Chapter 8

The ship's master compass

8.1 Introduction

Of all the navigation instruments in use today, the master compass is the oldest and probably the one that most navigators feel happiest with. However, even the humble compass has not escaped the advance of microelectronics. Although modern gyrocompasses are computerized the principles upon which they work remain unchanged.

8.2 Gyroscopic principles

At the heart of a marine gyrocompass assembly is a modern gyroscope consisting of a perfectly balanced wheel arranged to spin symmetrically at high speed about an axis or axle. The wheel, or rotor, spins about its own axis and, by suspending the mass in a precisely designed gimbals assembly, the unit is free to move in two planes each at right angles to the plane of spin. There are therefore three axes in which the gyroscope is free to move as illustrated in Figure 8.1:

- the spin axis
- the horizontal axis
- the vertical axis.

In a free gyroscope none of the three freedoms is restricted in any way. Such a gyroscope is almost universally used in the construction of marine gyrocompass mechanisms. Two other types of gyroscope, the constrained and the spring-restrained are now rarely seen.

In order to understand the basic operation of a free gyroscope, reference must be made to some of the first principles of physics. A free gyroscope possesses certain inherent properties, one of which is inertia, a phenomenon that can be directly related to one of the basic laws of motion documented by Sir Isaac Newton. Newton's first law of motion states that 'a body will remain in its state of rest or uniform motion in a straight line unless a force is applied to change that state'. Therefore a spinning mass will remain in its plane of rotation unless acted upon by an external force. Consequently the spinning mass offers opposition to an external force. This is called 'gyroscopic inertia'. A gyroscope rotor maintains the direction of its plane of rotation unless an external force of sufficient amplitude to overcome inertia is applied to alter that direction. In addition a rapidly spinning free gyroscope will maintain its position in free space irrespective of any movement of its supporting gimbals (see Figure 8.2).

Also from the laws of physics it is known that the linear momentum of a body in motion is the product of its mass and velocity (mv). In the case of a freely spinning wheel (Figure 8.3), it is more

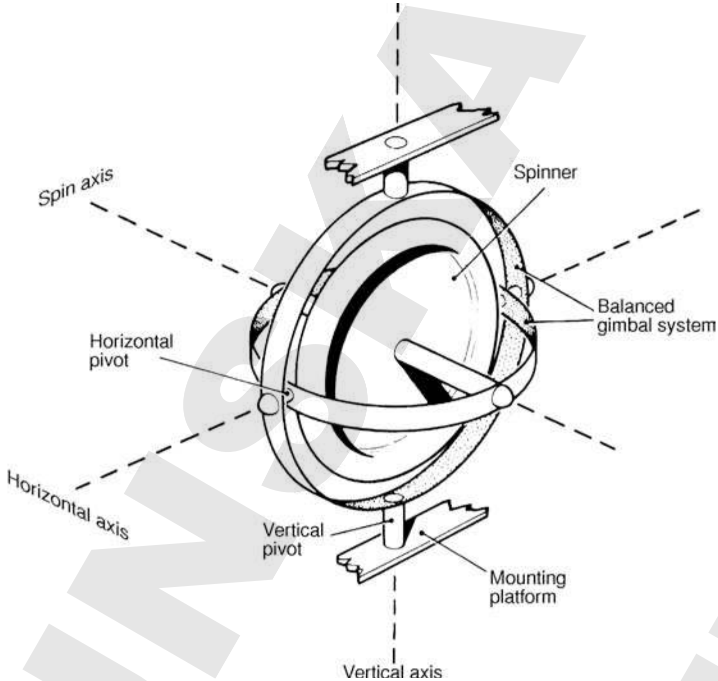


Figure 8.1 A free gyroscope. (Reproduced courtesy of S. G. Brown Ltd.)

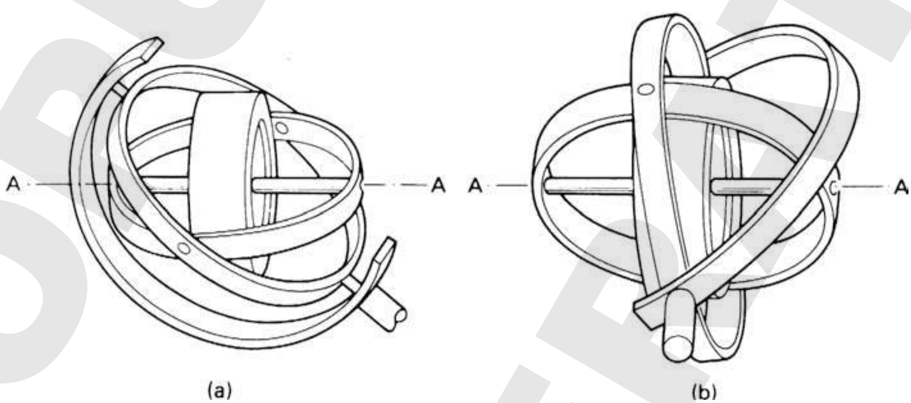


Figure 8.2 The gyrospin axis is stabilized irrespective of any movement of the supporting gimbals. (Reproduced courtesy of Sperry Ltd.)

convenient to think in terms of angular momentum. The angular momentum of a particle spinning about an axis is the product of its linear momentum and the perpendicular distance of the particle from the axle:

$$\text{angular momentum} = mv \times r$$

where r = rotor radius.

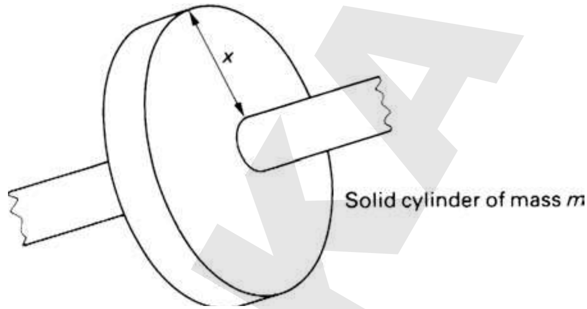


Figure 8.3 A spinning rotor possessing a solid mass.

The velocity of the spinning rotor must be converted to angular velocity (ω) by dividing the linear tangential velocity (v) by the radius (r). The angular momentum for any particle spinning about an axis is now:

$$m\omega r^2$$

For a spinning rotor of constant mass where all the rotating particles are the same and are concentrated at the outer edge of the rotor, the angular momentum is the product of the moment of inertia (I) and the angular velocity:

$$\text{angular momentum} = I\omega$$

where $I = 0.5\ mr^2$.

It can now be stated that gyroscopic inertia depends upon the momentum of the spinning rotor. The momentum of such a rotor depends upon three main factors:

- the total mass, M of the rotor (for all particles)
- the radius r summed as the constant K (for all the particles) where K is the radius of gyration
- the angular velocity ω.

The angular momentum is now proportional to ωMK^2. If one or more of these factors is changed, the rotor's gyroscopic inertia will be affected. In order to maintain momentum, a rotor is made to have a large mass, the majority of which is concentrated at its outer edge. Normally the rotor will also possess a large radius and will be spinning very fast. To spin freely the rotor must be perfectly balanced (its centre of gravity will be at the intersection of the three axes) and its mounting bearings must be as friction-free as possible. Once a rotor has been constructed, both its mass and radius will remain constant. To maintain gyroscopic inertia therefore it is necessary to control the speed of the rotor accurately. This is achieved by the use of a precisely controlled servo system.

