Since the dawn of human flight, it has been the goal of a few dedicated designers to reduce the airplane to its bare minimum—a pure flying wing. For some, it was a momentary time in their careers. For others, it has been a lifelong pursuit to perfect their vision of the flying wing. Their challenges have been many, and their success and acceptance by the piloting community varied.
France’s Charles Fauvel designed his first glider in 1933, and produced a series of flying wing gliders and motorgliders well into the 1970s. His AV45, with a Nelson H59A engine, used a low taper ratio and vertical fins. It is shown here over Cannes, France. The Northrop Grumman B-2 is the most recent evolution of the flying wing design.
The bird was studied by most aviation pioneers, but it was the Zanonia seed that was the inspiration for the early flying wing designers. This unique seed is a native of Java and is not only a good glider, but also a stable flier. Austrian Igo Etrich used it as a template for his first glider in 1904. Over the next few years he continued his experiments, including man-carrying versions. He eventually added power but gave up on the flying wing concept and added tail feathers. The result was the Taube, which means dove in German, a successful pre-World War I design whose graceful wings still reflected the shape of the Zanonia seed.

John Dunne was an Englishman also inspired by the Zanonia seed’s stability, and he believed the airplane should also be inherently stable. His was probably the first successful powered tailless aircraft, built in 1910. It was actually a swept-wing tailless biplane with a pusher engine and end-plates used as rudders. His designs were reportedly stable and eventually entered limited production before WWI.

After World War I, a few European designers again took up the flying wing challenge. This time their goal was increased performance by eliminating the drag of the tail feathers and long fuselage. Alexander Lippisch’s first flying wing designs were swept-wing gliders that used vertical tip fins as rudders. Unlike some of his counterparts, he felt vertical fins were still required for directional stability. Eventually he adopted a triangular, or delta, shaped wing that incorporated a swept leading edge and straight trailing edge. The main reason for this configuration at that time was to make the root chord long enough to enclose most of the engine and crew. Later on, researchers discovered wing sweep like this was beneficial in reducing drag near the speed of sound.

Though he built several gliders, Lippisch felt flying wings were not suited for soaring due to their lower maximum lift and difficulties in obtaining good handling qualities with high aspect ratio wings. He did feel they were well-suited for high-speed flight, though, and perhaps the most beautiful application of his delta wing concept was on the Concorde.

Lippisch’s views on flying wing gliders were not universally shared, though. France’s Charles Fauvel completed his first flying wing glider in 1933. He didn’t use the wing sweep commonly found on earlier flying wings, but, like Lippisch, he did use a low taper ratio and vertical fins. He...
designed and produced a series of flying wing gliders and motorgliders well into the 1970s. Though not familiar to U.S. aviators, Fauvel's designs are among the most numerous flying wing gliders ever built.

Perhaps the most well-known European flying wings were created by Germany's Walter and Reimar Horten. Like Lippisch's designs, their first flying wings were gliders, but the Hortens were firm believers that the flying wing was a good configuration for sailplanes. They also disagreed with Lippisch's view on needing separate vertical fins for directional control. Their resulting series of swept- and tapered-wing designs are some of the most elegant ever created and represent an aircraft in its absolute minimum form. Their efforts caught the eye of the Luftwaffe, for which they developed a few powered prototypes for evaluation during World War II. After the war, Reimar immigrated to Argentina and continued his flying wing work until his death in 1993.

The Europeans were not the only ones developing flying wing designs. In the United States, Jack Northrop's flying wings of the late 1930s and '40s are the most well-known. His efforts culminated in the building of the YB-49 bomber, although production was ultimately canceled in 1949. Decades later, Northrop Grumman Corp. was finally able to build its flying wing bomber, the B-2, and fortunately, Northrop was able to see the preliminary design of it before he died.

