

PART 1 : SECTION 1

CHAPTER 13

STABILITY

Introduction

1. Stability is a complex subject in which many factors play important parts. For the purpose of this chapter the subject is much simplified and only those considerations of practical concern to the pilot are explained.

Static and Dynamic Stability

2. The stability of an aircraft is its tendency to return to the original trimmed position after having been displaced. The term is referred to the three axes of rotation : longitudinal, lateral, and normal (directional).

3. **Static Stability.** If an aircraft, trimmed in steady level flight, is disturbed in some way, it is said to be statically stable if it tends to return to the equilibrium position, and statically unstable if it tends to depart further from the equilibrium position. If it remains in the disturbed position it is said to have neutral static stability.

4. **Dynamic Stability.** Although an aircraft may be statically stable in that, after a disturbance, the first tendency is to return to the equilibrium position, it may overshoot and then attempt to correct itself again, thus setting up a type of oscillation known as a phugoid. If the phugoid damps out, the aircraft is dynamically stable. If it increases in size the aircraft is dynamically unstable, and if it persists without either increasing or decreasing the aircraft has neutral dynamic stability.

5. **Subsidence and Divergence.** If an aircraft, after a disturbance, gradually regains its trimmed position without overshooting, it is statically and dynamically stable, and the motion is called subsidence. If on the other hand it continues to move away from the trimmed position it is both statically and dynamically unstable, and the motion is called divergence. Fig. 1 illustrates these characteristics and it should be noted that, whereas an aircraft can be both statically stable (tends to return to the disturbed position) and dynamically unstable (divergent phugoid), if it is statically unstable then it must always be dynamically unstable.

The Three Axes

6. An aircraft can rotate about three axes at right angles to each other : the longitudinal axis, the lateral axis, and the normal (directional) axis.

7. **Longitudinal Axis.** The longitudinal axis is a line running fore and aft through the C.G. and is the axis about which the aircraft rolls. Stability about this axis is known as lateral stability.

8. **Normal Axis.** The normal axis is a line running vertically through the C.G. and is the axis about which the aircraft yaws. Stability about this axis is called directional (weathercock) stability.

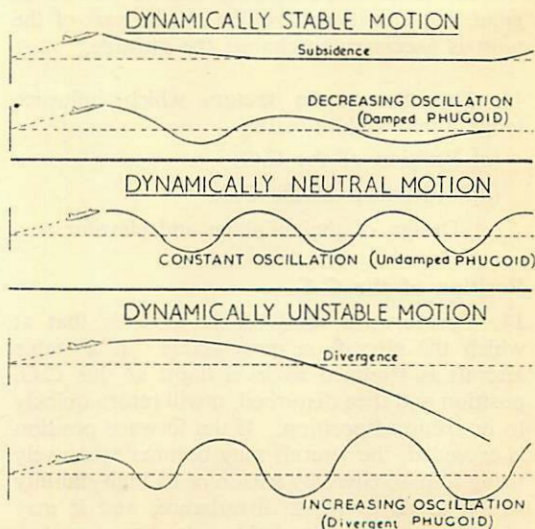
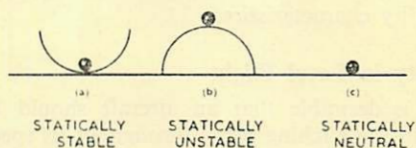


Fig. 1. Types of Stability

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9. **Lateral Axis.** The lateral axis is a line running spanwise through the C.G. at right angles to the other two. Movement about this axis is termed pitching, and stability about it is called longitudinal stability.

10. As all three axes are fixed in relation to the aircraft, they change direction in space when the aircraft attitude is altered. Therefore whatever the attitude of the aircraft, rolling, pitching, and yawing remain relative to the respective axes and do not necessarily indicate motion relative to the ground. An aircraft may be unstable about two of its axes and stable about the third, or stable about one and unstable about the others.

### LONGITUDINAL STABILITY

11. The longitudinal stability of an aircraft can be separated into :—

(a) Stability when in steady level flight. This is a function of the static stability characteristics.

(b) Stability when in accelerated flight, as in manoeuvres. This is a function of the dynamic stability characteristics.

