Twist Distributions for Swept Wings, Part 3

In Part 1 we defined and provided examples of lift distributions. Part 2 examined stalling patterns of various planforms and introduced the notion that sweep angle and coefficient of lift can affect the angle of attack of outboard wing segments. Three consistent themes have been underlying the discussion thus far: (1) achieve and hopefully surpass the low induced drag exemplified by the elliptical lift distribution without creating untoward stall characteristics, (2) reduce adverse yaw created by aileron deflection without adversely affecting the aircraft in pitch, and (3) maintain an acceptable weight to strength ratio. In Part 3 we will describe a method of achieving the second goal.

Sweep and twist

Figure 1 (reprint of Figure 8, Part 2) shows the increasing upwash which affects outboard segments of a swept untwisted wing as it produces lift. Although exaggerated in the diagram, the overall tendency is clear and does appear in practice.

While there are several ways of reducing the tendency for the wing tip to stall, like careful consideration of airfoils or addition of wing fences, there are advantages to imparting some twist to the wing in the form of washout (leading edge down).

Figure 2 illustrates the case where the wing is twisted such that each wing segment has the same angle of attack as related to the oncoming air flow. Since the increasing upwash ahead of the wing is directly proportional to the amount of lift produced by inboard wing segments, this illustration is obviously accurate for only one aircraft velocity and attitude. The general concept is, however, very important.

Vectors

Mass, length, pressure and time can be defined by single real numbers. The length of a spar for a two meter sailplane, as an example, may be 39 inches. As there is a unit of measurement, inches in this case, the spar length is a scalar quantity. The number which provides the magnitude, 39, is considered a scalar.

Force, on the other hand, has both a magnitude and a direction, and is therefore classified as a vector quantity. A five pound brick resting on a table in a gravitational field may be represented as shown in Figure 3A and 3B. If another five pound brick is placed on the first brick, the situation can be depicted as in Figure 3C. Note that the arrowhead always indicates the direction of the force, while the length of the line indicates the magnitude of the force.

There are two basic forces of interest to aerodynamicists - lift and drag. In a wind tunnel, the investigator may measure the lift and drag of the airfoil by setting up two scales. One scale will measure the lift generated by the section through a balance system which has its axis vertical to the tunnel test section and hence the air flow. Another scale is set up with its axis parallel to the air flow to measure drag.

The investigator can rotate the airfoil section through negative and positive angles of attack relative to the air flow. As the angle of attack increases or decreases, both lift and drag will vary. Regardless of the angle of attack, generated lift is always measured perpendicular to the air flow and drag parallel to the air flow.

Figure 4A demonstrates how two vectors having the same source may be resolved into a single vector by constructing a simple parallelogram. Since lift and drag are always perpendicular to each other, they can always be resolved into a single vector by means of a rectangle (a parallelogram which has intersections of 90 degrees).

We can also perform this operation in reverse. That is, given a single vector and the angle(s) of the parallelogram, the separate component vectors may be derived

As an example, we know that the lift vector is always perpendicular to the air flow and the drag vector is always parallel to it. By constructing the requisite rectangle on the resultant, we can define the lift and drag vectors. This process is shown in Figure 4B. We can perform a similar procedure on the weight vector, thereby establishing two separate component vectors — one parallel to the direction of flight and one perpendicular to it.

The upper illustrations in Figure 5 provide a depiction of the vectors involved in sustained, constant velocity flight. The upper illustration, Figure 5A, shows a powered aircraft in straight and level flight. The weight of the aircraft, W, is counteracted by the generated lift, L. The drag, D, is counteracted by the generated thrust, T. There is a single vector, R_1, which can represent the combined lift and drag forces, and a single vector R_2 which can represent the combined thrust and weight vectors.

These two resultant vectors are calculated by constructing a parallelogram using the two known vectors. R_1 and R_2 are of equal magnitude and opposite direction in this case, and the aircraft is therefore flying at a constant velocity. If thrust is increased, as shown in Figure 5B, the T vector length increases, indicating increased thrust, thus changing the shape of the parallelogram. The aircraft accelerates horizontally. To maintain straight and level flight after application of additional thrust, aircraft trim must be adjusted so the wing continuously generates only enough lift to exactly match the aircraft weight. R_2 becomes longer and rotates forward. The drag force D then increases as the aircraft velocity increases. Drag will increase until it exactly matches thrust — R_1 becomes the same length as, and in opposite direction to, R_2. Once drag and thrust are again equal, the aircraft is once more stabilized in straight and level flight. The aircraft velocity will be greater and constant, the amount of lift will be unchanged, the coefficient of lift will be lower, and the wing will be operating at a lower angle of attack.

The lower illustrations in Figure 5 depict the case of a powerless aircraft of the same design. It is in gliding flight. In Figure 5C the aircraft is moving forward at a constant velocity and slight downward angle. We know the direction of the air flow, so R_1 can be resolved into the lift and drag vectors which are perpendicular to each other, as described previously. The resultant vector, R_1, is of exactly the same magnitude as R_2 and in the opposite direction, so the aircraft is flying at constant velocity. There is no engine to generate thrust so the weight W alone forms R_2. R_2, however, can be dissociated into two component vectors. One component vector, parallel to D, can be denoted T (thrust), the other can remain unnamed.

Consider the flight path and note that the lift vector remains at ninety degrees to the air flow and the drag vector remains parallel to the air flow. This is the same as seen in the previously described powered example.

As the glide angle steepens, the portion of the weight which is considered thrust increases. At the same time, the lift decreases and the drag increases. See Figures 6A and 6B.

To help explain this, take a look at the extreme. Figure 6C shows the glider in a sustained true vertical dive. The wing is operating at the zero lift angle of attack and so lift has been reduced to nothing. Drag makes up all of R_1 and weight makes up all of R_2.

If in a vertical dive we adjust the angle of attack so that it matches what was required for straight and level flight, the lift will be the same as during straight and level flight and it will be oriented exactly in the horizontal. See Figure 6D. The drag vector will also be the same length as before the change in attitude and will remain parallel to the air flow. The resultant R_1 is rotated nearly ninety degrees from the vertical. The lift force immediately begins accelerating the wing horizontally while the weight accelerates the aircraft vertically downward. As the horizontal speed increases, the air flow changes direction so there is a reduction in the angle of attack. If we consistently maintain the initial angle of attack, the aircraft will pull out of the dive.

