A PHYSICAL VIEW OF WING AERODYNAMICS

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INTRODUCTION

Wings are used to provide lift for flight in the atmosphere. Lift can be achieved by wings having almost any airfoil section, but the drag of wings is very sensitive to profile and extremely critical to efficient flight. While providing essential lift, wings are also responsible for producing well over half of the drag of current sailplanes which have relatively efficient wings.[1] The purpose of this discussion is to summarize practical insight as to how wings work, for those who design, build and use them to fly.

Inspiration for this effort was provided by countless articles about wings which I believe are confusing and perhaps delay progress, because they mix engineering techniques and physical phenomena in such a way as to distort our understanding.

FUNDAMENTAL PREMISES

The first point to be made is that wings fly through air; air does not flow past wings. In flight, air moves out of the way as the wing passes through.

Almost every aerodynamics treatise talks about "flow over the wing" and this visualization creates problems with physical understandings. Those familiar with aerodynamics will say that whether the wing passes through air or the air flows past the wing, the forces and moments will be the same, and they are right. The wing obviously produces effects on the air, and if changes in conditions of the air after the passage of the wing are determined, they can be related to forces that the air produced on the wing. It is also true that excellent flight simulations can be achieved in wind tunnels where accurate, quantitative measurements can be made with flows past a stationary model.

However, many misconceptions about the forces on wings have resulted from incorrect interpretations of the relative flow effects. You have heard statements like, "The molecules flowing over the upper surface must go faster to reach the trailing edge at the same time as the ones flowing past the lower," for instance. And there are those who talk of "circulation around the wing," and downwash and vortices "which affect the lift and drag." Common sense tells us that flow does not really circulate around a wing in flight, nor in a wind tunnel, for that matter. These statements derive from analytical methods developed to predict aerodynamic effects. For example, scientists have learned that by superimposing circulating and lineal flow fields for assumed inviscid fluids that calculations can determine local pressures and velocities on the surfaces of two-dimensional shapes. Thus, the circulation appears to be coupled with lift. It is certainly true that measurements of vortices and downwash can be used to infer forces on wings. While useful engineering techniques, they do not explain what physically happened to produce lift and drag. Quite often conditions are ineptly presented in a manner that mixes causes and effects, simply confusing laymen, and frequently misleading engineers as well. It is these pitfalls that are, I hope, avoided, by separating the physical causes and effects.

Although seemingly very different, air and honey are both fluids, both have properties such as density and viscosity, and both obey the same physical laws, although their density and viscosity values are quite different. This hard-to-believe truth is mentioned because friction forces on a wing are very important, and everyone can accept the fact that friction drag would be high if a wing were flying through honey. A term called Reynolds Number, named after the scientist who, in 1874[2], explained the relationship between shear forces, fluid properties and flow conditions providing aerodynamicists a basis for taking different density and viscosity conditions into account. Such relationships affect quantitative results, but are not critical to understanding the big picture about how wings work.

FLUID FORCES ON WINGS

ONLY TWO TYPES OF FORCES

PRESSURE, ACTING NORMAL TO SURFACES

FRICTION, ACTING TANGENT TO SURFACES

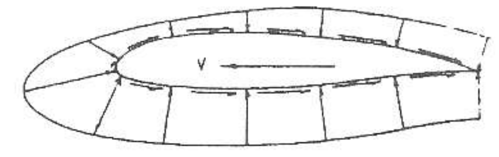


FIGURE 1.

RESOLUTION OF FORCES INTO LIFT AND DRAG COMPONENTS

PRESSURES PRODUCE LIFT

FRICTION CAUSES DRAG

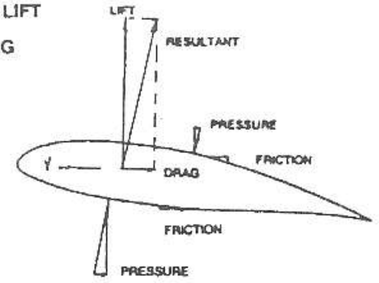


FIGURE 3.

FLUID FORCES ON WINGS

The physical effects on a wing are the direct result of only two types of fluid forces:

1) Pressure, which always acts normal to the surface, and

2) Friction, which always acts along the surface.