#### Stability in Level Flight

12. It is desirable that an aircraft should be stable in the pitching plane throughout its speed range. Such stability should be sufficient to ensure that the pilot can maintain his attitude, at any time, without undue concentration. On the other hand stability should not be so great that considerable effort on the part of the pilot is necessary to change the attitude.

13. The three main factors which influence longitudinal stability are :—

- (a) Position of the C.G.
- (b) Movement of the C.P.
- (c) Design of the tailplane and elevator.

#### Position of the C.G.

14. The forward limit of the C.G. is that at which the aircraft is most stable. If a stable aircraft is trimmed in level flight at this C.G. position and then disturbed, it will return quickly to its trimmed position. If the forward position is exceeded, the aircraft may become excessively tiring to manoeuvre by reason of its high stability which tends to resist disturbance, and it may also become uncontrollably nose-heavy at low speeds. This last consideration is most important

while landing when, with full up-elevator, it may not be possible to round-out unless the speed is increased to obtain greater elevator power.

15. As the C.G. is moved aft the degree of stability decreases, and when disturbed from a trimmed position with the C.G. further aft the aircraft returns less quickly to trimmed flight. Eventually a C.G. position is reached at which the aircraft remains in the disturbed position with no tendency to regain the trimmed position. This is known as the neutral point of the C.G., at which position neutral stability prevails. Any movement of the C.G. further aft produces instability ; and on disturbance the aircraft will diverge further from the original position unless stopped by the pilot.

16. From the pilot's point of view variation in the C.G. position is felt by the amount of stick force necessary to displace the aircraft from its trimmed attitude. At forward C.Gs. stick forces can be fairly high, so much so that prolonged manoeuvring can quickly become fatiguing. At aft C.G. positions stick forces are noticeably lighter.

17. When a stable aircraft is disturbed by the pilot from its trimmed position into a nose-up attitude, it will require an initial pull force on the control column to change the attitude and a continued pull force to hold the disturbed attitude at what would be a lower speed. The amount of pull is proportional to the stability ; with a neutrally stable aircraft, following an initiating force in the required direction, there is a negligible force required to hold the aircraft in the disturbed position.

18. When the aircraft is unstable, only a very slight pull force is needed to change the attitude ; the slight initial pull has to be changed quickly to a push force to hold the disturbed attitude and prevent the aircraft from diverging. When attempting to restore the aircraft to its original attitude, the initial push force on the control column would have to be quickly reversed to hold the aircraft in the required attitude and to prevent it from dropping into a steadily increasing dive. An unstable aircraft is thus constantly attempting to change its attitude and the pilot is continually having to check these attempts, *i.e.* level flight is difficult to maintain.

19. **Position of the Centre of Pressure.** This varies with the angle of attack, tending to move forward as the angle of attack increases, and

vice versa. Remembering that the aircraft rotates about its C.G., it will be seen that if the C.P. moves ahead of the C.G. a nose-up movement will be applied to the aircraft. The opposite occurs when the C.P. moves behind the C.G. at small angles of attack. The position of the C.P. is a function of the angle of attack and is governed by the following factors :—

(a) *Angle of Attack.* When the I.A.S. is lowest, just before the stalling angle is reached, the C.P. is generally at its forward point of travel on the chord. At maximum level speed the C.P. is at a point far aft, possibly about 70 per cent. on a highly cambered aerofoil. The amount of movement of the C.P. varies, depending on the aerofoil section used. Most symmetrical sections have little or no movement. Generally speaking, the greater the camber the greater is the C.P. movement.

(b) *Weight.* The greater the weight of an aircraft the greater the lift that the wings must provide. For a given I.A.S., therefore, increased weight means an increased angle of attack and consequently a possible forward movement of the C.P. Conversely, the release of bombs and the consumption of fuel may cause an aft movement of the C.P., as a smaller angle of attack is required for level flight at the reduced weight.

(c) *Looping Accelerations.* Positive accelerations in the looping plane (turning, dive recovery, and loops) require an increase in the angle of attack and a forward movement of the C.P.

(d) *Turbulence.* In turbulent air the inertia of the aircraft maintains it in a comparatively steady attitude against variations in speed and direction of airflow. The angle of attack and C.P. position therefore fluctuate.

