PART 1 : SECTION 1

CHAPTER 12

MANŒUVRES

Introduction

1. Changes in the attitude of an aircraft in flight can take place in any one, or combination of, the three major axes described below. During manœuvres considerable forces are at work on the airframe, and these may be large enough to cause damage or even structural failure if the aircraft is manœuvred without consideration of the limits for which the airframe has been designed.

2. This chapter deals with the basic principles of manœuvres and the origin and nature of the forces involved.

Axes of Movement of an Aircraft

3. **Longitudinal Axis.** This axis is a line running fore and aft, through the C.G. movement of the aircraft about this axis is called rolling, and it is sometimes referred to as the rolling axis.

4. **Normal Axis.** This axis is a line, perpendicular to the longitudinal axis, running through the C.G. Any motion about this axis is called yawing, and the axis can be referred to as the yawing axis.

5. **Lateral Axis.** This axis runs spanwise through the wings and the C.G. at right angles to the other axes. Rotation about this axis is termed pitching, but if any component of the forward flight velocity acts parallel to this axis the subsequent motion is called side slip or skid. The axis is also known as the pitching or looping axis.

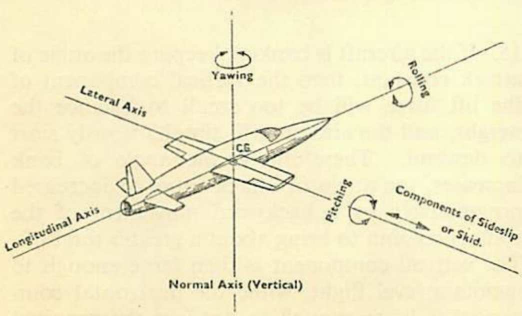

Fig. 1. The Three Major Axes

6. The three axes are fixed relative to the aircraft irrespective of its attitude. Fig. 1 shows the major axes and the possible movements about them.

Acceleration

7. Any aircraft or body in motion is subject to three laws of motion (Newton's laws) which state that :—

(*a*) All bodies tend to remain at rest or in a state of uniform motion in a straight line unless acted upon by an external force, *i.e.* they have the property of inertia.

(*b*) To change the state of rest, or motion in a straight line, a force is required. To obtain a given rate of change of motion and/or direction the force is proportional to the mass of the body. It follows that for a given mass, the greater the rate of change of speed and/or direction the greater is the force required.

(*c*) To every action there is an equal and opposite reaction.

Most manœuvres involve changes in direction and speed, the degree of change depending on the manœuvre involved. Any change of direction and/or speed necessarily involves an acceleration, which is often evident to the pilot as an apparent change in his weight. During an acceleration the aircraft is not in equilibrium since an out-of-balance force is required to deflect it continuously from a straight line.

8. While a body travels along a curved path it constantly tries to obey the first law and travel in a straight line. To keep it turning a force is necessary to deflect it towards the centre of the turn. This force is called *centripetal force*. To this force there is an equal and opposite reaction called *centrifugal force*. Centripetal force can be provided in a number of ways. A weight, on the end of a piece of string, that is swung in a circle is subjected to centripetal force by the action of the string. If the string is released the centripetal force is removed and the equal and opposite reaction (centrifugal force) disappears simultaneously. The weight, conforming to the first law, then flies off in a straight line *at a tangent to the circle.*

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9. To clarify the difference between centripetal and centrifugal force, consider a body (Fig. 2) which moves along a series of straight lines AB, BC, CD, and DE, each inclined to its neighbour at the same angle. When it reaches B it is subjected to an external force f1 acting at right angles to AB, which alters its path to BC. At c a force f2, acting at right angles to BC, alters the path to CD and so on.

10. If the path from A to E consists of a greater number of shorter lines the moving body will be deflected at shorter intervals, and if the lines are infinitely short the intermittent forces blend into one continuous force F and the path becomes the arc of a circle. F will act at right angles to the direction of motion, *i.e.* towards the centre of the arc. The reaction to F, the centrifugal force, is equal in size and opposite in direction.

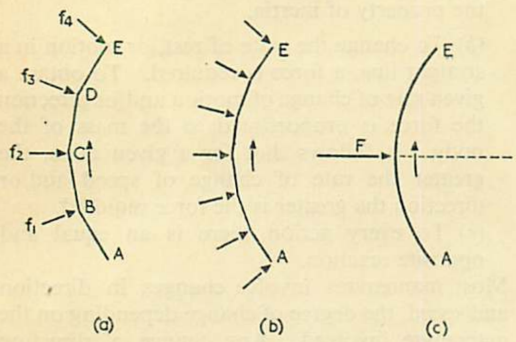


Fig. 2. Centripetal Force

Gravity

11. The symbol *g* denotes the rate of acceleration of a body falling freely under the influence of its own weight, *i.e.* the force of gravity. The acceleration is about 32·2 feet per second per second (ft./sec.^{2}) at the earth's surface when measured in a vacuum so that there is no drag acting upon the body. The force of gravity varies with the distance from the earth's centre and therefore differs slightly at different points on the earth's surface, since the earth is not a perfect sphere. The weight of a body of a stated density and volume (mass) is proportional to the force of gravity and so varies slightly. For practical purposes *g* can be considered to be constant at sea level, irrespective of the geographical location. As altitude is increased, *g* falls off progressively, but in unaccelerated flight this effect is negligible at present operating heights.

