1975

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Dennis, James C., "Fluid Mechanics in the Elementary Laboratory" (1975). *Faculty Publications*. 10.
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Cite as: The Physics Teacher **13**, 93 (1975); https://doi.org/10.1119/1.2339082

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Fluid Mechanics in the Elementary Laboratory

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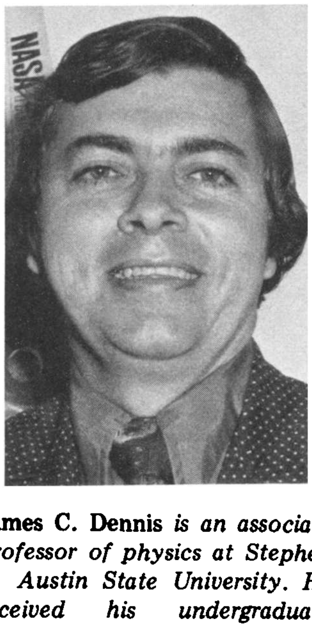
Five years ago Dr. William Jacobson[1] argued persuasively in *The Physics Teacher* that science education in the United States could be made more flexible and in the process more palatable by the institution of a wide range of interdisciplinary programs in the secondary schools and universities. He pointed out that sociology, psychology, and philosophy were being excluded from contemporary physics programs, and that furthermore, these were the very disciplines that were attracting increasing numbers of students in a time when antiscience was in vogue. Since 1969 many of Dr. Jacobson's ideas have been transformed into successful programs—witness the integration of psychology and culture with physics in the relevant approach,[2] the emphasis on causality in the new discovery approach,[3] the formation of channels of communication between science and liberal arts students via the phenomenological approach,[4] and the inclusion of behavioral objectives in the "fun" physics[5] laboratory.

Dr. Jacobson also commented on the small amount of applied physics available to the elementary student. Although the popularity of technology is on the upswing, the physics of technology has yet to receive much attention in textbooks. One notable exception has been engineered by the Technical Education Research Center (TERC), publishers of a series of modules on basic physics based on familiar devices such as the electric fan and pressure cooker.[6] Some other experiments which can be done with an electric fan are presented in this article.

One area of physics where applications are of interest to a broad range of students is fluid mechanics. However, very little fluid mechanics can be found in the elementary physics textbooks, and even less use is made of it in laboratory manuals. The shortage of laboratory exercises in this area led us to design a series of interrelated experiments that have provided actual research opportunities for undergraduates. The participant (1) calibrates a simple water manometer, (2) measures the velocity of a wind stream with the manometer, (3) learns what a wind tunnel is and what he can do with one, (4) measures some performance characteristics of scale model airplanes with the wind tunnel, and (5) measures the net lift on a section of airplane wing using the manometer. If the student is interested in obtaining numerical values of performance characteristics, he can perform some additional exercises with a water displacement gauge described below. Students are encouraged to set up their own research projects on wing, windmill, fan, etc., design.

The manometer (Fig. 1) is constructed from two coffee cans connected at the bases by flexible tubing. A 1/16" piece of copper tubing serves as the pressure inlet to the manometer. One can is open and the other has an airtight lid and a nozzle to which is attached the pressure inlet. The open can supports a posterboard scale and a pulley over which a cork



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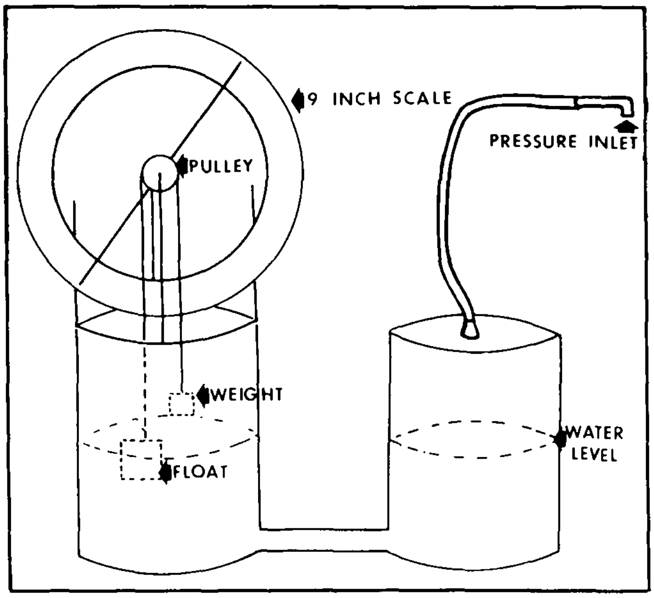

