New twist on an old wing theory

An improved understanding of the way wing twist affects aircraft drag has led to new technology that could yield substantial fuel and cost savings

A newly developed mathematical solution to a well-established theory of lifting wings has led to the development of improved technology that can significantly reduce the drag acting on an aircraft in subsonic flight. This drag reduction is accomplished through twisting of the wing, or some portion of the wing, in a special manner that depends on wing shape and aircraft operating conditions.

Of course, twisting the wing of an aircraft is not new. Only eight years after the first unpowered human flight by Otto Lilienthal in 1891, and more than four years before their first powered flight in 1903, the Wright brothers began experimenting with wing twist as a means of controlling the rolling motion of an aircraft. Many hours of watching birds in flight led Wilbur Wright to conclude that birds "regain their lateral balance when partly overturned by a gust of wind, by a torsion of the tips of the wings." This was one of the most important discoveries in aviation history.

Less than two decades later, Ludwig Prandtl published the first theory of lifting-wing, which allowed us to mathematically analyze and predict the effects of wing twist. In the 1920s, Hermann Glauert discovered from Prandtl's theory that twisting the two sides of a wing in a symmetric manner could affect the drag acting on the wing. Under some conditions, however, wing twist was found to reduce the drag, and for other conditions twist would increase it.

Using Prandtl's lifting-line theory, the elliptic wing of the WW II British Spitfire was designed to minimize induced drag, but was very expensive to manufacture. A newly developed solution to Prandtl's theory has shown that, with proper twist implementation, a wing of any planform shape can be designed to produce the same minimum induced drag as an elliptic wing.

The foundation of the recent technology improvement is a new analytical solution to Prandtl's theory that allows us to predict and maintain the proper distribution and amount of wing twist, which is necessary to minimize an important component of aircraft drag. With the modern sensors and flight computers used on most aircraft today, this new mathematical so-

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lution can be incorporated in an active feedback control system to provide the capability for adjusting wing twist on-the-fly, so that minimum possible drag is always maintained as the environment and operating conditions change.

This technology may eventually become one small part of a completely new generation of "morphing" aircraft that can automatically adapt to changing environmental conditions and mission requirements.

Understanding lift and drag

The vortices shed from the lifting wing of an aircraft in flight have a profound effect on the lift and drag produced on the wing. The pressure difference between the upper and lower surfaces of the wing is reduced near the wingtips, because air from the high-pressure region below the wing spills outward, around the wingtip, and back inward toward the low-pressure region above the wing.

Thus, as air flows over a wing, the air below the wing moves outward toward the wingtip, and the air above the wing moves inward toward the root. Where the flows near the upper and lower surfaces recombine at the trailing edge, the difference in spanwise velocity generates a trailing vortex wake. The vortex wake generated on each semispan of the wing rolls up about an axis trailing slightly inboard from each wingtip to form two large vortices, one trailing aft of each wingtip. These are commonly referred to as wingtip vortices, and the downward velocity induced between the wingtip vortices is called downwash. This downwash reduces the lift developed by the wing and creates a component of drag that is commonly known as induced drag. Aerodynamicists have studied analytical methods for predicting and reducing induced drag for most of the past century.

The classical lifting-line theory developed by Ludwig Prandtl and published in 1918 was the first analytical method to satisfactorily predict the performance of a lifting wing. Moreover, until the development of the digital computer in the early 1960s, it was the only analytical tool available for wing design. Early comparisons between results predicted from lifting-line theory and experimental data showed remarkable agreement. Even with modern computational fluid dynamics (CFD), it is difficult to improve on the induced drag predictions derived from lifting-line theory.

Prandtl's lifting-line theory is still widely used today, because it has the significant advantage of yielding closed-form solutions. Such solutions not only are many orders of magnitude faster to evaluate than modern CFD solutions, but also provide greater insight into how wing design parameters affect wing performance. Closed-form solutions are also well suited to the analytical methods used for design optimization and control.

The first closed-form solution to be obtained from lifting-line theory showed that induced drag could be minimized by using an untwisted wing of elliptic planform. Several aircraft have been designed and built with such wings—the best known is the WW II British Spitfire. While an untwisted elliptic wing produces minimum possible induced drag, it is much more expensive to manufacture than a simple rectangular wing.

