Aerobatics: Sport, Science, and Survival

Peter F. Bythrow

Since the inception of the airplane as a weapon of warfare, aerobatics has been inherent to the pursuit of aerial combat. The term itself conjures up the image of Manfred von Richthofen, the Red Baron of the "Flying Circus" squadron, in a Fokker triplane going head to head with Eddie Rickenbacker of the "Hat in the Ring" squadron in a Spad biplane. Partly because of this archaic image, aerobatics and aerobatic pilots are often viewed as daredevil and devil-may-care, when for the most part, nothing could be further from reality. The successfully completed aerobatic maneuver results from intellectual understanding, detailed planning, and hours of dedicated practice. It should not be confused with a bungee jump! This article aims to dispel some of the myths and preconceptions regarding aerobatic flight and the pilots who choose it as their sport. It will review in part the evolution of competitive sport flying as well as basic aerobatic maneuvers and their underlying physics. Aerobatic flight regulations and the application of aerobatic training to routine flight will also be addressed.
(Keywords: Aerobatics, International Aerobatic Club, Physics of flight, Sport aviation.)

INTRODUCTION

Perhaps no other athletic endeavor is so demanding of simultaneous cognitive processing and fine motor skills in a physically grueling and mentally stressful environment as the sport of aerobatics. Few other athletes must practice their art while experiencing sustained load factors of ±4 to 6 g (1 g = acceleration due to gravity at the Earth's surface = 9.8 m/s^2). Under these conditions, the aerobatic pilot who intuitively understands the underlying physics of a maneuver can, when all else is equal, be more adept at its execution than an equally skilled competitor without such intuitive knowledge. To the combat pilot, understanding and deftness in aerobatic flight have often meant the difference between life and death. As for nonaerobatic pilots, whose federally mandated initiation into attitude excursions is limited to 60° banked turns, they too can profit from the safety and situational awareness gained through aerobatic experience. The same holds for the airline pilot, whose primary responsibility is passenger safety.

The ability to maneuver an aircraft in controlled flight about the full range of all three axes (roll, pitch, and yaw) while maintaining complete awareness of one's dynamic environment is the hallmark of the aerobatic pilot. Skills thus acquired give the pilot the ability and confidence necessary to address almost any eventuality short of catastrophic airframe failure. To see how these skills are developed, this article will discuss the history of aerobatics, address fundamental maneuvers, and review some associated physics. It will also mention Federal Aviation Administration (FAA) regulations and the value of aerobatics in recurrent training.

THE EVOLUTION OF COMPETITIVE SPORT FLYING

In World War I as in Desert Storm, the fastest, most well-armed, least observable, and most maneuverable aircraft, piloted by the most skilled aviator, survived to fight another day. Most aerobatic maneuvers used today in civilian training and competition have evolved from early fighter tactics. In fact, the Immelmann maneuver, shown in Fig. 1, was named after the World War I German ace Max Immelmann. Although credited with its invention, his performance of the maneuver in combat is not confirmed.[1]

Even though combat aircraft can now sustain supersonic flight and are equipped with sophisticated air-to-air missiles, history has shown that air-to-air engagements seldom occur at supersonic speeds and still require maneuvers similar to those practiced in World War I, World War II, Korea, and Vietnam. These combat maneuvers were and are intended to gain a tactical advantage over an opponent and to maximize the use of the specific characteristics of one's own aircraft and weapons design. One of the more spectacular aerobatic feats of modern air combat was immortalized by aviation artist Keith Ferris in *MiG Sweep*, a portrayal of General Robin Olds's interception of a MiG-21 in the skies over North Vietnam.[2] In this classic energy fighter (F-4C) versus angles fighter (MiG-21) engagement[3] (Figs. 2a and 2b), the superior vertical penetration of the F-4C was used in a modified Immelmann and barrel roll maneuver to gain tactical advantage over the MiG-21, despite that aircraft's superior turning ability.

Civilian aerobatic flight has evolved separately from its antecedent in military air combat maneuvering. It is seldom performed to gain tactical advantage over an adversary, but rather to acquire proficient piloting skills or a competitive edge, or often just for the pure joy of it. Today, aerobatic competition in the United States is sponsored by the Experimental Aircraft Association (EAA) and the International Aerobatic Club (IAC; home page on the World Wide Web is located at http://acro.harvard.edu/IAC/iac_homepg.htm). Founded in 1953, the EAA advocates sport aviation and the construction of custom-built aircraft. This advocacy is best witnessed at the annual EAA fly-in held every summer in Oshkosh, Wisconsin. During the event, the uncontrolled field at Oshkosh acquires a temporary control tower and is transformed into the world's busiest airport.

The IAC was originally a separate organization but is now affiliated with the EAA. It supports and fosters aerobatic competition and safety and sets the requirements and standards of performance for aerobic competition. Tom Poberezny, former world aerobatic champion, is the president of the EAA, and world-class aerobatic competitor Linda Hamer is the president of the IAC. In conjunction with the Oshkosh EAA fly-in, the IAC sponsors an annual aerobatic competition in Fond du Lac, Wisconsin.

Today, there are five fundamental categories of competition: basic, sportsman, intermediate, advanced, and unlimited. These categories differ in both difficulty of the maneuver sequence and in performance required of the aircraft to execute the prescribed sequence. An unlimited category aircraft like the Pitts S2 might be seen competing in the basic or sportsman category, but you won't see a Clipped Wing Cub competing in the advanced or unlimited category.

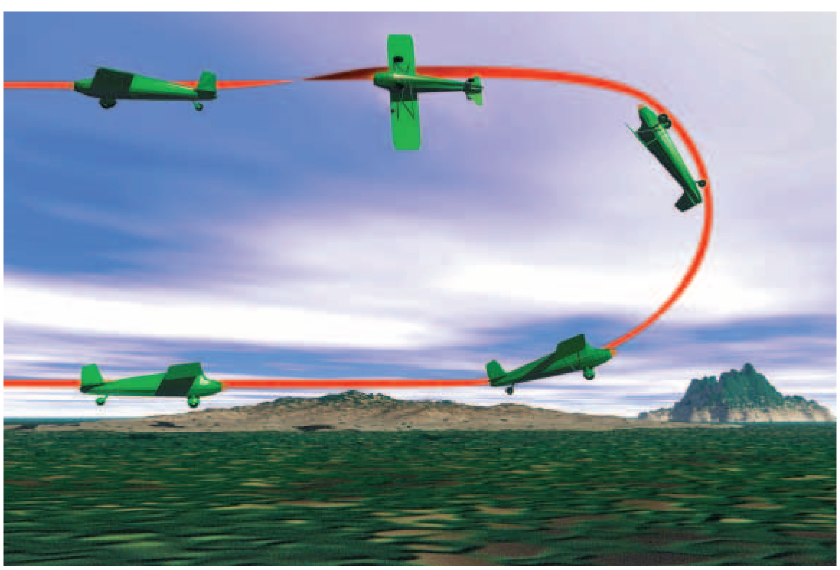

Figure 1. The Immelmann maneuver, executed by a vertical pull-up to the inverted and a 1/2 slow roll to the upright.