Fig. 1. Details of the manometer. The right-hand can is airtight except for the pressure inlet.

and a small weight are placed. The cork is weighted such that it barely floats. The needle indicator is glued to the pulley, which sits in a stiff wire frame. As the water level changes due to pressure changes at the inlet, the rotation of the pulley with needle indicator attached becomes a very sensitive indicator of pressure variations. The sensitivity is a result of the difference in size between pulley and cardboard scale. Ours was capable of reading 0.009 inches of water variation which corresponds to about 2×10^{-5} atmospheres. Wind stream velocity can be calculated by either pointing the pressure inlet tube into the wind or by holding it at right angles to the flow. Scale readings should be equal and opposite as is evident from the Bernoulli expression

$$\Delta P = (1/2)\,\rho_A v^2 = \rho_w g h, \qquad (1)$$

where ρ_w, ρ_A are the densities of water and air, respectively. The density of air is about 1.29 kilograms per cubic meter and the density of water is 1000 kilograms per cubic meter. The height of water displaced is h. With this instrument we measured a wind speed of 65 ft/sec from a small 3500 rpm blower. A pitot, only slightly more sophisticated, has both "cans" exposed to the airstream, one perpendicular and the other parallel to the stream. Pressure readings are independent of ambient pressure and such devices can be used as air speed indicators for airplanes.

We constructed our wind tunnel from 1/4 in. plywood and a heater duct blower. The cross sectional dimensions must be larger than those of the models to be tested. Inside the tunnel about a foot from the blower a wire screen and a stack of cardboard tubes act as air straighteners and as a pressure back-up device to smooth out fluctuations in pressure caused by the squirrel cage. Two plexiglass panels hinged to the tunnel exit function as turbulence eliminators. Without these the models oscillate in the wind stream. Whenever accurate results are desirable the effects of turbulence generated near the walls and an induced velocity associated with vortices produced near the walls must be taken into account. Turbulence can be significant if the model width exceeds 3/4 that of the tunnel, or if air straighteners and hinged panels are omitted. Considering the fact that our models tested were only slightly smaller (5-6 in. wingspan) than the tunnel (9 in.), it is possible that corrections to the L/D maxima for the models as shown in Fig. 3 might be significant.

Exact scale models available in almost any department store are excellent for testing in the tunnel. They are first attached to frames and the frames are supported above a force table by tension applied through four weights hanging from pulleys. This arrangement allows the frame to translate and twist in the wind stream without touching the force table. The model can rotate in two planes about the center of gravity of the entire system, one parallel to the wind stream (drag) and one perpendicular to the wind stream (lift). Two additional pulleys support strings attached to the top of the frame above the wing at right angles to one another (see Fig. 2).

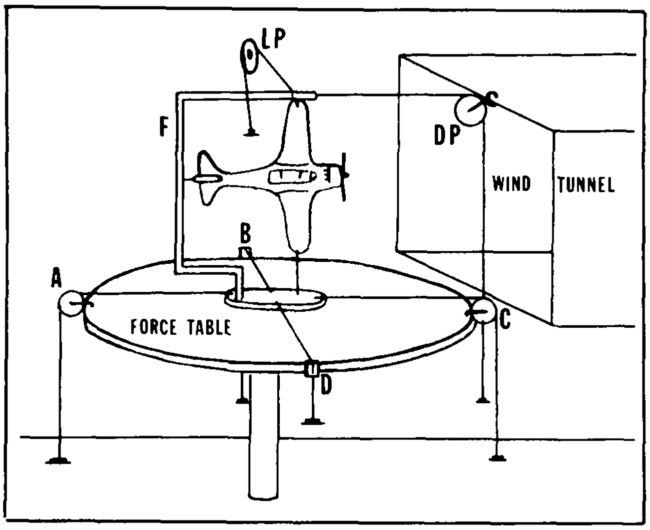

Fig. 2. Details of the L/D apparatus. A, B, C, and D support the frame and model through tension applied via hanging weights. DP and LP are the drag and lift counteracting pulleys, respectively and F is the lightweight frame.