8.2.1 Precession

Precession is the term used to describe the movement of the axle of a gyroscope under the influence of an external force. If a force is applied to the rotor by moving one end of its axle, the gyroscope will be displaced at an angle of 90° from the applied force. Assume that a force is applied to the rotor in Figure 8.4 by lifting one end of its axle so that point A on the rotor circumference is pushed

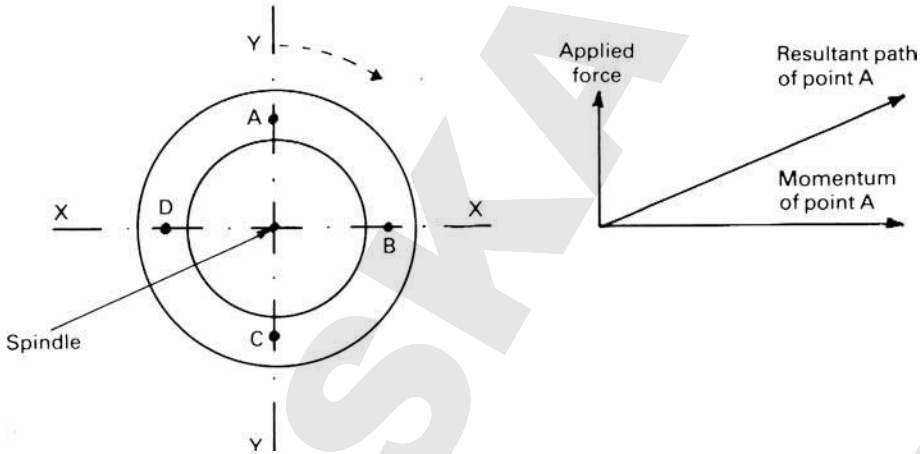


Figure 8.4 Gyro precession shown as a vector sum of the applied forces and the momentum.

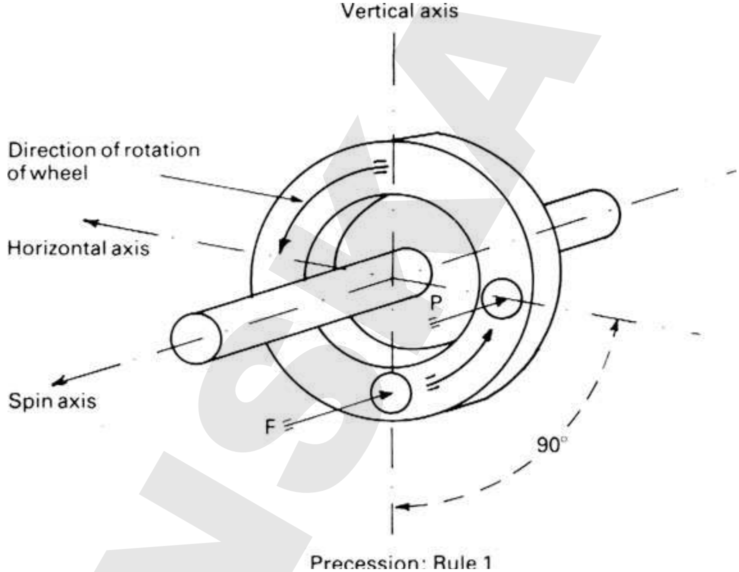
downwards into the paper. The rotor is rapidly spinning clockwise, producing gyroscopic inertia restricting the effective force attempting to move the rotor into the paper. As the disturbing force is applied to the axle, point A continues its clockwise rotation but will also move towards the paper. Point A will therefore move along a path that is the vector sum of its original gyroscopic momentum and the applied disturbing force. As point A continues on its circular path and moves deeper into the paper, point C undergoes a reciprocal action and moves away from the paper. The plane of rotation of the rotor has therefore moved about the H axis although the applied force was to the V axis.

The angular rate of precession is directly proportional to the applied force and is inversely proportional to the angular momentum of the rotor. Figure 8.5 illustrates the rule of gyroscopic precession.

8.2.2 The free gyroscope in a terrestrial plane

Now consider the case of a free gyroscope perfectly mounted in gimbals to permit freedom of movement on the XX and YY axes. In this description, the effect of gravity is initially ignored. It should be noted that the earth rotates from west to east at a rate of 15°/h and completes one revolution in a 'sidereal day' which is equivalent to 23 h 56 min 4 s. The effect of the earth's rotation beneath the gyroscope causes an apparent movement of the mechanism. This is because the spin axis of the free gyroscope is fixed by inertia to a celestial reference (star point) and not to a terrestrial reference point. If the free gyro is sitting at the North Pole, with its spin axis horizontal to the earth's surface, an apparent clockwise movement of the gyro occurs. The spin axis remains constant but as the earth rotates in an anticlockwise direction (viewed from the North Pole) beneath it, the gyro appears to rotate clockwise at a rate of one revolution for each sidereal day (see Figure 8.6).

The reciprocal effect will occur at the South Pole. This phenomenon is known as gyro drift. Drift of the north end of the spin axis is to the east in the northern hemisphere and to the west in the southern hemisphere. There will be no vertical or tilting movement of the spin axis. Maximum gyro tilt occurs if the mechanism is placed with its spin axis horizontal to the equator. The spin axis will be stabilized in line with a star point because of inertia. As the earth rotates the eastern end of the spin axis appears to tilt upwards. Tilt of the north end of the spin axis is upwards if the north end is to the east of the meridian and downwards if it is to the west of the meridian. The gyro will appear to execute one



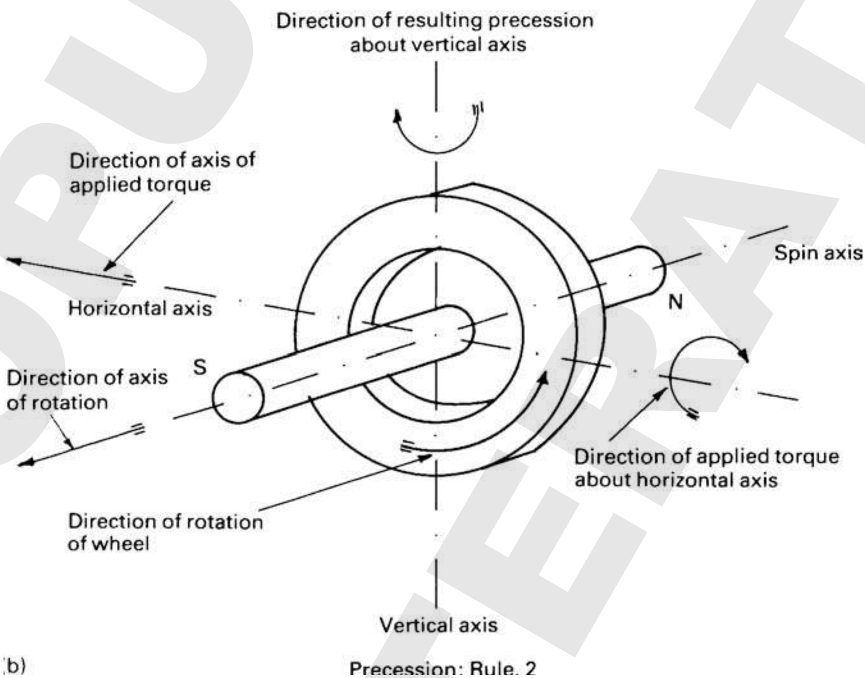


Figure 8.5 (a) Resulting precession P occurs at 90° in the direction of spin from the applied force F. This direction of precession is the same as that of the applied force. (Reproduced courtesy of Sperry Ltd.) (b) The direction of axis rotation will attempt to align itself with the direction of the axis of the applied torque. (Reproduced courtesy of Sperry Ltd.)

