ROYAL SCHOOL OF ARTILLERY

BASIC SCIENCE & TECHNOLOGY SECTION
GUNNERY STAFF/CAREER COURSES

FUNDAMENTALS OF GYROSCOPES

INTRODUCTION
1. The gyroscope is one of the most important devices available for a wide range of instrument systems applicable to both civil and military fields. Using its inherent stability and resistance to change of orientation, the gyroscope provides an independent source of data for attitude, azimuth, rate of turn and position. These properties are used in such applications as survey work, missile guidance, automatic pilots, attitude referencing, stabilising of weapon platforms and inertial navigation systems, for all three branches of the armed services.

PROPERTIES
2. The gyroscope has properties not unlike those of the earth. It is a mass, or rotor, spinning about an axis through its centre. The mass is supported by two circular rings called 'gimbals', one ring being mounted inside the other, and the pair are able to rotate within an outer frame. The axes of rotation for rotor, inner and outer gimbals are mutually perpendicular as illustrated at Fig.1. This type of structure is called a displacement gyroscope and it has two major properties:-

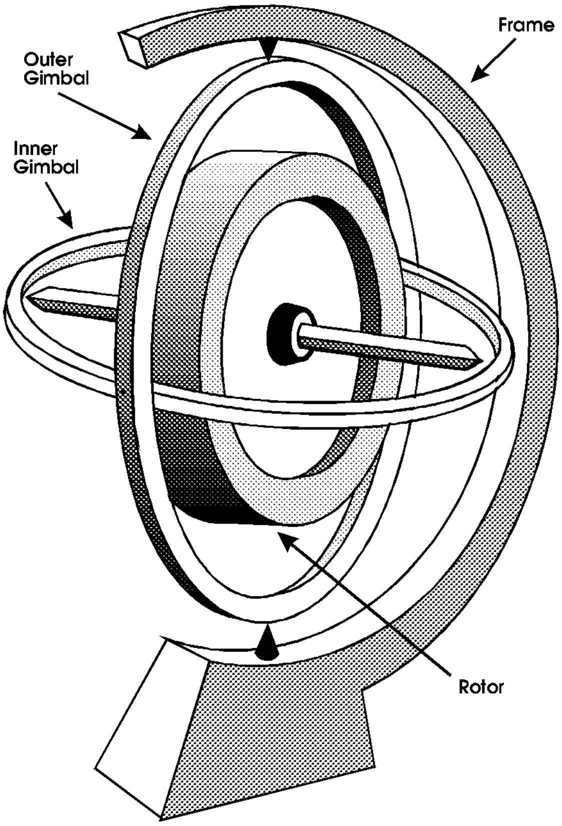


Fig.1. The Displacement Gyroscope

a. The frame may be angularly displaced in any direction and the gyro spin axis will remain aligned in space. In other words pointing along the same line into outer space from the earth.

b. If an external force, or torque, is applied to the axis of spin, the rotor does not move in the plane of the applied torque but about an axis mutually perpendicular to those of spin and torque.

LAWS OF GYRODYNAMICS
3. The two properties outlined in the last paragraph are called 'rigidity' and 'precession' and they provide the visible effects of the laws of gyrodynamics, which may be stated in the following form:-

a. If a rotating body is so mounted as to be free to move about any axis through the centre of mass, then its spin axis remains fixed in inertial space however much the frame may be displaced.

b. If a constant torque is applied about an axis, perpendicular to the spin axis, of an unconstrained, symmetrical, spinning body, then the spin axis will precess steadily about an axis mutually perpendicular to both spin and torque axes.

GYROSCOPE CLASSIFICATION
4. Gyroscopes may be classified in a number of ways, however, by far the most common is that of degrees of freedom. A degree of freedom is defined as an axis about which relative movement may be detected and measured. The relative movement may be that between frame and outer gimbal or between inner and outer gimbal. Movement about the spin axis is difficult to detect and is not normally attempted.

5. Some gyroscopes are designed to employ both degrees of freedom, as in the displacement gyroscope when it is used for attitude and azimuth applications, and some are designed without the outer gimbal, leaving only the inner gimbal free within the frame. This type has important specialist applications for rate of turn about the measurement axis and will be discussed again later.

