Teaching Aircraft Design to Undergraduate Students in a Mechanical Engineering Program

Dr. W. Jerry Bowman
Brigham Young University
Provo, Utah 84602

Abstract

This paper describes informal methods used to teach aircraft design to undergraduates in a traditional Mechanical Engineering program. Freshman and sophomore students are introduced to the topic by way of a club environment where they do a series of design, build, and fly projects. This paper will provide details about the specific design projects assigned and the method used to introduce the students to aircraft design.

Introduction

Each year, the Mechanical Engineering department at Brigham Young University admits 140 students into its undergraduate program. Typically, some of these students are interested in airplanes. Their enthusiasm makes it possible to experiment with different methods of teaching aeronautical engineering topics in a mechanical engineering environment.

As a minimum, the Mechanical Engineering students at Brigham Young University takes 131.5 semester hours to graduate. Forty of these hours are used to fulfill general education requirements. The remaining 91.5 hours are dedicated to math, science and engineering. In the engineering area, the students can select nine hours of courses from a list of technical electives. The remaining 82.5 hours are specified. The department offers one technical elective course that is related to airplane design. That course is offered once each year during the spring term. There are no airplane courses offered during the fall or winter semesters when most of the students are attending classes. As a result, in the past, few students have had an opportunity to study aeronautical topics.

To expand opportunities to learn about aircraft design to more students, three programs were initiated. The first was an R/C airplane club. The club members learn to design, build and fly their own airplanes. The second opportunity consists of special topics courses offered to small groups of students where they work on specific airplane design issues. The third opportunity is the student’s senior design project. Some seniors are selected to do aircraft related projects.
This paper will review the activities of the R/C airplane club. It will describe the projects the students have worked on and give examples of their successes and failures. The students definitely mature during the two or three years that they are involved in the program, better preparing them to do graduate work in Aeronautical Engineering after completing their Mechanical Engineering undergraduate degrees.

Club Learning

The students involved in the club are typically freshman or sophomores level students. They usually participate for 1-3 years. During the academic school year they do about three to five different design, build, fly (DBF) projects. These projects will be described below.

Early in the school year, one hour is spent teaching the student a simple airplane design process. The goal is to get the students involved as soon as possible designing, building and flying planes. Little time is spent on theory. Many details are left to later lectures or for the students to learn on their own. The students learn the relationships between airplane weight, wing surface area, velocity, and power. They learn simple relationships to size the aircraft horizontal and vertical tails and to locate the aircraft center of gravity. Appendix A is a copy of a handout given to the students to lead them through the simple design process.

After the first lecture, the students are encouraged to do calculations by hand or with a spread sheet to design their first airplane. The students are given an electric motor (www.allelectronics.com, Cat# DCM-166, $0.75) and propeller (www.homefly.com, Union U-80 propeller, $1.75) that weigh 0.07 N and can produce 0.2 W of power available (0.05 N of thrust) at a flight velocity of 4 m/sec. They are also given a battery pack made from two NiCad batteries (www.thebatterystation.com, Part# N-50AAA, 2 @ $2.00 each) that weighs 0.06 N and that can supply power to the motor for as long as 5 minutes. The motor, propeller and batteries are shown in Fig. 1. The students are challenged to design a free flight airplane that can fly with this propulsion system. The small amount of power provided by this combination of relatively heavy components make this a non trivial but possible design problem.

Figure 1: Motor, Propeller and Batteries Used for First Airplane Design
Below in Fig. 2 is a picture of some typical first airplanes. The students build the planes from balsa and tissue paper or from cut Styrofoam. The Styrofoam is cut using a CNC foam cutting machine available in our lab. Usually the first airplane the students build won’t fly. Often the airplanes are heavier after they are built than what the student assumed during the design process. Also it is often difficult to trim the airplane to obtain stable flight due to insufficient wing dihedral, vertical, or horizontal tail volume ratio. Also, often the students break their airplanes trying to fly them before they are trimmed. They seem to think if they can throw them a little harder, they might fly. After the first flight failures (and hopefully a few successes) we review the design process, teach a little more about stability, discuss what might have gone wrong with each airplane, and begin a second iteration. It typically takes 2-3 attempts before a successful airplane is built. A well built airplane can fly for as long as 5 minutes with the batteries supplied. After lots of crashes, a 5 minute flight is a long time for the students to feel good about their airplane as it slowly climbs and spirals overhead.

Figure 1: Typical First Free Flight Airplane

The first design project iterations typically take the entire fall semester. Because the learning is done in a club environment and not as part of a structured class, the students have to be self motivated to do the work. They don’t have weekly assignments to turn in. They spend
on average about 2 hours each week working on their planes. About 30-50% of the students that show up for the club meetings attend regularly. The remaining students attend once or twice and then never show up again. Second year students serve as club officers and mentors for the first year students. During the 2003-2004 school year, the supplies used by the students were funded by a mentored learning grant received from the university.

