Aeronautics and Rocketry

Efficient Propeller Design

(from http://sciencebuddies.com)

Objective

The goal of this project is to investigate how changes in chord length affect the efficiency of propellers.

Introduction

A propeller, like an airplane wing, is an airfoil: a curved surface that can generate lift when air moves over it. When air moves over the surface of a moving propeller on an airplane, the air pressure in front of the propeller is reduced, and the air pressure behind the propeller is increased. The pressure imbalance tends to push the airplane forward. We say that the propeller is generating *thrust*.

The same principle applies to helicopter propellers, only now the propeller rotates around the vertical axis. The pressure on top of the propeller is reduced, and the pressure underneath is increased, generating *lift*.

The illustration below (Figure 1) defines some terms that are used to describe the shape of a propeller. The *radius* (*r*) of the propeller is the distance from the center to the tip. The *chord length* (*c*) is the straight-line width of the propeller at a given distance along the radius. Depending on the design of the propeller, the chord length may be constant along the entire radius, or it may vary along the radius of the propeller. Another variable is the *twist angle* (β) of the propeller, which may also vary along the radius of the propeller.

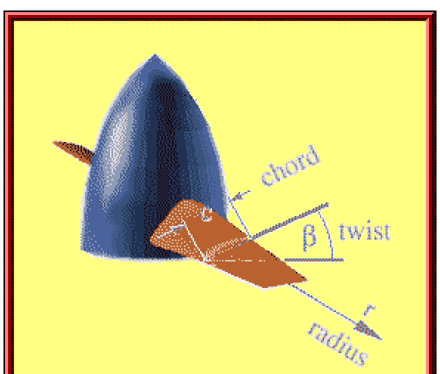

Figure 1. Illustration of terms used to describe propellers. The radius, *r*, of the propeller, is the distance from the center to the tip, along the center line. The chord length, *c*, is the straight-line width of the propeller at a given distance along the radius. The twist angle, β, is the local angle of the blade at a given distance along the radius (Hepperle, 2006).

In this project you will investigate how changing the chord length affects the efficiency of the propeller. You will keep the other design features (radius and twist angle) constant, changing only the chord length of the propeller. To measure the efficiency of the propeller, you'll connect the propeller to the shaft of a small DC motor. You will use the breeze from a household fan to make the propeller turn, which will cause the shaft of the motor to spin. In this configuration, the motor will act like a generator. You'll monitor the voltage produced by the motor to determine the efficiency of the propeller.

Terms, Concepts and Questions to Start Background Research

To do this project, you should do research that enables you to understand the following terms and concepts:

- propeller terms:
  - chord,
  - radius,
  - pitch,
  - rotational speed (measured in revolutions per minute or RPMs);
- airfoil,
- forces on an airplane in flight:
  - thrust,
  - drag,
  - lift,
  - weight.

Questions

- How do you think increasing the chord length will affect the efficiency of the propeller?

Bibliography

- Wikipedia is a good place to start for basic information on propellers: Wikipedia contributors, 2006. "Propeller," Wikipedia, The Free Encyclopedia [accessed November 21, 2006] http://en.wikipedia.org/w/index.php?title=Propeller&oldid=88680042.
- You'll definitely want to check out the Propellers section (among others) of NASA's Beginner's Guide to Aeronautics. This site is packed with useful information on the science of flight:NASA, 2006. "Beginner's Guide to Aeronautics," NASA Glenn Research Center [accessed November 22, 2006] http://www.grc.nasa.gov/WWW/K-12/airplane/guided.htm.

- For more advanced students, these webpages on aerodynamics of model aircraft by Martin Hepperle will be useful. There is even a Java program that you can use to test your design ideas on the computer before building them:
    - Hepperle, M., 2005. "Propulsion by Propellers," Aerodynamics for Model Aircraft [accessed November 21, 2006] http://www.mh-aerotools.de/airfoils/.
    - Hepperle, M., 2003. "JavaProp - Design and Analysis of Propellers," Aerodynamics for Model Aircraft [accessed November 21, 2006] http://www.mh-aerotools.de/airfoils/javaprop.htm.
    - Hepperle, M., 2006. "Propellers for F3D Models," Aerodynamics for Model Aircraft [accessed November 21, 2006] http://www.mh-aerotools.de/airfoils/pylonprops_1.htm#F3DOptimumPropeller.

Materials and Equipment

To do this experiment you will need the following materials and equipment:

- four (or more) propellers:
    - You'll need to make these with varying chord lengths (but identical radius and twist angles).
    - One potential source for materials to make these can be found at Freedom Flight Models (scroll down to see the propeller kits).
    - Another potential source for propellers would be a local hobby shop that sells airplane models.
    - If you are handy with tools and experienced with model building, you could also try carving propellers from a soft wood, like pine. It takes quite a bit of skill and patience to keep the twist angle the same for the different propellers!
- small 1.5-3 V DC motor (e.g., Radio Shack part number 273-223),
- 1/4 Watt, 4.7 kΩ resistor (e.g., Radio Shack part number 271-1124),
- jumper leads with alligator clips (e.g., Radio Shack part number 278-1156),
- digital multimeter (e.g., TM-162 from TechBuys.Net),
- fan.