Let me illustrate with some simple sketches, and with them, remind you of principles you learned long ago. First, look at a wing in cross-section passing through air. (Figure 1). You will note the pressure field represented by forces acting normal to the surface and friction forces acting tangent to the surface. While there are interactions between these effects as discussed later, they can be thought of as two distinct types of forces on a wing.

FRICTION AFFECTS PRESSURE FORCES

Scientists have determined that pressures along the surface of a moving body vary according to its shape. The difference in pressures on upper and lower surfaces of wings produce lift. But how is drag, the net force in the direction of flight, affected by these varying pressures around the shape? In 1744, a fluid physicist named D'Alembert proved that if a fluid produced no friction along a body, the pressures would vary around it so that, along the direction of movement, the summation of forces caused by pressures would cancel, thereby producing no pressure drag (Figure 2)[3]. This phenomenon has been reconfirmed by scientists again and again, although there is no "non-viscous" or "inviscid" fluid with which to make a perfect experiment. This remarkable finding and experiments with real fluids led, however, to the awareness that friction causes drag directly and also affects pressures which influence lift and drag.

A surface passing through a fluid encounters a shearing force between the fluid and the surface. As said earlier, this shearing force always acts along the surface, and varies with the conditions of the fluid at a local point. It has been shown experimentally that friction also causes the fluid near the surface to decelerate as it sticks to the surface, distorting the "apparent" aerodynamic shape of the body. This effect is described by the term boundary layer, as given in eloquent detail in 1904 by Prandtl.[4] Careful contouring can help reduce bound-

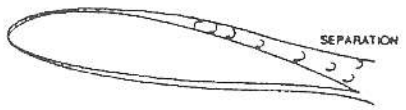
FRICTION AFFECTS PRESSURE FORCES

D'ALEMBERT'S PARADOX (1768)

A BODY MOVING THROUGH A FRICTIONLESS FLUID HAS NO DRAG

PRANDTL (1904)

FRICTION CAUSES BOUNDARY LAYER GROWTH AND SEPARATION



BOUNDARY LAYER CHANGES APPARENT SHAPE OF AIRFOIL

AND AFFECTS PRESSURE DISTRIBUTION

FIGURE 2.

EFFECT OF ANGLE OF ATTACK ON LIFT COEFFICIENT FOR TYPICAL 16% THICK AIRFOILS

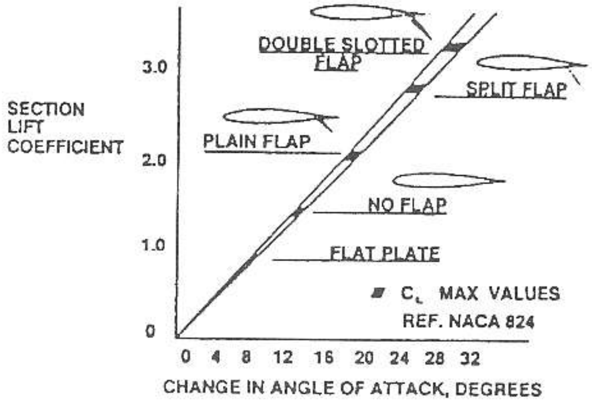


FIGURE 4.

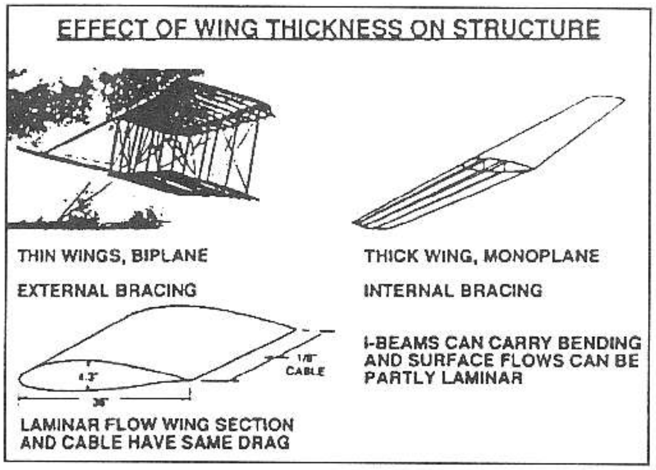


FIGURE 5.