12. If any object has, for example, a total force acting upon it equal to five times its own weight it will accelerate in the direction of the force at a rate five times greater than that due to gravity, namely 5*g*. Although *g* is a unit of acceleration it is often used, inaccurately, to indicate the *force* required to produce a given acceleration. Among pilots *g* is often used in this way to express the force accompanying a manœuvre in terms of a multiple of the static weight. For example, if a certain rate of turn (*i.e.* acceleration) necessitates a centripetal force of three times the aircraft weight then the turn is called a 3*g* turn. Since the force is felt uniformly throughout the entire aircraft and its contents, the crew also experience this force and acceleration and feel it as an apparent increase in weight which is proportional to the *g*. During straight and level flight an aircraft accelerometer shows 1*g*, for this is the normal force of gravity that is acting at all times on all objects. During inverted level flight the instrument reads $-1g$ and the pilot's weight, acting vertically downwards, is supported by his harness.

Calculation of Centripetal Force

13. The magnitude of the centripetal force during a given turn is directly proportional to the mass of the body (its static weight) and the square of the speed and is inversely proportional to the radius of turn. It is calculated from the formula :

$$F = \frac{WV^2}{gr} \text{ lb.}$$

where W is the weight (lb.), V the T.A.S. (ft./sec.), r the radius of turn (ft.), and *g* is a constant, 32·2 ft./sec.^{2}.

Turning

14. For an aircraft to turn, centripetal force is required to deflect it towards the centre of the turn. By banking the aircraft and using the horizontal component of the now inclined lift force, the necessary force is obtained to move the aircraft along a curved path.

15. If the aircraft is banked, keeping the angle of attack constant, then the vertical component of the lift force will be too small to balance the weight, and the aircraft will simultaneously start to descend. Therefore as the angle of bank increases, the angle of attack must be increased progressively by a backward movement of the control column to bring about a greater total lift. The vertical component is then large enough to maintain level flight, while the horizontal component is large enough to produce the required centripetal force.

16. **Increase of Power in a Turn.** The increased angle of attack brings with it an increase in drag which must be countered by an increase in power if the speed is to be prevented from falling and settling at a lower figure.

17. **Forces in a Turn.** Fig. 3 shows the forces in a turn and the increase in the total lift and horizontal component that is necessary to obtain the greater force required for a tighter turn. The tighter the turn at a given I.A.S. (the greater the rate of turn) the greater is the value of F and the angle of bank, W remaining unchanged. *The tightest turn for each I.A.S.* is obtained when the wings are producing the greatest lift (C_L max.) on the fringes of the stall, the corresponding angle of bank being the maximum that can be applied without reducing the length of W^1. At this point the angle of attack and induced drag are so high that full power is usually necessary to keep the speed constant, and many types of aircraft have not enough power to make a maximum rate level turn at a high constant I.A.S. It can be seen that a vertically banked turn cannot be done without losing height, since at this angle of bank W^1 is zero and the lift and inward component coincide to become infinitely great.

18. For a given *radius* of turn, irrespective of the weight, the angle of bank is determined by the speed, a high speed necessitating a steeper angle of bank and higher angle of attack to obtain the greater force necessary to reach the required radius of turn. The simple mathematics of this is given in the next paragraph.

19. From Fig. 3 it can be stated that :

$$\text{Tan}\ \theta = \frac{\text{Opp}}{\text{Adj}} = \frac{WV^2}{gr} \Big/ W = \frac{V^2}{gr}$$

In other words, the angle of bank depends only on the speed and the radius of turn, the weight factor having no effect.

Accelerated or *g* Stalls

20. It has been stated that by tightening the turn sufficiently the angle of attack eventually reaches the stalling angle. Warning of the approach of the stall is given, as at low speed, by the buffeting which begins when the airflow starts to become turbulent. If the wings stall unequally, as is usually the case, the aircraft rolls either into or out of the turn owing to the unequal distribution of lift over the wings, sometimes with a flicking motion. To recover, the control column is moved forward to decrease the angle of attack.

21. The accelerated stall, so named because it requires an acceleration to cause it, is also called a high-speed stall. This term is not altogether suitable, since the stalling angle can be reached during a level turn at a speed just above the normal stalling speed. The effect of *g* on the stalling speed is considered in more detail in subsequent paragraphs.

Pitch-Up (Swept-Back Plan Forms)

22. As explained in Chapter 6, pitch-up (self-stalling) is caused by stalling of the wing tips on swept-back plan forms. Pitch-up can occur during manœuvres, in the same way as *g* stalls, whenever the angle of attack is increased to an appropriate angle. Pitch-up precedes, and usually leads to, a *g* stall. Whereas the characteristic occurs in a mild form in the approach to a level flight stall, it usually takes a violent form under *g* and occurs without preliminary warning, resulting in a temporarily uncontrollable increase in *g* that can cause overstress. The *g* at which pitch-up takes place varies with altitude, becoming less as altitude increases. At the highest altitudes pitch-up can occur at figures as low as 2 to 3 *g*. Consequently any unavoidable overshoot, although forming an operational handicap, would not always overstress the aircraft. The severity of the pitch-up varies between aircraft ; most require 7*g* and more at low altitude to cause the characteristic. Pilots' Notes give detailed information on this characteristic whenever it is present.