(e) *Transient Disturbances.* Inertia may also cause the angle of attack to alter temporarily if forces acting on the aircraft alter quickly, for example, when the undercarriage is lowered or when flaps are operated.

20. **Design of the Tailplane.** As has been shown earlier, the function of the tailplane is to provide a countering force to any residual out-of-balance couples existing between the four main forces. If the angle of attack is increased by a disturbance, the wing lift is increased and the C.P. tends to move forward. The result is to change the couple about the C.G. set up by the original value of the lift and so the state of balance no longer exists. The tailplane has been subjected to the same increase in angle of attack. It is designed so that the increase in the tailplane lift

multiplied by the distance to the C.G. is greater than the unbalancing moment caused by the increased wing lift multiplied by its distance from the C.G. The aircraft is then restored to its trimmed position. At this position the tailplane angle of attack and the wing angle of attack are again at their trimmed values, and equilibrium has been restored.

21. Thus for a given increase in wing lift following a disturbance, if the C.P. moves far the unbalance will be greater than if no, or a very small, C.P. movement takes place. This is because the wing lift acts through the C.P. and variation of the C.P. increases the moment. On most high-performance aircraft, however, C.P. movement is small.

22. The interaction between the C.G., the C.P., and the tailplane, determines the degree of longitudinal stability, and the sum effect of these three factors decides whether or not an aircraft will be stable in level flight, *i.e.* when the  $g$  load on the aircraft is unity or nearly so. Some further practical aspects of stability in unaccelerated flight are given below.

#### Stick Forces in Dives

23. When diving a stable aircraft that has been trimmed for level flight, an increasing push force is necessary as the speed increases. The higher the degree of stability and the greater the speed the greater will be the push force required to maintain the dive. The pilot can trim these forces so that no holding force is necessary in the dive, but it must be remembered that a large pull force may be required to recover. The elevator trimmer is a powerful control and must always be used with caution, as careless use may mask large forces which require considerable effort to overcome during recovery.

24. If a stable aircraft has not been trimmed into the dive, recovery is effected by merely releasing part of the push force; and if the push force is high this must be done with care, otherwise the aircraft may pull out too quickly and impose  $g$  values large enough to cause black-out at a critical stage of flight.

25. When diving an unstable aircraft an increasing pull force is needed as the speed increases, and the angle of dive tends to increase. This pull force should not be trimmed out unless absolutely necessary, as the effect of trimming may be to cause a sudden reversal of the stick force from pull to push which, if not done quickly enough, may result in overstress.

26. Owing to lack of rigidity of the airframe (aero-elastic distortion) the stability characteristics of an aircraft may change as the speed increases. This effect must be distinguished from changes in stability caused through compressibility effects at high mach numbers.

### Stability Under $g$

27. Stability during manœuvring flight introduces complicating factors that preclude all but brief study of its theory. In level flight the aircraft is neutrally stable with the C.G. on the neutral point; but in manœuvring flight, *e.g.* in recovery from a dive, neutral stability may occur at a more forward or a more aft C.G. position. The position of the C.G. for neutral stability under  $g$  is called the manœuvre point. At this position a negligible stick force will be required to increase the  $g$  and to hold the resultant increase.

28. Ideally, when  $g$  is applied in a turn or a pull-out from a dive, a pull force should be required to impose and maintain the  $g$ . To increase  $g$  it should be necessary to increase the pull force. An aircraft that behaves in this way is stable in manœuvring flight. As for the level flight case, the size of the pull force will depend on the amount of  $g$ , the degree of stability, and the design of the tailplane and elevator.

29. In an aircraft that is unstable under  $g$  due to C.G. considerations the pull force disappears, often suddenly, as the  $g$  is increased; and a push force is required to prevent the aircraft from tightening the turn of its own accord, with the consequent risk of overstressing or stalling the aircraft, or blacking out the pilot. This tendency to pitch-up (tuck-in) is similar to that encountered when wing-tip stalling occurs on swept-wing aircraft.

30. Although it is desirable for an aircraft to be stable under all conditions of flight, it is sluggish and heavy to handle if it is too stable; also the changes of trim with speed are too large. The exact amount of stability which is designed into an aircraft varies with its intended role, being highest for large aircraft and least for fighter aircraft where a high degree of manœuvrability is required.

