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Aerospace Engineering, California Polytechnic State University, San Luis Obispo
An electric aircraft propulsion test rig was designed and fabricated to predict thrust, torque and battery discharge profiles for an electric aircraft. The original unit was purchased from ElectraFlyer and included the DC brushless motor, carbon fiber propeller, charger, electronic controller and lithium polymer batteries. Various components were constructed and purchased in order to fabricate the optimal test rig apparatus. This apparatus allows for simultaneous measurement of the torque and thrust of the system through the use of a biaxial sensor. The test rig also measures system voltage and current, which allows the user to determine the discharge profile of the lithium polymer battery pack at various throttle settings.

Nomenclature

I = current, Amps
P = power, Watts
V = voltage, volts
rpm = revolutions per minute

I. Introduction

With the increases in cost and concerns regarding future availability of conventional aviation fuel, plus the general environmental concerns associated with direct CO₂ output, there has been an emerging effort to produce a viable, electric powered aircraft suitable to General Aviation needs. The EAA (Experimental Aircraft Association) has embraced the concept, with prototype aircraft displays, presentations, forums at its Oshkosh AirVenture airshow. The CAFÉ Foundation has conducted symposiums around the subject of supporting electric airplane development, one of which we were in attendance. As the recent advancements in electric motor system design and in energy storage (battery) technologies appears likely to continue, the state of the art is at the brink of developing a practical electric light general aviation aircraft.

To date, there are motor gliders that have used electric power for initial take-off and climb. Prototype LSA (Light Sport Aircraft) sized electric aircraft are tantalizing close to matching early General Aviation aircraft that had reached enough utility (payload, range, speed) for widespread market acceptance.

The biggest challenge in the design of a general aviation class electric aircraft is in the development of an efficient propulsion system. The central goal of this effort was to assemble and test an electric aircraft propulsion unit. This process involved the purchase of the essential components, followed by the design and fabrication of the test rig that would be used to measure the systems performance characteristics. Additionally, this test rig is intended to be utilized as a lab exercise for future aerospace engineering students at Cal Poly who are taking Aero 401 (Propulsion).

The performance characteristics that are measured are system voltage, system current, temperature, motor torque and propeller thrust. The system voltage and current data can be used to measure the Li-polymer batteries discharge profile and develop the corresponding C rate. Also, torque and thrust measurements can be used for aircraft design purposes. Several weeks were spent researched the problem of how to simultaneously take all this data. The research produced several different configuration concepts which will be mentioned later. One extremely helpful form of research was a trip

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1 Cal Poly Aerospace Engineering Student

Aerospace Engineering, California Polytechnic State University, San Luis Obispo
to the Café Foundation’s Electric Aircraft Symposium in April were one of the guest speakers brought his companies electric propulsion test stand. Figures 1 shows the test stand from Joby Aviation [ref 1].

![Joby Aviation Test Stand](image1.png)

**Figure 1. Joby Aviation Test Stand**

II. Design Methodology

A. Equipment

   The equipment utilized within this project included the initial product received, the purchased parts, and the team constructed parts. The initial product received included the essential parts to the ELECTRAFLYER PROPUSLSION KIT. Once the initial propulsion system was examined, the plans for the Electric Propulsion Test Rig were developed. In order to accurately and safely measure the performance characteristics of thrust and torque for the electric propulsion system, a number of parts were purchased and even constructed. The initial product was the ELECTRAFLYER KIT was purchased from the Electric Aircraft Corporation. The kit as a whole is shown in Figure 2.

![ElectraFlyer Trike Kit](image2.png)

**Figure 2. ElectraFlyer Trike Kit**

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The kit was delivered as individual components. This included the electric motor, which was a DC 18 Hp (13.5kW) permanent magnet seen in Figure 3.

![DC Brushed Permanent Magnet Electric Motor](image3.png)

Figure 3. DC Brushed Permanent Magnet Electric Motor

Another piece of the initial product included six Lithium-Polymer (LiPo) batteries. Each battery has a nominal voltage of 12.5 V and a total capacity of 3.3kWh. Connecting these batteries in series produced the total system voltage and current necessary to run the electric motor at its maximum power setting. With the batteries also came a battery charger, which includes charge curve auto-shutoff shown in Figure 4.

![Battery Charging Unit](image4.png)

Figure 4. Battery Charging Unit
Also included in the kit was a 2 blade, 53” folding, carbon fiber pusher propeller with a two piece machined hub which can be seen in Figure 5. This propeller hub connection to the motor axel involves an shaft key. The shaft key included with the kit was the wrong size due to the noticeable amount of slack between the electric motor shaft and the propeller hub, therefore a new key was fabricated to securely fasten the propeller to the shaft.

