THE PHYSICS OF AEROBATIC FLIGHT

The pilot of high-performance aircraft must correct for the effects of many forces, but these forces can also be used to produce new families of aerobatic maneuvers.

C. R. O'Dell

The modern aerobatic aircraft represents a very advanced state of specialization that has resulted from an evolutionary path rather different from that of commercial or military aircraft. The construction of any aircraft is a series of compromises, the designer not being able to add much in one performance area without detracting from another. Over the last 30 years there have been enormous improvements in the design and performance characteristics of sport aircraft. Perhaps surprisingly, most of these developments have been made by custom builders, rather than large aviation manufacturers.

The step-by-step evolution has largely been by the method of "cut and try," guided simply by a basic knowledge of aerodynamics and good engineering sense. The people leading in these developments are not drafting room types but are usually the same people who have climbed into their finished products and, in the words of John Gillespie Magee Jr, "slipped the surly bonds of earth and danced the skies on laughter silvered wings." The current product of this continuing evolution is an aircraft capable of feats not dreamed of in the "golden age of aviation" before World War II, when sport aviation was highly visible to the public eye. Present-day aerobatic planes have such a high level of performance that the pilot must be mindful of some fundamental laws of physics that weren't important earlier—but which, when understood, can be applied to produce novel maneuvers that give pleasure to pilot and spectator alike. The purpose of this article is to describe to my fellow physical scientists the most important physics involved.

I'll avoid the questions that generally run, "Now why would an otherwise sane person climb into an airplane and want to turn it upside-down?" To those of us who do aerobatics it is one of life's great pleasures and a pleasure that is hard to resist. It's like being in charge of all the rides in an amusement park. Not only is the flying of aerobatics fun, it also increases the safety of regular flights, because pilots who have experienced spins or inverted flight during their training are likely to do the right thing if these events happen accidentally. Contest aerobatics has become the center of attention for the most skilled pilots, and the level of competition is now such that the winners are often decided by differences of hundredths of a percent in the total scores.

Primary design considerations

If one is to understand the special considerations for aerobatic flight it is important to first understand the very basic considerations of aircraft design, beginning with level flight and control about all three axes (see figure 1). The aircraft is maintained in level flight by the differential pressure generated between the top and bottom of the moving airfoil. The usual way to understand this is that in a laminar (smooth) flow, the pressure of a fluid decreases if its speed is increased—this is a result of Bernoulli's theorem,

$$p + \tfrac{1}{2}\rho V^2 = \text{constant}$$

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where p is the pressure of the fluid, ρ is its density and V its speed. An airfoil generates lift when the air going over the top moves faster than the air going under it.

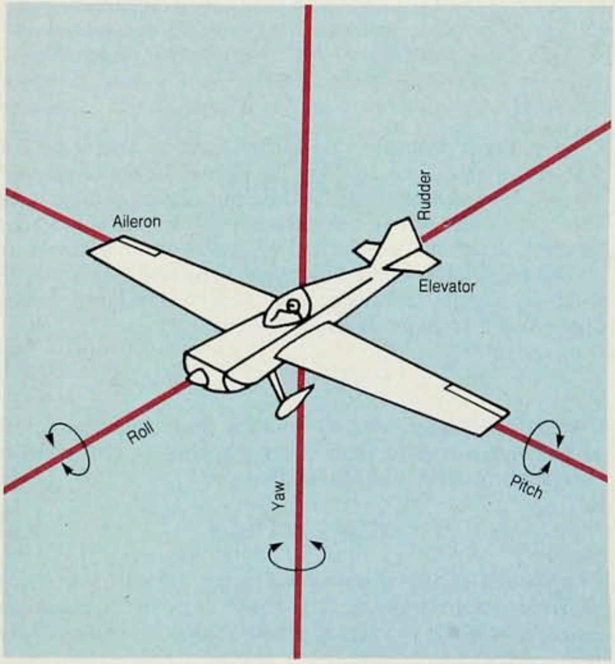
Most airplanes use asymmetrical airfoils to maximize their performance in level flight. For aerobatics, however, the pilot is frequently interested in flying inverted, with negative angles of attack, and therefore demands efficient performance in this flight regime. Aircraft designed for aerobatics are thus usually designed with symmetric airfoils, which give the same performance for both upright and inverted flight.