Loads During Turns

23. **The Load Factor.** The load, or loading on an aircraft during a turn, is the force acting on the structure owing to the increased lift generated by the wings to provide the requisite centripetal force. The loading is usually expressed as a multiple of the weight and is known in this form as the *load factor*. *It acts in the same direction as the lift force, to which it is equal.*

24. By calculating the centripetal force required for a turn the loading can be determined ; knowing the loading at a given rate of turn, the speed at which the *g* stall occurs can then be found.

25. **To Determine Centripetal Force and the Loading.** Consider an aircraft weighing 10,000 lb. flying at 156 knots (264 f.p.s.) in a turn of 600 ft. radius. The centripetal force would be :

$$\frac{WV^2}{gr} = \frac{10{,}000 \times 264^2}{32{\cdot}2 \times 600} = 36{,}074 \text{ lb.}$$

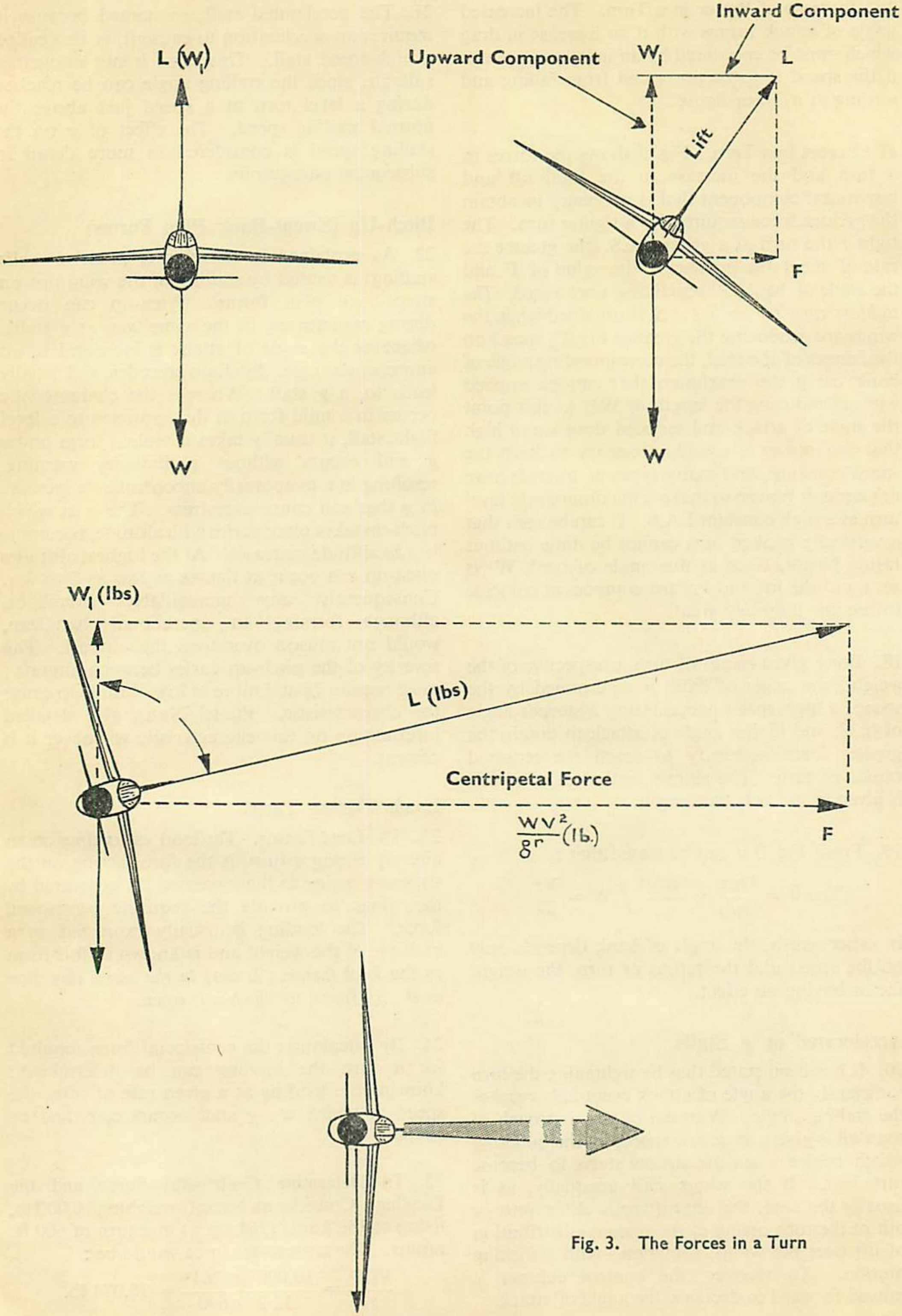


Fig. 3. The Forces in a Turn

From Fig. 3 it can be seen that the loading (which is equal to the total lift) can be found using Pythagoras' theorem, and is equal to :

$$\sqrt{F^2 + W^2}, \text{ which in this example is}$$

$$\sqrt{36{,}074^2 + 10{,}000^2} = 37{,}300 \text{ lb.}$$

Thus the wings are producing $\frac{37{,}300}{10{,}000} = 3{\cdot}73$ times the lift necessary for level flight, *i.e.* the loading on the aircraft can be said to be $3{\cdot}73\ g$.

