Classroom Activities in Aerodynamics

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CLASSROOM ACTIVITIES IN AERODYNAMICS

The study of aerodynamics provides a number of fascinating instructional avenues. The scope of scientific instruction ranges from simple demonstrations to complex measurements and calculations. In addition, the historical evolution of the development of aerodynamics and its contribution to the invention of the airplane is in itself a topic of study.

Activities associated with this lesson include some simple mechanisms for showing Bernoulli's Principle and semi-complex implements for demonstrating and measuring the aerodynamic forces of lift and drag. The latter involve demonstrations using a whirling arm and a portable wind tunnel. The objective of these lessons is to provide enjoyable techniques for teaching aerodynamics.

Bernoulli's Principle

Daniel Bernoulli (1700-1782) was a Swiss scientist who studied fluid flows. From his work emerged "Bernoulli's Principle." This law states that for a steady flow of a fluid, the total energy (combination of kinetic energy from the velocity of the flow, the potential energy from elevation and gravity, and the pressure energy exerted by the fluid) remains constant along its flow route. Therefore, when velocity increases, the pressure energy of the fluid must decrease to maintain a constant level of total energy. In simpler terms, as velocity increases, pressure decreases.

Bernoulli's Principle is used throughout the aviation industry. From the production of lift to the workings of a carburetor, the relationship between velocity and changes in pressure is paramount to the operation of aircraft.

Bernoulli on a Straw

Bernoulli's Principle may be illustrated using a simple device manufactured from common materials. To construct a Bernoulli on a Straw demonstrator, a straw, segment of cellophane tape, and strip of newspaper are needed. A milkshake straw works well. Milkshake straws may be distinguished from common soda straws by their inside diameters. The former use a larger inside diameter than the latter. Place a strip of newspaper that approximately measures 1¼" (3.17 cm) by 6" (15.24 cm) on a flat surface. Cut the tip of one end of the straw at a 45˚ angle to provide a bevel. Center the beveled tip of the straw so that the bevel is downward and around 1" (2.5 cm) from one end of the newspaper. The remaining 5" (12.7 cm) of newspaper should be free of the straw. Carefully attach the tip of the straw to the newspaper using cellophane tape. Ensure that the tape runs perpendicular to the straw
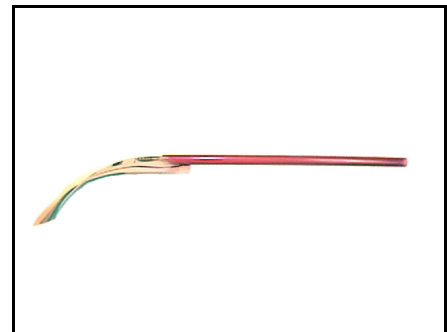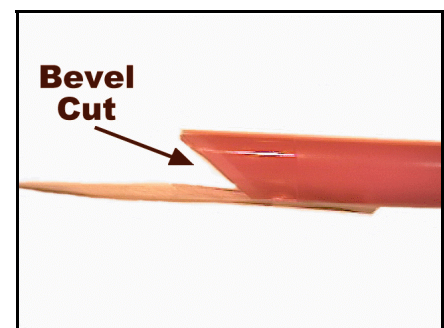

Figure 1: Bernoulli on a Straw

Bevel Cut

Figure 2: Modification to End of Straw

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and even with the tip of the straw without blocking the orifice. Lift the unit from the surface. The newspaper should droop away from the tip of the straw.

To fly the newspaper, raise the device to your lips (be certain that the newspaper is hanging beneath the straw) and blow through the free end of the straw. Depending on relative positions of the straw and the newspaper, the strip of paper should lift and become parallel with the length of the straw. Blowing excessively hard may produce a fluttering action. If necessary, begin the flight by blowing hard and lessen the airflow to achieve a steady flight.

Figure 3: Flying Bernoulli on a Straw

Another, and more telling, demonstration of Bernoulli's Principle is shown when raising the straw to a vertical position and blowing. In this example, the strip of newspaper is shaped like an inverted letter "J." By vigorously blowing through the straw, a low pressure of significant magnitude is produced. Such a pressure causes the newspaper to lift until it is parallel with the straw. At this point, the newspaper is vertical.

The effects of drag may be shown with this device. **<u>Caution:</u> Before walking or running with the Bernoulli on a Straw device in your mouth, make certain that you take the necessary precautions to avoid injuries and/or ingestion of the device. If you feel that you cannot safely conduct this demonstration, do not attempt it.** Place the unit in your mouth, walk forward, and blow through the straw until the paper rises. Try it again at a faster speed. For a real challenge, run forward while trying to lift the paper. Two forces are working against the lifting of the newspaper. First, drag is acting on the paper as it dangles from the end of the straw. The lifting force must overcome this measure of drag. Also, as you move forward, some of the velocity of the accelerated air flow is negated by the forward motion of the unit. This lessens the effect of the exhaled airflow.

The force producing the action associated with this demonstrator is Bernoulli's Principle and the pressure differential created. The air that passes over the newspaper is traveling at an accelerated rate. This generates a low pressure on that side of the newspaper. Because the other side of the paper has higher pressure, stationary air, a pressure differential is produced. When the force acting across the surface of the newspaper is sufficient to lift the paper, the newspaper moves in the direction of the low pressure.

Hot Wings (Hot Wheels® con Wings)

Another demonstration of Bernoulli's Principle may be performed using simple wings, Mattel Hot Wheels®, and a segment of track. Construct the wings from a manila folder. After trimming off the folder's tab, cut it in half so that the cut is perpendicular to the folded end. Shove one side of the folder towards the folded end to give the wing its shape. Staple the trailing edge of the wing so that it retains its airfoil shape. Glue the wing to the top of one of the

cars. Hot glue or epoxy work well for this purpose. Ensure that the cambered (curved) surface points towards the front of the car. Construct the second wing and attach it to the second car ensuring that the cambered surface is towards the front of the car. Place both cars on the track so that they are facing each other. Refer to the figure showing the top view of the Hot Wings.

