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

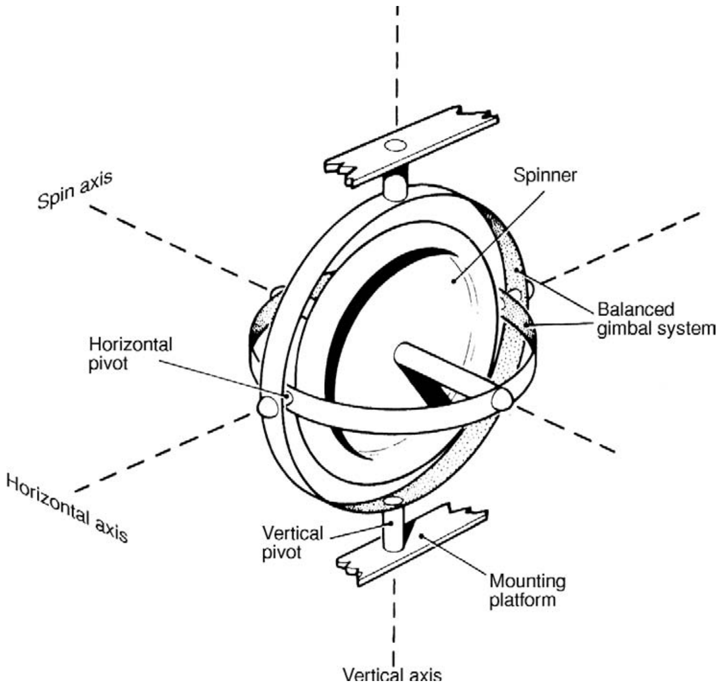


Figure 8.1 A free gyroscope. (Reproduced courtesy of S. G. Brown Ltd.)

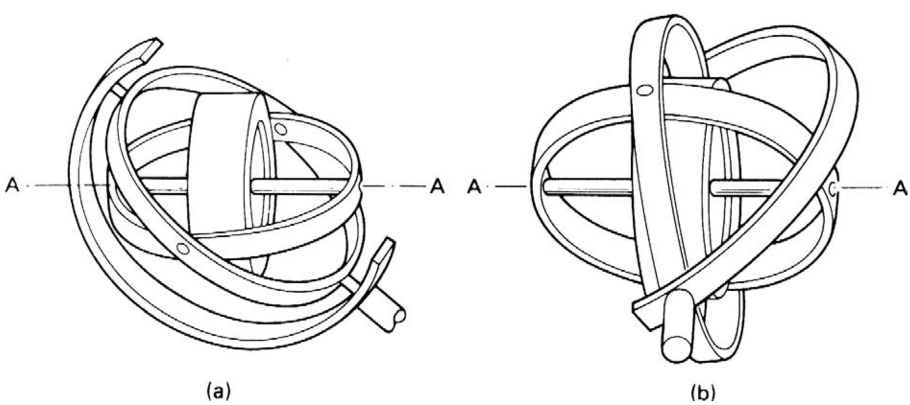


Figure 8.2 The gyrospin axis is stabilized irrespective of any movement of the supporting gimbals. (Reproduced courtesy of Sperry Ltd.)

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.

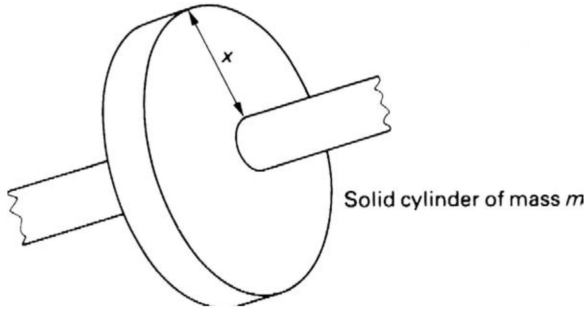


Figure 8.3 A spinning rotor possessing a solid mass.

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

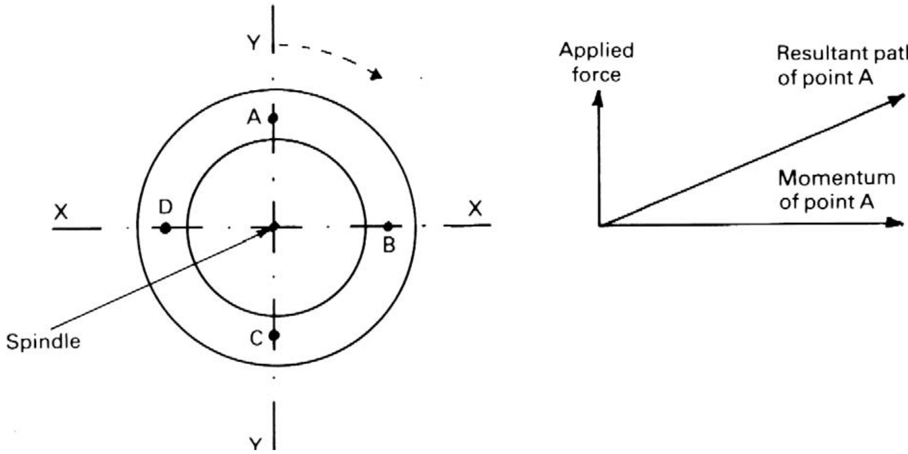


Figure 8.4 Gyro precession shown as a vector sum of the applied forces and the momentum.

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

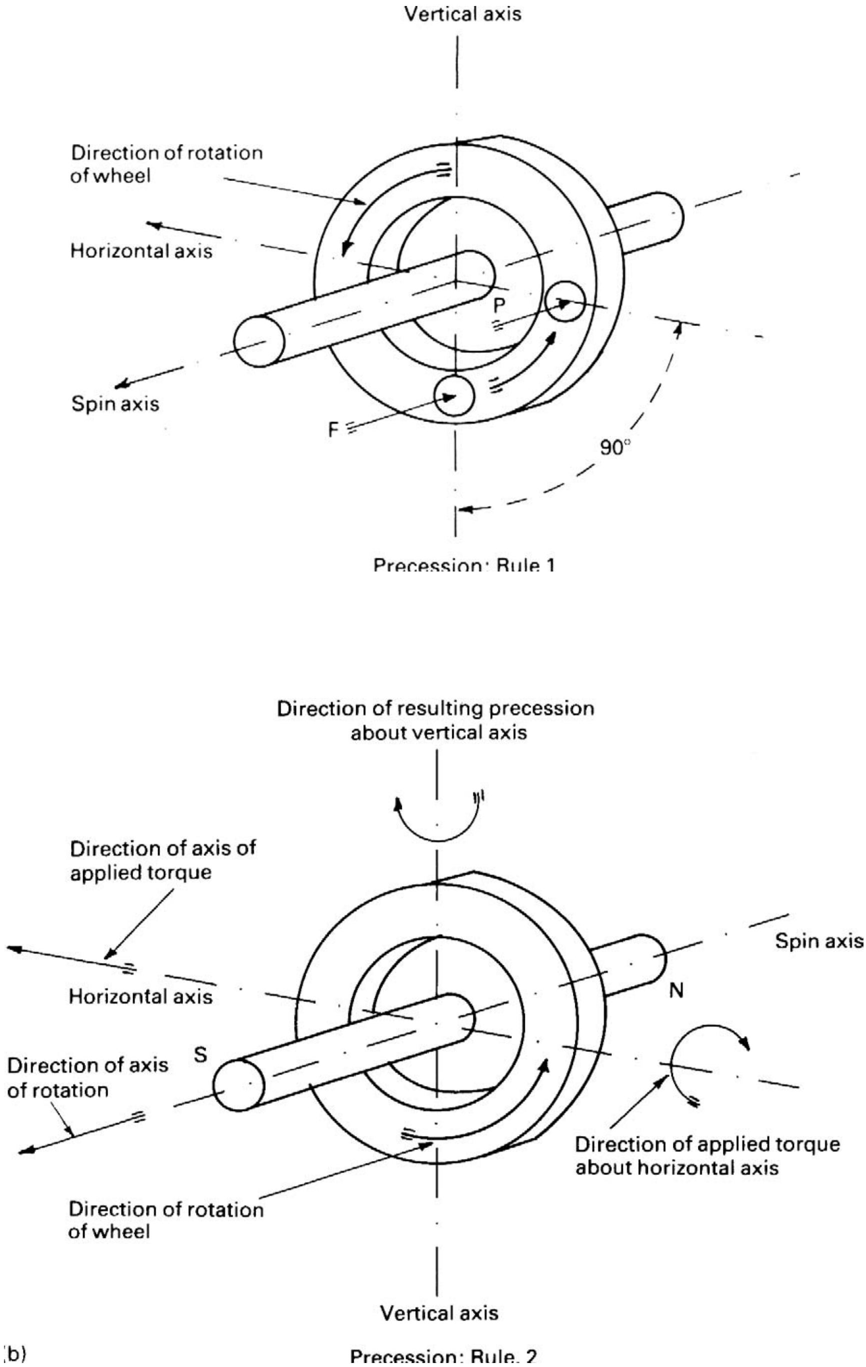
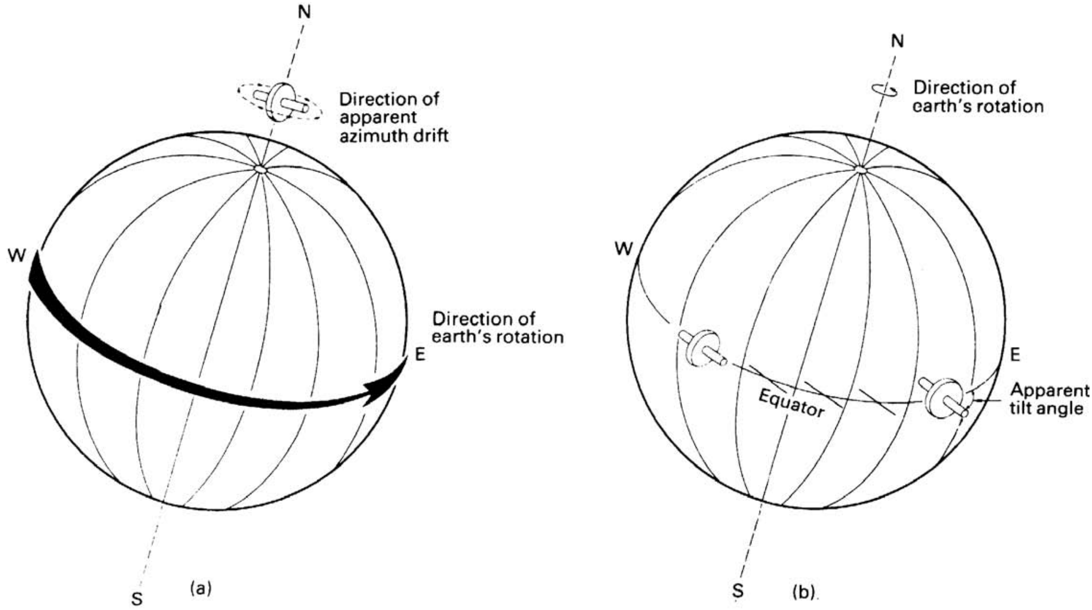


Figure 8.5 (a) Resulting precession P occurs at 90° in the direction of spin from the applied force F. This direction of precession is the same as that of the applied force. (Reproduced courtesy of Sperry Ltd.) (b) The direction of axis rotation will attempt to align itself with the direction of the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



Drift of the N end of the spin axis is to the E in the northern hemisphere and to the W in the southern hemisphere

Tilt of the N end of the spin axis is upwards if the N end is to the east of the meridian and downwards if it is to the W of the meridian

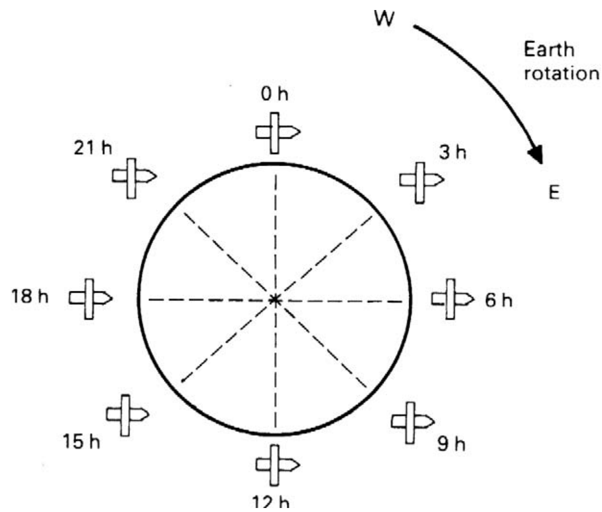


Figure 8.6 (a) Effect of earth rotation on the gyro. (Reproduced courtesy of Sperry Ltd.) (b)View from the South Pole. The earth rotates once every 24 h carrying the gyro with it. Gyroscopic inertia causes the gyro to maintain its plane of rotation with respect to the celestial reference point. However,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

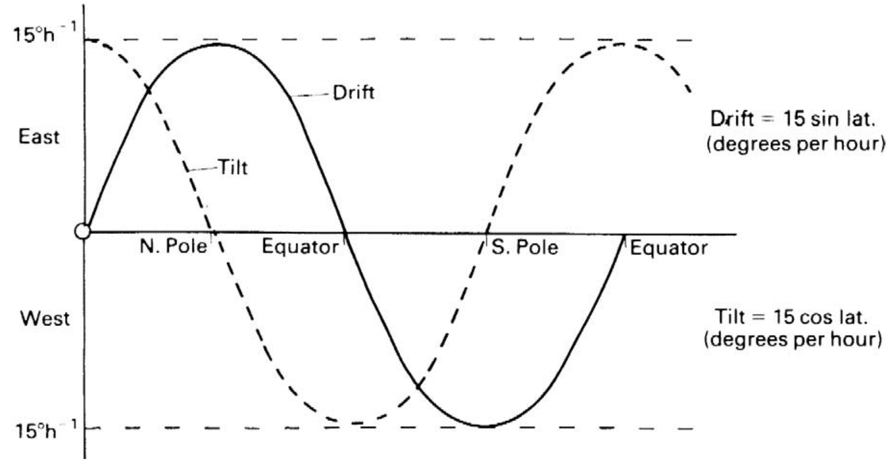


Figure 8.7 The graphical relationship between drift and tilt.

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.

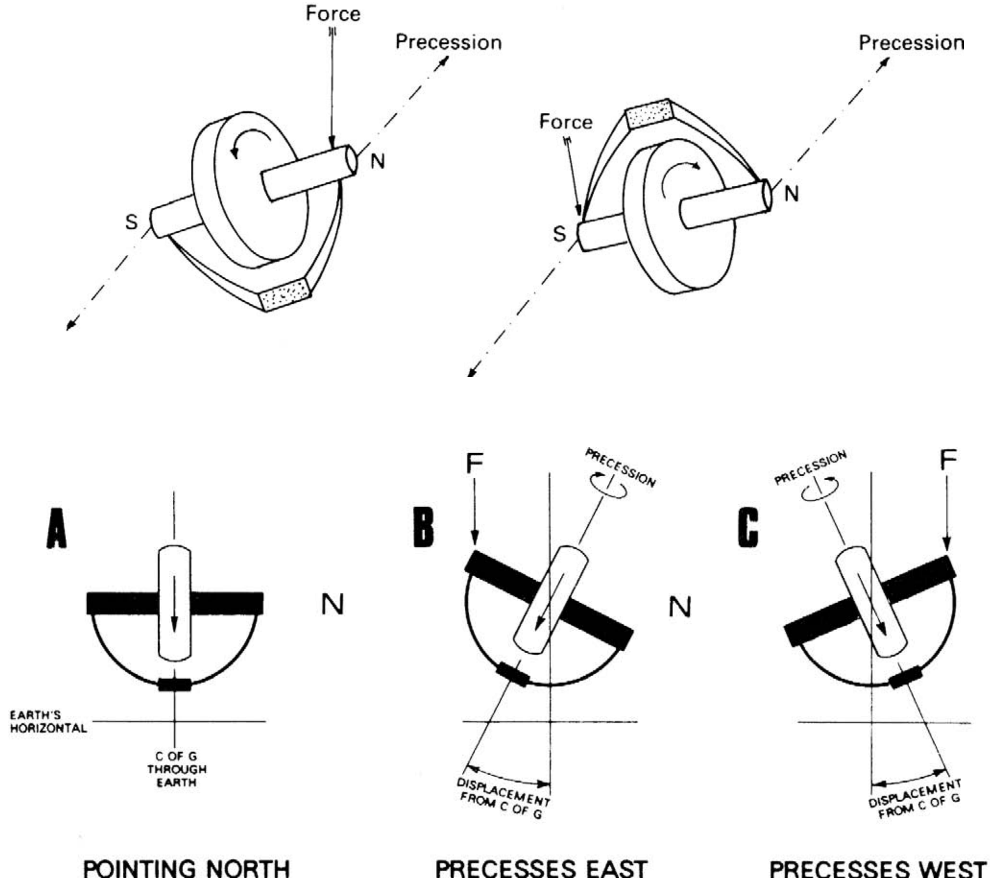


Figure 8.8 (a) Methods of gravity control: bottom-heavy principal and top-heavy control. (b) Principle of gravity control. (Reproduced courtesy of S. G. Brown Ltd.)

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.

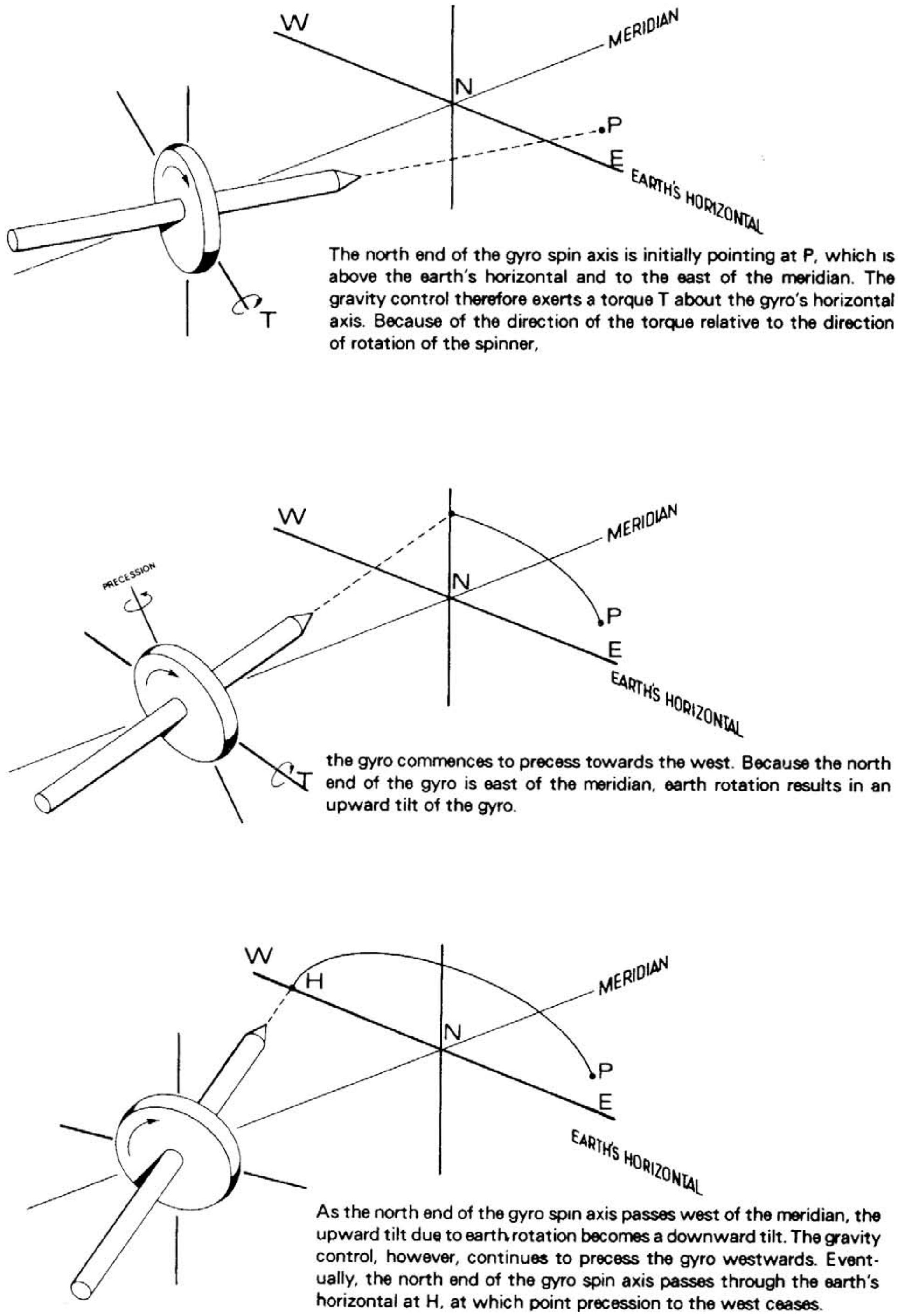
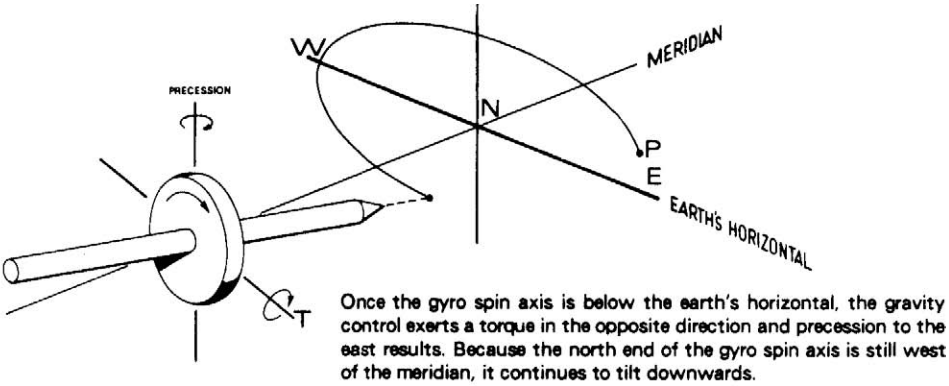


Figure 8.9 Behaviour of the gravity-controlled gyro (undamped). (Reproduced courtesy of S.G. Brown Ltd.)



