On the 'Wing... #161

Twist Distributions for Swept Wings, Part 1

Our curiosity got the better of us, and we asked "Why are designers of swept wing tailless models placing proportionally more twist in the outboard portion of the wing?" This series of articles will provide a comprehensive answer to that question.

Our intense interest in tailless aircraft now spans twenty years. Over those two decades, we have built a number of "plank" type 'wings and several swept 'wings. As we explained in a recent column, there are advantages and disadvantages to both of these planforms.

An introduction to twist distributions

The impetus to begin designing our own swept wing tailless aircraft was the presentation given by Dr. Walter Panknin at the MARCS (Madison Area Radio Control Society) Symposium held in 1989. Dr. Panknin provided a relatively simple method for determining the geometric twist required for a stable planform when given the span, the root and tip chord lengths, the root and tip airfoil zero lift angles and pitching moments, the sweep angle of the quarter chord line, the design coefficient of lift, and the static margin.

Dr. Panknin assumed that the wing twist would be imparted across the semi-span. That is, the root would be held at zero degrees and the tip twisted at some angle of washout, with the wing leading and trailing edges forming straight lines. Dr. Panknin's 'wing, the Flying Rainbow, along with Kurt Weller's Elfe II, utilized this type of twist distribution on tapered wings.

In looking at other swept wings of that time period, we were also attracted to Hans-Jürgen Unverferth's CO2. The CO2 was different from the Flying Rainbow and the Elfe II in that the wing was not tapered but rather of constant chord. Additionally, CO2 utilizes a twist distribution in which the inner half of the semi-span has no twist at all. All of the geometric twist is in the outer half of the semi-span. While the actual twist angle is identical to that computed for the Panknin twist distribution, pitch stability is not adversely affected and in fact may be slightly better.

More recently, Hans Jürgen and other swept wing designers have taken to imparting wing twist across three segments. From the root to one third of the semi-span there is no twist. About one third of the total twist is then put into the second third of the semi-span, and the remaining two thirds of the total twist is put into the wing between two thirds semi-span and the wing tip.

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Lift distributions

Nearly all aerodynamics text books devote pages to what is called the "lift distribution." The lift distribution for any straight (quarter chord line at 90 degrees to the centerline) wing can be graphically represented by a curved line superimposed over a standard X-Y coordinate system. The lift distribution curve traces the local circulation — the local coefficient of lift times the local geometric chord.

How is the lift distribution determined? Let's start by taking a look at the construction of the elliptical lift distribution. Assign the aircraft wing tips to the points 1.0 and -1.0 on the Y-axis of the coordinate system. Draw a circular arc above the Y-axis using the aircraft wing tips to define the diameter. A semicircle is formed which has the radius b/2 (the semi-span) and the area $\pi/2(b/2)^2$ which in this specific case is simply $\pi/2 = 1.57$.

Now drop vertical lines from the semicircle circumference to the Y-axis. Mark the mean (halfway) point on each vertical. Connecting these identified points creates an ellipse. (See Figure 1). This elliptical lift distribution is predominantly promoted as being the ideal, as represented in the planform of the British Supermarine Spitfire fighter of the World War II era.

Why would the designer want the lift distribution of his arbitrary wing to closely match that of the elliptical lift distribution? Because with the elliptical lift distribution, a discovery of Ludwig Prandtl in 1908 which he published in 1920, each small area of the wing is carrying an identical load and so is operating at the same local coefficient of lift, the downwash off the trailing edge of the wing is constant across the span, and the coefficient of induced drag (drag due to lift) is at its minimum point.

To construct the lift distribution for an arbitrary wing without twist or sweep, lay out the wing outline over the elliptical lift distribution with chord lengths proportioned such that the area of the wing is equal to that of the ellipse (one half that of the semicircle, in this case $\pi/4 = 0.785$). Draw a curve along the mean of the ellipse and the wing planform outline. (See Figure 2.)