ary layer growth and separation, but surface friction forces and pressure forces are always interrelated. Still, it is proper and useful to consider pressure forces and the friction forces separately, and how their effects combine when describing the physical forces acting on wings. Phillips provided interesting insight into pressure-friction drag relationships, and showed future potential for producing pressure thrust using active boundary layer control.[3]

RESOLUTION OF FORCES INTO COMPONENTS

For thoroughness, let us take a quick look at a simple diagram as a reminder of how a vector can be divided into two components.

Since we define the lift axis as perpendicular to the line of flight and the drag axis as parallel to the line of flight, the summation of pressure and friction force components on a wing along these axes are, by definition, aerodynamic lift and drag of the wing.

Again, I remind you that pressure forces provide the lift and that friction produces drag directly, but also modifies the pressure distribution which affects both lift and drag.[5]

Increases in angle of attack produce proportional increases in lift until flow separation occurs. For typical airfoils this change in lift coefficient is between 0.10 and 0.12 for each degree change in angle of attack. It is interesting that changes in lift with angle of attack changes are the same for flat or cambered wing sections.[6,7,12] In Figure 4, section lift coefficients are plotted against changes in angle of attack up to maximum values, for a flat plate and for typical NACA 4-, 5-, and 6- series airfoils.

The flat plate achieves maximum lift at the lowest angle. Thicker sections, including those with flaps, produce higher maximum lift values at higher angles of attack with the same linear trend. Unlike the flat plate, cambered sections may continue to produce higher lift values after some separation occurs, although the lift may not continue to increase linearly with increases in angle of attack. As shown, a flat plate can only produce a maximum lift value about half that of a normally cambered airfoil section. The sharpness of both the leading and trailing edges influence maximum lift. Separation occurs on the upper surface of an airfoil with a rounded trailing edge at lower angles of attack than when the trailing edge is sharp.

With refined knowledge of camber and boundary layer effects, thick wing sections have been developed to produce more lift and not much more drag than thin sections. Variable camber in the form of flaps can easily increase the lift of a given airfoil one and a half times, and multi-element flaps which also translate to increase wing area can provide three times as much lift as a wing with moderate camber.

While the first consideration in the selection of an airfoil is lift, the next and a very important trade-off consideration is drag, as this limits the tope speed, the minimum glide angle, the power required for propulsion, and the overall efficiency of the wing for producing lift.

EFFECTS OF WING THICKNESS ON STRUCTURES

Making aircraft light enough yet strong enough to fly was the first major challenge of aeronautical engineers. Not knowing about or appreciating the relevance of D'Alembert's findings about drag, early designers thought thin wings were necessary and it was clear that thin wings could not be made strong enough without external bracing.

The powerful benefits of streamlining were not understood for a long time, as most could not conceive of the fact that a small cable could produce as much drag as a large section of wing. The wire-braced biplane was the answer for the Wright brothers as illustrated by the picture of their first glider in Figure 5, and for others for a long time afterward. It was only after designers finally understood that properly contoured thicker wing sections allowing internal structures could produce much lower drag values and greater lift than thin sections with external bracing, that cantilevered structures began to be used for wings. A thicker wing may look heavier to a layman, but since wings are not solid, the greater spar depth of a thicker section allows lighter wings of the same bending and shear strength. And since every ounce in the aircraft structure is an ounce less in payload, the relationship between wing weight and drag is still fundamentally important.

EFFECT OF WING THICKNESS ON LIFT AND DRAG

While thicker wings provide lighter structures, they obviously have more wetted surface area. Moving air out of the way of a thicker wing with flow sticking to the surface tends to promote separation and affect surface pressures, which tends to increase the drag. However, aerodynamicists have determined how drag effects can be significantly moderated by careful shaping of the airfoil, and this science has offered opportunities for striking improvements in lift/drag efficiencies of wings that Are suitably thick for structural integrity.