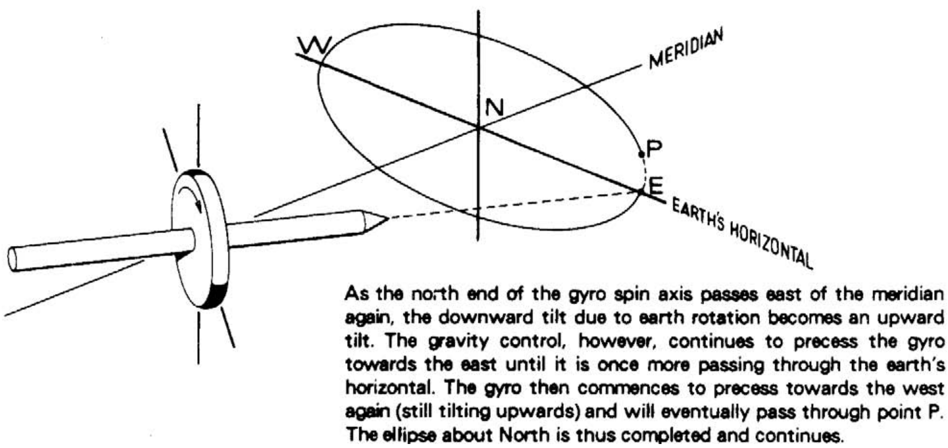


Figure 8.9 Continued

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.

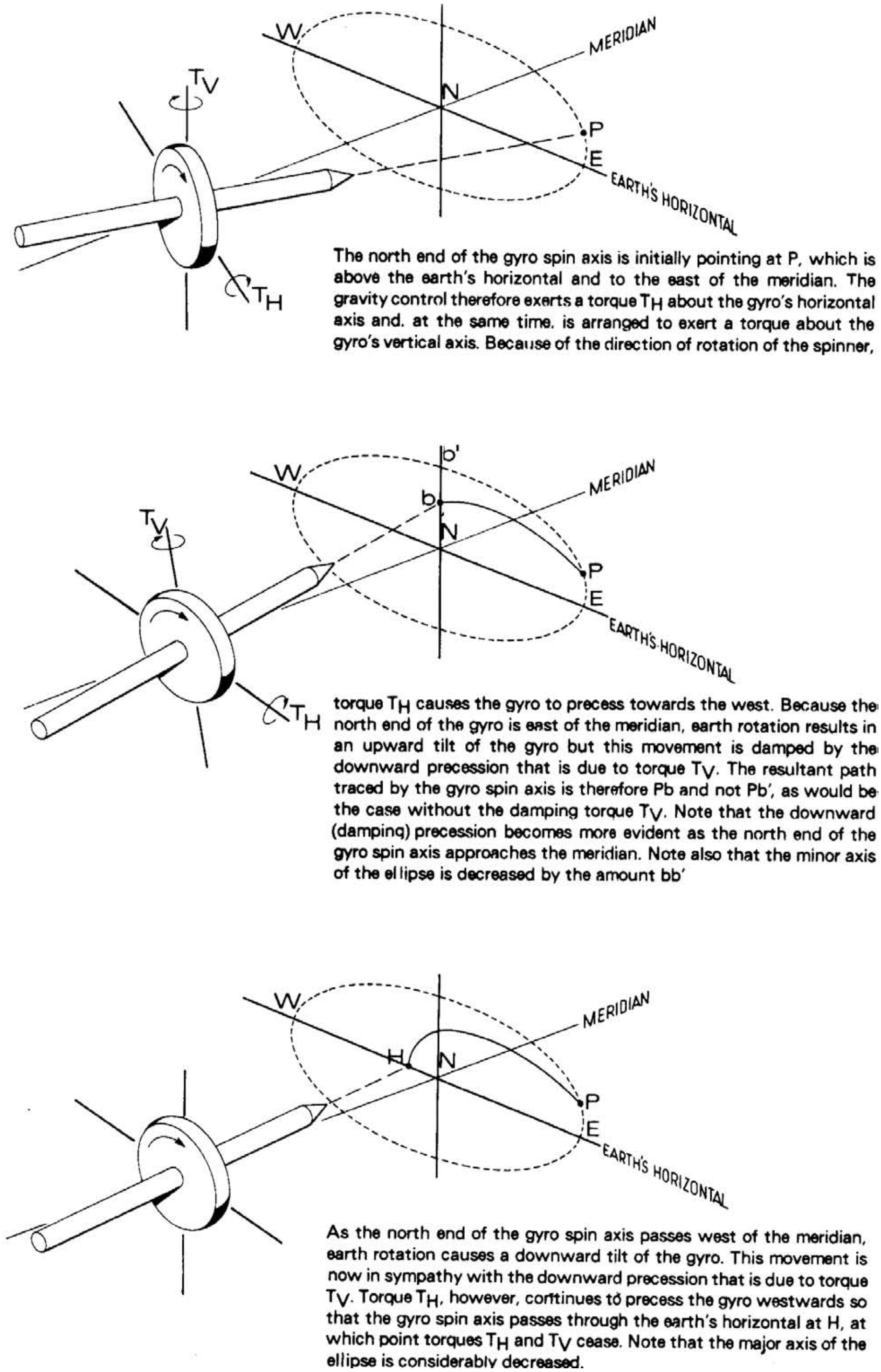


Figure 8.10 Behaviour of the gravity-controlled gyro (damped). (Reproduced courtesy of S.G. Brown Ltd.)

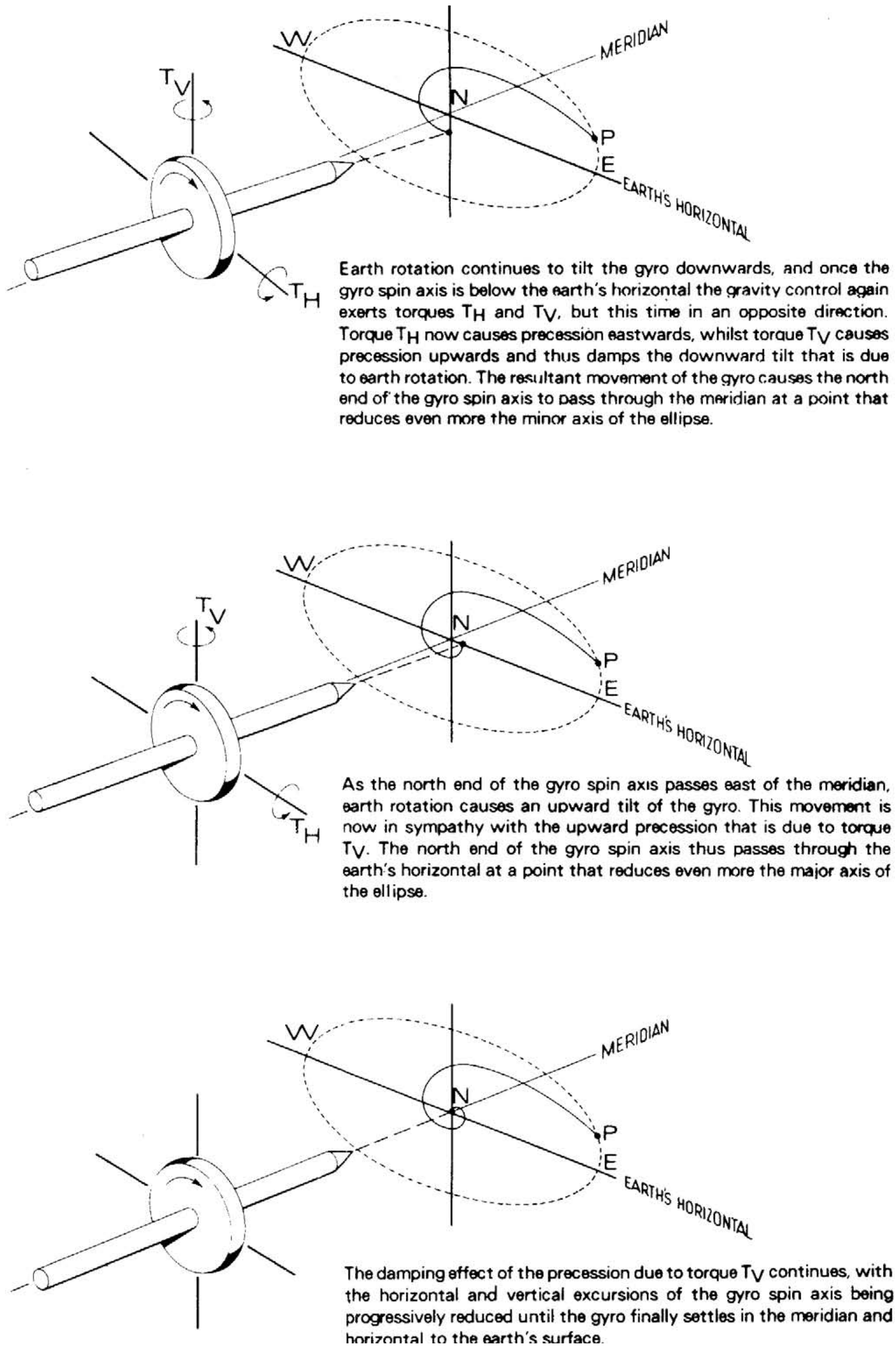


Figure 8.10 Continued

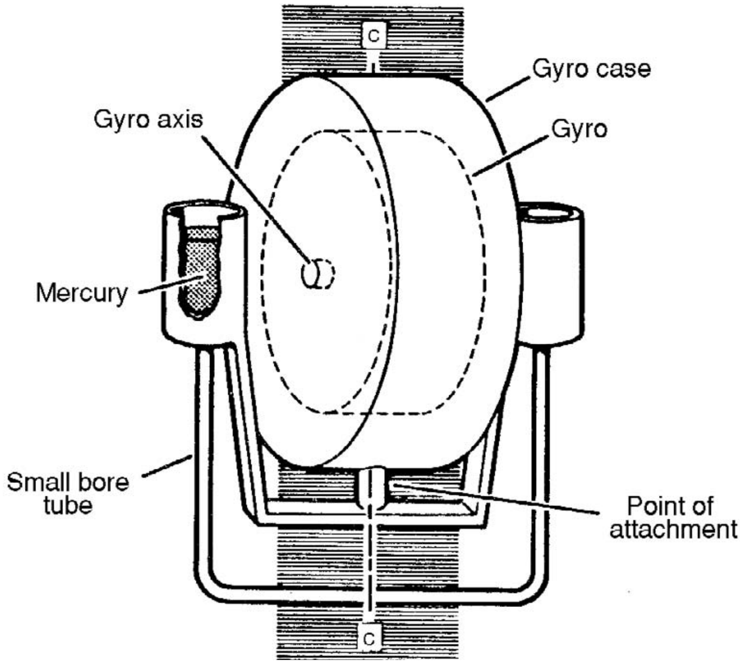


Figure 8.11 A method of applying 'offset damping' to the gyro wheel. (Reproduced courtesy of Sperry Ltd.)

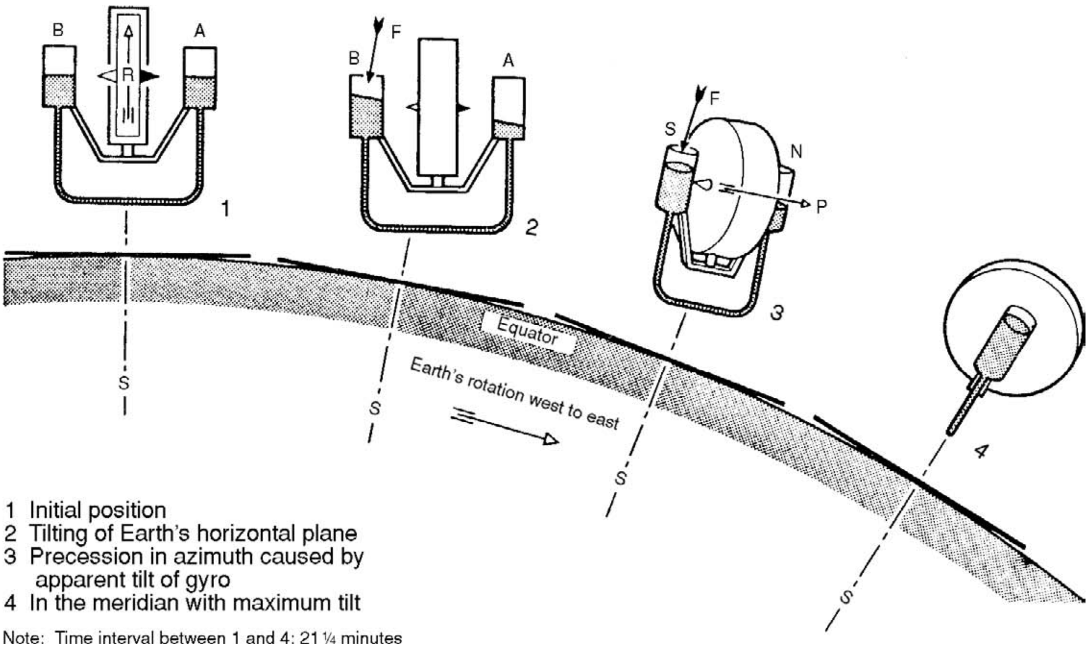


Figure 8.12 Precession of a controlled gyroscope at the equator.

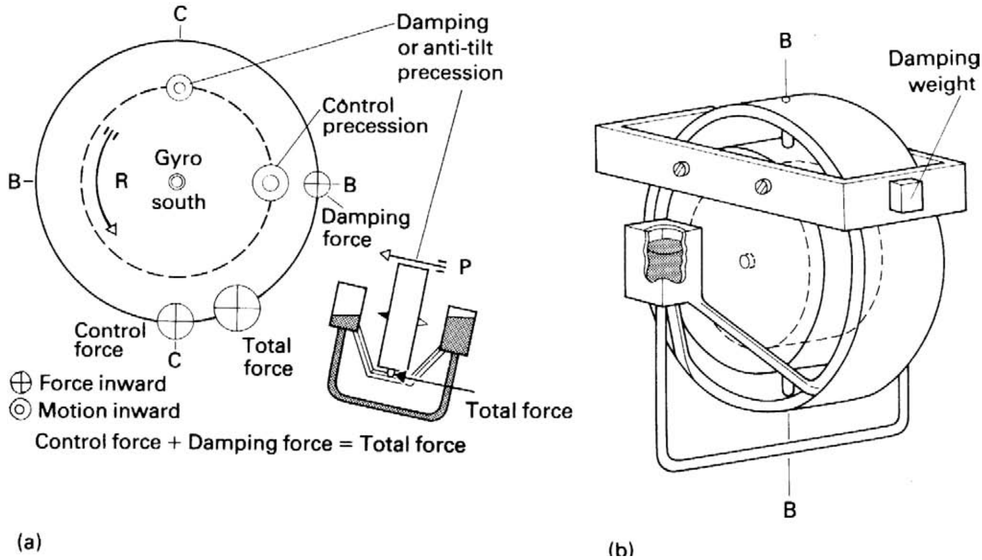


Figure 8.13 (a) Effect of control force plus damping force.(b) An alternative method of applying offset damping. (Reproduced courtesy of Sperry Ltd.)

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.

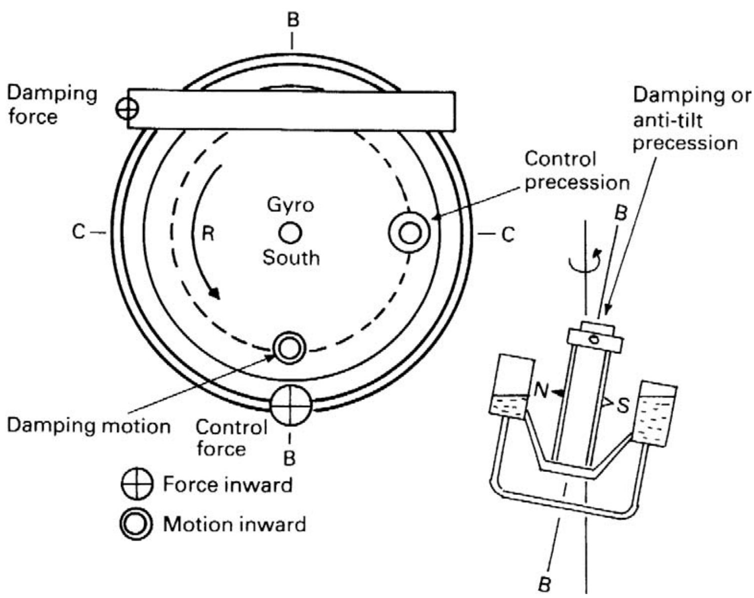


Figure 8.14 The effects of alternative damping application.

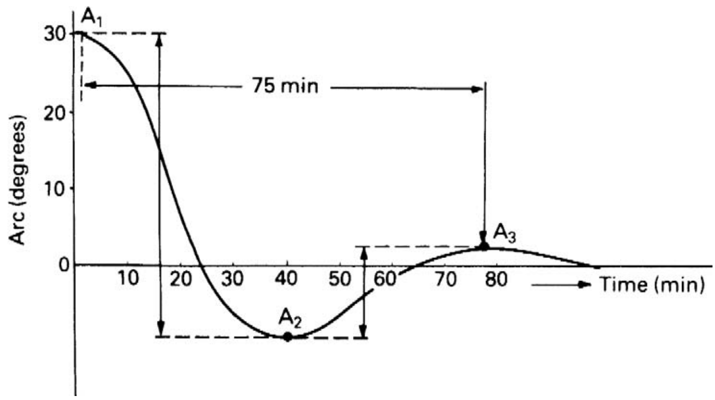


Figure 8.15 The settling curve of a typical gyro compass with a 75-min period.

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.

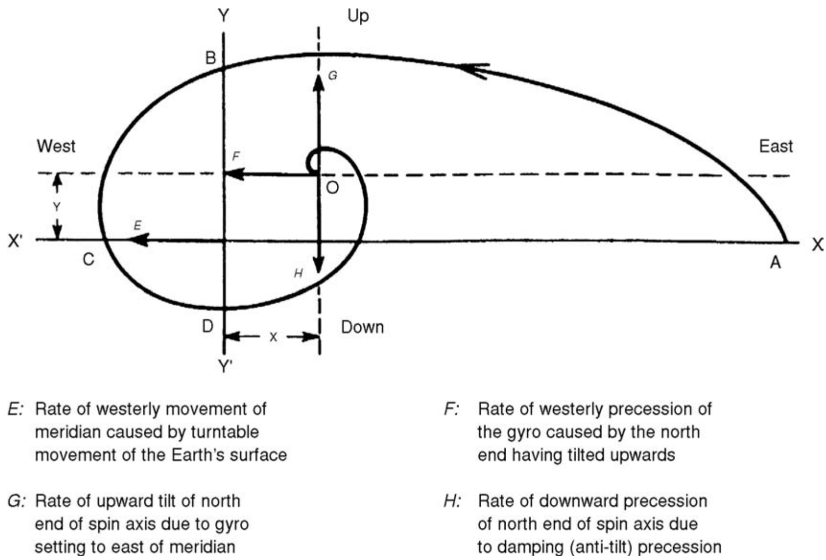


Figure 8.16 A curve showing error to the east and tilt caused by latitude on a settled gyrocompass. X is the angle away from the meridian and Y is the angle with the horizon (tilt). (Reproduced courtesy of Sperry Ltd.)

