On the 'Wing... #165

# Twist Distributions for Swept Wings, Part 5

*The Horten twist distribution has been the focus thus far, but it's now time to take a look at the twist distributions formulated by Irv Culver and Walter Panknin, make some comparisons, and derive a few conclusions.*

## The "middle effect"

First, a small digression is necessary in order to understand one remaining concept, the "middle effect." The Hortens' later designs included geometric modifications aimed at reducing or eliminating the "middle effect." Irv Culver's twist distribution is specifically formulated to eliminate the reduction in lift near the center of a swept back wing. Interestingly, the Hortens and Culver are trying to counter two different phenomena.

As the wing moves through the air, the air coming off the trailing edge is deflected downward. This is called the downwash. As the air approaches the wing, it moves up slightly to meet the wing. This is called the upwash. We've already illustrated these two properties in previous portions of this article series, pointing out the angle of attack is directly related to the position of the stagnation point.

If you look at an airfoil traveling through the air, you'll see that the air moving over the upper surface is moving faster than the wing is moving through the air. So too, the air along the lower surface is moving slower than the wing is moving through the air. From a vector mathematics perspective, if you subtract the velocity of the wing from the two air flows, the air over the upper surface is still moving from leading to trailing edge, but the air along the bottom of the wing is moving backward toward the leading edge. From this perspective, the air "circulates" around the airfoil in a clockwise direction as a wing producing lift moves right to left. The coefficient of lift is directly proportional to this circulation. See Figure 1.

According to Prandtl's lifting line theory, you can visualize a wing moving through the air as simply a line connecting the two wing tips along the quarter chord line with horseshoe shaped vortices coming from it and extending back to infinity. In this model, both downwash and upwash are accounted for: the air inside the vortices is being deflected downward, and the air outside the vortices is being deflected upward. The actual lifting line calculations, however, are both complex and extensive. Schrenk expanded Prandtl's lifting line theory to include taper, twist and control deflections, but not sweep. Multhopp expanded this theoretical framework further, but still did not fully account for the effects of sweep.

A swept wing can be viewed as a series of connected small wings, the leading edge of each slightly behind the leading edge of its inboard partner and in front of the leading edge of its outboard partner. Each small wing has an effect on the air flow of both its inboard and outboard partner, but the effect on the outboard partner is very much greater than the effect on the inboard partner. The upwash is not equal along the span but rather tends to progressively increase over the more outboard segments. (We've illustrated this concept in previous portions of this article series.)

Schrenk's approximation does not accurately portray a swept wing, and therefore does not account for the loss of circulation and associated loss of lift at the root and the increase of circulation and associated increase of lift at the wing tips.

Multhopp's method of determining the lift distribution, which involves established "control points" based on "central difference angles," does not account for sweep either, but was used by the Hortens as the best available model at the time. The H-II was the first of the Horten aircraft to use a bell-shaped, $\sin^x$, lift distribution, an outgrowth of the Multhopp paradigm.

The "middle effect" which is so often talked about regarding the Horten designs is simply an artifact of this inability to accurately predict the sweep induced changes in circulation, specifically a loss of lift at the center. This middle effect is strictly an artifact of the computation methods and is an error in analysis. The "middle effect" is not the loss of lift in the center area of the wing, it's the *unanticipated* loss of lift in the center area of the wing.

## Horten

The Hortens, in an effort to coordinate stalling behavior and center of gravity with other planform parameters, performed the necessary mathematical computations, but always found errors in their results. The aircraft did not behave exactly as predicted because the center of pressure was not at the location predicted. The Hortens believed the problem to be related to the intersection of the two quarter chord lines at the centerline, and envisioned colliding vortices. They constructed "bat tails" which substantially increased the root chord. Their intent in using the bat tail was to reorient the quarter chord lines of the two wings and eliminate the colliding vortices. On the H IV, the quarter chord lines meet at right angles to the centerline, while on the H VI the quarter chord lines actually bend backward. Despite these changes to the quarter chord line, the "middle effect" remained. Al Bowers has suggested that the Hortens might have realized they were looking in the wrong direction had they actually flown their Parabola design.

Despite their problems getting a handle on the "middle effect," the Horten twist distribution has the potential to reduce induced drag and allow turns to be accomplished without adverse yaw. But aircraft will operate as Dr. Horten envisioned only when all of the design parameters are utilized: moderate sweep angle, large taper ratio, carefully chosen airfoils (pitching moment), strong nonlinear twist distribution, "bell-shaped" span load (lift distribution), and outboard ailerons of defined size and configuration.

