letters

Sailing and the physics of lift

Thank you for Bryon Anderson's interesting and informative article, "The Physics of Sailing" (PHYSICS TODAY, February 2008, page 38). I especially enjoyed learning that the keel, not just the sail, acts to provide lift.

The article appears to adopt the traditional model: "An airplane wing is designed to cause the air moving over its top [the longer path] to move faster than the air moving along its undersurface." In that model, the "cause" is often based on the assumption that flows over the top and underside of the wing are isochronal. That assumption has been shown to be false; the flow time over the top of the wing is considerably shorter than that predicted by the dictum of equal time. Thus the model does not explain why a longer path should lead to higher flow speed.

Other difficulties arise with the traditional model. It does not explain the vital concave-downward curvature of the flow. It does not accurately predict observed average speeds near asymmetrical, symmetrical, inverted, or thin airfoils. The model does not predict point-to-point speeds—that is, from low speed near the leading edge over the top of the wing, to high speed in the region of maximum airfoil curvature, to free-stream speed near the trailing edge. The possibility of directly measuring the pressures of interest, rather than circuitously using the Bernoulli principle to calculate them from flow speeds, is not addressed. Additionally, the traditional model calculates pressure gradients from the very air speeds that are caused by those pressure gradients. Thus the traditional model seems to suffer from circular reasoning.

The article mentions an alternative model—"turning of the fluid flow." Indeed, airfoils are designed for establishing pressure gradients, which in turn result in observed changes in flow speed and direction, according to Newton's second law. Reversing that statement to claim that the changes of flow speed and direction above and below the airfoil result in pressure gradients is simply not correct. Thus the idea that the higher-speed air over the wing causes lower pressure above it by the Bernoulli principle reverses the correct assignment of cause and effect. Likewise with Newton's second law, net force causes acceleration; it is not correct to say that acceleration causes net force.

The model using Newton's second law in impulse and momentum form provides a consistent explanation of lift by deflection of the air stream, a fact that is lost with the use of the scalar Bernoulli equation. In addition, when the correct cause and effect are used, the Bernoulli principle becomes irrelevant to the explanation of pressure gradients established by airfoils.

Parenthetically, Anderson's question "whether the pressure difference arises entirely from the Bernoulli effect or partly from . . . redirection of the air" seems not to be meaningful. By any model, air must be deflected as a third-law reaction to lift.

Evan Jones
(revwin@yahoo.com)
Sierra College
Rocklin, California

Bryon Anderson's article on the physics of sailing provides a good introduction to the topic, but his discussion of wind-generated lift in sails, the effect that allows sailing to windward, leaves out the important concept of circulation. Anderson emphasizes the Bernoulli principle by explaining that the pressure difference between the upwind and downwind sail surfaces is due to the higher air speed on the downwind side. Anderson notes that "classic wing theory" ascribes the path length difference to asymmetry in the airfoil; however, the asymmetric airfoil is not a good model for sails because the path lengths along the upwind and downwind sides are almost the same. He points out that there are difficulties with classic wing theory and refers the reader to a NASA website. It is, however, well known by aircraft designers, and more recently by sailmakers, that lift is produced by circulation of air around the airfoil or sail and that viscosity plays a key role in its production.[1]

The simplest example of circulation-induced lift is the spinning ball, an effect exploited by baseball pitchers and known as the Magnus effect. Instead of spinning, a sail produces circulation by its shape and angle of attack to the wind. Because of the angle of attack, initially the upwind-side airflow attempts to turn sharply around the sail's trailing edge to rejoin the downwind flow. That sharp turn is resisted by the air's viscosity, producing a starting vortex near the trailing edge. By the Helmholtz theorem, a counterrotating, or bound, vortex must be induced around the sail. The strength of the circulation around the sail is such that the air flows smoothly off the trailing edge, an effect known as the Kutta condition. When the Kutta condition is established, the starting vortex disconnects from the sail and is left behind. Circulation causes air that would otherwise flow upwind of the sail to be deflected to the downwind side; this upwash effect results in the longer path length responsible for the higher downwind-side air speed and pressure drop.

Reference

1. C. A. Marchaj, *Aero-Hydrodynamics of Sailing*, Dodd, Mead, New York (1980); D. C. Wilcox, *Basic Fluid Mechanics*, 2nd ed., DCW Industries, La Cañada, CA (2000), chap. 10.