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.

8.7 Compass errors

The accuracy of a gyrocompass is of paramount importance, particularly under manoeuvring situations where the compass is interfaced with collision-avoidance radar. An error, either existing or produced, between the actual compass reading and that presented to the radar could produce potentially catastrophic results. Assuming that the compass has been correctly installed and aligned, the static compass errors briefly listed below, should have been eliminated. They are, however, worthy of a brief mention.

8.7.1 Static errors

An alignment error can be:

- an error existing between the indicated heading and the vessel's lubber line
- an error existing between the indicated lubber line and the fore and aft line of the vessel.

Both of these errors can be accurately eliminated by critically aligning the compass with the ship's lubber line at installation.

Transmission error

An error existing between the indicated heading on the master compass and the heading produced by any remote repeater is a transmission error. Transmission errors are kept to a minimum by the use of multispeed pulse transmission.

Variable errors

Variable compass errors can effectively be classified into two groups.

- Dynamic errors that are caused by the angular motion of the vessel during heavy weather and manoeuvring.
- Speed/latitude errors that are caused by movement of the vessel across the earth's surface.

The magnitude of each error can be reduced to some extent as shown in the following text.

8.7.2 Dynamic errors

Rolling error

The gyrocompass is made to settle on the meridian under the influence of weights. Thus it will also be caused to shift due to other forces acting upon those weights. When a vessel rolls, the compass is swung like a pendulum causing a twisting motion that tends to move the plane of the sensitive element towards the plane of the swing. For a simple explanation of the error consider the surge of mercury caused in both the north and south reservoirs by a vessel rolling. If the ship is steaming due north or south, no redistribution of mercury occurs due to roll and there will be no error (see Figure 8.17).

But with a ship steaming due east or west, maximum lateral acceleration occurs in the north/south direction causing precession of the compass. However, rolls to port and starboard are equal, producing equivalent easterly and westerly precession. The resulting mean-error is therefore zero, as illustrated in Figure 8.18.

If the ship is on an intercardinal course the force exerted by the mercury (or pendulum) must be resolved into north/south and east/west components (see Figure 8.19).

The result of the combined forces is that precession of the compass occurs under the influence of an effective anticlockwise torque. Damping the pendulum system can dramatically reduce rolling error. In a top-heavy gyrocompass, this is achieved by restricting the flow of mercury between the

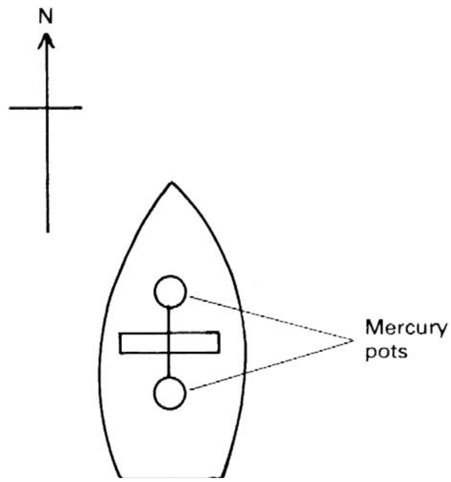


Figure 8.17 A ship steaming due north or south produces no roll error.

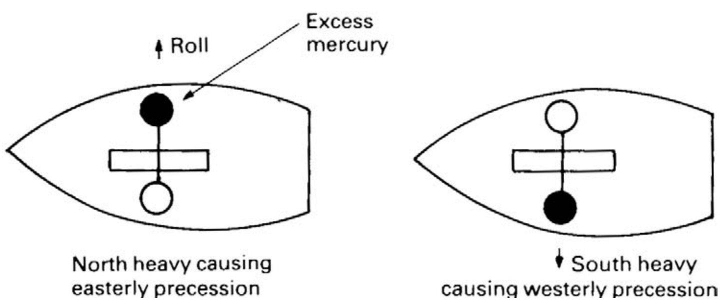


Figure 8.18 Precession rates created by a rolling vessel on an east/west course are equal and will cancel.

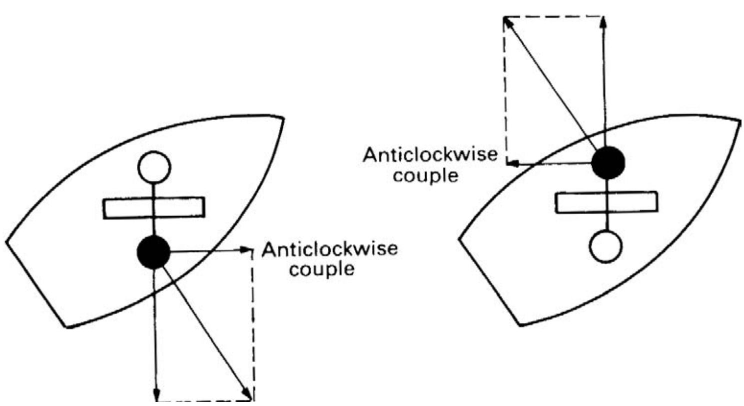


Figure 8.19 For a vessel on an intercardinal course, rolling produces an anticlockwise torque.

two pots. The damping delay introduced needs to be shorter than the damping period of the compass and much greater than the period of roll of the vessel. Both of these conditions are easily achieved.

Electrically-controlled compasses are roll-damped by the use of a viscous fluid damping the gravity pendulum. Such a fluid is identified by a manufacturer's code and a viscosity number. For example, in the code number 200/20, 200 refers to the manufacturer and 20 the viscosity. A higher second number indicates a more viscous silicon fluid. One viscous fluid should never be substituted for another bearing a different code number. Additionally since roll error is caused by lateral acceleration, mounting the gyrocompass low in the vessel and as close as possible to the centre of roll will reduce this error still further.

Manoeuvring (ballistic) error

This error occurs whenever the ship is subject to rapid changes of speed or heading. Because of its pendulous nature, the compass gravity control moves away from the centre of gravity whenever the vessel changes speed or alters course. Torque's produced about the horizontal and vertical axis by manoeuvring cause the gyro mechanism to precess in both azimuth and tilt. If the ship is steaming due north and rapidly reducing speed, mercury will continue to flow into the north pot, or the gravity pendulum continues to swing, making the gyro spin axis north heavy and thus causing a precession in azimuth.

In Figure 8.20 the decelerating vessel causes easterly precession of the compass. Alternatively if the ship increases speed the compass precesses to the west.

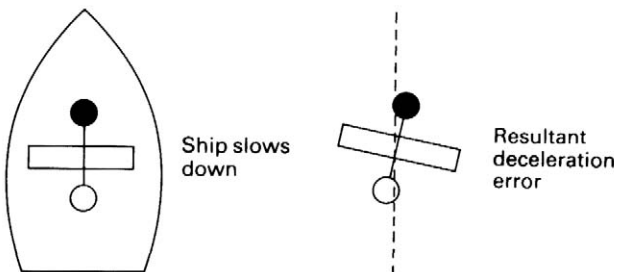


Figure 8.20 Resultant easterly error caused by the vessel slowing down.

Latitude (damping) error

Latitude error is a constant error, the magnitude of which is directly proportional to the earth's rotation at any given latitude. It is, therefore, present even when the ship is stationary. As has previously been stated, a gyrocompass will always settle close to the meridian with an error in tilt. To maintain the gyro pointing north it must be precessed at an angular rate varying with latitude. At the equator the earth's linear speed of rotation is about 900 knots and rotation from west to east causes a fixed point to effectively move at 900 × cos (latitude) knots in an easterly direction. For any latitude (λ) the rate of earth spin is $\omega = 15° \, h^{-1}$. This may be resolved into two components, one about the true vertical at a given latitude ($\omega \sin \lambda$) and the other about the north/south earth surface horizontal at a given latitude ($\omega \cos \lambda$) as illustrated in Figure 8.21.

The component of the earth's rotation about the north/south horizontal may be resolved further into two components mutually at right angles to each other. The first component is displaced $a°$ to the east

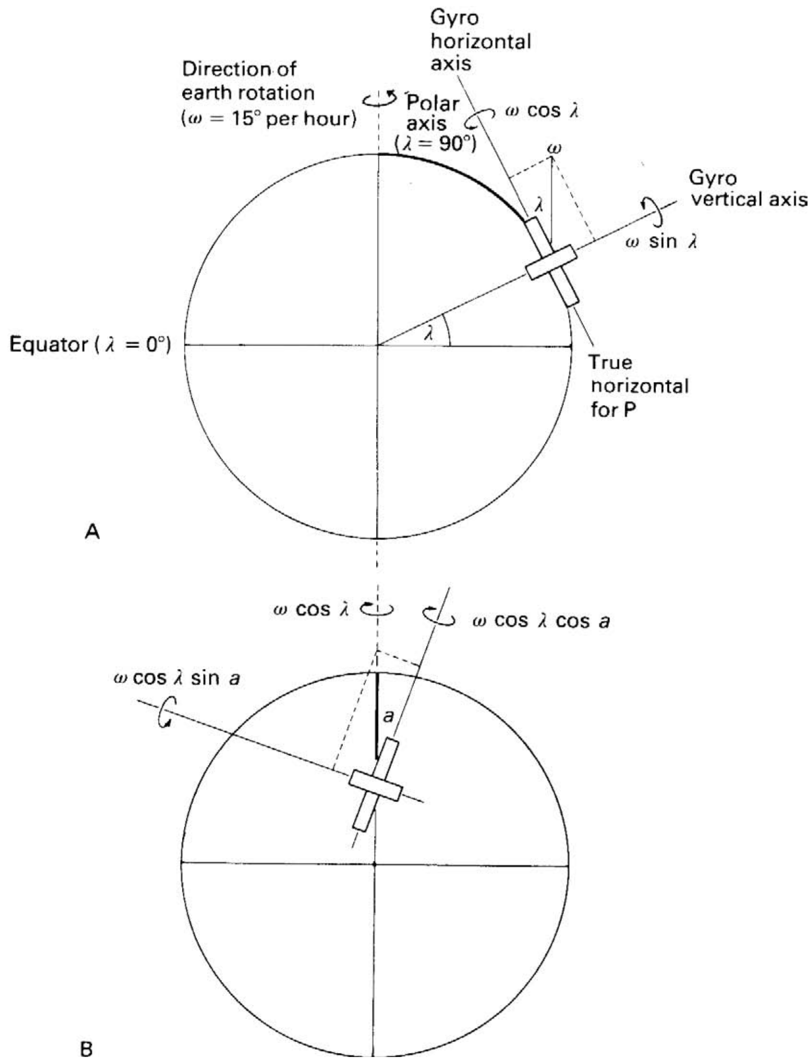


Figure 8.21 Apparent movement of a gyro. (Reproduced courtesy S. G. Brown Ltd.)

of the meridian producing a rate of spin $\omega \cos \lambda \sin a°$, whilst the other is $90 - a°$ to the west of north to produce a rate of spin $\omega \cos \lambda \cos a°$.

Correction for latitude error requires that a torque be applied to precess the gyro at an angular rate, varying with latitude, to cancel the error. This will be an external correction that can be either mechanical or electronic. For mechanical correction, a weight on the gyro case provides the necessary torque. The weight, or 'mechanical latitude rider', is adjustable thus enabling corrections to be made for varying latitudes. Another method of mechanical correction is to move the lubber line by an amount equal to the error. Latitude correction in a bottom-weighted compass is achieved by the introduction of a signal proportional to the sine of the vessel's latitude, causing the gyro ball to precess in azimuth at a rate equal and opposite to the apparent drift caused by earth rotation.

Speed and course error

If a vessel makes good a northerly or southerly course, the north end of the gyro spin axis will apparently tilt up or down since the curvature of the earth causes the ship to effectively tilt bows up or down with respect to space. Consider a ship steaming due north. The north end of the spin axis tilts upwards causing a westerly precession of the compass, which will finally settle on the meridian with some error in the angle, the magnitude of which is determined by the speed of the ship. On a cardinal course due east or west, the ship will display a tilt in the east/west plane of the gyro and no tilting of the gyro axle occurs – hence no speed error is produced. The error varies, therefore, with the cosine of the ship's course. Speed/course gyrocompass error magnitude must also be affected by latitude and will produce an angle of tilt in the settled gyro. Hence latitude/course /speed error is sometimes referred to as LCS error.

8.7.3 Use of vectors in calculating errors

With reference to Figure 8.22,

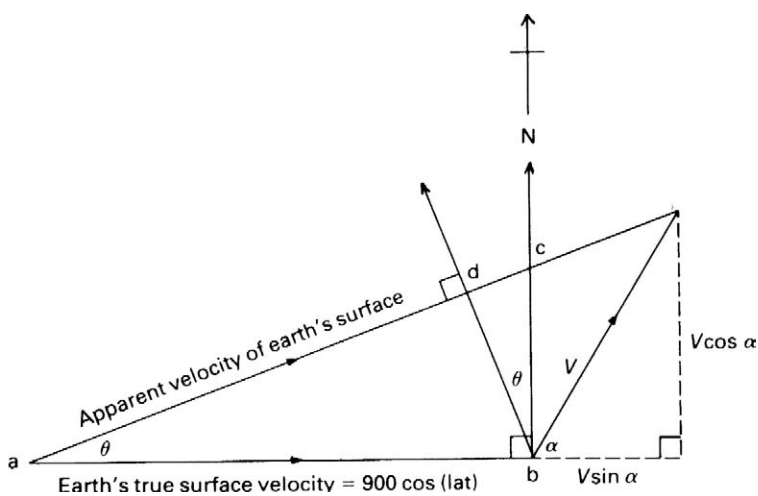


Figure 8.22 Use of vectors in calculating errors

$$
\begin{aligned}
V &= \text{ships speed in knots} \\
V \sin \alpha &= \text{easterly component of speed} \\
\alpha &= \text{ships course} \\
V \cos \alpha &= \text{northerly component of speed} \\
\text{angle acb} &= \text{angle dcb} \\
\text{angle abc} &= \text{angle bdc} = 90^\circ \\
\text{angle bac} &= \text{angle cbd} = \theta = \text{error}
\end{aligned}
$$

In triangle abc:

$$\text{Error in degrees} = \text{angle bac} = \theta = \tan^{-1} \frac{V \cos (\text{course})}{900 \cos (\text{latitude}) + V \sin (\text{course})}$$

Obviously the ship's speed is very much less than the earth's surface velocity therefore:

$$\tan \theta \simeq \frac{V \cos \text{(course)}}{900 \cos \text{(latitude)}}$$

The angle θ may be approximately expressed in degrees by multiplying both side of the equation by a factor of 60. Now:

$$\text{approximate error in degrees} = \frac{V \cos \text{(course)}}{15 \cos \text{(latitude)}}$$

8.8 Top-heavy control master compass

Produced before the move towards fully sealed gyro elements, the Sperry SR120 gyrocompass (Figure 8.23) is a good example of an early top-heavy controlled system. The master compass consists of two main assemblies, the stationary element and the movable element.

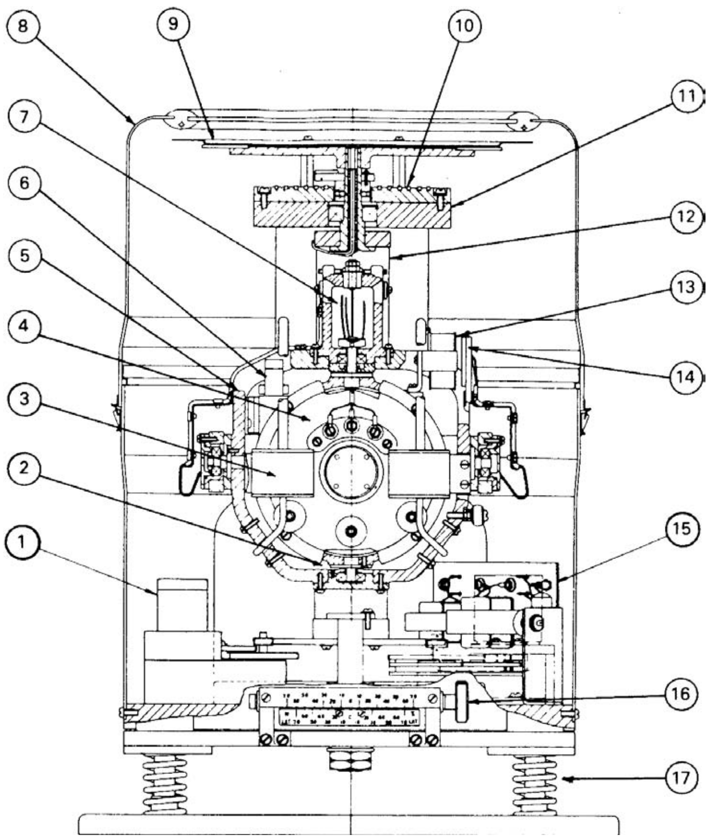


Figure 8.23 A south elevation sectional view of a Sperry master compass . Key:1. Stepper transmitter; 2. Support ball bearings; 3. Ballistic pots; 4.Rotor (encased); 5.Rotor case; 6. Damping weight; 7. Suspension wire; 8. Cover; 9.Compass card; 10.Slip rings; 11. Main support frame; 12. Phantom ring support assembly (cutaway); 13. Follow-up primary transformer; 14. Follow-up secondary transformer; 15. Follow-up amplifier; 16. Latitude corrector; 17. Spring/shock absorber assembly.

8.8.1 The stationary element

This is the main supporting frame that holds and encases the movable element. It consists of the main frame and base, together with the binnacle and mounting shock absorbers. The top of the main support frame (11) (Figure 8.23) holds the slip rings, lubber line and the scale illumination circuitry, whilst the main shaft, connected to the phantom ring (12), protrudes through the supporting frame to hold a compass card that is visible from above.

A high quality ball bearing race supports the movable element on the base of the main support frame in order that movement in azimuth can be achieved. The base of the whole assembly consists of upper and lower base plates that are connected at their centre by a shaft. Rotation of the upper plate in relation to the lower plate enables mechanical latitude correction to be made. The latitude corrector (16) is provided with upper and lower latitude scales graduated in 10 units, up to 70° north or south latitude, either side of zero. Latitude correction is achieved by mechanically rotating the movable element relative to the stationary element thus producing a shift in azimuth. The fixed scale of the latitude adjuster (16) is secured to the stationary element with a second scale fixed to the movable element. To set the correction value, which should be within 5° of the ship's latitude, is simply a matter of aligning the ship's latitude on the lower scale with the same indication on the upper scale of the vernier scale.

Also supported by the base plate are the azimuth servomotor and gear train, and the bearing stepper transmitter.

8.8.2 The movable element

With the exception of the phantom ring, the movable element is called the sensitive element (Figure 8.24). At the heart of the unit is the gyro rotor freely spinning at approximately 12 000 rpm. The rotor is 110 mm in diameter and 60 mm thick and forms, along with the stator windings, a three-phase induction motor. Gyroscopic inertia is produced by the angular momentum of the rapidly spinning heavy rotor. Rotation is counter clockwise (counter earthwise) when viewed from the south end.

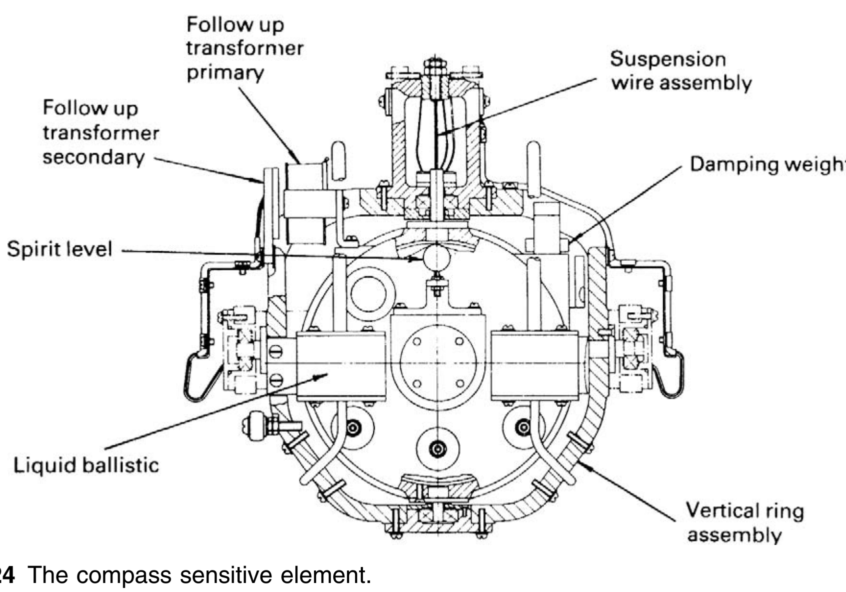


Figure 8.24 The compass sensitive element.