In Figure 6 a family of laminar flow airfoils having thicknesses from 6% to 21% of the chord are shown, along with the increases in maximum lift and minimum drag as affected by the thickness.[6] It is obvious that for this family of airfoils very thin sections are not as good for high lift and that the drag penalty for increasing thickness is not severe until the thickness becomes great. Suitable wing structures with thickness/chord ratios from 12% to 18% are commonly used today.

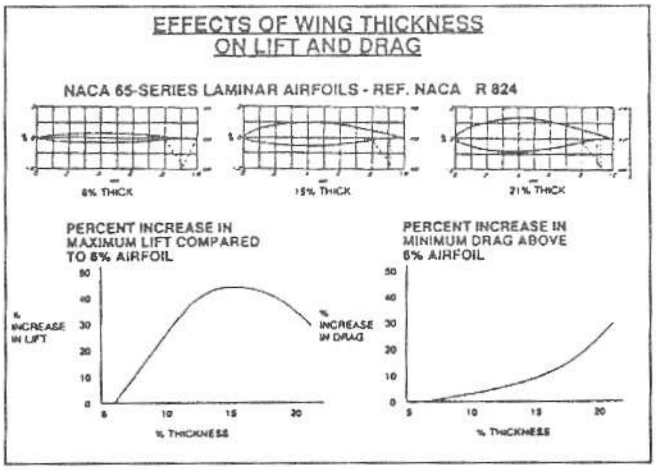


FIGURE 6.

FLAPS CHANGE CAMBER

The curvature on the surfaces of wings is known as camber. In the early days curvatures on both the upper and lower surfaces looked like parallel curves of turning vanes, as it was thought that such thin, curved shapes were most suitable for producing lift. What was learned from airfoil studies was that the lift is mostly affected by the camber on the upper surface and that the lower surface need not be concave to achieve high lift.

The Wright brothers used wing-warping as a way of changing camber and providing for roll control. Flaps on the trailing edges of wings, called ailerons, were later adopted as a simpler form of camber changing for control, and are still in use today (Figure 7).

On high performance gliders and aircraft, flaps are used to help maintain laminar flow and low drag values over a wide range of flight speeds, keeping the profile drag coefficients nearly constant at various speeds by adjusting the camber of the wing throughout the operating speed range. Increasing the camber at low speeds allows the wing to remain in the laminar flow, low drag angle of attack region, and reducing camber at high speeds also allows laminar flow and low drag values.[6] The benefits of using variable flap settings to improve laminar flow wing performance were known for many years before negative settings were widely used.

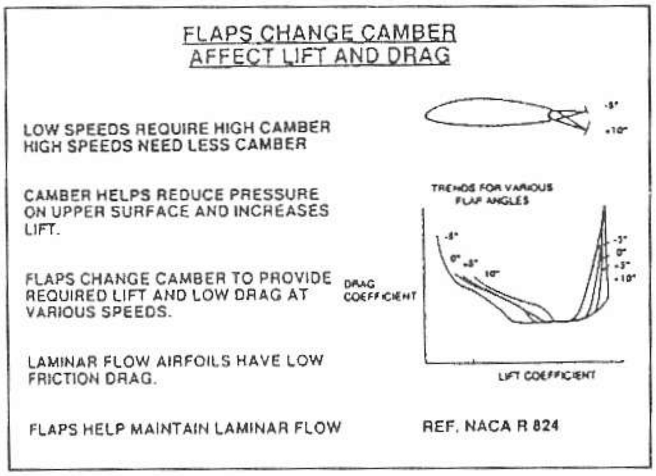


FIGURE 7.

AERODYNAMIC DEVELOPMENTS

The most significant discoveries and insights concerning the practical application of airfoil technologies occurred during the 1930's and 1940's through the efforts of scientists and engineers at the Langley Memorial Aeronautical Laboratory of the NACA, now known as the NASA Langley Research Center. Contributing to the usefulness of their work was the publication of reports describing methods and findings in a very systematic manner.[5] Notable are NACA Report 824 entitled *Summary of Airfoil Data* by Abbott, Von Doenhoff and Stivers dated 19456, and a book entitled *Theory of Wing Sections* by Abbott and Von Doenhoff published in 1949.[7] German scientists Richard Eppler and Franz X. Wortmann expanded NACA methods with special considerations for low speed airfoils and made significant contributions to the methods for designing laminar flow airfoils.[8,9,10] Sighard Hoerner collected data from many sources and greatly helped engineers with his reference materials.[11,12] Others have made important additions, but basic laminar aerodynamics methods and applications have benefited greatly from the efforts reported by these researchers. Perhaps most important were their findings about how the wing section or airfoil, including its contour and surface roughness, influence lift and drag relationships.