Perhaps the most overlooked U.S. flying wing developer is Waldo Waterman. He got bit by the flying car bug in 1911 through his friend Glenn Curtiss, but it would be 20 years before he was able to pursue his dream. He used the flying wing configuration not because he felt it was superior to a conventional design, but because it was best suited for his vision of a flying car. His first concept was a swept low-wing design called the Whatsit, which flew in 1932. It had some stability problems, which Waterman tried to address by adding a canard, but the aircraft was damaged in an accident. His second flying wing incorporated the lessons learned from the first, and this time it was a swept high-wing configuration. This design, the Arrowplane, apparently flew well and was entered in the Bureau of Air Commerce safe airplane competition in 1934. The goal of the competition was to design a $700 safe airplane. Though it met the contest requirements (except for cost), the more conventional-looking Hammond Model Y won.

Undeterred, Waterman took the Arrowplane wing design and developed a removable three-wheeled pod that became the drivable portion of the vehicle. A Studebaker car engine was installed behind the passengers. It turned a pusher propeller for flight and a transmission that engaged the wheels for ground operation. His new creation, the Arrowbile, later known as the Aerobile, was the first “practical” flying car, and six were made in the late 1930s. Appropriate funding to enter large-scale production was never attained, and after many years of hard work, Waterman finally concluded the flying car concept was too much of a compromise and moved on to other things. Later in life he joined EAA and was involved in converting the Corvair engine for aircraft use.

After WWII, most flying wing design work was done in the glider arena. Al Backstrom designed the Plank in 1954, and Jim Marske has been designing a series of flying wing sailplanes from the late 1950s until the present. Flying wing sailplanes had a small but dedicated group of builders, but it wasn't until the hang glider movement of the early 1970s that flying wing gliders started appearing in significant numbers. The first were flexible-skinned, delta-shaped designs fashioned after the work done by Francis Rogallo in the early 1950s. The performance of those early hang gliders was rather poor, so it wasn't long before new rigid-wing designs appeared, offering greater performance. Some of the first were the Icarus I and
II, designed by a teenager, Taras Kiceniuk, in 1971. It was a swept tailless biplane that looked similar to Dunne’s 1910 aircraft.

Two years later Kiceniuk came out with the Icarus V, a tailless swept-wing monoplane. It was the Icarus II, however, that achieved the greatest fame. In 1975, John Moody attached a MAC 101 engine to his Icarus II and made the first large-scale demonstration of a powered hang glider at EAA Oshkosh 1976. The ultralight era had begun, and soon many flatlanders were taking to the skies in powered versions of the Icarus II and a similar design called the Easy Riser.

Eventually, flying wing ultralights gave way to conventional designs, with the exception of the Mitchell Wing. Originally designed by Don Mitchell in 1976 as a hang glider, it had a slightly swept- and tapered-wing planform similar to Lippisch’s early gliders. It didn’t take long before a tricycle-gear power pod was designed for it, and like the tailless Easy Riser, it also became a popular design in the early days of the ultralight movement.

TECHNICAL OVERVIEW
At first glance, it seems mysterious that a flying wing can be stable in flight. After all, almost all airplanes have either a horizontal tail or a canard, so how can they fly without a tail?

All naturally stable airplanes, no matter what their configuration, follow the same aerodynamic principles. An airplane is considered stable in pitch (has a positive static margin) as long as its center of gravity (CG) is located ahead of the neutral point. Briefly, stability is the location of the neutral point along the wing’s mean aerodynamic chord (MAC) where a change in angle of attack will not result in any change in pitching moment.

A pilot flying with the CG at this neutral point location would find that the airplane would not try to return to the trimmed airspeed if disturbed in pitch, either by a gust or control stick movement, but instead it would try to stay at the resulting new angle of attack. This would require constant pilot attention and would be annoying at best and dangerous or deadly at worst. Flight testing by the National Advisory Committee for Aeronautics (NACA) during the 1940s revealed that when power effects were included, airplanes with a static margin of at least 8 percent had good flying qualities, and anything less than 3 percent MAC was considered dangerous. For comparison, the Horten brothers found their flying wings had the best handling characteristics with a static margin of 5 percent to 7 percent MAC.