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Experimental Procedure

1. Do your background research so that you are knowledgeable about the terms, concepts, and questions, above.
2. First you will need to make four (or more) different propellers, keeping the propeller radius and twist angle (pitch) constant, while systematically varying the chord length.
3. For testing, attach a propeller securely to the shaft of the DC motor. Depending on the materials used for the propeller, it could be taped on to the motor shaft, or drilled and press-fit.
4. Connect the 4.7 kΩ resistor across the terminals of the motor, and also connect the terminals to the voltage inputs for the multimeter.
5. Turn the multimeter to read DC volts, in the range for tens of millivolts.
6. Starting with the fan on low speed, hold the propeller/motor assembly in front of the fan. You'll want to test in the exact same spot each time.
7. The propeller may need a small push to start turning in order to overcome the internal friction of the motor. The moving air from the fan should keep the propeller turning after this. If not, turn the fan to the next speed and try again.
8. Observe and record the reading from the multimeter in a data table in your lab notebook. The reading will fluctuate slightly. You can round the reading to the nearest millivolt. Note that the reading will be quite sensitive to distance from the fan. Make sure that all of your measurements are taken at the same distance from the fan.
9. The mounting of the propeller to the motor may also affect the reading. If you are taping the propeller in place, you should repeat your measurements after removing and remounting the propeller to see how consistent your results are.
10. Repeat the measurements for each propeller.
11. Calculate the average voltage reading from the measurements for each propeller. More advanced students should also calculate the standard deviation.
12. Make a graph of the voltage produced (y-axis) vs. chord length of the propeller (x-axis). Is there a systematic relationship between chord length and rotational speed of the propeller?

Variations

- Test different propellers with different chord lengths while holding twist angle and *mass* of the propeller constant. To keep the mass constant, you will need to reduce the radius somewhat as the chord length increases. Do you find the same results as when the radius was held constant? Why or why not?
- Test the propellers at different fan speeds and compare the results. Do the same relationships between the propellers hold at all fan speeds?
- There are a number of possible variations on this project. Instead of examining the effect of the propeller's chord, you could investigate:
  - twist angle (pitch), Freedom Flight sells a handy jig for measuring the twist angle of a propeller (see Figure 2, below), or you could make one of your own.

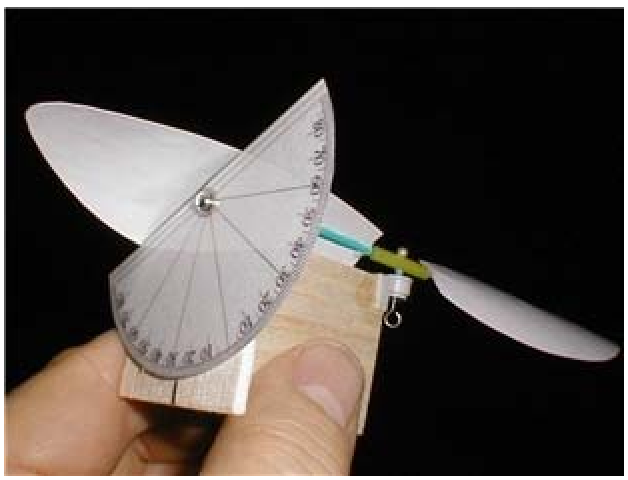

Figure 2. Propeller pitch gauge from Freedom Flight Models.

  - airfoil shape (camber of the propeller),
  - blade shape,
  - number of blades,
  - sweep (like a swept wing).
- This project uses an indirect method for measuring the propeller's rotational speed. Devise a way to measure the thrust produced by the propeller directly. For example, you could design a low friction mount for the motor that allows the motor to slide back and forth (along the propeller mount axis). Connect the motor to a gram spring scale to measure the force produced when the motor turns the propeller. How does thrust produced change with voltage applied to the motor? (Increasing voltage increases the rotational speed of the propeller.) How does the thrust measurement compare to the rotational speed measurement from this project?

The Wright Stuff: Using Kites to Study Aerodynamics

(from http://sciencebuddies.com)

Objective

The objective of this science project is to determine the effect of changing the bridle point—the point where the kite string, or control line, attaches to the bridle—on the kite's flying height, while keeping the length of the control line constant.

Introduction

Kites aren't just for kids. The Wright brothers used kites to test virtually every idea they had on airplane design before actually flying the test planes, and sometimes they flew their full-size gliders as kites to do additional tests.

Building and flying kites is a great way to start learning about aerodynamics. As you are flying the kite, you can actually feel your kite reacting to the wind through the changes in tension and motion of the string. If you've flown kites before, this science project can bring a scientific foundation to what you already know from experience. Who knows, maybe it will make you a better kite flier!

The science project you'll be doing has many possible variations. You can concentrate on kite design and compare flight performance as a design variable is changed. There are many types of kites to choose from, (for example: diamond, delta wing, and box) each with its own design elements, so you have a lot of choices. You can also choose which flight performance characteristic(s) you want to measure (for example: maximum height, string tension, lift capacity). Another way to go with this science project is to stick with a single kite design and investigate the effects of "trim" adjustments on flight (as in the Experimental Procedure example below). As you do your background research, think about which aspect of building and flying kites interests you most, and think about questions you might like to investigate.

