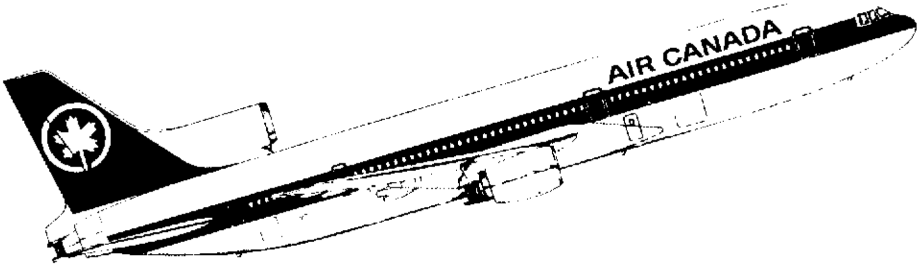
Inertial Navigation Systems

It took the human race over 900 years to progress from the primitive lodestone compass to a self-contained navigation system dubbed INS — the inertial navigation system. Here's a rundown on how it works.



Motion detection systems of incredible accuracy are used to display the position of aircraft, submarines, ships and missiles. The units compute the craft's speed by measuring acceleration, and its course by gyroscopic detection of deviation from a straight line. The instruments used are sensitive enough to be seriously affected by a speck of dust.

THE EARTH's rotation was discovered by Heraclides of Pontus in the 4th Century BC. During the next century, Erathosthenes of Cyrene calculated the circumference of the Earth to be approximately 38,500 km (24,000 miles), a figure undisputed for another 20 centuries.

Early writings suggest that the first lodestone compass was discovered by the Arabs or Chinese around 100 BC. The first reference to its use by Europeans is dated 1178. Also, the astrolabe was discovered about this period, the predecessor of the sextant, which was used to measure the angular elevation of stars and planets with respect to the horizon. This information was used in conjunction with elementary astronomical tables and time to plot a rudimentary navigational fix. Using this type of instrument, Columbus sailed to the New World.

The following inventions, together with Newton's Laws of gravitation, and Faraday's rules of electricity and magnetism, made INS a reality:

- an accurate marine chronometer (1766)
- the Foucault pendulum (1800)
- the marine gyro compass (1909).

The basics of INS

A basic inertial navigation system comprises the following subsystems:

- gyros
- accelerometers
- a computer.

A gyro is a device which, when spinning, points to a fixed position in space. To move the gyro from this position, pressure must be applied to the mounting frame (gimbals). If the gyro is moved up or down, it moves to the left or right. This action is called 'precession'.

An INS employs two gyro subsystems, one fitted in each horizontal plane or axis (X and Y). However, gyros are themselves subject to natural precession (errors) caused by the rotation of the earth (coriolis error) and the movement of the vehicle in which the gyro is fitted (attitude error). These errors are corrected by a servo or follow-up loop.

An accelerometer is an instrument which measures lateral movement and converts it to an electrical signal. To reduce errors in the accelerometers they are usually mounted to the gyro assembly. The electrical outputs from the instruments are converted to a suitable form and applied to the associated computer. Usually three accelerometers are fitted in a system, one in each axis (X,Y and Z).

The computer associated with an INS provides the following functions:

- coriolis correction
- latitude information
- attitude correction
- longitude information
- altitude or depth information
- distance travelled
- vehicle speed
- true or magnetic course data
- Earth's radius.

However, other systems are used in conjunction with INS to provide all the stated functions.

The computer runs an operational program automatically at a system switch-on, or manually via the associated control unit. The program employs algorithms to solve various forms of mathematical equations, using detected variable and fixed quantities generated within the system or externally. These include distance travelled, vehicle acceleration, and the Earth's radius and rotational rate.

Although a self-contained system, its accuracy deteriorates with running time. This requires some form of external positional updating every 24 hours. Radio navigation aids are normally used for this purpose. These includ Omega, Decca, LORAN and distance measuring equipment (DME).

A basic inertial navigation system is shown in Figure 1 and operates as follows.

The accelerometer output (1) is integrated to a velocity function (2). A second integral produces distance travelled (3). This is added to initial position (4) and updates the present latitude (7). Present latitude is processed to provide Earth-rate torque (8). The velocity function (5) is processed to give transport torque rate (6). This and Earth-rate torque are added to generate gyro correction (9).

