UNDERSTANDING WINGLETS TECHNOLOGY

From the original idea of Fred George (B/CA)

Properly designed winglets help tame wingtip vortices drag & improve overall performance despite arguments to the contrary.

Aircraft engineers would have us believe that aerodynamics is a mature science. If that were true, then pro and anti-winglet advocates might no be so strongly opposed. NASA' s Richard T. Whitcomb invented these nearly vertical wingtip extensions in the early 1970s as a means by which wing lift-to-drag performance could be increased.

Indeed, Whitcomb's research in 1976 indicated that winglets could reduce induced drag by 20 percent, resulting in about nine percent better lift-to-drag performance at 0.78 Mach for a specific wing loading. Whitcomb concluded that winglets produced twice the benefit of a wingtip extension with the equivalent area. As a result, winglets imposed much less weight and drag penalty than increasing wingspan.

Far from the simple wing end plates patented by Lanchester in 1897, Whitcomb's early 1970s-vintage winglets were carefully designed airfoils that harnessed the energy of the wingtip vortex.

Many of the original design principles still are used in the latest generation of winglets.

Whitcomb has attracted an impressive cadre of business and commuter aircraft manufacturers, as well as after-market modifiers, in the two decades since he first published his winglet research findings. Canadair, Gulfstream and Learjet, along with Israel Aircraft, Pilatus and Raytheon, have decided to fit winglets to their business or commuter aircraft. Each

of the these firms cites better wing performance gains than could be achieved by other types of wing modifications for the same weight and drag penalties.

Seattle-based Aviation Partners Inc. has developed winglets for the Gulfstream II that can boost range by as much as seven percent, according to the firm (October 1996, page 96). API claims that its fine-tuned winglets can increase the specific range of many other types of aircraft, including some large jet transports such as the Airbus 330 and 340, which already have small winglets as part of their original design.

But anti-winglet advocates, such as Cessna and Dassault, remain opposed to such non-traditional modifications to their planar wing designs. They claim that a properly designed wing needs no such devices and that it offers better performance over a wide range of speed, load and lift conditions.

Traditional aerodynamic design equations and computer codes were written for planar wing forms. Some of the debate over winglets may result from the relative lack of industry-standard, three-dimensional, wing design tools that can predict what effect winglets will have on wing performance, according to Fassi Kafyeke, Ph.D., Bombardier's manager of advanced aerodynamics. As a result, a large part of winglet design development still involves time-consuming wind tunnel and flight test trials, unless a firm has access to specialized aerodynamic computer software.

The popularity of winglets, though, continues to grow. This report will focus on why winglets work and some of the design considerations.

TWO DIMENSIONAL AIRFOIL

Bernoulli taught us that the total pressure of an incompressible fluid is the sum of the static pressure and the dynamic pressure. The laws of kinetic energy govern dynamic pressure. It varies with the square of the fluid velocity. As a result, the static pressure varies inversely as a function of total pressure minus the square of the fluid velocity. Plainly put, if you accelerate the fluid, the static pressure drops.

If the fluid is air and the means by which the fluid is accelerated is an airfoil, the side on which the fluid travels the greatest distance will have the highest velocity and lowest static pressure. The difference in the velocity on each side of the airfoil determines the static pressure differential. That is what generates lift.

The efficiency with which an airfoil generates lift is known as the lift coefficient. The actual lift force is a function of the lift coefficient, air velocity, air density and effective wing area.

Varying the airfoil's angle of attack has a direct bearing on lift coefficient because it changes the relative distance the air must travel over the upper and lower surfaces. This results in a change in the relative velocities over the two surfaces and thus a change in lift coefficient.

Lift coefficient increases almost directly with an increase in angle of attack up to a maximum point. Any increase in angle of attack beyond that point causes air flow separation on the upper surface and total loss-of-lift coefficient. Pilots know this point as the stalling angle of attack.