In Figure F4D, the aircraft has just been put into a steep dive from straight and level flight. The aircraft is assumed to be flying at the same speed as before the change in attitude. The weight vector can be broken down into its two component parts, as was done previously, and the thrust component is accelerating the aircraft in the direction of flight. The lift and drag vectors remain oriented to the direction of flight. R_1, the resolution of the lift and drag vectors, is rotated forward of the vertical, indicating that a portion of R_1 is directed in the horizontal direction. This small force is denoted in the illustration as T_i, induced thrust. If the angle of attack is held constant, the aircraft will pull out of the dive, just as in the previous example.

Induced thrust

We've used the term "induced thrust" in the previous paragraph, and there are some readers who may not believe that such a thing exists, despite having a knowledge of "induced drag." Perhaps one of the best examples of "induced thrust" is the action of a winglet. A very large number of aerodynamics texts describe winglets in detail, so we will not do so here. What we want to bring into focus is the production of induced thrust by the winglet.

The upper illustration of Figure 7 shows a wing from the rear, with the winglet structure defined by phantom lines. The air flow is shown traveling outboard along the bottom surface of the wing and inboard across the upper surface. The velocity of this movement is generally greater near the wing tip as shown by the lengths of the lines.

The air flow outboard of the wing tip is very close to circular, but remember, the free stream velocity is added to this circular motion, so the resultant air flow meets the winglet at an angle. The lift and drag vectors are shown in the lower illustration. Note the now familiar rotation of the resultant in reference to the winglet MAC/4 axis. (MAC/4 is the 25% chord point of the mean aerodynamic chord and is the origin for the winglet lift and drag vectors, just as for any wing segment. The MAC/4 axis and the yaw axis are in parallel planes in the presented examples.) The vector T_i is the induced thrust generated by the winglet.

We can extend the notion of "induced thrust" from a winglet to the outer segment of a lifting swept wing. Consider Figure 8A. In this case, an airfoil is generating some lift while the air flow is precisely horizontal. This is a situation identical to that when an airfoil with a zero lift angle of some negative value is set in a wind tunnel at zero degrees angle of incidence to the air flow. Note that the lift vector is vertical (ninety degrees to the air flow) and the drag vector is parallel to the air flow. The resultant is rotated at an angle behind the vertical quarter chord axis. In the wind tunnel, as the airfoil angle of attack is increased, the lift vector remains perpendicular to the air flow, the drag vector remains parallel to air flow, and the axis remains vertical, perpendicular to the air flow.

In Figure 8B, the air flow is coming from below at an angle of five degrees. The lift and drag vectors have rotated to match the air flow, and the resultant coincides with the vertical MAC/4 axis. Figure 8C shows the case where the air flow is coming up at an angle of ten degrees. The lift and drag vectors (and the resultant, of course) have rotated forward of the axis.

Figure 8D shows two situations which take place at an air flow angle of 15 degrees. We've shown a single lift vector and two drag vectors. If the drag is low, the resultant (R_1) remains well ahead of the axis. If the drag is excessive, however, the resultant (R_2) rotates behind the axis. This is an important concept to keep in mind.

The case of the outer segment of a twisted swept wing is shown in Figure 8E. The air flow is coming up at an angle of ten degrees and the airfoil is set at an angle of incidence of minus five degrees. As the wing section "sees" an angle of attack of five degrees, the lift is of the same magnitude as in Case 8B, but the resultant is rotated to a direction nearly identical to that of Case 8C.

It may be helpful to consider the outer portion of a swept back wing to be a "flattened" winglet, as the effects of the two are essentially identical.

Winglets, and swept wings with washout, can take advantage of the rotated R_1 because the angle of attack of the airfoil section can be held constant. The induced thrust which is produced may not seem like much of a force, but consider that if a wing section has an L/D of 20:1, R_1 must rotate forward of the vertical just 2.86 degrees in order for that part to get a "free ride." If R_1 can be rotated forward beyond 2.86 degrees, that portion of the wing is actually producing thrust. And as the L/D increases, the required angle of rotation gets smaller. See Figure 9 and Table 1.

Induced thrust and aileron deflection

And now the part you've been waiting for... Take a look at Figure 10.. This illustration is of the outer segment of a twisted swept back wing with aileron installed.

When the aileron is in neutral position, the resultant vector is directly over the projected yaw axis.

When the aileron is deflected downward, the lift is increased substantially. The resultant is rotated forward of the axis. This induced thrust actually pushes the wing forward.

When the aileron is deflected upward, the lift vector decreases in magnitude, reducing the induced thrust. (If the aileron deflection is large enough, the lift vector changes direction.) The resultant of the lift and drag vectors rotates behind the axis, pulling the wing backward.

In an aileron induced turn, adverse yaw in a swept wing planform can be reduced or eliminated entirely by means of manipulating the lift and drag vectors of the outer portion of the wing through appropriate wing twist.

When the wing tips are lifting downward, aileron deflection acts to reduce adverse yaw. This case can be envisioned by inverting the vector diagram for a (normal) upward lifting wing. We've done the inverting and placed the results in Figure 11.

Reducing adverse yaw

Figure 12 examines the case of the unswept wing with an elliptical lift distribution with aileron deflection for a left turn. (This diagram is a reprint of Figure 5 from Part 1.) The aileron deflection increases the drag of the wing semi-span having the downward deflected aileron and decreases the drag of the wing semi-span having the aileron deflected upward. This causes a roll to the left and a yaw to the right. This adverse yaw requires a compensating rudder deflection.

Figure 12 also examines the case of the swept wing which utilizes a lift distribution which is not elliptical but which does allow for coordinated turns by eliminating adverse yaw through induced thrust. The wing semi-span with the upward deflected aileron generates more drag than the wing semi-span with the downward deflected aileron. The wing rolls and yaws to the left. In this case no compensating rudder deflection is required.

