Unit 5

AIRCRAFT INSTRUMENTS

Two of the most important pieces of information for a safe flight are height and speed. Almost from the beginning of powered flight these have been provided to the pilot by instruments that utilise the ambient atmospheric pressure by means of a pitot/static system.

Static pressure

The ambient atmospheric pressure at any location is known as the static pressure. This pressure, in a standard atmosphere, decreases by 1 hecto- pascal (hPa) for each 27 feet (ft) increase in altitude at mean sea level. For simplicity this figure is usually approximated to 1 hPa per 30 ft gain in altitude. The rate of change of pressure with height is fundamental to the operation of the pressure altimeter, the vertical speed indicator and the mach meter. Each of these instruments uses static pressure to measure aircraft altitude, or rate of change of altitude.

Static pressure, that is the pressure of the stationary air surrounding an aircraft, irrespective of its height or speed, is sensed through a set of small holes situated at a point on the aircraft unaffected by turbulence. This sensing point is known as the static source. It is typically on the side of the fuselage or on the side of a tube projecting into the airstream.

Pitot pressure

As an aircraft moves through the air it displaces the surrounding air. As it moves forward it compresses the air and there is a pressure increase on the forward-facing parts of the aircraft. This pressure is known as dynamic pressure. Suppose a cup were to be placed on the front of an aircraft, with its open end facing forward. When the aircraft is stationary the pressure inside the cup will be the same as the surrounding air pressure. In other words it will be static pressure. When the aircraft begins to move forward the air inside the cup will be compressed and dynamic pressure will be added to the static pressure. The faster the aircraft moves, the greater the dynamic pressure will become, but static pressure will always also be present. The pressure measured on the forward-facing surfaces of an aircraft will be the sum of static pressure and dynamic pressure. This is known as pitot pressure, or total pressure, which is sensed by a forward-facing, open-ended tube called a pitot tube, or pitot head. Figure 1.1 is a simplified diagram of a pitot head.

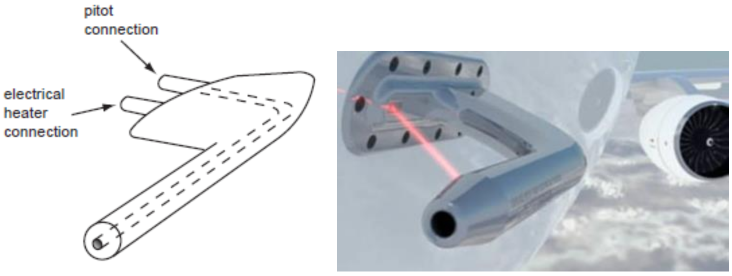

Figure 1.1 Pitot head.

The pitot head comprises an aerodynamically shaped casing, usually mounted beneath one wing, or on the side of the forward fuselage, clear of any turbulent airflow. Within the casing is a tube, the rear of which is con- nected to the pitot system, which conveys pitot pressure to the pilot's instruments. An electrical heating element is fitted within the tube to pre- vent the formation of ice, which could otherwise block the tube and render it useless. Drain holes are provided in the bottom of the tube to allow water to escape.

The dynamic element of pitot pressure is required to operate those air data instruments that display speed relative to the surrounding air, the airspeed indicator and the mach meter. Pitot and static pressure is supplied to the air data instruments through a system of tubes known as the pitot/static system. A schematic layout of the pitot/static system for a light aircraft is shown in Figure 1.2.