REGULATIONS

As one might expect, aerobatic flight is subject to more restrictive regulations by the FAA than flight in a less dynamic aerial environment. These regulations are designed primarily to protect the public at large from injury or loss due to the pursuit of sport aviation. The secondary reason for these regulations is to protect the pilot and passengers of the aerobatic aircraft.

The FAA defines aerobatics as "an intentional maneuver involving an abrupt change in an aircraft's attitude, an abnormal attitude, or abnormal acceleration not necessary for normal flight" (FAA Regulations, Part 91-103). The definition of normal attitude is generally considered to mean bank

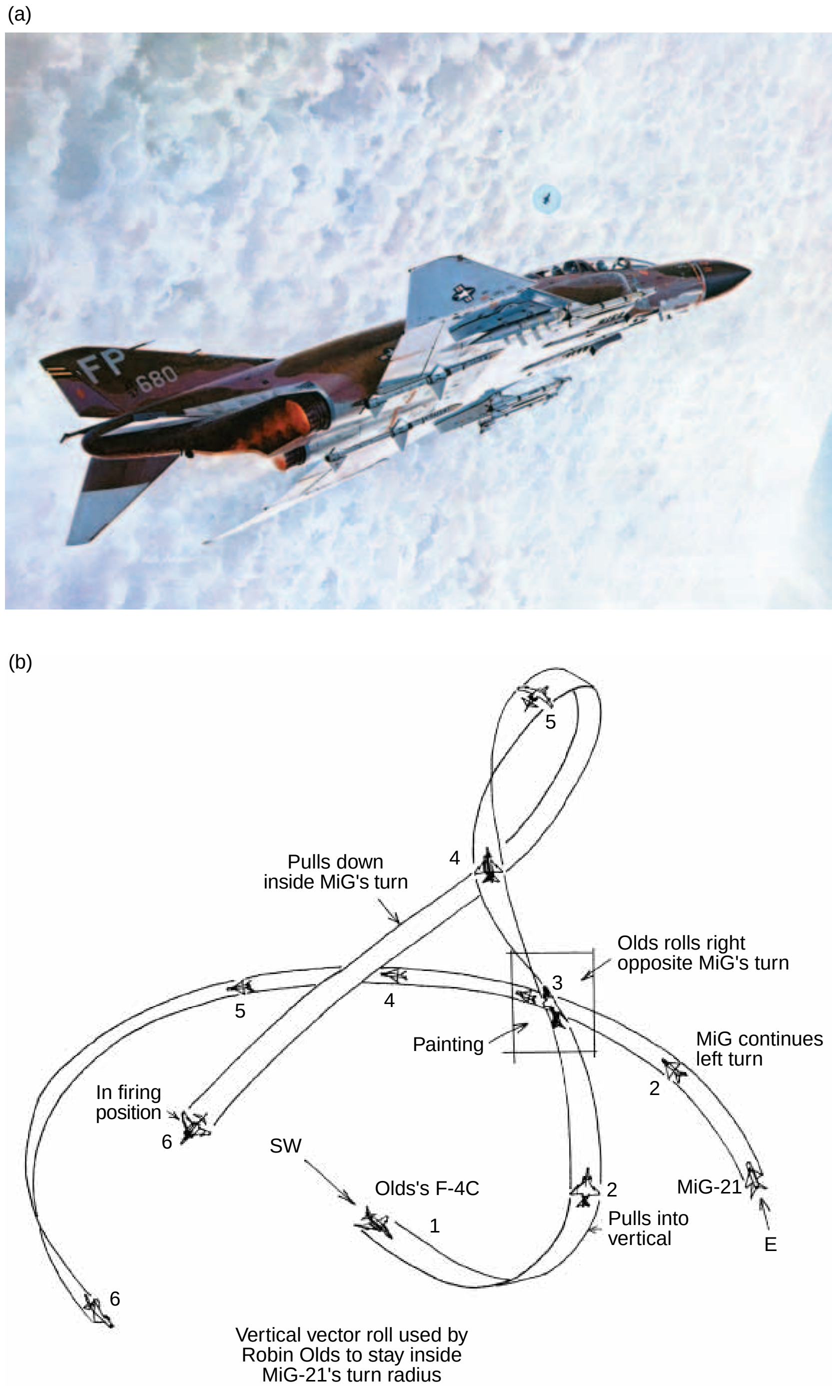

Figure 2. The *MiG Sweep*. (a) Oil painting of the F-4C (foreground) and MiG-21 (highlighted in background). (b) Example of combined aerobatic maneuvers used in exchanging energy for advantage in an air-to-air engagement. The view depicted in Fig. 2a is enclosed in the box. (Reprinted from Ref. 2 by permission.)

angles of 60° or less and pitch angles of ±30° or less. Under conditions of flight that exceed these limits, no person may operate an aircraft over any congested area of a city, town, or settlement; over an open-air assembly of persons; within a designated federal airspace or airway; below an altitude of 1500 ft; or when flight visibility is less than 3 statute miles.

In addition to these restrictions, each occupant of an aircraft conducting aerobatic flight must wear a certified parachute that has been inspected and repacked within the preceding 120 days. This regulation applies only when people other than crew members are onboard. Thus, a solo aerobatic pilot may perform without the use of a parachute (FAA Regulations, Part 91-107). Finally, the aircraft must be certified for aerobatic flight and must be operated within its aerobatic flight envelope.

A close reading of the preceding restrictions might lead one to believe that an aircraft operating at low altitude during an air show has broken an FAA regulation. This is not the case. An air show pilot must receive a certificate of waiver from the FAA by performing his or her low-altitude aerobatics for an FAA-certified aerobatic inspector before these routines can be performed for the public. The emphasis in regulation is always on public safety.