Swept wings without a vertical surface, like many of the Horten designs, can use wing twist in conjunction with sweep to produce coordinated turns, particularly at low speed (high C_L), as when thermalling. There may be some disadvantages to this methodology when flying at high speed (low CL), but the detrimental effects can be controlled by careful design of the ailerons, including their location, size, and deflection angles.

Coming in Part 4

The next installment will devote some space to the relationships between aileron configurations, wing lift distributions, and adverse and proverse yaw. And now that we have a method of reducing or eliminating adverse yaw, we can back up a bit and take a look at what wing sweep, increased upwash and wing twist can do for the first of those three points we keep mentioning, our quest to reduce induced drag.

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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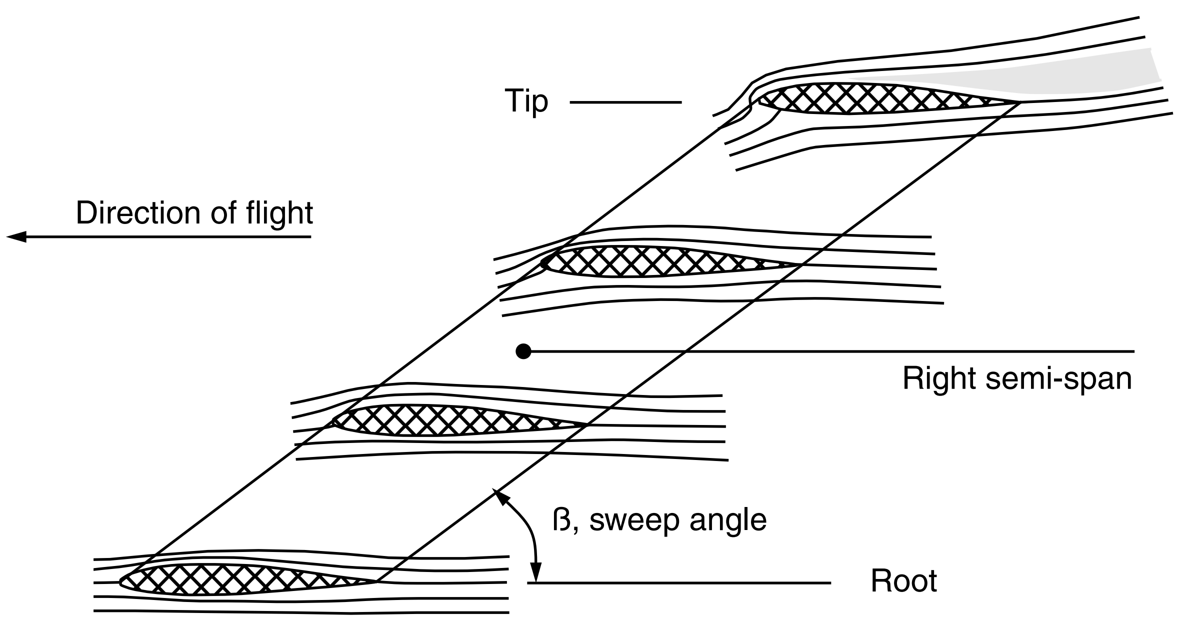

Figure 1. Movement of the stagnation point along the span of a swept back wing, exaggerated.

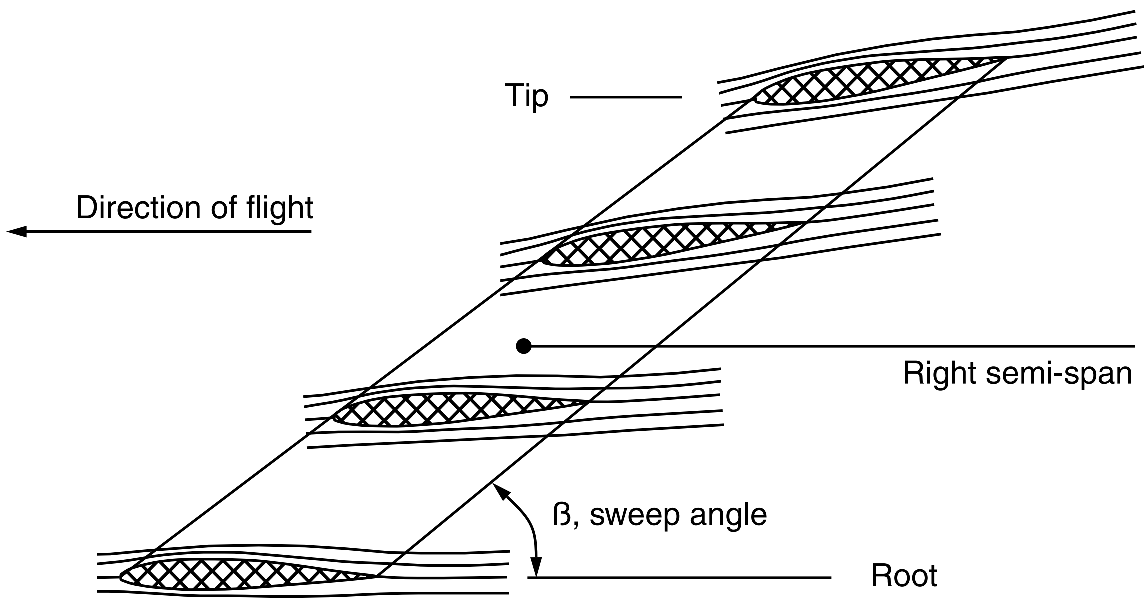

Figure 2. Alignment of wing sections to local flow
by means of geometric twist, exaggerated.