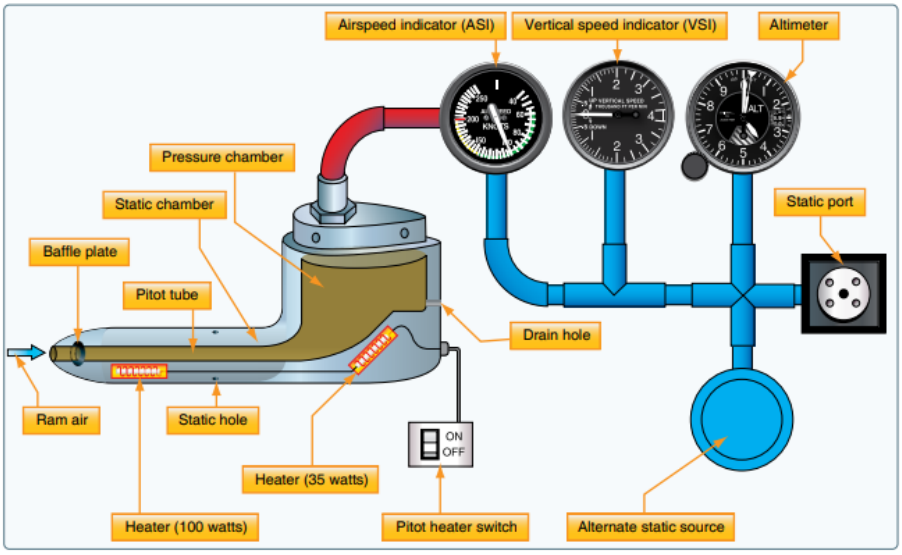

Fig 1.2 : Pitot/static system with instruments

The static source consists of a number of small holes in the side of the pitot head, connected to an annular chamber surrounding the pitot tube. This chamber is connected to the static system, which conveys static pressure to the pilot's instruments. A separate pipe connects the pitot tube to the pitot system. As with the pitot head shown in Figure 1.1, an electrical heating element is fitted to prevent blockage of the pitot and static sources due to icing and water drain holes are provided in the bottom of the casing. In some aircraft this type of pitot head is mounted on the fuselage near the nose and it may be duplicated, one each side, to compensate for crosswind effects.

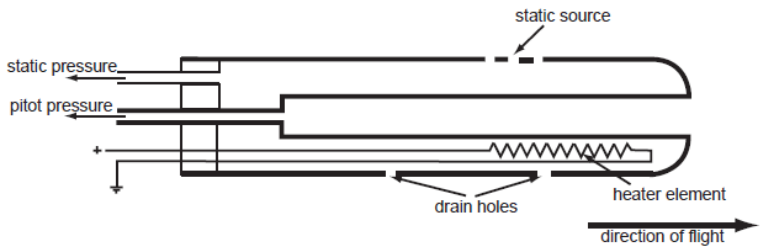

Figure 1.3 Pitot/static head.

Altimeter

The altimeter is an instrument that measures the height of an aircraft above a given pressure level. Pressure levels are discussed later in detail. Since the altimeter is the only instrument that is capable of indicating altitude, this is one of the most vital instruments installed in the aircraft. To use the altimeter effectively, the pilot must understand the operation of the instrument, as well as the errors associated with the altimeter and how each affect the indication.

The pressure altimeter

The function of the pressure altimeter is to indicate the aircraft height above a given pressure datum. It operates on the principle of decreasing atmo- spheric pressure with increasing height and is, in fact, simply an aneroid barometer that is calibrated to read pressure in terms of height. To do this, the manufacturer assumes that air pressure changes at a given rate with change of height. The international Standard Atmosphere (ISA) values are the data used for this assumption. In the ISA the temperature at mean sea level is +158C and the air pressure is 1013.25 hectopascals (hPa). The temperature lapse rate (the rate at which the temperature will decrease with increase of height) is 1.988C per 1000 ft (6.58C per kilometre) up to a height of 36 090 ft. Above that height the tem- perature is assumed to remain constant at756.58C up to a height of 65 600 ft..

Air is a fluid and it has mass, and therefore density. If we consider a column of air, its mass exerts pressure at the base of the column; the taller the column the greater the pressure exerted at the base. At any given height in the column the pressure exerted is proportional to the mass of air above that point and is known as hydrostatic pressure. Atmospheric pressure is assumed to decrease at a rate of 1 hPa per 27 ft gain in height at sea level, this rate decreases as height increases, so that at a height of say 5500 metres (18 000 ft) the same 1 hPa change is equivalent to approximately 15 metres (50 ft) change in height.

The pressure altimeter is calibrated to read height above a selected pres- sure datum for any specific atmospheric pressure. The element of the pressure altimeter that measures atmospheric pressure changes is a sealed capsule made from thin metal sheet. The capsule is partially evacuated, so that the surrounding atmospheric pressure tends to compress the capsule. However, a leaf spring attached to the capsule pre- vents this. The capsule may be of the diaphragm or the bellows type, as illustrated in Figure 1.4.