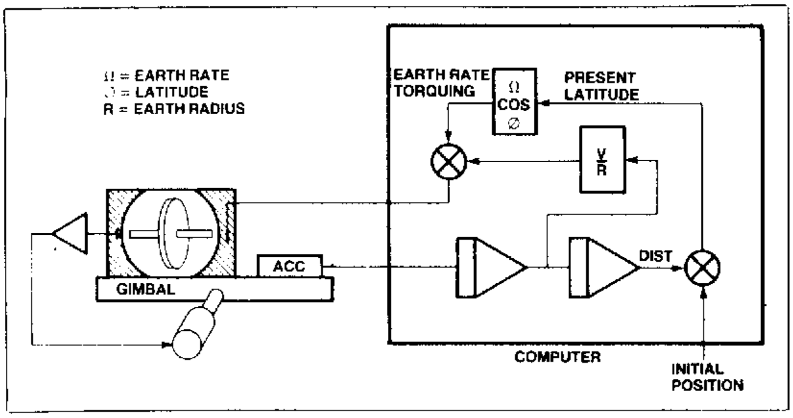


Fig. 1 Basic INS diagram.

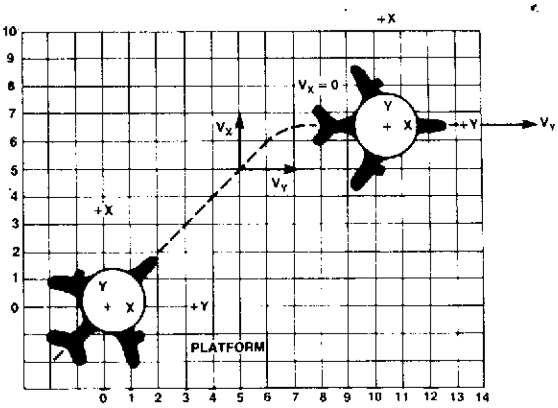


Fig. 2 Two-axis navigation grid.

This quantity causes the gyro rotor (10) to tilt with respect to the case and generate an output signal (11), which in turn is amplified to drive the gimbal motor (12). The gimbal motor moves the gimbal (13) in proportion to the Earth-rate and transport-rate terms, providing platform corrections.

Inertial navigation systems are fitted to military and commercial aircraft, surface ships of all types, submarines, hovercraft and space vehicles. To cater for this variety of system applications, the basic differences between types are as follows:

- a shipborne system requires precision gyro assemblies but less accurate accelerometers.
- an airborne system requires precision gyros and accelerometers.
- a missile-installed system requires less accurate gyros but precision accelerometers.

System description

An inertial navigation system can be divided into the following sections for the purposes of description:

- simplified INS operation
- accelerometers
- gyros
- types of gyro
- platform stabilisation
- platform corrections
- system alignment
- system computer.

Simplified INS operation

The objective of all forms of navigation is to guide a vehicle from one point to another, relative to a reference system. Figure 2 shows a grid reference system upon which the course of an aircraft has been placed, and provides vector representation of the movement of the X and Y-axis accelerometers.

Figure 3 illustrates a simple form of computer capable of resolving equations relating to vehicle displacement. Figure 4 presents a graphical indication of acceleration input and displacement output.

Accelerometers

A basic accelerometer, shown in Figure 5, comprises a precision-machine slug, or 'proof mass', which slides in a frictionless tube when lateral movement is detected. The slug is retained in the 'null' or zero position by springs. the magnitude of slug movement is a measure of acceleration, which is converted to an electrical signal by a 'pickoff unit'.

An alternative type of accelerometer, which operates on the pendulum principle, is detailed in Figure 6. This device provides displacement data in angular rather than linear form.

The relative movement of the mass in most accelerometers is restrained and therefore small, so small that it can only be detected by electrical measurement (via the pickoff). The pickoffs comprise a pair of primary coils, mounted to the instrument case. A secondary coil attached to the mass, sits between the primary coils in the null position.

An excitation supply, applied to the primary and secondary coils, is arranged to provide zero output at the null. Under acceleration, the secondary coil moves towards one or the other primary coils and changes the phase and voltage output. The phase relationship between primary and secondary coils determines the sense of the acceleration (plus or minus) while the amplitude is proportional to acceleration magnitude.