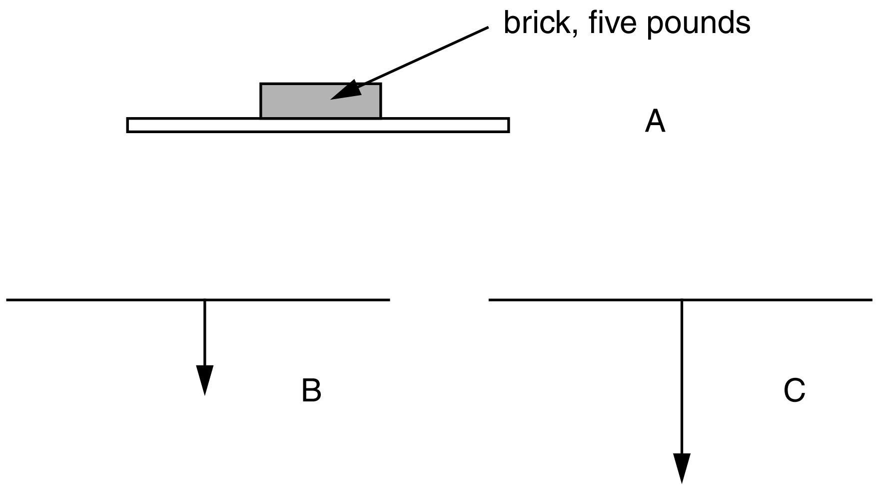

Figure 3. Examples of vector quantities.

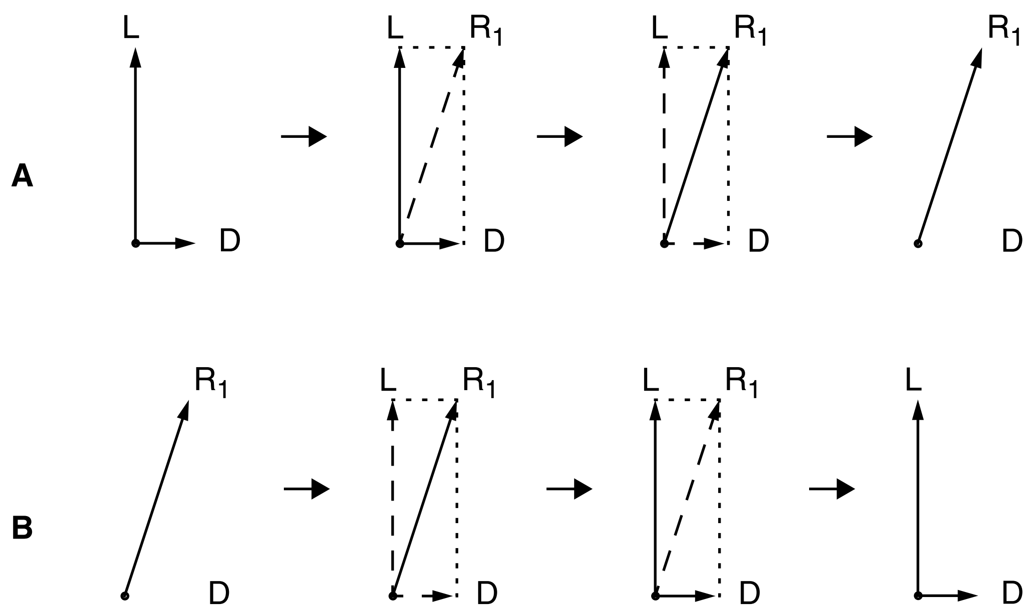

Figure 4. Calculation of resultant vectors

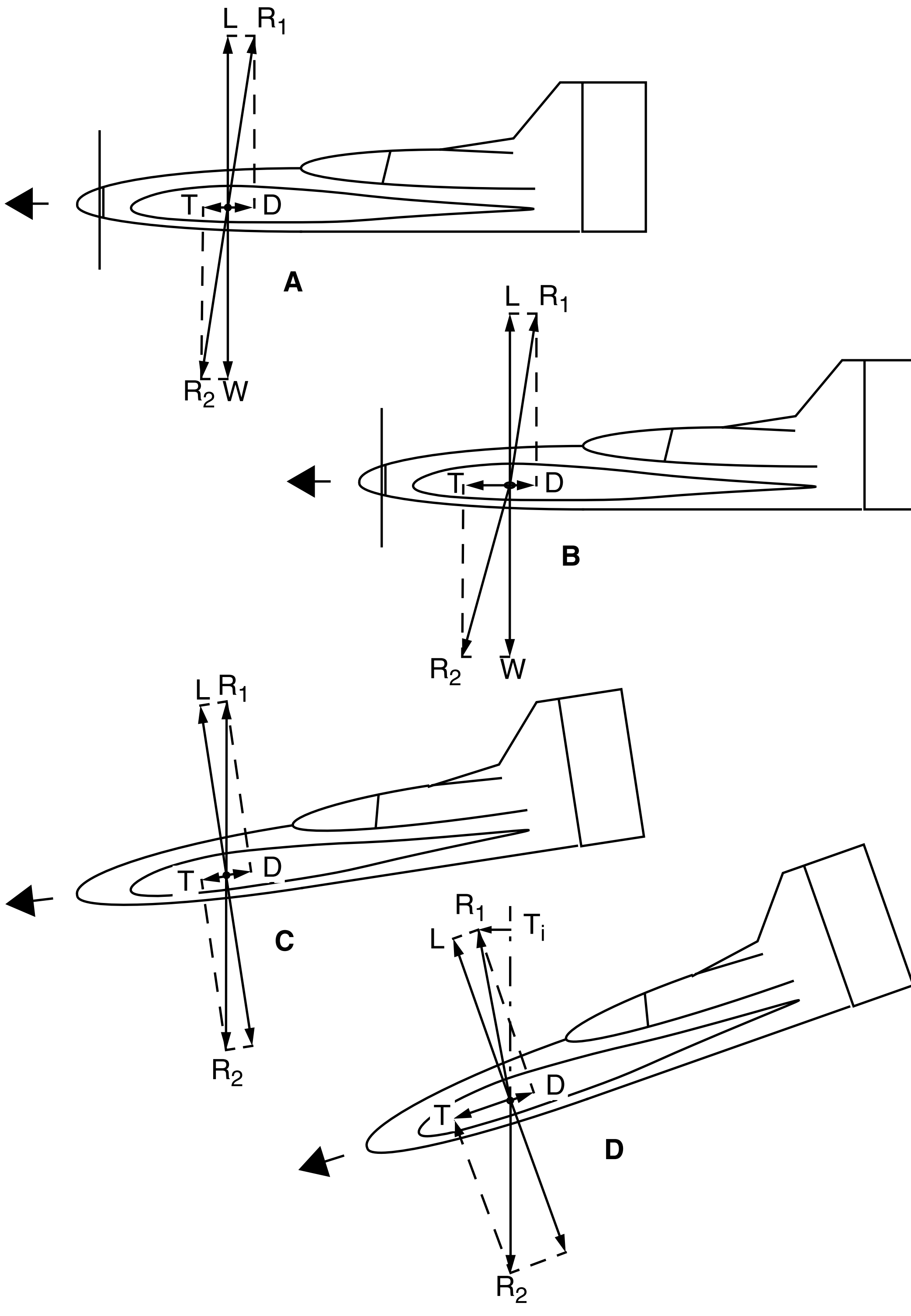

Figure 5. Force vectors on powered and unpowered aircraft which are otherwise identical.