26. **To Determine the Stalling Speed in a Turn.** The stalling speed in a turn can be shown to vary as the normal stalling speed $\times \sqrt{\text{load factor}}$. Therefore if the aircraft has a normal stalling speed of, say, 78 knots, the stalling speed in the turn considered above would be :

$$78 \times \sqrt{3{\cdot}73} = 151 \text{ knots}$$

which is only 5 knots lower than the air speed. Knowing the length of the vectors, the corresponding angle of bank can be found, by simple trigonometry, to be 74½°.

Recovery from Dives

27. All the considerations of turning apply equally to the recovery from a dive, which can be compared roughly to a turn in the looping plane. If an aircraft is in a dive at any angle with the speed either constant, increasing, or decreasing, the flight path for recovery is changed by moving the control column to increase the angle of attack. When this occurs the lift is increased in proportion to the speed and angle of attack ; and the increase in lift, over and above that required to balance the weight, supplies the necessary centripetal force and so the acceleration.

28. During a vertical dive the wings are at the angle of attack for zero lift since they are not required to supply any force. The only forces acting on the aircraft are the thrust and weight, which are both acting vertically downwards, and the drag which is acting vertically upwards.

29. Thus if an aircraft is diving vertically, the initial increase in angle of attack provides only centripetal force. As the flight path changes, more of the lift is required to balance the weight ; until at the lowest point of the recovery, when the aircraft is in level flight, the total lift both balances the weight and supplies the centripetal force ; *i.e.* if the acceleration remains constant during the recovery, the *loading* increases to a maximum at the lowest point.

30. If the aircraft (Fig. 4) is accelerated by $3g$ while diving vertically an accelerometer in the cockpit would show a loading of $3g$, for the wings are producing lift equal to three times the aircraft weight. At the bottom of the dive, still at an acceleration of $3g$, the accelerometer would show $4g$, *i.e.* the *loading* on the aircraft has increased since in level flight the wings must produce extra lift ($1g$) to balance the weight. At the top of a

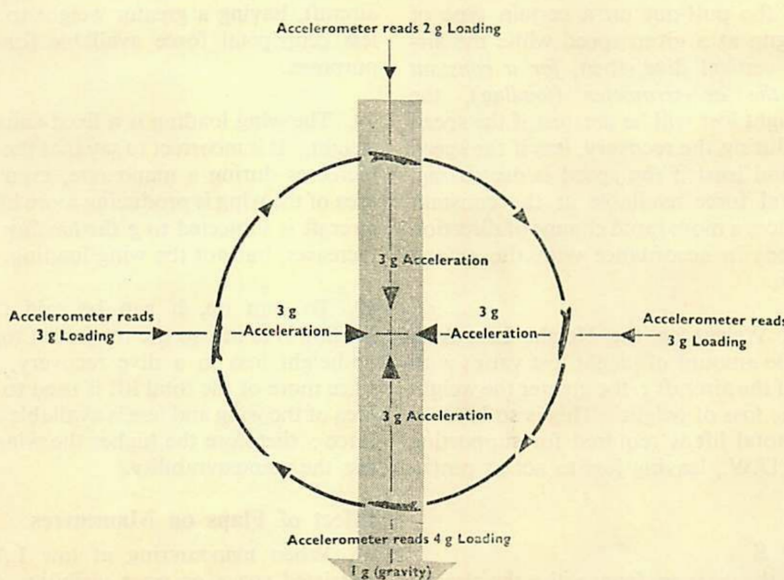


Fig. 4. Looping Accelerations

loop, still at an acceleration of $3g$, the accelerometer will read $2g$, since gravity, acting vertically downwards, supplies the additional g unit to make up the total acceleration, while the accelerometer reading shows only the loading on the wings.

31. If the loading at any part of the recovery is increased to a critical point the aircraft will stall at a speed equal to the normal stalling speed $\times \sqrt{\text{load factor}}$.

32. If the speed is high, then g loads high enough to cause structural failure can be placed on the aircraft before the stalling angle is reached. This is possible because, even at only moderate angles of attack, the high speed realizes very large increases in lift and imposes large accelerating forces. For this reason a pilot should familiarize himself with the characteristics of an aircraft before diving it steeply near the ground, as considerable height may be needed for recovery. Any attempt to hasten the recovery may cause either a g stall and so a greater loss of height, or serious damage to the aircraft. The g values experienced may, in any case, be so high that, even with the protection of anti-g suits, the pilot will black-out. At lower speeds, although the g that can be applied may not exceed the limits for the aircraft, the possibility of the g stall still exists.