THREE-DIMENSIONAL WING

Designing a wing would be duck-soup simple if it were a two-dimensional airfoil. But a wing has a finite length that ends at the wingtip. The difference in air pressure between the lower and upper surfaces of a wing causes the air to escape around the wingtip, which reduces the available lift.

The motion of the air rushing around the wingtip coupled with the velocity of the airflow through which the wing is flying causes a vortex to form near the wingtip, as shown in Figure 1. The tip vortices cause upwash and downwash air currents that alter the direction of the free stream flow around the wing.

WING THREE-DIMENSIONAL FLOW
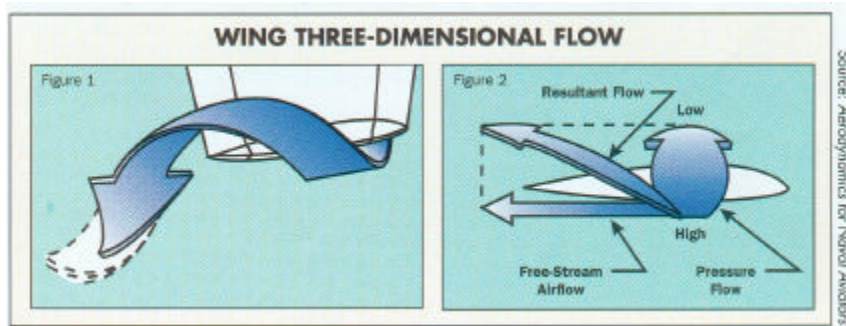
They induce a decrease in the angle of attack of the average relative wind flowing around the wing.

This has two undesirable byproducts, as shown in Figure 1. First, the wing generates lift perpendicular to the average relative wind. This diverts the lift vector away from the desired direction, which is perpendicular to the free stream. Induced angle of attack makes it necessary for the wing to generate more total lift than a theoretically, two-dimensional airfoil to produce the same effective lift.

Second, drag is induced. Diverting the lift vector causes a drag component to be generated that is parallel to the free stream airflow. The drag component varies as the cosine of the angle between total lift and effective lift vectors, as shown in Figure 2.

As a tip vortex becomes more intense, it induces more of a shift in the average relative wind. The greater the induced angle of attack, the more effective lift is reduced and induced drag is increased. And, if an aircraft gains weight, its wing has to operate at a higher angle of attack to generate more lift. That, too, increases tip vortex intensity. If only you could get rid of those troublesome tip vortices.

## WING SPAN, ASPECT RATIO, TAPER RATIO

The upwash/downwash effect of the tip vortices has its greatest influence on the wing section closest to the tip. The tip vortex has little effect on the average relative wind of the wing sections far inboard from the wingtip.

If you push the wingtips outboard, a smaller section of the wing will be affected by the tip vortices. That reduces the upwash/downwash effect which diminishes the induced angle of attack of the

average relative wind over the whole wing. It follows that if span were infinite, induced drag would be zero because there would be no wingtip; therefore, no tip vortex to create induced drag. In addition, without the tip vortices inducing a shift in the angle of the average relative wind, the wing's lift coefficient varies more directly with the wing's angle of attack relative to the free stream. That means the wing's lift coefficient will increase more sharply with increases in angle of attack, and it will produce its maximum lift coefficient at a lower angle of attack. As a result, a wing with an infinitely long span that has no tip vortices actually stalls at a lower angle of attack than a short wing that has intense tip vortices, as shown in Figure 3.

Induced drag, however, accounts for only about 40 percent of an airplane's total drag. The rest is parasitic drag and compressibility drag. A very large, long wing, one with almost an infinite span-to-chord aspect ratio, would have enormous parasitic drag. But, if the wing's span, chord and airfoil sections are scaled down to an appropriate size, the tip vortices still affect only a small percentage of the wing area.

