on the Wing B2

P.O. Box 975
Olalla, Washington
98359-0975
bsquared@appleisp.net
http://www.b2streamlines.com

Twist Distributions for Swept Wings, Part 3A

In an effort to be both focused and brief, we may have unintentionally passed on false information in Part 3. The column this month is therefore dedicated to resolving misconceptions promoted within the last "Twist Distributions for Swept Wings" installment (RCSD 09/02), specifically as related to Figure 4, reproduced here with modifications as Figure F4.

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 1A 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 1B. 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.

Figure F4A shows a powered aircraft in straight and level flight. To maintain straight and level flight after application of additional thrust (Figure F4B), aircraft trim must be adjusted so the wing continuously generates only enough lift to exactly match the aircraft weight. Drag will increase until it exactly matches thrust — R_1 becomes the same length as and in opposite direction to, R_2. Once the aircraft is again stabilized in straight and level flight, the aircraft velocity will be greater, the amount of lift will be unchanged, the coefficient of lift will be lower, the wing will be operating at a lower angle of attack.

Figure F4C shows a sailplane in a steep constant velocity glide. 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 same procedure can be used on the weight vector, resulting in one vector denoted

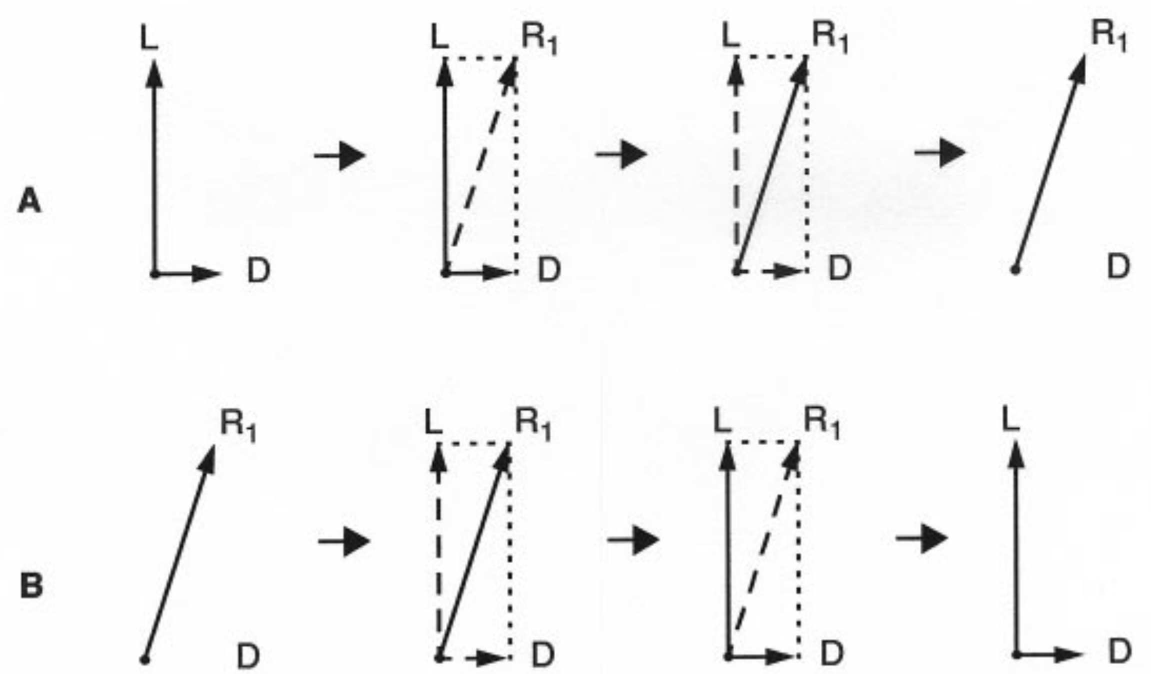

Figure 1. Calculation of resultant vectors

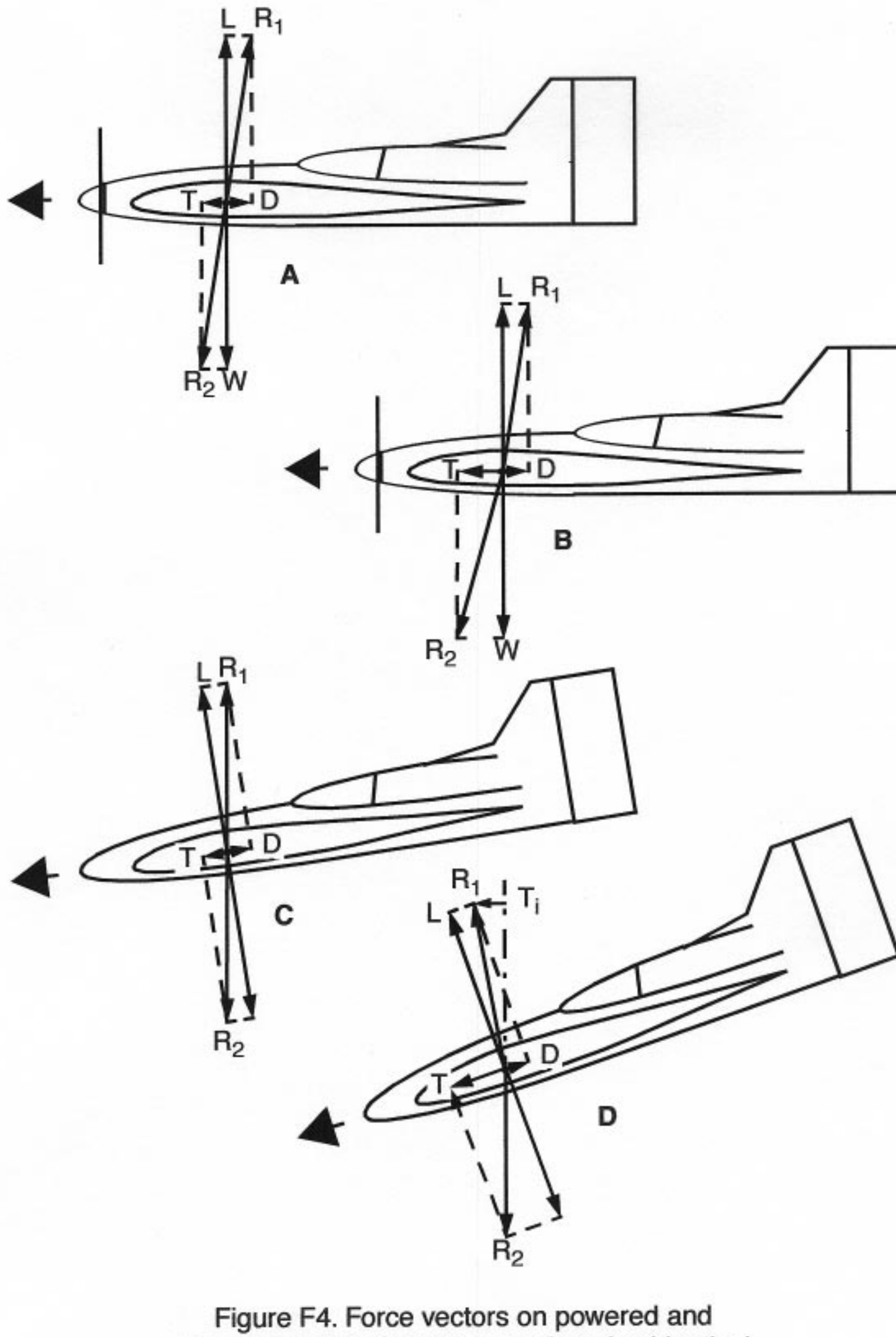

Figure F4. Force vectors on powered and unpowered aircraft which are otherwise identical.