In the wind stream lift torques cause the model to twist to the side away from the lift-counteracting pulley and drag torques twist the frame and model away from the wind stream. These torques are to be counterbalanced by weights hanging from the pulleys just mentioned. The restoring weight ratio (ordinary washers are fine for this purpose) is the so-called lift to drag ratio (L/D), normally measured as a function of the angle of attack. If the wings are tilted with respect to the fuselage such that max L/D is experienced at cruising speed, then the nose will be pointed into the wind. Near the critical angle drag increases much more rapidly with speed than lift: thus at combat speeds the angle of attack must be reduced and the nose will point downward in level flight. So that tail surfaces can provide a stabilizing lift, the "center of lift" sits slightly forward of the center of gravity. Tail stabilizers become less effective as the two centers approach each other, which is what happens with conventional low-speed airfoils as the airspeed increases (the center of lift moves back).

Measurement of lift is facilitated if the supporting pulleys

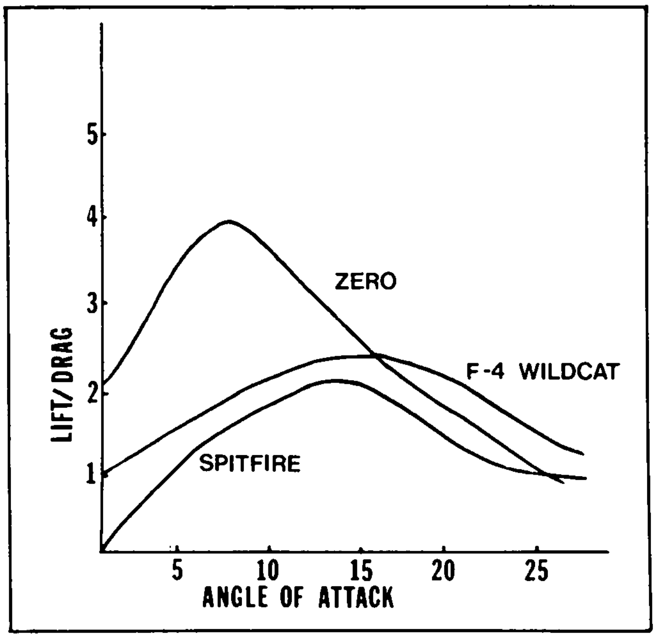

Fig. 3. Lift/Drag for three WW II fighter aircraft. The Spitfire evidently has a symmetric airfoil.

are attached to a force table. Attack angles (measured between the wings and the airstream) should not exceed 20° because impact lift on the fuselage assumes some importance at high angles and could complicate the results. Note in Fig. 3 how L/D peaks for each of the models of WW II aircraft. In the early days of the war with Japan, Mitshubishi Zeroes in spite of their superior maneuverability proved to be no match for the cumbersome F-4 Wildcats. Heavy armor and pilot skill made the difference. For a good account of early encounters between American and Japanese planes, see *Fork-Tailed Devils: The P-38* by Martin Caiden (Ballantine paperbook).

Large scale models (12-16 in.) are appropriate for an exercise requiring only a small squirrel cage blower and the water manometer. Bernoulli pressure distributions are communicated to the manometer via rows of evenly spaced holes drilled across the wing. The pressure inlet should not extend beyond the wing surface. Figure 4 illustrates the pressure distribution over a P51B Mustang wing (14 in. wingspan) at about one-third the length of the wing from the center of the plane.