The Horten twist distribution is such that the wing twist is concentrated over the outer portion of the wing, in the area where the sweep generated upwash is greatest. Computing the twist distribution is a rather complicated affair, and we've been so far unable to obtain formulae of use to modelers. Mathematically inclined readers may be interested in Reinhold Stadler's paper, "Solutions for the Bell-Shaped Lift Distribution."

## Culver

Unfortunately, Irv Culver did not write a comprehensive treatise on his twist formula. Rather, his description of its use is sparse, and its derivation not explained in any detail. Still, it is possible to understand the general thoughts behind Culver's paradigm.

Although Culver did not specifically mention the "middle effect," he did realize that lift of a swept wing is depressed in the area of the root. To compensate, some amount of up trim is required of the outboard elevons, depressing the lift generated by that area of the wing as well. Performance is substantially reduced as a result. In Culver's view, the ideal is to make the center portion of the wing produce more lift and thereby allow the wing tips to create more lift. At the design coefficient of lift, the lift distribution is near elliptical.

Another digression... The most simple method of creating a twisted wing is to use a single foam core and root and tip templates. Twist is then imparted by setting the two templates at the appropriate angles relative to each other. Cutting with a tensioned hot wire always creates a wing with straight leading and trailing edges. This is quick and simple, but the angle of twist does not change consistently across the semi-span. Rather, the angle changes at a more rapid rate near the root for wings with no taper, and near the wing tip if the wing is moderately tapered. As Culver uses wings with moderate taper in an effort to better achieve an elliptical lift distribution, it is the latter situation which Culver wants to avoid.

In an effort to compensate for the loss of lift in the center area of a swept back wing, Culver proposes placing most of the twist in the inboard 30% of the semi-span, say eight degrees. Three more degrees of twist are then imparted in the outer 70% of the semi-span for a total of eleven degrees. The increased angle of attack at the root increases the lift in that area. This allows the up trim of the elevons to be reduced, increasing the lift in that area as well. The Culver twist therefore requires constructing the semi-span of a foam wing in two parts rather than as a single panel.

As the sweep angle is increased, the Culver twist distribution calls for more twist. As the Culver twist distribution is aimed at maintaining an elliptical lift distribution at the design coefficient of lift, this is in keeping with the increased upwash which is anticipated will occur over the outer portion of the wing.

In flight, specially designed elevons are used to trim for low coefficients of lift. As the aircraft approaches a stall attitude, the root will stall first while the wing tips remain well below their stall angle. This makes a full stall across the entire span very unlikely.

There are a few limitations to the Culver twist distribution: it is accurate only for wings of modest sweep and taper, and the recommended design lift coefficient is for very high compared with other methodologies, particularly that of Dr. Walter Panknin. Since the Culver twist distribution is based on maintaining a near elliptical lift distribution, adverse yaw may be noticeable, particularly around the design coefficient of lift.

There are reports stating that swept wing aircraft utilizing the Culver twist distribution are both spin-proof and tumble-proof, and there is also at least one report stating the Culver twist distribution was incorporated into the wings of a number of Boeing commercial aircraft. These reports have not been corroborated by secondary sources, and it should be noted that Boeing commercial aircraft are of conventional tailed configuration and utilize both roll spoilers and rudder to counter adverse yaw.

A six meter (236 inch) span swept wing model using an approximation of the Culver twist distribution was constructed in Germany in 1987. The Stromburg 'wing utilized the Eppler 220 for the outboard portion of the wing and the Eppler 210 at the root, and had a sweep angle of 28.5 degrees. The twist angle at the root was 11.5 degrees, going to zero degrees at station .167 and remaining at zero degrees to the wing tip. Elevons consisted of "Junkers flaps" from station .833 outboard. This model performed extremely well, and was large enough to have a movie camera mounted at the CG and directed at the center section. Films taken during flight showed no air flow separation at the root during cruise, turning, high speed flight, or landing.

## Panknin

Dr. Panknin derived his twist paradigm from a paper by Helmut Schenk. Using airfoil zero lift angles and pitching moments, span and chords, sweep angle and static margin, a pitch stable tailless aircraft can be assured. The method relies heavily on Multhopp's approximation of the lift distribution, but includes a correction by D. Kuechemann so that it has good accuracy for sweep values for zero to beyond 30 degrees. (Schenk states the "middle effect" still exists using these calculations.)