PRECESSION

6. The second law of gyrodynamics indicates that as a result of applying torque about an axis perpendicular to the spin axis of a gyroscope rotor, movement of the axis, called precession, will take place. The direction in which precession occurs is dependent upon the direction of rotation for the mass and the axis about which the torque is applied. A rule of thumb guide is known as Sperry's Rule of Precession' and it is illustrated at

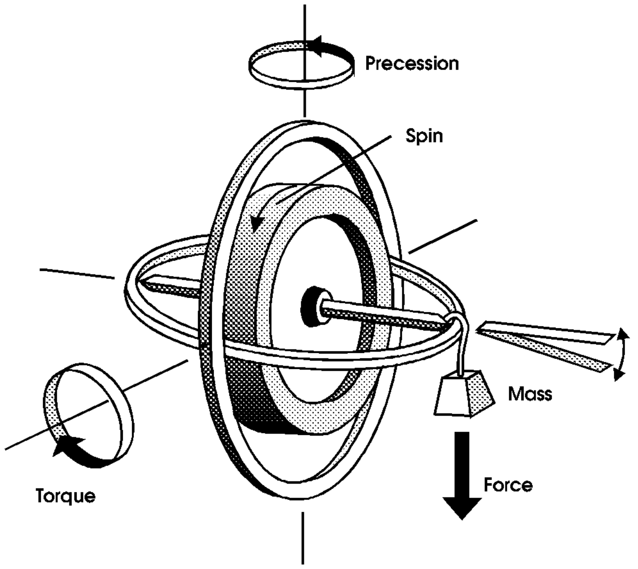


Fig.2. Sperry's Rule of Precession

Fig.2.

7. If the applied torque is due to a force acting at the inner gimbal, perpendicular to the spin axis, it can be transferred as a force to the edge of the rotor, at right angles to the plane of rotation. The point of application of the force should then be carried through 90° in the direction of rotation of the mass and this will be the point at which the force appears to act. It will move that part of the rim of the rotor in the direction of the applied disturbing force. The property of precession may be used to manipulate the spin axis of a gyro into the frame of reference required for its particular application.

RATE OF PRECESSION

8. When the rotor of a gyroscope is precessing, the rate of movement, or angular velocity, of that precession is directly proportional to the applied torque and inversely proportional to both angular velocity of the rotor and its moment of inertia. These facts are incorporated in the formula $\Omega = T/I\omega$ which indicates the rate of precession. Where:-

Ω = Angular velocity of precession.
T = The applied torque.
ω = The angular velocity of the rotating body.
I = The moment of inertia of the rotor.

ANGULAR MOMENTUM

9. The product $I\omega$ is known as the angular momentum of the body which comprises the rotor. Angular momentum may be described as the ability of the body to do work. Energy is stored in the rotor due to the rotational force of each particle of mass and the further the particle is from the axis of spin the more energy it will possess. Therefore the shape of the rotor is important because the overall energy must be a summation of all the smaller energies from each particle of mass comprising it. Hence, the stored energy is proportional to both the mass and the shape (mass distribution) of the body, incorporated in its moment of inertia, I, which is independent of the rate of rotation, ω. It is normal in gyroscope design to concentrate as much of the mass as possible at the periphery of the rotor, thus increasing the angular momentum. This has the effect of increasing its rigidity in space.

MECHANISM OF PRECESSION

10. The mechanism that produces precession is technically quite complex, however, it is possible to show the basic effects in fairly simple diagrammatic form as illustrated at Fig.3. A pair of rotating mass blocks, one each side of the axis, can be selected from the rotor, as shown, and the forces acting upon

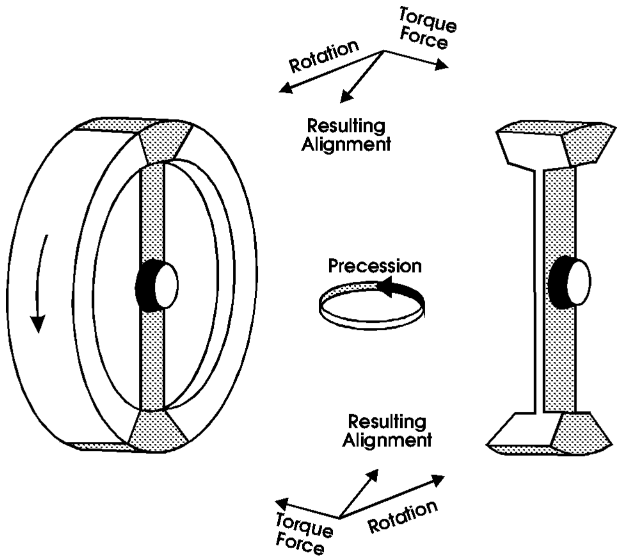


Fig.3. Forces Causing Precession

them during application of a torque represented.

