Aircraft Flight

This section will briefly review some of the basic mechanics associated with an aircraft in flight. As depicted in Figure 1, the basic forces associated with an aircraft in level flight are the lift, L, and drag, D, produced by the wings and body of the aircraft as well as the thrust, T, produced by the engines and the weight, W, of the vehicle. In cruise mode at a velocity of U at an altitude where the air density is ρ these steady forces must balance so that

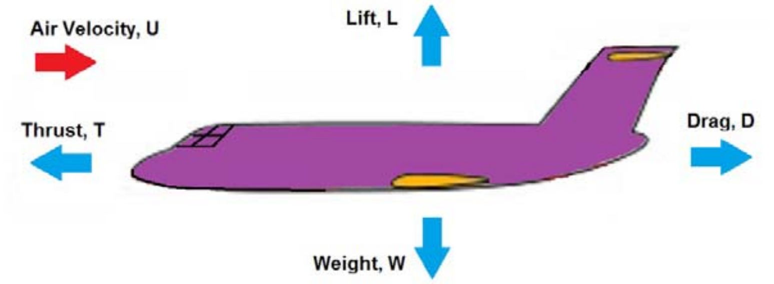

Figure 1: Forces on an aircraft in level flight.

$$T = D = \frac{1}{2}\rho U^2 A_P C_D^* \qquad \text{and} \qquad W = L = \frac{1}{2}\rho U^2 A_P C_L^* \tag{Dcg1}$$

where A_P is the wing planform area and C_L^* and C_D^* are the total lift and drag coefficients of the wings and fuselage of the aircraft. Therefore, to maintain the vehicle in level flight we must have

$$U = \left[\frac{W}{\frac{1}{2}\rho A_P C_L^*}\right]^{\frac{1}{2}} \tag{Dcg2}$$

and

$$T = W\,\frac{C_D^*}{C_L^*} \tag{Dcg3}$$

On the other hand, a gliding aircraft with no thrust would have forces as indicated in Figure 2 and, since the weight W, the lift L and the drag D must balance the glide angle (the direction of motion of

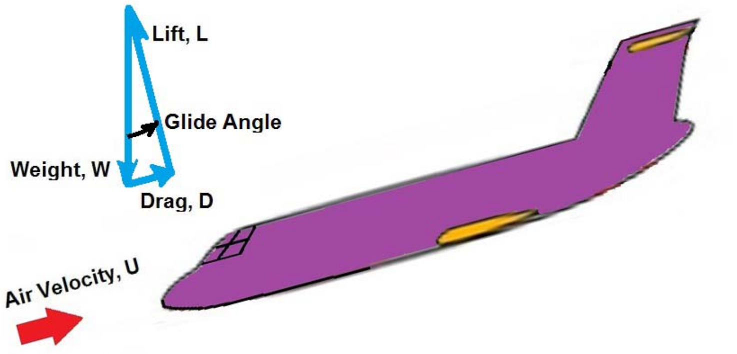

Figure 2: Forces on a gliding aircraft.

the aircraft relative to the horizontal) must be given by $\arctan D/L$. Hence, yet again, we encounter the important of the ratio of forces, L/D; here it determines the angle of descent of a gliding aircraft.

The terminology used in describing both the orientation and motion of an aircraft (or any vehicle) vehicle are as follows. The rotational motions and orientations are: *yaw* refers to the side-to-side twist about a vertical axis, *pitch* refers to the rotation about a lateral, horizontal axis and *roll* refers to rotation about a longitudinal, horizontal axis. The translational motions and orientations are: *heave* refers to vertical motion, *surge* refers to forward motion and *sway* refers to lateral motion.