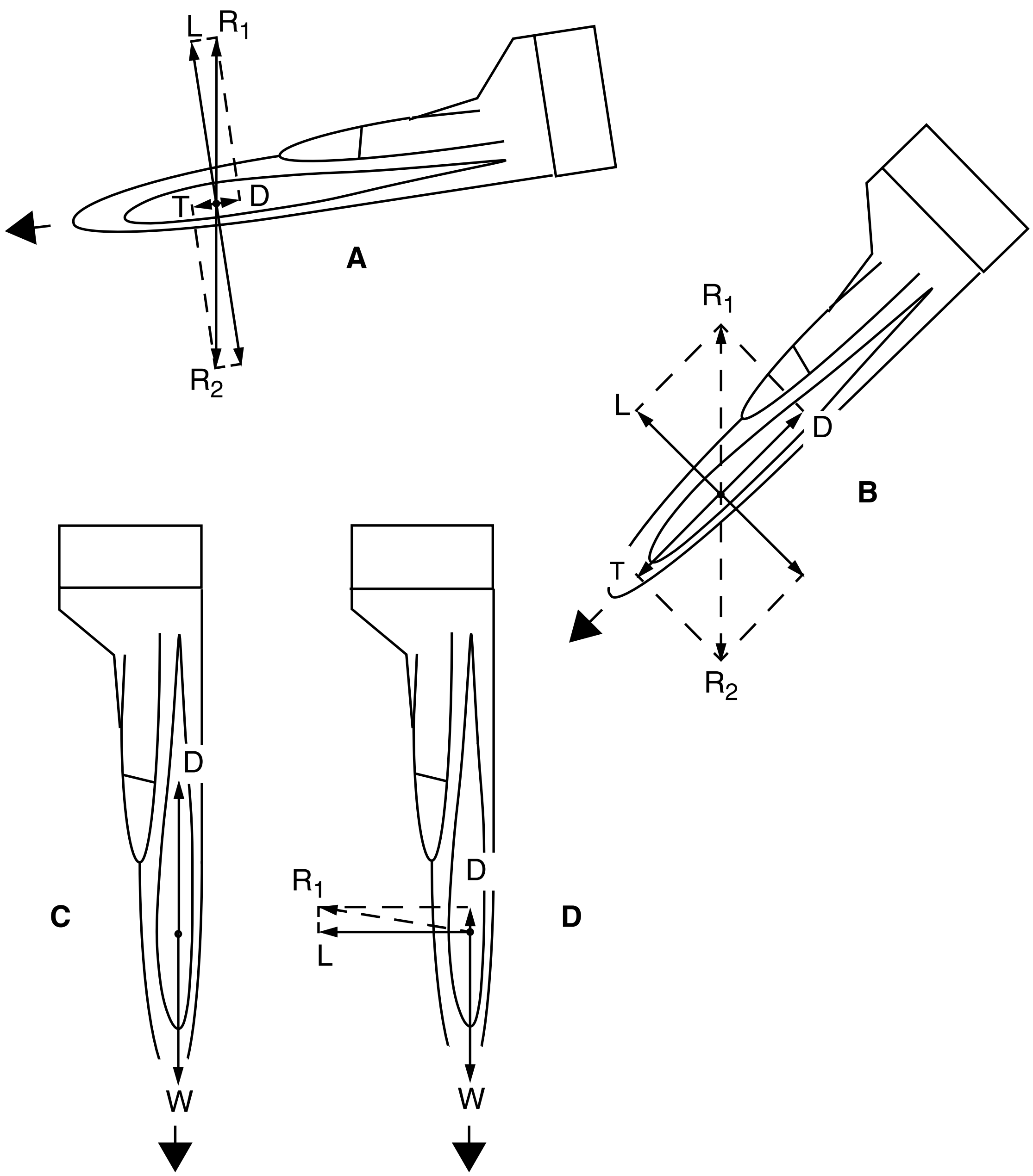

Figure 6. Force vectors on powered and
unpowered aircraft which are otherwise identical.

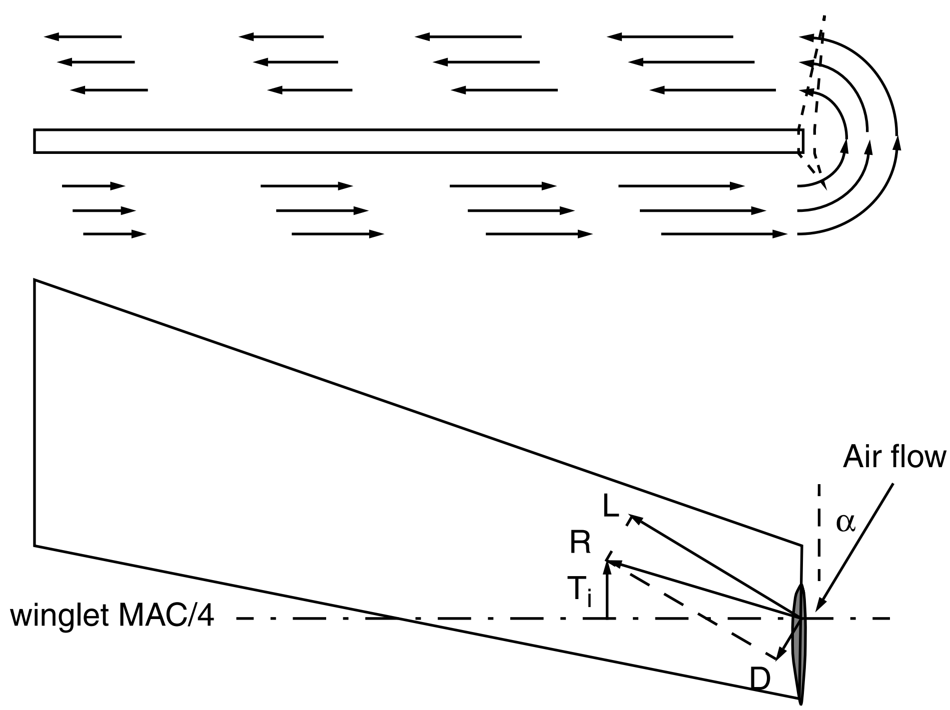

Figure 7. Induced thrust, T_i, generated by winglet.