The fuselage shape, propeller location, and vertical CG position impact the neutral point location for all configu-
rations, but for this discussion we are only going to focus on the wing and tail's contribution. The neutral point for a conventional design largely depends on the horizontal tail's size and distance from the wing and on the rate of change of the wing's downwash at the tail. Increasing the tail's size or distance from the wing results in the neutral point moving farther aft.

The lack of a horizontal tail on a flying wing means that its neutral point will be located at the wing's aerodynamic center, the point along the MAC where its pitching moment is constant. For most airfoils this is usually between 24 percent and 26 percent MAC. A wing's aspect ratio, sweep, and taper also impact this location to some extent. Sufficient wind tunnel data to assess these variables is rather limited, so I used a computer program available from www.DigitalAerodynamics.com to explore their impact. The results should not be used for design purposes, but rather to show the general trends of a flying wing's neutral point location as affected by sweep, taper and endplates.

Figure 2 indicates that a moderate amount of negative (forward) or positive (aft) sweep on a tapered wing does not impact the neutral point location much. This is not the case with a constant-chord wing, where the neutral point as a percentage of the MAC moves forward with aft sweep. Often endplates are used on swept wings to act as vertical fins. As the figure shows, their presence helps reduce this shift in the neutral point position with wing sweep on constant-chord wings.

Spanwise, a wing's MAC is located outboard about 44 percent to 50 percent of a wing's semi-span. You can see this in Figure 3, where the MAC is shown for several flying wing planforms. I projected their neutral points from the MAC to the wing's centerline. Since the CG needs to be ahead of this point, Figure 3 also gives a rough indication of the CG location. The pilot and engine (if powered) make up a large percentage of a small airplane's total weight, so their placement greatly impacts the ultimate CG location.

Locating the pilot and engine too far from the neutral point can make it difficult to achieve the desired CG location, so working the weight and balance of a proposed flying wing design is important at the layout stage. This is especially true for the pilot's location, since the pilot's visibility is most important. The plank or straight-leading-edge planform (as used by Marske) puts the pilot right near the leading edge. The pilots on swept-wing designs are often further aft, which can hinder their visibility. Often powered swept flying wings have an aft-mounted pusher installation, which allows the pilot to be located in a more favorable forward position.

Locating the CG ahead of the neutral point puts some demands on the design or selection of flying wing airfoils. Figure 4 shows the main forces acting on a stable flying wing glider. Looking at the figure, you can see that with the lift being applied aft of the CG, the wing would want to pitch nose-down. We need some kind of nose-up pitching moment to prevent this from happening. There are a couple of ways to achieve this, depending on the planform selected. An unswept wing requires an airfoil that generates a nose-up pitching moment to overcome the nose-down moment created by the wing's lift being located aft of the CG. The amount of pitching moment required can be estimated by the following equation:

\[
l = \frac{C_l}{C_m}
\]
CMo + CMe = S.M. x CL
Where:
S.M. = static margin (no propeller effects)
CMO = wing pitching moment coefficient
CL = wing lift coefficient
CME = elevator pitching moment coefficient

The equation shows the amount of pitching moment needed depends on the static margin and design lift coefficient. For the lowest drag, we don’t want any elevator deflection, so for the moment we’re going to ignore the elevator pitching moment term. An airfoil can be made to have a positive pitching moment by turning up (reflexing) the aft portion of the airfoil as shown in Figure 4. This airfoil is one Fauvel used on some of his sailplanes, and it has a positive pitching moment of about 0.035. Assuming a static margin of 5 percent MAC, a plank flying wing using the Fauvel airfoil would have an approximate trim lift coefficient (C_L) of 0.70 (0.035 divided by 0.05). Flying at any other C_L would require some amount of elevator deflection (either up or down).

If we increased the static margin to 10 percent MAC by moving the CG forward, the trim C_L would be reduced to 0.35. The change in pitching moment due to a 25 percent to 30 percent chord elevator is about 0.01 per degree of deflection, so getting back to a trim C_L of 0.70 would require at least 3.5 degrees of up elevator. That assumes the aircraft has a full-span elevator, which is rarely the case on flying wings, so a partial-span elevator would require even more deflection to keep the flying wing in trim. Moving the CG forward would require even more up elevator, which would result in more drag. This can result in a rather minimum useful CG range (compared to a conventional airplane) and is one of the main drawbacks of using an unswept flying wing planform.

