on the Wing
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Twist Distributions for Swept Wings, Part 2

Having defined and provided examples of lift distributions in Part 1, we now move on to describing the stalling patterns of untwisted and twisted wings, determining the angle of attack as from the location of the stagnation point, and how wing sweep affects the angle of attack across the semi-span.

Before officially starting this month's installment, we need to clarify something we covered in Part 1. In the section titled "Lift coefficient distributions," sentence four should read as follows: "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." The underlined words need to be added. One could argue that, at least from a mathematical standpoint, if any local portion of the wing has an infinite coefficient of lift ($c_l = \infty$) then the coefficient of lift for the entire wing will be infinite ($C_L = \infty$), but that reasoning does not explain the local condition at the wing tip in an easily understood way. We hope the additional wording makes the situation more clear.

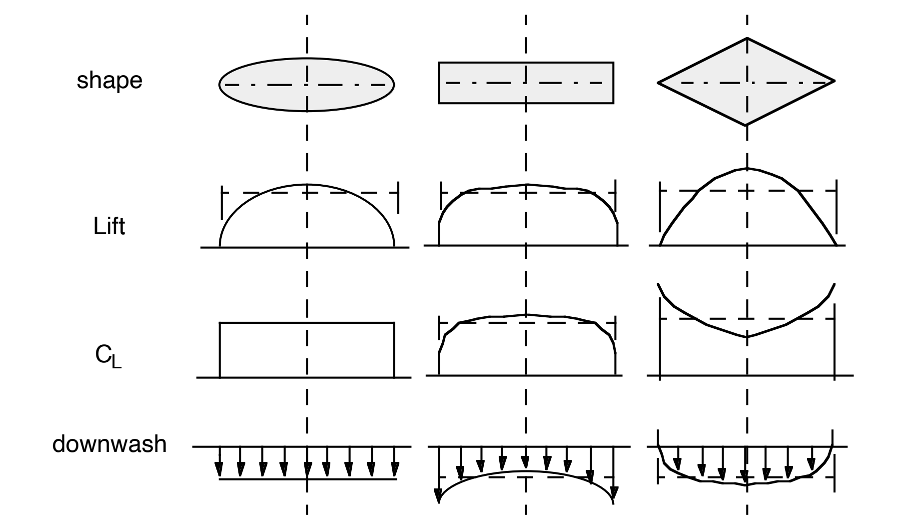

Figure 1. Three wing planforms and their associated lift distributions, coefficient of lift distributions, and downwash distributions.

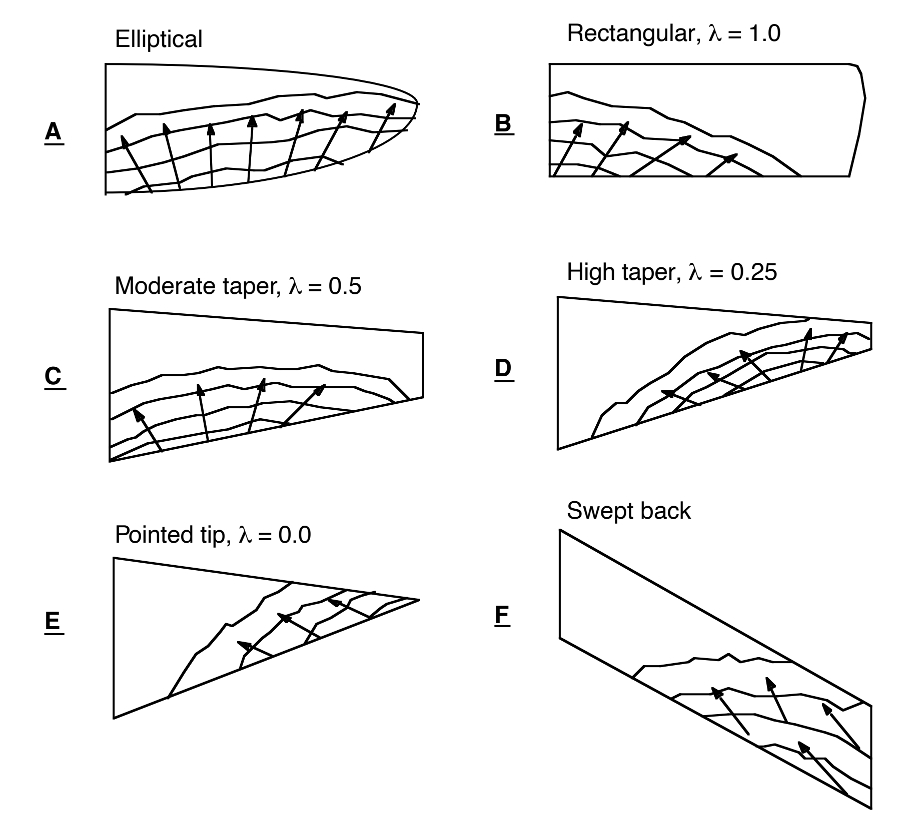

Figure 2. Stalling patterns of various untwisted wing planforms.