The motion of an aircraft is, of course, controlled by an array of control surfaces as sketched in Figure 3 and, with the engines, these are used to control not only the speed of the aircraft but its orientation. The ailerons, elevators and rudder are used to control the attitude and orientation relative to the oncoming air stream. The flaps are used, primarily during take-off and landing, to control the lift. Take-off and landing involve much lower speeds, U, and, since it must always be true in level flight that

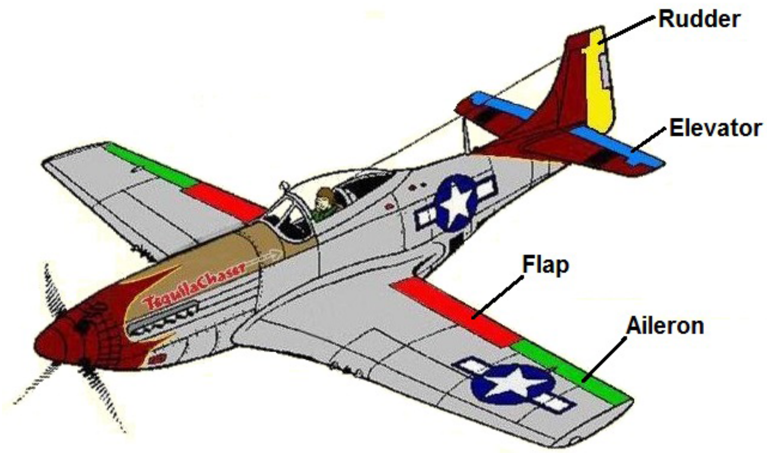

Figure 3: Basic aircraft control surfaces.

$$W = L = \frac{1}{2}\rho U^2 A_P C_L^* \tag{Dcg4}$$

it follows that the lift coefficient, C_L, generated by the wings (the major component of the total lift coefficient, C_L^*) must be increased to compensate for the reduced speed, U. In small light aircraft this is done mostly by changing the orientation of the plane. In large modern airliners it is accomplished by expanding the effective planform area, A, of the wings and, at the same time, increasing the effective angle of attack of the wings. These ends are accomplished by several devices but principally by extending large flaps at the back of the wings. Figures 4 shows the flaps on a Embraer ERJ 145 retracted (left) and fully extended (right); normally the flaps are gradually retracted following take-off and gradually extended as landing is approached. In addition, some aircraft are equipped with leading edge slats, protrusions that also increase the planform area and the effective angle of attack. Figure 4 demonstrates how these devices increase the lift coefficient (and effective angle of attack) while the lift-slope remains unchanged. By way of example, compare the take-off and cruise lift performance of a large modern airliner like the Boeing 757. The take-off speed at ground level (air density, $\rho \approx 1.22 kg/m^3$) is about $260 km/hr$ while cruise speed at $10,000 m$ elevation (air density, $\rho \approx 0.42 kg/m^3$) is about $930 km/hr$. Consequently the ρU^2 values differ by a factor of about 5 and this must be compensated for by a factor of 5 difference in the values of $A_P C_L$.

Stall is of course, another important feature of aircraft lift performance. As clearly seen by the lift and drag data presented in section (Dce), stall of a well-designed wing section usually occurs at an angle of attack of

Figure 4: Wing of an Embraer ERJ 145 showing the flaps slightly extended (left) and fully extended (right).

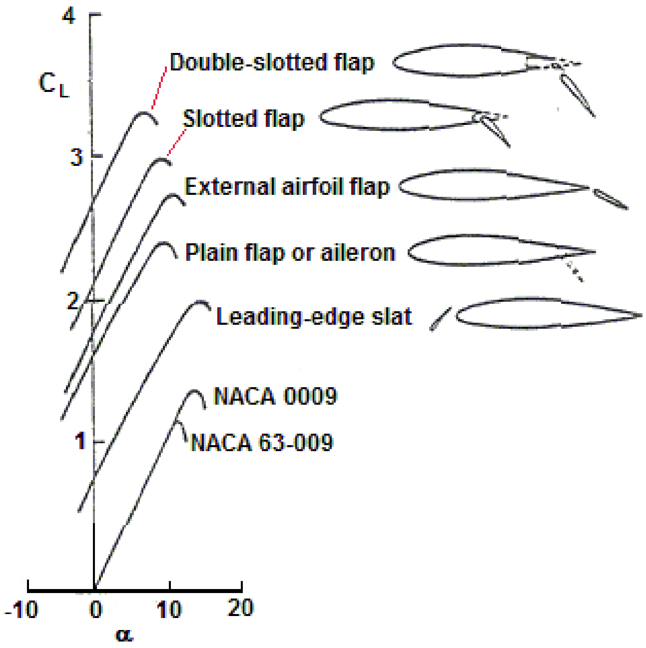

Figure 5: Various flap designs and their lift coefficients. Adapted from White (1999).