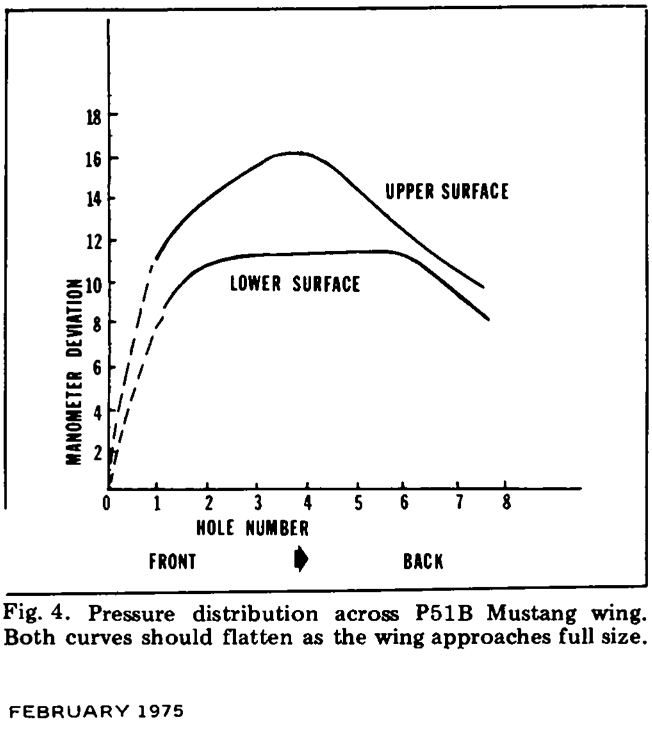

Fig. 4. Pressure distribution across P51B Mustang wing. Both curves should flatten as the wing approaches full size.

It is possible to obtain accurate numerical values of lift and drag with a water actuated balance similar in appearance to the manometer. In this case the coffee cans' function is to support the connecting glass tubes in their centers. A close-fitting glass float is placed in each tube and one is hung over the needle controlling pulley. The other float is connected via a pulley to the frame supporting the model (Fig. 5). It is easy to show that, if the wind force (multiplied by the balance) is large enough to support the water float,

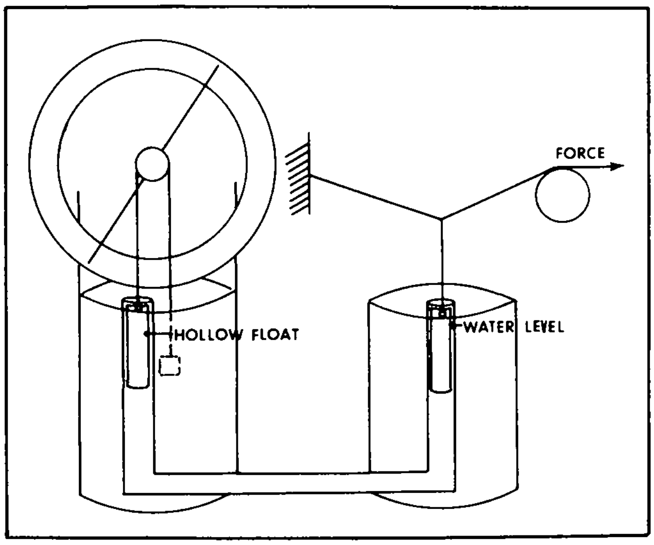

Fig. 5. Schematic of the balance. The needle indicator extends through the pulley.

$$F = K_1 \Delta y = K_2 \Delta R, \qquad (2)$$

where y is the vertical distance in the force triangle, Δy is the change in y, and ΔR is the scale change. The force gauge can be calibrated by hanging known weights from the frame-supporting pulley and recording the scale variation ΔR. Figure 6 shows that good measurements of forces equivalent to a gram are possible with this simple instrument. When individual lift and drag forces are known, it is customary to plot the ratio of lift or drag to the dynamic force vs. the angle of attack. The dynamic pressure is $(1/2)\ \rho v^2$ and the dynamic force is the dynamic pressure multiplied by the "planform" area. Net lift is given by the product of the slope of the lift curve, the dynamic pressure, the angle of attack, and the planform area which is the product of wingspan and the mean chord, or effective wing width.