Figure 4: Top View of Hot Wings

Space the cars apart to allow for forward movement of each car. Generate a low pressure between the wings by blowing in between them. You may either vigorously blow in between the two wings or use a blow dryer. As the air is accelerated, an area of low pressure is produced between the airfoils. A pressure differential is created between the outboard surfaces of the wings where the air is stationary and the inboard surfaces where the air is rapidly moving. When this pressure differential is distributed across the area of the wing, enough force is generated to propel the vehicles towards each other. Where these cars move in a horizontal direction, the force generated is similar to the lift developed by a wing in flight or a rotor of a helicopter as it revolves in its circular path. Examine the illustration depicting the action of the blow dryer.
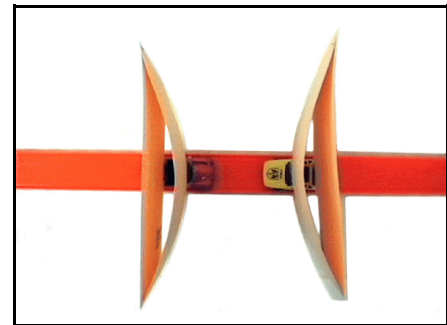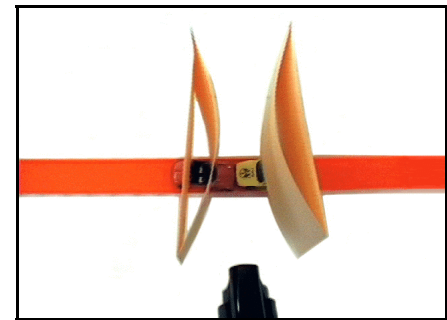

Figure 5: Hot Wings Respond to Low Pressure Generated by Blow Dryer

Lift and Drag

Lift and drag are two of the four forces that act on an airplane in flight. The remaining forces include gravity and thrust. Under normal operating conditions, lift is opposed by gravity (the total weight of the aircraft including occupants, fuel, baggage, etc.). Drag is a force generated during the production of lift and when an object passes through the atmosphere. The force of thrust is opposed by drag. There are various kinds of drag. Some of the more well known forms of drag include induced drag, parasite drag, profile drag, and interference drag.[1]

The production of lift involves the dynamic reaction of air passing over specially-shaped surfaces known as airfoils or wings. The shape of an airfoil is designed to generate the requisite amount of lift to support the weight of the aircraft throughout a variety of flight parameters. Most airfoils have a pronounced camber or curved surface that causes the mass of air flowing over the surface to accelerate in terms of velocity. As a consequence, the pressure along the cambered surface is reduced. With a reduction of pressure on one side of the airfoil and near-ambient pressure on the other, a pressure differential is established that acts on the surface area of the airfoil. The

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[1] *See Northrup's Aeronautical Institutes Aircraft Basic Science (1948) page 52 for additional information.*

magnitude of this force equals the amount of induced lift.

Another element in the production of lift is the downward deflection of air as it passes away from the airfoil. This movement of air provides a Newton action/reaction component to the production of lift. The downward action of the air provides an upward reaction to the wing. This lift is known as dynamic lift. The total lift of the airfoil is the combination of induced and dynamic lift.

Several factors affect the quantities of lift and drag produced as the airfoil experiences relative wind. The shape of the wing, the total surface area of the airfoil, the velocity of the flowing air mass (airspeed), and the angle at which the air strikes the airfoil (angle of attack) are key factors in the generation of lift and drag. In this unit, several examples demonstrating the shape of the airfoil, speed of flowing air mass, and angle of attack are presented.

Whirling Arm

The whirling arm first came into existence around 1746. It was used by Robins to study ballistic characteristics of cannonballs and other projectiles. He perhaps was trying to understand why artillery shells would reach a maximum distance in which no additional amount of gunpowder added meaningful length to the flight of the projectile. During this investigation, Robins used a whirling arm device to gather data concerning the resistance encountered by projectiles passing through the air. This force, known as drag, opposes the movement of articles through the atmosphere. The relationship between the speed of an object and the quantity of drag is basically exponential, when speed is doubled drag is squared.

Aviation pioneer, Sir George Cayley (1773-1857), was perhaps the first person to use a whirling arm device for the study of aeronautics. His work influenced the investigations of other aviation researchers, including the Wright Brothers. As illustrated in Figure 6, the whirling arm is mounted on a vertical axis. Sample airfoils are attached to the extremity of the whirling arm. A cord is wrapped around the vertical axle and attached to a weight. As the weight is allowed to fall, the unwinding action of the cord around the axle imparts a rotating motion to the arm. Consequently, the airfoil is subjected to a certain airspeed, or relative wind, as it sweeps through the air in a circular path.

Figure 6: Sir George Cayley's Whirling Arm of 1804

Through the use of this instrument, Cayley collected data relevant to the response of airfoils at varying angles of attack. His research with the whirling arm began in 1804. He discovered that an area of low pressure developed over the upper surface, or camber, of the wing as it
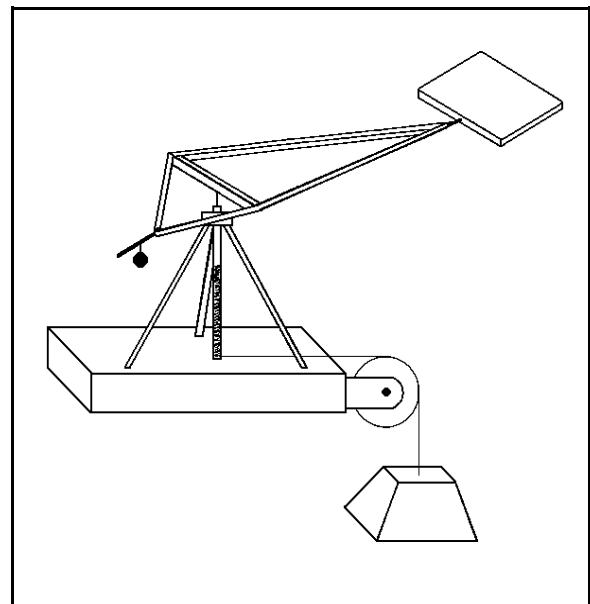
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travels through the air. Cayley also determined that the center of pressure moved as the angle of attack changed. The center of pressure is the location where the aerodynamic forces of a wing are concentrated. The angle of attack is determined by the relationship of the direction of the relative wind and an imaginary line, known as the chord line. The latter runs from the leading edge of an airfoil to the trailing edge. Leading and trailing edges refer to the front and rear portions of an airfoil in terms of air flow. Cayley used the information gathered during his study to produce successful gliders. His contributions to the science of aeronautics have earned him the title, Father of Aerial Navigation.

Whirling Arm Activities

Whirling arm activities are informative and loads of fun. The author first encountered this demonstrator at Minneapolis, MN under the instruction of Dr. Norm Poff. The author somewhat modified the wing-on-a-string device by adding a frame to increase airspeed and simplify operation. The frame also assists in terms of maintaining and changing angle of attack. A more elaborate version of the whirling arm includes an angle meter and airspeed indicator.