A sensitive spirit level graduated to represent 2 min of arc, is mounted on the north side of the rotor case. This unit indicates the tilt of the sensitive element. A damping weight is attached to the west side of the rotor case in order that oscillation of the gyro axis can be damped and thus enable the compass to point north.

The rotor case is suspended, along the vertical axis, inside the vertical ring frame by means of the suspension wire (7). This is a bunch of six thin stainless steel wires that are made to be absolutely free from torsion. Their function is to support the weight of the gyro and thus remove the load from the support bearings (2).

8.8.3 Tilt stabilization (liquid ballistic)

To enable the compass to develop a north-seeking action, two ballistic pots (3) are mounted to the north and south sides of the vertical ring. Each pot possesses two reservoirs containing the high density liquid 'Daifloil'. Each north/south pair of pots is connected by top and bottom pipes providing a total liquid/air sealed system that operates to create the effect of top heaviness.

Because the vertical ring and the rotor case are coupled to each other, the ring follows the tilt of the gyro spin axis. Liquid in the ballistic system, when tilted, will generate a torque which is proportional to the angle of the tilt. The torque thus produced causes a precession in azimuth and starts the north-seeking action of the compass.

8.8.4 Azimuth stabilization (phantom ring assembly)

Gyro freedom of the north/south axis is enabled by the phantom ring and gearing. This ring is a vertical circle which supports the north/south sides of the horizontal ring (on the spin axis) by means of high precision ball bearings.

A small oil damper (6) is mounted on the south side of the sensitive element to provide gyro stabilization during the ship's pitching and rolling.

The compass card is mounted on the top of the upper phantom ring stem shaft and the lower stem shaft is connected to the support ball bearings enabling rotation of the north/south axis. The azimuth gearing, located at the lower end of the phantom ring, provides freedom about this axis under a torque from the azimuth servomotor and feedback system.

8.8.5 Azimuth follow-up system

The system shown in Figure 8.25 enables the phantom ring to follow any movement of the vertical ring. The unit senses the displacement signal produced by misalignment of the two rings, and amplifies the small signal to a power level of sufficient amplitude to drive the azimuth servo rotor. Movement of the azimuth servo rotor causes rotation, by direct coupling, of the phantom ring assembly in the required direction to keep the two rings aligned.

The sensing element of the follow-up system is a transformer with an 'E'-shaped laminated core and a single primary winding supplied with a.c., and two secondary windings connected as shown in Figure 8.25. With the 'E'-shaped primary core in its central position, the phase of the e.m.f.s induced in the two secondaries is such that they will cancel, and the total voltage produced across R1 is the supply voltage only. This is the stable condition during which no rotation of the azimuth servo rotor occurs. If there is misalignment in any direction between the phantom and the vertical rings, the two e.m.f.s induced in the two secondaries will be unbalanced, and the voltage across R1 will increase or decrease accordingly.

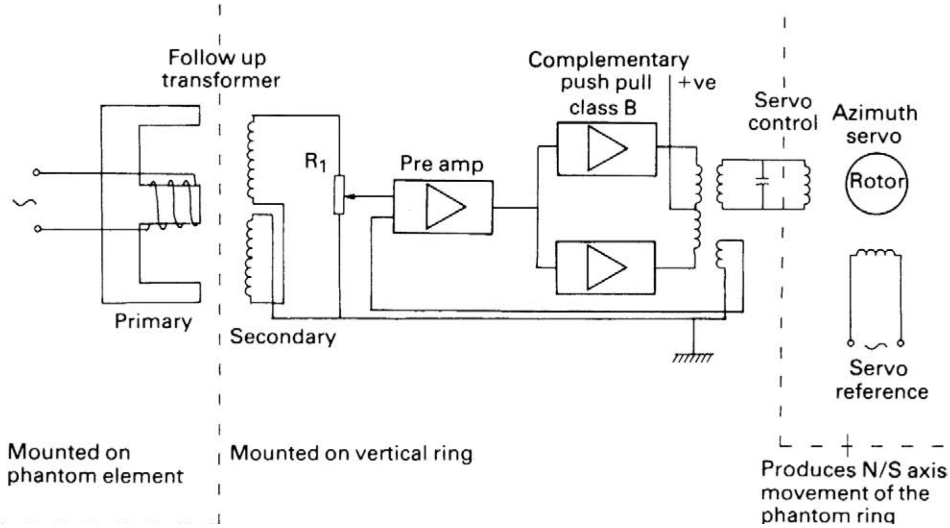


Figure 8.25 The Sperry compass azimuth follow-up circuit.

This error signal is pre-amplified and used to drive a complementary push/pull power amplifier producing the necessary signal level to cause the azimuth servo to rotate in the required direction to re-align the rings and thus cancel the error signal. Negative feedback from T2 secondary to the pre-amplifier ensures stable operation of the system.

Another method of azimuth follow-up control was introduced in the Sperry SR220 gyrocompass (Figure 8.26).

In practice only a few millimetres separate the sphere from the sensitive element chamber. The point of connection of the suspension wire with the gyrosphere, is deliberately made to be slightly above the centre line of the sphere on the east–west axis. At the north and south ends of the horizontal axis are

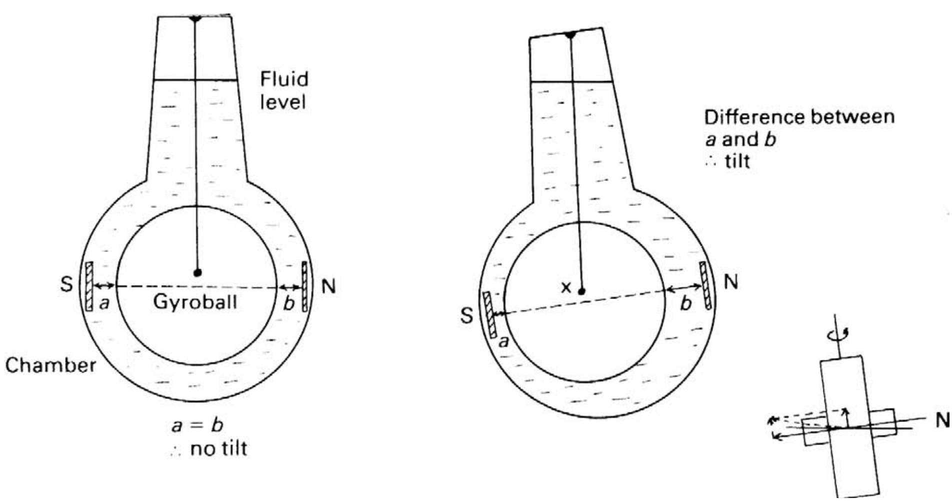


Figure 8.26 Simplified diagrams of the gyroball action in the Sperry SR220 gyrocompass.

mounted the primary coils of the follow-up pick-off transformers. With no tilt present, the sphere centre line will be horizontal and central causing distance *a* to be equal to distance *b* producing equal amplitude outputs from the follow-up transformers which will cancel. Assuming the gyrocompass is tilted up and to the east of the meridian, the gyrosphere will take up the position shown in Figure 8.26. The sphere has moved closer to the south side of the chamber producing a difference in the distances *a* and *b*. The two pick-off secondary coils will now produce outputs that are no longer in balance. Difference signals thus produced are directly proportional to both azimuth and tilt error.

Each pick-off transformer is formed by a primary coil mounted on the gyrosphere and secondary pick-off coils mounted on the sensitive element assembly. The primary coils provide a magnetic field, from the 110 V a.c. supply used for the gyrowheel rotor, which couples with the secondary to produce e.m.f.s depending upon the relationship between the two coils.

Figure 8.27 shows that the secondary coils are wound in such a way that one or more of the three output signals is produced by relative movement of the gyrosphere. X = a signal corresponding to the distance of the sphere from each secondary coil; ϕ = a signal corresponding to vertical movement; and θ = a signal corresponding to horizontal movement

In the complete follow-up system shown in Figure 8.28, the horizontal servomechanism, mounted on the west side of the horizontal ring, permits the sensitive element to follow-up the gyrosphere about the horizontal axis. This servo operates from the difference signal produced by the secondary pick-off coils, which is processed to provide the amplitude required to drive the sensitive element assembly in

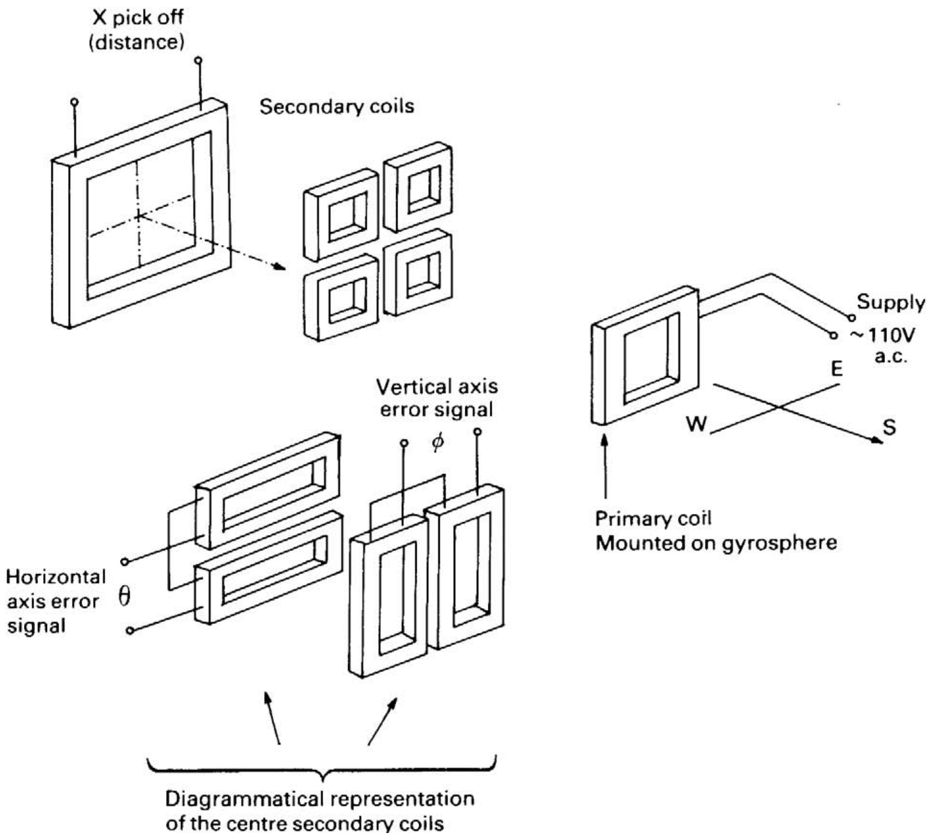


Figure 8.27 Follow-up signal pick-off coils.

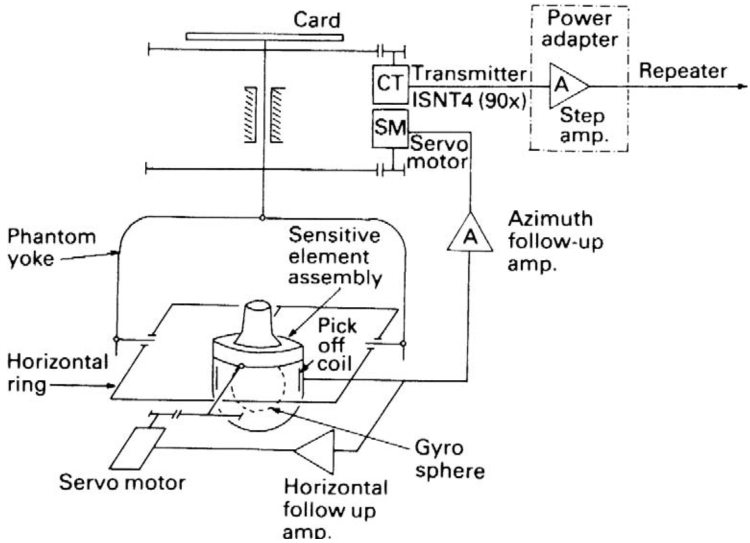


Figure 8.28 The Sperry SR220 follow-up system.

azimuth by rotating the phantom yoke assembly in the direction needed to cancel the error signal. In this way the azimuth follow-up circuit keeps the gyrosphere and sensitive element chamber in alignment as the gyro precesses.

8.9 A digital controlled top-heavy gyrocompass system

In common with all other maritime equipment, the traditional gyrocompass is now controlled by a microcomputer. Whilst such a system still relies for its operation on the traditional principles already described, most of the control functions are computer controlled. The Sperry MK 37 VT Digital Gyrocompass (Figure 8.29) is representative of many gyrocompasses available. The system has three main units, the sealed master gyrocompass assembly, the electronics unit and the control panel.

The master compass, a shock-mounted, fluid-filled binnacle unit, provides uncorrected data to the electronics units which processes the information and outputs it as corrected heading and rate of turn data. Inside the three-gimbals mounting arrangement is a gyrosphere that is immersed in silicone fluid and designed and adjusted to have neutral buoyancy. This arrangement has distinct advantages over previous gyrocompasses.

- The weight of the gyrosphere is removed from the sensitive axis bearings.
- The gyrosphere and bearings are protected from excessive shock loads.
- Sensitivity to shifts of the gyrosphere's centre of mass, relative to the sensitive axis, is eliminated.
- The effects of accelerations are minimized because the gyrosphere's centre of mass and the centre of buoyancy are coincident.

The system's applications software compensates for the effects of the ship's varying speed and local latitude in addition to providing accurate follow-up data maintaining yoke alignment with the gyrosphere during turn manoeuvres.

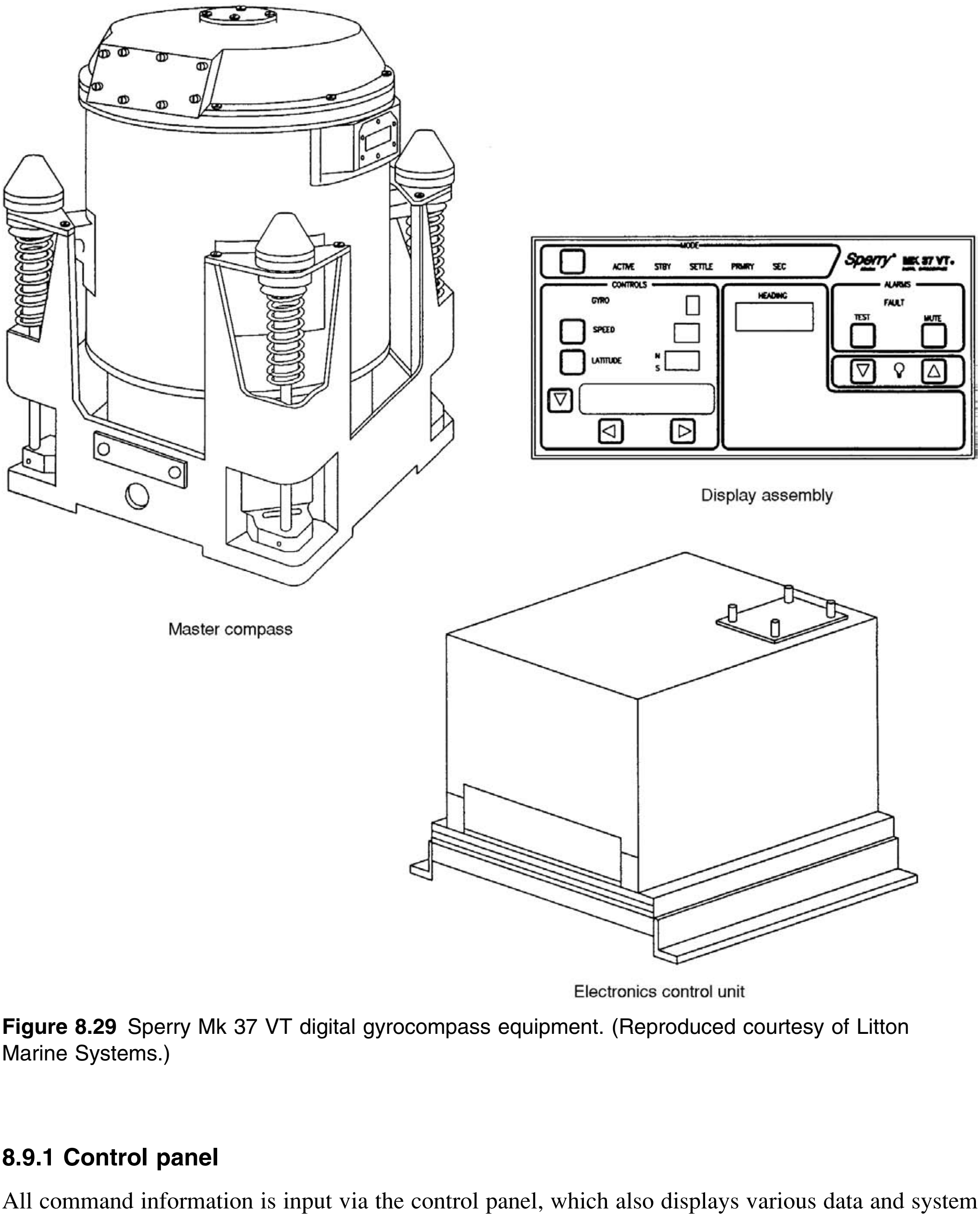


Figure 8.29 Sperry Mk 37 VT digital gyrocompass equipment. (Reproduced courtesy of Litton Marine Systems.)

8.9.1 Control panel

All command information is input via the control panel, which also displays various data and system indications and alarms (see Figure 8.30).

The Mode switch, number 1, is fixed when using a single system, the Active indicator lights and a figure 1 appear in window 13. Other Mode indicators include: 'STBY', showing when the gyrocompass is in a dual configuration and not supplying outputs; 'Settle', lights during compass start-up; 'Primary', lights to show that this is the primary compass of a dual system; and 'Sec', when it is the secondary unit.

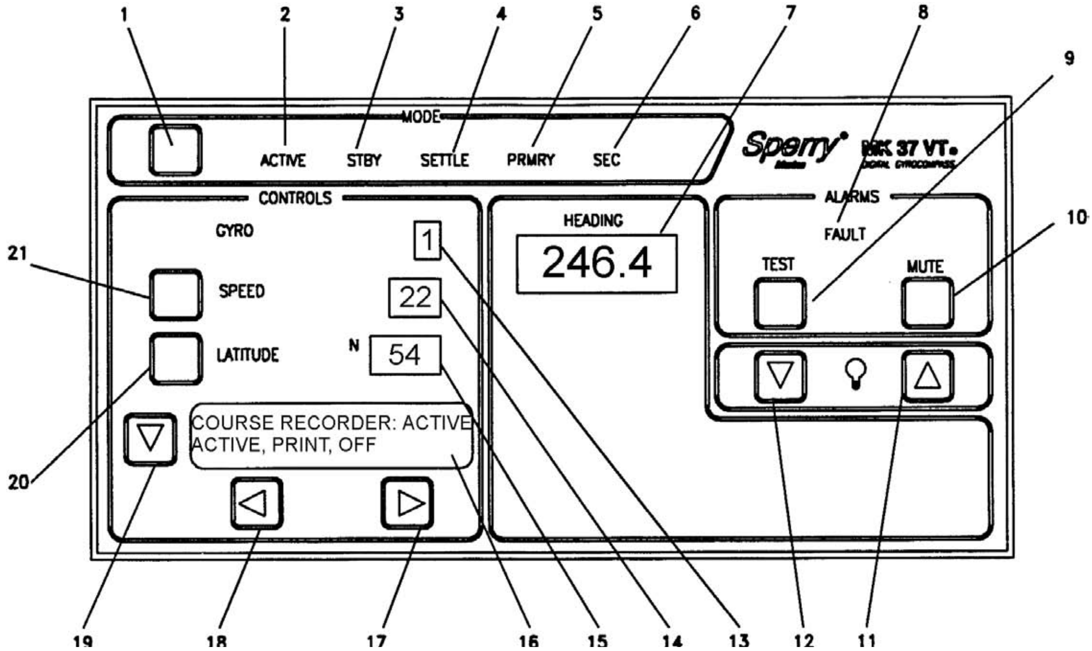


Figure 8.30 Sperry MK 37 VT control panel. (Reproduced courtesy of Litton Marine Systems.)

