

## Aircraft Balance

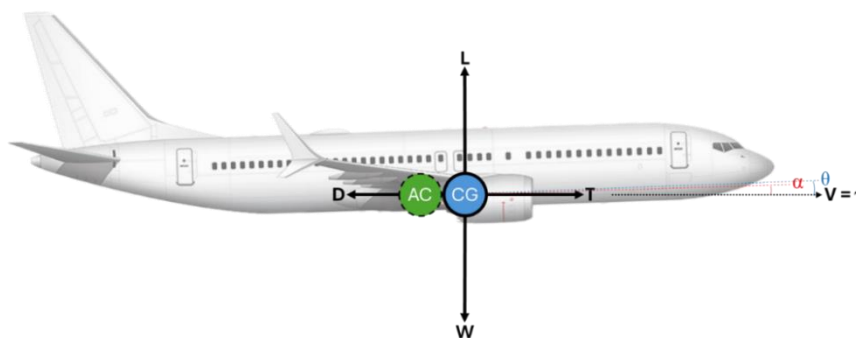
The following description of factors and variables that affect an airplane in flight elaborates on the topic only to the extent that is relevant to the present investigation. The objective is to give a conceptual idea of conditions that determine airplane balance and factors that have an impact on aircraft stability and controllability. In general terms, all forces affecting an airplane meet at its center of gravity (CG), whereas the pitching moment, which determines in part airplane stability, acts through the aerodynamic center (AC).

In straight and level constant-speed flight, the forces acting on the airplane are in equilibrium. In this balanced state, because of the law of action and reaction, drag (D) must be offset by sufficient thrust (T) from the engine or engines, and the airplane's weight (W= g) must be offset by lift (L), produced by the wings that have a specific form and position relative to the airflow. Excess thrust (high power setting) is used to accelerate the airplane or increase altitude, and conversely, thrust deficit is used to decelerate the airplane or decrease altitude.

The angle at which relative wind meets the wing is called angle of attack ( $\alpha$ ), which creates a pressure difference between the upper and lower surface of the wing. This pressure difference is needed to produce lift. The airplane's velocity vector (V) is projected along the flight path ( $\gamma$ ), while pitch angle ( $\theta$ ) is determined by the relationship between the flight path and angle of attack. Figure 1 shows an airplane in level flight, in which state the flight path angle and velocity vector are coincident.

Atmospheric effects around the airplane combine with airspeed, airplane shape and lift generation to create total drag that is in unaccelerated flight offset by a sufficient opposing force, i.e., thrust. Total drag is the sum of, among other variables, form drag, drag caused by the boundary layer on airplane surfaces, and induced drag that is present when lift is produced.

Total drag is affected by the angle of attack and shape of the fuselage and wing. The lower the airspeed, the higher angle of attack is needed to produce the equal amount of lift without changing wing geometry (typically camber and cord) by deploying the trailing edge flaps or leading edge slats, which are two most common types of high-lift devices.



**Figure 1** Forces acting on airplane.

## Static Stability

In balanced flight the shape, form and dimensions of the airframe combined with the location of the CG and AC affect the controllability and stability of the airplane. The CG can be described as the pivot point about which the airplane turns, while the AC is the point through which the aerodynamic forces required to produce lift act. Airplane design aims at a combination of a structural form and dimensions that defines airplane's static stability, ability to return to the

conditions of balanced state. This can be achieved if the AC is located behind the CG, in which case the airplane is easy to maneuver and regains the balanced state without control inputs.

Excessive stability may render the airplane overly sensitive to gusts (to exhibit so-called weathervane stability) or other disturbances, which require considerable control forces, whereas controlling an excessively unstable airplane would be difficult and under some circumstances even impossible without modern control augmentation systems (CAS).

Therefore, designers should always consider the airplane's planned flight envelope and operational requirements. The concept of stability can be opened by studying airplane motion about the three principal axes of the aircraft coordinate system. They are the longitudinal axis, lateral axis and vertical axis. Aircraft motions about these axes are called roll, pitch and yaw, respectively.

### **Long Period and Short Period Oscillations**

The combined effects of airplane shape and dimensions, airplane mass, CG location and aerodynamic forces also produce angular accelerations about the three axes. These accelerations exert an influence on airplane behavior at any given moment. Long period oscillations are inherent static characteristics of an airplane, while short period oscillations are dynamic and caused by deviations from the balanced condition. Both oscillation modes have desired and undesired characteristics.