With some graphical experimentation, we find that the lift distribution for a wing with a taper ratio of 0.45 almost exactly matches that of the elliptical lift distribution described by Prandtl. (See Figure 3.) The tapered planform has at least one advantage over the elliptical planform — it's far easier to build. But the elliptical planform has a stall pattern in which the entire wing is subject to stalling at the same time. At high angles of attack, small gusts can serve to trigger a stall on any portion of the wing span. A tapered wing with a nearly identical lift distribution will tend to behave in the same way.

Lift coefficient distributions

As stated previously, the lift generated by any wing segment is directly proportional to the coefficient of lift and the local geometric chord. This means that there is also a coefficient of lift distribution. For Prandtl's elliptical wing lift distribution, as has been described here, the local coefficient of lift is identical across the span. On the other hand, if the taper ratio is zero (the wing tip comes to a point), the coefficient of lift at the wing tip will be zero only in a truly vertical dive, but otherwise it will be infinite because the wing tip chord is nil. Any time this wing is called upon to produce lift, the wing tip will be stalled. From this extreme example, we realize the tip chord cannot be too small, as it will then be forced to operate at a higher coefficient of lift, leading to a local stalling of the wing. (See Figure 4.)

So called “tip stalling” can be inhibited by one or both of two methods. The first involves increasing the local chord near the wing tip, the second consists of imparting washout.

As we intuitively know, enlarging the wing tip chord reduces the local coefficient of lift. An enlarged wing tip chord is not so efficient as the true elliptical planform, but the penalty for using a perfectly rectangular wing is just 7% and so it may be an acceptable trade-off for a machine designed for sport flying.

Washout, on the other hand, while also reducing the coefficient of lift in the area of the wing tip, is good for only one speed. As the twist angle increases, the deleterious effects become stronger much more quickly as the coefficient of lift for the entire wing, C_L, moves away from the design point. If washout is too great, the wing tips can actually be lifting downward at high speeds. This puts tremendous loads on the wing structure.

Adverse yaw

One other effect of utilizing the elliptical lift distribution comes about as we add control surfaces to the wing. Outboard ailerons, for example, create different coefficients of induced drag depending on whether the surface is moved up or down. The control surface moving downward creates more lift and hence more drag than the surface moving upward. When rolling into a turn, therefore, the aircraft is forced into a yaw away from the direction of the turn. (See Figure 5.)

In conventional aircraft, this tendency can be reduced to some extent by what is called aileron differential. The upgoing control surface travels through a larger arc than the downgoing surface. While this tends to increase the drag on the downgoing wing, reducing adverse yaw to a great extent, many pilots find that some amount of rudder input is necessary to obtain a coordinated turn.

Reduction of rudder input is an important consideration in the quest to reduce overall drag while maneuvering, but the associated induced drag from the fin and rudder, a low aspect ratio flying surface, cannot be entirely avoided. For a swept flying wing without vertical surface, elimination of adverse yaw is obviously imperative, but aileron differential cannot be used in this case because of its effect on pitch trim. Some other means of eliminating adverse yaw must be devised.

Three major problems

And so we are forced to solve three problems when designing a tailless aircraft:

1. achieve and hopefully surpass the low induced drag as exemplified by the elliptical lift distribution without creating untoward stall characteristics,
2. reduce the adverse yaw created by aileron deflection without adversely affecting the aircraft in pitch, and

3. maintain an acceptable weight to strength ratio.

A relevant historical tidbit

The Wright brothers, along with their other accomplishments, were the first aircraft designers to determine that banking was necessary to turn, an idea which no doubt came from their experience with bicycles. While other early aviation pioneers had studied bird flight, the perspective of the Wrights while watching birds was very much different because of their cycling experiences. (Interestingly, their direct competitor, Glenn Curtiss, built and raced motorcycles.)