Number 7 indicates the Heading display accurate to within 1/10th of a degree. Other displays are: number 14, speed display to the nearest knot; number 15,latitude to the nearest degree; and 16, the data display, used to display menu options and fault messages. Scroll buttons 17, 18 and 19 control this display. Other buttons functions are self-evident.

8.9.2 System description

Figure 8.31 shows, to the left of the CPU assembly, the gyrosphere with all its control function lines, and to the right of the CPU the Display and Control Panel and output data lines.

The gyrosphere is supported by a phantom yoke and suspended below the main support plate. A 1-speed synchro transmitter is mounted to the support plate, close to the azimuth motor, and is geared to rotate the compass dial. The phantom yoke supports the east–west gimbal assembly through horizontal axis bearings. To permit unrestricted movement, electrical connections between the support plate and the phantom yoke are made by slip rings. The east–west gimbal assembly supports the vertical ring and horizontal axis bearings. See Figure 8.32.

The gyrosphere

The gyrosphere is 6.5 inches in diameter and is pivoted about the vertical axis within the vertical ring, which in turn is pivoted about the horizontal axis in the east–west gimbal assembly. At operating temperature, the specific gravity of the sphere is the same as the liquid ballistic fluid in which it is immersed. Since the sphere is in neutral buoyancy, it exerts no load on the vertical bearings. Power to drive the gyro wheel is connected to the gyrosphere from the vertical ring through three spiral hairsprings with a fourth providing a ground connection.

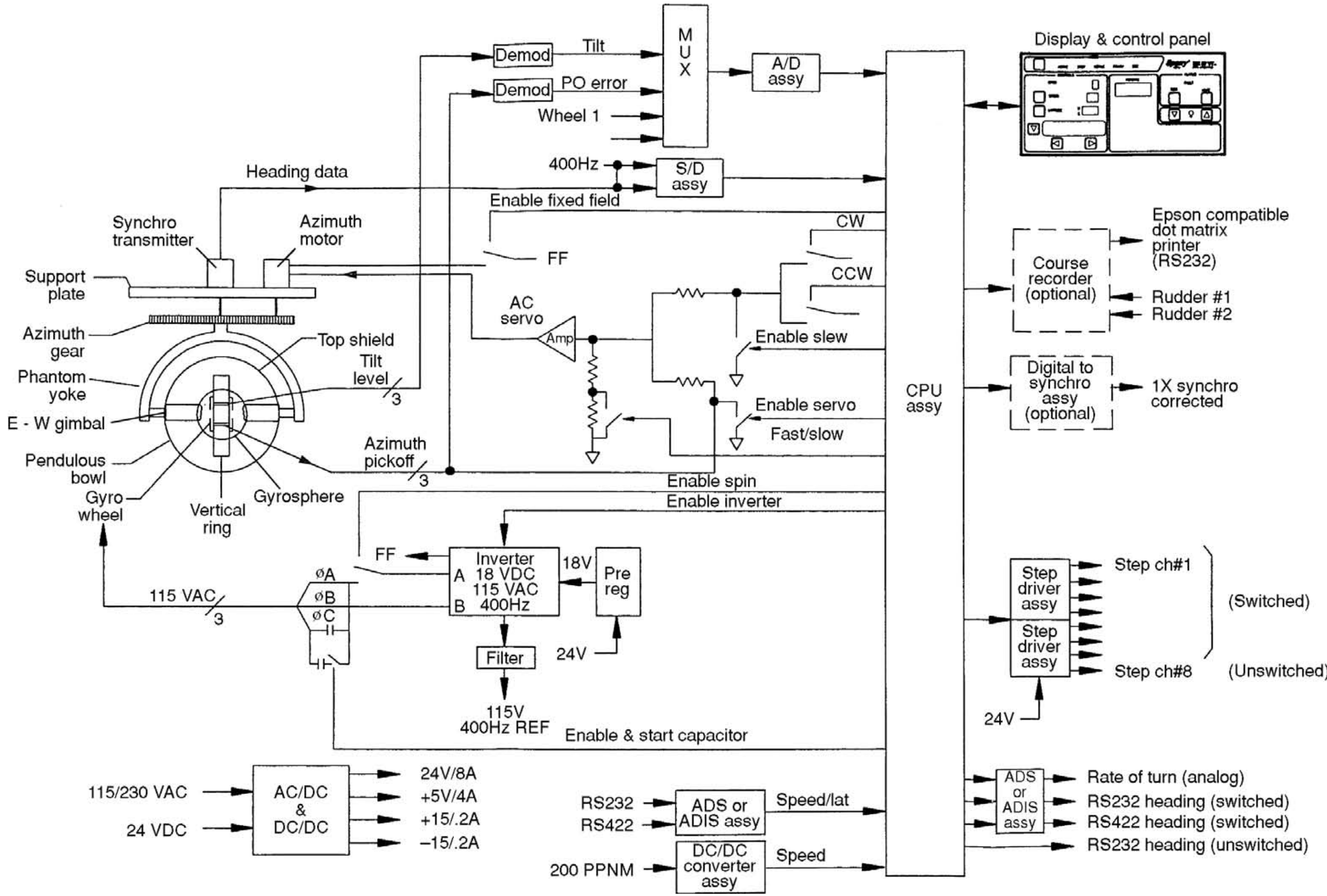


Figure 8.31 Overall functional block diagram. (Reproduced courtesy of Litton Marine Systems.)

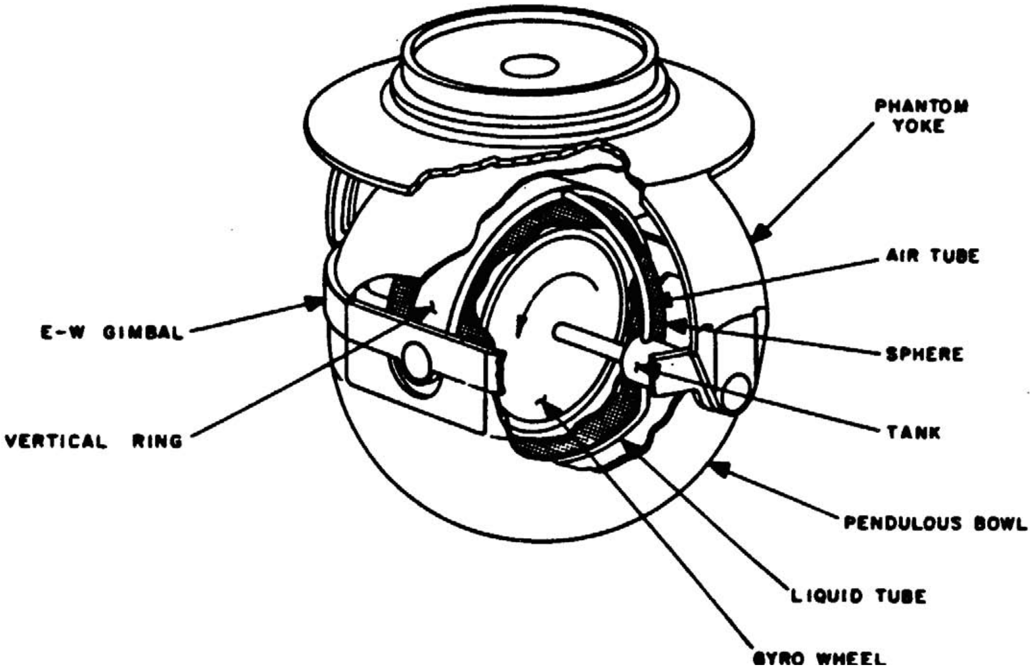


Figure 8.32 Ballistic system of the Sperry MK 37 VT gyrocompass. (Reproduced courtesy of Litton Marine Systems.)

The liquid ballistic assembly, also known as the control element because it is the component that makes the gyrosphere north-seeking, consists of two interconnected brass tanks partially filled with silicon oil. Small-bore tubing connects the tanks and restricts the free flow of fluid between them. Because the time for fluid to flow from one tank to the other is long compared to the ship's roll period, roll acceleration errors are minimized.

Follow-up control

An azimuth pick-off signal, proportional to the azimuth movement of the vertical ring, is derived from an E-core sensor unit and coupled back to the servo control circuit and then to the azimuth motor mounted on the support plate. When an error signal is detected the azimuth motor drives the azimuth gear to cancel the signal.

Heading data from the synchronous transmitter is coupled to the synchro-to-digital converter (S/D ASSY) where it is converted to a 14-bit word before being applied to the CPU. The synchro heading data, 115 V a.c., 400 Hz reference, 90 V line-to-line format, is uncorrected for ship's speed error and latitude error. Corrections for these errors are performed by the CPU using the data connected by the analogue, digital, isolated serial board (ADIS) from an RS-232 or RS-422 interface.

Interface data

Compass interfacing with external peripheral units is done using NMEA 0183 format along RS-232 and RS-422 lines. Table 8.1 shows data protocols.

Table 8.1 Sperry MK37 digital gyrocompass I/O protocols. (Reproduced courtesy of Litton Marine Systems)

Inputs	
Speed: Pulsed	Automatic. 200 ppnm
Serial	Automatic from digital sources. RS-232/422 in NMEA 0183 format $VBW, $VHW, $VTG
Manual	Manually via the control panel
Latitude	Automatic from the GPS via RS-232/422 in NMEA format $GLL, $GGA Automatic from digital sources via RS-232/422 in NMEA 0183 format $GLL Manually via the control panel
Outputs	
Rate of Turn	50 mV per deg/min (±4.5 VDC full scale = ± 90°/min) NMEA 0183 format $HEROT, X.XXX, A*hh<CR><LF> 1 Hz, 4800 baud
Step Repeaters	Eight 24 VDC step data outputs. (An additional 12-step data output at 35 VDC or 70 VDC from the optional transmission unit) 7 – switched, 1 – unswitched
Heading Data	One RS-422, capable of driving up to 10 loads in NMEA 0183 format $HEHDT, XXX.XXX, T*hh<CR><LF> Two RS-232, each capable of driving one load in NMEA 0183 format $HEHDT, XXX>XXX, T*hh<CR><LF> 10 Hz, 4800 baud 1 – 232 switched, 1 – 232 unswitched, 1 – 422 switched
Alarm Outputs	A relay and a battery-powered circuit activates a fault indicator and audible alarm during a power loss. Compass alarm – NO/NC contacts. Power alarm – NO/NC contacts
Course Recorder	(If fitted) RS–232 to dot matrix printer
Synchro Output	(If fitted) 90 V line-to-line with a 115 VAC 400 Hz reference. Can be switch or unswitched

CPU assembly

The heart of the electronic control and processing system, the CPU, is a CMOS architectured arrangement communicating with the Display and Control Panel and producing the required outputs for peripheral equipment. Two step driver boards allow for eight remote heading repeaters to be connected. Output on each channel is a + 24 V d.c. line, a ground line and three data lines D1, D2 and D3. Each three-step data line shows a change in heading, as shown in Table 8.2.

Scheduled maintenance and troubleshooting

The master compass is completely sealed and requires no internal maintenance. As with all computer-based equipment the Sperry MK 37 VT gyrocompass system possesses a built-in test system (BITE) to enable health checks and first line trouble shooting to be carried out. Figure 8.33 shows the trouble analysis chart for the Sperry MK 37 VT system. In addition to the health check automatically carried out at start-up, various indicators on the control panel warn of a system error or malfunction. Referring to the extensive information contained in the service manual it is possible to locate and in some cases remedy a fault.

Table 8.2 Step data lines output

Step data			*Step fraction*	*Heading*
D3	*D2*	*D1*		
0	0	1	0/6	Decrease
1	0	1	1/6	↑
1	0	0	2/6	
1	1	0	3/6	
0	1	0	4/6	↓
0	1	1	5/6	Increase

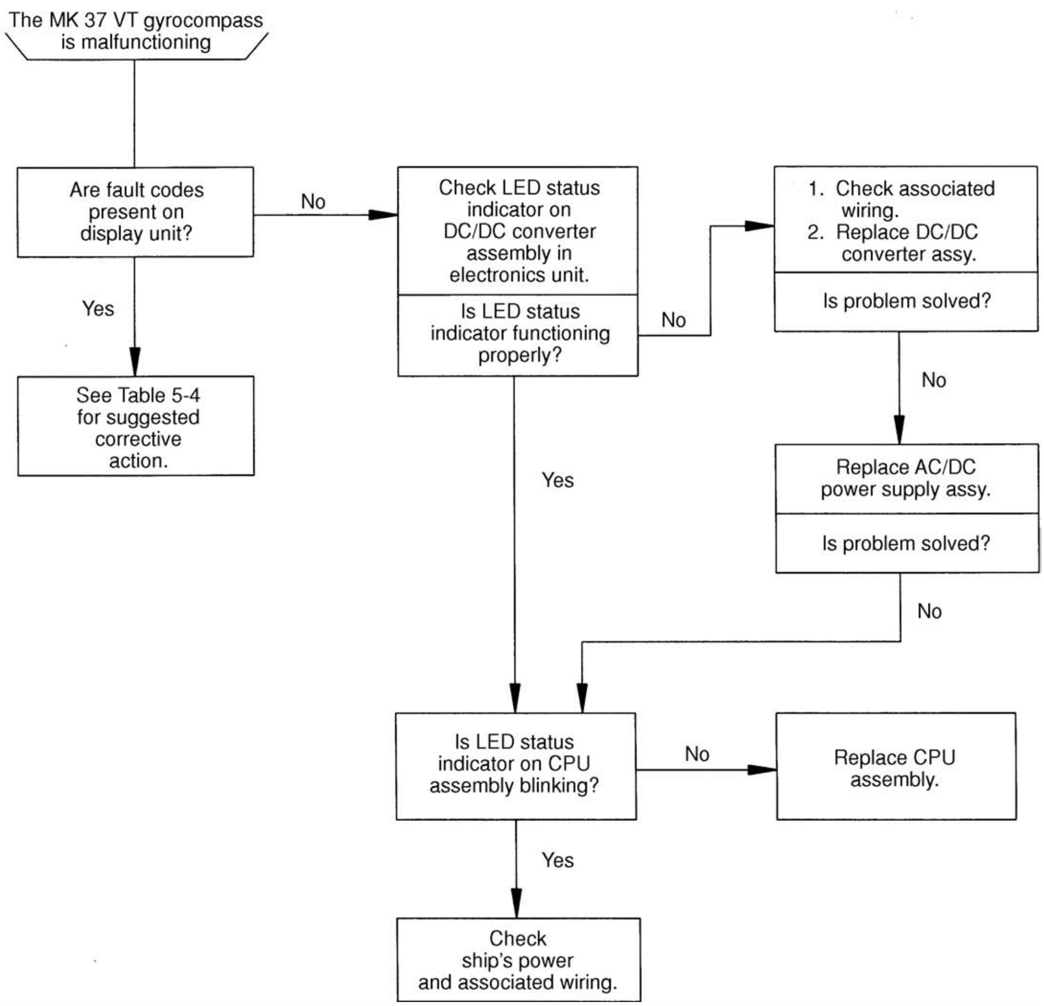


Figure 8.33 Sperry MK 37 VT digital gyrocompass trouble analysis chart. (Reproduced courtesy of Litton Marine Systems.)

Table 8.3 Part of a fault location chart for the Sperry MK 37 VT Compass. (Reproduced courtesy of Litton Marine Systems)

Symptom	*Probable cause*	*Remedy*
Course recorder leaves a blank page every 8–10 inches or has paper feed problems	Printer paper-release lever not in the middle, push-tractor position	Place level in the middle position for push-tractor installation
Repeater does not follow MK 37 VT heading	Repeater channel may not be on or not synchronized to the MK 37 VT heading	Check repeater switch on step driver assembly. Make sure repeater is synchronized to the MK 37 VT gyrocompass
Speed value does not change	Speed selection may not be in Auto	Verify that speed menu selection is in Auto. Check for faults on serial channel
Latitude value does not change	Latitude selection may not be in Auto	Verify that latitude menu selection is in Auto. Check for faults on serial channel
Manual transfer (dual system) does not occur	Other system may not be powered, attached, or may have a critical fault. Manual transfer must be initiated from the primary compass only	Verify that other system is powered, attached, and does not have a critical fault
Unit makes buzzing sound for at least 15 min after being switched on	If sound persists longer than 15 min, the ac/dc power supply assembly relay is bad	Replace ac/dc power supply assembly

As an example, Table 8.3 shows part of the MK 37 VT gyrocompasses extensive fault diagnosis table. Using this and the data displayed on the main display unit, it is possible to isolate the area of a malfunction.

So far this description has only considered gyrocompass equipment using a top-heavy control mechanism. Many manufacturers prefer to use a bottom-heavy control system. One of the traditional manufacturers, S.G. Brown Ltd, provides some fine examples of bottom-heavy gyroscopic control.

8.10 A bottom-heavy control gyrocompass

Modern bottom-heavy controlled gyrocompasses tend to be sealed gyroscopic units with full computer control and electronic interfacing. For the purpose of system description, this early gyrocompass is a good example of bottom-heavy control used to settle and stabilize a compass.

The gyroscopic element, called the sensitive element, is contained within a pair of thin walled aluminium hemispheres joined as shown in Figure 8.34, to form the 'gyroball'. At the heart of this ball is a three-phase induction motor, the rotor of which protrudes through the central bobbin assembly but is able to rotate because of the high quality support bearings. At each end of the rotor shaft, a heavy rimmed gyro spinner is attached to provide the necessary angular momentum for gyroscopic action to be established. Rotational speed of the induction motor is approximately 12 000 rpm.

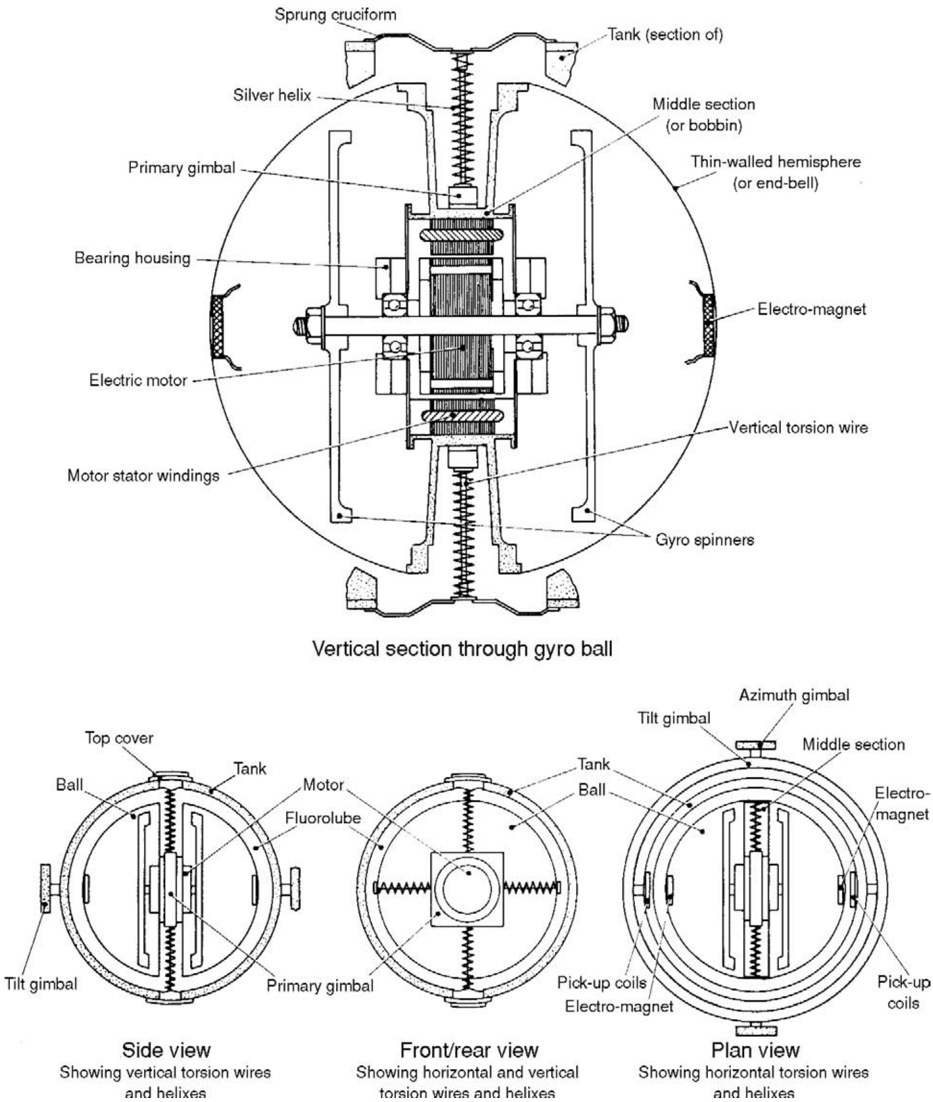


Figure 8.34 Arrangement of the gyroball. (Reproduced courtesy of S.G. Brown Ltd.)