33. **Effect of Speed on the Height Lost in a Pull-Out.** If the pull-out on a certain type of aircraft is begun at a given speed while the aircraft is in a vertical dive, then, *for a constant reading on the accelerometer* (*loading*), the amount of height lost will be greatest if the speed is increasing during the recovery, less if the speed is constant, and least if the speed is decreasing. The centripetal force available at the constant loading produces a more rapid change of direction at lower speeds in accordance with the second law of motion.

34. **Effect of Weight on the Height Lost in a Pull-Out.** The amount of height lost varies with the A.U.W. of the aircraft ; the greater the weight the greater the loss of height. This is so because more of the total lift is required for supporting the higher A.U.W., leaving less to act as centripetal force.

Rolling with *g*

35. If during the recovery from a dive the aircraft is rolled to change direction at the same time—sometimes called a rolling pull-out—severe loads may be placed on the structure even at g loads appreciably below the maximum permitted for straight recoveries.

36. In a manœuvre of this sort the wing is subjected to the twisting loads caused by the ailerons as well as those imposed by the high speed and angle of attack. For this reason Pilots' Notes sometimes give a limitation on the permissible accelerometer reading that may be reached in such a manœuvre.

Effect of Wing Loading on Manœuvres

37. The wing loading is the proportion of the static A.U.W. of the aircraft that is carried by unit area of the wings. Usually expressed in lb./sq. ft., it is obtained by dividing the weight by the area of the wings. So for a given wing area, the greater the weight the greater the wing loading. Wing loadings for typical training aircraft of the Provost type are about 20 to 25 lb./sq. ft., while those of operational aircraft range from about 50 lb./sq. ft. upwards.

38. If two similar aircraft having the same wing areas but different weights are manœuvred together (everything else being equal), the lighter aircraft will be able to turn on a smaller radius than the heavier one. From Fig. 5 it can be seen that if both aircraft are turning with the wings at the highest usable angle of attack (and thus developing the same total lift) the heavier aircraft, having a greater weight to balance, has less centripetal force available for acceleration purposes.

39. The wing loading is a fixed value for a given weight. It is incorrect to say that the wing loading increases during a manœuvre, even though unit area of the wing is producing more lift. When the aircraft is subjected to g the *loading* (load factor) increases, but not the wing loading.

40. To sum up, it can be said that as wing loading is raised so the minimum turning radius, or height loss in a dive recovery, is increased, since more of the total lift is used to support unit area of the wing and less is available as centripetal force ; therefore the higher the wing loading the less the manœuvrability.

Effect of Flaps on Manœuvres

41. When manœuvring at low I.A.S. or in a restricted space or poor visibility it is advantageous to lower the flaps to the take-off setting. In this way the margin above the stalling speed is

increased and the greater drag means that a higher power must be used for level flight ; the higher power, on piston-engine aircraft, gives a stronger airflow over the tail surfaces and improves control at low speeds ; on jet-engine aircraft the higher power enables a more rapid response to be obtained from the engine in an emergency when high power is needed. The minimum radius of turn is smaller with the flaps at the take-off setting since the C_L is higher (except at high mach number (para. 59)) and the greater drag means that more power is required for a sustained minimum radius turn at a constant speed.

Effect of Altitude on Manœuvres

42. Increase in altitude decreases the manœuvrability of all aircraft, and at their highest altitudes all aircraft are severely limited in the amount of *g* that can be applied without stalling. All changes in direction involve the application of *g* forces on the aircraft and whenever, for any reason, the amount of *g* is restricted, the manœuvrability of the aircraft suffers. At high altitude the manœuvre least affected is pure rolling, as this does not involve a change of direction.

43. There are three main reasons for the reduction in manœuvrability at high altitude :—

(*a*) The I.A.S./T.A.S. relationship.

(*b*) The reduction in C_L at increasing mach number.

(*c*) Reduction of thrust with altitude.

44. **I.A.S./T.A.S. Relationship.** If an aircraft is flying at a T.A.S. (I.A.S.) of 400 knots at sea level and a given elevator deflection is made, the resulting change in tailplane lift increases the angle of attack of the wing and so imposes an acceleration on the aircraft. The amount of *g* (the rate of change of direction) depends on the inertia of the aircraft (T.A.S.) and the magnitude of the force. At, say, 40,000 feet the same aircraft at a T.A.S. of 400 knots would have an I.A.S. of about 200 knots because of the reduced density at that altitude. Since all aerodynamic forces are governed by the strength of the $\frac{1}{2}\rho V^2$ factor, the same increase in angle of attack imposes a force proportional to the I.A.S. of 200 knots—about half the force obtained at sea level. Consequently the *g* realized would be less, as the inertia of the aircraft (T.A.S.) is unchanged, but the accelerating force is halved and the response of the aircraft therefore becomes sluggish. At higher altitudes the effect becomes more pronounced as the difference between I.A.S. and T.A.S. grows. For example, at altitudes of about 75,000 feet, although the T.A.S. may be supersonic, the manœuvring forces obtained from movements of conventional movable control surfaces are reduced to a point at which only fractional amounts of *g* can be obtained.