The simple altimeter

The capsule is mounted in a sealed casing, connected to the static source. Increased static pressure will cause the capsule to be compressed against the restraining force of the leaf spring, decreased static pressure will allow the leaf spring to expand the capsule. The spring force ensures that the extent of compression or expansion is proportional to the static pressure being mea- sured. This compression or expansion of the capsule is converted into rotary motion of a pointer against a calibrated scale by a system of linkages and gears. A schematic diagram of a simple pressure altimeter is shown in Figure 1.5. Expansion of the aneroid capsule will cause a lever to pivot about its attachment to the instrument casing. This lever is connected to a drum by means of a chain and its pivoting motion causes the drum to rotate. The drum is attached to a pointer, which will consequently rotate against a calibrated card scale.

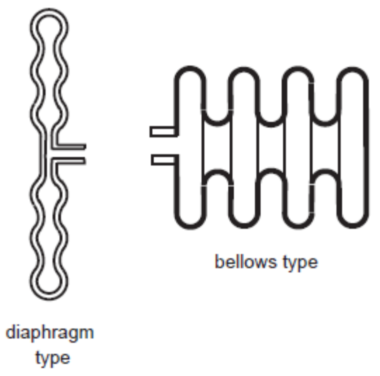

Figure 1.4 Aneroid capsule types.

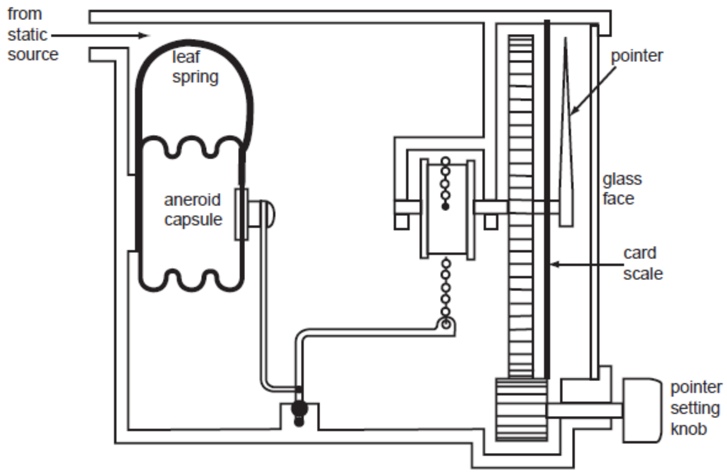

Figure 1.5 Simple pressure altimeter.

The airspeed indicator (ASI) It is essential for the pilot of an aircraft to know its airspeed, because many critical factors depend upon the speed of flight. For example, the pilot needs to know when the aircraft is moving fast enough for take-off, when it is flying close to the stalling speed, when it has accelerated to the speed at which landing gear and flaps must be raised and when it is approaching the
maximum safe flying speed, to name but a few. This critical information is provided by the airspeed indicator (ASI).

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The airspeed indicator measures dynamic pressure and converts this to an indication of airspeed. We have already seen that pitot pressure (P), as measured in the pitot tube, is a combination of dynamic pressure (D) and static pressure (S), i.e. P = D + S. It therefore follows that dynamic pressure is pitot pressure less static pressure, i.e. D = P - S. Thus, the function of the ASI is to remove the static pressure element of pitot pressure and use the resulting dynamic pressure to move a pointer around a graduated scale.

The instrument comprises a sealed case connected to the static source and containing a capsule supplied with pitot pressure. Hence, the static pressure element of pitot pressure inside the capsule is balanced by static pressure surrounding the capsule. Consequently, the capsule will respond only to changes in the dynamic pressure element of pitot pressure. The faster the aircraft flies through the atmosphere, the greater will be the resultant dynamic pressure and the capsule will expand. This expansion is trans- mitted to a pointer by means of gearing and linkages. The principle is illustrated schematically in Figure 1.8. A simple ASI typically uses a single pointer that moves around a scale calibrated in knots. More complex instruments may be used in high-speed aircraft, incorporating an angle-of-attack indicator or a mach meter.