To first order, the lift L generated by a wing of area A moving through the air at a speed V is given by

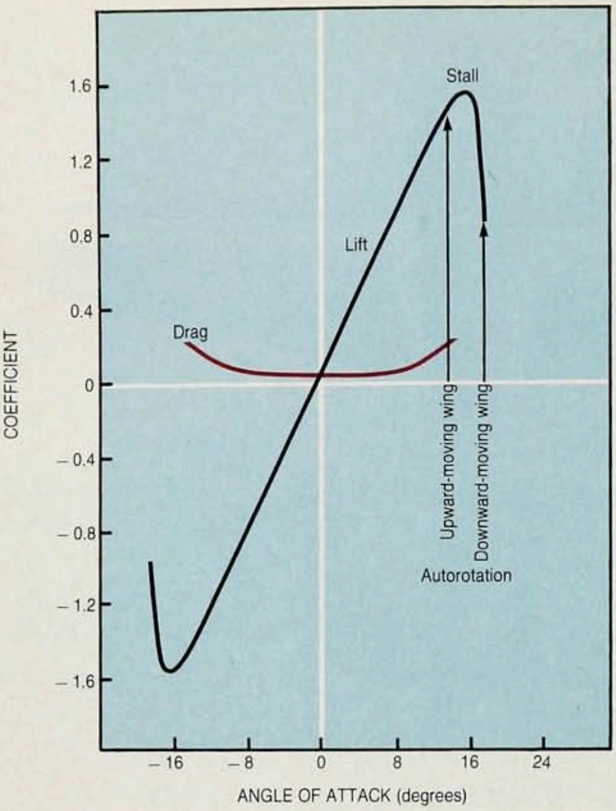
$$L = C_L \rho V^2 A/2$$

where the coefficient of lift C_L depends on the shape of the wing and the angle of attack, that is, the angle between the center line of the airfoil and the direction of flight. This means that if you move almost anything fast enough it will fly—the challenge is to do this efficiently. Airfoils are designed to produce high values of C_L while maintaining low values of the corresponding index for drag, C_D. Figure 2 shows the performance curves for a symmetric airfoil as a function of the angle of attack.

Above a critical angle, the coefficient of lift decreases and the coefficient of drag increases dramatically: This is the "stall angle." Above the stall angle the airflow no longer smoothly follows the wing profile but breaks down into turbulent eddies; the air pressure above the wing is therefore no longer reduced by the amount given by Bernoulli's theorem. Obviously, for ordinary flight a pilot will keep the angle of attack between zero and the stall angle.



Aerobatic aircraft. The photo shows a typical high-performance airplane. It is being flown by Bob Davis, who also built it. The diagram indicates the three axes of orientation of an aircraft, along with the names of the motions about these axes and the control surfaces that cause these motions. **Figure 1**



Lift and drag coefficients of an airfoil as functions of the angle of attack. The lift per unit area and velocity, given by C_L (black curve), increases monotonically until the flow disconnects from the wing at the stall angle. The vertical black lines indicate the angles of attack that the two wings encounter when the aircraft is in the condition of autorotation. The colored curve is for the drag coefficient C_D. **Figure 2**

Level flight requires a sustained force to overcome the friction, or drag, exerted by the viscous forces of the air. There are two components of the drag: one associated with the airfoil and other components of the airplane (the "section drag" or "parasitic drag"), the other induced by the lift itself. The section drag (ignoring end effects, or, effectively, for an infinitely long airfoil) is related to the speed of the airplane to first order by

$$C_D \rho V^2 A/2$$

The induced drag depends on both the coefficient of lift and the aspect ratio R of the wing, that is, the ratio of wingspan to wing width; it is given by

$$(C_L{}^2/\pi R)\rho V^2 A/2$$

The total frictional force acting on the aircraft is the sum of these two drag forces. The power required to maintain level flight of the aircraft at constant velocity is simply the power needed overcome the frictional force:

$$P = \tfrac{1}{2}\rho V^2 A(C_D + C_L{}^2/\pi R)$$

Because both coefficients are functions of the angle of attack, so is the power.

The power required for level flight, as given by the relation above, is shown in figure 3. The graph shows that more power is needed for higher speeds, which seems intuitively obvious. But the graph also shows that for very low speeds more power is again needed, which seems counterintuitive to many. The induced drag is responsible for this apparently paradoxical result: for low velocities the angle of attack must be high enough to produce a value of C_L large enough to support the weight of the aircraft; in that case the induced drag term becomes the dominant term, and more power is required for level flight—in fact, just as much as for high-speed flight.