Figure 3 **EFFECT OF ASPECT RATIO ON LIFT COEFFICIENT**

A high aspect ratio wing can produce almost twice as much lift as a low aspect ratio wing. A high aspect ratio wing, therefore, can be about half the size of a low aspect ratio wing and produce the same lift.
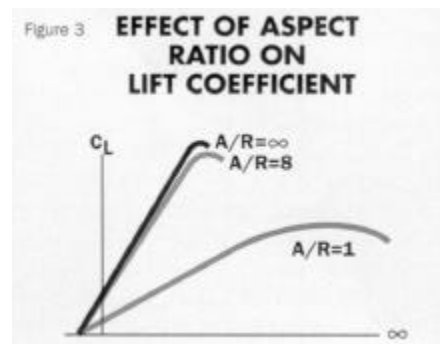
The desire for high aspect ratio and optimum aerodynamic efficiency must be balanced against other factors, such as material-strength-to-weight ratios, overall weight of the wing, internal fuel capacity and parasitic drag. For those reasons, the best aspect ratio for the average business aircraft wing might be seven or eight to one. For instance, the aspect ratios for the Hawker 800XP, Falcon 2000 and Beechjet 400A are 7.1, 7.6 and 7.8, respectively.

Certain very-long-range missions require higher aspect ratio wings. The Global Express, for example, has an 8.6 aspect ratio. Some aircraft have much lower aspect ratios because the designers modified a wing they inherited from an earlier model. The Learjet 35/36 series, for example, has a 6.2 aspect ratio.

Some aircraft have high aspect ratio wings, but the weight they gained during development caused excessive wing loading. The Challenger 600, for example, has an 8.5 aspect ratio, but ended up with a 91.3 pound/square foot wing loading, resulting in excessive drag due to increased angle of attack, higher lift coefficient and stronger tip vortices.

The tip-to-root-chord-length taper ratio also has an influence on induced drag. Prandtl, an early 20th century aerodynamic engineer, found that the lowest induced drag occurred when a wing had an elliptical load distribution. This theory had a strong influence on the wing design of the Supermarine Spitfire and Lockheed Constellation.

Such graceful curves, though, greatly increase manufacturing complexity. According to Daniel P. Raymer, a Rand Corp. consultant and aeronautical engineer, if a trapezoid-shaped wing has a 0.45 taper ratio, its spanwise loading will be very close to the ideal elliptical load distribution. This results in less-intense tip vortices and lower induced drag.

WINGLET EFFECTS

Stretching wingspan or increasing aspect ratio certainly reduces induced drag. Designers, though, have to balance the benefits of less induced drag against the costs of structural weight increases, more parasitic drag or cost considerations. For those reasons, they've often fitted their aircraft with winglets during the last two decades. The trend is increasing.

Winglets work because they efficiently produce aerodynamic side forces that divert the inflow of air from the tip vortex. That takes a rather sophisticated small wing, one that is sized, shaped, cambered and canted for a specific application and mounted on the wingtip where it will produce the most benefit and the least drag. A simple, large end plate would block the vortex, but an increase in span produces a much better lift-to-drag improvement because it is a more-efficient lifting surface than a flat sheet of metal or composite.

The winglet has a tip, just like a wing, so it also produces a tip vortex, albeit a much weaker one. The winglet's tip vortex is located far above the airflow over the wing, thus it has little influence on the airflow over the main wing. Whitcomb said that winglets might be termed "vortex diffusers."

Whitcomb optimized his original winglet design for the cruise speed and lift coefficient of a typical jet transport. He fitted the wingtip with a comparatively small lower winglet located near the wingtip leading edge and a much larger upper winglet farther aft. Whitcomb later concluded that the upper/lower winglet combination produced very small reductions in induced drag compared to the upper winglet alone and that it complicated ground clearance problems. Very few aircraft, as a result, presently use the upper/ lower winglet combination. Only upper winglets have been fitted to business aircraft, with virtually no exceptions.

Whitcomb's winglets were designed for transonic cruise speeds. Jet aircraft typically cruise at or above the critical Mach number, the free stream speed at which local airflow over some section of the aircraft, usually the wing, first reaches the speed of sound. At the critical Mach number, a shock wave forms as the air decelerates to subsonic speed aft of the point of maximum chord thickness.