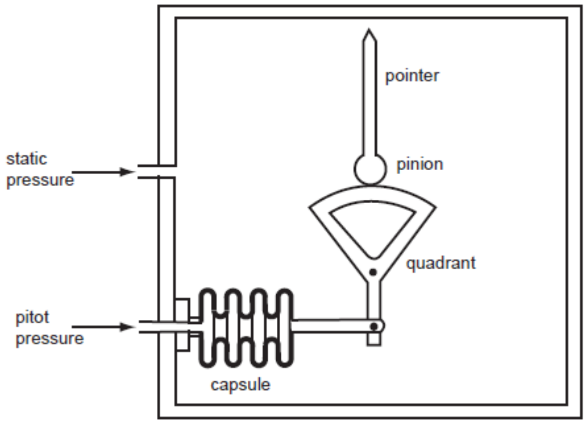

Figure 1.8 Principle of operation of the airspeed indicator.

Any point where air is brought to rest, such as in the pitot tube, is known as a stagnation point. At this point the kinetic energy of the air is converted to pressure energy. The pressure resulting is, of course, dynamic pressure and is denoted by the symbol Q. It can be shown mathematically that $Q = 1/2\ \rho V^2$, where ρ is the air density and V is the airspeed. As the aircraft climbs the air density decreases and the airspeed indicator reading will be lower than the true speed of the aircraft through the sur- rounding atmosphere. A simplistic way of thinking of this is to consider that as the aircraft moves through the air it is colliding with the air molecules; the faster it flies the more molecules it strikes in a given time period. The ASI indication of airspeed is based on the dynamic pressure measured, assuming an ISA mean sea level value of air density. Therefore, when the air density is lower, as with an increase of altitude, a given dynamic pressure (and therefore indicated airspeed) will only be achieved at a higher true airspeed.

Let us assume that it is flying in ISA msl conditions and is colliding with air molecules at a rate that causes the ASI to indicate 90 knots flight speed. When the aircraft climbs to a greater altitude the air density is less and so the molecules are further apart. In order for the ASI to continue to read 90 knots the aircraft must fly faster relative to the surrounding air in order to strike the same number of molecules within a given time period. Thus the true air speed, which is the speed of the aircraft relative to the surrounding atmo- sphere, increases.

Airspeed may be quoted in a number of ways and these are listed below:

ASIR: Airspeed indicator reading.

IAS: Indicated airspeed (IAS) is the speed indicated by the simple airspeed indicator reading (ASIR) corrected for errors due to manufacturing toler- ances in the instrument (instrument error), but not corrected for static pressure errors occurring at the static source (pressure error).

CAS: Calibrated airspeed (CAS) is the airspeed obtained when the correc- tions for instrument error (IEC) and pressure error (PEC) have been applied to IAS. These correction values are usually found in the Aircraft Operating Manual and may be reproduced on a reference card kept in the cockpit. CAS
= IAS + PEC. Calibrated airspeed used to be referred to as rectified airspeed (RAS).

EAS: Because air is a compressible fluid it tends to become compressed as it is brought to rest. At low to medium airspeeds the effect of compression is negligible, but above about 300 knots TAS the compression in the pitot tube is sufficient to cause the airspeed indicator to overread significantly. The greater the airspeed above this threshold, the greater the error due to com- pression. The effect is also increasingly noticeable at high altitude, where the lower density air is more easily compressed. The error produced by this effect is known as compressibility error. Compressibility error correction (CEC) can be calculated and when applied to the calibrated airspeed the result is known as **equivalent airspeed (EAS).** EAS = CAS + CEC.

TAS: The airspeed indicator only indicates **true airspeed** (TAS) when ISA mean sea level conditions prevail; any change of air density from those conditions will cause the indicated airspeed to differ from true airspeed. The greater the altitude, the lower will be air density and therefore IAS (and consequently EAS) will be progressively lower than TAS. The error due to the difference in density from ISA msl density can be calculated. When this density error correction (DEC) is applied to EAS the result is the aircraft's true airspeed (TAS). TAS = EAS + DEC. The com- pressibility error and density error corrections are embodied in the circular slide rule (navigation computer), from which TAS can be found using CAS and the appropriate altitude, speed and temperature settings.