For the second DBF project, the students are given a GWS pico flight pack (www.ehobby.com, $90.00 each). It contains a GWS R/C airplane radio receiver, two pico servos, a speed control, and a battery pack (150 mAh, NiCad, or 270 mAh NiCad). They are also given a DC 5.24 electric motor (www.homefly.com, $27.00 each) and matching propeller (same U-80 prop as used for the free flight planes). Along with the motor and propeller they are given a power available curve for the motor and propeller (Fig. 2). With this set of hardware, they are able to move into the radio controlled airplane world.

![Power Available Curve for the DC 5.24 Motor and the U-80 Propeller.](image)

With the GWS Flight Pack in hand, they set to work designing their first radio controlled airplane. The students are divided into small groups of 3-5 members per group. This is because we don’t have enough radios and components for each student to have their own. Figure 3 shows some airplanes built in the past. Similar to the free flight airplanes, the radio controlled planes don’t always fly, but the success rate is better than 50%. Our experience is that if the students follow good engineering design principles, the airplanes are more likely to fly. If the students are building based on intuition, the airplanes typically won’t fly. Hopefully, somewhere during the process of the designing, building and flying, the students gain an appreciation of design and its importance to successful flight of their airplane. The most common cause of
failure is due to structural problems caused by the students trying to make their planes as light weight as possible.

Figure 3: Examples of First Radio Controlled Airplanes.

The radio controlled planes are usually flying by the middle of the winter semester. As the planes eventually crash and break, the students recycle the components into new planes. The new planes are designed using increasing sophisticated spread sheets (first written for the original free flight plane). The individual team members begin to specialize in areas like design, construction, electronics, propulsion, and pilot.

We also encourage the students to make their planes smaller if possible. This is because BYU has established a reputation of making some of the smallest airplanes ever flown. We help them by supplying them with lighter weight components and batteries. Figure 4 is a picture of a second generation R/C plane. It used the same GWS pico flight pack as the first generation plane. The only difference was that the students were given a 700 mAh Li-Ion battery pack (www.eflightpacks.com, Part # ELiPo 700-2S, $24.50 each, 35 gm). The students were also encouraged to decrease the wing aspect ratio and design for a higher velocity to make a smaller plane.

By the end of one or two years of participation in the club, the students are better prepared to take part in more advanced activities. They also find ways to apply information learned in other classes to aircraft design. During the 2003-4 school year a group of seniors selected an aircraft design problem for their senior design project. Their goal was to build a fully autonomous airplane that could carry a 150 gm payload for one hour. One student focused on the overall aircraft design. He combined the design process with optimization methods from another class to come up with the best design. Another student used parametric CAD methods to quickly resize the aircraft during the optimization process. He also used the CAD software to calculate the planes moments of inertia for use by the planes flying qualities expert. A third student used information from a Dynamic Systems class and research on aircraft stability and control to predict the change in dynamic response of the aircraft due to changes in aircraft physical parameters. A forth student used information learned in a composites class to build a lighter and stronger aircraft structure. Their success was made possible in part due to experience gained in the R/C airplane club.
Conclusions

Brigham Young University offers an undergraduate degree in Mechanical Engineering but not Aeronautical Engineering. Each year, a few students express an interest in learning about airplane design. To meet their needs, a club has been formed to introduce the students to aircraft design.

This program has helped the students learn about airplanes and their design by designing, building, and flying their own planes. The students mature over the years. They become more sophisticated in their design methods. They begin to specialize in areas of aircraft design that most interest them. They often apply to graduate school at universities that have stronger programs in Aeronautical Engineering.
Appendix A: Airplane Design Process

**Find:** % Excess Power \( \left( \frac{P_a - P_r}{P_r} \right) \times 100 \)  \hspace{1cm} (1)

\( P_a \) = Power Available (W)

\( P_r \) = Power Required (W)

Power available is often measured for the motor/prop combination you plan to use for your airplane. Wind tunnel tests are used. Typical wind tunnel results look like the graph shown below:

\[ P_a(W) \]

\[ \text{max } P_a \]

\[ V_{pmax} \text{ Velocity, } V \left( \frac{m}{sec} \right) \]

From the graph, you can determine the maximum possible \( P_a \) and the airplane velocity that gives you that power. For your first plane assume \( P_a = 0.2 \text{ W @ V=4 m/sec} \)

Power required (\( P_r \)) is found using the equation:

\[ P_r = D \cdot V \]  \hspace{1cm} (2)

\( D \) = Drag (N)  \hspace{1cm} \text{Still to be found}

\( V \) = Velocity (m/sec)  \hspace{1cm} \text{Known from power available curve}

\[ D = C_D \frac{1}{2} \rho V^2 S \]  \hspace{1cm} (3)

\( C_D \) = Drag Coefficient  \hspace{1cm} \text{Still to be found}
\[ S = \text{wing surface area (}m^2) \quad \text{Still to be found (top surface of wing only)} \]

\[ \rho = \text{air density} \left( \frac{kg}{m^3} \right) \approx 1.1 \frac{kg}{m^3} \text{ for Provo, found from tables} \]