The Panknin methodology provides only the total twist required for longitudinal stability for a given monolithic wing with straight leading and trailing edges and a predetermined static margin. The computed twist values have been proven in practice to be extremely accurate for sweep angles of up to 30 degrees, tapered or constant chord wing.

Like the Culver formulae, the Panknin method lends itself quite easily to both custom written computer programs and commercially available spreadsheet software. In fact, a scientific calculator is sufficient when there are no time constraints. The defined twist angle can be used on a moderately tapered wing using the foam core construction method described previously, with straight leading and trailing edges from root to tip. Successful applications, however, include planforms with constant chord in which the twist begins at station 0.5, half the semispan, placing more of the twist over the outboard portion of the wing.

All of Dr. Panknin's designs, and our own designs based on Dr. Panknin's paradigm, incorporate winglets. These vertical surfaces assist in reducing oscillations in yaw in straight and level flight and act to reduce adverse yaw at the expense of some increase in drag. As we've stated in previous columns, thermal machines seem to climb better with winglets, racers track better with a single vertical fin mounted on the centerline.

## Conclusions

All three twist distributions have both positive and negative aspects.

The Horten twist distribution is based on the work of Prandtl and others, and has been supported by the more recent works of R.T. Jones and Klein and Viswanathan. The Horten paradigm has the potential to reduce induced drag and eliminate adverse yaw, but is computationally intensive and the twist distribution itself must be used in combination with a number of additional planform attributes.

The Culver twist distribution is centered on the elliptical lift distribution. This is a conservative approach which provides relatively low drag and good efficiency within a confined design point, but may be prone to adverse yaw, particularly when operating at the design coefficient of lift.

The Panknin twist distribution has proven itself over a nearly two decade period to be an accurate determiner of both required wing twist and center of gravity location. It has been used with great success by a very large number of international designers. Its major limitation is that it calculates only the twist required for pitch stability, but it can be used as a fundamental method of determining the approximate minimum twist required for a preliminary design.

Figure 2A shows the elliptical lift distribution for a conventional cross-tailed design as seen from behind. The fuselage and vertical surface have been neglected. Figure 2B shows the downwash pattern this lift distribution produces. Keep in mind the internal structure of the wing is required to support both itself and a fuselage and tail structure. Additionally, the fuselage must be strong enough to support itself and the mass and aerodynamic loads of the tail.

These factors, taken in combination, paint a picture of a relatively heavy aircraft with substantial surface and interference drag. Additionally, there is the surface and induced drag of the separate relatively low aspect ratio horizontal and vertical stabilizers. In flight, large amounts of drag are created in an effort to make coordinated turns. Given this perspective, the possibility of more efficient aerodynamics, as seen in Figure 2C, is obvious.

While a specially tailored single surface wing may be necessary to achieve this goal, a well integrated design approach for tailless aircraft is certainly very close, as demonstrated by the recent articles by Katherine Diaz in *Pilot Journal* and Carl Hoffman in *Popular Science*. It is only a matter of time before such design paradigms and appropriate construction technologies are available to modelers.

When designing a tailless planform, the type of twist distribution to be used should be one of the first decisions to be considered, and always relative to other aspects of the design such as prescribed task, design lift coefficient, and planform. There are a number of design “flowcharts” available to assist the novice designer, and we very much encourage readers to investigate their usefulness. The information presented in this series can be used to augment these resources and assist in developing viable, and perhaps cutting edge, designs.

