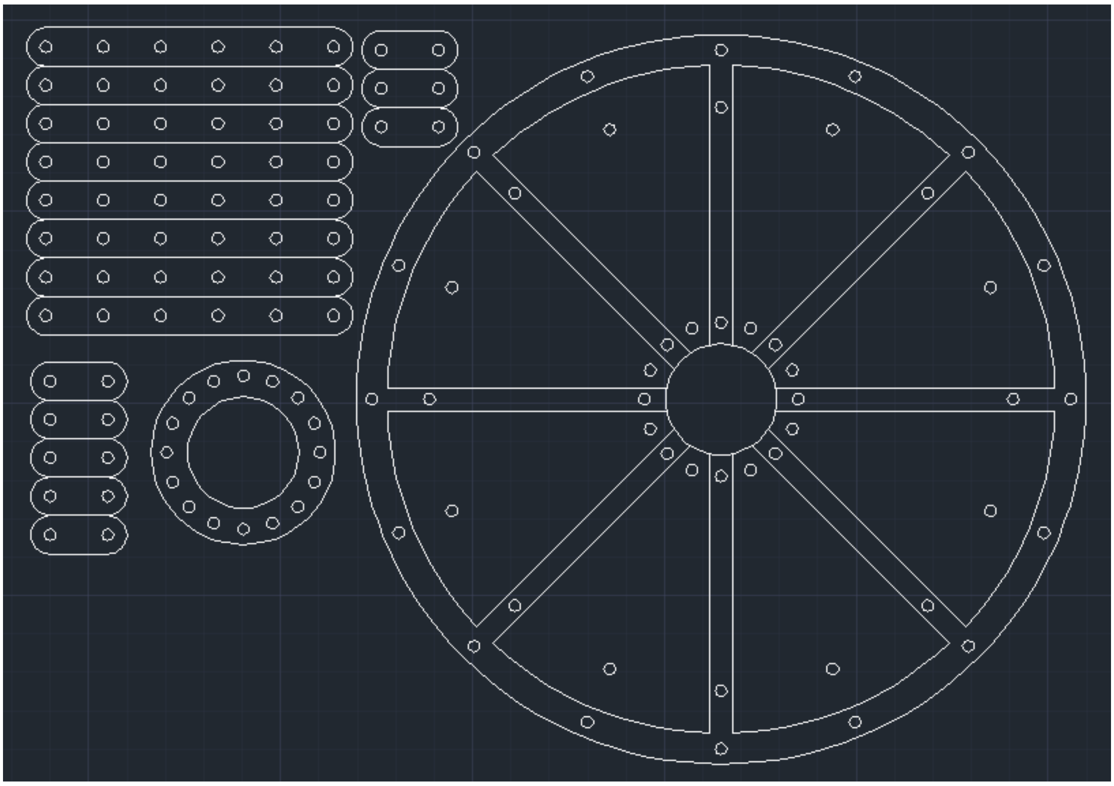


Figure F-3: AutoCAD of the wind shield.