Because of drag, the aircraft cannot maintain level flight below the velocity corresponding to the stall angle of attack and it cannot fly faster than the velocity corresponding to the maximum power of the available power plant. At any velocity between those limits, excess power is available that can be used for other purposes, such as climbing. The maximum excess power is available at the trough between dominance of the section drag and dominance of the induced drag; this usually comes at about 40% of the top velocity. More power in the engine increases the top velocity of the aircraft, and it also improves climb performance.

The source of the thrust that overcomes the drag and gravity forces on the aircraft is usually a propeller driven by a reciprocating engine. The propeller is simply a set of airfoils oriented so that the angles of attack are near the optimum along their spans. This is achieved by changing the angle of incidence (the angle between the chord of the propeller and the plane in which the propeller rotates). Near the hub of the propeller, the airfoils are moving slowly with respect to the aircraft, so the angle of incidence is large and the angle of attack remains small. The angle of incidence decreases out toward the tips of the propeller.

Performance considerations

To maneuver an airplane one makes use of movable portions of the aircraft that are far from the axes of rotation shown in figure 1: the ailerons, the elevators and the rudder. These can be moved into the airflow, producing local differential lift and resulting in motion about the corresponding axis. The elevators command pitch motion about the lateral axis; the rudders command yawing motion about the vertical axis; and the ailerons command rolling motion about the longitudinal axis. The smaller these moving surfaces are, the smoother is the airflow and the lighter is the aircraft, but the maximal rates of pitch, yaw and roll are also reduced; the areas of the control surfaces in aerobatic aircraft therefore are much larger than in ordinary airplanes.

Roll performance is measured by the angular velocity that can be maintained at full aileron deflection. Soon after the roll is started an equilibrium is established in which the turning moment of the deflected ailerons is matched by the moment of the opposite sign resulting from the differential lift of the wings (the ascending wing has a smaller angle of attack). For wings of similar profiles and aileron designs, a first-order theory predicts that the angular velocity ω of the roll is proportional to the ratio of the airspeed V to the wingspan D.

The design of modern aerobatic aircraft takes all these basic constraints into account in such a way as to produce the highest overall performance. The aircraft are light, have very high power-to-weight ratios, possess disproportionately large control surfaces and employ symmetric airfoils. In many aircraft one can rotate the propeller blades about their longitudinal axes during flight to adjust their angles of attack for maximum efficiency over a wide range of forward speeds—typically 0–300 km/hour. These "variable pitch" propellers operate at a constant rate of rotation, independent of the forward speed. The airframes are extremely strong, being designed with structural margins of safety 50% above the forces usually encountered in aerobatic competition flight. An airplane in an "unlimited category" competition flight typically experiences accelerations ranging from $+6g$ to $-5g$, as recorded by "G meters" on the aircraft.

There are additional forces that affect aircraft in ordinary and aerobatic flight. For example, to produce a rolling motion, one turns one aileron down and the other up; the difference in the lift forces on the two wings exerts a torque about the roll axis. However, the downward-positioned aileron produces more drag than the upward-positioned aileron, yielding a torque about the yaw axis, called adverse yaw; most aircraft must therefore use both rudder and ailerons to make a coordinated turn.

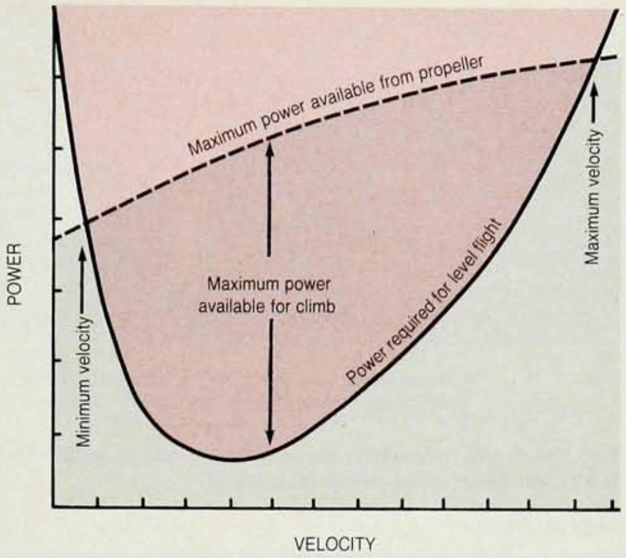
Another, perhaps surprising, source of yaw is the propeller. When an aircraft is operated at a high angle of attack, the propeller axis is of course also inclined with respect to the velocity, so the downward-moving propeller blade encounters a higher angle of attack and produces more forward thrust than its upward-moving counterpart. This means that the propeller, rotating clockwise (as viewed by the pilot behind the engine), produces a left yawing motion when the aircraft is at a high positive angle of attack. The higher the angle of attack and the more powerful the engine, the greater this yawing motion (known as the *P*-factor) will be.