The gyroball is centred within the tank by means of two vertical and two horizontal torsion wires forming virtually friction-free pivots. The torsion wires permit small controlling torques to be applied in both the vertical and the horizontal axes to cause precessions of the axes in both tilt and azimuth. In addition, the torsion wires are used to route electrical supplies to the motor. The gyroball assembly is totally immersed in a viscous fluid called halocarbon wax, the specific gravity of which gives the ball neutral buoyancy, at normal operating temperatures, so that no mass acts on the torsion wires.

The tank containing the gyroball sensitive element is further suspended in a secondary gimbal system, as shown in Figure 8.35, to permit free movement of the spin axis. This axis is now termed the 'free-swing axis' which under normal operating conditions is horizontal and in line with the local meridian. The secondary gimbal system also permits movement about the east–west axis. Each of the

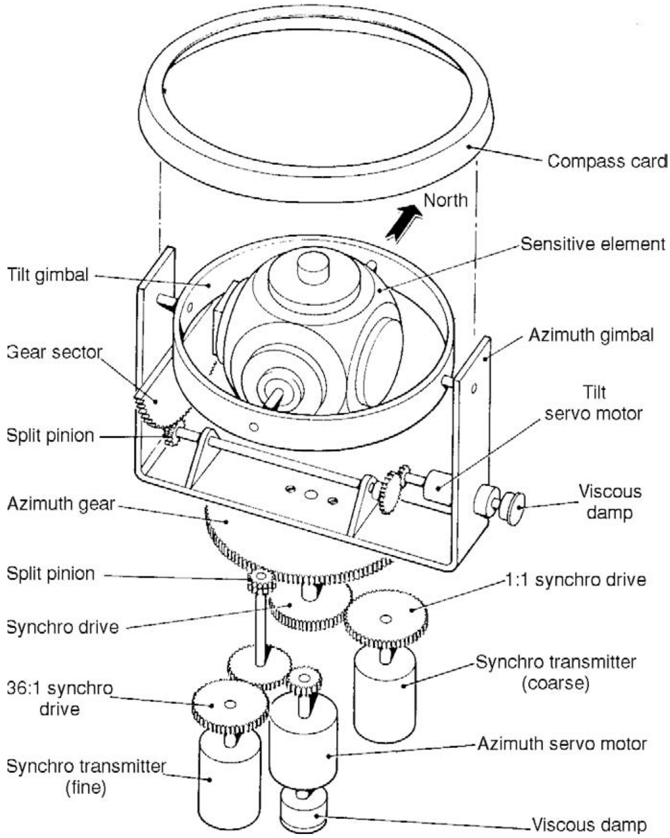


Figure 8.35 Schematics showing the arrangement of the secondary gimbals.

movable axes in the secondary gimbal system can be controlled by a servomotor, which in turn provides both tilt and azimuth control of the gyroball, via a network of feedback amplifiers.

An electromagnetic pick-up system initiates the signal feedback system maintaining, via the secondary gimbals and servomotors, the gyro free-swing (spin) axis in alignment with the north–south axis of the tank. If there is no twist in the two pairs of torsion wires, and no spurious torques are present about the spin axis, no precession of the gyroball occurs and there will be no movement of the control servomotors. The gyro spin axis is in line with a magnet mounted in each hemisphere of the gyroball.

Pick-up coils are mounted on the north/south ends of the containment tank and are arranged so that when the gyro-ball is in alignment with the tank, no output from the coils is produced. If any misalignment occurs, output voltages are produced that are proportional to the displacement in both tilt and azimuth. These small e.m.f.s are amplified and fed back as control voltages to re-align the axis by precession caused by moving the secondary gimbal system. The tiny voltages are used to drive the secondary gimbal servomotors in a direction to cancel the sensor pick-up voltages and so maintain the correct alignment of the gyroball within the tank.

With a means of tank/gyroball alignment thus established, controlled precessions are produced. Referring to Figure 8.36, to precess the gyroball in azimuth only, an external signal is injected into the tilt amplifier. The null signal condition of the pick-up coils is now unbalanced and an output is produced and fed back to drive the tilt servomotor. This in turn drives the tilt secondary gimbal system

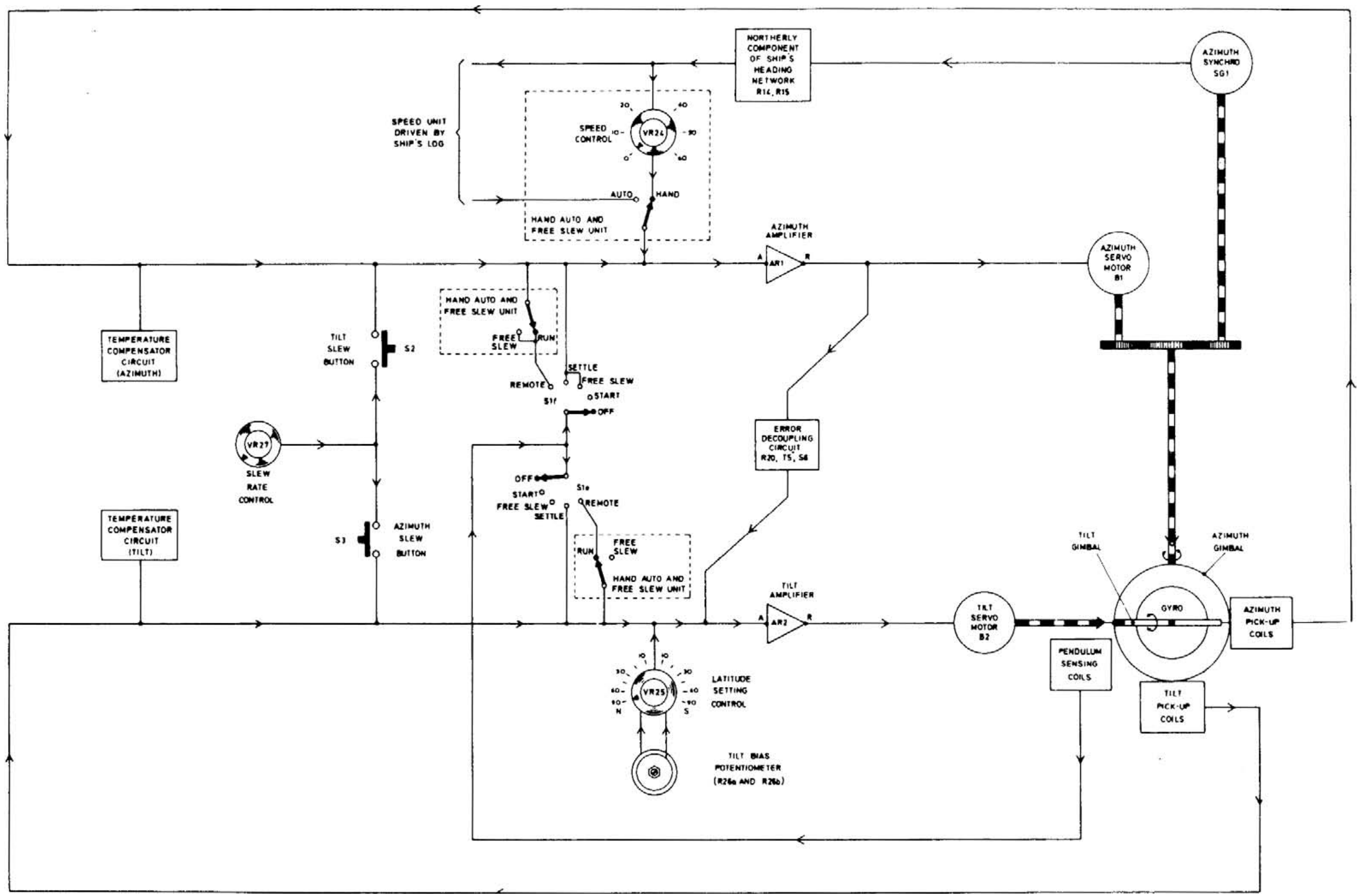


Figure 8.36 Compass circuits schematic. (Reproduced courtesy of S.G. Brown Ltd.)

to a position in which the tilt pick-up coil misalignment voltage is equal and opposite to the external voltage applied to the amplifier.

The tilt servo feedback loop is now nulled, but with the tank and gyroball out of alignment in a tilt mode. A twist is thus produced of the horizontal torsion wires, creating a torque about the horizontal axis of the gyroball and causing it to precess in azimuth. As azimuth precession occurs, azimuth misalignment of the tank/gyroball also occurs but this is detected by the azimuth pick-up coils. The azimuth servomotor now drives the secondary gimbal to rotate the tank in azimuth to seek cancellation of the error signal. Since the azimuth secondary gimbal maintains a fixed position relative to the gyro spin axis in azimuth, a direct heading indication is produced on the compass card mounted on this gimbal.

Control of the sensitive element in tilt is done in a similar way. Therefore signals injected into the tilt and azimuth servo loops, having a sign and amplitude that produce the required precessional directions and rates, will achieve total control of the gyrocompass.

It is a relatively simple task to control the gyroball further by the introduction of additional signals because each of the feedback loops is essentially an electrical loop. One such signal is produced by the 'gravity sensor' or 'pendulum unit'. The pendulum unit replaces the liquid ballistic system, favoured by some manufacturers, to produce gravity control of the gyro element to make the compass north-seeking.

To produce a north-seeking action, the gyroscopic unit must detect movement about the east–west (horizontal) axis. The pendulum unit is therefore mounted to the west side of the tank, level with the centre line. It is an electrically-operated system consisting of an 'E'-shaped laminated transformer core, fixed to the case, with a pendulum bob freely suspended by two flexible copper strips from the top of the assembly. The transformer (Figure 8.37) has series opposing wound coils on the outer 'E' sections and a single coil on the centre arm. The pendulum-bob centres on the middle arm of the 'E' core and is just clear of it. The whole assembly is contained in a viscous silicon liquid to damp the short-term horizontal oscillations caused by the vessel rolling.

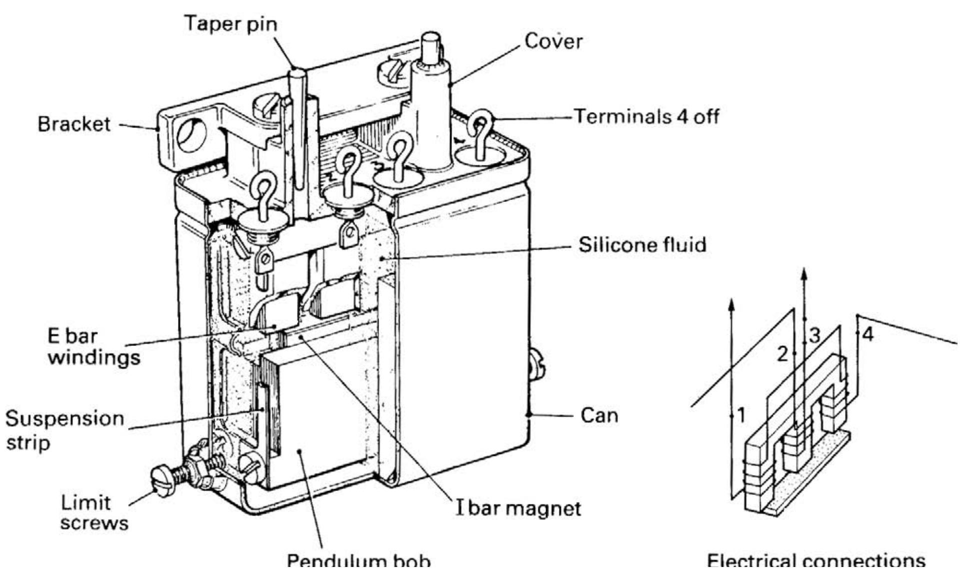


Figure 8.37 The pendulum assembly and its electrical connections. (Reproduced courtesy S. G. Brown Ltd.)

Initially the bob will centre in the middle of the 'E' core, but if the gyro tank tilts, the bob will offset causing the normally equalized magnetic field to be unbalanced and produce a stronger field on the outer arm towards which it is offset. The result is that a tilt signal, of correct sense and amplitude, is produced. This signal is fed to the tilt and azimuth amplifiers as required.

The output signal of the pendulum unit is also used to enable the gyro to settle in the meridian and become 'north settling'. A small carefully calibrated portion of the output signal is applied to the azimuth amplifier to cause azimuth misalignment of the gyro tank and hence a twist of the vertical torsion wires. The result is a tilt of the sensitive element, the direction of which depends on whether the gyro spin axis is north or south end up with respect to the horizontal. The amplitude of the pendulum signal fed to the azimuth amplifier will determine the settling period of the gyro, which for this compass is 40 min.

Loop feedback versatility is again made use of by applying signals in order to achieve the necessary corrections for latitude and speed errors. The injected signals result in the required precessional rates in azimuth, for latitude correction and in tilt, for speed correction.

8.10.1 Speed correction

A signal that is proportional to the ship's speed and the cosine of the ship's course, is coupled back to the azimuth amplifier to cause the gyroball to tilt in opposition to the apparent tilt caused by the northerly or southerly component of the ship's speed. The signal will therefore be maximum in amplitude when the course is due north or south, but will be of opposite sense. If the course is due east or west no correction is necessary. The system uses a 1:1 ratio azimuth synchronous transmitter SG1, which is mechanically driven by the azimuth servomotor gearing, and a balanced star connected resistor network as shown in Figure 8.38.

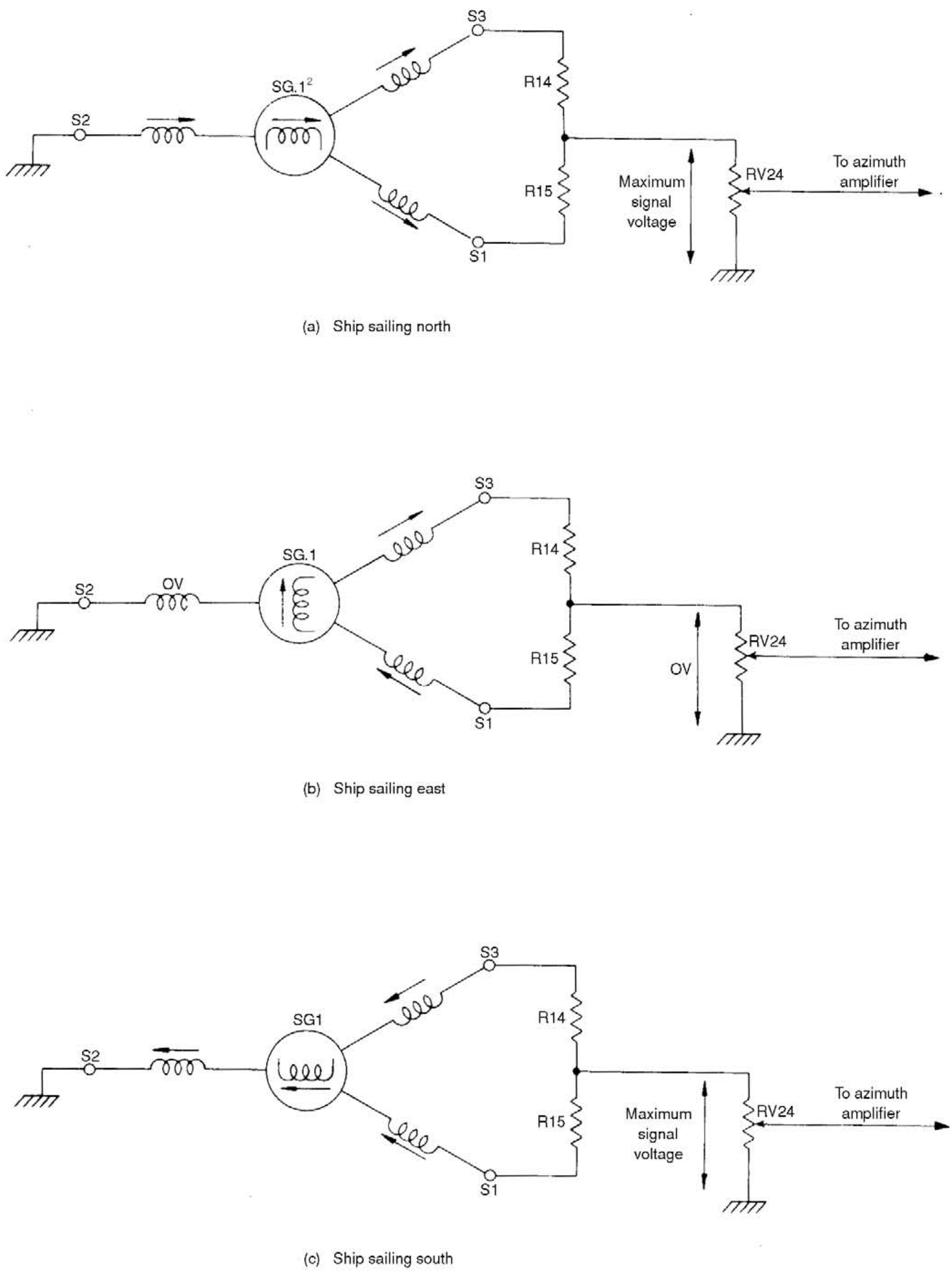
Alternatively an external signal derived from the ship's speed log may be used. In Figure 8.38 the error for a ship sailing due north is maximum and therefore the feedback signal produced across RV24, by the currents flowing through SG1, S1 and S2 coils, will be maximum. A portion of this signal, dependent upon the speed setting of RV24, is fed to the azimuth amplifier to produce a tilt of the gyroball. For a course due south, the signal is again maximum, but is of opposite phase to the northerly signal. This will cause an opposite tilt of the gyroball to be produced. With the ship sailing due east, the synchronous transmitter SG1 is in a position which will produce a zero signal across RV24 and no correction signal is applied to the azimuth amplifier irrespective of the speed setting of RV24. Any intermediate setting of SG1 will produce a corresponding correction signal to be developed across RV24.

8.10.2 Latitude correction

The latitude correction circuit provides a signal, proportional to the sine of the vessel's latitude, to cause the gyroball to precess in azimuth at a rate equal and opposite to the apparent drift caused by the rotation of the earth. This signal will be zero at the equator and maximum at the poles. It must also be of opposite phase for north or south latitudes. VR25 (see Figure 8.36), the latitude potentiometer, derives its signal from the 24V centre-tapped secondary winding of a transformer, and therefore has signals of opposite phase at either end. This control sets the amplitude of the correction signal and is manually adjusted.

8.10.3 Temperature compensation

Both the vertical and horizontal torsion wires may twist with a change in ambient temperature. A corrective signal is produced in each of the tilt and azimuth temperature compensation circuits to



Note:-
Arrows denote instantaneous current flow

Figure 8.38 Signal output of synchro SG1 for different headings. (Reproduced courtesy S.G. Brown Ltd.)

counteract any precession of the gyroball caused by a change in temperature. The corrective signals are produced in the compensation circuits and connected to the tilt and azimuth amplifiers in such a way that both signal amplitude and sense will cause torques to be produced which are equal and opposite to those produced by twisting of the torsion wires. The effect of ambient temperature on the torsion wires is therefore cancelled.

8.10.4 Error decoupling circuit

The accuracy of a gyrocompass can be seriously affected by violent movement of the vessel, particularly heavy rolling caused by severe storms and rapid manoeuvring. A carefully calibrated error signal is derived from the output of the azimuth amplifier (which will be present due to misalignment of the tank and gyro spin axis during such conditions) and applied to the tilt amplifier to control the tilt gimbals. The system will provide partial and adequate compensation for errors that arise due to violent rolling conditions. The correction system is more than adequate for fittings on Merchant Navy vessels that are rarely subjected to rapid manoeuvres.