11. The force causing rotation and that due to the applied torque are shown in the appropriate directions. All are in a plane perpendicular to the page. They must be added vectorially to arrive at the resultant force, which gives the direction of alignment of the wheel that forms the rotor mass, and if the force is continuous, so too is the precession. The axis about which precession occurs is vertical.

ROTOR DRIVE SYSTEMS

12. The method of rotor drive employed in a particular system will depend largely upon the role of the equipment in which it is used. There is little point in using a sophisticated, highly accurate drive mechanism that provides long term accuracy, when the gyro will be in use for such a short period of time that the capabilities will not be used anyway. Hence missiles tend to employ devices built down to the price and in use for a matter of seconds, whereas inertial platforms have gyros with long term accuracy built to last for many years. There are four major classes of gyro drive system available:-

a. Electrical.
b. Air Pump.
c. Gas discharge.
d. Mechanical.

ELECTRICAL GYRO MOTORS

13. Electrical drive may be of the DC or AC type. A DC motor involves commutation and therefore carbon brushes. At the rotor speeds involved, which need to be of the order 10,000 RPM to be effective, the brushes tend to wear quickly and regular servicing is required. Despite this many current light

aircraft gyroscopes use a DC drive motor.

14. AC motors are able to provide very much higher rotor speeds when three phase power supply is available. Synchronous induction motors of the three-phase type give rotor speeds of the order 24,000 RPM or more from a 400Hz supply. Sometimes an electronic oscillator may be used with its output split into the three phases. The great advantage here is that the oscillator may be driven from a DC supply.

15. The leads for any electrical rotor drive mechanism must be brought to the motor from the frame along both outer and inner gimbals. To avoid twisting of leads and subsequent failure of the drive, slip rings are used between gimbal and frame or gimbal and gimbal as necessary, particularly where 360° of rotation is needed. Usually full rotation of both gimbals is not required and flying leads may be used in some applications.

AIR PUMP GYRO MOTORS

16. Air is caused to flow through the gyro by an engine driven pump on the carrying vehicle, which may be of the pressure or vacuum type. It is more normal to employ the vacuum drive in long term gyros because the air reaching the rotor tends to be cleaner than with pressure systems so avoiding particles that can increase friction in both drive and gimbal bearings. The rotor has a series of slots or cups cut into the outer edge parallel to the spindle. Airflow is caused to pump into the cups providing the required rotational speed. The air is directed to the appropriate nozzle by a series of pipes connected through moving joints on the frame and gimbals. Speeds of the order 10,000 RPM are not unusual with this system, however, it does take time to acquire it.

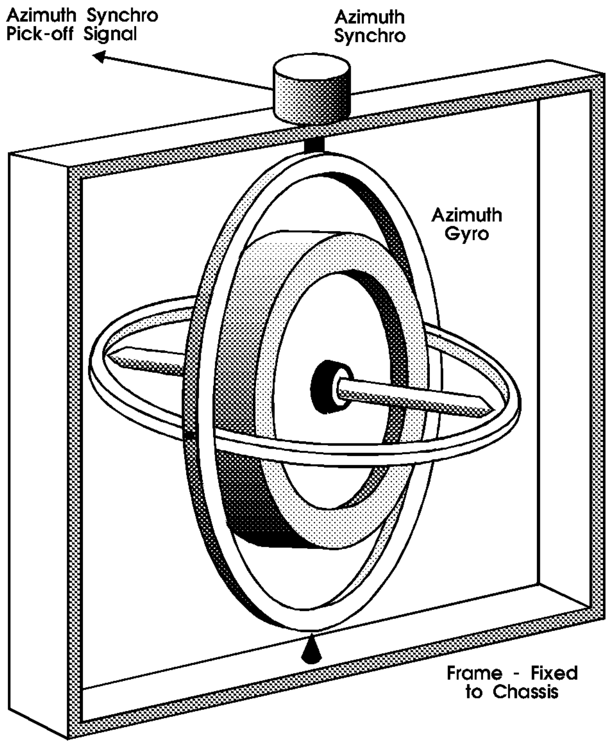


Fig.4. The Azimuth Gyroscope

GAS DISCHARGE GYRO MOTORS

17. This method is particularly appropriate with missile systems, where some of the exhaust gases from the propulsion system are diverted through channels to the rotor, in much the same way as for the air pump system. In this case, however, an initial blast of gas at very high pressure can be used to 'wind up' the rotor which is then left to freewheel for the remainder of the flight. It is particularly important that the rotor speed does not fall below the minimum required for missile control, during an interval equal to the longest possible flight time. In any case such drive systems are not used for run times of more than a few minutes at the most.