In a typical application, the accelerometer output is amplified and used to drive a phase sensitive demodulator. The dc output signal is used to reset the mass to null, while

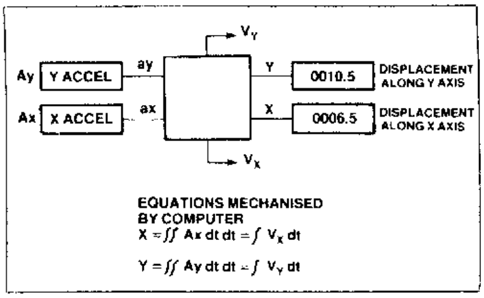


Fig. 3 Simple INS computer.

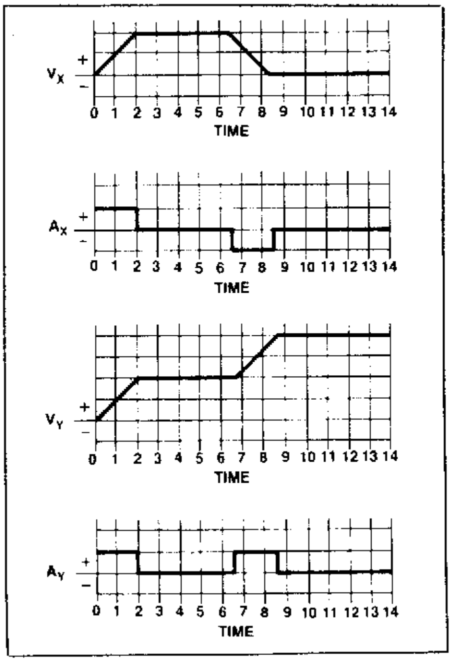


Fig. 4 Acceleration input and displacement output.

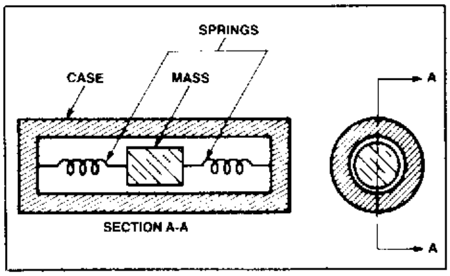


Fig. 5 General arrangement of a slug-type accelerometer.

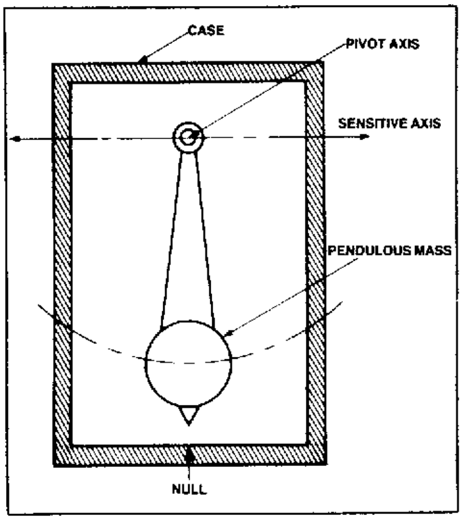


Fig. 6 General details of a pendulum-type accelerometer.

generating a sense and magnitude input signal to the system computer.

This action is called torque rebalancing, which instead of measuring mass displacement, measures the current required to return the mass to the null position. A torque rebalancing arrangement is shown in Figure 7.

Both types of accelerometer exhibit natural oscillatory characteristics, which are neutralised by immersion in damping fluid, carefully matched to the density of the mass to achieve neutral buoyancy. Other mechanical components reduce vibration and component instability to provide accuracies down to 10^{-6}g.

The latest types of accelerometer employ ceramic discs and capacitive pickoffs incorporated in a bridge circuit to detect acceleration displacement, the amount of electrical imbalance indicating the magnitude of the sensed acceleration. This signal is then used to operate a coil, called a force motor, to reset the ceramic discs. The reset current required by the force motor, or 'torquer', provides a computer input in a similar manner to the inductive type of accelerometer. However, the capacitive device uses fewer components and is much smaller.