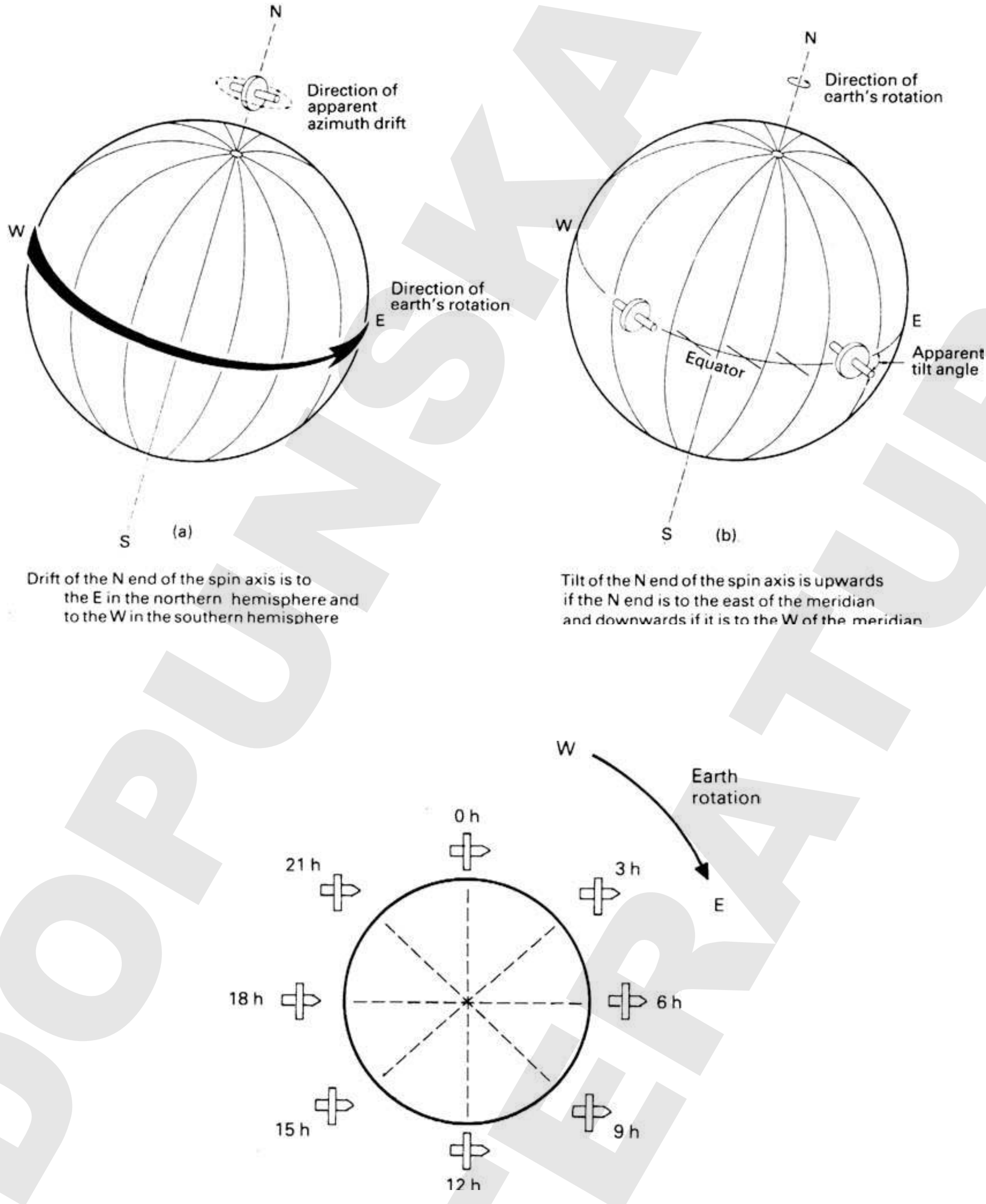


Figure 8.6 (a) Effect of earth rotation on the gyro. (Reproduced courtesy of Sperry Ltd.) (b)View from the South Pole. The earth rotates once every 24 h carrying the gyro with it. Gyroscopic inertia causes the gyro to maintain its plane of rotation with respect to the celestial reference point. However, in relation to the surface of the earth the gyro will tilt.

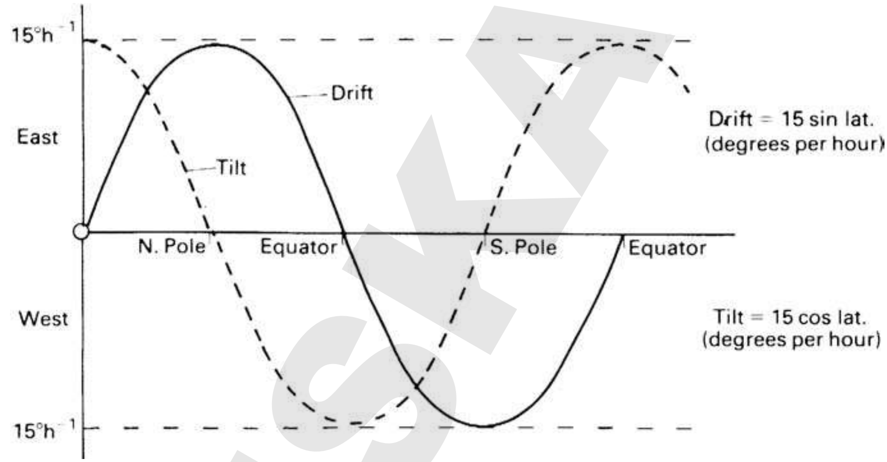


Figure 8.7 The graphical relationship between drift and tilt.

complete revolution about the horizontal axis for each sidereal day. No drift in azimuth occurs when the gyro is directly over the equator. The relationship between drift and tilt can be shown graphically (see Figure 8.7).

Figure 8.7 shows that gyro drift will be maximum at the poles and zero at the equator, whilst gyro tilt is the reciprocal of this. At any intermediate latitude the gyro will suffer from both drift and tilt with the magnitude of each error being proportional to the sine and cosine of the latitude, respectively.

When a gyro is placed exactly with its spin axis parallel to the spin axis of the earth at any latitude, the mechanism will maintain its direction relative to the earth. There is no tilt or azimuth movement and the gyro may be considered to be Meridian stabilized. As the earth rotates the gyro will experience a movement under the influence of both tilt and azimuth motion. The rate of tilt motion is given as:

$$\text{tilt} = 15° \cos \text{latitude (degrees per hour)}$$

where 15° is the hourly rate of the earth's rotation. The azimuth drift is:

$$\text{azimuth drift} = 15° \sin \text{latitude (degrees per hour)}$$

8.2.3 Movement over the earth's surface

The free gyroscope, as detailed so far, is of no practical use for navigation since its rotor axis is influenced by the earth's rotation and its movement over the earth's surface. The stabilized gyroscopic change in position of longitude along a parallel of latitude requires a correction for the earth's rotary motion. Movement in latitude along a meridian of longitude involves rotation about an axis through the centre of the earth at right angles to its spin axis. Movement of the mechanism in any direction is simply a combination of the latitudinal and longitudinal motions. The faster the gyroscope moves the greater the rate of angular movement of the rotor axle attributable to these factors.

8.3 The controlled gyroscope

It has been stated that a free gyroscope suffers an apparent movement in both azimuth and tilt of the rotor axis depending upon its latitudinal location. When fitted to a vessel the latitude is known and consequently the extent of movement in azimuth and tilt is also known. It is possible therefore to calculate the necessary force required to produce a reciprocal action to correct the effect of apparent movement. A force can be applied to the gyro that will cause both azimuth and tilt precession to occur in opposition to the unwanted force caused by the gyro's position on the earth. The amplitude of the reciprocal force must be exactly that of the force producing the unwanted movement, otherwise over or under correction will occur. If the negative feedback is correctly applied, the gyro will no longer seek a celestial point but will be terrestrially stabilized and will assume a fixed attitude.