MECHANICAL GYRO MOTORS

18. A rather crude sounding, but apparently effective method of rotor drive is by the use of clockwork type springs. The tension required is obviously very high indeed and a strong spring would be needed. The rotor is released at launch to unwind the spring. The same minimum speed requirement would exist in this method as for the gas discharge system.

GYROSCOPE CONFIGURATIONS

19. There are four basic configurations in which gyroscopes may be used. In the first three cases angular displacement about one or two axes is measured and in the last, rate of change of displacement, or angular velocity about a given axis is measured. All relate basically to the orientation of the spin axis of the gyroscope they employ and are classified as follows:-

a. Azimuth.
b. Vertical.
c. Single Axis.
d. Rate.

THE AZIMUTH GYROSCOPE

20. The azimuth gyroscope has its spin axis in the azimuth plane, or horizontal to the earths surface. It is designed to detect rotation about the vertical axis, in the manner of a compass system. To ensure that only azimuth rotation is measured the gyro must be 'caged', or tied, into a frame of reference prior to running the rotor up to the correct speed, called 'erecting' the gyro. For a missile system this is usually during the launch process.

21. From Fig.4, it can be seen that when the carrying vehicle manoeuvres in azimuth the frame will rotate, pivoting about the gyro vertical axis. The gyro will remain fixed in its erected orientation, causing the rotor of the synchro pick-off, which is connected by a shaft to the gyro outer gimbal, to change its position with respect to the stators. As a result angular data is fed back to the control system within the carrying vehicle. All signal are given with respect to the launch position, which may not be level, however, the gyro does form a highly stable reference upon which the control system is able to base its operations.

THE VERTICAL GYROSCOPE

22. The vertical gyroscope has its spin axis in the vertical plane and is designed to detect rotation about both the pitch and roll axes. Once again, prior to use the gyro must be 'caged' into the correct position by ensuring that the inner and outer gimbals are mutually perpendicular and that the spin axis is vertical to the carrying vehicle before the rotor is brought up to speed.

23. Fig.5, shows the layout for a typical vertical gyroscope. Two synchros are fitted at pivot points, one for pitch and the other for roll. The pitch synchro presents a little problem because the electrical connections need to be brought in and out. To do so they must be either free, in which case gyro movement is limited in one or both of the axes, or they pass along the inner gimbal to sliding contacts between inner and outer gimbal where they are then conveyed to the frame by a similar mechanism.

24. It will be apparent from what has been seen of the azimuth and vertical gyroscopes that if one of each is employed then

heading, or direction, together with pitch and roll information may be gained. There is also one redundant axis in the azimuth type which might or might not be employed.