NASA's Glenn Research Center has a great online kite simulation program (see Bibliography), which you can use as a learning tool for this project. It will help you get familiar with the basics of kite aerodynamics. It can also help you focus your ideas as you develop a hypothesis to test (or narrow down your list if you have a lot of ideas). Finally, you can use it to do a first-pass test on your hypothesis before you do your experiment with real kites. Keep in mind that a simulation is an idealized model of the real world. Any computer simulation contains assumptions, whether explicit or implicit, which may or may not be valid for particular conditions. It will be interesting to compare the results of the simulation and your real-life flight tests.

Terms, Concepts and Questions to Start Background Research

To do kite science project, you should do research that enables you to understand the following terms and concepts:

- The parts of the kite, especially the bridle and bridle point (where the control line attaches to the bridle)
- The four forces on a kite in flight: lift, weight, tension and drag
- How adjustments to the bridle length and bridle point are expected to affect the kite's angle of flight and other flight characteristics
- How to measure the altitude (height) at which your kite is flying
- How to fly a kite safely

For variations of this project, you should be able to explain in your own words how you expect your experimental variable(s) to affect the flight behavior of your kite(s), in terms of the forces on the kite in flight.

Bibliography

- TPT. (2006). Kites by Danielle and Jasmine. *DragonflyTV, Twin Cities Public Television.* Retrieved May 5, 2008 from http://pbskids.org/dragonflytv/show/kites.html
- NASA's Glenn Research Center has excellent online aerodynamics resources. Their pages are extensively hyperlinked, so you can follow your own path through the material. A good place to start is the "Guided Tour" page, where you can scroll down to the section on Kites. NASA Glenn Research Center. (2006, October 5). *Guided Tours of the BGA.* Retrieved May 12, 2008 from http://www.grc.nasa.gov/WWW/K-12/airplane/guided.htm
- You can go directly to NASA's kite simulator page with this link: NASA Glenn Research Center. (2005, October 24). *Interactive Kite Modeler Version 1.4a.* Retrieved May 12, 2008 from http://www.grc.nasa.gov/WWW/K-12/airplane/kiteprog.html
- This page describes a graphical method for estimating the altitude of your kite: NASA Glenn Research Center. (2006, March 20). *Graphical Maximum Altitude.* Retrieved May 12, 2008 from http://www.grc.nasa.gov/WWW/K-12/airplane/kitehighg.html
- Make sure you follow the safe kite-flying practices described on NASA's kite safety page: NASA Glenn Research Center. (2006, March 21). *Kite Safety.*

Retrieved May 12, 2008 from http://www.grc.nasa.gov/WWW/K-12/airplane/kitesafe.html

- There are many sources of information on building and flying kites. The Drachen Foundation is one good online source: The Drachen Foundation. (2008). *Kite Basics.* Retrieved May 12, 2008 from http://www.drachen.org/about_kites_basics.html
- Don't miss their excellent page on kite building, including information on knots used in building and flying kites and a wind chart to help estimate wind speed (Beaufort Scale):
  The Drachen Foundation. (2008). *Kite Building.* Retrieved May 12, 2008 from http://www.drachen.org/about_kites_building.html

Materials and Equipment

- Kite (1); any design that uses a bridle string with an adjustable bridle point (for example: diamond, box, sled)
- Computer with Internet access (for using NASA's online Kite Simulator program)
- Measuring tape
- Kite string and reel
- Tool to measure angles (for estimating the altitude of your kite; see: http://www.grc.nasa.gov/WWW/K-12/airplane/kitehighg.html).
  You can make this tool yourself with:
  - Stiff cardboard (2 pieces), 1 with angle markings and 1 pointer
  - A fastener to attach the pointer
  - Protractor
  - Marker
- String (about 50 ft. long)
- An observer to help you make the altitude measurements
- Lab notebook
- Graph paper
- Safe, open space to fly your kite
- Breezy day

Experimental Procedure

1. First, do your background research on kite aerodynamics.
2. Select a design and build your kite. Be sure to choose a kite type that uses a bridle string.
3. Use the NASA Kite Simulator program, from the Bibliography, to make a model of your kite and "test fly" it. Complete instructions for using the simulator are on

the program's webpage. Here are some screenshots of the Kite Simulator program for reference, and an outline of the procedure you will follow to use it:

a. Use design mode to make a model of your kite (select from Design Mode, Trim Mode, and Fly Mode by pressing the appropriate button in the simulator). Press the *Shape* button and then select the desired kite type from the drop-down list.

