vortex filaments which consist of the tip or trailing vortices coupled with the bound or line vortex. The tip vortices are coupled with the bound vortex when circulation is induced with lift. The effect of this vortex system is to create certain vertical velocity components in the vicinity of the wing. The illustration of these vertical velocities shows that ahead of the wing the bound vortex induces an upwash. Behind the wing, the coupled action of the bound vortex and the tip vortices induces a downwash. With the action of tip and bound vortices coupled, a final vertical velocity ($2w$) is imparted to the airstream by the wing producing lift. This result is an inevitable consequence of a finite wing producing lift. The wing producing lift applies the equal and opposite force to the airstream and deflects it downward. One of the important factors in this system is that a downward velocity is created at the aerodynamic center (w) which is one half the final downward velocity imparted to the airstream ($2w$).

The effect of the vertical velocities in the vicinity of the wing is best appreciated when they are added vectorially to the airstream velocity. The remote free stream well ahead of the wing is unaffected and its direction is opposite the flight path of the airplane. Aft of the wing, the vertical velocity ($2w$) adds to the airstream velocity to produce the downwash angle ϵ (epsilon). At the aerodynamic center of the wing, the vertical velocity (w) adds to the airstream velocity to produce a downward deflection of the airstream one-half that of the downwash angle. In other words, the wing producing lift by the deflection of an airstream incurs a downward slant to the wind in the immediate vicinity of the wing. *Hence, the sections of the wing operate in an* average *relative wind which is inclined downward one-half the final downwash angle.* This is one important feature which distinguishes the aerodynamic properties of a *wing* from the aerodynamic properties of an airfoil *section*.

The induced velocities existing at the aerodynamic center of a finite wing create an average relative wind which is different from the remote free stream wind. Since the aerodynamic forces created by the airfoil sections of a wing depend upon the immediate airstream in which they operate, consideration must be given to the effect of the inclined average relative wind.

To create a certain lift coefficient with the airfoil section, a certain angle must exist between the airfoil chord line and the *average* relative wind. This angle of attack is α_0, the section angle of attack. However, as this lift is developed on the wing, downwash is incurred and the average relative wind is inclined. Thus, the wing must be given some angle attack greater than the required section angle of attack to account for the inclination of the average relative wind. Since the wing must be given this additional angle of attack because of the induced flow, the angle between the average relative wind and the remote free stream is termed the induced angle of attack, α_i. From this influence, the wing angle of attack is the sum of the section and induced angles of attack.

$$\alpha=\alpha_0+\alpha_i$$

where α = wing angle of attack
α_0 = section angle of attack
α_i = induced angle of attack

INDUCED DRAG

Another important influence of the induced flow is the orientation of the actual lift on a wing. Figure 1.30 illustrates the fact that the lift produced by the wing sections is perpendicular to the average relative wind. Since the average relative wind is inclined downward, the section lift is inclined aft by the same amount—the induced angle of attack, α_i. The lift and drag of a wing must continue to be referred perpendicular and parallel to the remote free stream ahead of the wing. In this respect, the lift on the wing has a component of force parallel to the remote free stream. This component of lift in the drag direction is the undesirable—but unavoidable—conse-