around 15^o. As the stall angle is exceeded the lift decreases abruptly while the drag increases dramatically. Thus the lift/drag ratio drops precipitously and the aircraft literally drops out of the sky. To bring it back under control the pilot must dive and twist to accelerate the plane and achieve an operational orientation of the aircraft. A particularly difficult version of stall, known as *deep stall*, occurs with aircraft whose elevators are mounted high on the tail as depicted in Figure 6. In deep stall the elevators may lie in the wake of the stalled main wings and thus be much less effective in bringing the aircraft back under control. Stall-spins are a particularly dangerous problem for small aircraft because of the difficulty of regaining control of the aircraft. For this reason, wing cuffs (see section (Dcd)) are often fitted to the aircraft in the

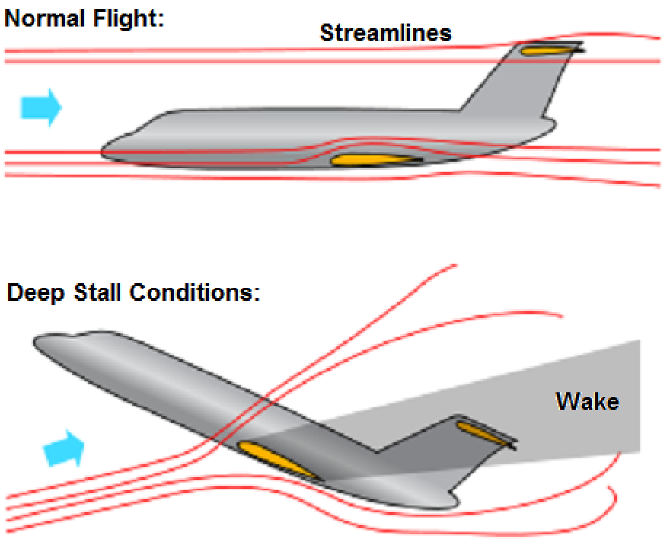

Figure 6: Mechanism of deep stall.

following way. The spanwise section of the wing closest to the fuselage is fitted with wing cuffs that allow maintenance of a specific airspeed or attitude. This reaches its critical angle before the outer, spanwise section that consequently allows some control after the inner section has stalled. This greatly helps the pilot to regain control of the aircraft.

Another aerodynamic feature of a modern airliner that is evident to the casual observer are the spoilers attached to the rear of the suction surface of an airliner wing. These lift up just after the aircraft has landed, causing massive flow separation from the suction surface, effectively killing the lift and stabilizing the aircraft against sudden wind gusts. Yet another feature are the wing-tip attachments that are intended to improve the lift of the wing by reducing the wing-tip vortex formation. However, the additional drag they create significantly reduces their effectiveness.

Helicopter aerodynamics are complicated in a number of ways. Conventional helicopters have a single large rotor whose blades encounter the wakes of other blades as they rotate and these encounters make the aerodynamics complicated, unsteady and noisy. The torque reaction on the body of the helicopter necessitates a smaller tail rotor that stabilizes the rotation of the body. In addition forward motion of the the aircraft combined with the rotation of the main rotor means that a main rotor blade moving forward on one side would experience a higher incident velocity than the blade on the other side that is rotating backward. Unless some compensation were made this would result in a torque that would roll the aircraft toward the backward moving side. It was a remarkable Russian-born engineer, Igor Sikorsky, who solved this problem by devising a mechanism that, in one form or other, is incorporated in all modern helicopters. This mechanism mechanically adjusts the angle of attack of each blade as it rotates so as to minimize this torque.

Another area of continuing aerodynamic development is in automobile fluid dynamics. Ever since the American race-car pioneer Jim Hall began applying knowledge of fluid flow to the problem of creating down-force that would allow faster cornering the subject of race-car (and by extension road vehicle) aerodynamics has become an important component of automobile racing and development. Formula One and Indy Cars rely heavily on the tuning of both the front and rear mounted airfoils.