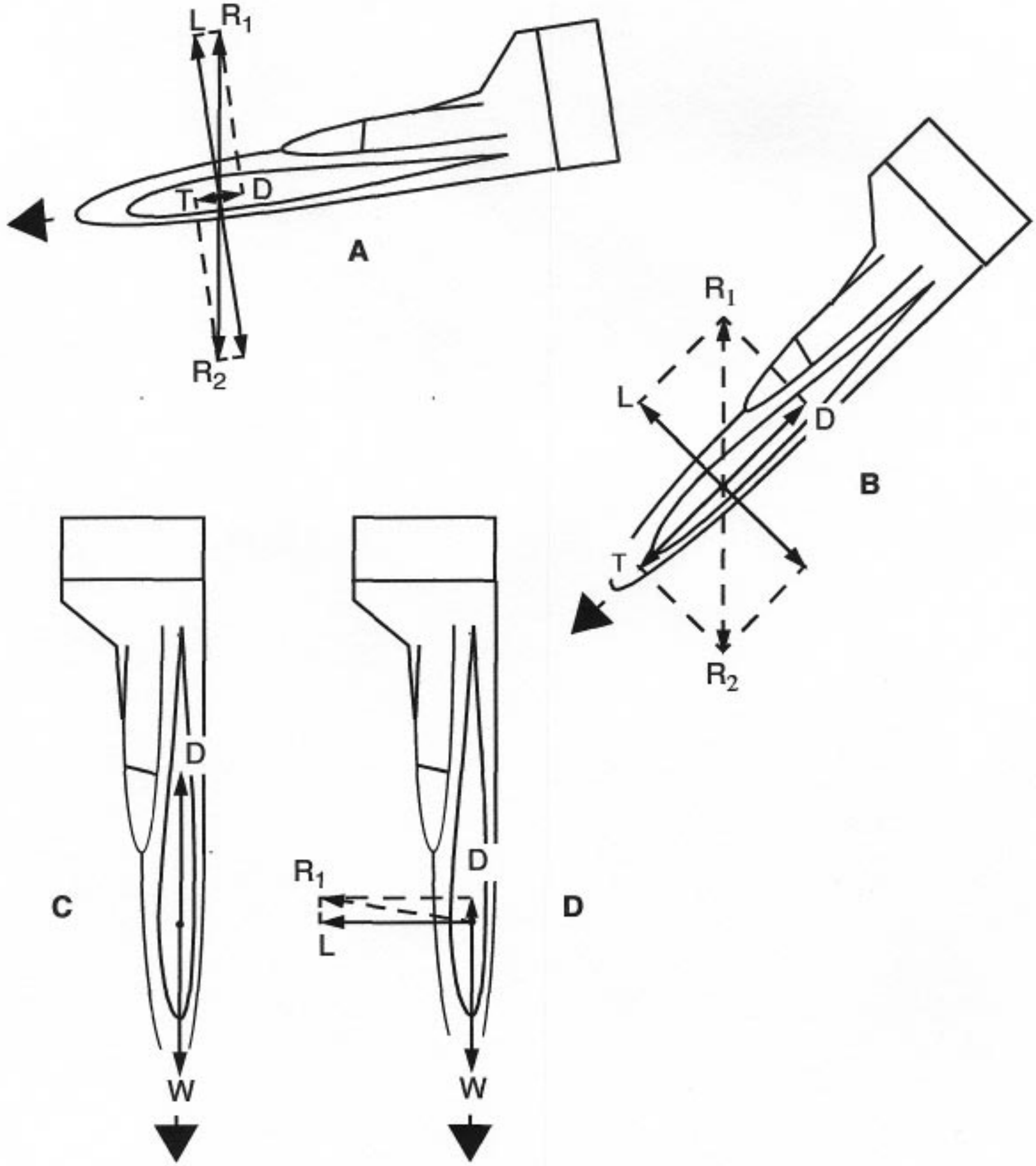

Figure 2. Force vectors on powered and unpowered aircraft which are otherwise identical.

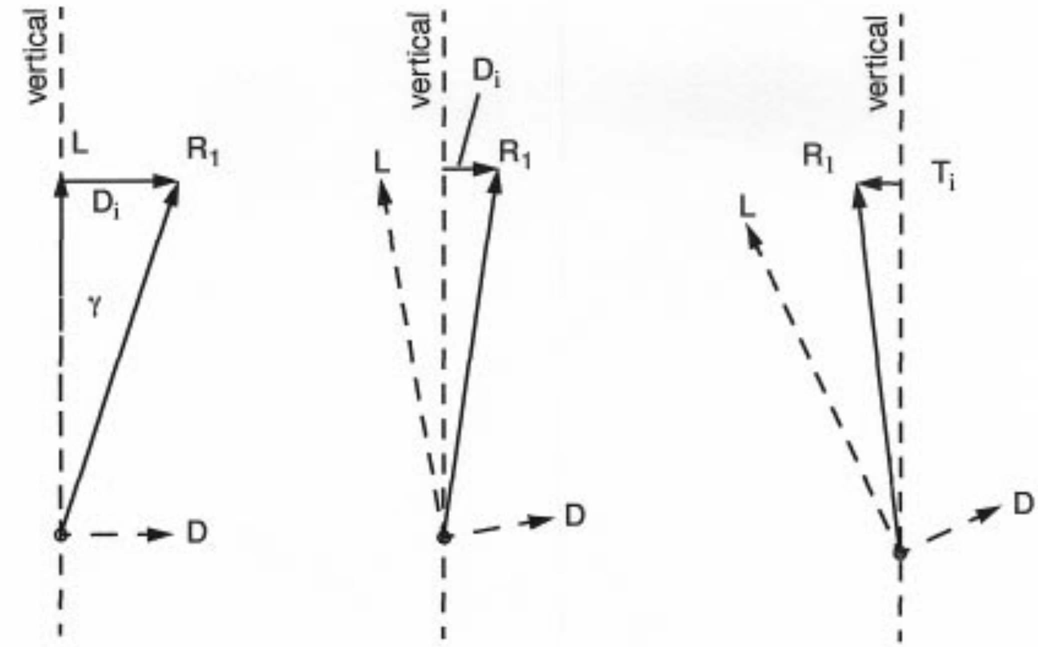

Figure 3. Force vectors demonstrating reduction of induced drag, D_i, and development of induced thrust, D_i, by rotation of lift and drag resultant, R_1.

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

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

T (thrust), and another unnamed vector.

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 2A and 2B.

To help explain this, take a look at the extreme. Figure 2C 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 2D. 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.

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 3 and Table 1.

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