If the gyro is drifting in azimuth at '*N*' degrees per hour in an anticlockwise direction, an upward force sufficient to cause clockwise precession at a rate of '–*N*' degrees per hour must be applied vertically to the appropriate end of the rotor axle. The result will be that the gyro drift is cancelled and the instrument points to a fixed point on earth. Gyro tilt movement can also be cancelled in a similar way by applying an equal and opposite force horizontally to the appropriate end of the rotor axle. Although the gyro is now stabilized to a terrestrial point it is not suitable for use as a navigating compass for the following reasons.

- It is not north-seeking. Since the recognized compass datum is north, this factor is the prime reason why such a gyro is not of use for navigation.
- It is liable to be unstable and will drift if the applied reciprocal forces are not precise.
- A complex system of different reciprocal forces needs to be applied due to continual changes in latitude.
- Because of precessional forces acting upon it through the friction of the gimbal bearings, the mechanism is liable to drift. This effect is not constant and is therefore difficult to compensate for.

8.4 The north-seeking gyro

The gyrospin axis can be made meridian-seeking (maintaining the spin axis parallel to the earth's spin axis) by the use of a pendulum acting under the influence of earth gravity. The pendulum causes a force to act upon the gyro assembly causing it to precess. Precession, the second fundamental property of a gyroscope, enables the instrument to become north-seeking. As the pendulum swings towards the centre of gravity, a downward force is applied to the wheel axle, which causes horizontal precession to occur. This gravitational force acting downward on the spinner axle causes the compass to precess horizontally and maintain the axle pointing towards true north.

The two main ways of achieving precessional action due to gravity are to make the gyro spin axis either bottom or top heavy. Bottom-heavy control and a clockwise rotating gyro spinner are used by some manufacturers, whereas others favour a top-heavy system with an anticlockwise rotating spinner. Figure 8.8(a) illustrates this phenomenon.

With bottom-heavy control, tilting upwards of the south end produces a downward force on the other end, which, for this direction of spinner rotation, produces a precession of the north end to the west. In a top-heavy control system, tilting upwards of the north end of the gyro produces a downward force on the south end to causes a westerly precession of the north end. The result, for each arrangement, will be the same.

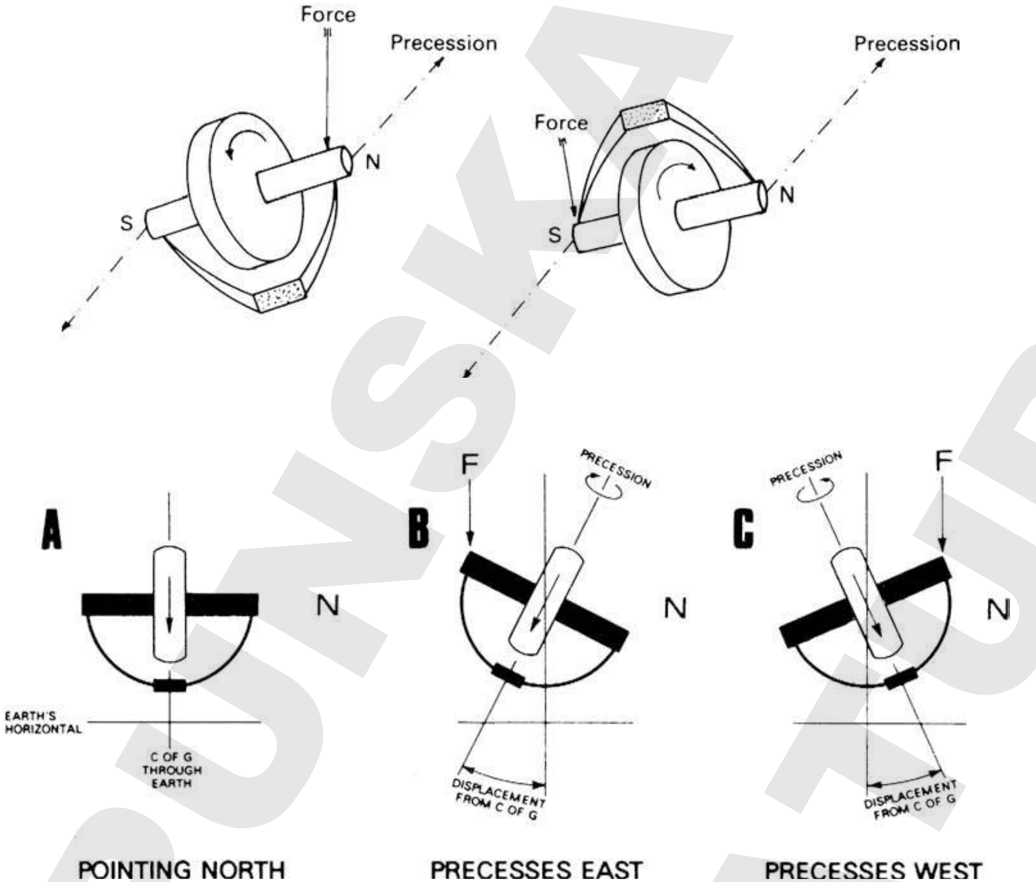


Figure 8.8 (a) Methods of gravity control: bottom-heavy principal and top-heavy control. (b) Principle of gravity control. (Reproduced courtesy of S. G. Brown Ltd.)

8.4.1 Bottom-heavy control

Figure 8.8(b) illustrates the principle of precession caused by gravity acting on the bottom-weighted spin axis of a gyroscope. The pendulous weight will always seek the centre of gravity and in so doing will exert a torque about the gyro horizontal axis. Because of the earth's rotation and gyro rigidity, the pendulum will cause the gravity control to move away from the centre of gravity. The spinner is rotating clockwise, when viewed from the south end, and therefore, precession, caused by the gravitational force exerted on the spin axis, will cause the northeast end of the spin axis to move to the east when it is below the horizontal. A reciprocal action will occur causing the northeast end of the spin axis to precess towards the west when above the horizontal. The spin axis will always appear to tilt with its north end away from the earth (up) when to the east of the meridian, and its north end towards the earth (down) when to the west of the meridian (see Figure 8.9).

This action causes the north end of the spin axis, of a gravity-controlled undamped gyro, to describe an ellipse about the meridian. Because it is undamped, the gyro will not settle on the meridian. Figure 8.9 shows this action for a gyro with a clockwise rotating spinner. The ellipse produced will be anticlockwise due to the constant external influences acting upon the gyro. The extent of the ellipse will, however, vary depending upon the initial displacement of the gyro spin axis from the meridian and from the earth's horizontal. The term 'north-seeking' is given to the undamped gravity controlled gyro mechanism because the northeast end of the spin axis describes an ellipse around the North Pole but never settles. Obviously such a gyro is not suitable for use as a precise north reference compass aid.

8.4.2 The north-settling gyro

The ellipse described by the previous gyro mechanism possesses a constant ratio of the major and minor axes. Clearly, therefore, if the extent of one axis can be reduced, the length of the other axis will be reduced in proportion. Under these conditions the gyro spin axis will eventually settle both on the meridian and horizontally. If the gyro axis is influenced by a second force exerting a damping torque about the vertical axis, so as to cause the spin axis to move towards the horizontal, it is obvious from Figure 8.10 that the minor axis of the ellipse will be reduced.