Materials needed for this exercise include a sheet of paper, 2 segments of straw 2" (5 cm) in length (use a milk shake size drinking straw), cellophane tape, a hole punch, 2 lengths of fishing line, and a frame. See the illustration of "A Simple Whirling Arm" for information concerning the construction of the frame from PVC pipes. Fold the paper in half along its longest axis. Locate and make holes in the folded sheet about ¾" to ⅞" (1.9 cm to 2.22 cm) from the creased-edge using the hole punch. Be certain to align the holes to correspond with the grooves cut into the horizontal PVC members. If you are using a standard hand-held hole punch, make the holes as far in from the folded edge as allowed by the punch so that the holes are near the wing's center of pressure. Carefully pre-fit the straws in their holes. This measure will be helpful during final assembly. If you have trouble working the straw segments through the paper, cut a slight angle or bevel at one end of the straw and insert this end. Do not tear the holes during this operation. Remove the straw segments. Next, form the airfoil by sliding the upper half of the folded sheet so that its free edge is shoved towards the folded edge about ½". Vary the amount of camber (how much curve the upper surface has) by trying different measurements (e.g., ¼", ⅜", ½", ¾", 1", etc.) to see the relationship of camber on lift. Apply a couple pieces of cellophane tape to the free edge of the upper surface so
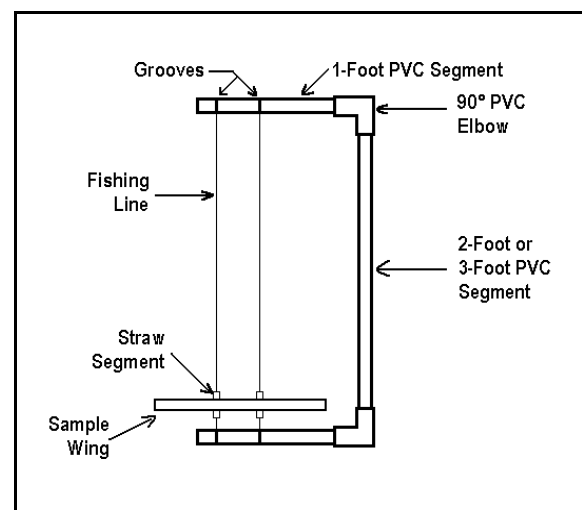

Figure 7: A Simple Whirling Arm

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that the paper retains its airfoil shape. Reinsert the straw segments through their holes in the upper and lower surfaces of the wing. They should have a firm fit. If needed, wrap a little tape around the portions of the straw segments that protrude from the wing to secure them in place. Thread the lengths of fishing line through the straws. Assemble the frame by attaching a 90˚ PVC elbow to each end of the vertical member (refer to Figure 7). You may elect to use ½" PVC pipes for the frame when constructing it for use with small children. For older children and adults, ¾" PVC is appropriate. When using the Whirling Arm with lower grade levels, it may be advantageous to limit the height of the unit to two feet. Frames for older children and adults should be three feet tall.

Assemble the Whirling Arm by firmly pushing and twisting the elbows onto the vertical frame member to produce a tight, friction fit between the parts. A friction fit is all that is required to hold the pieces together. Insert a 1-foot segment of PVC in the remaining hole in each elbow. Ensure that the machined grooves are away from the elbow.

The grooves may be made on a table saw using a shallow cutting depth to about ½ the wall thickness of the pipe. To make a clean cut in PVC, install the saw blade backwards (so it rotates in the opposite direction of rotation). As before, push and twist the segments into the elbows to ascertain an adequate friction fit. Adjust the elbows by twisting so that the 1-foot PVC segments are parallel along the same plane. For right-handed units, place the frame of the whirling arm in your right hand and extend the device away from your body. Install the wing so that the leading edge (the folded edge) is facing forward.

Figure 8: Angle Meter at 10˚

The same technique should be used to construct left-handed models, only hold the frame in your left hand and point the leading edge so that it points forward. Attach the lines to the frame. The fishing lines must be tightly stretched across the frame. If the lines are loose, the wing will be hindered in its ability to freely travel up and down the frame assembly. To obtain the slight amount of tension needed to keep the fishing lines taut, adjust the length of the lines or position the knots so that the vertical frame member is gently bowed. Ensure that the lines run parallel to each other.

A more advanced whirling arm may be constructed to include an angle meter and airspeed indicator. The design is similar to the Simple Whirling Arm with the following differences. Instead of making the frame in the shape of the letter "C," the frame is
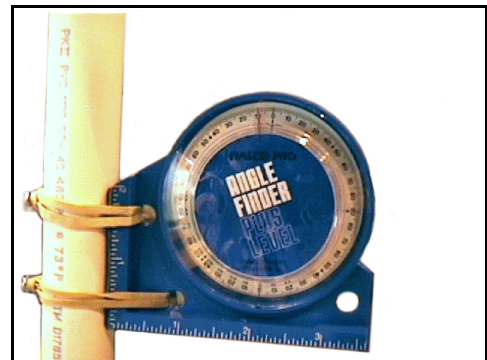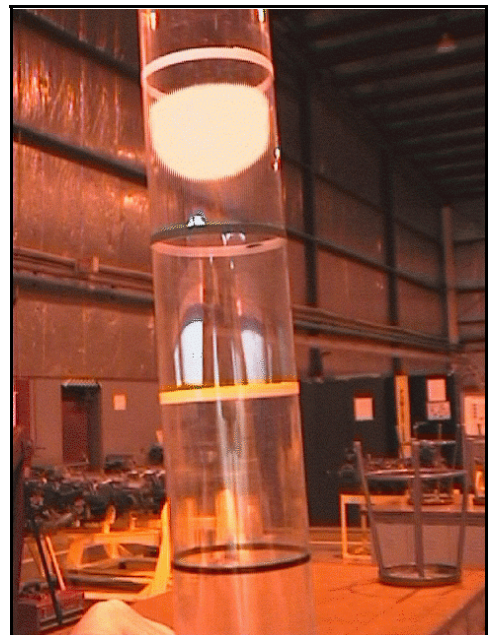

Figure 9: Airspeed Indicator

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rectangular. To keep the fishing lines taut, rubber bands are used. The fishing line is attached to the lower horizontal member at one end and a rubber band at the other end. The rubber bands are engaged in the grooves of the upper horizontal member. It is important to ensure that the lines run parallel to each other to prevent binding. A couple of screws are added to each vertical member to provide a method for attaching the angle meter using rubber bands. By having attachment points on each vertical member, the angle meter may be quickly moved from one side to the other to switch from a right-handed model to a left-handed model and vice-versa. See the associated illustration. The angle meter may be used to more accurately measure the performance of wings based on angle of attack.

The airspeed indicator is situated in the center of the upper horizontal member. A pitot-type arrangement is used to power the indicator. The airspeed indicator may be pivoted between its two upper elbows to allow straight passage of the inlet air at varying angles of attack. The transparent tube is equally incremented with different colored rings. Inside the tube is the indicator. As the air enters the pitot opening, the indicator is lifted in proportion to the airspeed. See the illustration entitled, "Airspeed Indicator." The velocity of the wind is just below the white ring.