The mach meter

The speed at which sound travels through the air is known as the speed of sound, or sonic speed. This speed varies with air temperature and therefore with location. The speed of sound at any specific location is known as the local speed of sound (LSS). Aircraft that are not designed to fly at supersonic speeds usually suffer both control and structural problems when the airflow over the air- frame, particularly over the wings, approaches the LSS. Consequently it is essential that pilots of such aircraft be aware of the aircraft's speed rela- tive to the LSS. This is especially important at high altitude, since the speed of sound decreases with temperature, and air temperature decrea- ses with altitude in a normal atmosphere. Hence, the greater the alti- tude, the lower the LSS. The aircraft's speed relative to the LSS is measured against a scale in which the LSS is assigned a value of 1. The limiting speed above which control problems may be encountered is known as the critical mach speed and is assigned a value known as the critical mach number (Mcrit). Supposing that, for a particular aircraft, this speed happens to be 70% of the LSS, then the critical mach number would be 0.7. The mach number (M) is the ratio of the aircraft's true airspeed (TAS) to the LSS. This may be represented by the equation:

$$M = \frac{TAS}{LSS}$$

Thus, if an aircraft is flying at a TAS of 385 knots at an altitude where the LSS is 550 knots, the aircraft's mach number is 385 / 550 = 0.7. Clearly, if the aircraft were flying at a TAS of 550 knots in these conditions its mach number would be 1.0 and it would be flying at sonic speed. Since mach number is the ratio of TAS to LSS it follows that mach number is also dependent upon local air temperature. At any given true airspeed the aircraft's mach number varies inversely with temperature. Thus, an aircraft climbing in standard atmospheric conditions at a true airspeed of 573 knots would reach mach 1 at an altitude of 36 090 feet, whereas at sea level its mach number would have been 573 / 661 = 0.87. The mach meter is essentially a pressure altimeter and an ASI combined in one instrument. Its purpose is to indicate the aircraft's airspeed relative to the LSS.

We have seen that the LSS decreases with air temperature and, therefore, with altitude in a normal atmosphere. The mach meter contains an altitude capsule similar to that in the pressure altimeter. Static pressure is supplied to the sealed instrument casing and the aneroid altitude capsule will expand against a light spring as static pressure decreases with increasing altitude. Figure 1.11 is a schematic diagram showing the principle of operation of the mach meter. The instrument also contains an airspeed capsule, the inside of which is connected to pitot pressure. As airspeed, and therefore dynamic pressure, increases the airspeed capsule will expand, exactly as in the ASI.

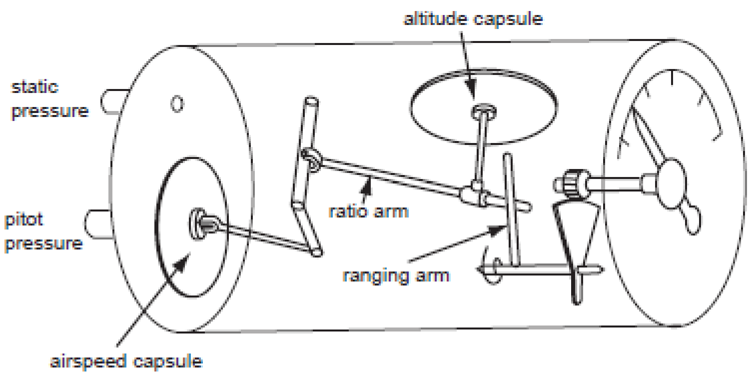

Figure 1.11 Mach meter principle of operation.

The movement of the altitude and airspeed capsules is transmitted to the mach meter pointer through a system of mechanical links and gears. The pointer rotates against a dial calibrated to show the aircraft speed in terms of mach number.

As a pressure instrument the mach meter cannot measure the ratio of TAS to LSS, but it satisfies the requirement by measuring the ratio of dynamic pressure (pitot - static) to static pressure. This can be expressed as:

$$M = \frac{(p - s)}{s}$$

The vertical speed indicator (VSI)

The vertical speed of an aircraft is otherwise known as its rate of climb or descent and the VSI is alternatively known as the rate of climb/descent indicator (RCDI). The purpose of the VSI is to indicate to the pilot the air- craft's rate of climb or descent, typically in feet per minute. Since it is rate of change of height being indicated it is necessary to create a pressure difference within the instrument whilst a height change is occur- ring, and to arrange that the magnitude of the pressure difference is pro- portional to the rate of change of height. This is achieved by a metering unit within the instrument, which is illustrated in schematic form in Figure 1.13.