The Wrights also had the ability to separate the major problem of controlled powered flight into manageable components. Propulsion was separated from the production of lift, and stability was separated from control, for example. In fact, their solution to the problem of flight incorporated only one integrated system, the wing, which provided lateral control, structure, and lift. It was Wilbur's twisting of the inner-tube box, through which the idea of wing warping was derived and the internal bracing of their wing structure was devised, which provided the insight needed to create a controllable flying machine capable of carrying a human pilot/passenger.

But the flying machine they created, while tremendously successful, for all practical purposes ended the use of birds as models for aircraft design. As an indicator of this, the Wrights saw their early successes and records in powered flight quickly surpassed by the inventions of others. Curtiss, for example, solved the problem of banking turns with separate control surfaces rather than wing warping. His aileron system is still in use today.

The Wright's separation of a huge problem into smaller more easily solved problems has continued to be the hallmark of aircraft design for 100 years, and aviation has made nearly unbelievable strides during that century. But there are a growing number of aircraft designers who wish to go back to the bird model. They wish to design an aircraft which is the minimum required for efficient controlled flight by integrating lift, stability and control into a single structural component.

A bird is a biological system which has been very successful for a very long time. To be successful in the competitive environment of nature, a flying bird needs more than just lift, stability, and control. A bird must also be efficient at flying. That is, it must have a very low energy expenditure. Minimum drag while moving through the air is of course of major importance in this regard, as is a very light airframe because extra weight increases the energy drain on the system.

We can see through direct observation that birds have no vertical surfaces, yet birds are able to make beautiful coordinated banked turns without any evidence of adverse yaw. Perhaps birds do not make use of Prandtl's elliptical lift distribution.

What's next?

As a prelude to future installments, let us ask a series of provocative questions:

• What if we found that the elliptical lift distribution does not lead to the minimum induced drag, as has been dogma in most aerodynamics texts since Prandtl introduced the concept in 1920?
• What if we found a way to produce "induced thrust" in addition to, and without increasing, the "induced drag" produced by the creation of lift?
• What if we could increase the wing span and aspect ratio without increasing the required strength of the spar at the wing root?
• What if the answers to all of the above questions are related?

We'll cover all of this and more in future installments!

Ideas for future columns are always welcome. *RCSD* readers can contact us by mail at P.O. Box 975, Olalla WA 98359-0975, or by e-mail at <bsquared@appleisp.net>.

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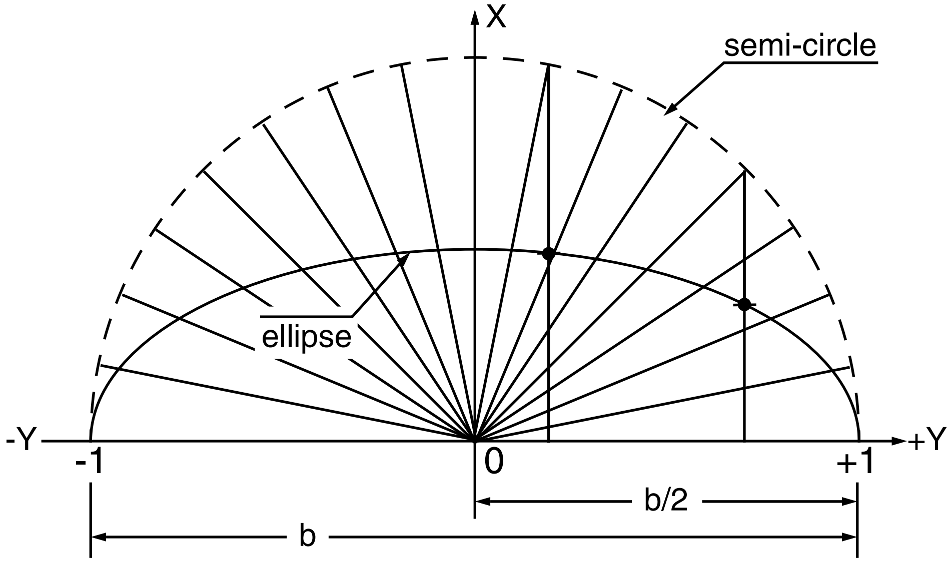