AIRPLANE CHARACTERISTICS

Many aircraft are considered capable of aerobatic flight, from the F-16 to the Clipped Wing Piper Cub (the shortened wing offers improved roll rate over the standard Piper Cub wing) and everything in between. Tex Johnson, chief test pilot for Boeing Aircraft in the 1950s, even believed that the venerable Boeing 707 jet transport was capable of aerobatic flight. By completing a barrel roll at low altitude in full view of Air Force and Boeing officials, he proved this to be true! Anecdotally, when later called on the carpet for his actions, it is said that he received both a reprimand and a bonus, since the Air Force bought the Boeing 707 for its all-jet KC-135 tanker fleet.

In civil aerobatic training and competition, the range of aircraft from which to choose is narrower, but only somewhat. Competition aircraft encompass the relatively simple and inexpensive ($8,000–$35,000) such as the Bellanca/American Champion Citabria (airbatic spelled backwards) to the Unlimited Class Extra 300 ($250,000–$500,000). Figure 3 shows the author in a midrange ($45,000–$100,000) Bellanca/American Champion Decathlon.

The designation of an aerobatic aircraft is fundamentally a function of structural load factors and power plant features (inverted fuel and oil systems, etc.). All of the aircraft cited here have at least one thing in common: Beyond the limit load factor, the aircraft may sustain damage, and beyond about 1.5 times that limit, the aircraft will experience structural failure and the pilot will experience distress. All aircraft designated as aerobatic are designed with minimum structural load factors of +6 and –3 *g*, but many are designed for load factors in excess of ±10 *g*.

BASIC AEROBATICS

Aerobatic routines performed in training or competition generally consist of a sequence of maneuvers that are drawn directly from or are modifications of the basic aerobatic building blocks, i.e., the loop, the slow roll, the barrel roll, the spin, and the snap roll. Nearly all other aerobatic maneuvers, except perhaps the "Lomcevak"[4] (a torque-coupled poststall maneuver named for the shudder one experiences after taking a stiff drink; possibly devised by an inebriated Czech contestant on the evening before the 1962 world championships), are combinations or modifications of these five maneuvers.

Loops

What could be more simple? From level flight, pull back on the stick and the nose comes up until all you see is sky. Then keep pulling until all you see is ground. Continue pulling to return to level flight. This is most often the novice's view of the loop as an aerobatic maneuver. Following these directions, one might achieve a shape similar to that shown in Fig. 4a; the desired shape, however, is depicted in Fig. 4b.

Figure 3. The author is shown piloting the Bellanca/American Champion Decathlon.

(a)
(b)

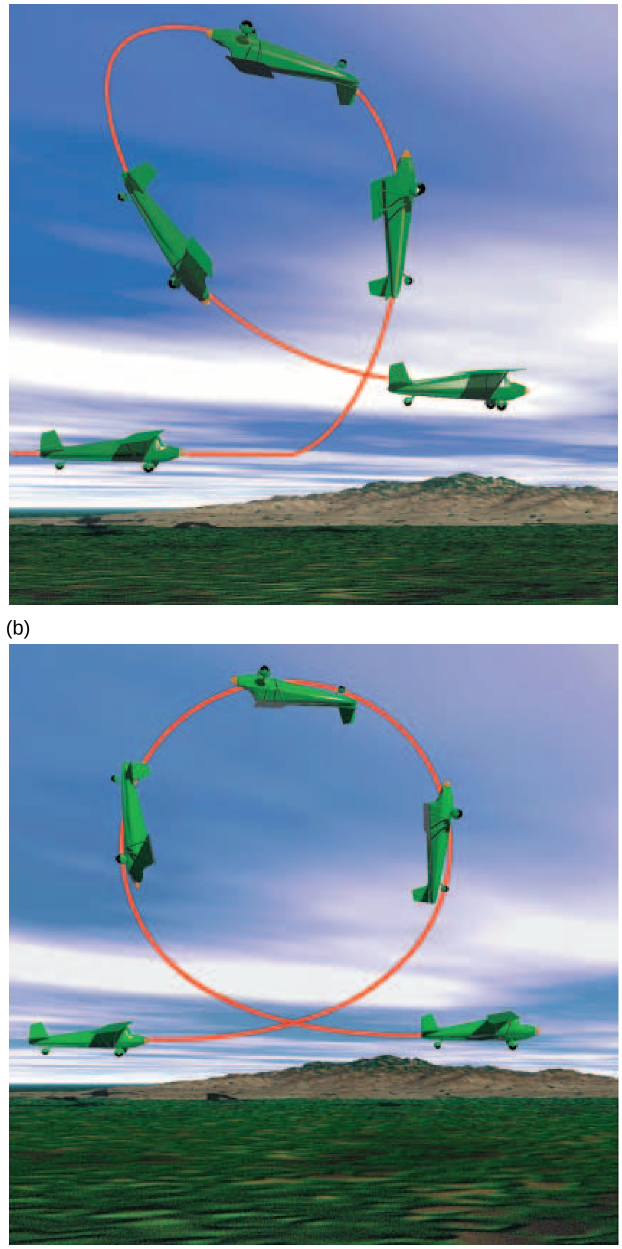

Figure 4. Two views of the loop: (a) incorrectly attempted and (b) correctly executed.

The difference between Figs. 4a and 4b is the precise control of **G** forces (the load factor) and the **P** factor (propeller- and engine-induced yaw forces) as functions of θ (the angle between the wing chord line and the horizon, which, when properly executed, equals the angle at which the aircraft has moved through the circle) and $\mathbf{V}_\theta$ (the velocity of the aircraft tangent to the loop). The geometry of the loop and the forces experienced are shown in Figs. 5a and 5b. As one might expect, the loop is entered from level flight at a fixed airspeed and power setting. The objective of the maneuver is then to inscribe a figure of constant radius R (a circle) in the vertical plane.