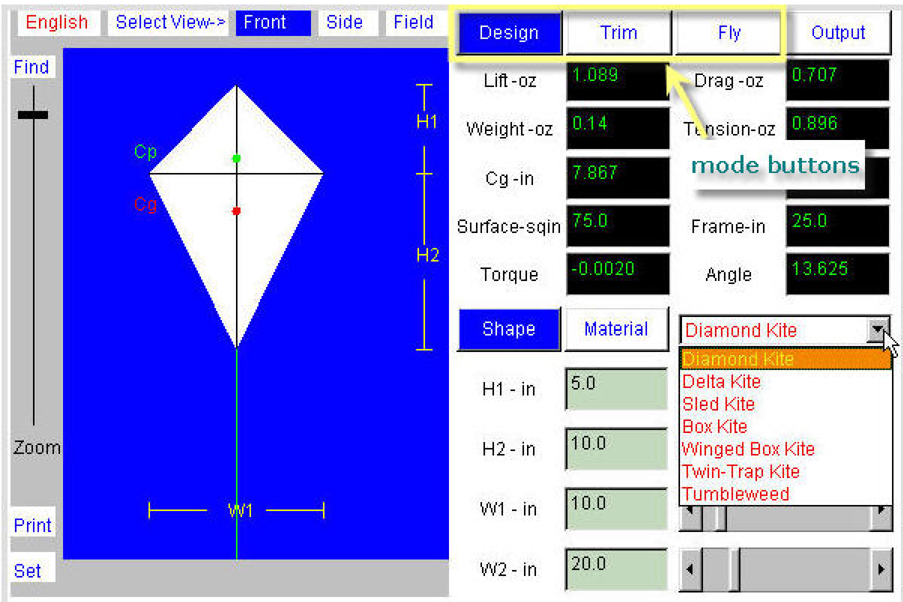

Figure 1: Selecting a shape for your kite in design mode.

b. In design mode, you can also select the type of materials your kite is made of. Press the *Material* button, and then make your selections from the drop-down lists.

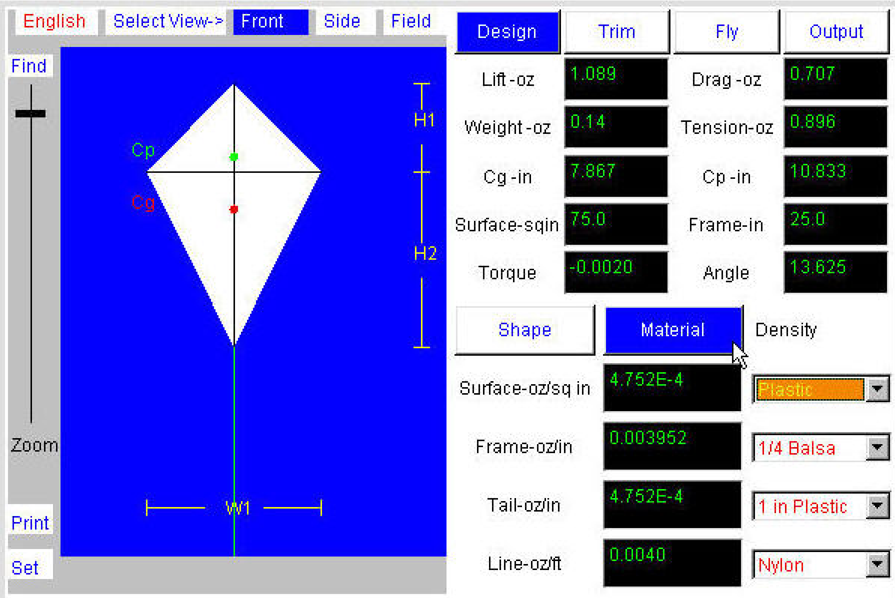

Figure 2: You can also select materials for your kite while in Design Mode.

c. You can use the dimension controls to change the shape of your kite. To change dimensions, you can type in a number, or use the arrows or sliders to make adjustments. You can choose English or metric units.

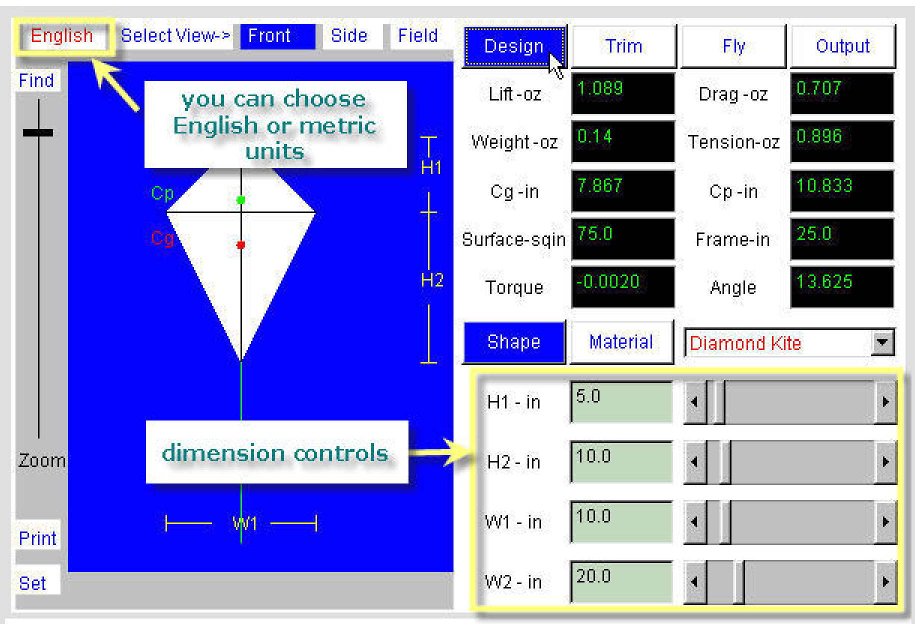

Figure 3: Change dimensions with the sliders or by typing numbers in the boxes.

d. Use trim mode to make adjustments to bridle point. You can use the arrow keys to make adjustments in small steps. B-Bridle: changes the total length of the bridle string. K-Knot: adjusts the bridle point; this is the distance from the tail to the control line knot. T-Tail: is the length of the tail. As you make adjustments, you'll see immediately what effect this has on the angle of the kite.