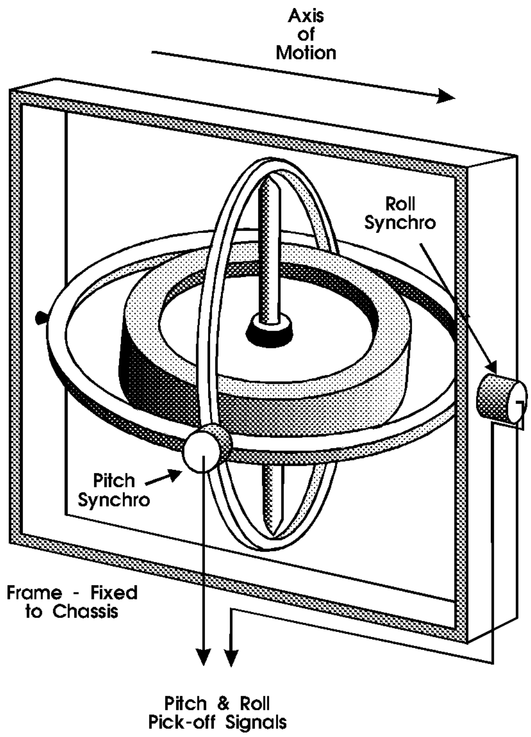


Fig.5. The Vertical Gyroscope

THE SINGLE AXIS GYROSCOPE

25. The single axis gyroscope is designed to detect rotation about a sole specified axis, as the name implies. To allow this the outer gimbal of a displacement gyroscope is removed, leaving only the inner gimbal and the rotor mounted into a frame. Two further types of gyroscope are produced by this method, both of which are discussed later in the text. It can be seen that the device has three definable axes, those of spin, input rotation and output precession respectively. It should also be clear that, unlike the previous gyroscopes, it is not relative movement of the frame that is measured but actual movement of the spin axis.

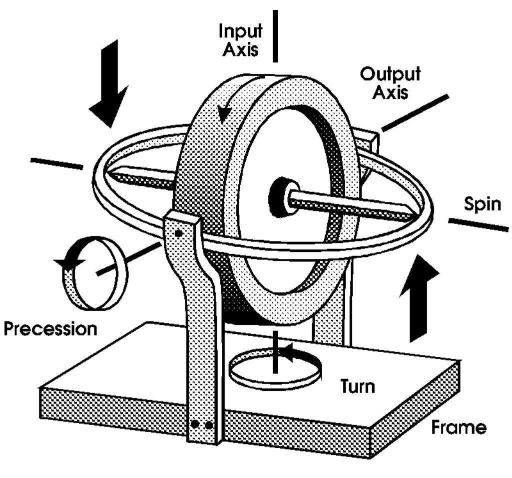


Fig.6 The Single Axis Gyroscope

26. A single degree of freedom gyro is shown at Fig.6. Rotation about the input axis, in this case the azimuth axis, causes precession to occur about the output axis. A pick-off between gimbal and frame detects the angular displacement and feeds it to the appropriate control system. These devices can be very sensitive about the axis of interest leading to high accuracy angular data. Similar gyros may be fitted in the three mutually perpendicular axes giving accurate movement detection about any axis. It should be noted that the range of precession is limited because the spin axis eventually aligns with the input axis and precession would then cease.

THE RATE GYROSCOPE

27. Rate gyroscopes are essentially modified single degree of freedom devices in which the gimbal is connected by a restraining system to the frame. Such a mechanism is illustrated at Fig.7. In this case restraint is exercised by springs, however, electronic and hydraulic methods may be used to achieve it. Device output is an angle proportional to the 'rate of rotation' about the input axis. This may be specified in radians, degrees or mills per second as required.

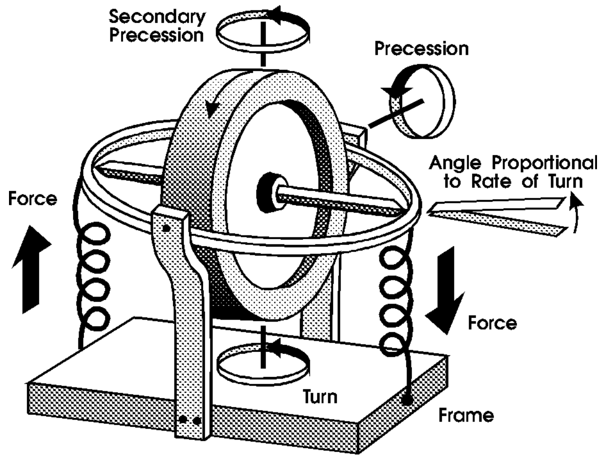


Fig.7. The Elementary Rate Gyroscope

28. From Fig.7, it can be seen that when the gyro is rotated at a 'constant rate' about the input axis, in this case anti-clockwise when viewed from above, the rotor attempts to precess about the output axis, in this case anti-clockwise when viewed from the left hand end. This precession is opposed by the springs which generate forces on the inner gimbal, in this case pushing up at the left hand end and pulling down at the right hand end. The forces present will now be considered when the gimbal has precessed through an angle as illustrated at Fig.7.

29. In opposing precession the springs generate a secondary force upon the rotor shaft. This secondary force is proportional to the angle through which the gimbal has moved, the larger the angle the greater the force and vice-versa. In Fig.7, it can be seen that the secondary force is pulling down at the right hand end of the spin axis and since the force is perpendicular to the spin axis, it must produce precession.