Figure 1. Construction of elliptical lift distribution

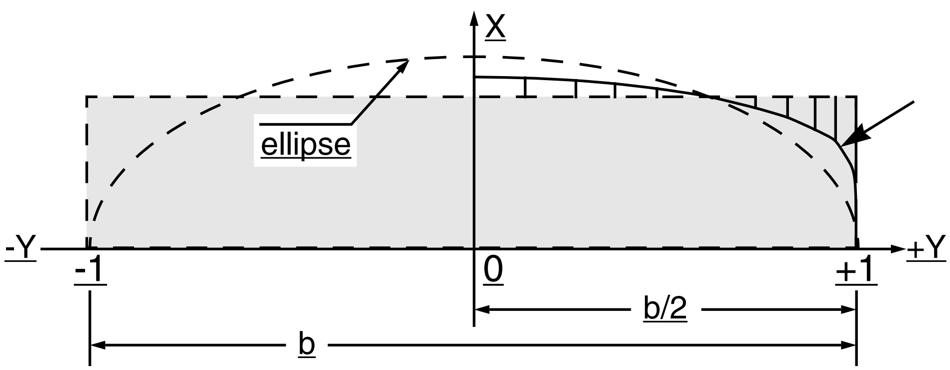

Figure 2. Construction of lift distribution
for untwisted rectangular wing.

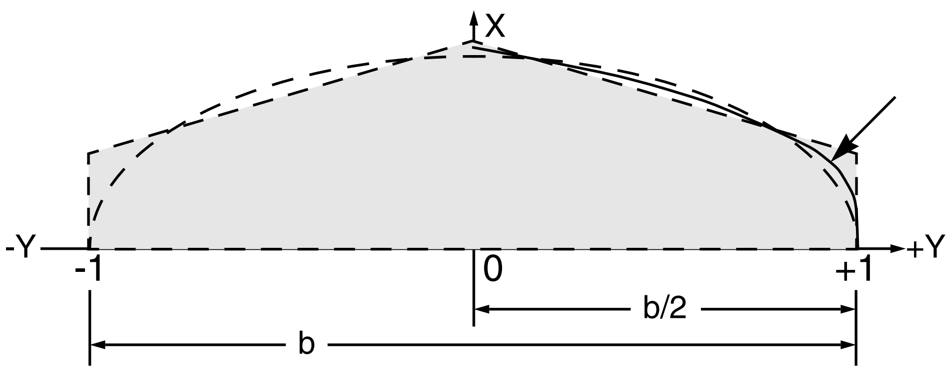

Figure 3. Construction of lift distribution
for untwisted wing with taper ratio of 0.45.