As the north end of the spin axis moves to the west of the meridian, the earth's rotation will cause a downward tilt of the axis. This effect and the torque (Tv) will cause the gyro axis to meet the earth's horizontal at point H, which is a considerable reduction in the ellipse major axis. As Figure 8.10 clearly shows this action continues until the gyro settles in the meridian and to the surface of the earth, point N.

8.4.3 Top-heavy control

Whereas the previous compass relies on a bottom-weighted spin axis and a clockwise spinning rotor to produce a north-settling action, other manufacturers design their gyrocompasses to be effectively top-weighted and use an anticlockwise spinning rotor. But adding a weight to the top of the rotor casing produces a number of undesirable effects. These effects become pronounced when a ship is subjected to severe movement in heavy weather. To counteract unwanted effects, an 'apparent' top weighting of the compass is achieved by the use of a mercury fluid ballistic contained in two reservoirs or ballistic pots.

As shown in Figure 8.11, each ballistic pot, partly filled with mercury, is mounted at the north and south sides of the rotor on the spin axis. A small-bore tube connects the bases of each pot together providing a restricted path for the liquid to flow from one container to the other. The ballistic system is mounted in such a way that, when the gyro tilts, the fluid will also tilt and cause a displacement of mercury. This action produces a torque about the horizontal axis with a resulting precession in azimuth.

Consider a controlled gyroscope to be at the equator with its spin axis east west as shown in Figure 8.12. As the earth rotates from west to east the gyro will appear to tilt about its horizontal axis and the east end will rise forcing mercury to flow from pot A to pot B. The resulting imbalance of the ballistic will cause a torque about the horizontal axis. This in turn causes precession about the vertical axis and the spin axis will move in azimuth towards the meridian. The right-hand side of the gyro spin axis now moves towards the north and is referred to as the north end of the spin axis. Without the application of additional forces, this type of gyro is north-seeking only and will not settle in the meridian. The north end of the spin axis will therefore describe an ellipse as shown in Figure 8.9.

As the extent of the swings in azimuth and the degree of tilt are dependent upon each other, the gyro can be made to settle by the addition of an offset control force.

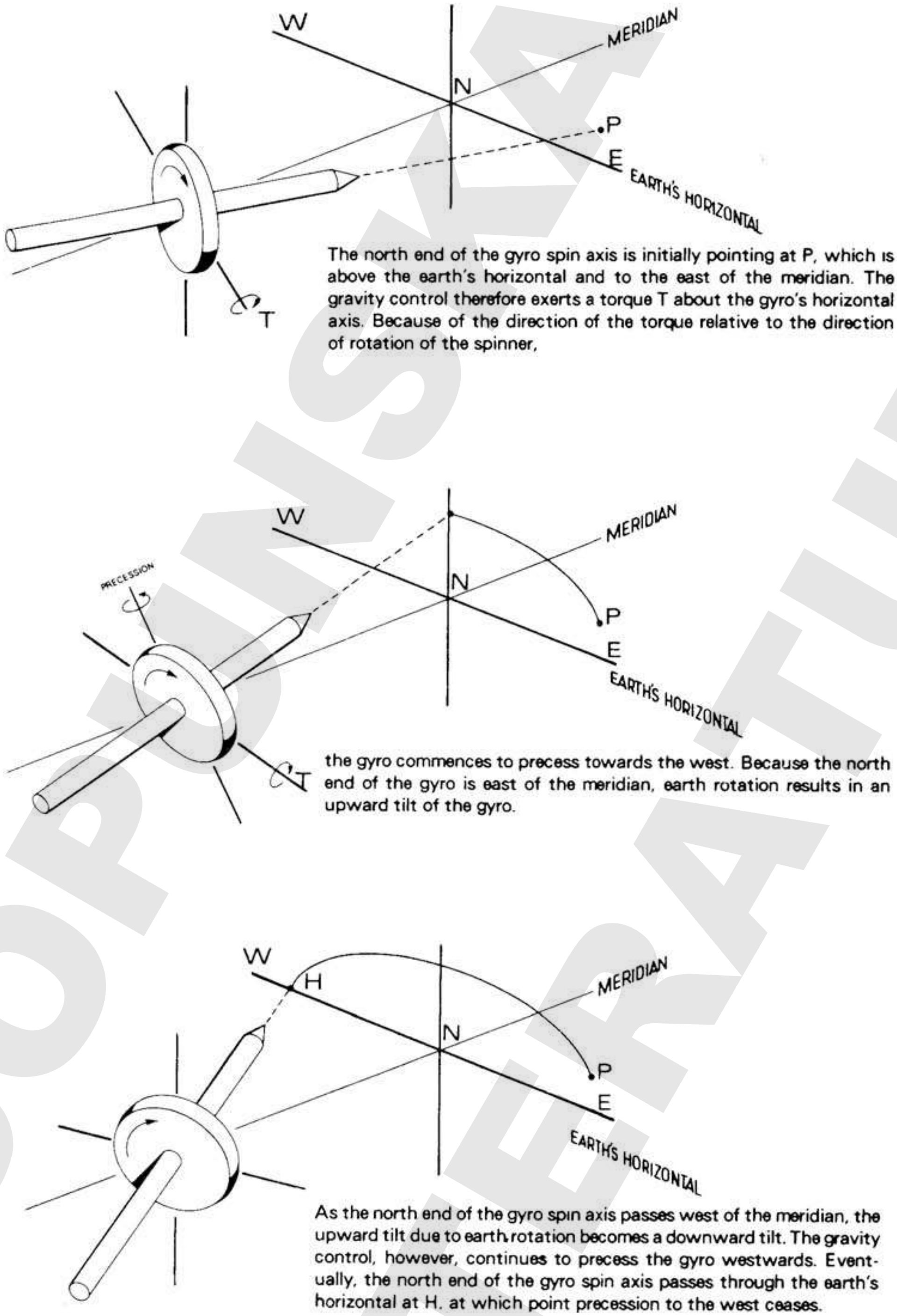
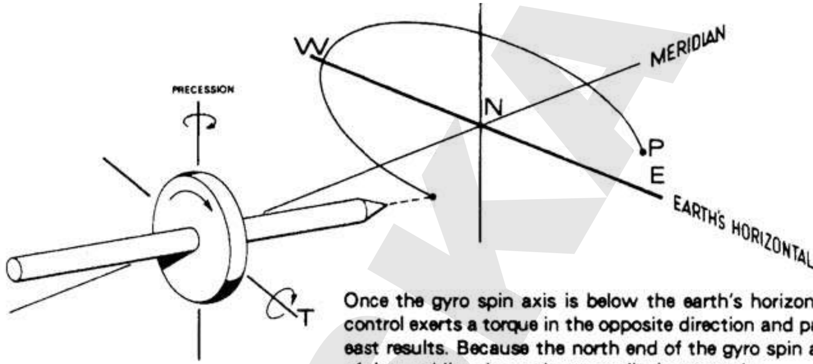
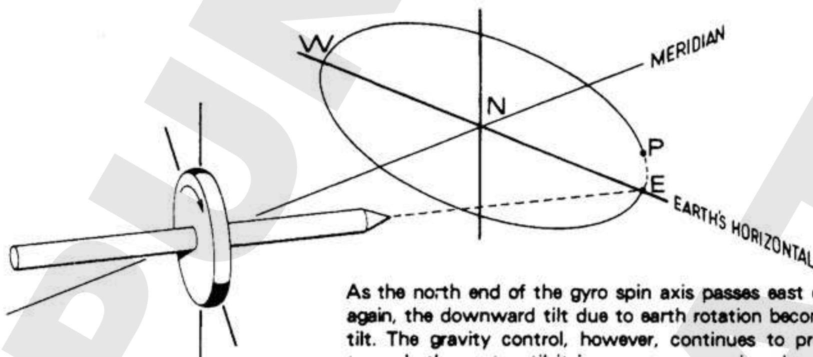


Figure 8.9 Behaviour of the gravity-controlled gyro (undamped). (Reproduced courtesy of S.G. Brown Ltd.)