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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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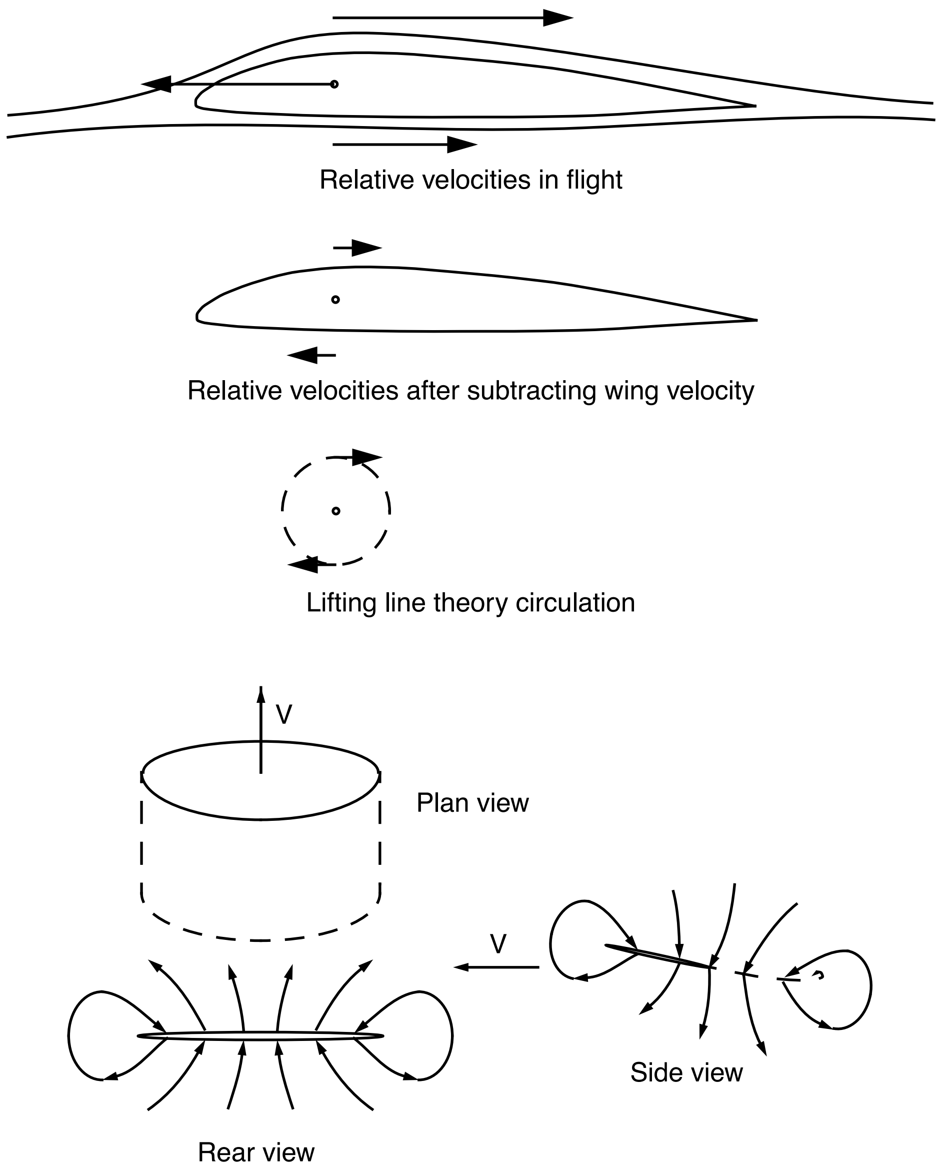