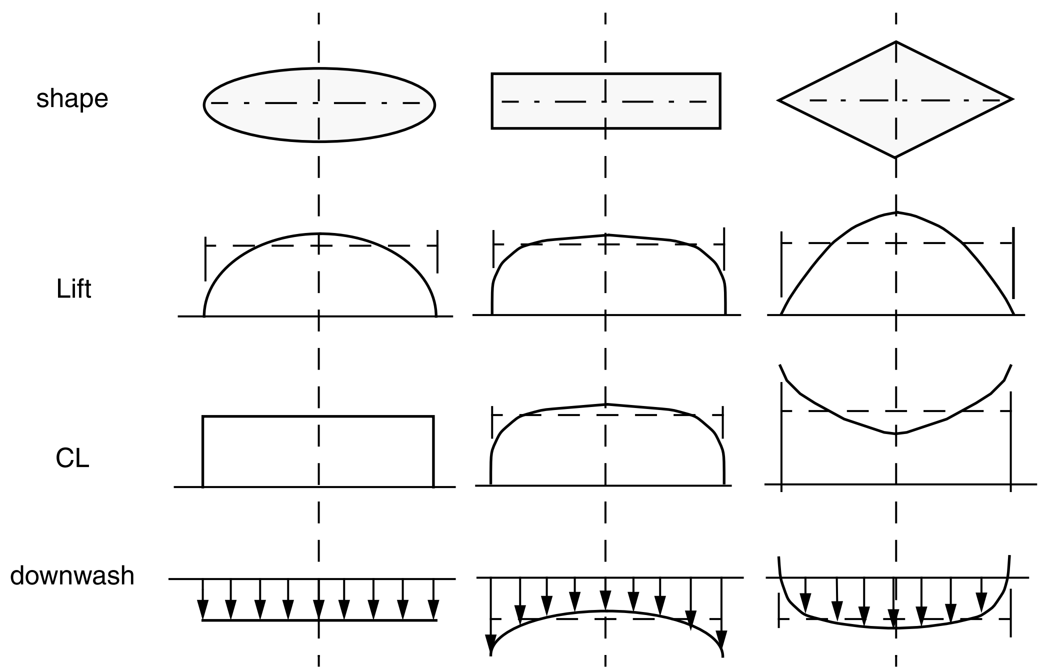

Figure 4. Three wing planforms and their associated lift distributions, coefficient of lift distributions, and downwash distributions.

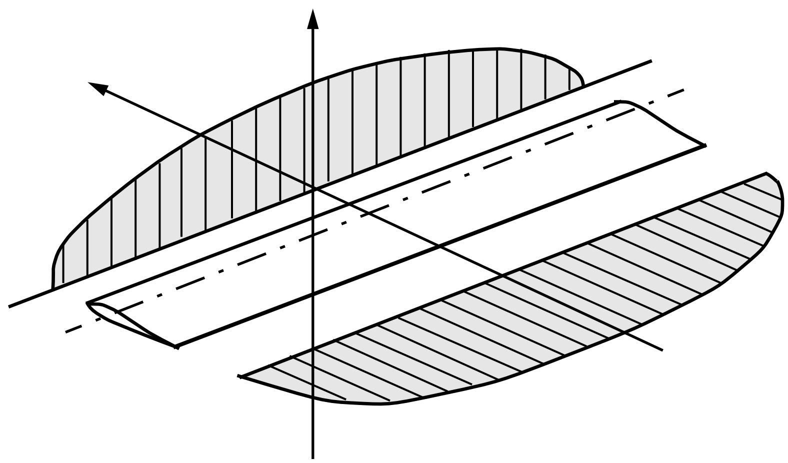

Figure 5a. Lift and drag profiles for untwisted rectangular wing in straight and level flight and no control surface deflection.

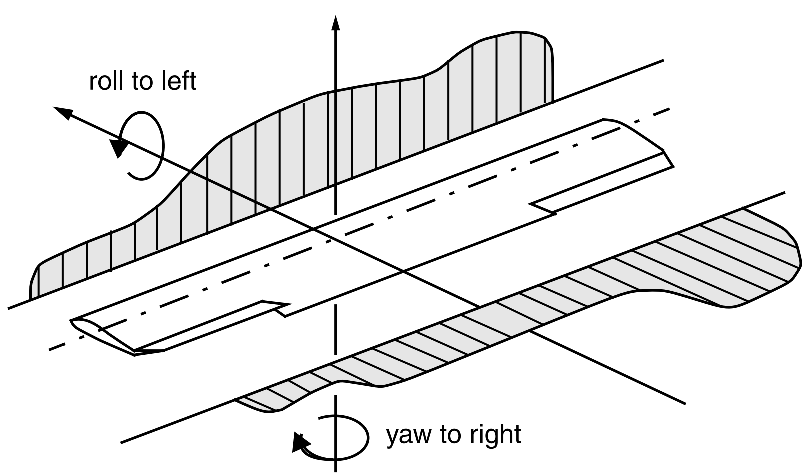

Figure 5b. Lift and drag profiles for untwisted rectangular wing with aileron deflection for left bank, no differential.