Tailless Flying Wings

By Irv Culver

During the past 50 to 60 years the author has observed several airplanes, gliders and sailplanes of tailless design. The impression received is that little is commonly known about the aerodynamics, flight dynamics or aerolastics of tailless designs.

Everything has good and bad elements. All aircraft designs naturally exhibit good and bad design characteristics. Within this paper we will discuss only the bad elements of tailless designs and how to make them better.

TUMBLING

The first critical concern is the possibility of tumbling. The author made a theoretical study of tumbling (i.e., auto rotation in pitch). The technical explanation of this phenomenon is that pitch damping becomes negative for some designs at high values of Θ/V where Θ = pitch angular velocity and V = forward speed. A lay explanation of this is: for some designs pitch tumbling will occur if rapid nose-up pitch is applied at low speed, or if the design has a nose up hook in the pitching moment curve at high angles of attack. **(Figure 1)**

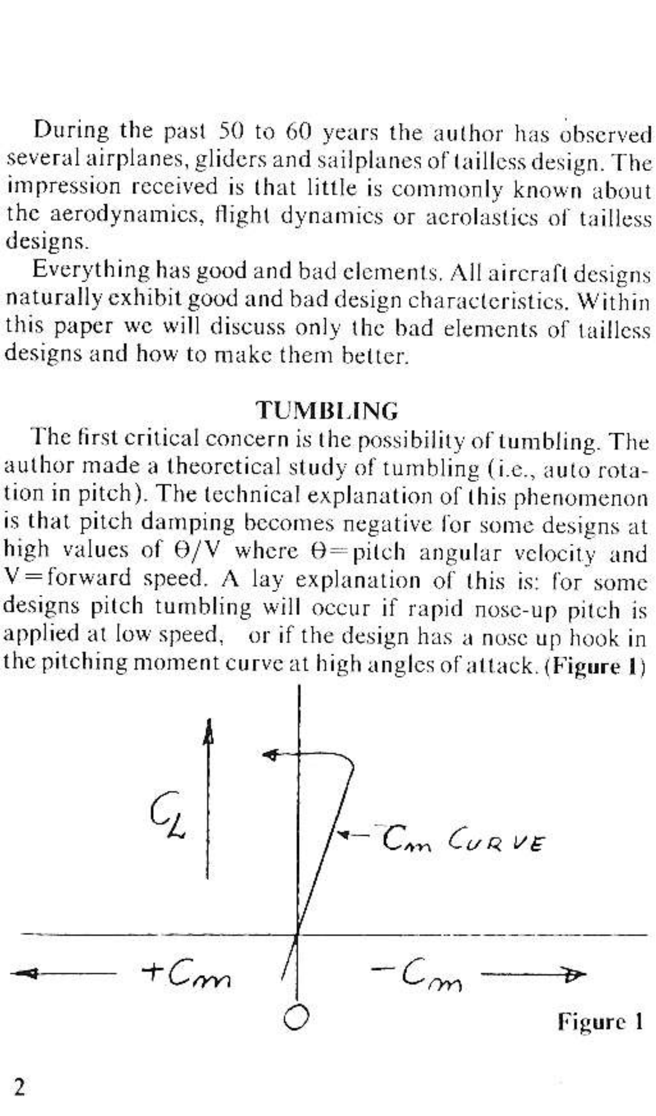


Figure 1

The reason tumbling is a problem is that the machine gets trapped in its own lift circulation or vortex. The tumbling study suggested that a simple criteria for the border line between tumbling and not tumbling, for the case of the CG in the wing chord plane vertically and at 25% of the MAC, was $D/C = 2$ where C is the *average* chord and D is the trailing edge kink dimension. **(Figure 2)**

Figure 2

About twenty cardboard models were made to check the theory, with varying values of AR (aspect ratio), sweep and taper ratio. These models approximately confirmed the theory. That is, anything less than $D/C = 2$ could tumble if adequate pitch rate was applied at low speed.

Next, the effect of vertical offset of the CG: for CGs of "1" average chords above or below the chord, plane tumbling if induced would not continue. Further studies of the effect of vertical CG offset may be in order.

PITCH AND YAW DAMPING

The second bad factor is the lack of pitch and yaw damping from the pilot's point of view. Some pilots have no adverse comments to make about the handling qualities of tailless designs. This is especially true of helicopter pilots, since they are used to machines with "0" or negative damping. However, many pilots are prone to PIO when under adverse conditions, like rough air in a machine with low pitch or yaw damping. High sweep angles alleviate this problem.

