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Science of Sailing

Introduction

The sailboat has been in existence for several thousand years. Until only about 150 years ago, when the steam engine became more practical, the sailboat was the main vessel for traveling over water. Learn about the basics of sailing, Newton's law of motion and Bernoulli's principle as well as comparing the advantages of a square sail and a triangular sail.

Concepts

- Newton's third law of motion
- Bernoulli's principle
- Net forces
- Sailing principles

Background

Naturally, a sail generates motion by capturing wind and using the current of the wind to move a boat. A sail with a larger surface area harnesses more wind, generates more thrust, and makes the boat move faster. However, there must be a balance between the weight of the sail and the amount of wind it captures. A large, heavy sail may end up slowing the boat down or tipping it over.

A square sail is the most efficient sail when sailing downwind. It captures all the wind with a large surface area and the wind pushes the boat forward. However, the large surface area does have a drawback of producing the most drag. Also, square sails are difficult to manage—furling (wrapping up), unfurling, and rotating the sail around the mast to capture wind at an angle can take a long time and requires several sets of hands. The main drawback of a square sail is that it cannot be used to travel into the wind. It only allows a sailboat to travel with the wind.

A triangular sail, also known as a *lateen* sail, is a much more versatile sail. For the same height and width, a triangular sail will capture half the wind compared to a square sail, meaning a boat with a triangular sail will travel about half the speed of a boat with a square sail in the same wind. The benefits of a triangular sail, however, have made them ubiquitous on nearly every sailboat. A triangular sail has the lowest drag, is easy to manage, and has the major advantage of allowing a sailboat to travel into the wind (at an angle) in a process known as *tacking*.

A triangular sail can generate forward thrust into the wind due to its orientation with the direction of the wind and the net forces that result from the action–reaction forces on the sailboat according to Newton's third law of motion (see Figure 1).

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{13294_Background_Figure_1}
To prevent the boat from tipping over, a keel is added to the bottom of the boat. The keel is the long "fin" that provides a counterforce to the force of the wind on the sail, allowing the boat to go forward without tipping over. The keel uses drag from the water to balance the "backward" motion from the wind, resulting in an overall forward moving sailboat. Without a keel (or friction on the wheels, in the case of the sail car) the sailboat would slide sideways as it moves and would have only a small amount of forward motion into the wind.

Along with Newton's third law of motion, a triangular sail is also influenced by Bernoulli's principle. Bernoulli's principle states that the faster a fluid moves over a surface, the lower the pressure will be on that surface. Wind currents not only flow over the inside portion of the sail, but the outside as well. The wind that strikes the inside of the sail puffs the sail outward slightly (due to Newton's third law). This puffed-out sail forms a type of airfoil (similar to that of an airplane wing). Therefore, the air that travels over the outside portion of the sail travels at a faster rate. This faster moving air reduces the pressure on the outside of the sail (see Figure 2). Now, there is high pressure on the inside and low pressure on the outside of the sail. Air moves from high pressure to low pressure (in the form of wind) and therefore this isolated pressure difference helps to "pull" the sailboat into the wind.
{13294_Background_Figure_2}

Experiment Overview

Build a sail car and experiment with a square sail and a triangular sail to learn the advantages and disadvantages of both types of sails.

Materials

Clamp, pinch

Nut to fit thick screw

Nuts to fit thin screw, 2

Ruler

Scissors

Screw, thick

Screws, thin, 2

Straws, 5

String, 30"

Tape, transparent

Tissue paper, 1 sheet

Wheels, 4

Wood board with holes and eye screw, ¾" x ¾" x 4½"

Safety Precautions

The materials in this kit are considered nonhazardous. Take a one or two minute break in between blowing trials to avoid becoming lightheaded.