The shock wave intensifies as the supersonic to subsonic speed change becomes more abrupt.

A strong shock wave

CLASSIC WINGLET DESIGN

Figure 4

Tip-to-Root Chord Taper Ratio = 0.30

Height = 0.10 to 0.20 Wing Semi-Span

Lower Winglet
• Ground Clearance Problems
• Only Benefit at High Lift Conditions

• Winglet Leading Edge at or Aft of Wingtip Max Thickness to Chord (T/C) Point
• Winglet T/C = 0.08 Wingtip T/C
• Winglet Camber Much Greater Than Wingtip Camber
• Winglet Has Higher Critical Mach Number

Angle of Incidence = -4°

• Negative Angle of Incidence for Tip Vortex Induced Local Flow

causes turbulent airflow separation behind it, thereby substantially increasing drag. (Supercritical wings are designed to maintain supersonic airflow over a large part of the chord. This moves the shock wave aft and weakens its intensity.)

Whitcomb positioned the leading edge of the upper winglet at the point of maximum chord thickness at the wingtip. The object was to prevent the increased velocity over the winglet's inside surface from boosting the speed of the high velocity air over the forward section of the upper surface of the wing near the tip. That prevented the winglet from reinforcing the shock wave of the wing section near the tip.

Experimentation indicated that the winglet's trailing edge should be positioned near the wing's trailing edge for maximum effectiveness.

The winglet has a pronounced effect on wing bending moment. The winglet produces an inward load as it diverts the tip vortex. In addition, the wingtip section produces more lift, which increases the bending moment. The combination of the two forces greatly increases the overall bending moment of the wing, which becomes a major factor in integrating winglets into a wing's design.

Increasing the height of the winglet produces more of a decrease in tip vortex. However, the greater loads imposed upon the wing result in a compromise between aerodynamic and structural engineering. Balancing the two factors results in a typical winglet height of about 10 to 20 percent of the wing semi-span.

With winglets, the outboard sections of the wing produce more lift, which changes the wing's root-to-chord elliptical load distribution. Whitcomb found the elliptical load distribution could be preserved if the winglet had approximately a 0.3 taper ratio and a side force loading about the same as the wing loading.

The choice of winglet airfoil has a strong influence on shock wave drag. The winglet's critical Mach number should be higher than the wing chord section to minimize its shock wave and prevent it or
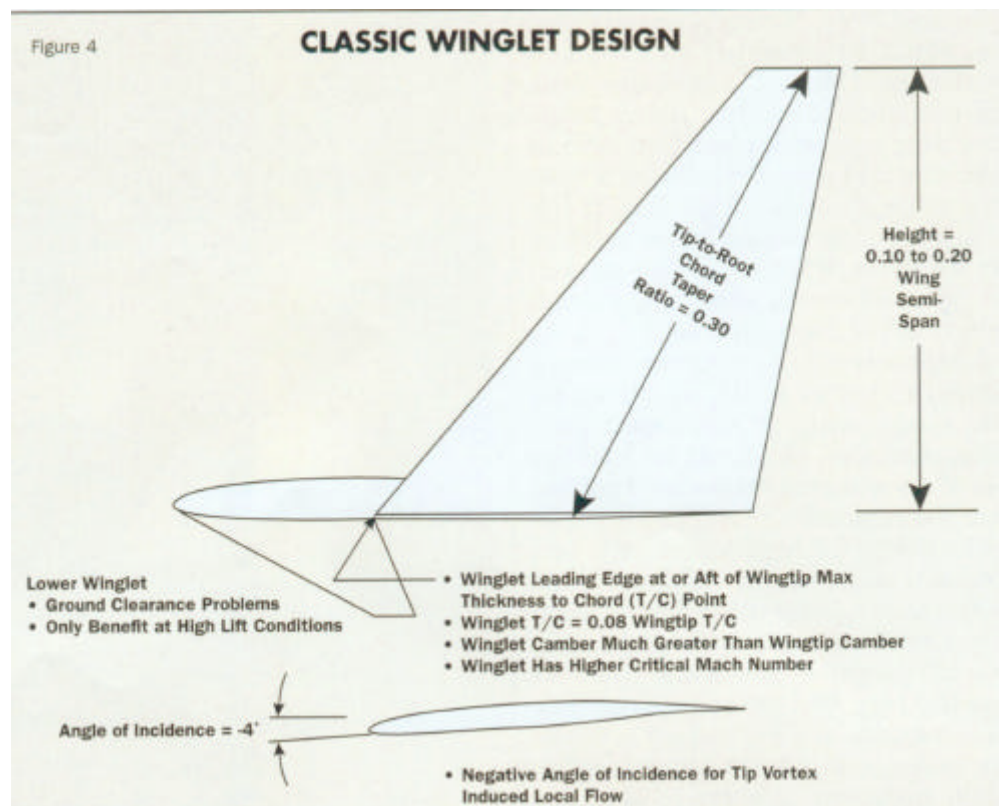
reduce it from reinforcing the shock wave of the main wing near the tip. Whitcomb chose an airfoil with significantly more camber than the wing, but with an eight percent thickness-to-chord ratio.