Gyros

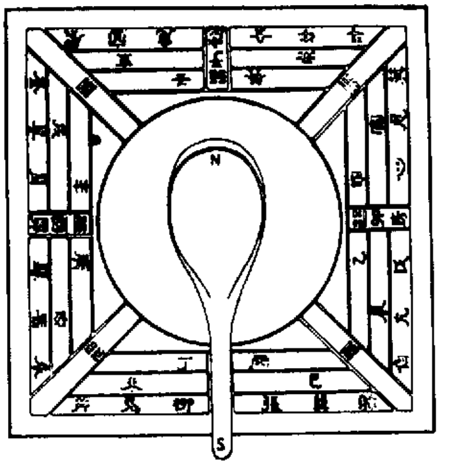
In 1750, a Swiss mathematician called Euler studied the behaviour of spinning rotors and documented his findings. A century later, a Frenchman, Foucault, constructed a device to demonstrate the Earth's rotation. He called it a gyroscope, from two Greek words — gyros (to turn) and skopios (to see or view). A German, Dr. Kaempfe, produced the first marine gyro compass, followed three years later by Elmer Sperry, who set the standard for gyro compass design until the introduction of INS in the 1950s. A modern gyro contains the following items:

- wheel assembly
- gyro motor
- spin bearings
- float elements
- signal pickoffs
- torque elements
- lead-in wires
- magnetic shields
- case.

The majority of the angular momentum of a spinning gyro is provided by the wheel assembly, which is a compromise of design factors. These include weight, rotation speed, diameter and construction material. Gyro wheels are usually manufactured of beryllium, to take advantage of its mechanical stability. However, titanium and stainless steel are used for some applications.

A gyro wheel is driven by a polyphase synchronous hysteresis motor, which is excited by a high frequency supply in order to achieve the required operating speed. The relative inefficiency of the motor is overcome by saturating the rotor to produce a virtual permanent magnet motor. However, the hysteresis motor has the ability to maintain, at synchronous speed, any load that it can accelerate from a dead stop.

The spin bearings are either long-life conventional ball bearing assemblies or gas-lubricated bearings. The latter eliminate metal-to-metal contact between surfaces once the device is operating. To achieve this state, the bearings run in a bath of gaseous lubricant, usually helium or hydrogen. This reduces wear to nil while the gyro is rotating, and provides an unlimited life expectancy, determined by the number of system stop-start cycles.



Primitive Chinese compass consisting of a magnetic spoon resting on a polished copper plate.

The gyro float elements provide support for the spin bearings, gyro wheel, torque elements, and pickoffs, as well as forming a sealed enclosure around the rotating components. Floatation comprises suspension of the gyro sensing elements in liquid, in a similar manner to the slug of an accelerometer. However, gimballed (two-axis stabilised) rotor assemblies do not require floatation and are called 'dry gyros'.

The signal pickoff units monitor the angular displacement of the rotating components with respect to the gyro case and produce an electrical output proportional to this displacement. The pickoff elements are either inductive or capacitive devices which are highly sensitive electrical transducers, excited by an

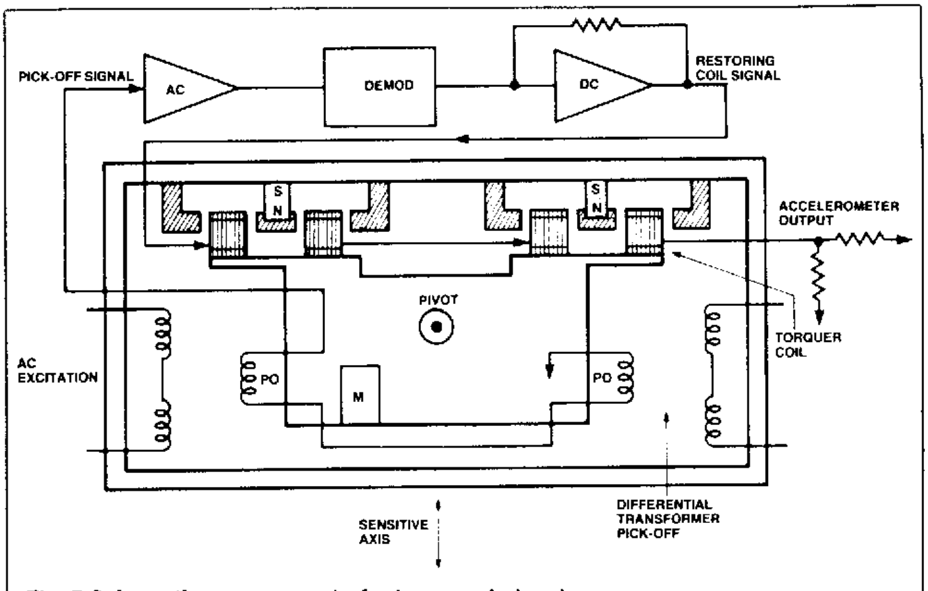


Fig. 7 Schematic arrangement of a torque rebalancing servo.

ac supply. Their characteristics ensure that they produce negligible heat and are capable of resolving the smallest increments of motion inherent in a gyro system.