Three dimensional circulation as wing accelerates from rest

Figure 1

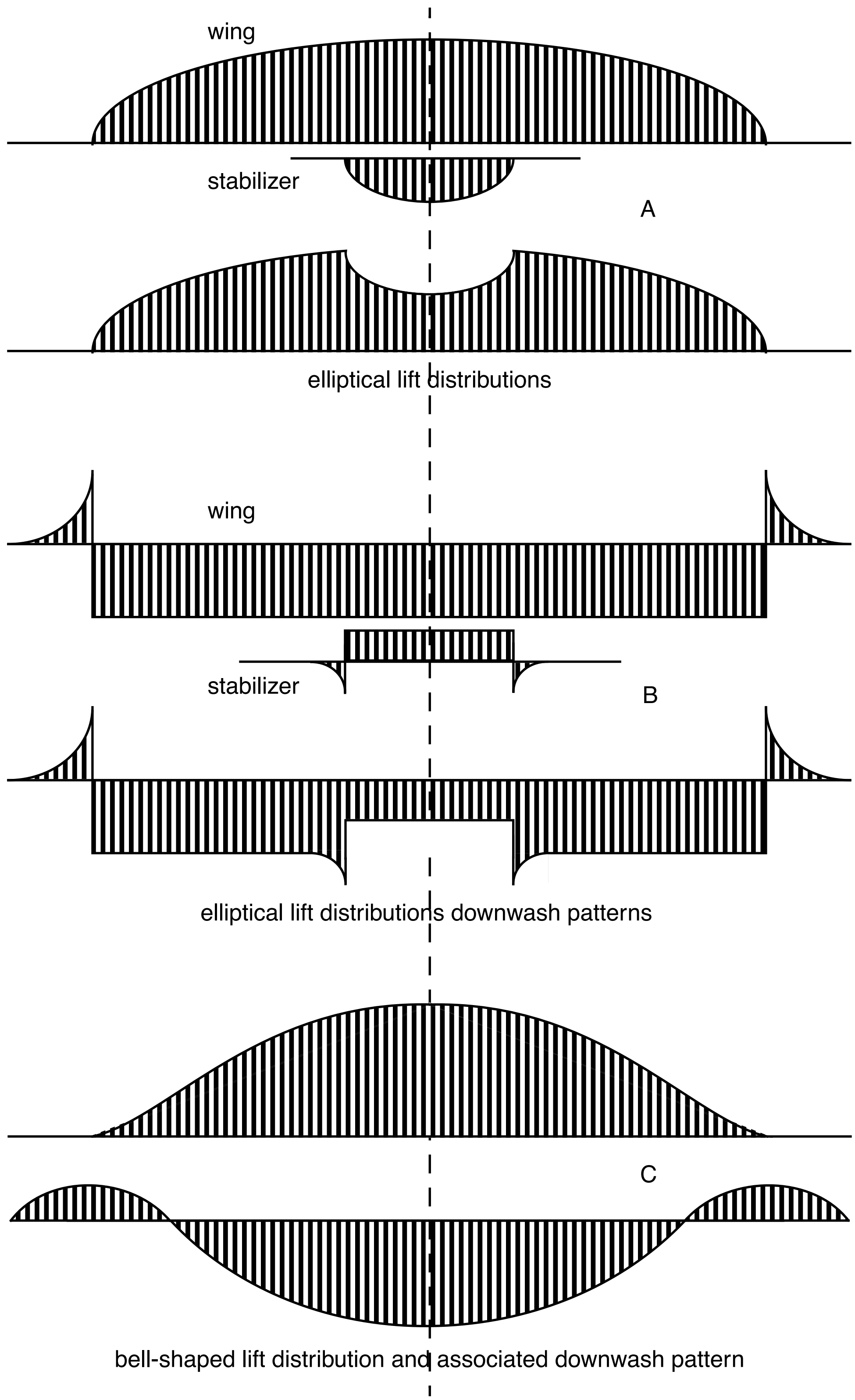
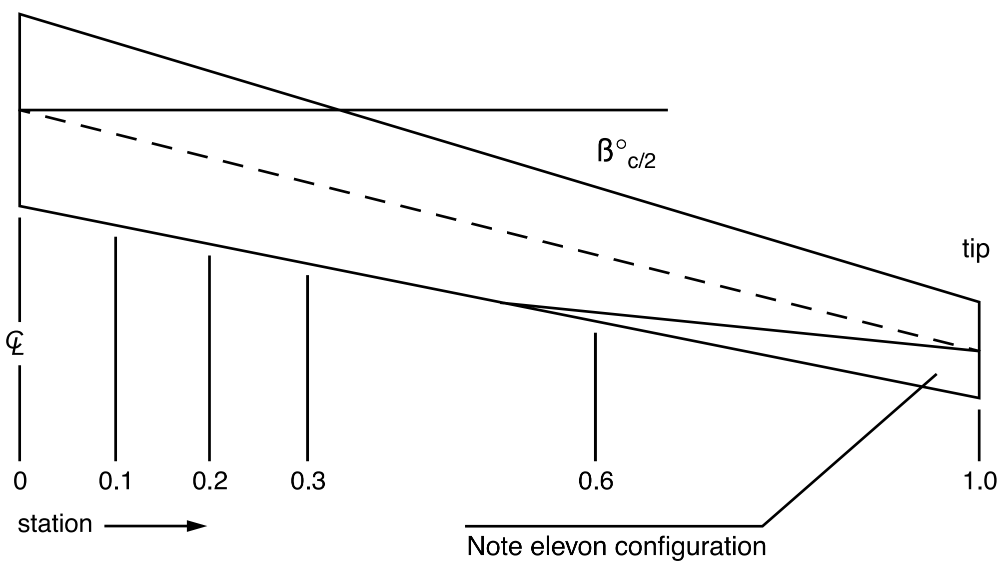

wing
stabilizer
A
elliptical lift distributions
wing
stabilizer
B
elliptical lift distributions downwash patterns
C
bell-shaped lift distribution and associated downwash pattern