31. The criterion of manœuvrability is the stick force required to apply an acceleration of 1  $g$ . For fighters the stick force varies from a minimum of 3 lb. to some slightly higher figure, and in the case of heavy aircraft the minimum is about 15 to 20 lb. The value of stick force per  $g$  (s.f.p.g.) is an important consideration in the design of the aircraft.

## LATERAL AND DIRECTIONAL STABILITY

### Introduction

32. The effects of lateral and directional stability are so closely interlinked that it is difficult to separate them. A disturbance which initially involves only lateral stability will, when the aircraft reacts, involve directional stability at the same time.

### Directional Stability

33. Consider two weathercocks, each consisting of a piece of wire pivoted at one end and with a fin at the other end, one pointing into the wind and the other trailing with the wind. The first is obviously unstable. If it is displaced slightly out of wind the whole weathercock will swing round until it is trailing with the wind. The second position is stable. If the fin is pushed out of wind and then released, it will return promptly to its trailing position.

34. Consider also an aircraft which is pivoted about the normal axis. If, when it is yawed, the aircraft tends to return to its original position pointing into the wind, it is said to have positive directional stability. For a given amount of yaw, size of fin, and airspeed, the greater the vigour with which it blows back the greater is the directional stability.

35. The purpose of the fin is to provide this stability. Without a fin most aircraft would be

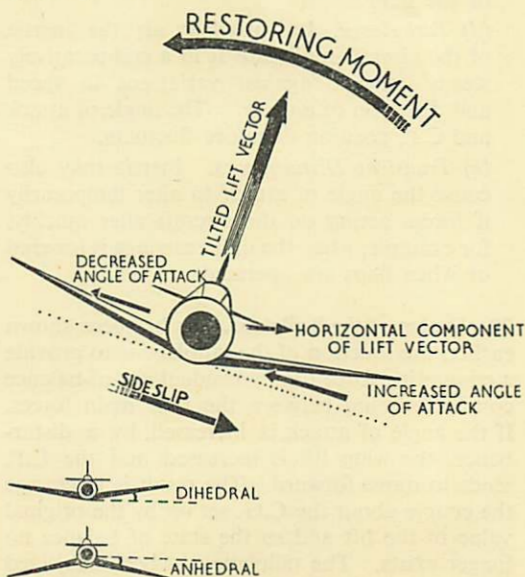


Fig. 2. Lateral Stability

unstable directionally because the centre of pressure of a tear-drop-shaped body is ahead of the C.G., and thus some fin would be necessary for even neutral stability.

### Lateral Stability

36. If an aircraft is displaced about the longitudinal axis (the rolling plane) there is no restoring moment available. After the disturbance, however, the tilt of the total lift from the wings, which now has a horizontal component, causes a side-slip towards the lower wing. The side-slipping motion sets up side loads on the wings and fuselage; in a stable aircraft these result in correcting forces which restore lateral level. If after initial disturbance the aircraft regains lateral level it is then said to be laterally stable. Lateral stability is obtained by one, or a combination of, the following methods:—

- (a) Inclining the wings to give a dihedral angle.
- (b) Sweeping the wings back.
- (c) Placing most of the keel surface above the C.G.
- (d) Using a high wing and a low C.G. position.

### Dihedral Angle

37. When a wing is inclined upwards from the lateral axis the included angle is the dihedral angle (Fig. 2). A wing that is inclined downwards has an anhedral angle. When an aircraft with a dihedral angle is banked, the tilted lift vector, through its horizontal component, sets up a side-slipping velocity towards the lower wing tip (Fig. 2). The effect of the dihedral angle is to cause the airflow to meet the lower wing at a larger angle of attack than the higher wing and thereby increase the lift on the lower wing and set up a restoring moment to right the aircraft. The effect is aided, to some extent, by the fuselage shielding the upper wing.