Once the gyro spin axis is below the earth's horizontal, the gravity control exerts a torque in the opposite direction and precession to the east results. Because the north end of the gyro spin axis is still west of the meridian, it continues to tilt downwards.



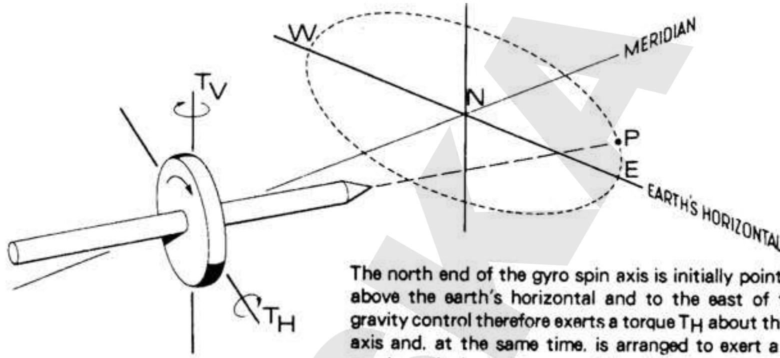
As the north end of the gyro spin axis passes east of the meridian again, the downward tilt due to earth rotation becomes an upward tilt. The gravity control, however, continues to precess the gyro towards the east until it is once more passing through the earth's horizontal. The gyro then commences to precess towards the west again (still tilting upwards) and will eventually pass through point P. The ellipse about North is thus completed and continues.

Figure 8.9 Continued

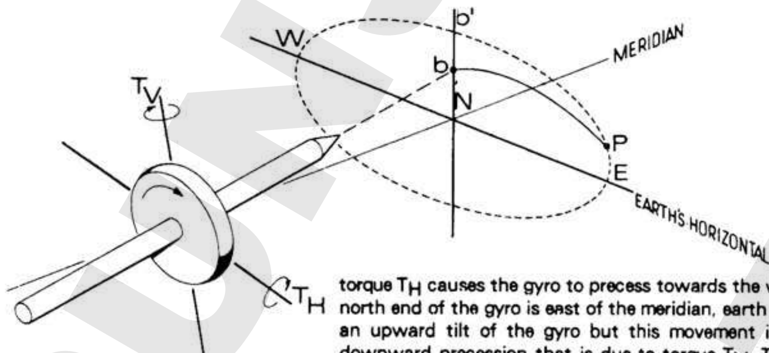
8.5 A practical gyrocompass

The apparent tilting of the gyroscope can be reduced by producing an offset controlling force, which in effect creates 'anti-tilt' precession allowing the unit to settle in the meridian. This is achieved by creating a force about the vertical axis to cause precession about the horizontal axis. This is achieved, in this gyro system, by offsetting the mercury ballistic controlling force slightly to the east of the vertical. The point of offset attachment must be precise so that damping action causes the gyro to settle exactly in the meridian. A comparatively small force is required to produce the necessary anti-tilt precession for the gyrocompass to be made suitable for use as a navigation instrument.

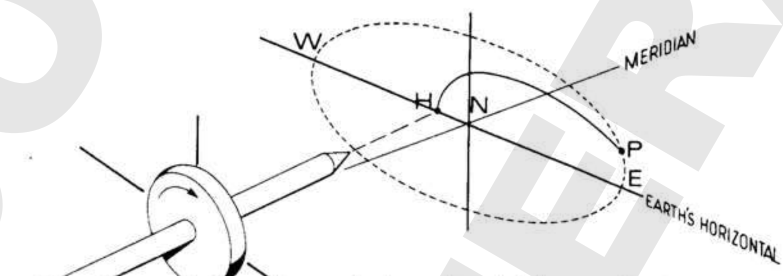
Figure 8.10 shows the curve now described by the north end of the damped gyrocompass which will settle in the meridian. An alternative and more commonly used method of applying anti-tilt damping is shown in Figure 8.13.



The north end of the gyro spin axis is initially pointing at P, which is above the earth's horizontal and to the east of the meridian. The gravity control therefore exerts a torque T_H about the gyro's horizontal axis and, at the same time, is arranged to exert a torque about the gyro's vertical axis. Because of the direction of rotation of the spinner,

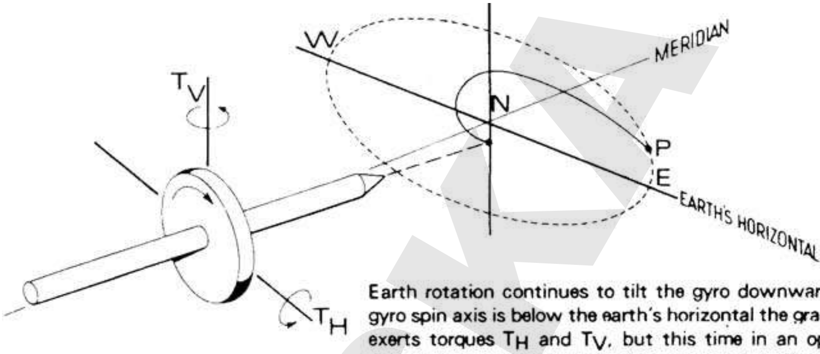


torque T_H causes the gyro to precess towards the west. Because the north end of the gyro is east of the meridian, earth rotation results in an upward tilt of the gyro but this movement is damped by the downward precession that is due to torque T_V. The resultant path traced by the gyro spin axis is therefore Pb and not Pb′, as would be the case without the damping torque T_V. Note that the downward (damping) precession becomes more evident as the north end of the gyro spin axis approaches the meridian. Note also that the minor axis of the ellipse is decreased by the amount bb′

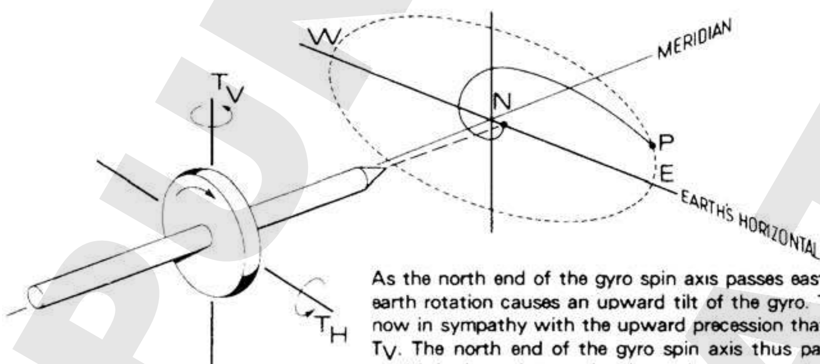


As the north end of the gyro spin axis passes west of the meridian, earth rotation causes a downward tilt of the gyro. This movement is now in sympathy with the downward precession that is due to torque T_V. Torque T_H, however, continues to precess the gyro westwards so that the gyro spin axis passes through the earth's horizontal at H, at which point torques T_H and T_V cease. Note that the major axis of the ellipse is considerably decreased.