Figure 2

## Culver Twist Formulae:

$$\alpha^\circ_{RT} = C_{L_D} \times \beta^\circ_{\frac{1}{2}C} \times \pi \times \left(1 - \frac{1}{AR+1}\right) \times \frac{1}{\left(\frac{2\pi}{1 + \frac{2}{AR}}\right)}$$

$$\alpha^\circ_S = \alpha^\circ_{RT} \times \left[(1 - station)^{\left(\frac{AR + 2\pi}{2\Pi}\right)}\right]$$




Where:

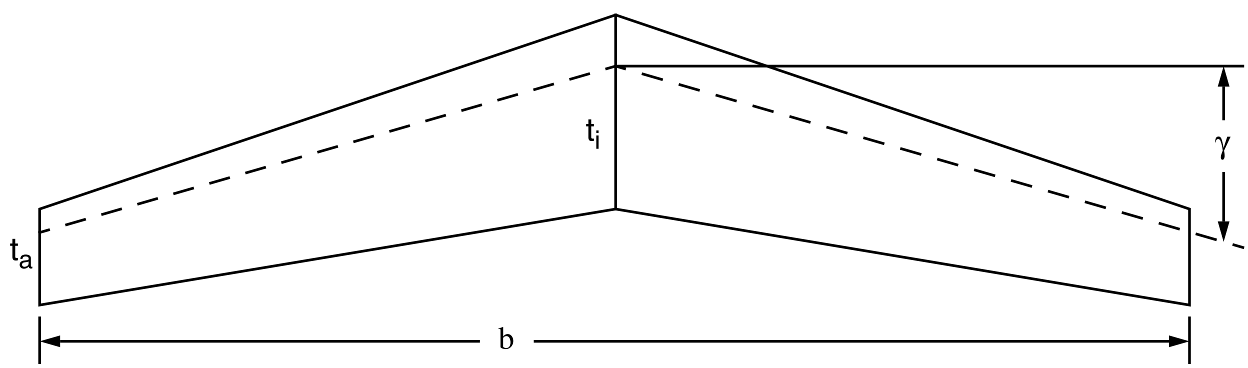
| | |
|---|---|
| $C_{L_D}$ | = design $C_L$ for twist computation |
| AR | = aspect ratio of the complete wing |
| ß° | = sweep angle of the c/2 line in degrees |
| $\alpha^\circ_{RT}$ | = total twist angle of the zero lift ($\alpha_{L0}$) lines from root to tip in degrees |
| $\alpha^\circ_S$ | = angle of the zero lift ($\alpha_{L0}$) line at any station relative to the tip zero lift ($\alpha_{L0}$) line in degrees |
| (1 - station) | $= 1 - \left\{\frac{\text{distance out from ℄}}{\text{span/2}}\right\}$ |

Notes: Method works best with taper ratios which approximate elliptical chord distribution and with moderate sweep angles (around 20 degrees). $C_{L_D}$ should be 0.8 for machines designed for speed, 1.0 to 1.2 for high performance sailplanes. Elevon configuration imposes little drag penalty when trimming for flight at lower $C_L$ values.

## Panknin Twist Formulae:

$$\alpha°_{total} = \frac{(K_1 \cdot C_{M_i} + K_2 \cdot C_{M_a}) - (\bar{C}_L \cdot St)}{1.4 \cdot 10^{-5} \cdot \lambda^{1.43} \cdot \gamma}$$

$$\alpha°_{geo} = \alpha°_{total} - (\alpha_{L0root} - \alpha_{L0tip})$$




Where:

b = wing span
$t_i$ = root chord
$t_a$ = tip chord
$\lambda$ = aspect ratio, $b/t_m$
$\gamma$ = angle of sweep back, measured at quarter chord
$C_{Mi}$ = root moment coefficient
$C_{Ma}$ = tip moment coefficient
$\bar{C}_L$ = aircraft coefficient of lift
St = static margin, decimal value
$\tau$ = $t_a/t_i$, taper ratio
$t_m$ = $(t_a + t_i)/2$, average chord
$K_1$ = $1/4 \cdot (3 + 2\tau + \tau^2)/(1 + \tau + \tau^2)$
$K_2$ = $1 - K_1$

Note: $K_1$ and $K_2$ are factors derived by Schenk and depend on taper ratio

Notes: Assures pitch stability for given static margin only. Gives designer full control over airfoil choice and other parameters. Accurate over a wide range of taper ratios and sweep angles, including forward sweep.