The motion of the propeller is also a source of torque about the roll axis. This is simply a result of Newton's law of action and reaction: The rapid clockwise rotation of the propeller tends to produce a slower (because the airplane is much more massive than the propeller) counterclockwise rotation of the entire aircraft; among pilots, the effect is referred to simply as "torque."

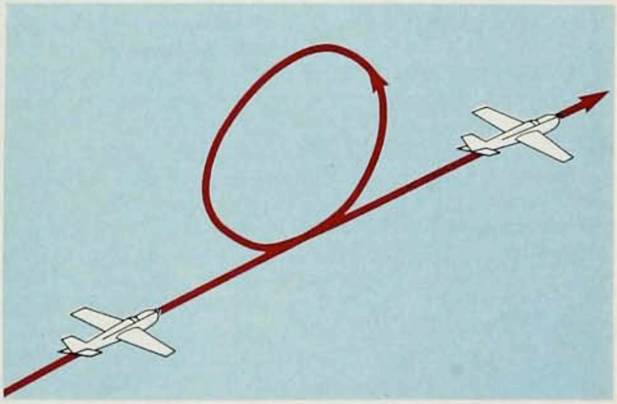
A normally troublesome coupling between yaw and roll occurs when an aircraft is operated near the stall angle of attack and begins to rotate rapidly about its yaw axis. The change in the airflow caused by the additional motion increases the angle of attack of the inward wing and decreases its lift, while the opposite takes place for the outward wing. This strong differential lift produces a rapid rolling motion (that is, a spin about the longitudinal axis), a condition called autorotation, which continues until the yawing motion is stopped. (See figure 2.) This unanticipated coupling of two normally independent motions is one of the primary causes of fatalities in general aviation, through the notorious stall–spin accident. To aerobatic pilots, this coupling is just another means of control, one more way to make the aircraft do what they want.

Perhaps the most surprising coupling—to someone operating the controls of an airplane, if not to a physics student—is due to the precession of the propeller. The rapidly spinning propeller acts as a gyroscope; its rotation axis and angular momentum are directed along the longitudinal axis of the aircraft. If one attempts to twist the spin axis about the pitch or yaw axis, the actual motion of the spin axis is at right angles to the applied torque—just as it is for spinning bicycle wheels, tops and gyroscopes. That is, the gyroscope effect produces an additional torque at right angles to the disturbing torque: Setting the controls for motion about the pitch axis can produce yaw, and, vice versa, trying for yawing motion can produce pitch.

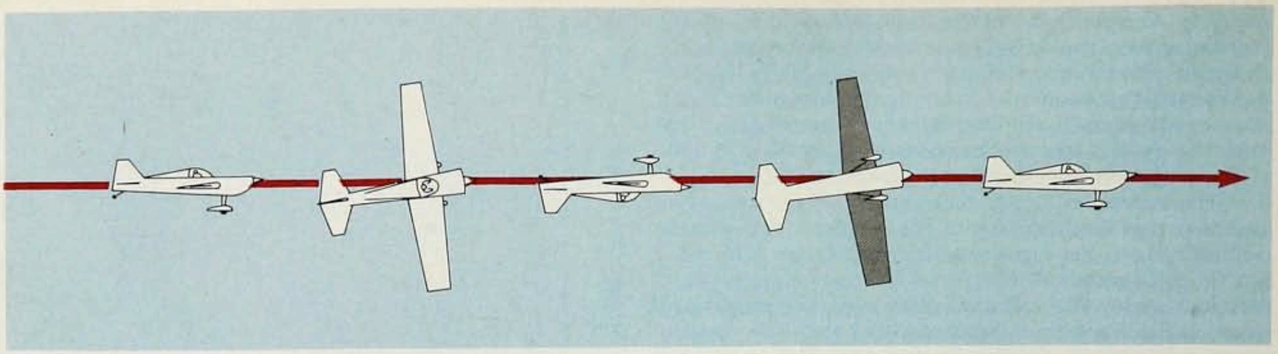
The one major controversy in design of aerobatic aircraft is the continuing debate between proponents of the monoplane and of the biplane, an unresolved issue since the first high-performance monoplanes of Louis Bleriot. The monoplane has great advantages in streamlining and visibility, but pays a weight penalty to provide the strong, internally cantilevered supporting wing spar. Its roll rate can also be jeopardized: The streamlining produces higher velocities, but often not enough to make up for the longer wings and the increased moment of inertia. The biplane's shorter wings make for a higher intrinsic roll rate, but its performance is compromised by the correspondingly higher drag associated with the low aspect ratio of the wing. But the biplane can be lighter than a monoplane for the same structural strength, because the closed-truss spar arrangement does not require a massive cantilever, and so the arguments continue. Suffice it to say that the most recent world competitions have seen monoplanes and biplanes used with comparable success. If there is an edge in competi-