Low directional and lateral stability or low longitudinal stability are the most common forms of long period oscillations. Low directional and lateral stability may lead to so-called Dutch roll, which involves rolling and yawing motions and may be unpleasant to airplane occupants. Phugoid, which appears as slow altitude and pitch angle variations, may produce similar feelings. Therefore, in an ideal case, the airplane should be able to self-dampen long period oscillations, either by static stability or CAS functions such as yaw damper to compensate for Dutch roll or altitude hold for phugoid alleviation. Short period oscillations are rapid motions caused by control inputs – of which adverse yaw is an example – or they may be triggered when the balanced condition is perturbed by a gust or turbulence.

Airplane behavior during both long and short period oscillations can be examined and described by analyzing the frequencies, amplitudes and periods of the motion. Desirable characteristics include an inherent tendency to resist and effectively dampen both oscillation modes, in which case the airplane is said to be stable. Conversely, an indifferent (the term means an airplane that generally sustains oscillating motion) or unstable (airplane that amplifies oscillation) airplane requires considerable pilot attention, and under some circumstances safe operation may be affected.

### **Effects of Air Currents on Transport-category Airplane**

Atmospheric currents can at a general level be divided into horizontal displacements of air masses caused by differences in pressure fields, vertical currents caused by temperature differences, boundary layer turbulence that occurs between air masses of different composition, and vertical currents associated with cloud masses. The characteristics of these most prevalent types of current range widely from steady state flow to chaotic, turbulent clashes. Turbulence is a local phenomenon, and its behavior may be impossible to predict or observe accurately. Larger and more stable high-energy currents may occur over larger areas.

Assessment of the effects of a single vertical current on the airplane helps understand laws that may cause undesirable changes in airplane behavior. The impact of two different vertical currents on a large airplane is explained below in two examples.

The default values used in the examples are not direct representations of the conditions that existed during the encounter under investigation, but they give a good overall picture of the phenomenon and add to the understanding of forces to which the airplane and its occupants were subjected.

### Scenarios

The following approximate default values for the airplane and atmospheric conditions were defined for the examples.

- wing area  $S = 130 \text{ m}^2$
- airplane mass  $m = 60,000 \text{ kg}$
- true airspeed  $V = 225 \text{ m/s}$  (KEAS 280)
- lift curve slope  $C_{L\alpha} = 5$  (typical of transport-category airplanes)
- air density at flight altitude  $\rho = 0.5 \text{ kg/m}^3$  (approx. FL 270)
- gravitational acceleration  $g = 9.81 \text{ m/s}^2$
- vertical current velocity  $w = 10 \text{ m/s}$

When the airplane hits a vertical current at true airspeed  $V$  and the vertical velocity of the rising current is  $w$ , the angle of attack ( $\alpha$ ) tends to increase by  $w/V$  [rad]. Without going into details of the airplane's momentary response, it can be estimated that the current increases lift by:

$$\Delta L = 0,5\rho VwSC_{L\alpha} \quad (1)$$

The effects of lift change on flight dynamics shall be examined in relation to the airplane's mass  $W = mg$ . Dividing the lift change by the mass gives a ratio of these variables, which represents a non-dimensional change in the load factor:

$$\Delta n = \Delta L/W = 0,5\rho VwC_{L\alpha}/(W/S) \quad (2)$$

colloquially known as G-change. Its effect is essentially directed at the CG, and it attempts to alter the airplane's motion in a direction perpendicular to the flight path.

#### Example 1:

The wing area of the airplane is  $S$ , and its mass at the time of the occurrence is  $m$ . The airplane is flying at density altitude  $\rho$  at true airspeed  $V$ , when it is subjected to a sudden upward-directed vertical current at velocity  $w$ . As a result, as derived from formula (2), load factor at the CG increases by  $\Delta n_{CG} = 0.62$ , and the level flight load factor increases to  $G_{CG} = 1 + 0.62 = 1.62$ .

If the current is directed downward at the same velocity, the level flight load factor decreases to  $G_{CG} = 1 - 0.62 = 0.38$ .