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Procedure

Sailboat Assembly

1. Obtain the materials to construct the sailboat as shown in Figure 3.
{13294_Procedure_Figure_3}
2. Use the thinner screws and smaller nuts to secure the wheels onto the wood board. Do not overtighten the nut. Make sure the wheels are secure, but still spin freely on the screw axle.
3. The thicker screw will act as the mast anchor for each sail design.
4. Obtain the straws, tissue paper, scissors and tape to build the two sails.
5. Cut the tissue paper into two 5" x 5" square pieces. Save the remaining tissue paper for additional experiments (if time allows).
6. Cut three straws to 5½" lengths and two straws to 6" lengths.
7. Tape one 5" x 5" tissue paper sheet onto two of the 5½" straw "yardarms" as shown in Figure 4. Notice that the end of the tissue paper wraps around the straw slightly at the top and bottom. This will help keep the tissue paper secure.
{13294_Procedure_Figure_4}
8. Tape one 6" straw "mast" onto the centerline of the square sail unit made in step 7 (see Figure 5).
{13294_Procedure_Figure_5}
9. Obtain the second 5" x 5" tissue paper sheet.
10. Cut this sheet at a diagonal to create two equilateral triangles.
11. Obtain one 5½" and one 6" straw piece.
12. Tape the triangular sheet of tissue paper, the 5½" straw yardarm, and 6" straw mast together as shown in Figure 6.
{13294_Procedure_Figure_6}
13. Cut three 10" lengths of string.
14. Tie or tape one end of one string to the end of the straw yardarm of the triangular sail (see Figure 7).
{13294_Procedure_Figure_7}
15. Tie or tape one end of each of the remaining pieces of string to the top straw of the square sail (see Figure 7).

Procedure

1. Obtain the assembled sail car, square sail and triangular sail.
2. Place the square sail onto the mast support screw.
3. Clamp or tape the strings attached to the yardarm to the eye screw at the back of the sail car. Make sure the string is taut and the sail does not twist (see Figure 8A).
4. Position the car on the tabletop with the bow (front) of the sail car pointed directly away.
{13294_Procedure_Figure_8_Top view}
5. Place your mouth in line with the sail (parallel to the tabletop) and gently blow on the sail (see Figure 9). Observe the motion of the sail car and record your observations of the sail's reaction and the car's motion in Data Table 1 on the Science of Sailing Worksheet.
{13294_Procedure_Figure_9}
6. Next, position the car in the same location on the tabletop as before, but rotate the car to a 45-degree angle (see Figure 10B).
7. Repeat step 5. Blow from the same distance, and with the same amount of force. Observe the motion of the sail car and record your observations of the sail's reaction and the car's motion in Data Table 1.
8. Repeat step 5 for each of the three remaining car positions shown in Figure 10. Blow from the same distance and with the same force for each trial. Observe the motion of the sail car and record your observations of the sail's reaction as well as the car's motion in Data Table 1.
{13294_Procedure_Figure_10}
9. Obtain the triangular sail.
10. Remove the square sail from the sail car and place the triangular sail onto the mast screw.

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11. Rotate the sail to a 45-degree angle (see Figure 11).
{13294_Procedure_Figure_11}
12. Clamp or tape the string attached to the mast to the eye screw at the back of the sail car. Make sure the string is taut and the sail does not twist (see Figure 8B).
13. Repeat steps 4–8 for the sail car with the triangular sail to observe the motion of all five car positions (see Figure 11).
14. Experiment with the angle of the square sail. Is it possible to change the angle of the square sail relative to the centerline of the sail car in order to use the square sail to travel into the wind? Remember, a square sail can only be rotated by at most 45 degrees from its original position (perpendicular to centerline). Position the car so that its centerline is at an angle of 100 degrees to the wind direction. Record the approximate sail angle with respect to the centerline of the car and observations in Data Table 2. Perform two to three trials at different sail and centerline angles (see Figure 12).
{13294_Procedure_Figure_12}
15. Experiment with the angle of the triangular sail. Position the sail to have an angle between 10–20° with respect to the centerline. Determine the largest angle at which the sail car can be rotated into the wind and still produce forward thrust (movement into the wind). Record the sail angle with respect to the centerline of the car, the angle of the car with the wind, and all observations in Data Table 2. Perform two to three trials at different sail and centerline angles (see Figure 12).
16. Consult your instructor for appropriate storage procedures.

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