It is important to note at this point that the lift to drag ratio will depend upon the model size. Compare maximum L/D and optimum angle of attack for the models from Fig. 3 with full size values of 7-10/1 and 5°-10°, respectively, for WW II fighter aircraft.[7] The experimental aerodynamicist can simulate a full-scale test with models by increasing the "Reynold's number" of the testing apparatus until it matches the full-scale value.

The Reynolds number,[8] given by

$$R = \frac{\text{air speed x wingspan x air pressure}}{\text{viscosity}} \qquad (3)$$

is a measure of the turbulence generated by the model. Large R's, unavoidable in full-scale testing, are possible with reduced scale tests if the air speed or the pressure (closed pressurized tunnel) is increased or the viscosity is decreased. Cryogenic testing with near-zero viscosity liquids is relatively new. Even under the best of experimental conditions, the aerodynamicist cannot assure the test pilot who will fly the first production model that all will go according to plan. Surface features such as texture and protrusions can affect an airstream in unpredictable ways even when R's are matched. It's no wonder that "bigger is definitely better" in the aircraft design industry.

Student projects involving wind tunnels and the simple gauges may be diverse: problems with air and water flow around sails, boat hulls, blowers, windmills, etc., are numerous and can lead to legitimate research. For example, students can do a number of things with a fan that are not suggested in the TERC module. They can measure the efficiency by measuring the wind speed and a cross sectional area of the stream and with the relationship

$$P_{\text{out}} = \text{Force x velocity} = (1/2)\,\rho v^3 A, \qquad (4)$$

where P is power, ρ is the mass density of air, v is wind speed and A is the cross sectional area of the fan. P_{out} is then compared to the electrical power used by the fan. An exhaustive study might involve the use of a variable-speed motor to measure the efficiency as a function of blade frequency. One could also use the fan as a windmill by impinging another wind stream upon it and measuring the power generated by the fan-windmill. We do a similar experiment here and measure the power output by timing the rate of ascent of a weight hanging from a pulley centered on the axis of the windmill.

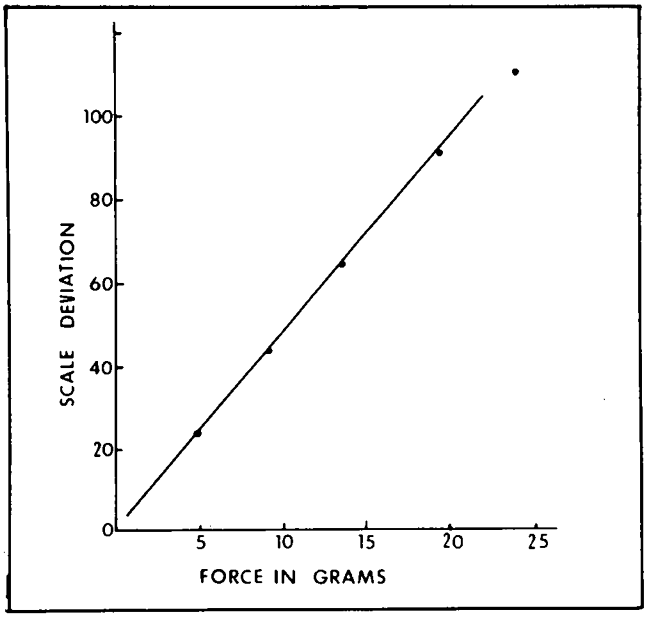

Fig. 6. Calibration curve for the water-actuated balance shown in Fig. 4.

Applied physics can make basic physics relevant and it can do it without sophisticated equipment. The fear of "future shock" often dissuades teachers from straying from the basic, boring path, but big machines and blinking lights are not needed to make the "technological connection" in the elementary laboratory.

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The International Union of Pure and Applied Physics is organizing a conference on physics education in schools and universities to be held in Edinburgh, Scotland July 29 to August 6, 1975. For further information write to:

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