Stalling patterns for untwisted wings

The lift generated by any wing segment is a product of the local coefficient of lift and the local chord length. Referring to Figure 1 (a reprint of Figure 4 from Part 1) we can see the results of this formula as applied to three wing planforms. The ideal lift distribution is the elliptical as shown in the left column. Note the local coefficient of lift (c_l) is identical across the entire span, as is the downwash. While the elliptical wing planform is efficient, it is difficult to build and, because the c_l is the same across the span, all segments of the wing are equally susceptible to stalling. See Figure 2A.

The rectangular wing, with its constant chord, Figure 2B, tends to stall at the root first. This is because the local coefficient of lift progressively decreases for those wing segments nearer the tip. This takes some of the load off them, inhibiting stalling. Note also from the middle column of Figure 1

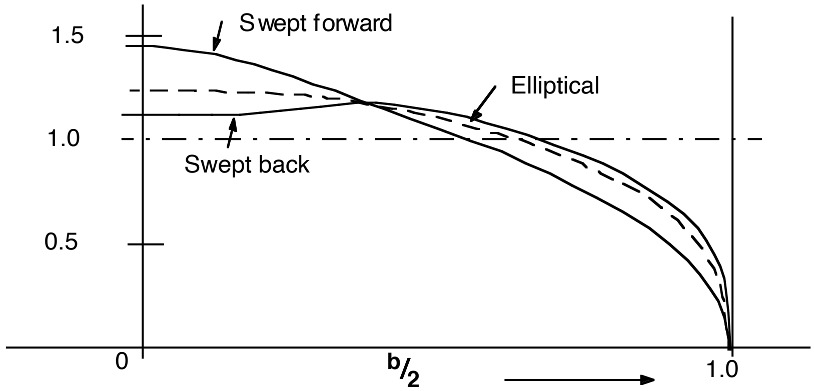

Figure 3. Representative lift distributions for swept forward and swept back wings compared to ideal elliptical lift distribution.

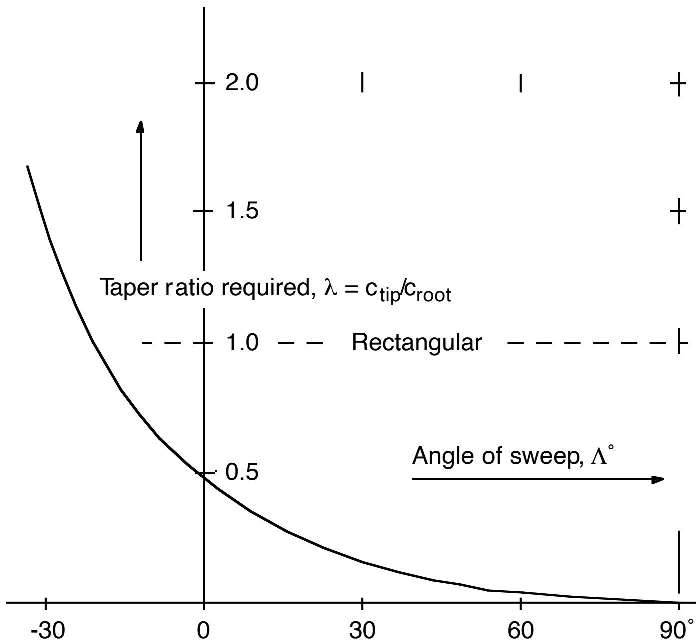

Figure 4. Taper ratios theoretically required for near-elliptical lift distribution for swept wings.

that the rectangular wing tip vortex is quite large, indicating substantial outward flow across the lower surface, and substantial inward flow across the upper surface.

The diamond planform (right column Figure 1 and Figure 2E), unless in a vertical dive ($C_L = 0$) is stalled to some extent at all times. Note that although the local coefficient of lift at the wing tip tends to be infinite, the actual amount of lift generated is very low because of the diminishing chord, and the downwash in the tip region tends to zero. The stalling pattern for this wing planform grows inward from the trailing edge of the wing tip and toward the leading edge. From this information, it does not seem like a delta wing would be useful, but the airflow over a severely swept wing, which a delta is, is far different from the airflow over the straight wing described in this instance.