LIFT AND DRAG RELATIONSHIPS

As indicated earlier, the fact that the lift of a two-dimensional wing varies directly with angle of attack is fascinating in its simplicity. The changes in lift with changes in angle of attack for wings of finite span are different for each aspect ratio, ad the lower the ratio, the less the lift increases with increases in angle of attack.

Once these findings about lift have been explained, they appear logical and are easy to accept. The principal difficulty comes when trying to understand airfoil shape effects on drag. Part of the problem is due to the many terms that have been used in describing it. "Profile" drag is used to describe drag that includes both pressure and friction effects; this is what an experimenter measures on a two-dimensional wing model. "Induced" drag is sometimes called the "drag due to lift," because it is related to the flows round the ends of a finite wing which is producing lift, and can e calculated approximately for a wing of finite span and aspect ratio, if the lift is known. A somewhat vernacular but descriptive form of drag is "crud" or "parasite" drag produced by joints, rivet heads, gaps, waviness and artifacts of manufacturing. The leakage of flow through gaps around ailerons and protuberances like antennas or pitot static probes is sometimes called parasite drag. And then there is "interference" drag for interactions between wings and bodies or tails and the like which is sometimes referred to as "bookkeeping" or "additive" drag. There is overlap in some of these drag definitions and most require interpretation and summation to obtain the total drag. This is why remembering the simple physical fact as stated earlier helps our insight: only pressure and friction forces affect the lift and the drag, no matter what causes them.

Friction drag is directly related to surface area. Friction drag is reduced by maintaining laminar flow conditions as long as possible, as drag with laminar flow is less than that with turbulent flow. Laminar flow is easier to maintain if the surface pressures along the surface are decreasing in the direction of flow, which occurs as long as the wing continues to increase in thickness. Obviously this favorable pressure gradient condition cannot be maintained to the trailing edge and where it changes, transition to turbulent flow is more likely. At very low speeds, boundary layer transition from laminar to turbulent may not occur directly, and a phenomenon known as a laminar separation "bubble" may appear. This bubble may increase drag more than a direct transition to turbulent conditions, and turbulators at such a location which produce drag directly, but cause transition, are able to reduce drag.

For pressure drag considerations, the airfoil designer's challenge is to minimize boundary layer growth and delay separation as long as possible. Optimizing the shaping of airfoils is being done better as refined analytical methods are combined with better experimental results. Applying airfoil data properly requires consideration of the desired operating conditions, the wing area necessary to meet the lift goals, the shape or planform of the wing, the wing-body juncture, the tip characteristics, and the probable application of control surfaces and flaps or camber-changing devices.

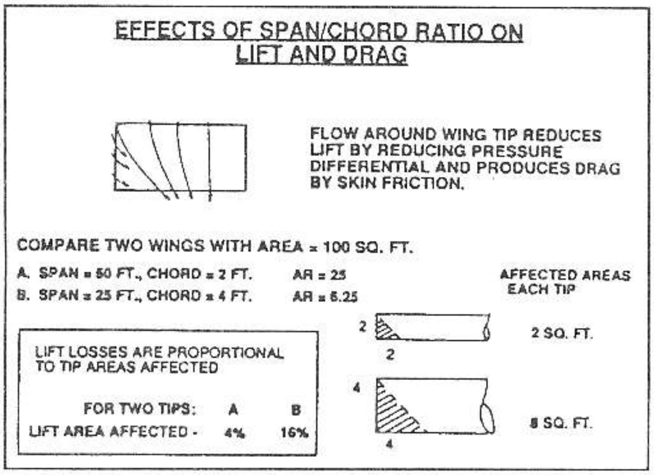
EFFECTS OF SPAN AND SHAPE

Wings of finite span have "end effects" caused by differences in pressures above and beneath the wing (Figure 8). These effects are most pronounced at low speeds, as when climbing under high lift conditions.[6]