This design provided the best tradeoff in low- and high-speed lift characteristics, along with a reasonably light weight structure. It had a somewhat higher critical Mach number than the wing section near the tip.

Whitcomb's winglets were toed out at the root, thus giving them negative incidence to the free stream. However, the tip vortex induces a positive angle of attack over the winglet. The side force vector, being perpendicular to the average relative wind over the winglet, actually provided a slight thrust component. Kafyeke's term for this forward component is "negative drag."

Trial and error experimentation indicated that a four degree toe out was optimum for Whitcomb's tests. The tip vortex is

According to Aviation Partner's Inc., some benefits of spiroid technology are: 10.5 percent lift/drag improvement; elimination of wingtip vortex concentration; improved climb performance; and increased operational safety and efficiency.

strongest near the winglet root, thus it induces more angle of attack at the root than the tip. That enabled Whitcomb to build a winglet with no geometric twist and achieve the desired, gradual reduction in lift toward the tip of the winglet.

Giving the winglet a slight cant angle or dihedral also improves its aerodynamics. Whitcomb found that this reduced the interference at the junction of the winglet and wingtip at transonic speeds and that it pushed the tip vortex outboard, thus further reducing nearby vortex intensity. The optimum cant angle for Whitcomb's experiment was 15 degrees.

Whitcomb research showed that carefully designed winglets could improve the lift-to-drag ratio of the wing by nine percent, compared to four percent for a span increase of equivalent area.

WINGLETS ON BUSINESS AIRCRAFT

We do not have enough space to cover each business aircraft winglet design. Instead, we'll focus on a few trendsetters.

Learjet was the first firm to install winglets on a business aircraft, and the results were impressive. Just over a year after Whitcomb first published his findings, Learjet's chief test pilot, Peter T. Reynolds, started test flying a Learjet fitted with the "Longhorn" wing, which was a 20-series Learjet wing from which the tip tanks were removed and to which six-foot wing extensions and winglets were added. The Learjet 25 fuselage was mated to the Longhorn wing and the Learjet 28 was created. Without the tip tanks, fuel capacity shrank by more than 1,450 pounds, however.
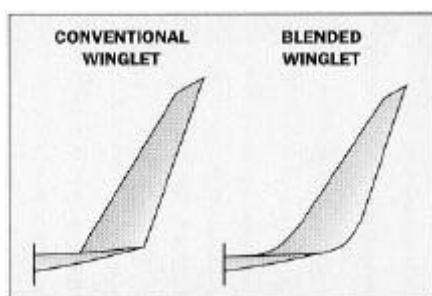
The comparison between the blended winglet and the conventional winglet shown in this illustration contrasts the large radius transition section and spanwise blending of the Gulfstream II winglet with the absence of a meaningful transition section for the conventional winglet. High aspect-ratio blended winglets have demonstrated they are 60 percent more effective than conventional winglets.