To operate the whirling arm, hold the frame vertical in the appropriate hand. Extend your arm fully from your body to obtain the maximum airspeed. The wing should be free to move up and down along its guidelines. Noting which end constitutes the leading edge of your wing and holding the frame straight out, rotate your body in the direction of the leading edge (counter-clockwise for right-handed people and clockwise for lefties). An alternative method for generating the necessary relative wind for flight is to walk briskly or run with the device. Observe that the wing travels up the string as it produces sufficient lift. With a little practice, the operator will be able to carefully control the quantity of lift so that the wing maintains a certain height during flight. To eliminate the effects of centrifugal force during flight, walk briskly, or run, in a straight line with the whirling arm.
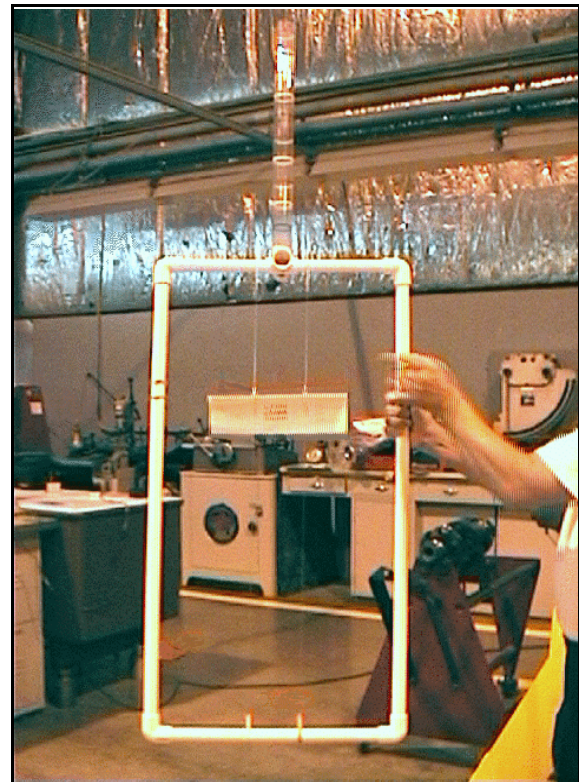

Figure 10: Wing in Flight

To demonstrate the relationship between lift production and airspeed, spin (pirouette) or run at faster and slower speeds. Try different angles of attack (angle made

between the airfoil and relative wind) by tilting the frame. Invert the wing and see how it responds in regard to airspeed and angle of attack. If it is windy, try to make the wing fly by pointing its leading edge into the wind. The airfoil responds like the wing of an airplane or rotor of a helicopter.

Lift Generated by the Whirling Arm

As operators become familiar with the flight characteristics of their airfoils and the operation of the whirling arm, they may fly the wing and maintain a certain altitude (the wing rises a certain distance and remains in place). At this point, the forces of lift and gravity are in balance. Stated another way, lift equals gravity when the altitude is constant. Therefore, to determine the amount of lift, one needs to know the weight of the flying machine. As the weight of the wing used in this demonstration varies with the type of paper used, the length of the straw segments, and the quantity of tape attached to the wing, the weight of the unit should be measured and recorded before final assembly, if such information is appropriate for the particular grade level. The author measured a sample wing and found that it weighed 5 grams. Converting grams to pounds (multiply by 0.0022), the wing weighed 0.011 pounds. Disregarding the relatively negligible amount of friction produced between the fishing line and the interior of the straws, the amount of lift needed to suspend the airfoil at a constant altitude is basically equal to its weight. Therefore, when the sample airfoil maintains its altitude, 0.011 pounds (5 grams) of lift are produced.

Work, Power, and Horsepower

When conducting this demonstration as a physics lesson, other variables (e.g., work, power, and horsepower) may be computed. Such information is vital in terms of aeronautical engineering. If, however, it is deemed unsuitable for a particular grade level, the following calculations should be avoided.

   To determine the quantity of work needed to attain a particular altitude, multiply the weight of the flying machine by the altitude. For example, when a 1-pound object is lifted 1 foot, 1 foot-pound of work is performed. In this example, when the airfoil that weighs 0.011 pounds rises to an altitude of 1 foot, 0.011 foot-pounds of work are performed.

   If the variable time is measured to determine how long it took to perform this quantity of work, power may be calculated. If the sample airfoil reached its 1-foot altitude in 1 second, then 0.011 foot-pounds per second were needed to lift the wing in that time frame. By dividing this value by 550, the amount of horsepower may be determined. If 0.011 foot-pounds per second of power were generated, the quantity of horsepower equals 0.00002. This value may be express using scientific notation: 2 times 10 to the negative 5th power (2×10^{-5}).

Summary to the Whirling Arm

Through the use of the whirling arm, the concepts of lift, gravity, airspeed, and angle of attack may be introduced and discussed. In addition, as this demonstration mimics early whirling arm tests conducted by Sir George Cayley

as early as 1804, historical aspects of the study of aerodynamics by early pioneers may be discussed. Cayley and several other early investigators, such as Otto Lilienthal, Hiram Maxim, and Samuel Langley, used whirling arms. From their work emerged the science of aeronautics.

A Wright-Style Wind Tunnel

Wilbur and Orville developed a wind tunnel to study aerodynamics. Some of the credit for encouraging the Brothers to use a wind tunnel belongs to aviation enthusiast and physician, George Spratt. He was a guest at the Wright Brothers' camp at Kitty Hawk during 1901, 1902, and 1903. He was originally invited to Kitty Hawk by Octave Chanute. Because the Brothers were undertaking the dangerous challenge of gliding, Chanute may have invited Spratt to serve in his medical capacity in the event of injuries. Having a passion for the study of aeronautics, Spratt interacted with Wilbur and Orville and through such deliberations suggested the use of a wind tunnel. In later years, Spratt had something of a feud with the Wrights because he felt that he should have been given credit for encouraging the Brothers' use of a wind tunnel. The mechanism suggested by Spratt simultaneously measured lift and drift. Drift was used for the modern term drag. Wilbur and Orville were unable to create a scale that accurately measured lift and drag at the same time. After abandoning the duplex design, they made separate scales to independently measure lift and drag. Their new scales worked with great success. For additional information on the issue of the controversy of Spratt's contribution to the wind tunnel work of the Wright Brothers, refer to the footnote on page 554 and the letter from Wilbur to Spratt dated October 16, 1909 on pages 967 and 968 in Marvin McFarland's *The Papers of Wilbur and Orville Wright* (1953). A number of Wright Brothers historians (e.g, Thomas Crouch, Fred Kelly, Fred Howard, and others) also address this issue.

The wind tunnel scales developed and used by the Wrights were based on a parallelogram design. As the airfoils responded to the flow of air, the scale moved by the action of pivot points located at each end of the units. Through the use of pivoting arms and straps that were connected to the extremities of the pivoting arms, movement of the scales kept the straps, and the items attached to them, at a constant angle as air passed through the wind tunnel.

The Wrights constructed their wind tunnel scales from old hacksaw blades and wheel spokes. The airfoils were formed from 20-gauge steel and wax. Solder was used to affix the sample airfoils to the balancing scales. As the scales responded to the reaction of the sample airfoil, their movement kept the airfoil at a constant angle to the air flowing through the tunnel. They balanced the reaction of the airfoil against a number of plates placed along the scale to develop drag. The wing, which was placed on its end, did not have to support its own weight as it moved along a horizontal path rather than up and down. Consequently, the lift developed by the wing established an equilibrium with the drag producing plates. Their wind tunnels were developed to compare the work of Otto Lilienthal, a noted glider and aerodynamicist of the era, with the results they were receiving from the glider trials.