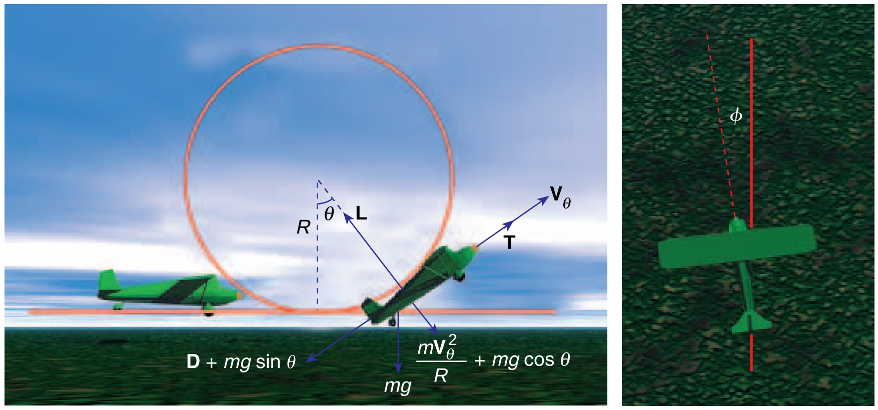

Figure 5. Execution of a loop. (a) Geometric forces experienced during a properly executed loop. (b) The effect of the **P** factor during the loop. The variables are the same as those described in the text except for **D**, which is the force due to drag.

Equal entry and exit altitudes and airspeeds are also desired outcomes of the loop. The pilot's control feedback loop is fed by two inputs, θ and **G**. To maintain a constant radius, the pilot must vary the load factor, which is determined through vestibular sensations, although a G meter is generally available for confirmation of these senses. The appropriate **G** force applied through control stick inputs (Fig. 6) is a function of θ, and θ is determined by visually referencing the wing chord line to the horizon as shown in Fig. 7 from a pilot's point of view.

It is a simple matter to write the differential equations required for Fig. 5 if one assumes no forces acting out of the plane of the loop:

$$\dot{\mathbf{V}}_\theta = \frac{\mathbf{T}}{m} - \frac{C_d \rho S}{2m}\mathbf{V}_\theta^2 - g\sin\theta,$$

$$\dot{\mathbf{V}}_R = \frac{\mathbf{V}_\theta^2}{R} + g\cos\theta - \frac{\mathbf{L}}{m},$$

$$\dot{\theta} = \frac{\mathbf{V}_\theta}{R},$$

where

C_d = coefficient of drag,

ρ = air density,

S = surface area of the airfoil,

$\mathbf{L}$ = lift force supplied by the wing,

$\mathbf{T}$ = thrust provided by the engine,

m = mass of the aircraft, and

$\mathbf{G} = \mathbf{L}/m$.

The $(\cdot)$ denotes the derivative with respect to time.

Unfortunately, since θ must vary from 0 to 2π, the small angle approximation of $\theta = \sin\theta$ cannot be used, and the equation must be solved numerically as shown in Fig. 6 or by a sophisticated analog computer (i.e., the pilot).

In an actual loop, aerodynamic forces do, in fact, act out of the plane of the loop, as shown in Fig. 5b. At high power, high angle of attack (the angle between the wing chord line and the relative wind), and low airspeed—conditions encountered in the second quarter of the loop—the **P** factor causes the airplane to yaw to the left. (Specifically, in this case, left yaw is caused primarily by the higher angle of attack of the downward-moving right-hand propeller blade.) This movement increases the angle ϕ out of the plane (as shown in Fig. 5b), requiring the pilot to apply right rudder to remain in the plane of the loop during the climbing portion of the maneuver. As speed increases in the descending portion of the loop, right rudder is removed, and some left rudder may be needed until level flight is reestablished.

Let's look again at what the aerobatic pilot actually does when accomplishing a perfectly executed loop. First, the area is visually scanned for other traffic. Second, entry airspeed and power settings are established, and in level flight the aircraft is aligned with a heading reference located on the ground. Third, a smooth pull-up is initiated with an acceleration between 3 and 4 *g*. Simultaneously, the pilot references

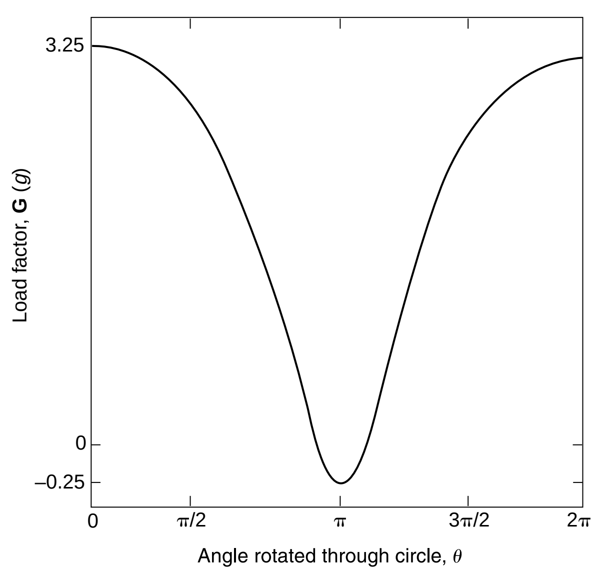

Figure 6. Load factor **G** experienced by the aircraft and pilot as a function of angle $\boldsymbol{\theta}$.