Wings with large to moderate taper ratios, $\lambda = \sim 0.4>$, have stalling patterns approaching that shown in Figure 2C and tending toward that of the rectangular wing planform (Figure 2B). Wings with small taper ratios, $\lambda = <\sim 0.4$, have stalling patterns approaching that of the highly tapered planform shown in Figure 2D and tending toward that of the diamond wing planform, Figure 2E.

The most interesting stalling pattern, however, is that of the swept back wing, as depicted in Figure 2F. Although the wing tip has the same chord as the root, the stalling pattern is entirely different than that of the unswept rectangular wing.

Lift distributions and stalling patterns of swept wings

Figure 3 compares the elliptical lift distribution with representative lift distributions for swept forward and swept rearward wings. The swept back wing shows an increase of lift near the wing tips and a noticeable depression of lift near the wing root. The swept forward wing shows an increase in lift near the wing root, and depressed lift near the wing tip.

Before speaking to why this is so, it should be mentioned that we can attempt to tailor the lift distribution of swept wings to closely approximate the lift distribution of the elliptical planform by modifying the taper ratio. Figure 4 shows in graphical terms the taper ratios required for this approximation as based on the sweep angle.

While we can modify the lift distribution to more closely match the elliptical ideal by adjusting the taper ratio, the stalling pattern does not appreciably improve. The stalling pattern still tends to grow inboard from the wing tip. This is seen in Figure 5.

The swept back wing, when stalled, tends to pitch up into a deeper stall as the center of lift moves forward when the rear of the wing is stalled. As the (elevon) control surfaces are normally placed outboard, they are in a stalled region of the wing. A swept forward wing will suffer from a somewhat similar malady. When the root of a swept forward wing stalls, the wing tips remain unstalled and the center of lift moves forward, pitching the nose up. Aileron control is maintained, but at the expense of a possible severe pitch up and deep stall.

Despite having identical root and tip chords and sharing what some would consider dangerous stall behavior, we bring up these two cases as an example of how sweep can effect the air flow over the wing. The two swept wings in this example have different stall patterns caused by the imparted sweep.

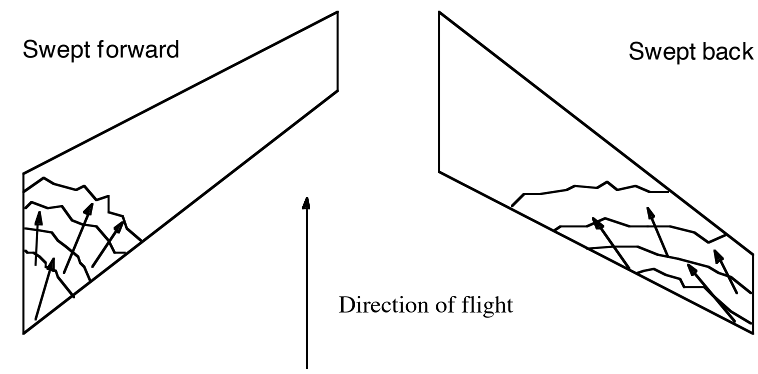

Figure 5. Stalling patterns of swept back and swept forward untwisted wing planforms.

Sweep and angle of attack

An airfoil which is creating lift demonstrates three important characteristics:

- The air going over the top of the section accelerates, the air going along the bottom decelerates. If the smoke stream is pulsed, these velocity differences are easily seen. Figure 6 was derived from a smoke tunnel photograph using this methodology. The acceleration differential is seen in the varying size of the pulses and the varying distances between them. (Some mixing of the smoke with clear air takes place because of turbulence caused by the boundary layer interfacing with air which is moving more rapidly.)
- The air rises toward the section as it approaches the leading edge. This is seen in Figure 6 as well. This portion of the air flow is called the "upwash."
- The air is deflected downward aft of the airfoil section. The section acts as a vane, turning the air stream downward. Termed "downwash," this flow is an important consideration in the design of conventional tailed aircraft as it influences the size and placement of the horizontal stabilizer.