45. **Reduction of C_L at Increasing Mach Number.** As explained in para. 59, the C_L of any wing at a given angle of attack is reduced as mach number is increased. The reduced C_L means that for any manœuvre involving *g*, the available

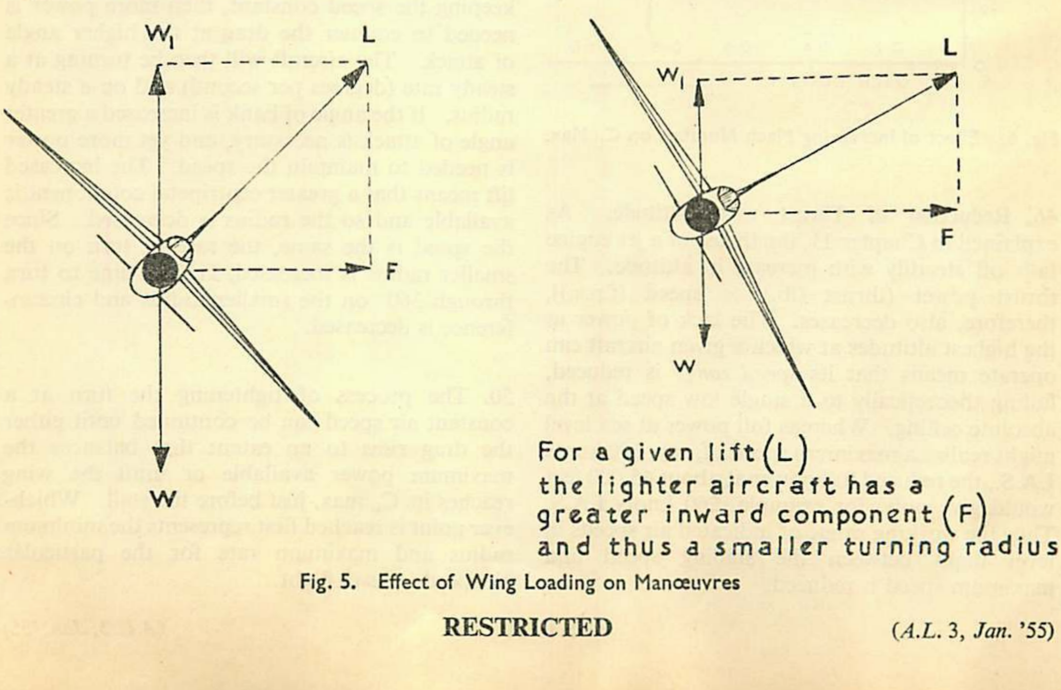


Fig. 5. Effect of Wing Loading on Manœuvres

lift (and hence accelerating force) is less and the amount of *g* that can be applied without stalling is therefore restricted. On aircraft that use a fixed or variable-incidence tailplane in conjunction with the usual elevator, compressibility effects usually cause a marked reduction, culminating in some instances in a total loss of elevator effectiveness. Recovery from the resultant dive is made when control effectiveness is regained in the denser air at lower altitudes, or when speed is reduced. The decay in elevator effectiveness necessitates larger movements to obtain a required change in direction ; and at the highest altitudes full elevator movement is required to obtain even small amounts of *g*. The weakness of this type of tailplane/elevator combination can be overcome by using an all-moving tailplane ; nevertheless the loss in wing C_L in the presence of compressibility still occurs. Fig. 6 shows the effect of mach number on the C_L max. of two wings, one swept and the other unswept.

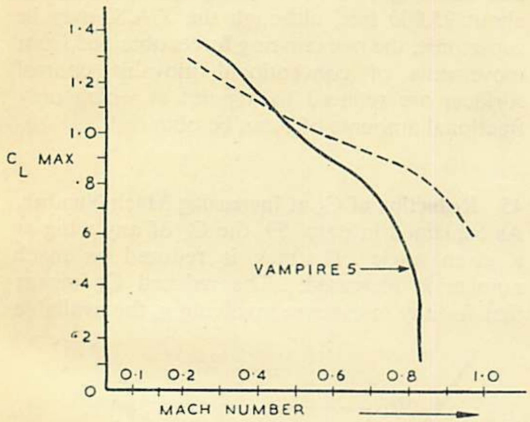


Fig. 6. Effect of Increasing Mach Number on C_L Max.

46. **Reduction of Thrust with Altitude.** As explained in Chapter 11, the thrust of a jet engine falls off steadily with increase in altitude. The thrust power (thrust (lb.) × speed (f.p.s.)), therefore, also decreases. The lack of power at the highest altitudes at which a given aircraft can operate means that its *speed range* is reduced, falling theoretically to a single low speed at the absolute ceiling. Whereas full power at sea level might realize a maximum speed of, say, 650 knots I.A.S., the reduced full power at about 45,000 feet would give only, for example, 260 knots I.A.S. Thus the working range of indicated air speeds in level flight between the stalling speed and maximum speed is reduced.

47. The lack of power also affects the amount of *g* that can be applied. Any increase in *g* involves an increased angle of attack and so increased total drag, therefore the small amount of power available may not be sufficient to allow sustained turns without a reduction in the already low I.A.S. This effect is proportional to altitude and is most noticeable at or just below the ceiling, where even fractional amounts of *g* cause either a loss in I.A.S., a *g* stall, a reduction of altitude, or all three.