30. When the action of the secondary force is applied to the edge of the gyro rotor and then moved through 90° in the direction of rotation, as demanded by Sperry's rule, the direction of this secondary precession is obtained. Clearly the secondary precession must be in the same direction as the original turn.

31. Since the frame rotation which caused the secondary precession and the secondary precession itself are in the same direction, an equilibrium point is reached, at which the force from the springs creating the secondary precession is

such that the rate of secondary precession becomes equal to the original rate of turn of the frame. At this point the tilt angle remains constant, indicating the rate of turn. Rate of turn could now be determined by measuring the tilt angle, either mechanically by pointer or electrically by synchro, with respect to the frame.

32. Should rate of turn be increased, the tilt angle is increased by additional precession and secondary precession increases to create a new equilibrium at the increased rate of turn. On the other hand, if the rate of turn is decreased, the tilt angle falls due to reduced precession and secondary precession decreases to create a new equilibrium at the reduced rate of turn. When rate of turn is constant, then:-

Secondary Precession $\propto$ Angle of Deflection
$\propto$ Spring Torque
But Spring Torque $= k\theta$ (θ=Angle of Deflection)
Where, k, is the coefficient of spring tension.
Now Actual Precession $= T/I\omega$
$\therefore$ Secondary Precession $\propto T/I\omega$ (Where T=Spring Torque)
$\therefore$ Secondary Precession $= k\theta/I\omega$
But Secondary Precession = Rate of Turn
$\therefore$ $k\theta$ = Rate of Turn × $I\omega$ radian

33. This shows that the angle to which the gimbal tilts is proportional to the rate of turn about the measurement axis. Should the turn be about an axis that is not coincident with the measurement axis, then the detected rate of turn will deteriorate in proportion to Cos ϕ, where, ϕ, is the angle between measurement and rotation axes. Hence, when $\phi=0°$, Cos $\phi = 1$, and all of the rotation is detected.

ERRORS IN GYROSCOPES

34. Consideration of the gyroscope so far has assumed that all bearings are friction free and that it is simply necessary to wind the rotor up to speed in the correct frame of reference and leave it to do its job. This is true of the short term guided missile gyroscopes used in air defence weapons and the like, however, when the longer term devices used in ICBM's, survey work and other such systems are considered, a number of inherent problems, which cause misalignment of the spin axis, begin to increase in significance. Any erroneous change of data from a gyroscope is referred to as wander, it has a number of causes depending upon application and orientation.

GYROSCOPE WANDER

35. Movement between the spin axis and its frame of reference may be broken down into two main causes, 'real wander', which is actual misalignment of the spin axis due to mechanical defects in the gyroscope, and 'apparent wander', which is detected movement of the spin axis but this time due to movement of the reference frame in space rather than spin axis misalignment.

36. Wander in a gyro is termed 'Drift' or 'Topple' depending upon the axis about which it takes place. If the spin axis wanders in the azimuth plane it is called 'drift' and in the vertical plane it is called 'topple'. It will be recognised from previous work that azimuth gyroscopes tend to drift and vertical gyroscopes tend to topple. However, in either case, once wander is established, both drift and topple could be present at the same time. It should be noted that drift and topple could have components of both real or apparent wander.

REAL WANDER

37. The problems of friction in gimbal bearings and imperfect balancing of the rotor cause torques to be set up perpendicular to the rotor spin axis, this leads to precession and actual movement, or real wander, of the spin axis. Unfortunately, despite the fact that a large element of the resulting misalignment is predictable and could thus be 'tuned out', a certain amount always remains that will change in both direction and quantity for each new time the gyro is erected. This last component is known as 'random wander' and much of gyroscope design in recent years has been concentrated into reducing this random element to the minimum possible for a given application.

APPARENT WANDER

38. There are two main causes for apparent wander one due to rotation of the earth and the other due to movement over the earth's surface of the carrying vehicle, whether by land sea or air. If an observer, stationary on the earth's surface, is considered relative to his surroundings and space, it will be seen that the observer moves along a curved path in space as the earth rotates. Also, if it is possible to stop the earth rotating and then get the observer to move across its surface, once again the movement takes place along a curved path in space. Both cases are shown at Fig.8.