Span loadings that are elliptical have been shown to produce efficient lift and drag characteristics, and also tend to produce efficient cantilever structures that taper in planform and thickness toward the tips as shear and ending moments diminish. Taper ratios for wings having a tip chord about half that of the root have been found to be good. Also, sweepback tends to turn flow outward and forward sweep tends to direct flows inboard. Increasing sweepback near the tip has been found to be beneficial for reducing tip losses.

EFFECT OF SIMPLE WING TIP SHAPES

Perhaps the simplest wing tip is made by simply chopping off the end of a wing, leaving edges unrounded.


EFFECTS OF SPAN/CHORD RATIO ON LIFT AND DRAG

FLOW AROUND WING TIP REDUCES LIFT BY REDUCING PRESSURE DIFFERENTIAL AND PRODUCES DRAG BY SKIN FRICTION.

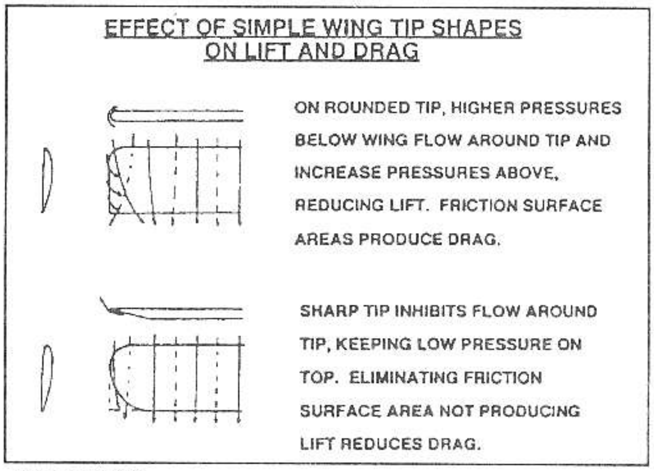
COMPARE TWO WINGS WITH AREA = 100 SQ. FT.

A. SPAN = 50 FT., CHORD = 2 FT. AR = 25
B. SPAN = 25 FT., CHORD = 4 FT. AR = 6.25

LIFT LOSSES ARE PROPORTIONAL TO TIP AREAS AFFECTED

FOR TWO TIPS:	A	B
LIFT AREA AFFECTED -	4%	16%

FIGURE 8.


EFFECT OF SIMPLE WING TIP SHAPES ON LIFT AND DRAG

ON ROUNDED TIP, HIGHER PRESSURES BELOW WING FLOW AROUND TIP AND INCREASE PRESSURES ABOVE, REDUCING LIFT. FRICTION SURFACE AREAS PRODUCE DRAG.

SHARP TIP INHIBITS FLOW AROUND TIP, KEEPING LOW PRESSURE ON TOP. ELIMINATING FRICTION SURFACE AREA NOT PRODUCING LIFT REDUCES DRAG.

FIGURE 9.

While not pretty, such tips have been found to be better than many in use. On rounded tips, higher pressure air from the lower surface flows easily to the upper surface because the curved end of the wing allows boundary layer air at relatively low speeds to remain attached to the surface and make the turn (Figure 9). This reduces the lift but does not reduce the drag.

It has been shown by experiment [13,14,15] that a simple sharp-edged tip, with planform shaped by passing an imaginary plane at about 15 degrees through the lower and upper surfaces of the wing, inhibits the flow around the tip. I have included a picture of a bird wing-tip (Figure 10), to remind you that nature has been showing us how to design wing tips for a long time. This buzzard wing pictured is shaped overall like the sharp tip example, and notice how each individual feather, which has a tip of its own, is also shaped that way.

HOW WINGLETS REDUCE DRAG

Under high load conditions, many bird wing tips and individual tip feathers bend upward to form winglets. They are called winglets because they are small wings, and they produce lift and drag just like big wings.[16] They help the performance of gliders under some conditions because their lift, which mostly acts toward the center of the glider, also has a forward component that produces thrust (Figure 11).