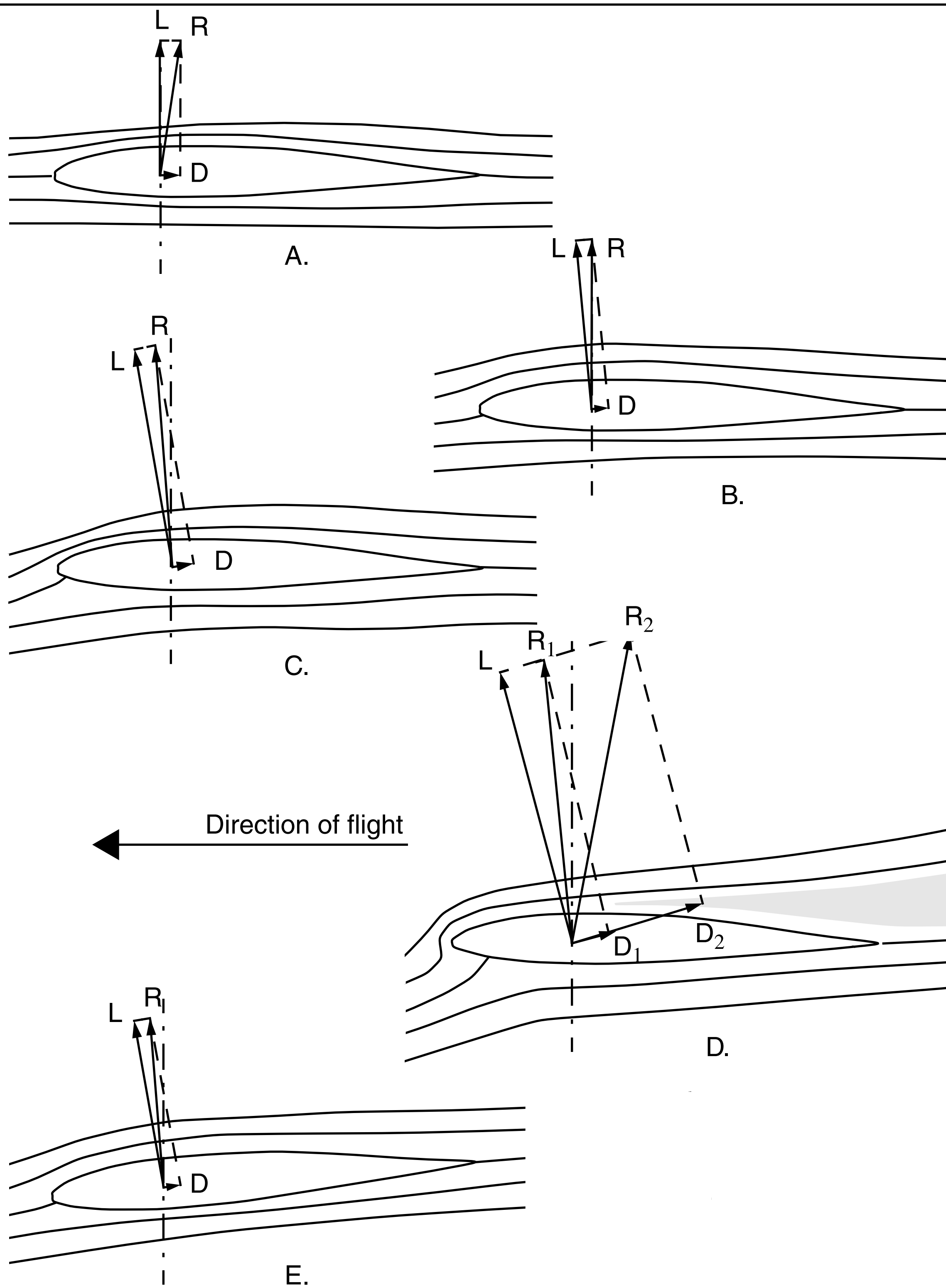

Figure 8. Rotation of lift vector caused by upwash, and a single case of the effect of twist on that rotation.