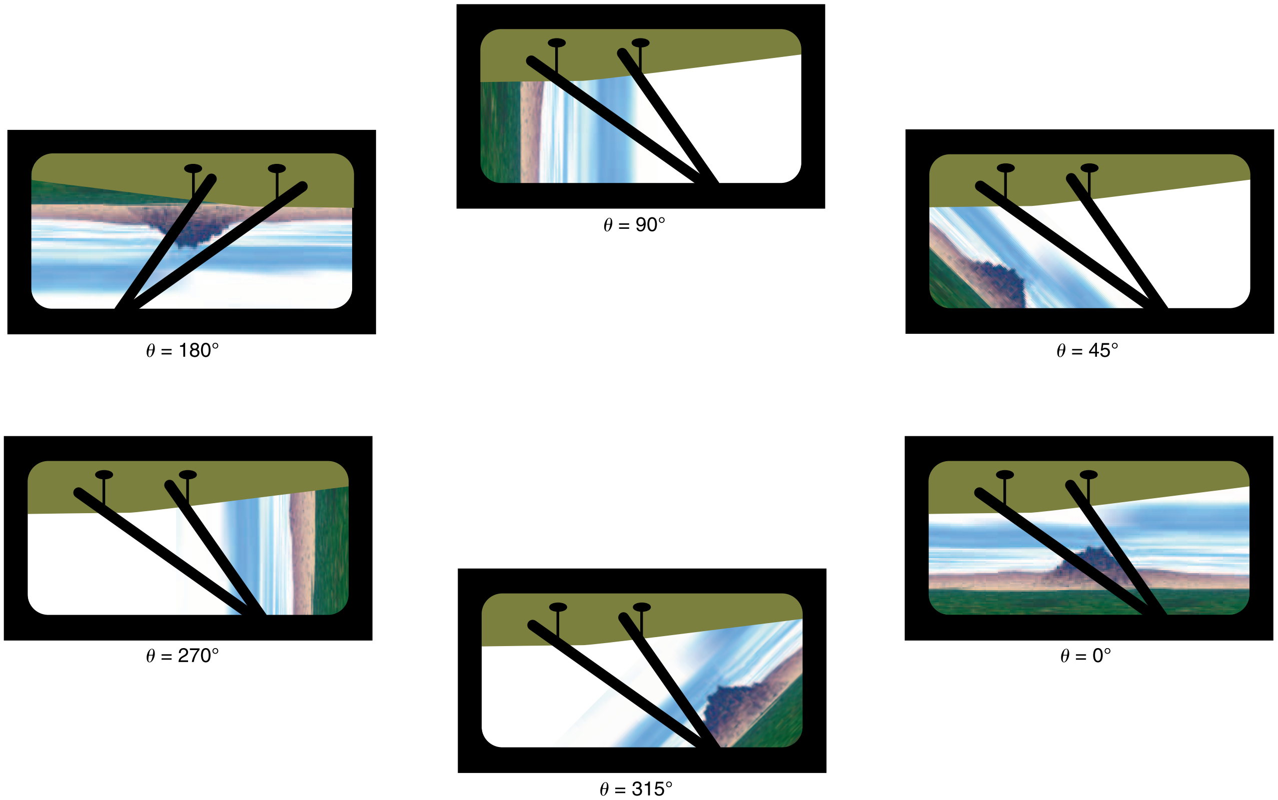

Figure 7. Variation of angle θ as viewed by the pilot during a loop.

the aircraft's attitude (θ and ϕ) by looking at each wing's alignment with the horizon on both sides of the aircraft. Fourth, if required, right rudder is gently applied to maintain alignment in the vertical plane ($\phi = 0$) while simultaneously reducing aft control pressures gradually ($\theta = 3\pi/4$), thereby reducing **G** as well until a slight sense of weightlessness is experienced at the top of the loop ($\theta = \pi$). The process is reversed on the "back side" of the loop, with **G** increasing and right rudder decreasing until level flight is again achieved at the entry altitude, airspeed, and heading.

Having looked at one of the simplest aerobatic maneuvers, I will now describe a few others that are more complex in terms of both dynamics and execution.

Rolls

Roll maneuvers can be classified into three types: the slow roll, the barrel roll, and the snap roll. (The so-called aileron roll is just a modification of the slow roll and is most often executed in very high performance aircraft. For reasons that will become obvious, the snap roll will be discussed in the next section.) Both the slow roll and barrel roll are accomplished by the smooth application of control inputs about all three axes.

The objective of the slow roll is to roll the aircraft about the longitudinal axis while maintaining the fixed orientation of that axis in space. Since lift acts normal to the chord line of the wing, independent of aircraft attitude, pitch and yaw forces must be applied in a continuously varying manner to keep the aircraft from turning, climbing, or descending throughout the 360° roll. Figure 8 shows the motion of the aircraft and the sequence of control inputs as viewed from inside the cockpit during this maneuver.

After aligning heading with a prominent visual reference (e.g., a distant mountain peak or highway), the slow roll is initiated from level flight by applying a slight aft stick (elevator) movement, causing the aircraft's nose to pitch up about 10°. Aileron is then applied in the desired direction of roll simultaneously with coordinated rudder application. After about 10° of roll as referenced to the horizon, the pilot must apply forward control stick pressure and rudder pressure opposite the direction of roll to eliminate the tendencies of the aircraft to turn and the nose to fall below the horizon. Forward elevator deflection and opposite rudder deflection continue to increase throughout the first 90° of roll. Forward stick pressure continues to increase until about –1 to –2 g is experienced at the inverted or 180° position. During this second 90° of roll, opposite rudder deflection is gradually decreased to zero at 180°.

From the inverted position through 270°, forward stick pressure must be gradually decreased while the