Power as a function of velocity. The power available from the propeller increases slowly with aircraft velocity while the power required to sustain level flight varies considerably, being dominated by induced drag (a function of C_L) at low velocities and by parasitic drag (associated with C_D) at high velocities. **Figure 3**



Loop maneuver. The aircraft encounters rapidly varying centrifugal forces as the velocity varies. At the bottom the net force is high, but at the top of the loop, where the gravitational and centrifugal forces are in opposite directions, the net force can be nearly zero—putting the pilot into free fall. **Figure 4**

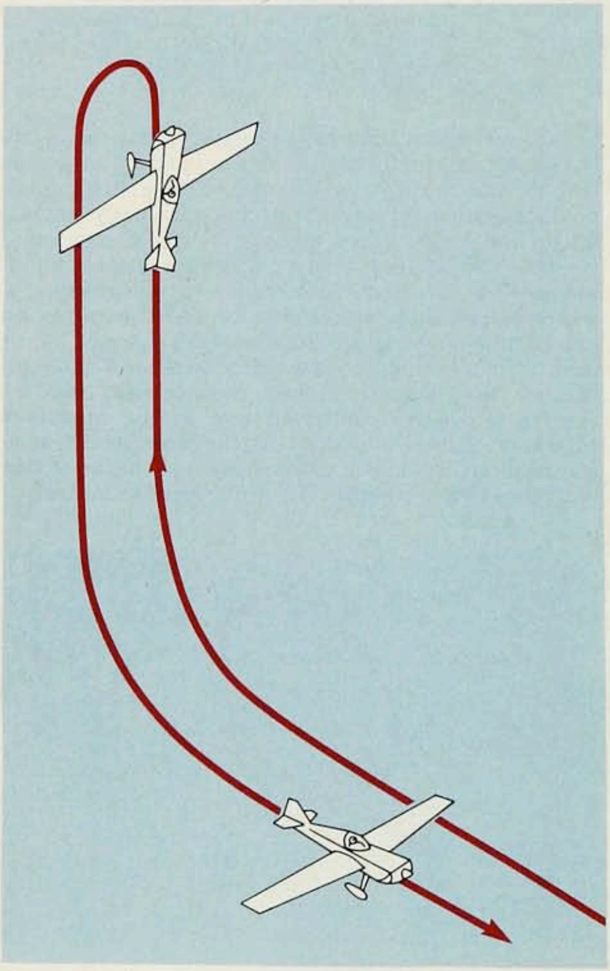


Roll maneuver involves a 360° rotation about the longitudinal axis while the center of gravity of the aircraft maintains a straight flight path. **Figure 5**

tion, it lies with the symmetry of the monoplane, which allows good flying to be easily recognized.

Maneuvers

There are thousands of standardized aerobatic maneuvers with agreed-upon performance criteria. In this article I can describe only a few out of this plethora, so I have selected some that draw upon the basic physics described above.



Hammerhead maneuver. The aircraft climbs vertically until its velocity drops to almost zero, at which point the pilot uses the rudder to deflect the remaining airflow and slipstream from the propeller and thereby pivot the aircraft about its vertical axis. **Figure 6**

The loop (see figure 4) is the most elementary of the aerobatic maneuvers, but it requires strict attention to many disruptive forces that tend to move the aircraft out of the plane of the loop or keep the loop from being circular. The maneuver depends primarily on pitch control, with the pilot using the elevators to sustain a circular flight path while the speed varies from its highest value at the entry to its minimum at the top. In the reference frame of the pilot, the centrifugal force at the entry adds to the force of gravity and the stresses on the aircraft are high there. At the top, not only is the centrifugal force directed upward, opposing gravity, but the speed of the aircraft is reduced (because of conservation of energy), so the resultant force on the aircraft is quite low. The loop is much more difficult to fly than it appears because the high angle of attack and rapid pitching motion at the entry result in disturbing yaw from the *P*-factor and precession of the propeller, and the very high power input at low velocity on top causes the propeller-reaction torque to produce an important roll disturbance.