### Sweepback

38. When an aircraft with a swept-back plan form is banked by a disturbance, the changed direction of the airflow due to the side-slip results in the airflow over the lower wing passing over a shorter effective chord with a greater effective camber than that of the raised wing. As with dihedral, the upper wing may also suffer through being shielded. The final result is, as before, a relatively greater amount of lift from the lower wing which restores lateral level. The stabilizing effect is also increased by the effectively higher aspect ratio of the lower wing and effectively lower aspect ratio of the

upper wing, the difference being caused by the change in the effective chord (Fig. 3).

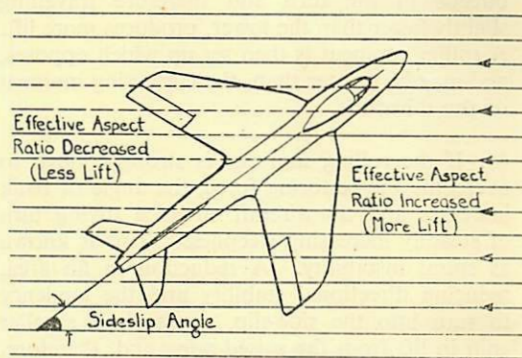


Fig. 3. Effect of Sweepback on Side-slipping Aircraft

39. On some aircraft with sharply swept-back wings the degree of inherent lateral stability is excessive, and to decrease the stabilizing effect the wings are set at an anhedral angle to partially neutralize the restoring moment.

### High Keel Surface

40. During a side-slip considerable force is exerted on the side surfaces (the keel surface) of an aircraft, and a turning moment about the C.G. is created. If the keel surface above the C.G. produces a greater moment than that below it, the result will be a correcting moment which will assist in restoring lateral level.

### High Wing and Low C.G.

41. With the wing in a comparatively higher position in relation to the C.G. a pendulous effect arises when the aircraft side-slips. During the side-slip the drag of the wing, acting above the C.G., allows it to swing down until it is once more vertically below the lift and the aircraft is laterally level.

## INTERACTION BETWEEN LATERAL AND DIRECTIONAL STABILITY

42. There are two main combinations of lateral and directional stability which should be considered: spiral instability and oscillatory instability.

### Spiral Instability

43. It has been shown that the lateral stability of an aircraft depends on the forces that tend to right the aircraft when a wing drops. However, at the same time the keel surface (including the

fin) tends to turn the aircraft into the yawed airflow, in the direction of the lower wing. Once this turn has been started the higher wing, being on the outside of the turn and therefore travelling slightly faster than the lower, produces more lift. A rolling moment is then set up which opposes, and may be greater than, the correcting moment of the dihedral.

44. If the rolling moment is strong enough to overcome the restoring force, the angle of bank increases and the aircraft enters a diving turn of steadily increasing steepness. This is known as spiral instability. A reduction in fin area, reducing directional stability and the tendency to turn into the side-slip, results in a smaller gain in lift from the raised wing and, therefore, in greater spiral stability.

45. This form of instability is not very important, and most aircraft are, in fact, spirally unstable. Many high-performance aircraft, when yawed either by the prolonged application of rudder or by asymmetric power, will develop a rapid rolling motion in the direction of the yaw, and may quickly enter a steep spiral dive; this is due to the interaction of the directional and lateral stability. This characteristic is noteworthy, particularly when flying under asymmetric power at low speeds, as excessive yaw caused by too much power and insufficient rudder control to balance it can quickly put the aircraft into a dangerous attitude.

### Oscillatory Instability

46. Oscillatory instability is more serious than spiral instability, and is commonly found to a varying degree in combinations of high wing loading, sweepback (particularly at low I.A.S.), and high altitude. Oscillatory instability is characterized by a combined rolling and yawing movement, or wallowing motion. When the rolling predominates the motion is called *Dutch rolling*; when the yawing motion is predominant it is known as *snaking*. When the aircraft is disturbed laterally the subsequent motion may be either of the two extremes; but in both instances the aircraft is loath to settle down. This can be merely unpleasant or possibly dangerous under instrument conditions. On fighter aircraft it can interfere seriously with the efficiency of the aircraft as a gun platform. The aerodynamic causes of oscillatory instability are complicated, but are mainly concerned with the amount of dihedral, sweepback, and keel surface (the area of the fin and rudder). A simple explanation of one form of Dutch rolling is given in para. 46A.