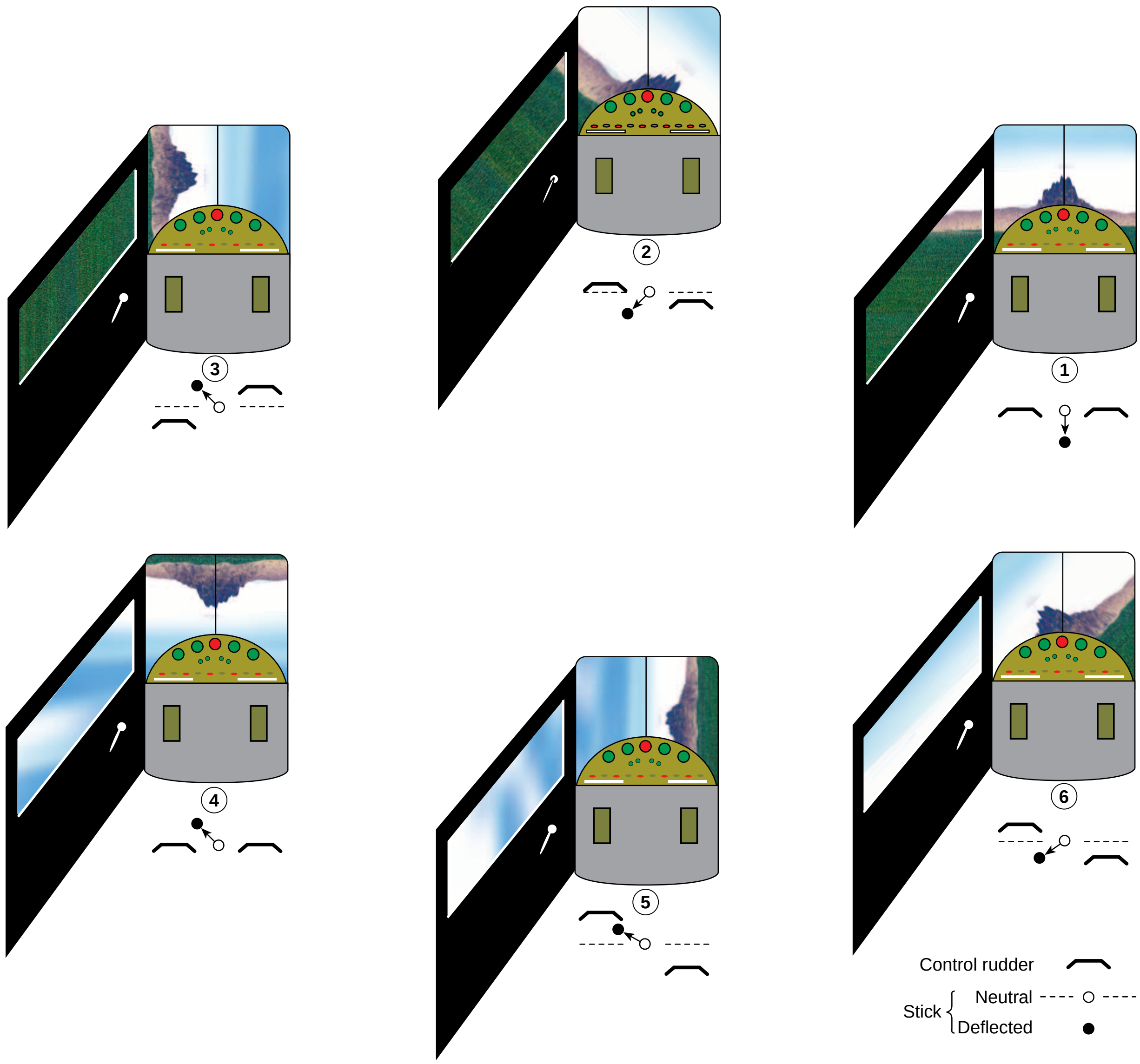

Figure 8. The slow roll and control inputs as viewed from inside the aircraft.

pilot deflects the rudder in the direction of roll. Past the 270° position, pro-rudder deflection begins to decrease to neutral, and elevator or pitch forces are gradually reduced from forward to neutral at 360° of roll.

During the slow roll, the pilot determines the precise amount of control forces required to complete the maneuver by visually determining aircraft attitude above or below the horizon and left or right of the preselected visual heading reference. For example, in the first 90° of roll, if the aircraft's nose begins to fall below the horizon, more opposite rudder is required, whereas if the nose drifts (in a left roll) to the left of the visual reference, more forward elevator pressure is required. The properly executed slow roll is a challenging maneuver, but it forms the foundation for many others such as the point roll, the Immelmann, and the Cuban 8.

The barrel roll differs dramatically from the slow roll. In this maneuver, roll and yaw control inputs are always coordinated (in the same direction, thus keeping the sum of lift and centripetal force normal to the wing's chord line), and **G** is kept positive or zero. In a properly executed barrel roll, a glass of water set on the aircraft's glare shield should remain in position, and the level of the water should remain parallel with the wing. Figures 9 and 10 show the pilot's view and the view from behind the aircraft, respectively, as a barrel roll is properly executed. Figure 10 shows that although the pilot's view after 270° of roll (position 4 in Fig. 9) is one in which the aircraft's nose is below the horizon, the actual figure of the maneuver is accomplished entirely above the entry altitude.

One begins the barrel roll from level flight at a fixed power setting. After selecting a ground reference point