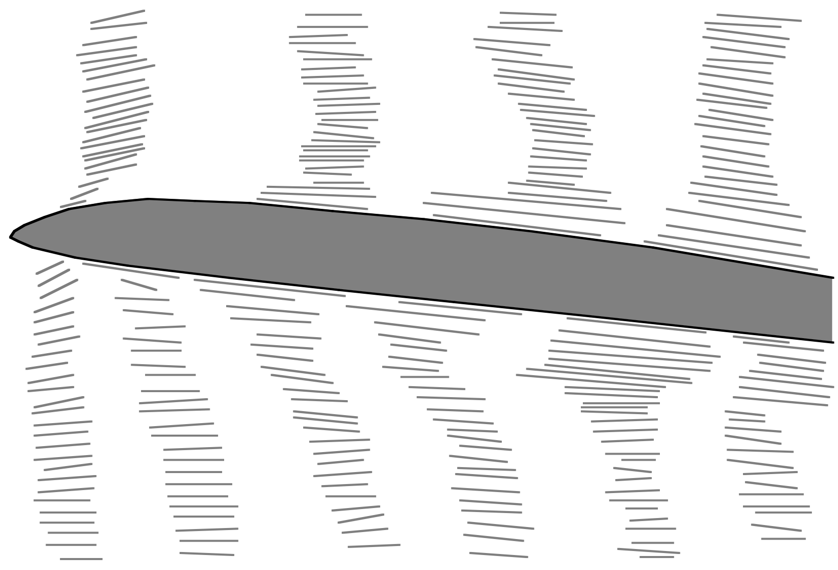

Figure 6. Air flow over a section as visualized through pulsed smoke streams.

Going back to the second characteristic, there is a point near the leading edge where an air molecule actually comes to rest at the airfoil surface. This point is termed the stagnation point, and its location can be used to determine the section angle of attack. As the angle of attack increases from the zero lift angle, the stagnation point moves further aft along the bottom of the airfoil. See Figure 7.

The air flow around a straight wing with an elliptical lift distribution is such that the location of the stagnation point remains consistent across the semi-span. On a swept back wing, we find any segment of the wing has an effect on the upwash of the section immediately downstream and hence outboard from it. The stagnation point thus moves rearward along the bottom of the lower surface, indicating an increasing angle of attack toward the wing tip. Figure 8 provides an exaggerated illustration of this behavior on an untwisted wing. Because of wing sweep, the effective angle of attack at the wing tip is greater than the effective angle of attack at the wing root. It's little wonder the wing tips are proportionally overloaded and subject to stalling.

To maintain a constant angle of attack across the entire span, some amount of washout (leading edge down) must be imparted to the outer portion of the wing. This will reduce the tendency of the wing tips to stall first.

A note about washout

On a conventional tailed sailplane, it is common practice to place some amount of washout in the outer wing panel(s) to assist in reducing the tendency to "tip stall." The problem with this methodology when used on a straight wing is that each spanwise wing segment is seeing the air approaching at the same angle, and the local angle of attack as defined by the location of the stagnation point is entirely dependent upon the segment angle of incidence. When the entire wing is called upon to generate very small coefficients of lift the root is flying at a relatively small angle of attack, and the wing tips may be flying at an angle of attack which is below the

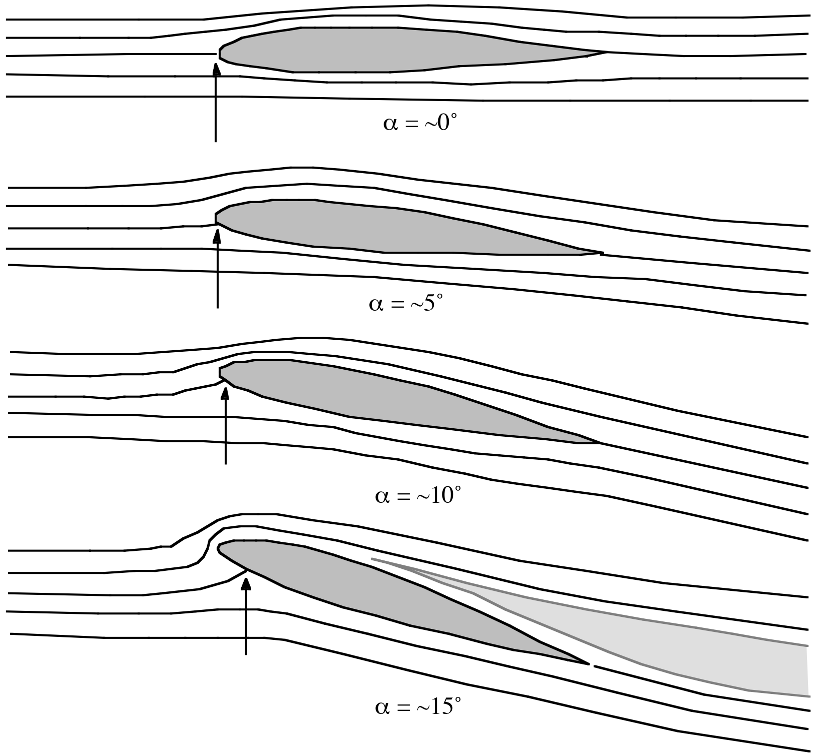

Figure 7. Rearward movement of the stagnation point and increased upwash ahead of wing with changes in angle of attack.