#### Example 2:

In addition to lift, vertical currents have an impact on longitudinal balance. As the angle of attack ( $\alpha$ ) increases when the airplane is subjected to a vertical current, an inherently stable airplane attempts to counter this increase and pitch the nose down to regain the angle of attack for the balanced condition. Conversely, when a vertical current causes a decrease in angle of attack, the airplane tends to self-correct by raising the nose. As can be judged from the

foregoing, vertical currents cause angular accelerations and resulting angular rates about the CG.

Example 2 describes the effects of a disturbance in the forward (*FWD*) and aft (*AFT*) sections of the cabin. This is relevant because the distance from the CG affects motion at various points of the airplane.

When the upward directed vertical current ( $w$ , blue arrow) shown in example 1 increases the load factor at the CG ( $G_{CG}$ ), this results at least in most cases in a corrective pitch-down angular motion in order to regain a balanced condition. Angular acceleration at the onset of this motion results in a local load factor increase aft of the CG ( $G_{AFT}$ ) and in a corresponding load factor decrease forward of the CG ( $G_{FWD}$ ) as shown in the figure below. The additional impact due to this local load factor change can be significant in the forward and aft sections of the airplane.



When the pitch-down angular acceleration of  $0.3 \text{ rad/s}^2 = 17.2^\circ/\text{s}^2$  caused by the airplane's tendency to return to balanced flight is added to the foregoing load factor increase  $\Delta n_{CG} = 0.62$  at the CG, local momentary load factor at a distance  $x = 15 \text{ m}$  aft of the CG would increase by  $\Delta n_{AFT} = 0.3 \cdot x/g = 0.46$ . As a result, local load factor would increase from the level-flight value of 1 to  $G_{AFT} = 1 + 0.62 + 0.46 = 2.08$ . Similarly, at a point 15 m forward of the CG, angular acceleration would lower local load factor, and the perceived load factor would be no more than  $G_{FWD} = 1 + 0.62 - 0.46 = 1.16$ .

A study of the effects of angular accelerations caused by a negative, or downward directed, vertical current  $w$  shows more drastic results. Load factor at the CG is again decreased by  $\Delta n_{CG} = 0.62$ , which combined with the pitch-up angular acceleration of  $0.3 \text{ rad/s}^2$  would lower local load factor further at a point 15 m aft of the CG by 0.46 to  $G_{AFT} = 1 - 0.62 - 0.46 = -0.08$ , or to a **negative** value. Correspondingly, at a point 15 m forward of the CG, the disturbance would generate local load factor  $G_{FWD} = 1 - 0.62 + 0.46 = 0.84$ .



Load factor  $G_{AFT}$  caused by a downward directed current will be sufficient to lift unrestrained occupants and items toward the ceiling. The figure on the next page shows the local load factors discussed above in the tabular form.

The theoretical values used in the examples of vertical current velocities, angular accelerations and other variables should be considered generic for transport-category airplanes and thence not directly applicable to the investigated occurrence. However, they serve to a sufficient degree the purpose of describing interactions between the forces affecting aircraft balance.



UPDRAFT	$G_{AFT}$	$G_{CG}$	$G_{FWD}$
$\uparrow 10 \text{ m/s}$	2.08	1.62	1.16
$0 \text{ m/s}$	1.0	1.0	1.0
$\downarrow 10 \text{ m/s}$	-0.08	0.32	0.84

Generally speaking, the effects of turbulence-triggered disturbances inside an airplane are accentuated with the increase of the distance from the CG. From this follows that in modern transport-category airplanes with wing-mounted engines, the aft section is the most critical area considering the disturbances explained above.

### Summary

Aircraft loading has a bearing on the impact of disturbances triggered by vertical currents, because a light load and gross weight reduction due to fuel burn make the airplane increasingly prone to disturbances. High true airspeed and high air density typical of low altitudes also increase susceptibility to disturbances, but in passenger-carrying airplanes their resultant effect, which is the decisive factor, is assumed to be the most marked during en-route descent when the airplane is still flying at a relatively high altitude. It can be stated further that disturbance-induced angular accelerations exert significant local impact in different sections of the airplane. Particularly in the aft section, local load factor changes can be of significantly higher magnitude compared to those experienced at or forward of the CG.