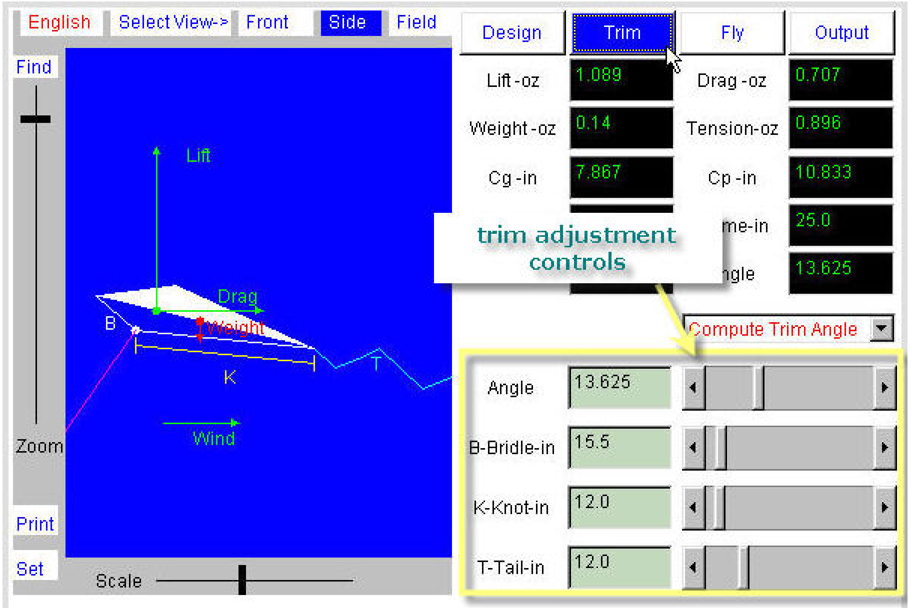

Figure 4: Use the arrows to make adjustments in small steps.

e. Your trim adjustments may make the kite unstable, but don't worry, it's easy to fix. Make your adjustments in small steps with the arrow keys. If the kite becomes unstable, back off on your adjustments by a step or two. Remember that you can always go back to the starting conditions by pressing the *Set* button.

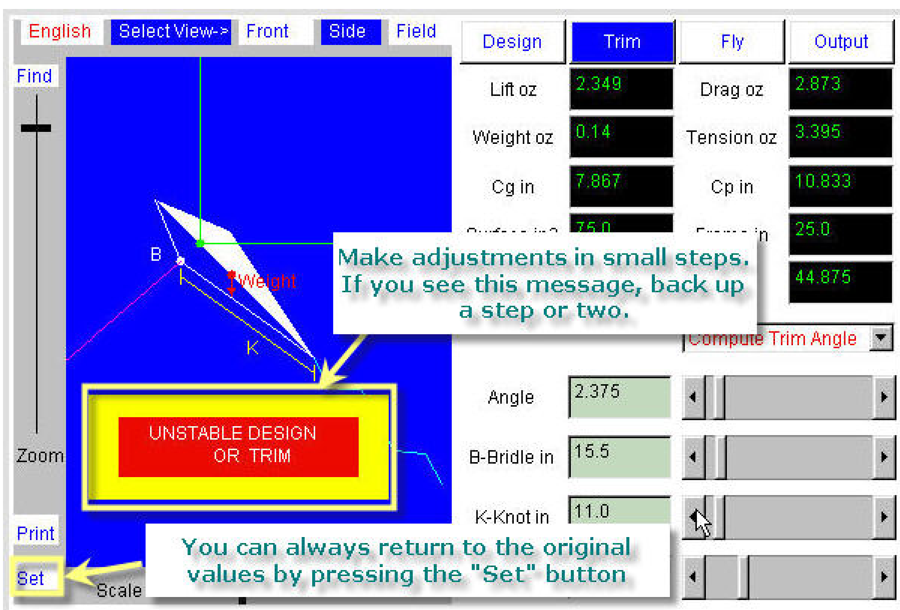

Figure 5: Don't worry, it's easy to correct mistakes.

f. Switch to fly mode to see how your change to the bridle point (in trim mode) affects the kite's flying height. There are controls at the bottom for entering your flying conditions. To convert wind speed from miles per hour to feet per second, multiply by 1.47 (5280 feet/mile * 1 hour / 3600 seconds). Remember to keep the flight conditions constant throughout your simulation, and throughout your experiment in the field.