8.10.5 Slew rate

The purpose of the slew rate control VR27 (see Figure 8.36) is to rapidly level and orientate the gyro during the start-up procedure. The potentiometer VR27 is connected across the 24 V centre-tapped secondary winding of a transformer and is therefore able to produce an output of opposite phase and varying amplitude. The signal voltage level set by VR27 may be applied to the input of either the azimuth or tilt amplifiers separately by the use of push buttons. The buttons are interconnected in such a way that the signal cannot be applied to both amplifiers at the same time.

If the output of VR27 is firstly applied to the tilt servo amplifier (by pressing the azimuth slew button) the gyro will precess towards the meridian. If the tilt slew button is now pressed, the gyro will be levelled by applying the output of VR27 to the azimuth servomotor. The slew rate control VR27 adjusts the rate at which the gyro precesses and not the extent of precession, which is a function of time. It is essential that this control is centred before either slew button is pressed, otherwise a violent kick of the gyro ball will occur in one direction making compass alignment more difficult to achieve. The selector switch S1 must be in the 'free slew' position during this operation.

8.11 Starting a gyrocompass

As has been previously stated, from start-up a gyrocompass needs time to settle on the meridian. The time taken depends upon the make, model and the geographic location of the compass, but in general it is between one and several hours. The duration also depends upon whether the gyro wheel is already rotating or not. If the compass has been switched off, it will take much longer to bring the compass into use. Inputting the ship's heading to reduce the initial error factor can reduce the time period. As an example, the following section considers the start-up procedure for the Sperry MK37 VT Digital Gyrocompass.

At power-up and prior to entering the settle mode, the system performs the automatic 'bite' procedure to determine if the equipment is operating within specified parameters. The CPU also initializes the system hardware and communication channels. During this procedure the gyro wheel is checked for movement. If it is stationary, the system ops for a cold start, if it is rotating a hot start is programmed. During a cold start, if no heading data is input to the system when requested, the gyrocompass selects Automatic.

8.11.1 Cold starting the compass

After an initial period, during which the bite is active, the following sequence is initiated and the settle indicator lamp will be lit.

- Two bleeps prompt the operator for a heading input. If heading data is not entered within 5 min, the gyro switches to an 'auto level' process.
- Assuming heading data has been input, the yoke will be offset based on this data. It will be slewed from the meridian, either clockwise or anticlockwise.
- The gyrowheel is brought up to speed within 14 min.
- The yoke is slewed back and forth to level the ballistic. This action takes about 4 min.
- Again assuming heading data has been input, the gyrocompass will settle within 1 h and the settle indicator lamp goes out. If no heading data was entered, the compass will automatically settle within 5 h.

Other inputs to the gyrocompass are as follows.

- Heading: in the range 0 to 359°. If the entered heading is in error by more than 20° from the true heading, the compass takes 5 h to settle.
- Initialize and Synchronize Step Repeaters. An operator selects a repeater and when requested uses the keypad's left or right arrow switches to scroll the display to the repeater's current position. After 10 s the system steps the repeater to the compass heading. It is essential to repeat and double check this procedure because there must be no alignment errors in a repeater system.
- Speed Input. Using the left or right arrow keys, an operator inputs a speed in the range 0–70 knots.
- Latitude Input. Using the arrow keys, an operator inputs latitude in degrees north or south of the equator.

8.12 Compass repeaters

Remote analogue compass repeaters are simply mechanized compass cards driven either by a stepper motor or a synchro bearing transmission system. Digital heading displays can also be produced by digitizing the stepper 'grey code' waveform before applying it to a suitable decoding system. This section deals with the most popular bearing transmission systems.

8.12.1 Stepper systems

Figure 8.39 shows a mechanical switching stepper system which, because its robustness, is still found on many merchant ships for bearing transmission to remote repeaters. The rotor of the transmitter is geared to the azimuth ring gearing of the master compass. The transmitter is a multi-contact rotary switch that completes the circuit for current to flow through the appropriate repeater motor coils. The transmitter rotor has two rotating arms spaced at 165° to each other. Each rotor arm makes contact with copper segments arranged in four groups of three, with each segment being wired to its corresponding number in the other three groups.

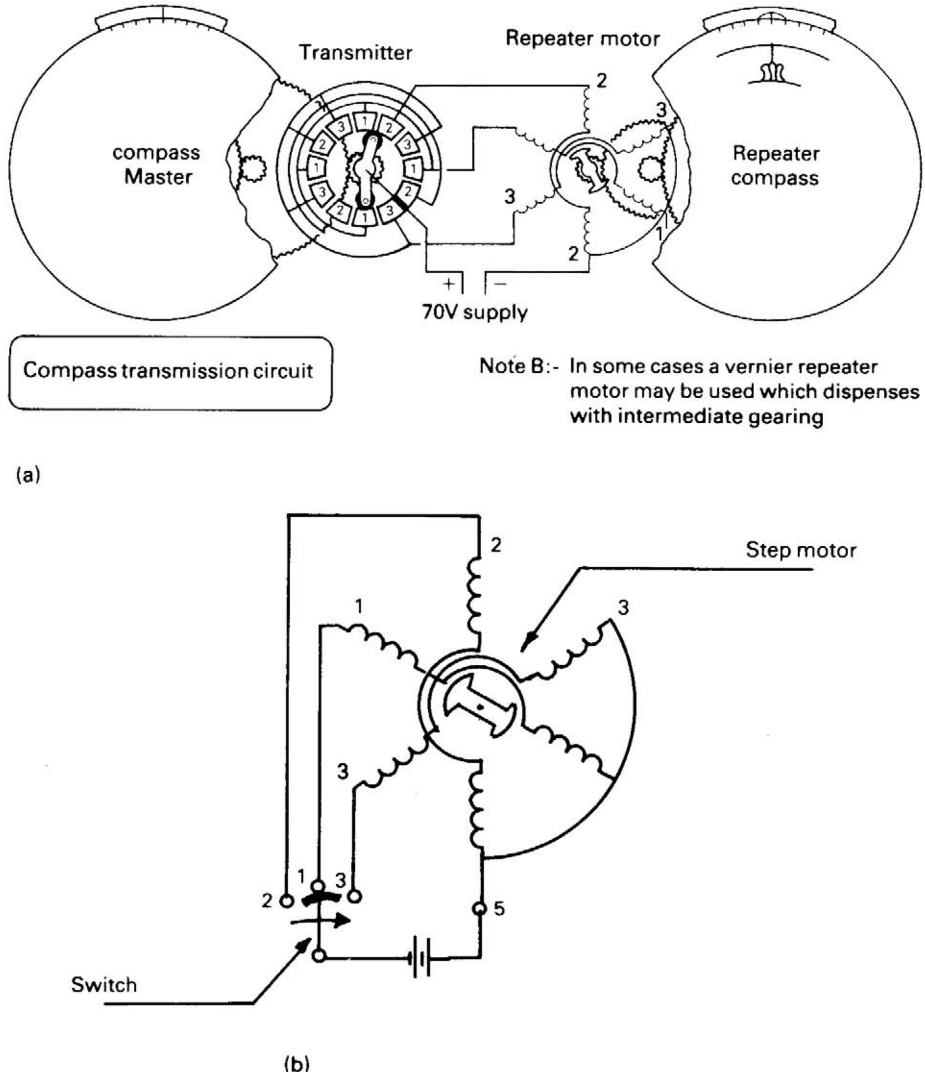


Figure 8.39 Stepper repeating system. (a) Early mechanical switching system; (b) diagrammatic representation of a simple step motor receiver. (Reproduced courtesy of Sperry Ltd.)

The gear ratio of transmitter rotor to azimuth gear is 180:1. Therefore:

$$\begin{aligned} 180\text{ rev} &= 360^\circ \\ 1\text{ rev} &= 2^\circ \\ 12\text{ seg} &= 2^\circ \\ 1\text{ seg} &= 2/12^\circ \text{ or } 10\,\text{min of arc} \end{aligned}$$

The rotating arms make 12 steps per revolution. Because of the 180:1 gear reduction, each step therefore corresponds to 1/6th of a degree or 10 min of arc on the compass card.

A simplified step by step receiver is shown in Figure 8.39(b). Three pairs of coils are wound, and located at 60° intervals on the stator assembly of the receiver. The rotor is centrally located and capable of rotating through 360°. With the switch in the position shown, current flows through the series connected coils (1) and, under the influence of the magnetic field produced, the rotor takes up the position shown. As the switch moves to position 3, its make-before-break action causes current to flow through both coils 1 and 3 and the rotor moves to a position midway between the coils, due east–west. The next movement of the switch energizes coil 3 only causing the rotor to line up with this coil. In this way the rotor is caused to rotate one revolution in 12 steps. The construction details of a step motor are given in Figure 8.40.

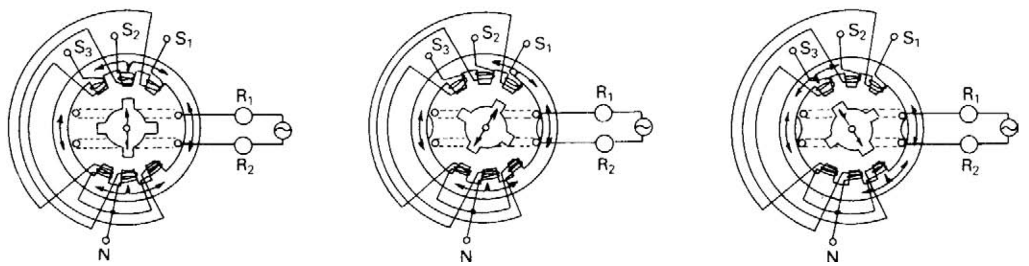


Figure 8.40 Construction details of a step motor.

A stepper system such as this may also be used as part of a 'direct digital control' (d.d.c.) system in which signals are generated digitally to control movement of the repeater. Such a stepper system uses a cyclic binary code or gray code for its operation. The gray code is easily produced using shaft or disc encoders geared to the compass azimuth gearing.

8.12.2 Synchro systems

A synchro is a device that uses the basic principle of a single-phase transformer with magnetic coupling between a rotating primary (rotor) and a number of secondaries (stators). For the purpose of this description three secondaries are located at 120° intervals on the stator. The rotor may be rotated through 360° within the laminated stator assembly holding the three secondary windings. The primary coil is energized by a low frequency a.c. applied via slip rings located on the main shaft. The magnitude and phase of the secondary induced e.m.f.s is dependent upon the relative position of the rotor in relation to the stator windings.

Figure 8.41 shows a synchro repeater system using the basic 'synchro error detecting' method of operation common to many control applications. The rotor of the synchro transmitter is reduction geared to the azimuth ring of the gyrocompass. A reference low frequency a.c. supply to the transmitter rotor coil couples with the three secondaries to produce e.m.f.s which cause current to flow around the three circuits. Each current flow produces a magnetic field around the corresponding receiver secondary and a resultant error signal is induced in the receiver rotor coil. No error signal is produced if the system is in the synchronous state with the transmitter and the receiver rotors at 90° to each other.

The error signal present, when the rotors are not synchronized, is directly proportional to the error angle (ψ) existing between the horizontal and the plane of the rotor. This error signal is amplified to the level required to drive a servo to turn the compass card. Also mechanically coupled to the servo

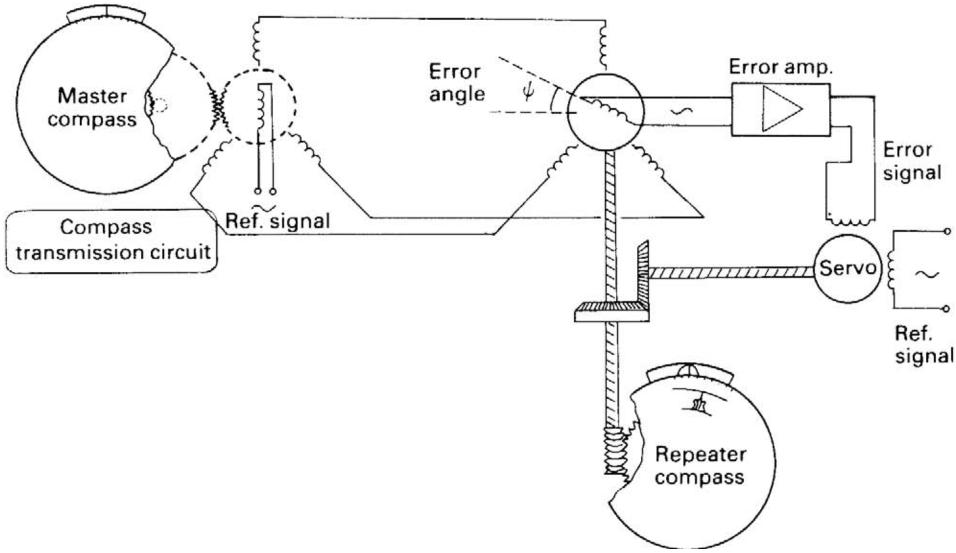


Figure 8.41 A synchro bearing transmission system .

shaft is the receiver rotor that turns to cancel the error signal as part of a mechanical negative feedback arrangement. The receiver rotor will always therefore line up (at 90°) with the transmitter rotor to produce the synchronous state.

8.13 The magnetic repeating compass

Magnetic compasses are still popular with mariners and can easily be converted into a repeating compass with the addition of a flux gate assembly. A flux gate element is effectively a magnetometer that is used to detect both the magnitude and the direction of a magnetic field. Flux gate elements in common use are of the 'second harmonic' type, so called because if excited by a fundamental frequency, f, an output voltage will be generated which varies in both phase and amplitude, depending upon its position within the magnetic field, at a frequency of $2f$.

8.13.1 Construction

The basic flux gate consists of two thin wires of mumetal or permalloy, each contained in a glass tube around which is wound a coil. Two such assemblies are used. They are mounted side by side and parallel to each other. The two coils are connected in series so that their magnetic fields are in opposition when a low frequency a.c. (typically 2 Hz) is applied. Mumetal is used for the wire cores because of its property of magnetically saturating at very low levels of magnetic flux. (Mumetal magnetically saturates at a field strength of approximately 8 ampere turns per metre compared to 250 000 ampere turns per metre for steel wire.)

A secondary coil, wound around the whole assembly, provides a mutually induced e.m.f. as the output voltage.

Figure 8.42 illustrates the basic construction of a simple flux gate. Note that the primary coils are connected in series. In a practical unit a balancing system would be included to ensure that in the

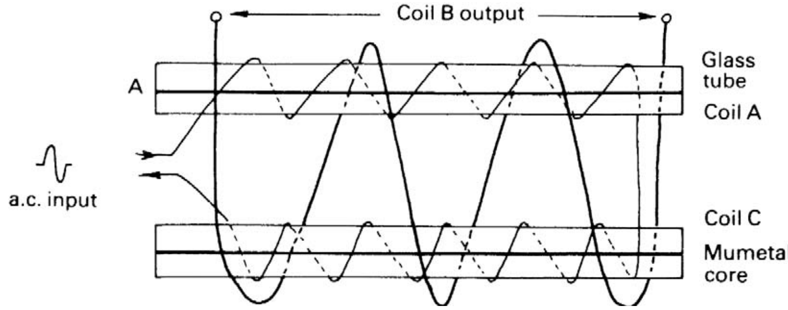


Figure 8.42 A basic flux gate showing the primary windings of equal turns around tubes A and C and a secondary coil wound around the whole assembly.

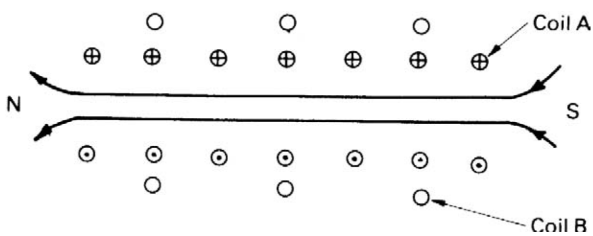


Figure 8.43 A cross-section of part of a flux gate. Current flowing in coil A is 'into the diagram' on the top half of the winding and 'out' on the bottom.

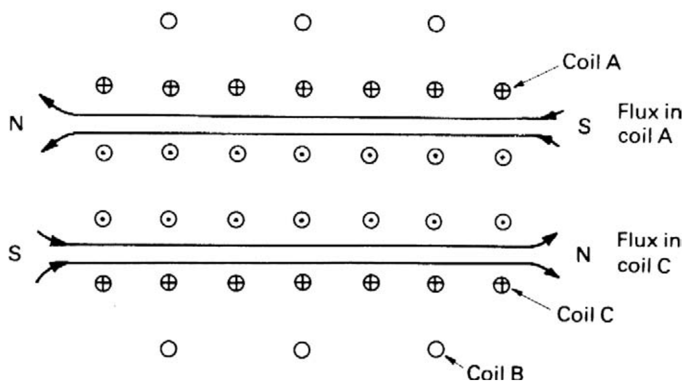


Figure 8.44 A cross-section of a completed flux gate.

absence of any externally produced magnetic field, the magnetic field produced by the two primary windings will cancel and consequently no output will be generated. If the current in coil A changes (see Figure 8.43), the magnetic flux it causes will correspondingly change either in value or direction. Any change will produce a self-induced e.m.f. across coil A and a mutually-induced e.m.f. across coil B. Figure 8.44 shows a cross-section of a complete flux gate with coils A and C forming the primary function and coil B the secondary output coil.

If the magnetic fluxes produced by both coil A and C are of the same value but of opposite polarity, there will be no mutually induced e.m.f. in coil B. This is because the two magnetic fields linking with

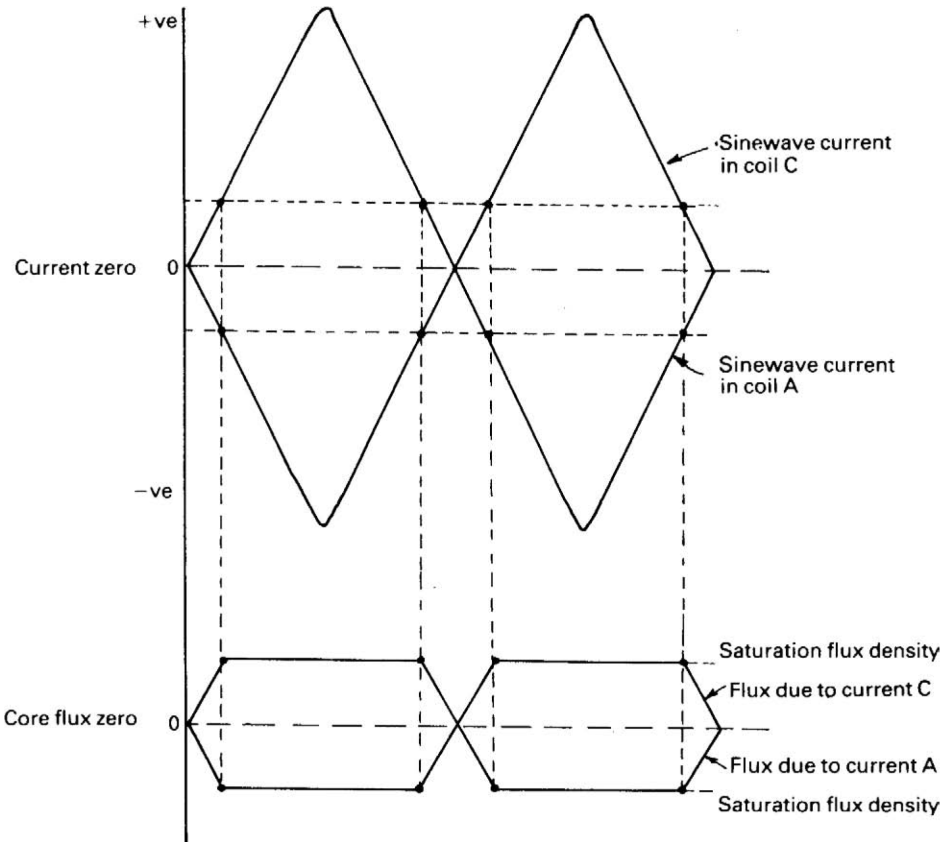


Figure 8.45 Currents and flux saturation levels.

the turns of coil B will be effectively zero. This state can only exist if the two coils A and C are connected in series causing the current flow through the two coils to be the same value at any instant. When this is the case the system is said to be balanced and the output voltage across coil B will be zero.

Figure 8.45 shows the currents and flux saturation levels for both coil A and coil C when the assembly is balanced.

If a permanent magnet is placed in proximity of the flux gate as shown in Figure 8.46 its magnetic field will produce cancelling fields.