- Before you can find \( C_D + S \) you need to estimate the weight of the airplane

\[
W_{\text{total}} = W_{\text{motor/prop}} + W_{\text{batteries}} + W_{\text{payload}} + W_{\text{structure}} \quad (4)
\]

Find a scale and weigh your batteries, motor/prop, and payload. (For your first plane \( W_{\text{motor}} = 0.07 \text{ N}, \ W_{\text{batteries}} = 0.06 \text{ N} \))

The structure weight of your airplane is a fraction of your total airplane weight. It can range from about 40% to 60% depending on the materials you select. For example, let \( W_{\text{structure}} = XW_{\text{total}} \). If you substitute this into Eq. (4) you get:

\[
W_{\text{total}} = \frac{W_{\text{motor/prop}} + W_{\text{batteries}} + W_{\text{payload}}}{1 - X}
\]

With an estimate of the total weight, you can now estimate of the wing area \( (S) \) required to generate enough lift. This is how it’s done

\[
L = W_{\text{total}} = \frac{1}{2} \rho V^2 C_L S. \quad (5)
\]

\( L = \text{lift} \)

\( C_L = \text{lift coefficient} \)

For now assume \( C_L = 0.5 \) to 0.6. (We’ll learn more about this some other day)

Solve Eq. (5) for \( S \)

\[
S = \frac{2W_{\text{total}}}{\rho V^2 C_L} \quad (6)
\]
Using Eq. 6 you can find how much wing area you will need to provide enough lift to balance the weight of the airplane during flight.

Now to find the drag coefficient, $C_D$. It is calculated using the equation:

$$C_D = C_D^0 + KC_L^2$$

$C_D^0$ ≈ 0.1 or less if you are careful and have an aerodynamic plane. Finding $C_D^0$ is a lesson in itself. $C_D^0$ is called the zero lift drag coefficient.

$$K = \frac{1}{\pi e_0 AR}$$

$\pi = 3.14$

$e_0 =$ Oswald efficiency factor ≈ 0.9

$AR =$ wing aspect ratio $= \frac{b^2}{S}$

Where $b =$ wing span (tip to tip distance)

You can pick the value of aspect ratio (AR) you want to use for your plane. Usually larger values are better from an aerodynamics point of view but worse from a structures stand point. A typical value is between 4 & 8. Once $S$ and $AR$ are known, you can use the definition of aspect ratio to find your plane’s wing span, $b$. Knowing $S$ and $b$, you can find the planes average wing chord.

- Finally, we have everything we need to calculate, Drag using Eq. 3, Power Required using Eq. 2, and % Excess Power using Eq. 1. Do the calculations. If the % excess power is greater than zero, your airplane has a chance of flying. If it is less than zero, your airplane probably won’t fly. Some ways to increase excess power are: $C_L \uparrow$, $P_a \uparrow$, $AR \uparrow$, $C_D^0 \downarrow$, $e_0 \uparrow$, $W \downarrow$. For your first plane, it is easiest to vary aspect ratio and weight to obtain a feasible plane. Try to design your 1st airplane so you have as much excess power as possible. 100% would be great.

- Sizing of the vertical and horizontal tails.

The horizontal and vertical tails are important for your plane to fly well. They provide pitch and yaw stability. For the vertical and horizontal tails, both the surface area and the moment arm from the tail to the airplane center of gravity are important. The parameters we use to size the tails are called the tail volume ratios. They are defined as
Horizontal Tail, Tail Volume Ratio: \[ V_{HT} = \frac{l_{HT}S_{HT}}{cS} \approx 0.7 \]

Vertical Tail, Tail Volume Ratio: \[ V_{VT} = \frac{l_{VT}S_{VT}}{bS} \approx 0.04 \]

Above, \( l_{HT} \) and \( l_{VT} \) are the moment arms from the airplane center of gravity to the tail, \( S_{HT} \) and \( S_{VT} \) are the surface area of the horizontal and vertical tails respectively, \( S \) is the surface area of the wing, \( b \) is the wing span, and \( c \) is the mean chord length for the wing. Locate and size the tails so the tail volume ratios are close to the values given in the equations above.

- Build your airplane so it looks something like the one in the figure below. You will need to calculate your own values for \( S, b, c, S_{HT}, l_{HT}, l_{VT} \).

Some other practical suggestions are:

1. Develop a method to plug and un-plug your batteries from the motor to turn the motor on and off. You will also be able to charge the batteries using the plug.

2. Make the wing so it can slide along the body of the airplane. This will be important when you first fly the airplane. You will need to adjust the location of the wing relative to the airplane center of gravity. This is best done by being able to move the wing forward and back along the fuselage. Rubber bands or tape can be used to hold the wing in place once you’ve found the best location for it. For your first flight, start with the center of gravity slightly ahead of the center of your wing.

3. Attach your wing so its angle of attack is 4-5° higher than the horizontal tail’s angle of attack.

4. Before assembling your plane, weigh the structure to make sure is isn’t heavier than you assumed during your calculations.
Motor & Propeller  
Wing & Batteries (~ 4° relative to tail)  
Vertical and Horizontal Tail  
(~1” of dihedral for each foot of span)