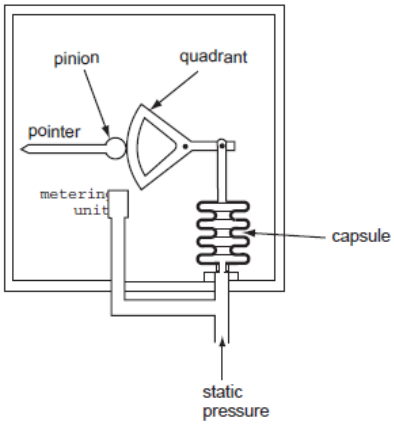

Figure 1.13 Vertical speed indicator principle of operation.

Static pressure is led directly to the inside of a capsule and also to the inside of the sealed instrument casing via a metering orifice. The capsule is connected to a pointer through linkages and a quadrant and pinion gear. Whilst the aircraft is in level flight the pressure in the capsule is the same as that in the casing and the pointer is in the horizontal, nine o'clock position indicating zero. When the aircraft enters a climb, static pressure begins to fall and this is sensed virtually immediately within the capsule. Pressure in the instrument casing is now greater than that in the capsule, since air can only escape at a controlled rate through the restricted orifice of the metering unit. The pressure difference causes the capsule to contract, driving the pointer in a clockwise direction to indicate a rate of climb. The faster the aircraft's rate of climb, the greater will be the pressure difference between capsule and casing and the greater the capsule compression, driving the pointer further around the scale.

During a descent the increasing static pressure will be felt virtually instantly within the capsule, but the pressure in the instrument casing will rise at a slower rate due to the effect of the metering unit. Hence the capsule will expand, against a spring, driving the pointer in an anti-clockwise direction to indicate a rate of descent proportional to the pressure difference, which is in turn proportional to the rate of descent. When the aircraft levels out at a new altitude the pressure in the instru- ment casing will equalise with that in the capsule and the pointer will return to zero. A typical VSI presentation is shown in Figure 1.14. It should be noted that the scale graduation is logarithmic, having greater spacing at lower rates of climb. This is deliberate, to facilitate easy interpretation when small changes of height are being made.

Gyro fundamentals

Gyroscopic instruments are of great importance in aircraft navigation because of their ability to maintain a constant spatial reference and thereby provide indication of the aircraft's attitude. The principal instruments that use the properties of the gyroscope are the directional gyro, the artificial horizon or attitude indicator and the turn and bank indicator.

Gyroscopic properties

The gyroscope used in these instruments comprises a rotor, or wheel, spinning at high speed about an axis passing through its centre of mass and known as the spin axis. A simple gyro rotor is illustrated in Figure 2.1. When a rotor such as that in Figure 2.1 is rotating at high speed it exhibits two basic properties, known as rigidity and precession. It is these properties that are utilised to give gyroscopic instruments their unique features.

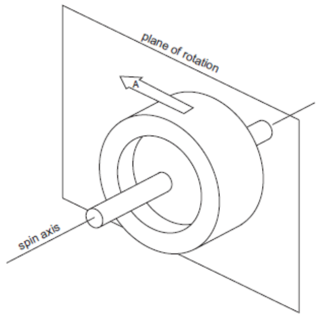

Figure 2.1 Gyro rotor

Turn and bank indicator (rate gyro)

The purpose of the turn and bank indicator is to measure and display the aircraft rate of turn and to indicate whether the aircraft is correctly banked for a co-ordinated turn with no slip or skid. To measure the rate of turn, i.e. rate of movement about the yaw axis, the instrument employs a rate gyro that is sensitive to movement about the aircraft yaw axis only. The bank indication is a separate device using a combination of gravitational and centrifugal force.