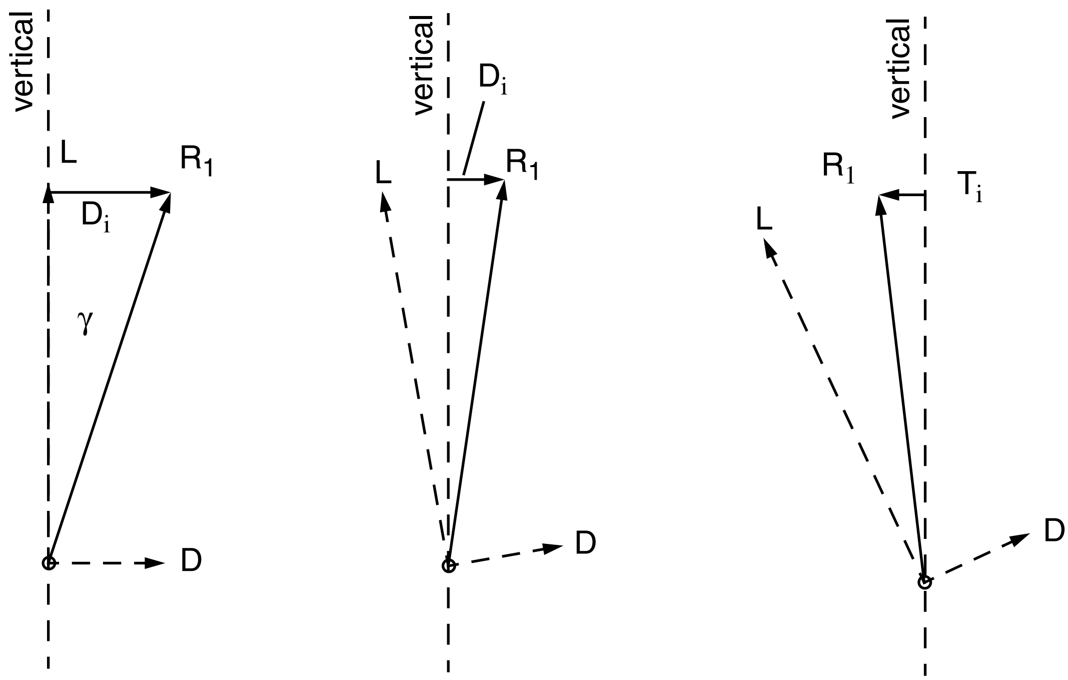

Figure 9. Force vectors demonstrating reduction of induced drag, D_i, and development of induced thrust, T_i, by rotation of lift and drag resultant, R_1.

Table 1: L/D and required rotation of R_1 for $D_i = 0$

L/D	γ, $R_1\angle$vertical
10:1	5.71 degrees
20:1	2.86 degrees
30:1	1.91 degrees
40:1	1.43 degrees

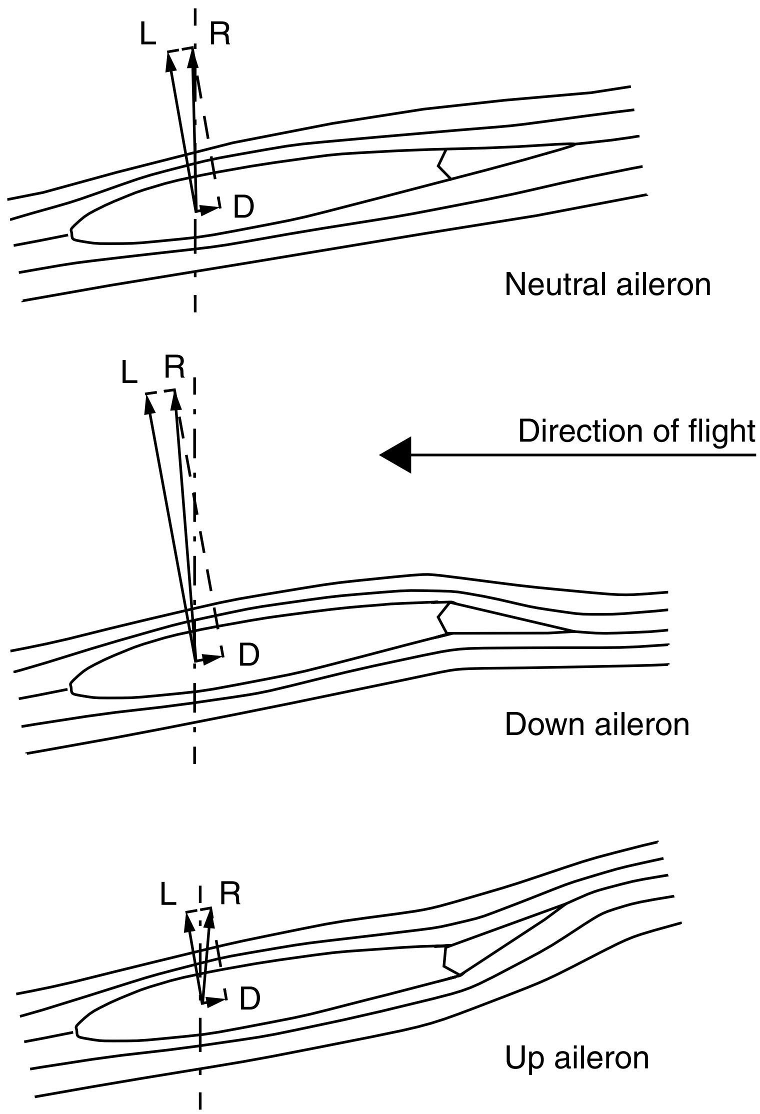

Figure 10. Generalized representation of the direction and strength of forces when the outboard aileron of a twisted swept wing is deflected.