The swept flying wing designer has more options. Wing twist combined with zero or positive pitching moment airfoils can be used to allow the wing to fly at a desired
trim $C_L$ without any elevator deflection. Calculating the amount of twist needed is pretty tedious, so commercially available computer programs make the job much easier.

Northrop’s early flying wings used symmetrical airfoils (which have zero pitching moment) and wing twist as needed to obtain the desired trim $C_L$. The Hortens also used a symmetrical airfoil at the wingtip, but at the root they used their own custom airfoils that had some camber and a little reflex to reduce the pitching moment to zero.

The twist on conventional wings is often linear, meaning it twists at a constant rate along the span. This is not necessarily desirable for swept flying wings, especially if no vertical fins are used for directional stability. That’s because of the adverse yaw caused when deflecting ailerons for roll. Eliminating the vertical fin means some other way must be used to overcome this problem. The Hortens solved this by concentrating most of the twist in the outer portion of the wing, which results in a bell-shaped lift distribution. They found that that using such a distribution essentially eliminated the adverse yaw problem. Another option is to use vertical tip fins. A benefit of using tip fins is that they act as endplates and increase the effective wingspan, thereby lowering the drag due to lift. Often a portion of the fin is hinged to move outboard only to act as a drag rudder. By inclining the hinge line aft, the outward deflecting rudder experiences a downward force at the wingtip and thereby allows coordinated turns to be made with rudder alone.

The stall characteristics of an aft swept wing are generally poor—especially if the wing is tapered. Plank or swept-forward wing designs tend to stall first at the root while leaving the ailerons unstalled, and that is one of
the major plusses for that configuration. Twist on a swept wing does help reduce the tip-stalling tendency, but there is another potentially dangerous characteristic that shouldn’t be overlooked. Back in the 1940s, the NACA compiled its wind tunnel data for wings with varying sweep and taper. The data showed some swept wings had a stable pitch break, where the wing had an increasing nose-down pitching moment in the stall regime, but others did not. The researchers found a correlation between sweep, aspect ratio, and stable stalling characteristics. The results of their study are shown in Figure 5, where sweep and aspect ratio combinations below and to the left of the curves had stable stall breaks.

One particular swept flying design caused somewhat of a stir back in the 1970s—the Kasperwing. The story began in Canada in the 1950s when Stefan Brochocki designed the BKB-1, a swept, constant-chord sailplane that used endplates for directional control. He was joined by Fred Bodek, who helped with some of the detail design, and Witold Kasper, who also helped with the construction. The glider was flown in 1959 and eventually ended up in Seattle with Kasper, who had gone to work for Boeing. Kasper found during flight testing that the sailplane had some peculiar characteristics. First, he could make the wing tumble at will. Second, he could fly it in a post-stall mode in a parachute-like decent. Kasper theorized that a spanwise vortex was forming along the top of the wing during this phase of flight.

This Kasperwing was named grand champion ultralight at EAA AirVenture in 1995. It was built and flown by the late Steve Pinkham.
Kasper later built a new version of the glider that differed from the original by incorporating triangular-shaped trailing edge extensions at the wingtips. These extensions were flexed to allow the glider to be in trim at the desired flight condition (instead of using wing twist like the original version). Kasper eventually built a powered version that included some upper surface flaps intended to help control the spanwise vortex while flying in a deep stall. This aircraft was damaged on its first flight attempt. He received three patents for his vortex lift concepts, but I could find no independent research to validate the theories Kasper presented in his patents or book. In the 1980s Kasper worked with Cascade Ultralights to design a weight-shift ultralight using the planform of his later glider. If nothing else, Kasper discovered that a swept, constant-chord flying wing equipped with endplates has controllable post-stall flight characteristics.

Flying wings are a niche-type aircraft that, within its limitations, may be an ideal solution for certain applications. Those interested in pursuing a flying-wing design should plan on doing their homework on the subject and proceed with extreme caution.

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