The torque elements, which reposition the gyro assembly, are either synchro devices or dc force motors. These elements are manufactured to precision tolerances as they are required to produce high, variable precession velocities associated with components of Earth-rate varying with latitude.

The lead-in wires or ribbons connect the ac supply to the gyro motor, provide a signal path for the pickoffs, and apply input signals to the torquing elements. Mechanical errors produced by the lead-in wires are reduced by design.

Magnetic shields, which are made of steel alloys, are placed around the gyro assembly to reduce the effects of stray magnetic fields. These fields could produce unwanted torque on the moving parts.

The case provides a protective, gastight enclosure for the gyro assembly, and acts as a frame for the moving parts. The inside of the case is fitted with sensors which indicate the presence of moisture, high temperatures and excessive pressure.

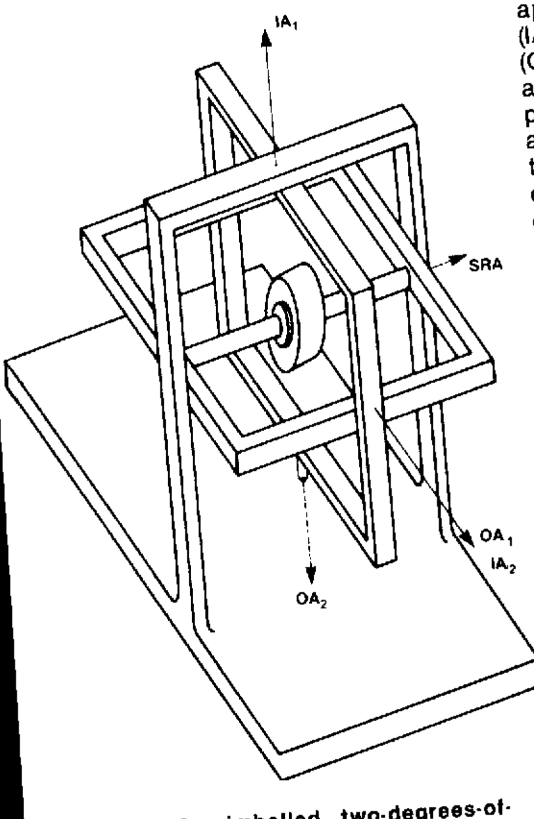
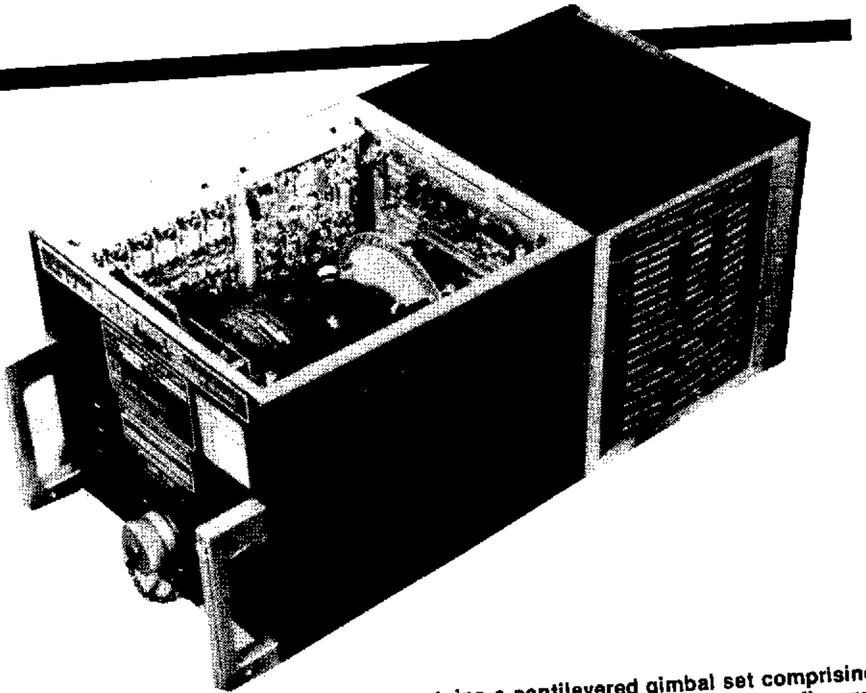