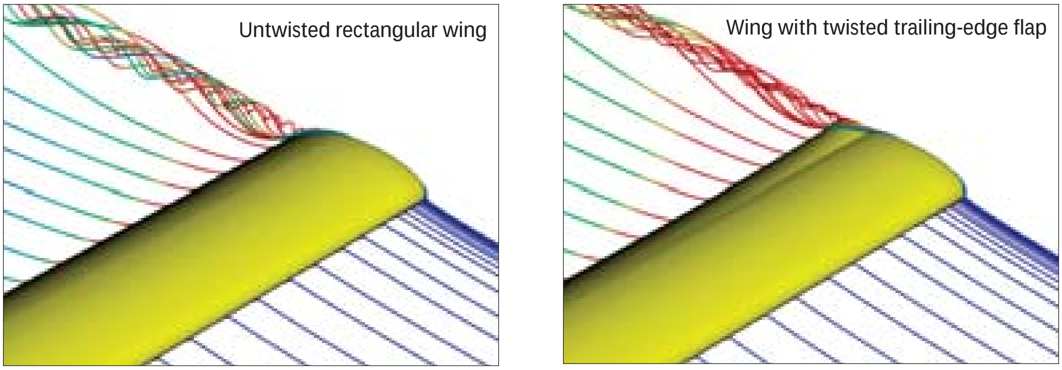
A later analytical solution to Prandtl's theory showed that, while an untwisted tapered wing produces more induced drag than an elliptic wing, it produces significantly less induced drag than an untwisted rectangular wing of the same aspect ratio. The solution showed that, for untwisted wings with linear taper, optimum taper occurs when the tip chord is about 35-40% of the root chord.

This result, first published by the famous English aerodynamicist Hermann Glauert in 1926, has sometimes led to the conclusion that a tapered wing with a tip-to-root chord ratio of about 0.4 always produces significantly less induced drag than a rectangular wing of the same planform area and aspect ratio developing the same lift. As a consequence, tapered wings have long been used as a means of reducing induced drag. The results first presented by Glauert can be misleading unless one bears in mind that these results apply only to the case of wings with no twist. The choice of an untwisted wing is quite arbitrary and is not the choice that produces minimum induced drag on a lifting wing, except for the special case of an elliptic planform.

A new solution

A new closed-form solution that includes spanwise variation in wing twist has recently been developed from Prandtl's lifting-line theory (see http://twisteron.usu.edu). This solution shows that the conclusions sometimes reached from the results first published by Glauert are erroneous. It shows that an unswept wing of any planform shape can be designed with proper twist implementation to produce less induced drag than any tapered wing with no twist. This analytical lifting-line solution has been validated by comparison with CFD results and was found to be in excellent agreement with this modern computational method.

The twist that is required to minimize induced drag on a wing of any planform shape


Untwisted rectangular wing

Wing with twisted trailing-edge flap

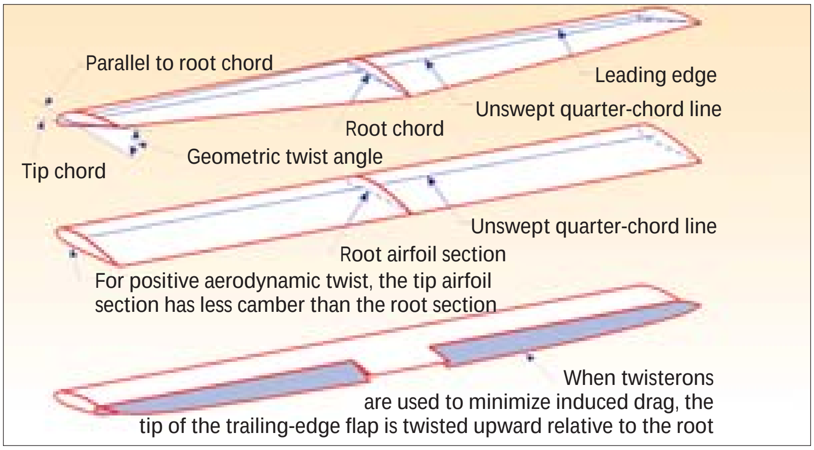
Modern CFD computations show that Prandtl's lifting-line theory accurately predicts the induced drag acting on both untwisted and twisted wings. Here the color of the streamlines indicates the magnitude of the flow vorticity, with blue representing zero vorticity and red signifying maximum vorticity.

can be implemented in several ways. The method most commonly used is called geometric twist. When pure geometric twist is employed, the wing cross section at each location along the wingspan has an airfoil shape that is geometrically similar to that of the root cross section. However, the outboard airfoil sections are rotated relative to the root section. To minimize induced drag on a rectangular wing, the trailing edge of the outboard sections must be rotated upward relative to the inboard sections, to produce a continuously decreasing local angle of attack.

Another method sometimes used to effectively twist a wing is called aerodynamic twist. For a wing with pure aerodynamic twist, the chord line of the airfoil cross section at each location along the span of the wing is exactly parallel with the chord line of the root airfoil section. The effective twist is achieved through a smooth variation in the airfoil section geometry between the root and the tip of the wing. If aerodynamic twist is to be used to minimize induced drag on a rectangular wing, the airfoil section camber must be progressively reduced as the spanwise coordinate moves outboard from the root toward the wingtip.