Through the use of the wind tunnel the Brothers were able to further their study of aerodynamics and develop successful airfoils from their wind tunnel experiments. They also studied how close to place wings to each other and determined optimum shapes for the leading edges of airfoils and wooden braces used in the construction of their aircraft.

Dueling Airfoil, Lift

The wind tunnel presented in this section offers a number of aerodynamic demonstrations. The first two are primarily visual as they place different airfoils in opposition to each other to demonstrate which has the greater aerodynamic force. In the first experiment the airfoils generate lift. In the second, they develop drag.

To change sample airfoils on the scales developed by the Wrights, a source of high heat was needed as they soldered the sample units to the balancing scale. The frame used in the Wright-Style Wind Tunnel is designed to allow for quick changes from one airfoil to another using knurled nuts. Consequently, a comparison from the performance of one wing versus another is easily accomplished. Also, multiple airfoils may be mounted on the frame. Furthermore, objects other than airfoils may easily be mounted on the frame mechanism (e.g., model rockets). This feature adds a measure of versatility to the unit.

In the first demonstration the two airfoils are mounted on the upper and lower forward parallel straps. The cambers, or curved surfaces of the wings, face each other. A protractor is fitted under the airfoils to set up their angles of attack (the angle at which the wing meets the air).

To determine which airfoil produces the greatest amount of lift, activate the fan and observe the reaction of
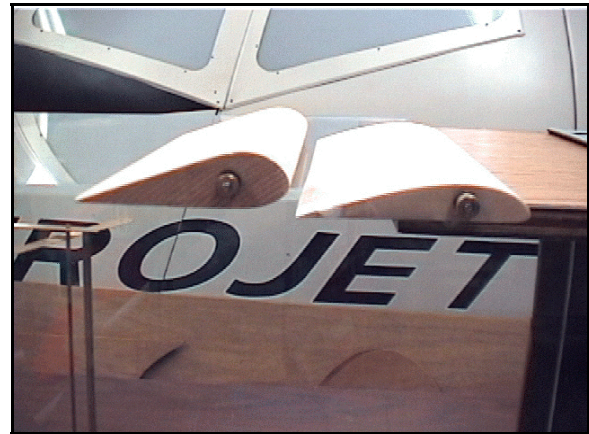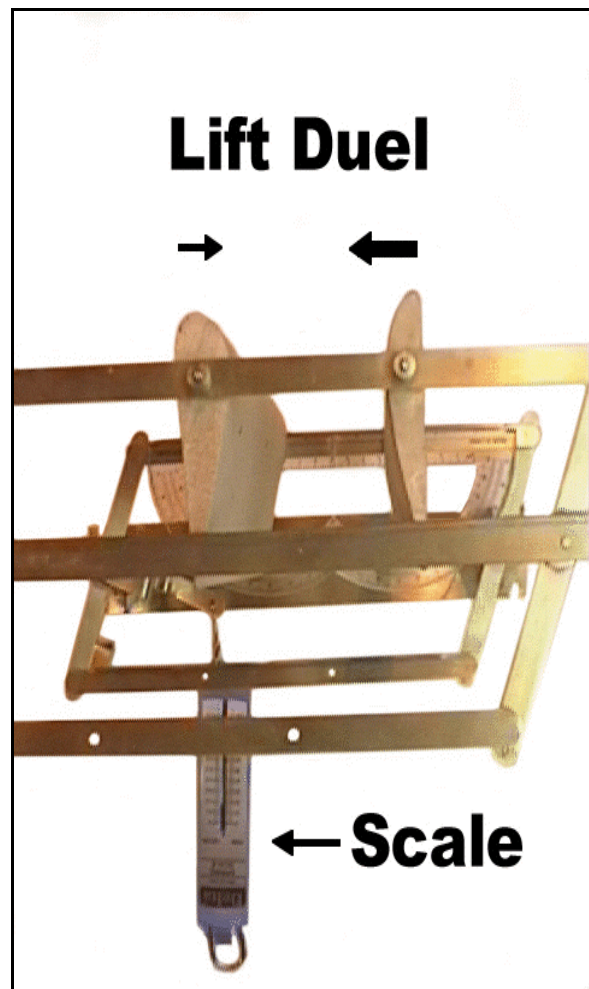

Figure 11: Sample Wings

Figure 12: Lift Duel. The Wing on the Right Generates More Lift Than the Wing on the Left for the Same Angle of Attack.

the unit. Viewing the mechanism from the rear, if the unit shifts to the right, the airfoil on the left is producing the greater quantity of lift and vice versa if the airfoil on the right is producing more lift. If they are generating an equal amount of lift, the scale remains stationary. It is possible to measure the difference in lift from one wing to the other. When the stronger wing is situated on the right side of the parallel straps, a gram scale may be connected to the special arm attached to the left pivoting mechanism. As the frame moves to the left, the gram scale reads the difference in lift between the two airfoils. For additional information, refer to the **"Lift Duel"** figure and the section entitled **"Measuring Lift of an Airfoil."**

In this demonstration, the two wings have the same surface areas and chords. The one on the left has a thicker camber while the one on the right has a smaller degree of camber. When the wings are placed at the same angle of attack using the attached protractors, a surprising result is produced. The thinner wing generates more lift than the thicker wing. The scale attached to the lift arm indicates the difference in lift. When the lift is nearly the same, there is little response from the scale. This demonstration is helpful in designing the shape of a wing. The airfoils used in this series of illustrations are shown in the figure entitled, **"Sample Wings."**

One exercise that may be undertaken during this experiment is not only to determine which airfoil is producing the greater amount of lift, but change the angle of attack of the weaker wing until its lift equals that of the stronger wing at a lesser angle of attack. Another exercise is to see which wing stalls first. A stall is an aerodynamic condition in which the flow of air around the airfoil becomes disturbed and the production of lift is reduced or greatly minimized. To demonstrate a stall, position one wing at a moderate angle of attack. Increase the angle of attack on the other wing in gradual increments (e.g., 3˚). Note the wing that receives the increases in angle of attack becomes stronger and stronger until a certain angle of attack is reached. From that point, additional increases in angle of attack allow the fixed wing to overpower the wing at the high angle of attack position. This is due to the stalling of the latter.