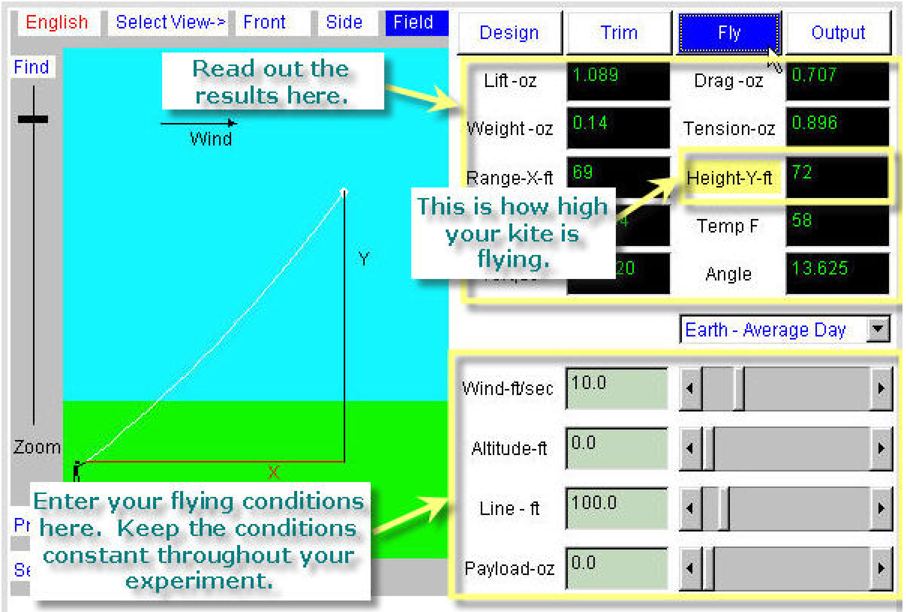

Figure 6: Enter your flying conditions, then read out the height (Y) of the kite.

4. Use the results from your simulation experiment to help decide how long to make your bridle string, and where to try placing the bridle point. Then go out and do an actual flight test. It is best to repeat your test two or three times for each condition.

5. Here is an example data table (use numbers from your own kite and experiments):

Example table for collecting flight data

Trial #	**Bridle Length**	**Bridle Point**	**Flying Height**
1	15.5	12.5	63
2	15.5	12.5	62
3	15.5	12.5	65
1	15.5	12.0	72
2	15.5	12.0	70
3	15.5	12.0	73

6. This link has a detailed procedure for measuring the flying height of your kite: http://www.grc.nasa.gov/WWW/K-12/airplane/kitehighg.html
(You can check it out by measuring an object of known height.)

Variations

- From your background research, or perhaps from your experience flying kites, you will probably have your own ideas for changing a kite design and predicting what will happen. Once you are familiar with the Kite Simulator program, you will see that it can be a great tool for testing your predictions. If an answer surprises you, go ahead and build the kite and see what happens in the real world.
- Here are some suggestions to get you thinking. We're sure you can come up with many more on your own:
    - More surface area more lift, right? But more surface area also means more material, and more material means more weight. Which one wins out? How does it depend on the choice of material?
    - Can you devise a diamond kite design with the center of pressure and the center of gravity in the same spot? Is this design more or less stable in flight? Why?
    - What is the optimal length for a tail? Does it depend on wind conditions? Why?

What Makes a Good Aerodynamic Design?

(from Science Buddies - http://sciencebuddies.com/)

Objective

The goal of this project is to measure the change in flight characteristics of gliders resulting from changes in glider design.

Introduction

When you think "paper airplanes," your first thought is probably of the garden-variety glider quickly folded from a sheet of paper. This project will introduce you to an entirely different construction technique for building paper gliders. Instead of using a single sheet of ordinary paper, the parts for these gliders are built up (laminated) in several layers, cut from thicker, stiffer paper stock. With this method, you can make paper gliders that are much more like the real thing than a simple folded paper airplane. The laminated construction technique is not difficult to learn, and the materials are inexpensive. There are even commercial kits available to help you get started but, with a little experience, you'll be ready and able to try your own designs.

Terms, Concepts and Questions to Start Background Research

To do this project, you should do research that enables you to understand the following terms and concepts:

- fuselage,
- airfoil,
- camber,
- dihedral,
- aileron,
- vertical stabilizer,
- horizontal stabilizer,
- elevator,
- rudder,
- center of lift,
- center of gravity.

Questions

- What are the three forces acting on a glider in flight?
- What relationship between these forces holds for stable flight?

Bibliography

- You'll definitely want to check out the Gliders section (among others) of NASA's Beginner's Guide to Aeronautics. This site is packed with useful information on the science of flight: http://www.grc.nasa.gov/WWW/K-12/airplane/guided.htm.
- This is a really good book, with pictures of many different airplane designs and information about how well they flew in the contest. The book also has chapters on paper glider design and construction, and tips for adjusting ("trimming") gliders for best flying: Editors of *Science 86*, 1985. ***THE** Paper Airplane Book: The Official Book of the Second Great International Paper Airplane Contest.* New York, NY: Vintage Books.
- The Whitewings website has tips on laminated paper glider construction, adjustment and flying (click on the link for "Assembly/Tuning/Piloting" and step through the list of topics): AG Industries, 2004. "Assembly/Tuning/Piloting Whitewings," AG Industries. http://www.whitewings.com/what/index.html.
- This website has a plan for a simple glider built with laminated construction methods. You can print the plan on cardstock or smooth Bristol board and then build the plane: Ivey, M., 2004. "High Performance Paper Airplanes," Zovirl Industries, Mark Ivey's Weblog [accessed November 14, 2006] http://zovirl.com/2004/01/15/high-performance-paper-airplanes-g-1/.