Either geometric or aerodynamic twist can easily be incorporated in the design of a wing, if the desired twist distribution is fixed and does not change with operating conditions. To minimize induced drag, the geometric and/or aerodynamic twist must vary along the span of the wing in a special way that depends on the planform shape of the wing. However, the amount of wing twist required to minimize induced drag is a strong function of gross weight, altitude, airspeed, and normal acceleration. With proper twist implementation, a wing of any planform shape can be designed to produce the same minimum induced drag as an elliptic wing of the same aspect ratio, operating at the same conditions. Such twist-optimized wings are much simpler and less costly to manufacture than an elliptic wing.

Proper twist implementation can reduce the induced drag acting on a lifting wing by as much as 15%. At the airspeed that results in minimum overall drag, the induced drag is typically about 50% of the total drag, and at much lower airspeeds, the induced drag can dominate the total drag. Thus, implementation of optimum twist can significantly reduce the total drag on an airplane. However, if fixed twist alone is implemented, the wing can be optimized for only one design operating condition. This means that, if the airplane is to operate over a wide range of airspeed, altitude, and/or gross weight, the implemented fixed twist must be a compromise for the range of operating conditions that will be encountered during different mission phases.



For positive aerodynamic twist, the tip airfoil section has less camber than the root section

When twisterons are used to minimize induced drag, the tip of the trailing-edge flap is twisted upward relative to the root

Methods for implementing the wing twist needed to minimize induced drag include geometric twist, aerodynamic twist, and twisting full-span trailing-edge flaps called twisterons.

Twisterons

To avoid the limitations associated with minimizing induced drag by means of fixed wing twist, it is possible to implement the twist distribution needed to minimize induced drag by using full-span trailing-edge flaps that can be twisted along their length to produce a continuous spanwise variation in wing twist. These control surfaces, called twisterons, can also be deflected symmetrically as flaps and/or asymmetrically as ailerons to generate high lift and provide roll control.

This prototype aircraft has operational twisterons; the wingtip vortex responsible for induced drag is shown in red.

The advantage of using twisterons to establish the wing twist needed to minimize induced drag is that the twist can be varied, to maintain minimum induced drag over a wide range of operating conditions. The aircraft can be fitted with sensors to determine gross weight, normal acceleration, air density, and airspeed. The sensor outputs can be used in an active feedback control system to maintain minimum induced drag as the operating conditions change. Because most of the parameters that affect optimum wing twist also affect the required elevator deflection, the induced drag can be nearly minimized by properly linking the twisteron deflection to the elevator deflection.

Another advantage of using twisterons to minimize the induced drag produced by the main wing of an airplane is a reduction in the up-elevator deflection required to trim the aircraft at low airspeeds. When twisteron deflection is varied with airspeed so as to maintain minimum induced drag, an increasing nose-up pitching moment is produced by the twisting wing as airspeed is reduced and twisteron deflection is increased. This reduces the negative lift on an aft horizontal stabilizer, which is typically required at low airspeeds, and provides additional savings in drag over that realized for the wing alone.

Using twisterons on transport aircraft could result in significant fuel savings. Here the right-hand wingtip vortex is outlined in the cloud below and aft of the lead aircraft.

UAV experiment

Students at Utah State University have designed, built, and flown an experimental UAV with operational twisterons. Designed for 7-*g* maneuvers, this electric-powered aircraft has a wingspan of 10 ft, a gross weight of 35 lb, and a top speed of 100 mph.

During the aircraft's design and development, another beneficial side effect of twisteron deflection was discovered. The change in the wingtip vortices that is brought about by twisteron deflection produces a change in the downwash induced on an aft tail, which further reduces the elevator deflection needed to trim the aircraft over a wide range of airspeed, gross weight, and normal acceleration. This results in a further reduction in total aircraft drag, beyond that provided directly by the twisterons. For a prototype created by Utah State University, this reduced the total drag by as much as 20% during some mission phases.

Potential applications

The Air Force is currently funding a multidisciplinary research program to support development of the next generation of intelligence, surveillance, and reconnaissance (ISR) aircraft, including high-altitude, long-endurance UAVs. Because of endurance requirements (possibly 24-48 hr), these ISR aircraft will require a very high vehicle fuel fraction and must operate efficiently over a wide range of gross weight, altitude, and airspeed. At the maximum-endurance airspeed, induced drag acting on an aircraft is typically more than 50% of the total drag. Thus, future ISR aircraft could benefit significantly from twisting trailing-edge flaps, which could maintain minimum induced drag during all phases of operation.

Perhaps the greatest potential benefit could come from the use of twisterons on transport aircraft. A large jet transport weighing about 750,000 lb will typically burn more than 75 gal of fuel per minute, and half of its total weight can be fuel. In 2004, according to the FAA, U.S. civil aviation aircraft are expected to consume more than 24 billion gal of jet fuel. With consumption of this magnitude, a fuel savings of even a fraction of a percent is very significant. Twisterons have the potential for reducing fuel consumption for a typical transport aircraft by approximately 2.5%.