By placing winglets properly in the air flowing around the tip, the winglet uses that change in flow direction to allow its forward lift or thrust component to recover some of the performance that would be lost in induced drag. In some cases, winglets also tend to direct flow over the outboard end of ailerons, and reportedly improve roll control in circling, climbing flight.[17,18]

Winglets offer the most promise for span-limited configurations, like the FAI Standard and 15-meter classes of gliders. The addition of winglets which do not violate the 15-meter limit offer a few points of improvement in maximum lift/drag ratio, which occurs at low speed, high lift conditions, but their benefits decrease as speed increases and the angle of attack necessary to produce lift decreases. The speed at which winglet drag becomes greater than its thrust is a trade-off which must be considered. The design challenge is to balance the maximum drag benefits at low speeds without hurting

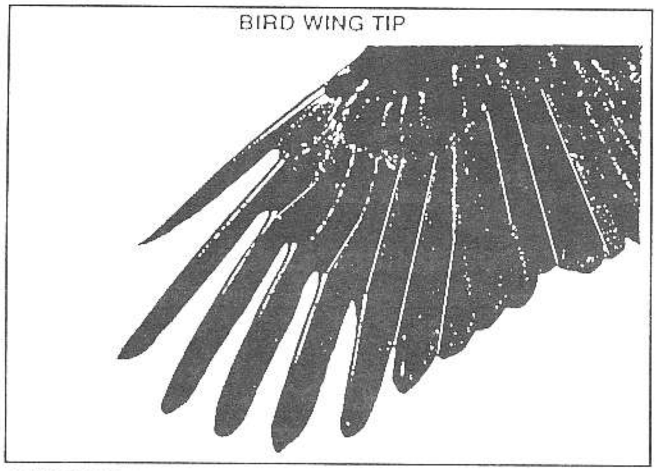
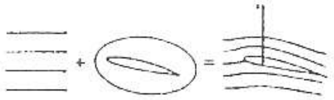


FIGURE 10.

ENGINEERING METHODS - POTENTIAL FLOW THEORY FOR LIFT

LINEAR AND CIRCULAR FLOWS CAN BE SUPERIMPOSED TO GET PRESSURE DISTRIBUTION AND LIFT.



UNIFORM LINEAR FLOW + PURE CIRCULATION = INCOMPRESSIBLE, INVISCID FLOW

CIRCULATION IS NOT A CAUSE OF LIFT, BUT RATHER A MATHEMATICAL FORMULATION FOR THE DISTRIBUTION OF PRESSURES WHICH ALLOWS THE CALCULATION OF LIFT.

WHEN A VALUE OF CIRCULATION IS OBTAINED, LIFT CAN BE CALCULATED:

$L = \rho V \Gamma$ (CIRCULATION)

FIGURE 12.

the high speed performance. The higher the percentage of time spent at low speeds as when climbing, the more beneficial winglets are.

There is also a structural reason why winglets might offer merit, and that is the fact that their thrust effect does not increase the wing root bending moment as much as direct span extensions would. It might therefore be possible to make a lighter wing using winglets than one with a longer span. The torsional effect of winglets must be considered carefully, however, as flutter possibilities may be worsened on thin wings by the twisting tendency of winglets.

This discussion on winglets has been directed at upturned tips, but many gliders have downturned tips to provide contact with the ground. A downturned tip produces a lift vector away from the centerline of the aircraft, just the opposite from the upturned winglet. Again, I cite nature as an example, as there are no soaring birds with downturned wingtips.

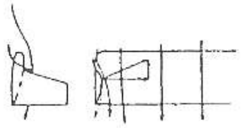
ENGINEERING METHODS RELATED TO PHYSICAL FACTORS

In the introduction it was indicated that misconceptions about physical effects may have been caused by mixing engineering methods into the explanations about how wings worked. Years before wings were built, fluid physicists developed methods for describing flows and the physical relationships between densities, pressures and temperatures. Water was a most important fluid and its transport was of great importance. These studies led to the discoveries of principles governing fluid flows and analytical treatments for calculating relationships for flows in pipes and channels. These fluid physics principles were very helpful to early aerodynamicists, as at low speeds, air behaves like water. By applying the theories of superimposing imaginary linear and circular flows, they were able to design shapes with camber which could produce lift (Figure 12).