The reactions of the airfoils under different conditions provide great visual demonstrations on aerodynamics. Such reactions further emphasize the importance of
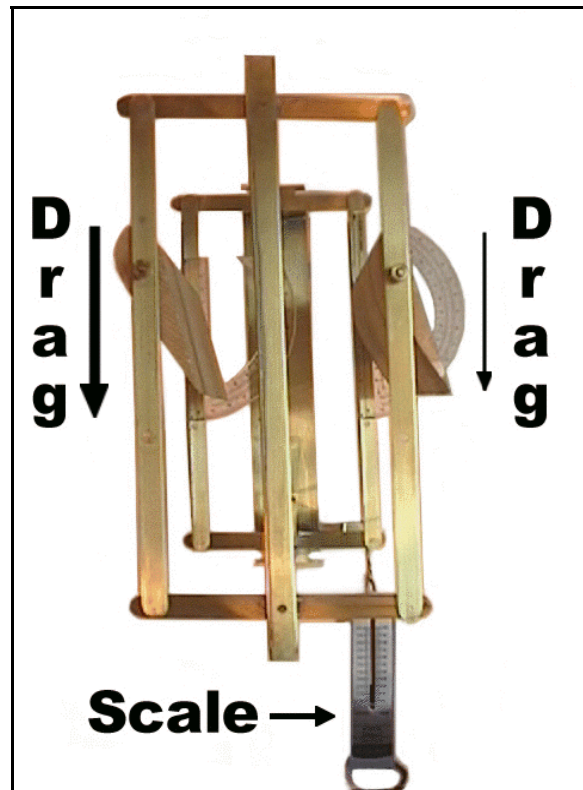

Figure 13: Dueling Drag Demonstration. The Wing on the Left Generates More Drag Than the Wing on the Right.

observation during scientific inquiries.

Dueling Airfoils, Drag

To determine which airfoil generates the greatest amount of drag, position the frame and airfoils as shown in the corresponding **"Dueling Drag Demonstration"** illustration. Set the angles of attack of each wing and activate the fan. Note that the wing with the greatest amount of drag causes the corresponding parallel straps to travel aft and the wing with the least amount of drag to journey forward. To equalize the drag, increase the angle of attack of the lesser wing until the quantity of drag between the two airfoils is balanced.

The difference in drag between the two airfoils may be measured when the airfoil with the greatest drag is mounted on the left-hand parallel straps. Attach a spring scale to the mechanism as illustrated in the **"Dueling Drag Demonstration"** figure and the section entitled, **"Measuring Drag of an Airfoil."** Activate the fan and read the scale. If the difference in drag is substantial, the scale reacts accordingly. In this illustration, the wing on the left generates more drag than the wing on the right.

After comparing the quantities of lift and drag produced by these two airfoils, the one with the thinner camber produces more lift for the same airspeed and angle of attack while generating less drag than the thicker wing. It may be concluded that the thin wing is more efficient than the thick wing for the range of airspeeds and angles of attack used during these experiments.

Measuring Lift of an Airfoil

This derivative of the Wrights' wind tunnel was manufactured so that a spring-scale may be used to measure the amount of lift and drag generated by the airfoils and other objects placed within the wind tunnel. This feature provides easy quantification of lift and drag. In addition, the same frame mechanism is used for measuring both lift and drag. To measure airspeed, an anemometer is placed inside the tunnel during the testing process. Knowing the quantity of lift produced at a particular airspeed with a certain surface area provides the data necessary to perform a number of aerodynamic calculations (e.g., the coefficients of lift and drag, predicting the quantities of lift for different airspeeds, the lift/drag ratio, and so forth).

Figure 14: Measuring Lift

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To measure lift, secure an airfoil, or airfoils, and protractor(s) to the forward parallel straps and adjust the desired angle(s) of attack. Be certain that the camber(s) is(are) pointing to the left side of the frame mechanism as viewed from the rear. Position the frame mechanism in the lift position as shown in the figure entitled, **"Measuring Lift."** Connect the spring-scale to the lift arm. The lift arm is a segment of flat stock attached to the left-hand pivot arm and shaped like the letter "Z". The hole at the extremity of the lift arm receives the hook from the spring-scale. The other end of the spring-scale is connected to a hook screwed into the base of the wind tunnel. Install the anemometer by engaging the slotted screw holes in the base of the anemometer holder with the screws protruding above the base of the wind tunnel.

Figure 15: Anemometer

Turn on the anemometer by selecting the desired units of speed (knots, feet-per-minute, meters-per-second, or miles-per-hour).

After setting-up the tunnel as indicated, turn the fan switch to its on position. Change the speed of the fan to witness the relationship between airspeed and lift production. As the airspeed through the tunnel is established, the quantity of lift is displayed on the spring-scale. The anemometer provides the airspeed in the increments selected. This data may be plugged into the following formula for lift, $LIFT = C_L S V^2 \rho / 2$ where:

C_L = **the Coefficient of Lift**

S = Surface Area of the Airfoil in Square Feet

V = Velocity in Feet Per Second. Velocity is squared during the calculation process.

ρ = **Mass Density of Air in Slugs Per Cubic-Foot. A standard value for ρ at sea-level is 0.002377.**[2]

Using algebra, the LIFT formula may be manipulated to solve for the coefficient of lift. By plugging in numbers obtained during wind tunnel tests, the coefficient of lift for the sample airfoil at that particular angle of attack may be calculated. After the coefficient of lift is determined, the quantity of lift at different airspeeds may be estimated. Likewise, the results of altering the surface area of a wing of a particular coefficient of lift may be calculated. One is able to determine how much surface area of a specific wing is needed to provide a certain level of lift. Such exercises provide excellent challenges for those who wish to further their understanding of the principles of aerodynamics.

The Wright Brothers used a formula for lift that was slightly different. It was, $LIFT = C_L S V^2 k$ where:

C_L = **the Coefficient of Lift**

S = Surface Area of the Airfoil in Square Feet

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[2] **See _A History of Aerodynamics_ (1997) by John D. Anderson, Jr. page 307 for additional information.**

V = Velocity in Miles Per Hour. This value is squared when performing calculation.

k = Smeaton's Coefficient of Air Pressure

Through their aeronautical research, the Wrights determined that the widely accepted Smeaton's Coefficient of 0.005 was excessive and served to overestimate lift. This resulted in designing aircraft with lifting surfaces that were unable to generate the quantity of lift calculated by the formula.   After adjusting the Smeaton value to 0.0033, the results of their gliding experiments tallied with their calculations. There was another outcome of adjusting the formula for calculating lift, they could now accurately design wings to lift the expected weight of a powered machine. History recorded the results of this endeavor on December 17, 1903.[3] Prior to having the ability to accurately design wings for a certain amount of lift, creating aircraft was something of a gamble as the maker never knew with certainty whether or not the aircraft was going to be able to develop sufficient lift for flight.

A good exercise to undertake when measuring lift is to graph the quantity of lift developed at different angles of attack. Set up the graph with the vertical axis incremented in grams of lift and the horizontal axis revealing angles of attack. After plotting the results, connect the dots to illustrate the lift characteristic of the wing.

To further enhance your knowledge of aerodynamics, plot the performance of another wing that has a different shape. Compare the results of the two wings and highlight the strengths and weaknesses of each.