![Figure 5. Carbon Fiber Pusher Propeller](image)

The final piece of the ElectraFlyer kit was the controller. The controller was an electronic pulse width modulation speed controller and it is what controllers the motor torque and rpm. Furthermore, a power dial (throttle) and switch was included. The power dial allows for easy operator use of the controller. The kit also included some specific parts, such as resistors, fuses, and Anderson connectors. Lastly, a digital motor temperature display with a probe was included.

Purchased parts were also needed for connections, safety, and the overall test rig apparatus. ¼ mild steel was purchased from McCarthy Steel in Paso Robles, CA. The dimensions of the purchased steel were 9.5”x6.5”, 2-9.25”x6”, and 2-9.5”x9.25”. Another part needed was an I-beam, U-channel, or box beam to mount the test rig apparatus. A box beam was found from the M.E. Department at Cal Poly. Its dimensions are 5” x 2” x 5ft.

To determine the gage of the wires needed for the motor set-up, the necessary current was calculated. Since the motor has a max power output of 18 horsepower (13.42 kW) and the total voltage of the batteries was 75 volts, the current was calculated using basic circuit theory (Joule’s Law).

\[
P = IV
\]

The max current was found to be 179 amps, which was used to determine the wire gage using an ampacity chart. Multi-strand welding cable was chosen for its superior flexibility over single strand wire. Flexible wire was needed to minimize interference in the thrust measurement as rigid wire would hinder the motor from moving freely along the shaft. From table 1 it was determined that a #2 gage cable was needed.

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Table 1. Suggested Ampacity for Welding Cable#
Electrical shunts are used to measure high amperage current. Shunts have an extremely low resistance, which when configured in series within the circuit, allows the voltage across the shunt to be measured. Knowing the shunt size allows the actual current to be calculated, thus allowing the current in the circuit to be measured. Based on the determined amount of current the batteries could produce, an appropriate size shunt was chosen. Two shunts were purchased with different current ratings. One was rated for 200 amps with a maximum voltage output of 100 millivolts. The second was rated for 300 amps with a maximum voltage output of 100 millivolts. This second shunt was a backup in case the 200 amp shunt fails. In figure 6, the dimensions can be seen for the shunts.

One of the most important goals of this project was the ability to measure both torque and thrust. One of the early test rig design ideas included mounting the apparatus on rails and measuring the displacement to obtain thrust and also attaching a moment arm to a strain gauge to determine the torque. Due to the frictional losses in the rails and moment arm it was determined that this method would not be the most accurate and efficient design. Therefore, a multi-axis sensor was used to take the measurements simultaneously. This sensor had to be able to measure the entire range of torque and thrust loading exerted by the motor and propeller respectively. After extensive research into the applicable sensor technology and using the published motor and propeller data to determine the loading range, a Torque & Thrust Biaxial Sensor from FUTEK Advanced Sensor Technology, Inc. was purchased. This sensor was mounted at the end of the shaft and outputs an amplified analog signal, which was then converted to a digital signal using a digital-to-analog converter, which will be discussed later. It can measure thrust and torque up to 500 lbs and 500 in-lbs respectively which covers the desired range with a factor of safety of 2. The sensor can be seen in Figure 7.
Several additional parts were constructed in the lab. A saddle to carry the electric motor was constructed from the previously purchased ¼ mild steel. This saddle was designed to hold the electric motor and connect to the shaft where the sensors would be located. The saddle was designed first in SolidWorks and once the dimensions for the saddle were selected, the steel was welded and cut accordingly. Both can be seen in Figure 8.

Another lab constructed component was a wooden box to house the six lithium polymer batteries, where they could be wired in series and lead to a single output. Figure 9 shows the completed battery box.
A box beam was cut and installed to act as the apparatus base support. A flange to connect the shaft to the motor saddle was also needed to fit a ¾ in. shaft and mount to the opposite side of the propeller on the saddle.

In order to measure both thrust and torque, bearings that operated in both directions where needed to minimize losses, therefore improving the accuracy of the data. Regular linear bearings would limit the ability to measure torque and the opposite for regular rotary bearings. It was discovered that linear-rotary bearings were the most effective solution. Linear-rotary bearings are capable of movement in both directions. In the test setup, the shaft was 3/4” to easily integrate into the thrust/torque sensor. After analyzing the potential forces applied the 3/4” solid steel shaft and the 3/4” bore linear-rotary bearings were found to sufficiently handle the loading. These bearings, next to the pillow blocks, are shown in Figure 10.
B. Test Stand Design Process

The test stand includes two levels. On the bottom level are the six battery packs wired in series, the charger, and most of the wiring for the electronics. A diagram for the electronics was created and can be seen in Figure 11.