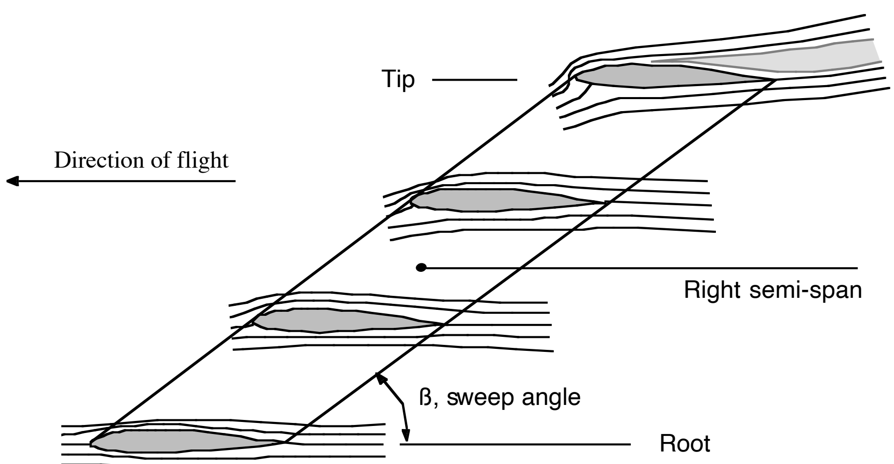

Figure 8. Movement of the stagnation point and changes to effective angle of attack along the semi-span of a swept back wing, exaggerated.

zero lift angle. The wing tip then generates lift in the downward direction. In the 1920's and 1930's, when sailplane designers were building wooden sailplanes with higher and higher aspect ratios, wings with insufficient torsional strength were destroyed by the aerodynamic forces generated by excessive wing twist.

On a swept back wing, the angle of attack as seen by each wing segment increases toward the wing tip. For a specific coefficient of lift, washout can therefore be used to correlate the angle of attack of the wing tip with the angle of attack of the wing root. At some particular speed (C_L) the entire wing will be operating at the same local coefficient of lift (c_l) across the entire span. This is not quite as good as the lift distribution of an elliptical wing, which remains elliptical over a very large range of speeds, but it is a definite improvement over an untwisted swept wing. So long as the root is developing lift, the outboard segments will continue to see an increasing upwash. While required torsional strength is dictated by both sweep and twist, it is handled well with modern design and construction materials and methods.

Are swept wings worth the effort?

From what we've said thus far, it would seem like getting a swept wing to perform in a fashion similar to the elliptical lift distribution, with its accompanying efficiency, would require a major effort. After all, the lift distribution is now dependent upon three variables — sweep, taper and twist — rather than simply taper and twist alone as with a straight planform. The addition of sweep to the design environment magnifies the number of complex computations required.

At this point in our discussion, it would appear the only clear advantages to be derived from a tailless swept wing planform would come from either drag levels lower than those of a conventional tailed airplane or improved handling characteristics, both of which have the potential to significantly improve performance.

Whether the gains to be achieved are worth the time and effort involved in obtaining them has always been open to question. A synthesis of concepts and technology may change that balance in the future. There are avenues of approach, first presented decades ago, which now look quite promising. The advent of low cost supercomputers which are able to quickly run the sophisticated software required to handle exceptionally complex iterative processes is bringing recent advancements in computational fluid dynamics to creative individuals outside the formal aircraft industry.

What's next?

As we mentioned in Part 1, there are three major hurdles to be overcome in order to design an efficient swept wing: (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; (3) maintain an acceptable weight to strength ratio.

This column has focused on the first of these difficulties, and it would appear there may be acceptable solutions available. However, it would be quite valuable to not only achieve the high efficiency of the elliptical lift distribution, but to surpass it. Surprisingly, achieving that elusive goal may be one of the results of solving the second problem, the topic of the next installment.

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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