Measuring Drag of an Airfoil

The same frame mechanism and scale are used for measuring the drag of an airfoil. To convert the wind tunnel from the lift to the drag mode, unfasten the hook of the spring-scale from the lift arm and loosen the three knurled nuts securing the mechanism to the deck of the wind tunnel. Rotate the entire implement 90˚ in a counter-clockwise direction as viewed from the top. Ensure that the slots at the ends of the mechanism engage their corresponding anchoring hardware and tighten the three knurled nuts. Reposition the spring-scale so that the hook is engaged through the hole of the drag arm fastened to the aft pivoting
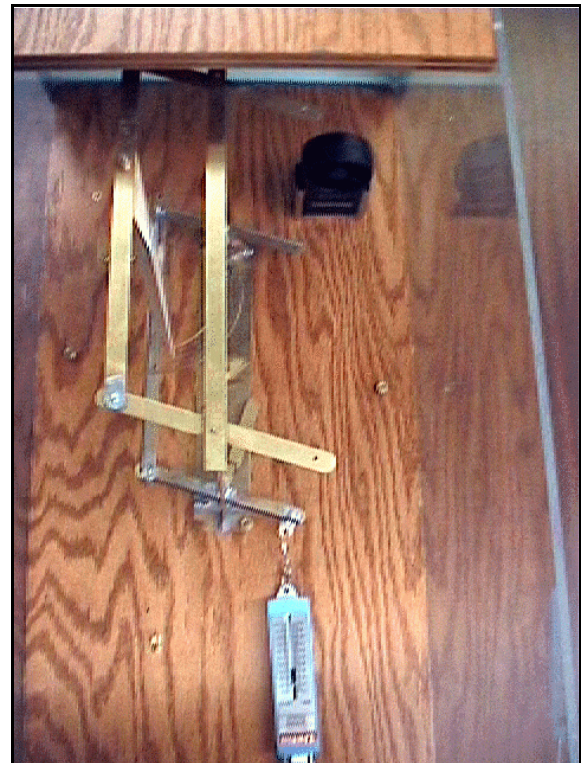

Figure 16: Measuring Drag of an Airfoil

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[3] *See Marvin McFarland's* <u>The Papers of Wilbur and Orville Wright</u> *(1953) pages 573 - 577 for additional information on the lift formula used by the Wrights and a portion of their aeronautical research.*

arm. The other end of the spring-scale is attached to a hook screwed into the deck of the wind tunnel. Refer to the illustration entitled *"Measuring Drag of an Airfoil"* for additional information.

To further explain the action occurring in the drag illustration, consider the following. The air is traveling from the top of the illustration to the bottom. The airfoil is attached to the left-hand parallel straps. To measure the amount of drag at a certain angle of attack, the trailing edge of the airfoil is aligned with the protractor. Set the angle of attack so that it matches that of the airfoil used for determining the quantity of lift in the previous section. As the air flows through the wind tunnel, the wing produces both lift and drag. In the drag mode, the wing is trying to move to the left as a result of the lift production and is moving aft from the drag generated by the passing air. The scale mechanism allows the wing to travel aft as the two pivoting arms rotate in a counter-clockwise direction as viewed from the top. The force of the drag is transmitted to the spring-scale where the quantity of drag is measured. The airfoil in the **"Measuring Drag of an Airfoil"** illustration produced eight grams of drag at an airspeed of 18.8 mph.

To demonstrate the relationship between angle of attack and the quantity of drag, change the angle of the airfoil and measure the amount of drag. The basic reaction to increasing angle of attack is that drag increases. Likewise, change the speed of the fan for any given angle of attack and note the amount of drag registered on the spring-scale. Again, the quantity of drag increases with increases in airspeed. The relationships between airspeed and drag and angle of attack and drag are fundamental in the study of aerodynamics.

The basic formula for drag is: $DRAG = C_D S V^2 \rho / 2$. In this formula:

C_D = the Coefficient of Drag

S = Surface Area of the Airfoil in Square Feet

V = Velocity in Feet Per Second. The velocity is squared during calculations.

ρ = Mass Density of Air in Slugs Per Cubic-Foot. A standard value for ρ at sea-level is 0.002377.[4]

As with the exercises involving lift calculations, after performing measurements in the wind tunnel, values may be plugged into the drag formula. The resulting calculations may be used to determine drag characteristics of a particular airfoil at certain angles of attack. In addition, the **Lift/Drag Ratio** of an airfoil may be determined. This is an important measure of a wing's efficiency.

Perform a series of drag measurements similar to those taken when plotting the lift graph. Record the quantity of drag and plot them. Mark the vertical axis in units of grams of drag and the horizontal axis in terms of angle of attack. After connecting the dots, compare the lift and drag graphs of the wing. Are the graphs linear or curvilinear? Are the graphs similar in shape? This exercise should increase one's understanding regarding aerodynamics.

As with the lift graphs, it may be advantageous to plot the performance of more than one wing. This will help to

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[4] ***See A History of Aerodynamics (1997) by John D. Anderson, Jr. page 307 for additional information.***

identify good and bad points of each wing.

LIFT/DRAG Ratio

One important issue concerning the design of an airfoil is its **LIFT/DRAG RATIO** (L/D). Because drag is a byproduct of the relative motion of an object as it passes through the atmosphere, drag is generated as an airfoil, and the entire aircraft, experiences relative wind. In other words, for an airfoil to develop lift in the traditional manner, it must have relative wind. It makes no difference whether the airfoil travels through the atmosphere or whether the atmosphere passes around the airfoil or a combination of the two, when an airfoil experiences relative wind, drag is created.

Another issue that should be considered is the effectiveness of airfoils at certain angles of attack. Because the coefficients of lift and drag are dependent on the angle of attack, designers may determine the greatest L/D ratio of an airfoil. In such cases, the wing is producing its most favorable quantity of lift for the amount of drag generated. This information is useful when calculating flight characteristics of an aircraft.

To calculate the L/D ratio of an airfoil, divide the coefficient of lift by the coefficient of drag (**L/D RATIO = C_L ÷ C_D**).[5] As each coefficient may be determined as indicated in the previous sections, an exercise using the wind tunnel could involve the determination of the best L/D ratio of a particular airfoil.

Where this technique is useful for examining the aerodynamic characteristics of a particular airfoil, a more pragmatic approach to calculating the L/D ratio is to include the entire drag generated by the aircraft. In other words, because portions of the aircraft generate drag without producing lift, the L/D ratio of the aircraft may be calculated using the following formula: **AIRCRAFT L/D RATIO = C_L ÷ (Wing Drag + All the Other Drag)**.[6]

Using the data accumulated during the lift and drag exercises, calculate the coefficients of lift and drag for a series of angles of attack. Graph your results with the coefficient of lift representing the vertical axis and the coefficient of drag for the horizontal axis. In addition, make a graph of the L/D ratio by calculating the L/D ratio for varying angles of attack. Plot this information on a graph where the vertical axis represents L/D ratios and the horizontal axis indicating angles of attack. As before, perform these graphing operations on more than one airfoil to enhance the lesson on aerodynamics.