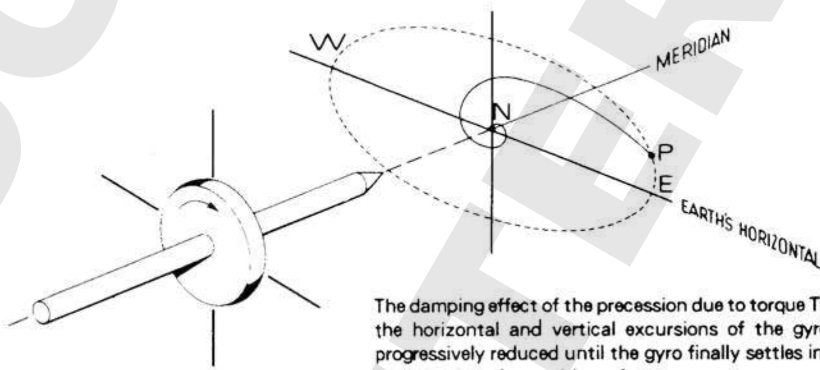
Figure 8.10 Behaviour of the gravity-controlled gyro (damped). (Reproduced courtesy of S.G. Brown Ltd.)



Earth rotation continues to tilt the gyro downwards, and once the gyro spin axis is below the earth's horizontal the gravity control again exerts torques T_H and T_V, but this time in an opposite direction. Torque T_H now causes precession eastwards, whilst torque T_V causes precession upwards and thus damps the downward tilt that is due to earth rotation. The resultant movement of the gyro causes the north end of the gyro spin axis to pass through the meridian at a point that reduces even more the minor axis of the ellipse.



As the north end of the gyro spin axis passes east of the meridian, earth rotation causes an upward tilt of the gyro. This movement is now in sympathy with the upward precession that is due to torque T_V. The north end of the gyro spin axis thus passes through the earth's horizontal at a point that reduces even more the major axis of the ellipse.



The damping effect of the precession due to torque T_V continues, with the horizontal and vertical excursions of the gyro spin axis being progressively reduced until the gyro finally settles in the meridian and horizontal to the earth's surface.

Figure 8.10 Continued

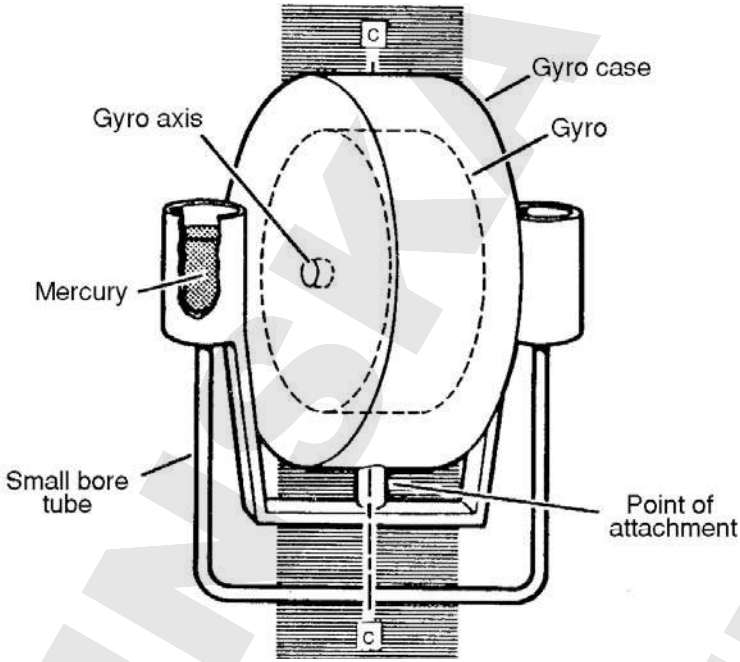


Figure 8.11 A method of applying 'offset damping' to the gyro wheel. (Reproduced courtesy of Sperry Ltd.)

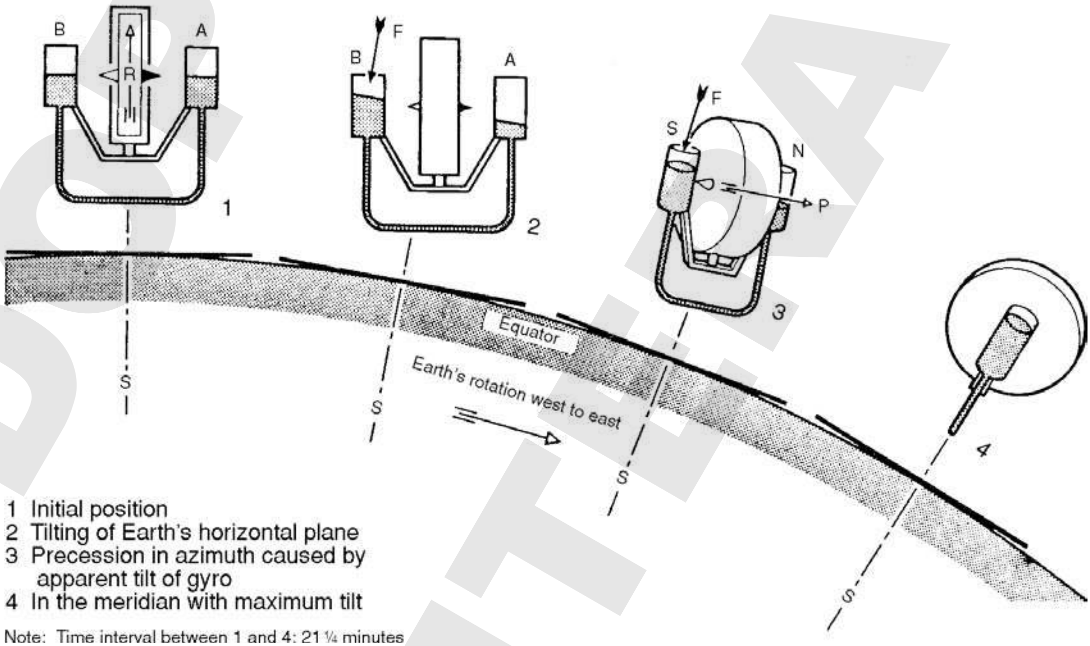


Figure 8.12 Precession of a controlled gyroscope at the equator.

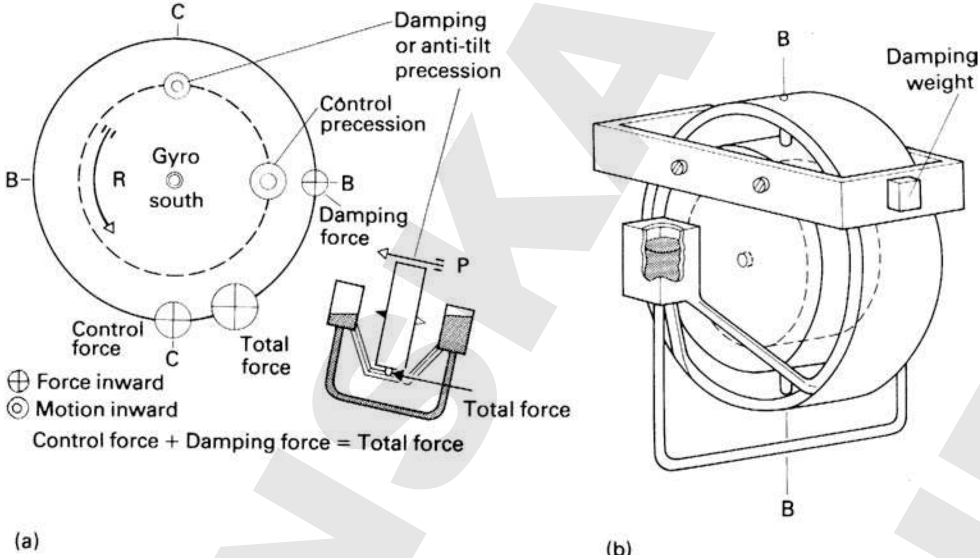


Figure 8.13 (a) Effect of control force plus damping force.(b) An alternative method of applying offset damping. (Reproduced courtesy of Sperry Ltd.)