SPAN-LOADING

The third problem is the poor span-loading achieved by twisting the wing using straight leading and trailing edges. For a tapered wing this gives a twist distribution that looks like **Figure 3** if you hold the tip at 0 angle.

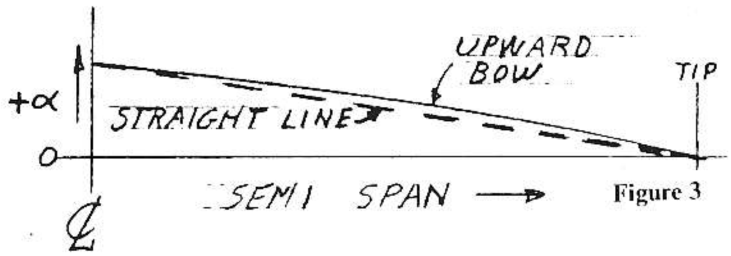


Figure 3

The reason for the upward bow is that for straight leading and trailing edges the vertical offset difference of these edges due to twist is proportional to the span, but to find the twist angle you must divide this local offset by the local chord. Now the optimum twist distribution for a swept-back wing looks like **Figure 4**. If you superimpose these two curves you get a picture like **Figure 5.**

Figure 4

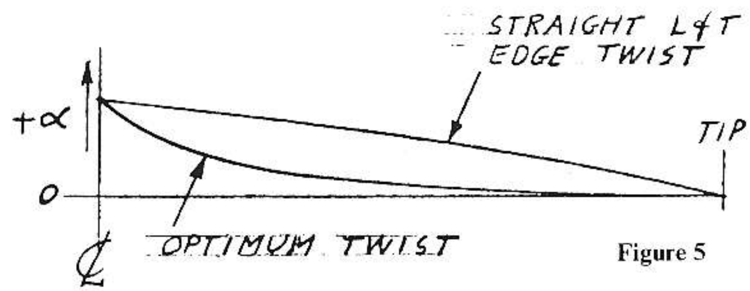


Figure 5

The straight leading and trailing edge twist results in a span loading for a swept-back wing that looks like **Figure 6** when trimmed in pitch. You must push down at the tips to balance the loss of lift at the C_L to trim in pitch.

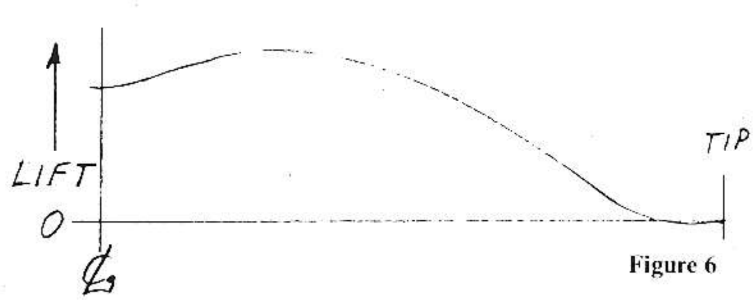


Figure 6

Now the minimum C_{Di} (induced drag) corresponds to a span loading that looks like **Figure 7.**