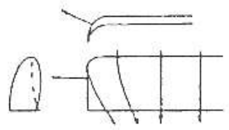
All these analytical techniques depend on simplifying assumptions about the fluids and processes, such as assuming incompressible, inviscid fluids and isentropic interactions. Mathematically determined lift depends on the assumed circulation, and it is common for aerodynamicists to discuss circulation effects on lift because of this method.

The simplest way to envision lift, is to imagine pressure taps all over a wing capable of measuring local static pressures for each small element of the wing surface (Figure 13). The summation or integration of the

HOW WINGLETS REDUCE DRAG



WINGLET PRODUCES LIFT INBOARD WITH A FORWARD OR THRUST COMPONENT. THIS COMPONENT MUST BE GREATER THAN PROFILE DRAG OF WINGLET.



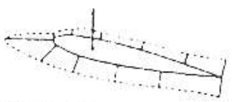
TURNED DOWN TIP PRODUCES LIFT OUTBOARD. FORWARD COMPONENT NOT LIKELY TO PRODUCE MORE THRUST THAN DRAG.

BOTH WINGLET TYPES AFFECT STABILITY - MUST BE CONSIDERED.
TURNED DOWN TIPS REDUCE LATERAL AND DIRECTIONAL STABILITY.

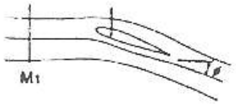
FIGURE 11.

ENGINEERING METHODS RELATED TO PHYSICAL EFFECTS

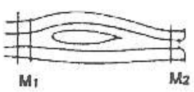
CALCULATE OR MEASURE PRESSURE DISTRIBUTION;
LIFT = $\int PdA$



MEASURE MOMENTUM AND DOWNWASH ANGLE;
CALCULATE LIFT = $M_1 \sin Ø$



MEASURE STREAM MOMENTUM BEFORE AND AFTER WING;
DRAG = $M_1 - M_2$



MEASURE STREAM MOMENTUM BEFORE AND AFTER TIP;
DRAG = $M_1 - M_2$

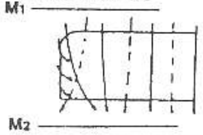


FIGURE 13.

vertical pressures times their relevant areas would give the lift for the entire wing. Note that no circulation, downwash, vorticity or such is considered in this pressure distribution-integration method.

The laws presented by Newton concerning conservation of mass, momentum and energy are useful for calculating changes in the fluid stream, and the "wake rake" technique is often used to determine the drag of an airfoil section, as it gives a good approximation of the profile drag, including both friction and pressure effects.

If the momentum is measured before wing passage and the turning or downwash angle downstream of the wing is determined, this momentum change due to the turning angle can be related to lift. These effects are much easier to talk about qualitatively than to measure, however,

KEY POINTS SUMMARY

In closing, it is humbly acknowledged that this simple treatise falls far short of providing complete insight into the complex physical phenomena involved in wing/air interactions. In addition to having much more to learn, books could be written about what is known At best, this attempt to present physical effects in simple terms may help to encourage better application of known facts. A few key points are restated for reference.

1. Wings are for providing lift with the lowest drag. It is easy to obtain lift; the challenge is to do so with the lowest drag. Wings produce more than half the drag of aircraft for most flight conditions.
2. Pressure and friction are the only fluid forces acting on wings. They produce all the lift and all the drag, and cause all the downwash, vortices and other influences on the air through which the wing flies.
3. Lift is the result of pressure-area forces normal to the line of flight, and is due to the differential between the pressures on the upper and lower wing surfaces.
4. Viscous effects cause friction drag on all surfaces in moving contact with fluids.
5. Friction causes flow separation, reduces lift and increases drag.
6. Flaps change camber and affect both lift and drag.
7. Wing tip shapes influence both lift and drag.
8. Winglets produce drag; to improve performance they must produce off-setting lift ad/or thrust components.
9. Engineering methods relating causes and effects can be confused with physical factors.

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