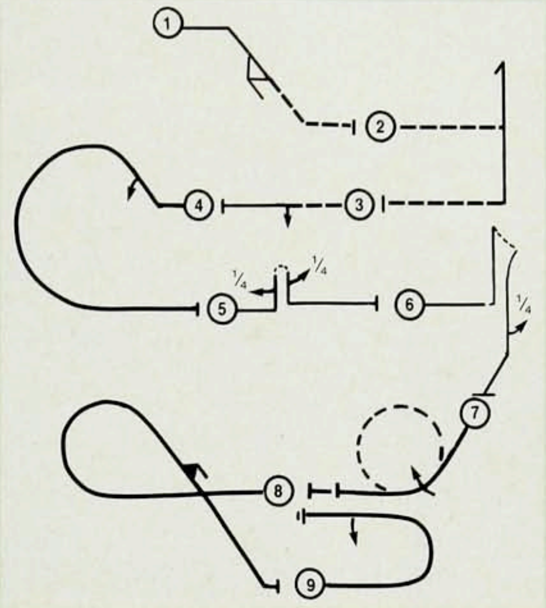
The roll (see figure 5) is similarly simple in appearance and complex in performance. If one simply sets the ailerons, the aircraft describes an irregular descending track because the changing wing orientation produces a changing lift. The performance criteria, however, require the aircraft to travel in a straight line. As the roll starts, the lift vector from the aircraft wings moves away from the vertical, so one must increase the angle of attack and use the elevators to maintain a straight-line path. By the time the aircraft has rolled 90°, the wings cannot produce useful lift; instead one must use the aircraft fuselage as a crude airfoil, controlling its angle of attack with the rudder. By 180° the wings again provide the lift, but since the aircraft is inverted, the angle of attack must be negative. Adverse yaw produces a yawing motion, which is useful at some parts of the maneuver and at other times must be corrected with the rudder. Adverse yaw is useful at the 90° point in that it helps to lift the nose, but is in exactly the wrong direction at the 270° point, since it is helping to pull the nose down. Obviously the pilot is very busy during this maneuver, with none of the controls except the aileron being left in one position for very long.

The snap roll may, to a spectator, appear very similar to the roll, but the physics is very different. In a snap roll one flies the aircraft along a straight path and then abruptly brings the angle of attack to the stall angle, immediately followed by applying full yawing motion through the rudders. The resultant autorotation about the longitudinal axis is at an angular velocity much higher than is possible for the ordinary roll. If the entry velocity is sufficiently high the aircraft will continue to track the

Aerobatic competition flight in a sailplane

The illustration shows how a sequence of maneuvers is combined in an aerobatic competition flight. The symbols used to show the maneuvers come from a standardized catalog of figures published for power aerobatics by Jose L. Aresti in 1967. This particular sequence was one of the known compulsory flights for world competition in 1987.

The sailplane is towed to an altitude of 1200 meters along the centerline of a 1-km-square competition zone. After release, the pilot flies at the best angle of glide speed (about 80 km/hour) and noses down (at **1** in the figure) to enter a half snap roll, recovering to inverted flight at 240 km/hour. Smooth application of forward pitch (at **2**) brings the aircraft to the vertical; at the apex of the climb it executes a full hammerhead turn. It emerges inverted and rolls to upright flight (at **3**); next comes a 45° climb (at **4**) followed by a five-eighths loop. The aircraft emerges from the loop at high speed (280 km/hour) to allow enough time (at **5**) for a vertical quarter roll followed by a very small outside half loop and a diving quarter roll. The net force on the aircraft is essentially zero at the top of the half loop. The next maneuver (at **6**) starts again with a vertical climb, but now one holds the airplane vertical until it stops and begins to slide backward in a tailslide. The vertical line is re-established after one causes the airplane to "swap ends," and one performs another diving quarter roll so that the aircraft recovers to nearly level flight perpendicular to the original flight direction (to compensate for any sideways wind component). The next maneuver (at **7**) is probably the busiest for the pilot: a roll superposed on a 90° turn! The penultimate maneuver (at **8**) is a five-eighths loop followed by a diving half roll (this is half of a "Cuban eight" maneuver). The last maneuver (at **9**) is a half loop with a connected half roll.



At the end of this sequence the aircraft will have descended to about 400 m, well above the minimum allowed altitude of 200 m. The on-board recording meter will show maximum accelerations of $+5.5g$ (encountered at the start of maneuver **5**) and $-3.0g$ (encountered in pushing up in maneuver **2**).

original straight line. One stops the rolling motion by straightening the rudder to remove the yaw and unstalling the wings at the right time to resume level flight. Of course, the initial pitching motion produces precession in yaw, and the yawing motion induced by the rudders tends to alter the angle of attack. Since there is lots of drag at the high angle of attack used, one normally needs full engine power, so there is also a high propeller-reaction torque.