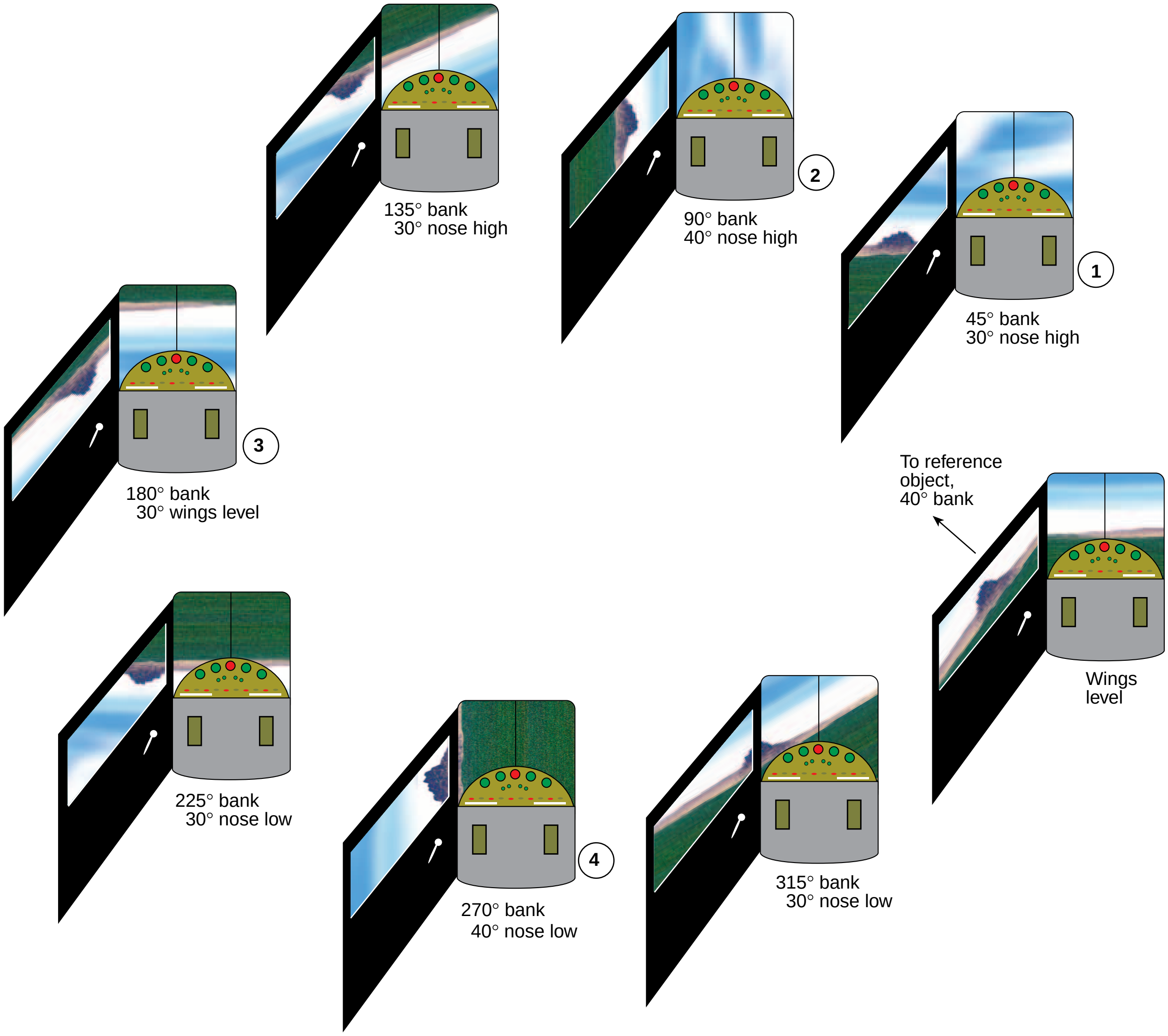

Figure 9. Pilot's view of a barrel roll. Positions 1 through 4 correspond to those shown in Fig. 10.

about which the roll will be executed, the pilot orients the aircraft's heading between 30° and 45° to one side of the selected reference. The roll is then executed in the direction of the distant reference point.

To initiate the barrel roll, the pilot begins a slow pull-up and a gradual coordinated roll. The maximum pitch angle reached should equal the heading offset from the selected reference point and should be accomplished as a bank angle of 90° is achieved. The pilot must be cognizant of the effects of rapidly changing airspeed on required control surface deflection, since roll rate and pitch attitude during the maneuver are constantly varying functions of airspeed.

As the airspeed decreases and the pitch angle increases, more elevator and aileron deflection is required. After the 90° bank angle is achieved, roll is continued, and aft elevator pressure is decreased to approximately zero as the wing's level inverted (180° bank angle) position is reached. The nose should be at or slightly above the horizon at this point.

Aircraft heading is now plus or minus (depending on the direction of roll) twice the initial reference offset angle. From the inverted position, the roll is continued with gradually decreasing aileron deflection and gradually increasing aft control stick pressure. The 270° point in the roll is achieved simultaneously with a pitch attitude that is an equal amount below the horizon as the initial heading offset angle. Finally, a return to level flight is achieved by continuing the roll and increasing aft control force until initial heading, altitude, and airspeed conditions are reached.

Essentially an energy management exercise, the barrel roll is the combination of a loop and a roll executed simultaneously. This maneuver has many pitfalls for both the novice and the experienced pilot, but the one that can cause the most distress is reaching

Figure 10. The barrel roll viewed from behind the aircraft. Positions correspond to those shown in Fig. 9.

position 3 in Fig. 9, i.e., wings level inverted, in a nose-low attitude. This can cause the pilot to pull the aircraft through the vertical, with resulting high airspeeds and high **G** forces. That combination, if not avoided and corrected for at the earliest possible time, could lead to structural failure. The prepared practitioner of the barrel roll will anticipate this possibility, and, if finding that a nose-low condition exists at point 3, will immediately apply forward control pressure, roll to the upright attitude, and recover from the ensuing dive. This response allows the pilot to correct the error and improve the maneuver during another practice session! Any pilot should be aware that this response is appropriate if ever an inverted attitude is inadvertently established.

Spins

The spin has evolved from an accidental occurrence to be avoided into a family of precisely controlled aerobatic maneuvers, including the normal spin, inverted spin, flat spin, and snap roll. Each of these maneuvers relies on a partial stall and autorotation to effect entry and sustain the maneuver. Autorotation is achieved by inducing a stall on one wing while maintaining some lift on the other wing. This can be seen in the plot of lift coefficient (C_L) versus angle of attack (α) shown in Fig. 11. The result of this action is a tendency for the aircraft to rotate toward and about the stalled wing. If autorotation is induced rapidly at relatively high airspeed, creating a sufficiently great difference in lift between wings, the aircraft rotates about the velocity vector, thus executing a snap roll.

The normal upright spin (Fig. 12) is entered from slowly decelerating level flight, with the aircraft's pitch attitude roughly 30° above the horizon. In this configuration, the stalling angle of attack is reached gradually as airspeed decreases. Just before the stall (as determined by referencing airspeed with various other sensory inputs), the pilot rapidly applies aft control stick forces and simultaneously applies full, smooth, and rapid rudder control inputs in the direction of desired rotation. The stalled wing will generally drop, and the forward-moving wing will rise. The aircraft will then enter the developed spin after roughly 1/4 turn.[5]

Precise recovery from the spin is a matter of proper control inputs, timing, and visual references on the ground. Recovery is initiated before reaching a predetermined heading by applying rudder opposite the direction of spin to stop rotation as well as smooth but rapid forward elevator control to recover from the stall. The precise timing of the recovery control inputs will

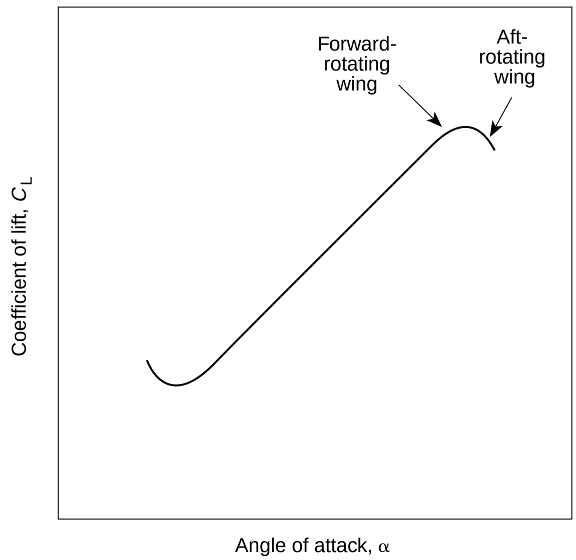

Figure 11. The coefficient of lift versus angle of attack during autorotation.