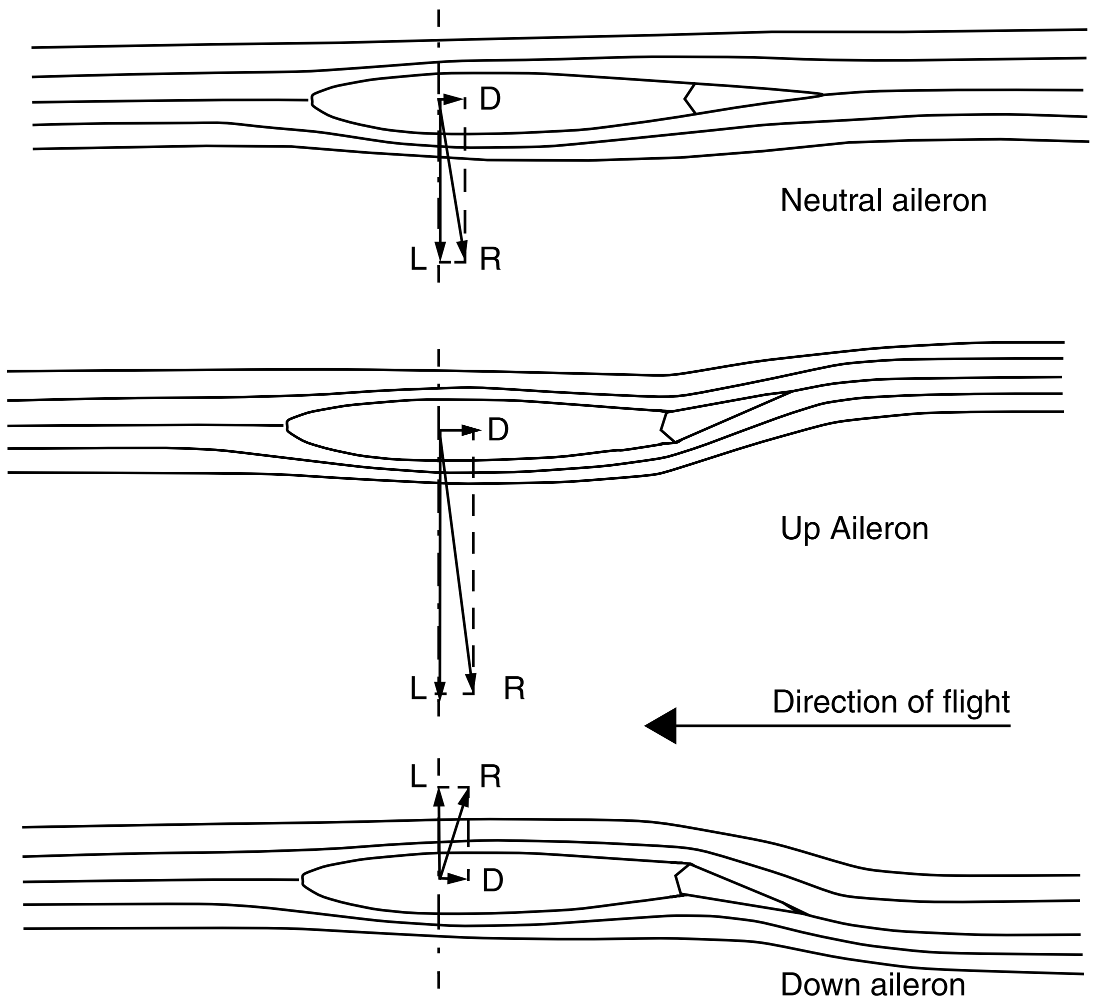

Figure 11. Generalized representation of the direction and strength of forces when the outboard aileron of a downward lifting wing segment is

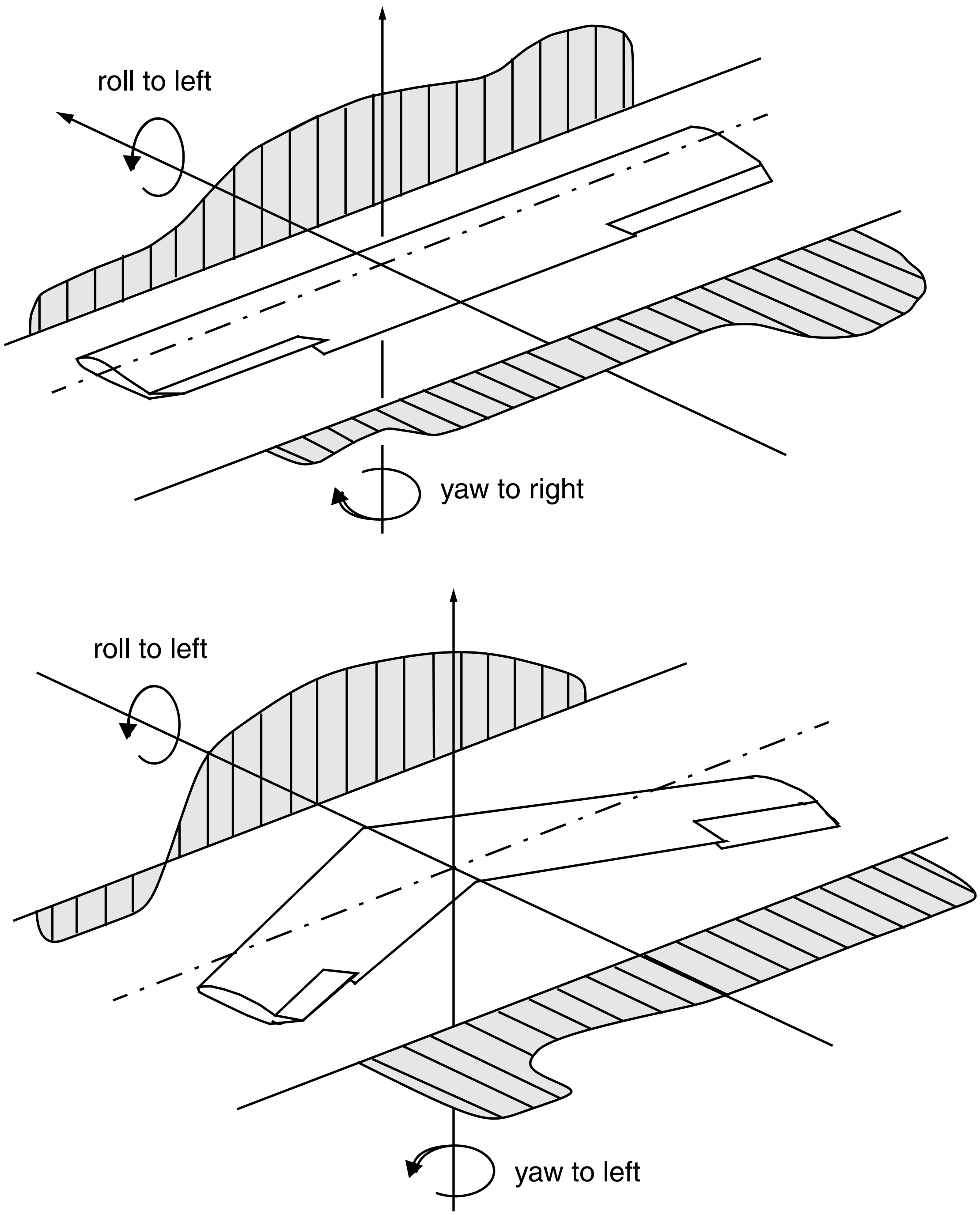

Figure 12. Lift and drag profiles for an untwisted rectangular wing with aileron deflection for left bank, no differential (upper), and for a twisted swept wing with washout, no differential (lower).