In the parts of the cores that carry flux in the same direction as the magnet, the core will saturate with a lower value of coil current. In the other half of the same core the two fluxes will oppose so that this part of the core does not saturate until a much larger current is flowing. These two effects will therefore not affect the balancing of the core fluxes so there will be no mutually induced e.m.f. across the secondary coil B. If the permanent magnet is now placed parallel to the two cores of the flux gate, as in Figure 8.47, an imbalance occurs.

The flux due to the magnet will now be in the same direction as that due to the coil current in one core but in the opposite direction in the other. The magnet will cause one core to saturate with a lower value of coil current and the other to require a larger value of coil current for saturation to occur.

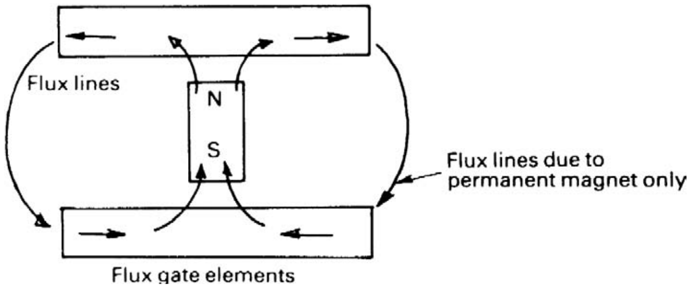


Figure 8.46 Flux lines due to the addition of a permanent magnet to the flux gate.

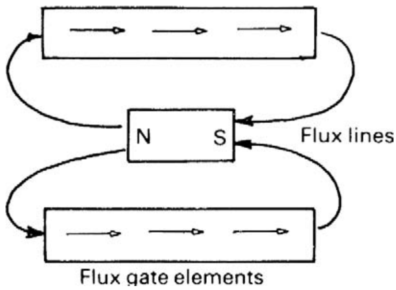


Figure 8.47 Flux lines with the permanent magnet in line with the flux gate.

Figure 8.48 shows how the permanent magnet flux affects the flux produced in each core by the low frequency a.c. primary current on each half cycle of input voltage.

Figure 8.49 shows that the value of the a.c. induced into coil B is twice the frequency of the energizing supply, but depends upon the amplitude of the permanent magnet field. The output also varies as the cosine of the angle between the line of the magnet and the flux gate. The a.c. output is then amplified and used to drive a servomotor which rotates the gate until the output is zero. This corresponds to the magnet being at an angle of 90° to the gate elements.

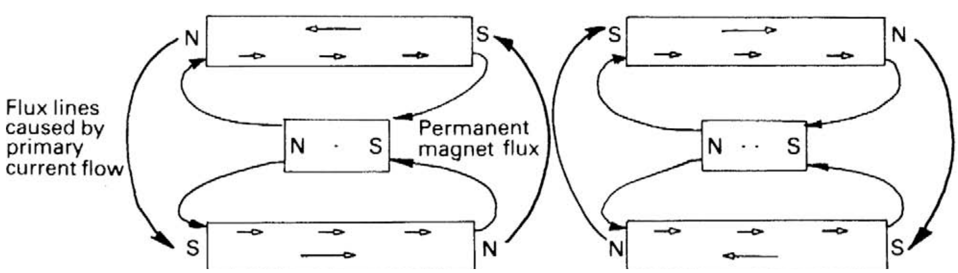


Figure 8.48 The intensity of the magnetic flux in each core is changed on each half cycle of primary alternating current.

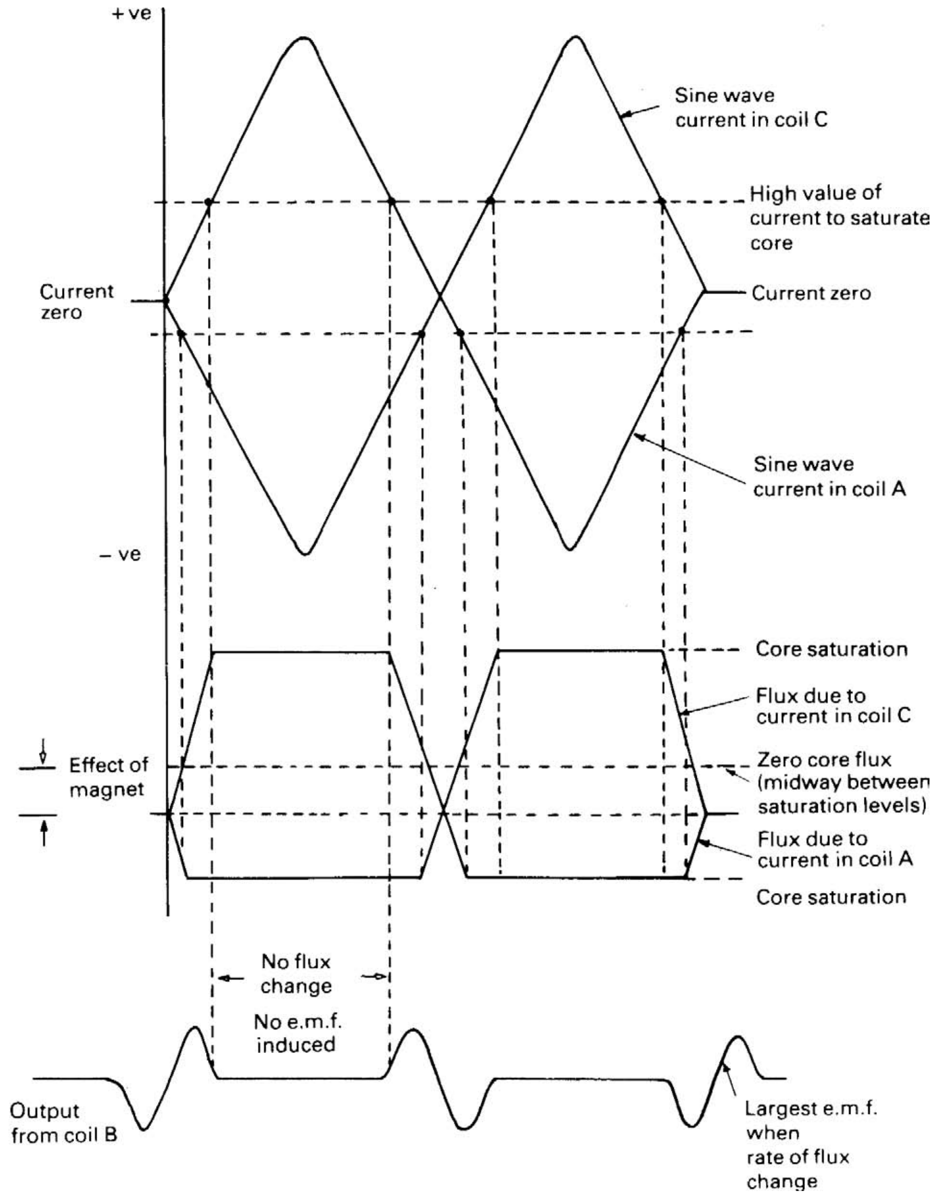


Figure 8.49 An illustration of the fluxes and output e.m.f. produced by an unbalanced flux gate assembly.

8.13.2 Practical flux gate systems

There are currently two main systems of flux gates used in a repeating compass. The simplest of these uses a flux gate in conjunction with an ordinary magnetic compass as shown in Figure 8.50.

The flux gate is mounted on a rotating platform below the compass card of a standard marine magnetic compass and uses the north-seeking property of a permanent magnet. The core elements of the flux gate will therefore come under the influence of the permanent magnetic field produced by the

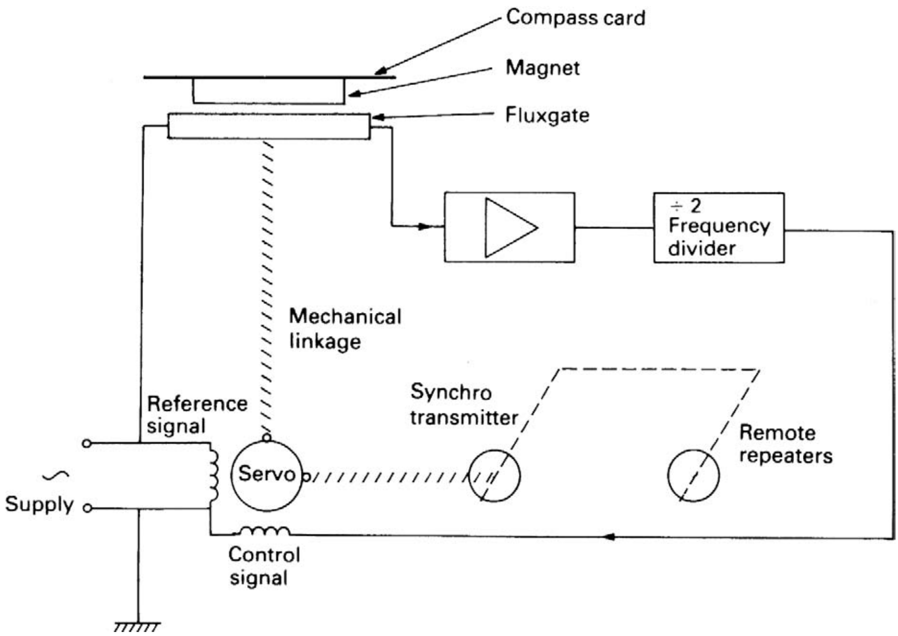


Figure 8.50 A flux gate system used in conjunction with a magnetic compass.

compass pointer. As previously shown, the magnetization will have maximum effect when the flux gate and the compass magnet are parallel and zero effect when they are at 90° to each other. This point is referred to as the NULL point. The resultant output voltage from the secondary winding of the flux gate varies as the cosine of the angle between magnet and flux gate. Output from the flux gate secondary winding is amplified and its frequency divided by two before being applied to the control winding of a servomotor. This servo, which is mechanically coupled to the flux gate platform, drives the whole assembly towards a null point.

Assuming the flux gate and magnet are not at 90° to each other, an output from the flux gate secondary is produced which, after processing, is fed to the control winding of the servomotor. The reference winding supply is taken directly from the low frequency oscillator. This ensures that correct phasing of the servomotor is achieved and that the flux gate will always be driven towards the correct null point. When the null point is reached, the servo amplifier input falls to zero causing the servo to stop. The flux gate is therefore always kept in correct alignment with the compass magnet.

8.13.3 Dual axis magnetometer magnetic compass

As an alternative to using a flux gate in conjunction with a magnetic compass, it is possible to use a dual axis magnetometer to sense the earth's magnetic field to produce an indication of flux direction. The earth's magnetic lines of force are not horizontal to the earth's surface, thus it is necessary that the angle between the lines of force and the earth's surface be resolved into both vertical and horizontal components, as shown in Figure 8.51.

If we assume that a vessel is heading due north as shown in Figure 8.52, the two horizontally-orientated flux gates sense the magnitudes of the earth's horizontal magnetic flux lines diminished by

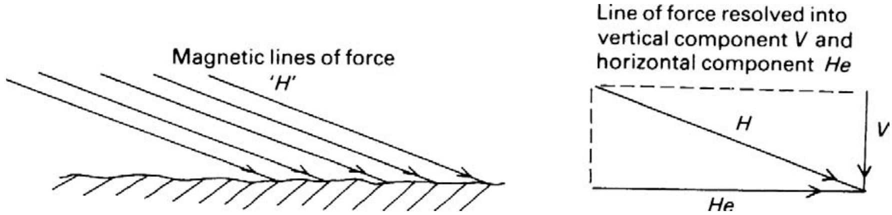


Figure 8.51 An illustration showing how the lines of force of the earth's magnetic field may be resolved into vertical and horizontal components.

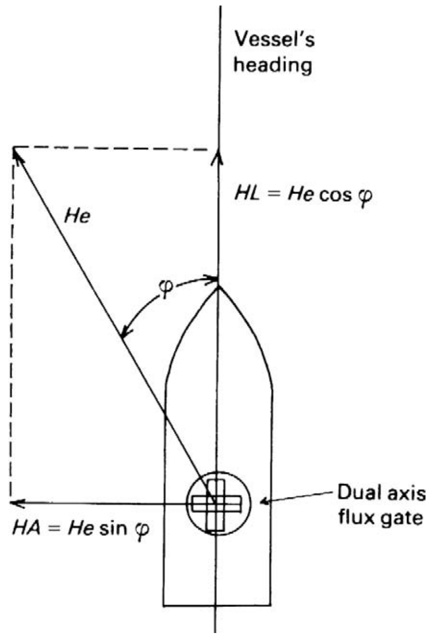


Figure 8.52 The vessel's course shown as a cosine function of *He* – the direction of the earth's magnetic field.

sine and cosine functions of the heading. The resulting outputs produced, designated *HL* and *HA*, are derived as shown in Figure 8.52.

In Figure 8.53, flux gate 1 is mounted along the fore and aft line of the vessel and flux gate 2 athwartships. The fore and aft line component of the earth's magnetic field causes flux gate 1 to produce an output voltage proportional to the amplitude of this component. Similarly, gate 2 produces an output proportional to the athwartships component. Both signals are coupled to the stator coils of a synchro that produces two magnetic fields proportional to the amplitude of the original fields acting upon the flux gates. The line of the resultant field within the synchro is the same as the direction of the earth's magnetic field, *He*.

Output from the rotor of the synchro is connected, via a servo amplifier, to drive a servomotor which rotates the synchro rotor mechanically until it is at 90° to the resultant field, at which point output from the rotor is zero and the servo stops. The synchro rotor is thus kept in alignment with the resultant direction of the magnetic field within the synchro, which in turn depends upon the direction,

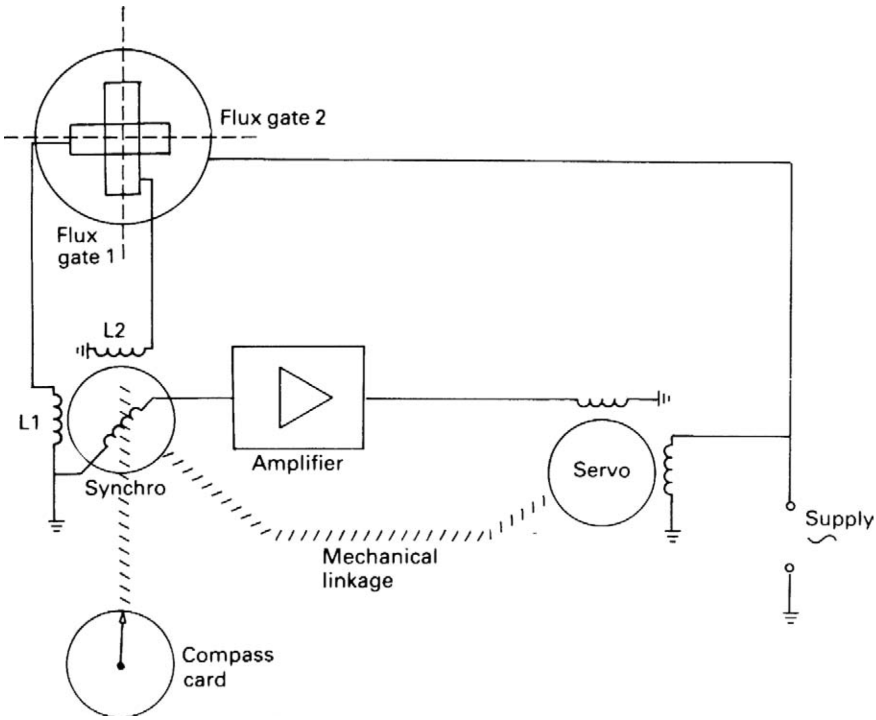


Figure 8.53 A simplified diagram of a dual axis magnetometer type of magnetic compass.

relative to both flux gates, of the earth's magnetic field. A compass card is directly driven by the rotor of the synchro. Remote repeaters can be fitted, as illustrated in the previous case, by the use of a synchro transmission system. A compass has thus been produced which eliminates the conventional pivoted magnet arrangement to provide an electrical indication of magnetic north.

8.14 Glossary

Angular momentum	In the case of a gyrowheel, this is the product of its linear momentum and the radius of the rotor.
Ballistic pots	Containers of viscous liquid to add damping to a gyrocompass.
BITE	Built-in test equipment. Automatic or manually commanding equipment test circuits.
Compass repeaters	Remote display of compass information.
Controlled gyroscope	One in which the movement caused by earth rotation is controlled.
Drift	The apparent movement in azimuth of a gyroscope due to earth rotation.
Dynamic errors	Errors caused by the angular motion of the vessel during heavy weather or manoeuvring.
Flux gate	The electrical sensing unit of a magnetic compass.
Free gyroscope	A gyroscope with a spin axis fixed by inertia to some celestial reference point and not to a terrestrial point. Not suitable as a gyrocompass.

Follow-up	A system enabling control of the gyro when it is fitted on board a moving platform.
Gyroscope	A perfectly balanced wheel that is able to spin at high speed symmetrically about an axis.
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.
Latitude error	A constant value error the magnitude of which is directly proportional to earth rotation at any given latitude.
Linear momentum	The product of mass and velocity.
Manoeuvring error	An error caused by a vessel's rapid changes of speed and/or heading.
North-seeking gyro	One which is partly controlled and as a consequence will seek to locate north but will not settle. Further control is required to convert this type of gyro into a compass.
North-settling gyro	One which is fully controlled and will settle to point north.
Precession	Movement at 90° from the applied force. If a force is applied to a spinning rotor by moving one end of its axle, the gyroscope is displaced at an angle of 90° from the applied force.
Rolling error	As the name suggests, this error is caused by a vessel rolling. The error cancels when the ship is steaming north or south and is maximum when following an east/west course.
Settling time	The period taken for a gyrocompass to settle on the meridian from start-up.
Slew rate control	A control setting an electrical input to rapidly level and orientate the gyro during start-up.
Stepper systems	A step motor compass repeater circuit.
Synch. systems	A synchronous motor compass repeater circuit.
Tilt	By virtual of precession, the earth's rotation causes the spin axis to tilt upwards to an angle dependent upon its position in latitude.
Transmission error	An error existing between the master compass and any repeaters.

8.15 Summary

- There are three axes in which a gyroscope is free to move: the spin axis, the horizontal axis and the vertical axis.
- In a free gyroscope none of the three axes is restricted.
- A free gyroscope is subject to the laws of physics, the most important of which, when considering gyrocompass technology, is inertia.
- Precession is the term used to describe the movement of the axle of a gyroscope under the influence of an external force. Movement of the axle will be at 90° to the applied force.
- Tilt is the amount by which the axle tilts because of the gyroscope's position in latitude.
- Azimuth drift is the amount by which the axle drifts due to the earth's rotation.
- A controlled gyroscope is one with its freedoms restricted.
- A north-seeking gyroscope is a controlled gyro that never settles pointing north.
- A north-settling gyroscope is a damped controlled gyro that does settle on the meridian.
- Bottom- and top-heavy controls are methods used for settling a north-seeking gyroscope.

- A gyrocompass fitted on board a ship is affected by dynamic errors. They are rolling error, manoeuvring error, speed and course error and latitude or damping error. All these errors are predictable and controllable.
- When starting from cold, gyrocompasses require time to settle on the meridian. A settling time period of 75 min is typical.
- Stepper systems are transmission devices that relay the bearing on the master compass to remote repeaters.
- Magnetic repeating compasses are based on flux gate technology.
- A flux gate is an electrical device that interprets the compass bearing to produce control functions.

8.16 Revision questions

1. Describe what you understand by the term gyroscopic inertia?
2. What do you understand by the term precession when applied to a gyrocompass?
3. Why is a free gyroscope of no use for navigation purposes?
4. How is earth's gravity used to turn a controlled gyroscope into a north-seeking gyroscope?
5. How is a north-seeking gyroscope made to settle on the meridian and indicate north?
6. When first switched on a gyrocompass has a long settling period, in some cases approaching 75 min. Why is this?
7. Explain the terms gyro-tilt and gyro-drift.
8. How is a gyrocompass stabilized in azimuth?
9. What is rolling error and how may its effects be minimized?
10. Why do gyrocompass units incorporate some form of latitude correction adjustment?
11. What effect does an alteration of a ship's course have on a gyrocompass?
12. What are static errors in a gyrocompass system?
13. When would you use the slew rate control on a gyrocompass unit?
14. Why is temperature compensation critical in a gyrocompass?
15. What is a compass follow-up system?
16. What is a compass repeater system?
17. A flux gate is the central element of magnetic repeating compasses. Explain its operation.
18. Flux gate elements are known as 'second harmonic' units. Why is this?
19. What are the advantages of using a dual axis magnetometer in preference to a flux gate?
20. Why is a magnetic repeating compass not influenced by the vessel's position in latitude or by violent manoeuvring?