**CONNECTION DIAGRAM**

![Connection Diagram](image)

**NOTES:**
1. Suggest 4 ga cable or heavier
2. Copper motor temp bracket for sensor
3. Battery is 75.6 V charged, 67 nominal
4. NO SHUNT LOCATIONS, SCHEMATIC

The box beam base support was fastened to the top of the table. Attached to the box beam are the two linear-rotary bearings and a bracket to mount the sensor to. The shaft running through the bearings was 3/4” to interface with the sensor without any unnecessary reductions in the shaft diameter. The shaft was also connected to a motor saddle, in which the motor sits. The test set up can be seen in Figures 12 & 13.
The slot seen in Figure 12 was where the shaft of the motor emerges from the saddle. The motor saddle was necessary because the way the motor was constructed, the motor itself can only be mounted on the side with the motor shaft. The propeller was directly connected to the motor shaft and will have a protective cage surrounding it to prevent injury.

The motor and its saddle were heavy therefore a simple FEA stress analysis was performed and it was determined if the steel shaft could indeed take the loading. This analysis is shown in Figure 14.
III. Procedure for Use

A. Battery Pack Charging

A battery charging unit designed specifically for these lithium-polymer batteries makes battery charging a simple procedure. The batteries are connected to the charger through a pigtail wire off of the main circuit. This wire was soldered into a connector lug which plugs directly into the charger. The charger plugs into a typical 120 volt wall outlet. It takes approximately 3 hours to charge the batteries from discharged to full.

B. Motor Operation

This section details explicit motor operation instructions. It was important that the procedure was strictly followed to prevent damage to the motor and controller.

Motor start up instructions:
1. Check that throttle is CLOSED
2. Ensure that both main and pre-charge switches are OFF (open)
3. Connect battery pack to circuit
4. Check that switch controller is OFF
5. Turn panel meters ON
6. Turn pre-charge switch to ON position and wait for voltage to rise on meter (this must be done before main switch is turned on)
7. Turn main switch ON
8. Turn controller ON

At this point, increase the throttle to the desired setting. It was important to note that with an electric motor, the propeller will reach the desired RPMs almost instantaneously as opposed to a gas engine which will have a spool up time.

C. Testing
The controller and sensor output data in analog format so a National Instruments DAC was utilized with LabView for ease of measurements.

The custom design of the electric aircraft propulsion test rig allows for the measurement of several performance characteristics simultaneously. The bi-axial sensor mentioned earlier outputs the torque and thrust values of the system for aircraft design and performance calculations. However, since this testing is not done in a wind tunnel the calculations are for static thrust shown in Figure 15.

![Propeller Thrust](image)

**Figure 15. Propeller Static Thrust Curve**

Also, a voltmeter and ammeter measure the system voltage and current respectively. These values are used to calculate the power of the motor and thus the motor rpm. With both torque and rpm known, the motor curve in Figure 16 is constructed.

![Motor Curve](image)

**Figure 16. Permanent Magnet Motor Curve**

The system voltage is also used to determine the battery discharge profile shown in Figure 17. This chart shows how the system voltage drops with as the batteries lose charge at various discharge, or C rates. This test provides a good approximation of the endurance of an electric aircraft that uses this particular propulsion system.
Additionally, a more in depth test would be to measure the cell voltage after each discharge cycle and record the value. After completing a large amount of discharge cycles, the cell degradation can be measured and plotted as seen in Figure 18.

![Discharge Curves](image1)

**Figure 17. Li-Polymer Battery Discharge Curves**

**D. Shutdown Procedure**

After testing is completed, throttle the motor to the off position and then turn the controller off. Ensure that both the pre-charge and main switches are flipped to the off position. Turn off panel meters and disconnect battery from circuit. If the batteries are to be stored for a long period of time without use, it is recommended that they be discharged to approximately 40% and stored in a cool location. This will reduce the capacity loss that naturally occurs in storing lithium-polymer batteries due to temperature and charge level.

![Cycle Graph](image2)

**Figure 18. Li-Polymer Cycle Graph**

**IV. Conclusions**

The design and fabrication of an electric aircraft propulsion system came with various obstacles and difficulties. However all of these adversities were overcome and the design provides easy use for future aerospace engineering students. The system allows students and faculty to further understand what it is like to fly and design an electric vehicle. This apparatus not only allows students to measure all the performance characteristics mentioned, but also permits students to further understand the pros and cons of electric aircraft. This new understanding will open further research for the university into failure modes and effects analysis and advanced operating procedures for electric aircraft. This test apparatus is only the beginning to a new wave of university electric aircraft research and testing.