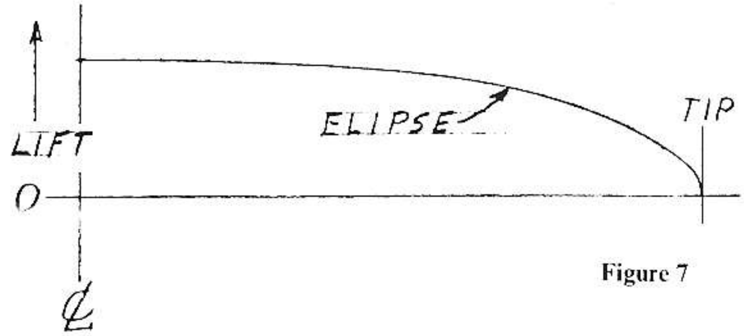
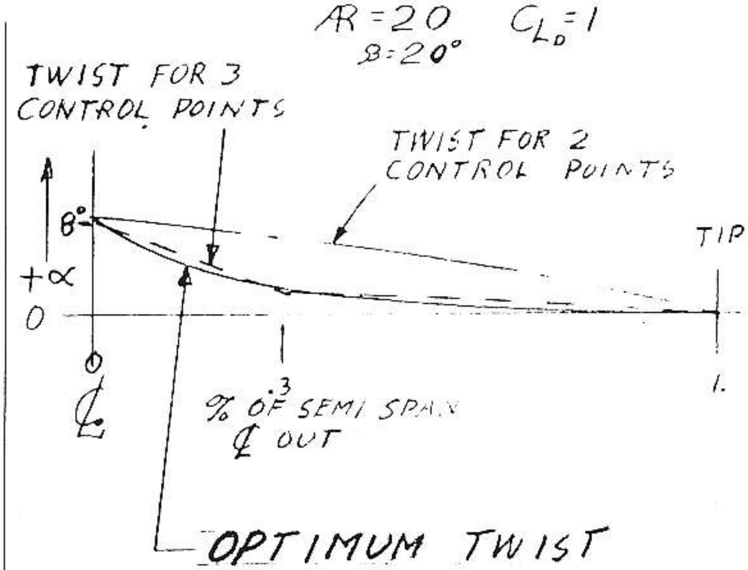
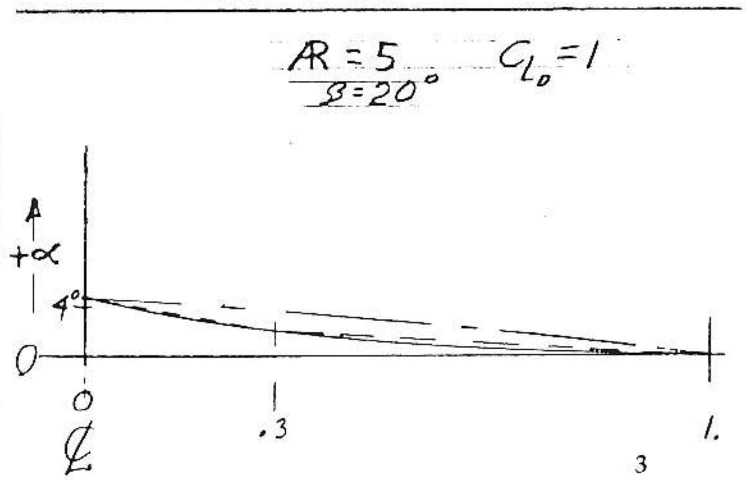


Figure 7

If you restore the lift near the C_L you will not have to push down at the tips. So why not twist the wing appropriately to achieve this optimum span loading and reduce the induced drag? The question is: why put span on a machine and then drastically reduce its effect? The answer appears to be that it is not simple to build a wing with the optimum twist distribution. A compromise using three control points, like root and tip plus one at 30% out from C_L and twisting around the main spar. This would produce a wing with almost perfect twist distribution without much additional work.

Figures 8 and 9 show optimum twist for two wings of widely different aspect ratios, both for a sweep angle at the 50% chord of 20° and designed to optimum at lift coefficients of 1. It is apparent that twisting with 3-control points comes very close to optimum twist distribution, whereas 2-control points gives large errors.





The author wracked his feeble brain to reduce the complicated theory to a practical set of equations for near optimum twist of swept-back wings of modest taper ratios (near elliptical chord distribution). The simplified equations do not go to an infinite angle at the C_L like the basic theory. Who knows what an infinite angle looks like?

The simplified equation are broken into two parts: total twist root to tip for the chosen design C_{LD} and an equation for the distribution of the twist. These equations deal with the twist of the 0 lift lines (α_{LD}) of the airfoils. If you are using airfoils from a handbook you can find (α_{LD}) by looking at the characteristics **(Figure 10).**

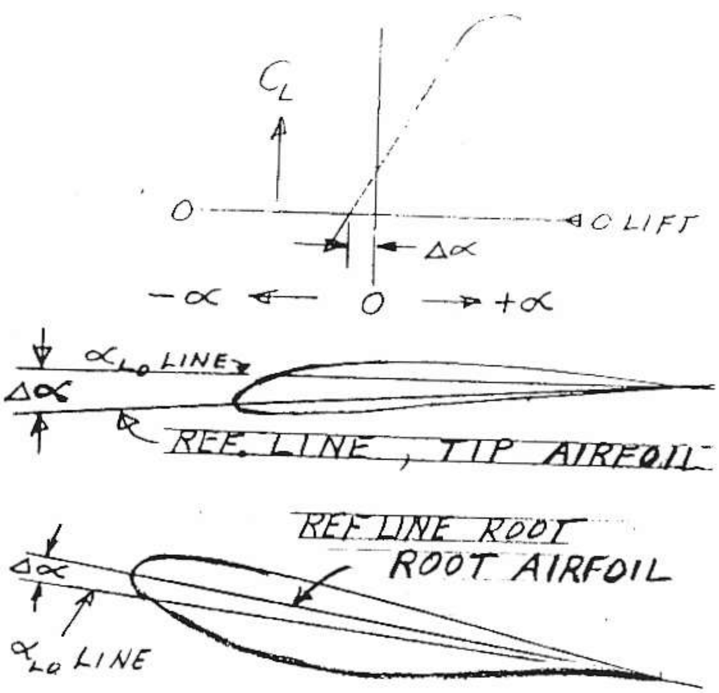


Figure 10

It "looks" inverted and it *is!* Avoid use of any airfoil with a high C_{mo}. The airfoil at approximately 30% of the span out from the C_L *could* have a slight forward camber, but not inverted.