Materials and Equipment

- The materials for this project are simple: paper and glue. However, the paper needs to be chosen carefully. Ordinary copier or notebook paper is not stiff enough. The paper used for the Whitewings kits is Japanese Kent paper, which you may be able to find at your local stationery store. Alternatively, ask for sheets of cardstock. Smooth bristol board, available at art stores, is a little heavier, but still useable. As for glue, ordinary white glue, Itoya O-Glue or PentelRoll are all fine choices.
- The easiest way to learn the construction methods for laminated gliders is to buy and build one of the available "Whitewings" kits. Kits are available for single or multiple gliders. They are available in many hobby shops, and also online http://www.whitewings.com/.

- Remember that each model will need to be properly adjusted ("trimmed") in order to achieve its best possible flying. See the Bibliography for more information.
- For timing your flights, you'll need a stopwatch, or a watch with a second hand.
- For measuring the distance of your flights, you can use yard markers on a football field, or you can use a tape measure to set up your own set of distance markers in the open area where you are flying your gliders.

Experimental Procedure

There are many possible experiments you can try with paper gliders (for some specific examples, see the Variations section, below). Here are some suggested measurements for quantifying your experiments:

- flight distance,
- time aloft,
- flight maneuvers (i.e., descriptions of the flight: did the glider stall, dive, flip over, turn right, turn left, etc.).

With regard to experimental methods, here are some things to keep in mind:

- There will be variations in performance from flight to flight for the same glider, so you should make sure to perform repeated trials for each condition. We suggest at least five trials for each condition (more trials won't hurt).
- To minimize variability, make all of your test flights under the same conditions.
- Change only one variable at a time when testing. If you are interested in more than one variable, that's great! (You'll just have to make more planes.)

Variations

Here is a sample of project ideas for experimenting with paper gliders. As your knowledge and experience grow, you will be able to add to this list on your own. The variations are arranged in order of increasing difficulty.

- **How Do Stabilizers Affect Glider Flight?** As you are building the glider, leave off either the vertical or horizontal stabilizer (or build multiple gliders, with and without these parts). Test-fly the glider(s) with and without each type of stabilizer. What effect does each type of stabilizer have on flight?
- **What is the Optimal Size for a Stabilizer?** Use the same basic design for a series of four or more planes, but vary the size of one of the stabilizers (vertical or horizontal) from smaller to larger than normal. Measure the flight

performance of each glider. Think about how might you control for the difference in weight distribution.

- **Design for distance.** Do your background research and develop a hypothesis about what type of glider will fly the furthest. Build a series of 4 (or more) gliders with one variable element changing systematically through the series to test your hypothesis.
- **Design for Time Aloft.** Do your background research and develop a hypothesis about what type of glider will fly the longest. Build a series of 4 (or more) gliders with one variable element changing systematically through the series to test your hypothesis.
- **Investigating More Than One Design Element.** Your hypothesis may involve more than one design element. For example, you may be interested in investigating both dihedral angle and camber. In order to compare planes with only one variable changing, you would need to build two (or more) planes for each dihedral angle you want to test, each with varying wing camber. Then you can make pair-comparisons where only dihedral angle was changed, or pair-wise comparisons where only wing camber was changed.

Why Do Aerobie Flying Rings Go So Much Further Than Frisbees?

(from http://sciencebuddies.com)

Objective

The objective of this project is to explore the aerodynamics of flying rings. What effect do various design modifications (e.g., increasing weight near perimeter, increasing weight near center, curving the leading edge, decreasing the size of the center cut-out) have on flight distance?

Introduction

In this project you will come up with a hypothesis to explain why flying rings travel farther than flying disks and make your own flying models from paper plates (or Bristol board) to test your hypothesis. If you have more than one hypothesis, it's easy to expand your project. The materials are inexpensive, and flying disks and rings are not hard to make.

Your background research should help you to come up with a hypothesis to test. The experimental procedure section has some suggestions on construction methods for building flying rings and disks. There are also tips on test-flying and measurement.

Terms, Concepts and Questions to Start Background Research

To do this project, you should do research that enables you to understand the following terms and concepts:

- lift,
- drag,
- weight.

Questions

- What forces act on flying rings and disks in flight?
- What is (are) the major difference(s) in these forces between flying rings and disks?