48. Considering the sum of all these characteristics on the aircraft it can be seen that all control movements must be made gently at high altitude because of the lack of lift in the presence of the adverse altitude effects. Harsh movements can easily cause loss of speed which is not easy to regain because of the low power available to accelerate the aircraft, or *g* stalls or pitch-up and a fairly rapid loss of height which, again, is not easy to regain.

MINIMUM-RADIUS AND MAXIMUM-RATE TURNS

Theoretical Considerations

49. Theory indicates that *for each air speed* there is a minimum radius of turn and a maximum rate of turn. Consider an aircraft cruising at 150 knots. If the aircraft is made to turn slightly, keeping the speed constant, then more power is needed to counter the drag at the higher angle of attack. The aircraft will then be turning at a steady rate (degrees per second) and on a steady radius. If the angle of bank is increased a greater angle of attack is necessary, and yet more power is needed to maintain the speed. The increased lift means that a greater centripetal component is available and so the radius is decreased. Since the speed is the same, the rate of turn on the smaller radius is increased, *i.e.* the time to turn through 360° on the smaller radius and circumference is decreased.

50. The process of tightening the turn at a constant air speed can be continued until either the drag rises to an extent that balances the maximum power available or until the wing reaches its C_L max. just before the stall. Whichever point is reached first represents the minimum radius and maximum rate for the particular air speed in level flight.

51. Assuming that the power available is insufficient to keep the speed constant and that there is still a margin of angle of attack in hand, then the turn can be tightened further only by a spiral dive, in which gravity supplies the extra force to balance the drag at the higher angle of attack. The higher angle of attack at the same air speed means that the total lift is increased and therefore that an increased centripetal force is obtained which turns the aircraft on a still smaller radius, at the same time further increasing the rate of turn.

52. Starting at a lower speed and carrying out the same procedure, the aircraft would again arrive at the point at which the turn could not be increased without a loss in speed or a stall. In this case, however, the minimum radius would be larger than that of the aircraft in the first example, and the rate of turn would be less.

53. Theoretically, therefore, when turning in level flight, the higher the air speed that can be maintained on the power available the smaller is the radius of turn and, automatically, the higher is the rate of turn. This effect becomes obvious when the simple mechanics are considered. Any wing that is flying at the point of stall (C_L max.) at a high air speed must be producing more lift than the same wing, at the same angle of attack, at a lower speed. Therefore the faster moving wing has a greater horizontal component of the total lift available to act as centripetal force, *i.e.* it turns on a smaller radius. Because the radius is smaller and the speed along the radius higher, the time taken to turn through 360° is less than that of the slower aircraft.

54. To summarize the conclusions so far, it can be stated that, when turning in level flight, the higher the air speed that can be held with the power available *at the angle of attack for C_L max.* the smaller is the radius of turn and the higher the rate of turn.

55. As the sustained speed increases and the radius decreases, the accelerometer reading (*g*) increases. This is a natural consequence of the increasing *load factor* needed to achieve the smallest radius.

56. The table sets out the theoretical minimum radii and maximum rates of turn for a Meteor aircraft at various I.A.S. values. It shows clearly that high speed has a beneficial effect on rate and radius of turn.

I.A.S.	*g*	Angle of Bank	Radius of Turn	Time (secs.) to turn through 360°
100	1	Nil	—	—
120	1·44	46°	1,220	37·6
150	2·25	63½°	1,000	25·0
200	4	73½°	920	17·2
300	9	83½°	895	11·1
400	16	86½°	894	8·35
500	25	88°	893	6·65

Note that above 300 knots the radius falls only slightly but that because the speed is higher, rate of turn is increasing steadily. In normal flight the high induced drag on entry into a steep turn at high speed causes the speed to fall rapidly in spite of the use of full power ; and while this is happening, theory indicates a gradually increasing radius and decreasing rate of turn. In practice, this rule is modified by compressibility effects as explained below.

Effect of Compressibility on Theoretical Figures

57. Theory states that the stalling speed in a turn varies as the square root of the applied *g*, *i.e.* if the level flight stalling speed is 100 knots then the stalling speed at 9*g* would be $\sqrt{9} \times 100$, or 300 knots. However, in practice it is found that only 5 or 6*g* is required to stall the aircraft at this speed ; in other words, the wings cannot produce the lift that theory indicates they should at the angle of attack for C_L max.

58. It has been shown that at the point of stall, lift equals C_L max. $\frac{1}{2}\rho V^2 S$. Since for a given turn all the factors in the formula except the C_L are fixed, the only way of accounting for the loss of lift is by a reduction in the C_L max. appropriate to the speed and angle of attack.

Variation in C_L Max.

59. Fig. 6 shows C_L max. plotted against mach number for a Vampire 5. It is evident that, even at low mach numbers, the compressible nature of air has a definite effect on the lift produced by a wing. The reasons for the decaying C_L max. are :—

(*a*) *Early Onset of Compressibility*. With the wing at a high angle of attack there is a greater venturi effect over the upper surface of the wing, and so the local air speed over this area is accelerated to a greater mach number than at small angles of attack.