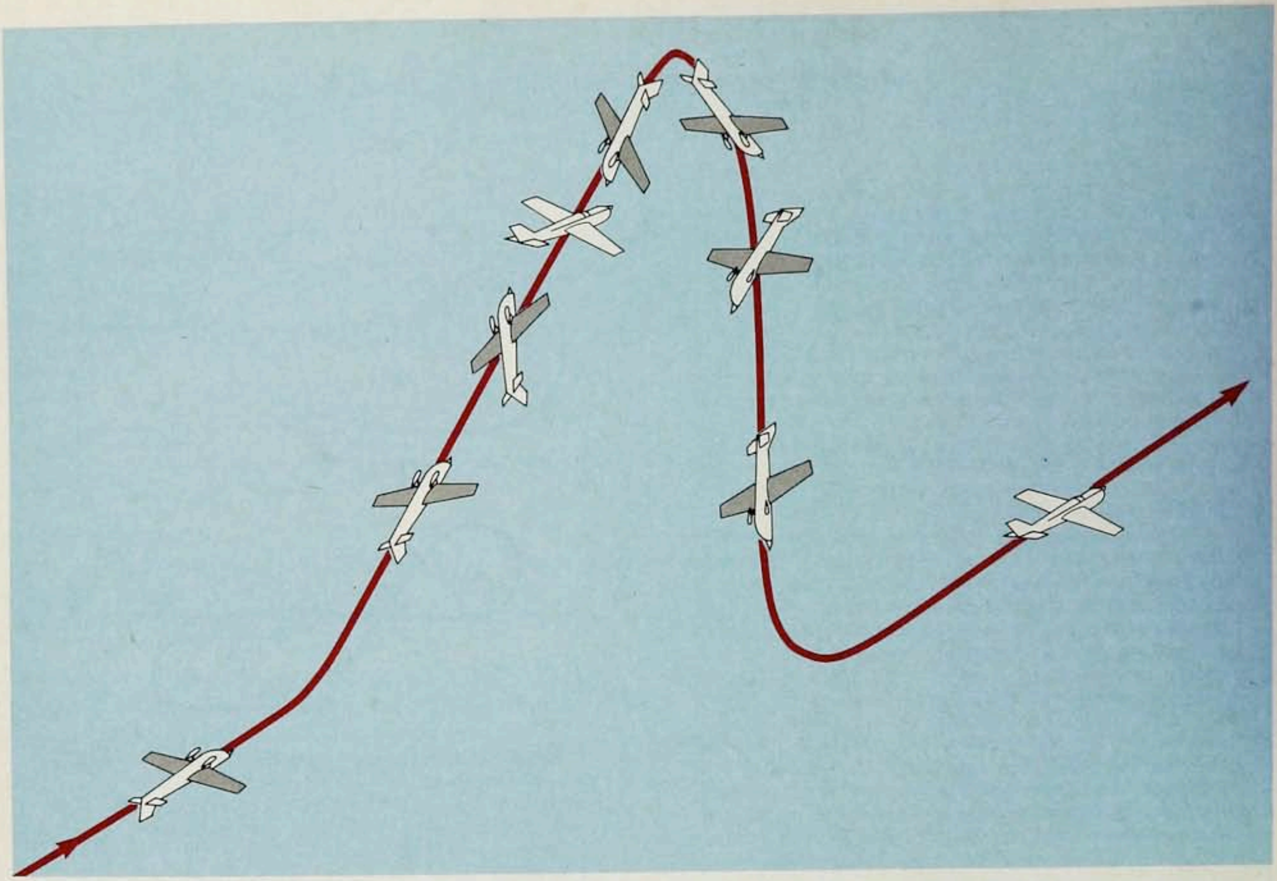
The hammerhead maneuver is shown in figure 6. It involves entry at a high velocity followed by an abrupt pitch up to an exactly vertical attitude. As the velocity drops to near zero, one applies full rudder control, pivoting the aircraft in the plane of the wings, then completing the maneuver with a vertical dive and resumption of level flight. Since the outward wing in the pivot is moving much faster than the inward wing, one must correct for differential lift with the opposite aileron and for the precession of the yawing propeller by applying forward pitch control through the elevator.