To partially regain fuel capacity, Learjet created a second model, the Learjet 29, which had larger fuselage fuel tanks that held almost 700 pounds more fuel, but shrank cabin length by more than two feet. The Longhorn wing had nearly 14 percent more area than the 20-series wing and a 7.25 aspect ratio compared with 5.46 for the original wing. In addition, it had a boost in effective aspect ratio due to winglets. As a result, Learjet 28s and 29s could cruise comfortably at FL 470 to FL 490 instead of FL 410 for the Learjet 25. Less induced and parasitic drag, along with higher cruise altitudes, enabled the Learjet 28 and 29 to cruise on up to 26 percent less fuel at altitude. The fuel bum improvements on day-to-day missions were less impressive because of the thirst of the 20 series turbojet engines during taxi, takeoff, climb and approach. However, on a 1,200-nm mission, the Learjet 29 burned 16.5 percent less fuel than a Learjet 25D, according to Reynolds' report.

Much of the improvement is due to lower wing loading and higher aspect ratio. But the improvement attributable to winglets was close to seven percent at long-range cruise.

Similar to Whitcomb's design, Learjet canted the winglets 15 degrees and gave them a slight toe out. Up to the aircraft's 0.81 Mmo maximum operating Mach limit, there was very little flow separation at the wingtip-to-winglet junction caused by interference.

Reynolds found that the winglets slightly increased dihedral effect. Without winglets, but in spite of the tip tanks, the Learjet 25 has weakly damped Dutch roll characteristics. In contrast, the Learjet 28 and 29 have very mildly divergent Dutch roll characteristics. Reynolds determined that the advancing wing' s winglet stalled at six to eight degrees of sideslip, causing an increase in induced drag and a "large stabilizing moment." In other words, the aircraft yawed back into the direction of the slip and the amplitude of the yaw and roll oscillations slowly increased.

The Learjet 25's yaw damper gain was tweaked up and the Learjet 28/29 had no more problems with Dutch roll. The Longhorn Learjet's decrease in wing loading and increase in lift coefficient resulting from a higher aspect ratio and winglets broadened the margin between high-speed and low-speed buffet to 65 knots, according to Reynolds. This trait made it easy to fly the Learjet 28/29 at FL 450 to 510. More importantly to Learjet's future, the Longhorn wing's improved performance allowed the larger and heavier Learjet 50 series and 60 series to use the same wing, thus greatly reducing the development cost of these new models.

Even the latest business aircraft equipped with winglets rely heavily upon Whitcomb's research. Bombardier's Global Express, for example, has an 8.6 aspect ratio that is effectively increased by its winglets. These are far different from the first-generation winglets fitted to Canadair Challengers in the early 1980s. The Global Express winglets were designed with a proprietary, three-dimensional computer code, under the supervision of Dr. Kafyeke.

The Global Express' winglets have a more sophisticated, supercritical airfoil section that creates less of a shock wave. That enables the leading edge of the winglet root to be moved forward without causing interference drag at transonic speeds. They also are taller than the Challenger's winglets. However, Whitcomb's influence remains present. The Global Express' winglets have almost no twist, approximately a one-third taper ratio and are toed out three to four degrees. They're also canted 15 degrees and have about an eight percent thickness-to-chord ratio.

In spite of the Global Express' relatively high 8.6 aspect ratio, winglets boost its range performance by as much as four to seven percent.

Aviation Partners Inc. blended winglets, designed for after-market applications, have produced similar results. In contrast to most other winglets, including the original Whitcomb design, API's winglets are joined to the wingtip in a constant radius curve, rather than a relatively sharp angle junction.