46A. **Dutch Rolling.** Consider a swept-wing aircraft seen in plan form (Fig. 4). If the aircraft is yawed, say to starboard, the port wing generates more lift due to the larger expanse of wing presented to the airflow, and the aircraft accordingly rolls in the direction of yaw—an effect similar to that of dihedral. However, the advancing port wing also has a higher drag, due again to the larger area exposed to the airflow. The higher drag on the port wing then causes a yaw to port which results in the starboard wing obtaining more lift and reversing the direction of roll. The final result is the undulating motion in the directional and lateral planes which is called Dutch roll. Since the motion is caused through an excessive restoring force, one method of curing the defect is to reduce the amount of stability by setting the wings at a slight anhedral angle. Fig. 4 shows that the effect of the anhedral is to cause the angle of attack on the advancing wing to reduce, and that on the retreating wing to increase, thus reducing the stability and the consequent tendency to Dutch roll. Other methods are also used including automatic stabilizers (yaw dampers).

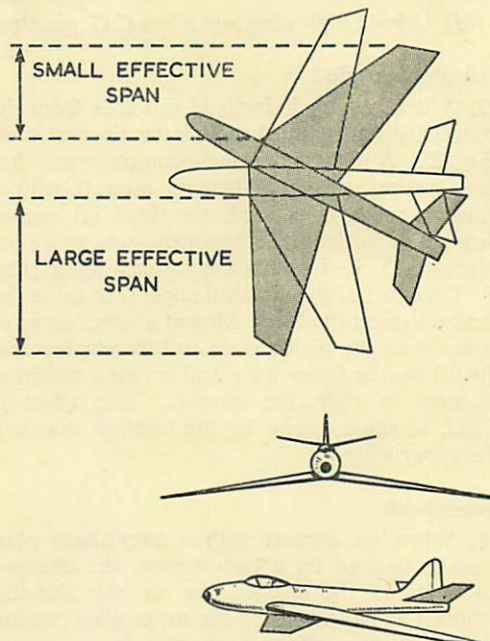


Fig. 4. Dihedral Effect of Sweepback and Destabilizing Effect of Anhedral

### Automatic Stabilizers

47. On some aircraft subject to oscillatory instability, automatic stabilizers are fitted to damp out the motion. The rate at which the aircraft moves is usually too rapid for the pilot

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to phase his attempts at correction and efforts to do so generally result in a worsening of the situation. Automatic stabilization is achieved by fitting a device which is very sensitive to side-slip and which causes the rudder movements to be phased against the side-slipping to damp out the motion. When the side-slipping is eliminated, any rolling movements disappear simultaneously.

#### Roll with Yaw

48. When any aircraft is made to yaw, either by the application of rudder or (with multi-engined aircraft) by the failure of an engine, the immediate effect is to roll the aircraft in the same direction as the yaw. This characteristic of all stable aircraft is caused by the resulting side loads acting on the dihedral angle of the wings and the change in effective aspect ratio between the wings due to side-slip.

49. The roll-with-yaw characteristics of swept-wing aircraft are more pronounced than those of unswept wings. If the nose of an aircraft with sweepback is yawed to port so that the aircraft side-slips to starboard, the airflow will be at a larger angle to the starboard wing than to the port and will travel over a shorter chord,

so effectively increasing the aspect ratio and thus the wing efficiency. Over the port wing the opposite occurs, added to which is the blanking effect of the fuselage over a large area of wing. This situation creates a strong rolling motion to port. *This characteristic is most pronounced at high angles of attack*, when the pilot must guard against yawing the aircraft, intentionally or otherwise, to an extent that induces a rolling tendency that cannot be countered by the reduced effectiveness of the ailerons. This state of affairs is most liable to occur when landing in strong crosswind conditions.

50. To reduce the strength of the roll-with-yaw effect most swept-wing aircraft have no dihedral angle, or even negative dihedral (anhedral), and rely on the sweepback alone to obtain a dihedral effect.

51. The roll-with-yaw characteristics of these wings can be usefully employed to raise a wing that has dropped at the stall. Whereas a fairly large movement of the rather ineffective ailerons may be required, a small movement of the rudder to yaw the nose away from (*i.e.* side-slip towards) the dropped wing will effect a rapid correction.

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