Arne W. Fliflet
(arne.fliflet@nrl.navy.mil)
Alexandria, Virginia

Anderson replies: I agree with almost everything in these two letters

Letters and opinions are encouraged and should be sent by e-mail to ptletters@aip.org (using your surname as "Subject"), or by standard mail to Letters, PHYSICS TODAY, American Center for Physics, One Physics Ellipse, College Park, MD 20740-3842. Please include your name, affiliation, mailing address, e-mail address, and daytime phone number on your attachment or letter. You can also contact us online at http://www.physicstoday.org/pt/contactus.jsp. We reserve the right to edit submissions.

concerning the generation of lift by an airfoil. The fact that lift is described by "circulation" around a foil has been known for almost a century, since the introduction of the Kutta–Joukowski theorem. Reference 2 in my February article discusses circulation in mathematical detail.

The article as originally submitted contained a brief reference to circulation and lift. However, I decided that lift for a foil would need to be presented in detail elsewhere. I used the space available to discuss the application of lift to sails and keels and the concepts of resistance, induced drag, hull speed, and so forth, that determine how a sailboat performs. I did provide a quick review of "classical" lift theory while indicating that the basic physical understanding is hard to arrive at. I refer the reader to Ross Garrett's attempt to do that in his book *The Symmetry of Sailing*.[1] In chapter 3 he outlines three ways for understanding lift. First is the "flow line method," which describes classical lift theory and arrives at Bernoulli's principle applied to a foil. Garrett's second way, "momentum change," emphasizes that macroscopically a foil must have the net effect of deflecting the fluid flow in order to derive lift. That is obvious, but must be appreciated. His third way to understand lift is the "mathematical approach," which introduces circulation, using several fluid flow theorems leading to the Kutta–Joukowski theorem. That approach is what engineers use to calculate lift, but it does not provide a clear physical description of lift. Several websites discuss lift.[2]

I am aware that airflow around a foil is not isochronal. I was careful not to say that it is. The flow over the "top" is faster and arrives at the end of the foil sooner than the flow along the "bottom." That difference in flow times leads to circulation. Because the flow is faster over the top, the pressure is reduced, as verified by measurement—which I did mention. Whether that is the cause of lift or the consequence of circulation becomes, I think, a matter of semantics.

References

1. R. Garrett, *The Symmetry of Sailing: The Physics of Sailing for Yachtsmen*, Sheridan House, Dobbs Ferry, NY (1996).
2. See, for example, A. Gentry, "The Origins of Lift," http://www.arvelgentry.com/origins_of_lift.htm.

Bryon D. Anderson
(bdanders@kent.edu)
Kent State University
Kent, Ohio

Most pressurized elements aren't simple cubic

I have a comment regarding the three contributions under the heading "Some Elements Go Cubic Under Pressure" in the Letters section (PHYSICS TODAY, October 2007, page 17).

The *s* orbitals of all atoms are relativistically stabilized because, unlike for all other orbitals, their probability density at the nucleus is greater than zero. The relativistic contribution to the energy increases with nuclear charge, gradually, even if nonlinearly, across the periodic table. There are many illustrations of that phenomenon in chemistry, such as the increasing redox stability of carbon-group cations from Ge^{2+} to Sn^{2+} to Pb^{2+}, the decreasing melting point from zinc to cadmium to mercury, and the increasing difficulty of hybridization of the *s* and *p* valence orbitals in elemental structures.

The last of those three phenomena is nicely manifested in the gradual decrease in bond angle of oxygen-group elements, from sulfur to selenium to tellurium to polonium. Elemental sulfur forms nearly tetrahedral bond angles, characteristic of sp^3 hybridization, and Se and Te form similar structures with sharper angles. In polonium, the *s* and *p* orbitals will not mix anymore because the *s*-orbital energy is too low, so the bond angle is 90°. It is only natural that a high enough pressure would increase the relativistic stabilization of the *s* orbitals in Se and Te (or other *s*, *p* elements) enough to bring them into the polonium-type structure with bonds formed from unhybridized *p* orbitals. The relativistic effect is a factor shaping the periodic system, and it affects more than just the heaviest elements.

Pavel Karen
(pavel.karen@kjemi.uio.no)
University of Oslo
Oslo, Norway

Legut, Friák, and Šob reply: Relativistic effects are important in solid-state physics and chemistry. However, in our experience, they are usually not strong enough to promote a phase transition to the simple cubic structure under pressure. The figure below shows the energy–volume curves of tellurium and polonium in their ground-state structures and of Te in the simple cubic structure, calculated with relativistic effects included (the energies are given relative to the ground-state energy E_0). If we compare it with figure 2 in our paper,[1] in which the relativistic effects were ignored, we see that the transition pressure needed to transform the trigonal spiral to the simple cubic structure, proportional to the slope of the common tangent of both energy–volume curves, is about twice as high in the nonrelativistic Te as in the relativistic case. Also, the energy difference between the two structures of Te is considerably higher in the nonrelativistic Te. Hence, the relativistic effects somewhat facilitate that phase transition in Te but are not the driving force. In Po, the relativistic effects are strong enough to reverse the order of the two structures.[1]

Those considerations, however, are