Rate gyroscope

Since the rate gyroscope is required to be sensitive to movement about the yaw axis it follows that its spin axis must be perpendicular to that axis, i.e. horizontal. The gyro rotor is mounted in a gimbal with its spin axis aligned with the lateral axis of the aircraft. The single gimbal is pivoted fore and aft in the instrument casing, in line with the aircraft longitudinal axis. The gyro rotor spins up and away from the pilot. The general arrangement showing the principle of operation is shown in Figure 2.17. It will be seen that the gyro has freedom of movement about two axes only, the lateral spin axis and the longitudinal precession axis. When the aircraft yaws about the vertical axis this applies a force to the gyro rotor at the front, in line with the spin axis. Let us suppose that the aircraft is turning to the left. This applies a torque force about the yaw axis in an anti-clockwise direction viewed from above. This is as though a linear force were applied to the front of the gyro rotor on the right side in line with the spin axis, as illustrated at Figure 2.17. The gyro will precess this force 90^0 in the direction of rotation, so that it becomes torque acting in a clockwise direction about the longitudinal axis, precessing the gyro so that the gimbal begins to tilt to the right. The extent to which the gimbal tilts is limited by a spring connecting the gimbal to the instrument casing. As the spring is stretched it exerts a force on the gimbal opposing the precession. When the two are in balance the gimbal is held at a tilt angle that is proportional to the rate of turn, because the precession is equal to the rate of turn and the angular momentum of the gyroscope. Thus, the greater the rate of turn, the greater the tilt of the gimbal. The gimbal actuates a pointer, which moves against a calibrated scale on the face of the instrument to indicate rate of turn. The actuation is such that when the gimbal tilts to the right the pointer moves to the left and vice versa.

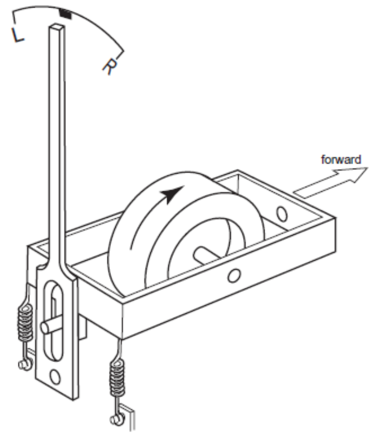

Figure 2.17 Turn and bank indicator - principle of operation.

The speed of rotation of the turn indicator gyro is relatively low, typically about 4500 rpm. It is critical that its speed is maintained constant, since this is a vital factor in ensuring that precession remains constant relative to rate of turn. A warning flag will appear on the face of the instrument when the gyro rotational speed is outside limits. Rate of turn is classified numerically, where rate 1 equals 180^0 per minute, rate 2 equals 360^0 per minute, rate 3 equals 540^0 per minute and rate 4 equals 720^0 per minute. These may also be quoted as 3^0, 6^0, 9^0 and 12^0 per second, respectively. An aircraft maintaining a rate 1 turn for 2 minutes will therefore turn through 360^0.

Bank indication

The bank indication given by the turn and bank indicator displays to the pilot whether or not the aircraft is correctly banked for the turn being made. If the aircraft is banked excessively it will tend to slip toward the centre of the turn, whereas if it is underbanked it will skid outwards, away from the centre of the turn. Hence the name by which this instrument was once commonly known, the turn and slip indicator. The display is provided by a device quite separate from the rate gyroscope of the turn indicator, and typically comprises a curved glass tube filled with liquid and containing a ball. When the aircraft is in level flight, gravity ensures that the ball lies in the centre of the curved tube, as shown in Figure 2.18(a). When the pilot is making a properly co-ordinated banked turn the glass tube, which is attached to the instrument, will be banked with the aircraft and the resultant of centrifugal force and gravitational force will keep the ball in the centre, as shown at Figure 2.18(b). Suppose now that the aircraft is turning, but that the bank angle is greater than it should be, i.e. the aircraft is overbanked. The centrifugal force acting on the ball is less than the gravitational force and the ball falls into the lower part of the tube, as shown in Figure 2.18(c). This indicates to the pilot that the aircraft is slipping into the turn. If the aircraft is underbanked the centrifugal force acting on the ball is greater than the gravitational force and the ball will be moved into the upper part of the tube, indicating that the aircraft is skidding out of the turn. This is shown in Figure 2.18(d). Figure 2.18(e) shows the turn and bank indications during a properly co-ordinated 2 minute (rate 1) standard turn.

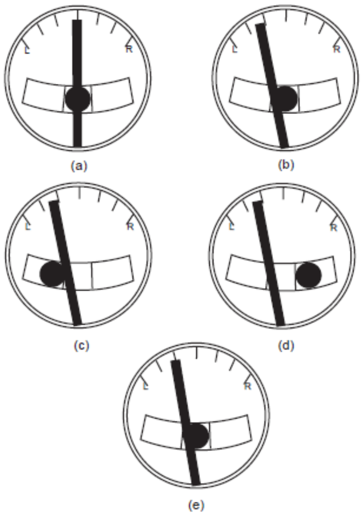

Figure 2.18 Turn and bank indications.