Bibliography

- The Exploratorium, 1997. "What effect does the rim of a frisbee have on its flight?" Sport! Science [accessed February 10, 2006] http://www.exploratorium.edu/sports/ask_us_sports_october.html.
- NASA has a great reference site on Aerodynamics. Even though there is not anything specific on frisbee flight, you can still learn a lot about how frisbees fly by learning about aerodynamic forces on other types of airfoils. Check out the Gliders section, and the Lift Simulator program. http://www.grc.nasa.gov/WWW/K-12/airplane/guided.htm.
- For information on the science behind Aerobie flying rings, see: "The Science of Aerobie Sport Toys," Aerobie, Inc. [accessed February 14, 2006] http://www.aerobie.com/Science.htm.
- For making rings from paper plates, you'll need to know how to find the center of a circle. This link tells you how: Dr. Math, 1996. "Finding the Center of a Circle," Ask Dr. Math Forum, Drexel University [accessed February 14, 2006] http://mathforum.org/library/drmath/view/54822.html.

Materials and Equipment

To do this experiment you will need the following materials and equipment:

- Bristol board (smooth surface, *not* vellum surface; available at art supply and stationery stores),
- or paper plates,
- white glue,
- compass and pencil for drawing circles,
- scissors,
- tape measure,
- string,
- tape,
- marking pen,
- helper.

Additional items that may come in handy:

- pennies (or washers) for weight,
- tools for forming curved or shaped edges: silverware, plastic cutouts.

Experimental Procedure

Developing a Hypothesis

1. Do your background research and learn about the forces on flying disks and rings in flight. How do the forces differ between the two? How do you think this will affect flight distance?
2. Carefully examine commercial flying ring and flying disk products and note differences between them. For each of the differences, think about the forces acting on these objects as they fly, and try to predict the aerodynamic consequences.
3. For example, an obvious difference between the disks and rings is the open space in the center of the ring. What aerodynamic effect(s) result from opening up the center of a disk?
4. Test your hypothesis by building a series of rings (3–5), which systematically vary the design element of interest. To continue with the example above, you could build a series of rings with successively smaller open diameters in the center.

Construction Tips for Paper Rings and Disks

1. You can use Bristol board (recommended) or paper plates to make your flying rings/disks. (If you use paper plates, see the Bibliography for a way to find the center of a circle, so you'll know where to put your compass point.)
2. Use your compass to draw circles for your rings. Building up your rings from multiple layers will make them stiffer, and they will fly better (see below).
3. If you want to add weight to your rings, try extra laminations of the appropriate diameter, or glue pennies or washers in between layers. (Sobey, 2000, 55)
4. When building your flying models, change only one design variable at a time. For example, if you are investigating the effect of the diameter of the open center, all of the rings should have the same outer diameter, mass, edge curvature, etc. Only the size of the center opening should change.
5. How can you keep the mass constant but still have more material covering the center opening? The key is to build your rings out of more than one layer of paper (laminated construction). Laminated construction has multiple advantages.
    a. Your design can redistribute the material between different layers to keep the mass constant. For example, as you add material in the center of one layer (to decrease the open diameter), you remove an equal area of material from another layer (or layers). (It's easy to calculate how much mass you are adding. Since the paper has uniform thickness, the mass will be proportional to the area. The area of a ring is just the area of the outer circle minus the area of the inner circle.)

b. You can explore how the distribution of mass (e.g., more mass towards edge vs. more mass towards center) affects flight performance.
c. By gluing together two or more layers (laminated construction), you will end up with a stiffer ring or disk, which will fly better.
d. A way to further increase stiffness is to compensate for the "grain" of the paper by rotating the disks relative to the original orientation before gluing them. Most papers bend more easily in one direction than the other (usually there is more resistance to bending in the long axis of the paper). If you systematically rotate the strong axis of the separate layers, your finished ring will be stronger. For example, with a two-layer ring, rotate one layer 180°/2 = 90° before gluing. For a three-layer ring, rotate each layer 180°/3 = 60° relative to the previous layer.

6. Glue the layers together carefully with white glue. Spread the glue evenly and make sure all edges are glued down tight.
7. Wait for the glue to dry (overnight is best) before test-flying.
8. If you want to curve the edges of your flying rings/disks, you can use the a piece of silverware (like the curve on a spoon where the bowl meets the stem). Work at the edge of a table, with the edge of your disk sticking out. Carefully bend the rim of your ring with the spoon. Rotate the ring and bend a uniform curve all around the edge. (Sobey, 2000, 57–58) Alternatively, make a curve-forming tool by cutting a plastic lid in the desired shape.

Test-Flying and Measurement

1. For measuring your flights, you'll need a tape measure and a helper.
2. If your tape measure is not as long as your typical throw, make a longer tape measure using a piece of string. Mark off regular intervals with tape labels and a marker, and you're in business.
3. Do your best to keep the conditions for all of your test flights constant. Try to throw with the same arm motion and speed for each ring.
4. Do at least 10 test flights for each ring. Record the results in your lab notebook.
5. Make one or more graphs to show your results. In this example, you could graph flight distance vs. center open diameter.

Variations

- For a flying disk project, see: The "Ultimate" Science Fair Project: Flying Disk Aerodynamics.
- Think about other flight characteristics you can test. For example, think about curved flight paths. The drag component is very different between the two designs, what affect does this have on tendency of disks and rings to curve in

flight? (See The "Ultimate" Science Fair Project: Flying Disk Aerodynamics for suggestions on throwing and measuring curved flight paths.)

- Laminations on top vs. underneath. If you curve the edge of your rings downward, would you expect more drag from ring laminations added to the top or to the bottom surface?