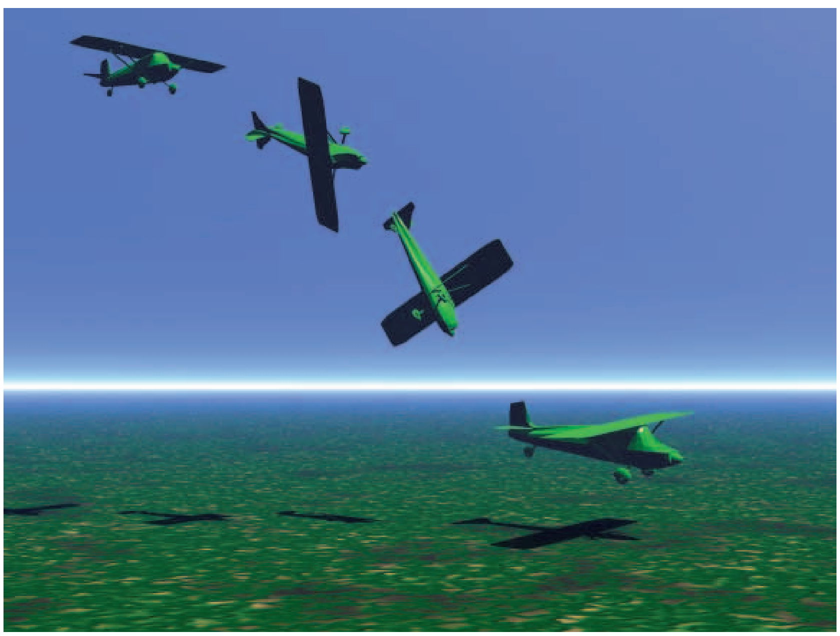

Figure 12. The motion of an aircraft in a normal upright spin (one turn).

depend on the rate of rotation and the inherent response time of the aircraft being flown. By precisely timing these inputs, the proficient aerobatic pilot can stop rotation and recover from the spin on any predetermined heading, even after experiencing multiple rotations.

As discussed previously, the snap roll is the result of autorotation induced from an accelerated stall. Viewed from the ground, this roll appears as a spectacular corkscrew motion in which the aircraft's nose comes up above the horizon, the wings swap position in a rapid 360° rotation, the nose returns to the horizon, and the aircraft continues on its original heading as if nothing had happened (Fig. 13). What has in fact occurred is a complex combination of aerodynamic and gyroscopic responses to control inputs.

To accomplish the snap roll, the pilot enters from level flight at a safe airspeed. (The airspeed selected is such that full and abrupt control inputs can be made without causing structural damage to the aircraft. The highest airspeed at which this may be accomplished is called maneuvering speed. Generally, the snap roll is entered slightly below maneuvering speed, but at a high enough airspeed that a stall is avoided during recovery from the snap.) For the upright snap, rapid, smooth, but forceful full-aft elevator control is applied. This action changes the aircraft's pitch attitude without significantly changing its direction of forward motion. The pilot experiences roughly +4 *g*, and the wings undergo an accelerated stall. Almost coincidentally with the application of aft elevator control, the pilot applies rapid, smooth, but forceful full rudder in the desired direction of the snap, resulting in immediate autorotation. As autorotation begins, the pilot relaxes some of the aft control pressure, and the rate of rotation increases.

Recovery is initiated after about 315° of roll by relaxing almost all aft pressure and simultaneously applying opposite rudder to stop on the original heading and at the original altitude. In most aerobatic aircraft, forward momentum remains nearly constant since the snap is so abrupt and engine thrust is on average directed along the original flight path. Therefore, entry airspeed is recovered nearly concurrently with the return to level flight. Abrupt aft stick motion causes the plane of rotation of the propeller to rotate aft about the aircraft's pitch axis. Since the propeller is spinning clockwise as viewed from inside the aircraft, this results in a gyroscopic precession which pulls the nose of the plane to the right. Thus, in most aircraft, the snap roll accomplished to the right is generally more rapid than to the left.

RECURRENT TRAINING

Many pilots choose straight and level flying over loops, rolls, and spins; aerobatics as a sport or for competition is not for everyone. But the two-dimensional pilot can learn something about the straight and level world of flying from an aerobatic training session. The

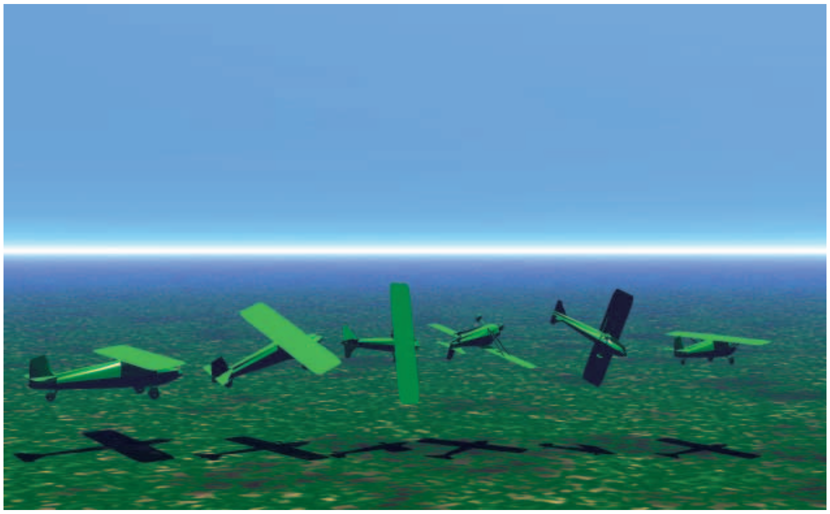

Figure 13. The motion of an aircraft in a snap roll.

average pilot never encounters spin training during the trek from Student to Private through Instrument and Commercial flight ratings, except if he or she obtains certification as an airplane flight instructor. Likewise, inverted flight is rarely encountered. For the two-dimensional pilot, the most comfortable flight condition is one of coordinated flight while experiencing +1 g. If one becomes inverted owing to any inadvertent flight condition (be it natural or man-made) and maintains a comfortable, coordinated flight, one courts disaster because at +1 g from inverted flight the aircraft must fly through the vertical with ever-increasing airspeed. If the ground is not encountered first, the aircraft may exceed V_{NE} (maximum structural airspeed), possibly resulting in structural failure and disintegration. A minimum of recurrent aerobatic flight instruction can reduce the pilot's desire to act only on what feels right and allows the pilot to think through the maneuver and respond appropriately.

SUMMARY

Aerobatics as a sport has a long history and a bright future. Lower-cost higher-performance aircraft are now being designed and built from composite structures. The limits of maneuvers are being pushed at both the designer and pilot ends. Thus, aerobatic pilots now have the opportunity to excel in more precise and more demanding maneuvers than ever before.

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