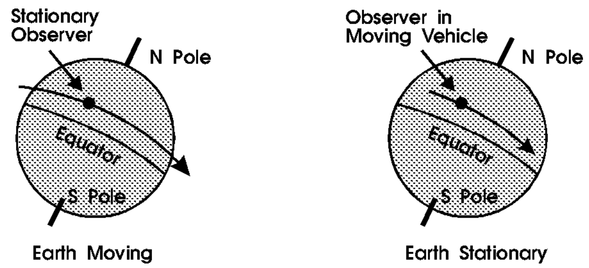


Fig.8. The Possibilities for Apparent Wander

39. When a land, sea or airborne vehicle is moved across the surface of the earth, both rotational components occur at one and the same time. It should be realised that in each of the cases no real or actual movement of the gyroscope spin axis occurs in space, however, movement of the frame of reference occurs which gives very similar effects. Hence, in gyroscopes used for long term purposes, such as inertial platforms and survey work, these errors must be calculated and allowed for by the system. In some cases it is possible to use the effects to properly erect the device in the first place.

THE RATE INTEGRATING GYROSCOPE

40. Modern gyro-based systems have become steadily more accurate as a result of acquiring more sensitive, lower wander rate gyroscopes. The gyros used in many cases are single degree of freedom types, possibly mounted in clusters of three, each sensitive about one of the three mutually perpendicular axes. Such a gyro is illustrated at Fig.9.

41. In these devices, the constraint normally offered by the springs in a rate gyro is applied by the use of a viscous liquid between inner gimbal and frame. Viscous liquids have the property of tending to prevent sliding motion between the two surfaces either side of them, the molecules being treacle-like, thus causing friction between the two surfaces The degree of

viscosity is dependent upon the temperature of the liquid, as with the oil in a motor car engine, thus, to achieve specified operating characteristics the gyros are often temperature stabilised using built-in heaters and an electronic control system.

42. The viscous liquid also has the effect of supporting the weight of the inner gimbal, leading to the term 'floated' being used in the gyro description. ie, Floated Rate Integrating Gyroscope. In this way bearing friction is reduced, leading to a reduction in the errors that could normally be expected from this source.

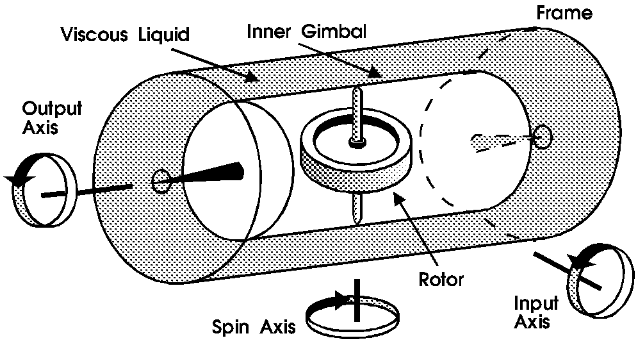


Fig.9. The Rate Integrating Gyroscope

OPERATION

43. Rotation of the frame about the input axis causes torque to be applied to the inner gimbal, and hence the rotor, via the output shaft spindles. This torque causes precession and rotation of the inner gimbal, according to Sperry's rule. As the gyro is precessing, friction between inner and outer containers, through the viscous liquid, causes restraint to be applied to the inner gimbal.

44. If the rate of rotation about the input axis is constant, the gimbal initially accelerates, under precession, to a rotation rate such that the viscous restraint equals the applied torque caused by this precession. The inner gimbal then rotates at a steady rate about the output axis that is proportional to the applied torque, and hence, the rate of input rotation.

45. The inner gimbal is connected, via the output axis shaft, to an electrical output device, such as a potentiometer or synchro. The instantaneous rate of change of the output signal is proportional to the rate of rotation about the input axis, thus, this rate of change can be extracted via a differentiating circuit. The total movement of the output shaft is proportional to the overall amount of rotation of the input shaft, called the 'time integral' of the input rotation, In more simple terms this means that a given total output can be obtained from either a long term low level rate of rotation, or a short term high level rate of rotation. Hence, the process of integration is implied.

46. Output axis rotation may be made equal to, less than, or greater than the input rotation by changing the viscosity of the liquid between inner gimbal and frame. By careful design the ratio between output and input movement may be of the order 10 to 1. This increase in gimbal sensitivity is usually called the 'gimbal gain' and accounts for the extreme accuracy of gyros used in such applications as meridian sensing and inertial navigation position determination. Overall accuracy is dependent upon the particular application, however, wander rates as low as 0.003° per hour are not uncommon.