The three maneuvers described above all involve entry and exit at the same speed and altitude, but this is not the case for all maneuvers. Many finish at higher altitudes and lower velocities, others at lower altitudes and higher speeds. Thus, when one flies maneuvers in sequence in a constrained volume, as in competitions and airshows, one must give careful attention to how the maneuvers are combined, so that the potential energy gained in the altitude increase in one maneuver can be converted to kinetic energy in the next.

The torque roll is a modern maneuver made possible by the development of aircraft with small moments of inertia (due to their short wings and lightweight construction) and very powerful engines. One starts as in the hammerhead, except that as soon as the aircraft is vertical one begins a roll. One continues the roll as the aircraft slows and eventually stops, still vertical. Most remarkably, the roll is continued (now with reversed ailerons) as the aircraft begins to slide down. (The rolling motion at and near zero velocity is provided by the reaction to the torque of the propeller.) The falling reverse roll is continued until a limiting safe velocity is obtained, at which point one cuts the power, neutralizes the ailerons and uses the elevators to make the aircraft swap ends abruptly and point downward.

The Lomcevak. Perhaps the most spectacular maneuver in the repertory of the modern aerobatic aircraft is the Lomcevak (see figure 7). The name is from the Czech word for the shudder one gets after taking a very stiff drink; Czech pilots developed the maneuver, and the name is a pretty good description of what happens! The aircraft pushes up to an inverted climb and as the velocity falls to a safe value, one begins an "outside snap roll" (this is an ordinary snap roll, but with a high negative angle of attack) at full power with full right rudder, left aileron and negative-pitch elevator. As the aircraft's velocity nears zero the coupling of the control forces causes the aircraft to tumble end over end, eventually finishing in an inverted spin, from which one recovers to exit the maneuver. No maneuver is more spectacular, nor more likely to overstress the coupling of the propeller to the engine, so one sees it largely only in airshows and in unlimited competition.

While all these things are happening to the aircraft, they are of course also happening to the pilot. The effects of these forces on the blood supply and the inner ear are



The Lomcevak is actually a family of maneuvers, all of them involving strong coupling of yawing and precession forces. In the most dramatic part of the Lomcevak the aircraft tumbles end over end. **Figure 7**

the most important factors. High positive-G forces (that is, upward accelerations) tend to pool the blood supply in the lower parts of the body; the resulting lack of blood in the head can produce visual impairment and even temporary loss of consciousness if one does not take preventive measures. Fortunately, these measures work quite well over the brief periods for which one experiences the forces in aerobatic competitions and shows; only in very high-speed aircraft operating with large accelerations for long durations are "G suits" necessary. High negative-G forces drive blood into the head, but the cranium is a closed cavity, so no significant pooling occurs and the pilot experiences discomfort, but there is no risk of loss of vision or consciousness. The motion of the inner ear fluids and otoliths can produce disorientation, and even nausea, as the signals about orientation from the eyes don't agree with the inertial orientation signals from the inner ear. Fortunately, the brain seems to reprogram its responses to the novel combinations of inputs as the pilot builds up experience in aerobatics.

Sailplane aerobatics

Powered aircraft are not the only ones capable of aerobatic flight. World competition in sailplane aerobatics began in 1984 and United States national competition in 1986. Sailplane aerobatics differs in important ways from powered flight because the pilot must be even more conscious of the tradeoff of potential and kinetic energy as the sailplane rapidly descends through a sequence of maneuvers.

The complicating factors of precession and torque due to the propeller spin are of course absent, but this also means that they are not there to be used. Because of their much longer wings, adverse yaw tends to be much more important in sailplanes than in powered aircraft, but the induced drag at high angles of attack is less because of the wings' high aspect ratios. The long wings allow only slow rates of roll.

Vertical maneuvers tend to be much shorter than in powered planes. On the way up the gain in altitude corresponds to the kinetic energy brought into the maneuver, and on the way down the aircraft's very high streamlining allows rapid acceleration to the aircraft's limiting velocity. All of these factors make sailplane aerobatics seem much more limited, but to my mind the beauty of silent aerobatics makes it even more fun than powered flight.

The box on the previous page describes a typical sequence of maneuvers in an aerobatic competition flight in a sailplane.

Two national organizations can supply additional information about sport aerobatics:

▶ For powered aircraft: International Aerobatic Club, 758 Grovewood Drive, Cordova, Tennessee 38018

▶ For sailplanes: Sailplane Aerobatics Association, 3911 Riley, Houston, Texas 77005.

They can tell you about where you can see competitions and experience aerobatic flight yourself.

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