Damping gyroscopic precession by the use of weights provides a readily adjustable system for applying damping. The period of gyro damping is directly related to the size of the damping force, and thus the weight. If the weight is increased, the damping percentage will be increased. The effect of alternative damping application is illustrated in Figure 8.14.

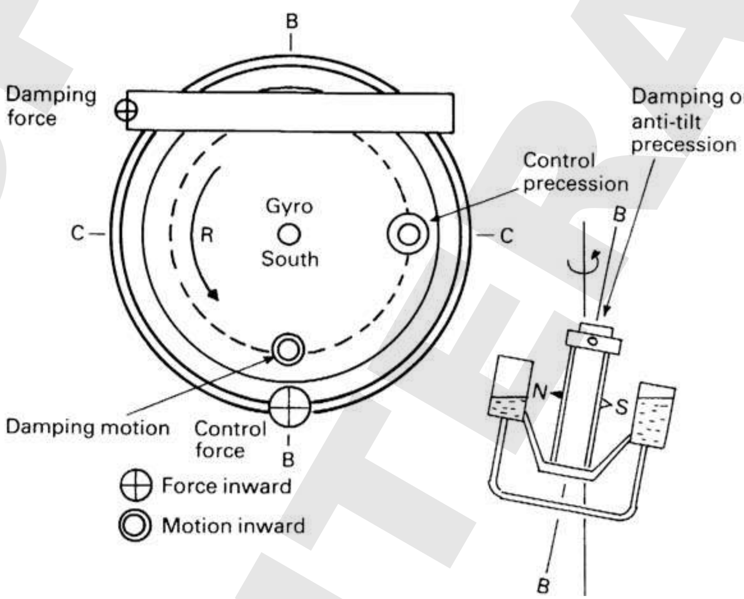


Figure 8.14 The effects of alternative damping application.

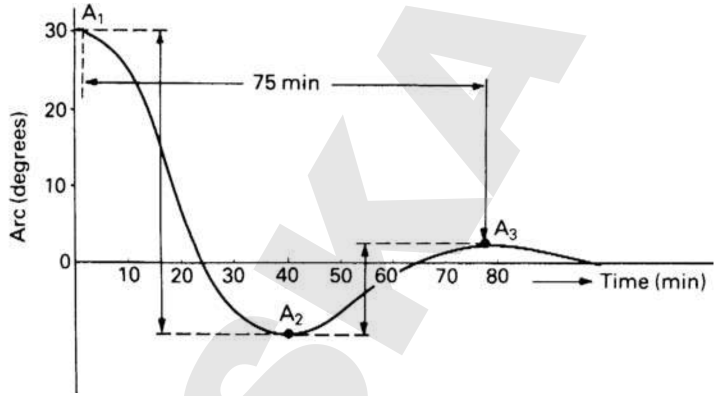


Figure 8.15 The settling curve of a typical gyro compass with a 75-min period.

The amount of damping required depends upon the rate of tilt of the gyro axle and as such will be affected by latitude. As has been shown previously, tilt is a maximum at the equator. It follows, therefore, that damping should also be a maximum at the equator. However, the damping period will always remain constant, at approximately 86 min for some gyros, despite the change of amplitude of successive swings to east and west of the gyro axle. All gyrocompasses therefore require time to settle. Figure 8.15 shows a typical settling curve for a gyro possessing a damping period of greater than 80 min. The time taken for one oscillation, from Al to A3 is termed the natural period of the compass.

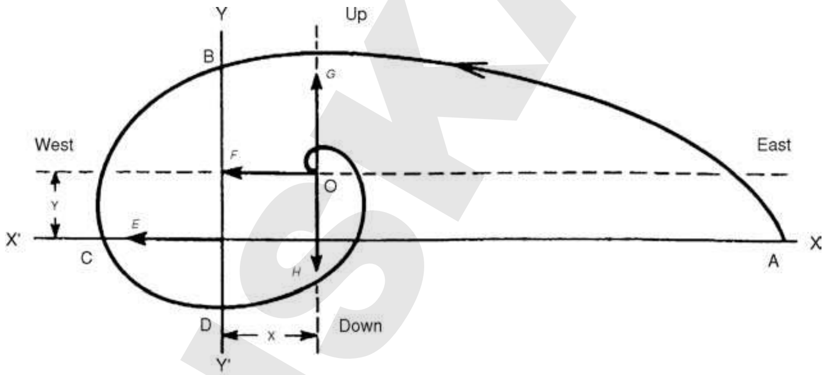
8.5.1 The amount of tilt remaining on a settled gyro

The settling curve traced by the north end of the gyrospin axis illustrated in Figure 8.10 assumes that the gyrocompass is situated at the equator and will, therefore, not be affected by gyro tilt. It is more likely that a vessel will be at some north/south latitude and consequently drift must be taken into account.

It has been stated that for a gyrocompass in northern latitudes, the gyrospin axis will drift to the east of the meridian and tilt upwards. For any fixed latitude the easterly drift is constant. Westerly precession, however, is directly proportional to the angle of tilt of the rotor axle from the horizontal, which itself is dependent upon the deviation between it and the meridian. At some point the easterly deviation of the north end of the spin axis produces an angle of tilt causing a rate of westerly precession that is equal and opposite to the easterly drift. The north end, although pointing to the east of the meridian, is now stabilized in azimuth.

As the north end moves easterly away from the meridian both the rate of change of the tilt angle and the angle itself are increasing. The increasing angle of tilt produces an increasing rate of downward damping tilt until a point is reached where the upward and downward rates of tilt cancel. The north end of the axle is above the horizontal although the rotor axle is stabilized. Figure 8.16 shows that the gyrocompass has settled, at point 0, to the east of the meridian and is tilted up.

The extent of the easterly and northerly (azimuth and tilt) error in the settled position is determined by latitude. An increase in latitude causes an increase in both the easterly deviation from the meridian and the angle of tilt above the horizontal. It is necessary therefore for latitude error, as the discrepancy is called, to be corrected in a gyrocompass.



E: Rate of westerly movement of meridian caused by turntable movement of the Earth's surface

F: Rate of westerly precession of the gyro caused by the north end having tilted upwards

G: Rate of upward tilt of north end of spin axis due to gyro setting to east of meridian

H: Rate of downward precession of north end of spin axis due to damping (anti-tilt) precession

Figure 8.16 A curve showing error to the east and tilt caused by latitude on a settled gyrocompass. X is the angle away from the meridian and Y is the angle with the horizon (tilt). (Reproduced courtesy of Sperry Ltd.)

As latitude increases, the effect of the earth's rotation becomes progressively less and consequently tilting of the rotor axle becomes less. It follows, therefore, that the rate of damping precession needed to cancel the rate of tilt, will also be less.

8.6 Follow-up systems

A stationary gravity-controlled gyrocompass will adequately settle close to the horizontal and near to the meridian, provided that it has freedom to move about the horizontal and vertical axes. However, if the gyrocompass is to be mounted on a ship, the base (phantom) ring needs to be capable of rotating through 360° without introducing torque about the vertical axis.

Freedom about the vertical axis is particularly difficult to achieve without introducing torque to the system. The most common way of permitting vertical-axis freedom is to mount the gyro in a vertical ring with ball bearings on the top and base plates. Obviously the weight of the unit must be borne on the lower bearing, which can create considerable friction and introduce torque. A number of methods have been developed to eliminate torque about the vertical axis. These include the use of high tensile torsion wires and buoyancy chambers, as described for each compass later in this chapter.