REVISION QUESTIONS

Each question has a single correct answer. Check each answer carefully before making your selection.

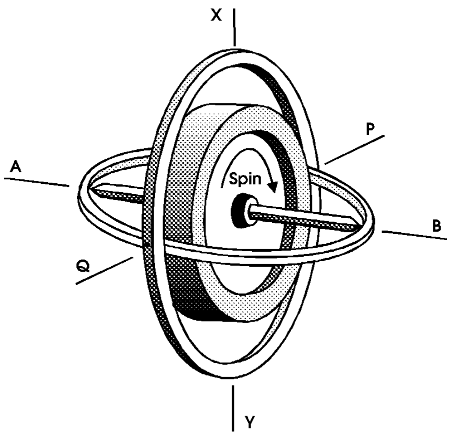
1. One of the properties of a gyroscope may be expressed by using the word PRECESSION. The meaning of this term is that:-

a. all of the components of a gyro follow each other in a specifically defined sequence
b. when the gyro rotor is subject to a torque perpen dicular to its spin axis, it will rotate about another axis
c. the gyro rotor remains aligned in space, however much the frame may be displaced
d. it has a single degree of freedom

2. The term DEGREE OF FREEDOM, when applied to a gyroscope, means that:-

a. the inner gimbal of a displacement gyroscope is free to rotate about the frame
b. the rotor is free to rotate about the inner gimbal
c. an axis exists about which rotation can be detected and measured
d. a specified clearance is required between the outer gimbal and the frame

3. A displacement gyroscope is rotating as illustrated below. A torque is applied to it in an anticlockwise direction when viewed from the 'Q' end of the P – Q axis. The resulting precession will be:-



a. clockwise when viewed from the 'Q' end of the P–Q axis
b. anticlockwise when viewed from the 'B' end of the A–B axis
c. clockwise when viewed from the 'Y' end of the X–Y axis
d. anticlockwise when viewed from the 'P' end of the P–Q axis

4. When considering the precession of a gyroscope rotor it is true to say that:-

a. rate of precession is inversely proportional to the applied torque
b. direction of precession is determined by direction of rotor spin
c. rate of precession is proportional to the angular velocity of the rotor
d. rotor mass distribution does not affect the rate of precession

5. A gyroscope is to be employed as the reference device for use with a SHORAD missile. The most likely choice of rotor drive mechanism is:-

a. AC electric motor
b. DC electric motor
c. gas discharge motor
d. none of the above

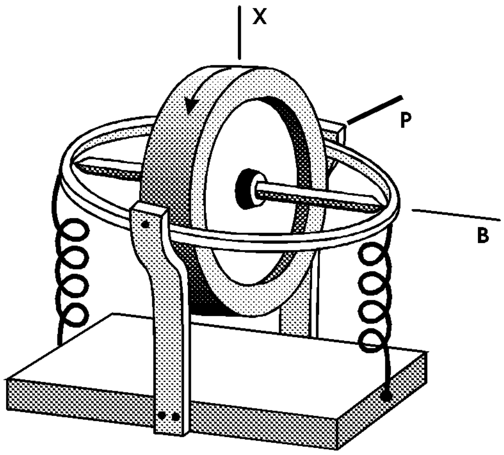
6. A vertical reference gyroscope is mounted so that its spin axis is:-

a. horizontal and it measures pitch and roll
b. vertical and it measures pitch and roll
c. horizontal and it measures azimuth displacement
d. vertical and it measures azimuth displacement

7. When considering a single axis gyroscope it is true to say that:-

a. the input axis, output axis and spin axis are all mutually perpendicular
b. the inner and outer gimbals are mounted perpen dicular to each other
c. it has two degrees of freedom
d. the range of precession is unlimited

8. In the gyroscope illustrated below, the:-



a. input axis is X and the output axis is P
b. frame is subject to secondary precession
c. X axis is normally mounted parallel to the axis about which measurements are to be taken
d. all of the above are true

9. Any gyroscope can suffer from errors due to a number of sources. One of them, called apparent wander, may be caused by:-

a. imbalances in the rotor
b. transportation of the gyro across the earth's surface
c. friction in the gimbal bearings
d. all of the sources above

10. In a rate integrating gyroscope:-

a. gimbal constraint is produced by springs
b. wander rates tend to be high
c. the inner gimbal floats in a viscous liquid
d. the rotor spin axis is in line with the output axis