The smooth curve, according to API, reduces shock interference between the winglet and wing near the tip, thus allowing the winglet chord to be extended forward of the point of maximum chord thickness at the tip. Just as important, API uses supercritical airfoil sections in its winglets that have shock waves that are farther aft and weaker than those of the original wing. As a result, there is little interference between the two shock waves.
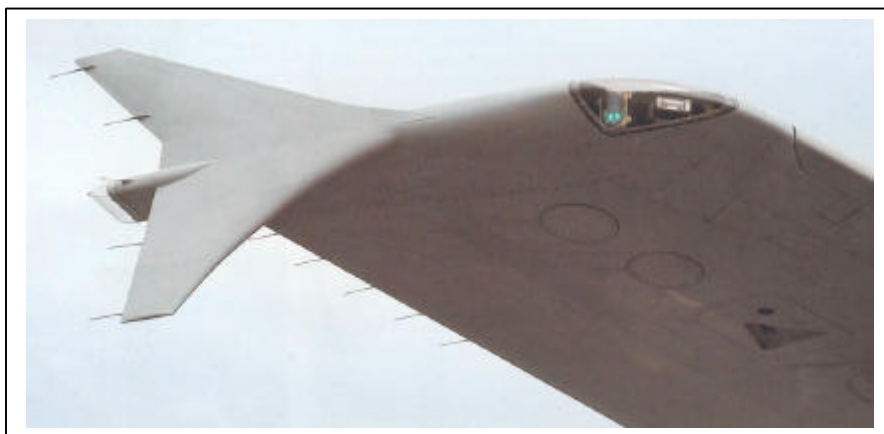
API claims that moving the winglet root forward also eliminates problems with small vortices that roll up from the highly swept wingtip area just ahead of the conventional winglet-towing junction at maximum chord thickness. Eliminating the roll-up vortex further reduces interference drag.

API claims up to seven percent better specific range at cruise altitude for its winglet-equipped G-IISP. The firm anticipates developing winglets for several other models of business aircraft and even some jetliners.

In spite of such performance gains, API's future wingtip modifications may not look at all like small wings. The firm is developing a spiroid tip modification that virtually eliminates the concentrated tip vortex. While much more complex than a winglet, API claims that the spiroid tip can boost range by as much as 10 percent.

API is developing the first spiroid tip applications for air transports. Reduced fuel burn will allow lower operating costs and higher payloads on everyday missions. This will make them cost-effective for commercial operators, according to API. Spiroid tips won't appear on business aircraft until sometime in the future.

Not all winglets are designed to improve high-speed cruise efficiency. On some turboprop aircraft, such as the Pilatus PC-12 and Raytheon 1900D, their primary purpose is to improve low-speed wing performance. At such high lift coefficients, they function mainly as end plates to block the high-intensity tip vortex and improve section lift coefficient near the tip. This can reduce stall speed, thereby resulting in lower V speeds and shorter runway lengths.

(In the case of the PC-12, adding winglets enabled the aircraft to meet the FAA's 61 KCAS maximum stalling speed requirement for single-engine aircraft. Pilatus later received a three knot waiver of that requirement.)

Winglets must be optimized for very specific wing lift coefficients and flight regimes. They can be fine-tuned for low speed or cruise lift coefficients, but not both. The aerodynamics of winglets designed for high-speed cruise have to be carefully fine-tuned because of the effects of compressibility and critical Mach number. Choice of airfoil section and flow interference characteristics of low-speed winglets is less critical.

In the face of such widespread acceptance, though, winglet opponents remain skeptical. They claim that winglets add more drag for the same benefit as increasing wing span and that more span buys better performance over a wide range of lift coefficients. "*A lot of winglets are put there by marketing departments"* said one veteran aeronautical engineer.

But winglet advocates seem to be prevailing. Winglets are sprouting from an increasing number of business and commuter aircraft because of demonstrated performance improvements. There's one other reason, according to one well-known modifier and winglet skeptic, *"It's also because they look sexy."*