All of these exercises are designed to deepen one's knowledge in the realm of aerodynamics. They are a fun way to get students to perform careful measurements and calculations. It also leads to discussions revolving around aeronautical engineering and aircraft designs. Encourage students to examine and compare airfoils used on different aircraft (e.g., training aircraft, corporate jets, crop dusters, acrobatic airplanes, rotorcraft, commercial jetliners, etc.).

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[5] *Refer to Aerodynamics for Naval Aviators (1960) pages 32 - 33 for additional information.*

[6] *See Northrop Aeronautical Institute's Aircraft Basic Science (1948) page 29 for additional information.*

Measuring Drag of a Rocket

Objects other than airfoils may be tested in a wind tunnel. The Wrights devoted a portion of their wind tunnel tests to determine the best shape of objects, such as wing struts, to minimize drag. Contrary to the popular belief prevalent at the time, a strut with rounded corners rather than sharpened leading edges provide the least amount of drag at the subsonic airspeeds used by the Wrights.

One article that may be demonstrated is a rocket. The ability to measure the drag of a rocket, or other article, is especially useful when illustrating the importance of proper design and construction of aeronautical vehicles. In the illustration depicting the rocket in the wind tunnel, the rocket is aligned to be streamlined with the flow of air. Only three grams of drag are generated. When the rocket is placed at a slight angle to the flow of air, to simulate the drag produced when the rocket flies in an irregular path, the drag increases. A minute amount of

Figure 17: Measuring the Drag of a Rocket

angle is all that is needed to tripled the quantity of drag. Such increases in drag serve to limit the apogee (highest altitude) achieved by the rocket during flight. This is an excellent demonstration when building similar rockets with groups of school children. The lesson is further bolstered during the flights of the rockets. When they compare the performance of rockets that fly straight versus those that fly with an irregular trajectory, they quickly learn the importance of critically aligning the nose cone, rocket body, and fins.
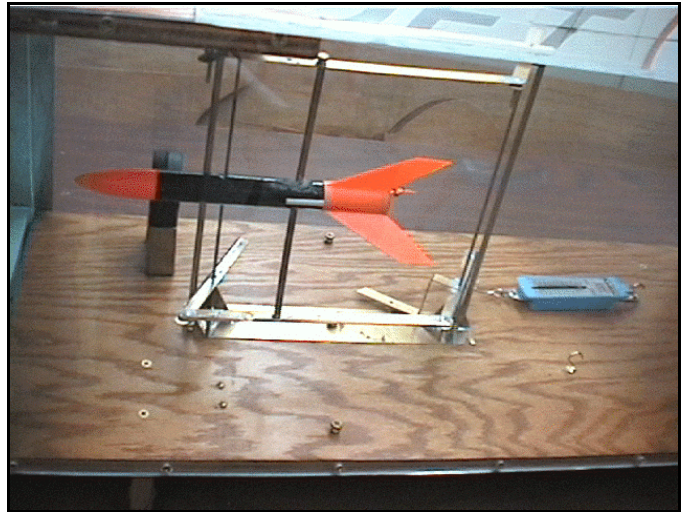
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Anderson, J. D., Jr.(1997). A history of aerodynamics and its impact on flying machines. Cambridge University Press, New York: NY.

Chapel, C. E. (Ed.). (1948). Aircraft Basic Science (1st ed.). Northrop Aeronautical Institute. McGraw-Hill Book Company, New York: NY.

Hurt, H. H., Jr. (1960). Aerodynamics for naval aviators. U.S. Government Printing Office, Washington: DC (NAVWEPS 00-80T-80)

McFarland, M. W. (Ed.). (1953). The papers of Wilbur and Orville Wright: Including the Chanute-Wright letters and other papers of Octave Chanute (Volumes 1 and 2). McGraw-Hill Book Company. New York: NY.

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NATIONAL STANDARDS FOR:
"CLASSROOM ACTIVITIES IN AERODYNAMICS"

Science Standards

Standard A: Science as Inquiry
- Abilities necessary to do scientific inquiry
- Understanding about scientific inquiry

Standard B: Physical Science
- Structure and properties of matter
- Motions and forces
- Interactions of energy and matter

Standard E: Science and Technology
- Abilities of technological design
- Understandings about science and technology

Standard F: Science in Personal and Social Perspectives
- Science and technology in local, national, and global challenges

Standard G: History and Nature of Science
- Science as a human endeavor
- Nature of scientific knowledge
- Historical perspectives

Unifying Concepts and Processes
- Evidence, models, and explanation
- Constancy, change, and measurement
- Form and function

Technology Standards

2. Understanding of the core concepts of technology.
3. Understanding of the relationships among technologies and the connections between technology and other fields of study.
6. Understanding of the role of society in the development and use of technology.
8. Understanding of the attributes of design.
9. Understanding of engineering design.
10. Understanding of the role of troubleshooting, research and development, invention and innovation, and experimentation in problem solving.
11. Ability to apply the design process.

Mathematics Standards

1. Number and Operations Standard:
- Compute fluently and make reasonable estimates.
2. Algebra Standard:
- Understand patterns, relations, and functions.
- Represent and analyze mathematical situations and structures using algebraic symbols.
- Use mathematical models to represent and understand quantitative relationships.

3. Geometry Standard:
   - Specify locations and describe spatial relationships using coordinate geometry and other representational systems.
4. Measurement Standard:
   - Understand measurable attributes of objects and the units, systems, and processes of measurement.
   - Apply appropriate techniques, tools, and formulas to determine measurements.
5. Data Analysis and Probability Standard:
   - Formulate questions that can be addressed with data and collect, organize, and display relevant data to answer them.
   - Select and use appropriate statistical methods to analyze data.
   - Develop and evaluate inferences and predictions that are based on data.
8. Communication Standard:
   - Use the language of mathematics to express mathematical ideas precisely.
9. Connections Standard:
   - Recognize and use connections among mathematical ideas.
   - Recognize and apply mathematics in contexts outside of mathematics.
10. Representation Standard:
   - Create and use representations to organize, record, and communicate mathematical ideas.
   - Select, apply, and translate among mathematical representations to solve problems.

Sources for National Standards

1. National Science Standards – National Research Council
   http://www.nap.edu/readingroom/books/nses/html

2. National Mathematics Standards – National Council of Teachers of Mathematics
   http://standards.nctm.org/document/index.htm

3. National Technology Standards – International Technology Education Association
   http://www.iteawww.org/TAA/Listing.htm

Ms Judy Stone, Curriculum Specialist at HQ Civil Air Patrol, identified the National Standards for "Classroom Activities in Aerodynamics". For questions related to standards, you may contact Ms Stone at 334-953-7590 or jstone@capnhq.gov.