(*b*) *Boundary-Layer Effects.* The higher pressure gradient leads to thickening of the boundary layer and therefore to a reduction in the rate of increase of lift with increasing angle of attack. (The stall occurs when the boundary layer separates.)

(*c*) *Buffeting.* Pre-stall buffeting may be strong enough to prevent an accurate turn being made at the maximum angle of attack.

60. The C_L max./mach number curve of most high-speed aircraft takes the approximate form of Fig. 6. The effect of sweepback is shown by the dotted line and the beneficial result is apparent.

Effect of Variation in C_L Max.

61. The effect of mach number on C_L max. is to modify the theoretical values of radius and rate of turn for a given set of conditions. To enable the modified characteristics to be studied more easily, they are presented in graphical form in Fig. 7, representative of a Meteor aircraft.

62. The heavy line of Fig. 7A shows the theoretical radius of turn assuming a constant C_L max. with increasing mach number. The broken line shows the effect on theory of the decay in C_L max. with mach number. Fig. 7B shows rate of turn (time to turn through 360°) against mach number. Again the full line shows the theoretical values and the broken line the actual values. It should be noted that the higher air speeds can only be maintained by a spiral dive.

63. It is generally considered that a maximum-rate turn is automatically a minimum-radius turn, but this holds good only on low-powered aircraft on which the speed for maximum rate of turn is low enough not to affect the C_L max.

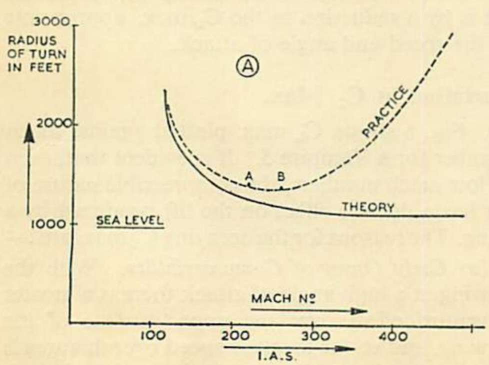
64. From Fig. 7A it can be seen that 240 knots is the I.A.S. for minimum radius. Now consider two aircraft, one flying at 220 knots and the other at 260 knots (points A and B). Both these aircraft are flying on the same radius but the faster aircraft will naturally complete the turn earlier, *i.e.* the rate of turn is higher. Fig. 7B shows that the maximum rate of turn occurs at about 350 knots.

Summary of Turning Performance

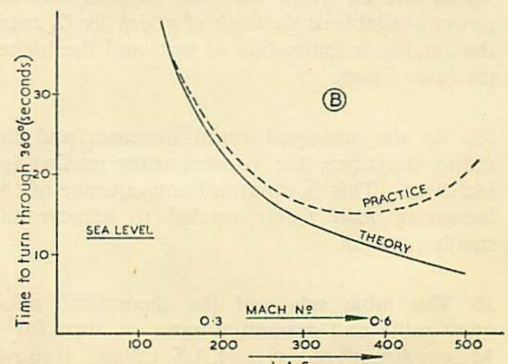
65. It is not possible to lay down any simple rule to determine the speeds for minimum-radius and maximum-rate turns. The exact speeds vary with altitude, the I.A.S. decreasing and the mach number increasing. However, the best speed for a maximum-rate turn is a little higher than the best climbing speed for the existing altitude.

66. The use of flap to increase C_L max. improves turning performance at low speeds only. Flaps cause a large increase in drag and a greater fall in C_L max. if used at high mach number because of their greater accelerating effect on the air passing over the upper surface of the wing. Since the advantage of speed in high altitude manœuvres is all-important, the use of flap under these conditions should be resorted to only after consideration of the overall situation.

67. For low-speed aircraft in which C_L max. is unaffected by mach number the theoretical teaching holds good, and the greater the speed that can be maintained the greater the rate of turn and the smaller the radius. A maximum-rate and minimum-radius turn is made at the same speed.



A. The Speed for Minimum Radius of Turn



B. The Speed for Maximum Rate of Turn

Fig. 7.

68. For high-performance aircraft, however, the C_L max. falls with mach number and the rate of increase of lift obtained by an increase of speed falls off. On aircraft which are essentially subsonic the drop in wing efficiency is progressive over most of the higher end of the speed range, and is most marked near the compressibility mach number of the aircraft.

69. As a result of the falling C_L max. there is a best speed for a minimum-radius turn and a higher speed for a maximum-rate turn. The speeds for both types of turn vary with altitude. Generally, for evasive purposes, maximum-rate turns are required ; therefore for operational purposes the speed should never be permitted to fall below the best climbing speed for the altitude ; an excess of speed is always an advantage and the speed should be kept as high as possible consistent with the task in hand.

70. The speed for a minimum-radius turn is usually low (240 knots for Meteor aircraft at sea level), and when manœuvring at low altitude (*e.g.* dive recovery) the speed should be kept as close to this figure as possible.

71. Sustained maximum *level* turns for most service aircraft will result in maximum rate *and* minimum radius, since few aircraft have the power to turn at a higher speed, at C_L max., than the speed for minimum radius. Only by the use of higher thrust/weight ratios can the ideal speed for absolute maximum-rate turns be reached.


LIGHTNING MK. 1
COVER PITOT HEAD