The design lift coefficient C_{LD} should be chosen to match the intended use between .8 and 1.4. Use .8 if high speed only is the goal. The author suggests 1 to 1.2 for high performance machines since the penalties are small if tapered elevons are used to trim for high speed (**Figure 11**).

Nomenclature:

C_{LD} = Design C_L for twist.

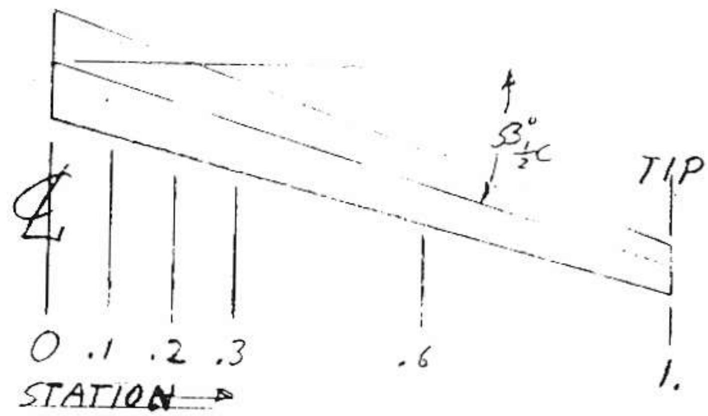
AR = aspect ratio of the complete wing

$\beta_{\frac{1}{2}c}^\circ$ = sweep angle of the ½-chord line in degrees

α_{RT}° = total twist angle of the 0 lift (α_{LO}) lines from root to tip in degrees

α_S° = angle of the (α_{LO}) line at any station relative to the tip (α_{LO}) in degrees

$$(1\text{-station}) = 1 - \frac{(\text{distance out from } C_L)}{\frac{1}{2}\text{ span}}$$



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

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

THIS IS THE EXPONENT TO (1-STATION)

AEROLASTICS

The next serious flight concern involves aerolastics. As you increase the wing sweep to improve handling qualities and reduce the possibility of tumbling, you increase the aerolastic coupling between wing flap bending and pitch thereby resulting in reduced pitch static stability at high speed.

An explanation in technical terms: If the wing tip is bent up at some angle Θ in the front view, the sweep angle β makes the apparent angle α of the tip change as seen by the air. First order equation (all angles in radians):

$$\Delta\Theta\beta \int \Delta\alpha$$

where $\Delta\Theta$ is an angle of deflection of the outer wing in bending, β is the sweep angle of the ¼ chord, and $\Delta\alpha$ is a change in angle of attack due to the elastic deflection angle $\Delta\Theta$. This effect is not serious unless you want to go fast with large sweep and high aspect ratio thin wings, and possible with glass spar caps.

The way to alleviate this problem is to mass (dynamic, not static) balance the elevons only at the tip for first mode symmetric flutter. This makes the elevons trailing edge heavy for the static pitch divergence mode, such that positive maneuvering tends to put the trailing edge down thus counteracting the nose-up tendency created above. A bob weight on the stick will also help (i.e., up acceleration results in nose-down stick forces). Additionally, designing the control runs in the wings out to the elevons so that up bending causes the trailing edge of the elevons to go down aids the situation.

Another explanation in physical terms might be, obviously, if you bend the wing up, the top surface of the wing shortens and the bottom lengthens. Therefore if you run wires out to the wing to the elevons (with the upper wire as close to the top of the wing as practical and the bottom wire close to the bottom and with the top wire going to the top horn on the elevon and the bottom to the bottom horn) then if you bend the wing *up* the trailing edge of the elevon will go *down*, offsetting the effects of the sweep.

Now, a few random notes. Swept-back wings have excessive roll due to yaw $+C_{l\beta}$ so I suggest using bent-down tips for fins and rudders. These could be cranked as much as 45°. Bent tips at 45° are so powerful in producing $-C_{l\beta}$ that the wing can have some dihedral to give ground clearance as indicated both by theory and paper model tests. Going up with the wing and down at the tip with 45° gave more ground clearance at the tip for the same roll due to yaw than vice versa. More sweep, more CG range, better handling qualities obviously should yield better performance for a flying wing configuration.