Fig. 8 A gimballed two-degrees-of-freedom (TDF) gyro.



A gimbal system, from Litton. This unit contains a cantilevered gimbal set comprising two non-floated, two-axis, precession-tuned rotor gyroscopes and three flexure-supported, non-floated, torque-to-balance accelerometers.

Types of Gyro

There are two main types of gyro used for INS applications, the single-degree-of-freedom (SDF) type and the two-degree-of-freedom (TDF) type. The TDF gyro can be either a floatation or a gimballed device; Figure 8 shows the latter.

The gimballed TDF gyro can accept two different input torques, 90° apart. The input axis for one torque (IA_1) is also the output for one pickoff (OA_2); the converse (IA_2 and OA_1) is also true. Therefore two TDF gyros provide four sensing axes, three (X, Y, and Z) of which can be controlled by two gyros. The redundant axis is caged or pegged in a closed loop servo condition.

By driving the rotor at the natural frequency of the support gimbals (tuned rotor) a rugged, unfloated gyro system is produced which has the following advantages over other gyro systems:

- reduction in components by 40%
- simplification of test and calibration procedures
- reduced manufacturing and repair costs
- improvement in reliability and mechanical performance
- increased system accuracy
- considerable reduction in size and weight.

An operational gyro of the tuned rotor type is shown in Figure 9. The rotor, which consists of a ring magnet encased in a soft iron return path fitted with a circumferential slot, is driven by a 400 Hz supply. The torquer (torque elements) comprises four coils, wound on a cylindrical former attached to the case. The coils in turn fit into a slot in the inertial ring where they can influence its magnetic field. The pickoffs are also magnetic devices consisting of differential transformers, which are influenced by the flux in the inertial ring. This method of pickoff can detect angular displacements in the order of 0.1 seconds of arc. To reduce non-magnetic, unwanted torques, the gyro operates in a low pressure hydrogen atmosphere.

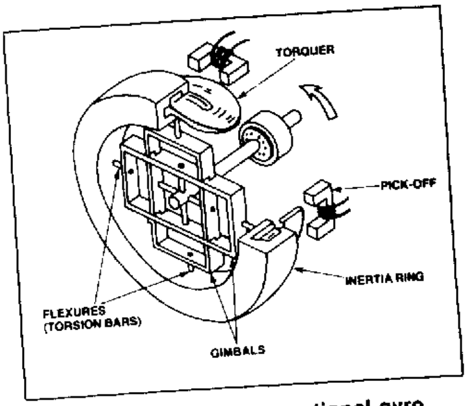


Fig. 9 A 'tuned rotor' operational gyro.

Platform Stabilisation

The gyros, accelerometers and associated equipment are known as the 'inertial platform' or 'platform' to distinguish them from the electronic, electrical and fixed components which form the rest of an INS installation.

The rotating gyro assembl possesses angular stability; the ac celerometers do not, and therefore must be stabilised. this is achieved by mounting the gyros and accelerometers to a common platform. As the gyro case is attached to the same assembly as the accelerometers, their angular movement reflects the displacement between the gyro case and the rotor. These changes in movement are detected and held to a tolerable level, which in turn stabilises the platform. The application of this technique is detailed in Figure 10; however, the circuit shown is for one axis (X) only.

As the signal detected by the pickoff varies, the demodulator provides a drive signal of the opposite polarity to the platform drive motor, which adjusts the platform attitude accordingly. Over-correction is prevented by secondary servo loops.

Stabilisation in three axes (X,Y and Z) requires two gyros and three accelerometers, one in each axis. However, the Z-axis is generally used to generate platform correction terms and in airborne systems to provide altitude information, whereas the X and Y axes are used to generate navigational information.

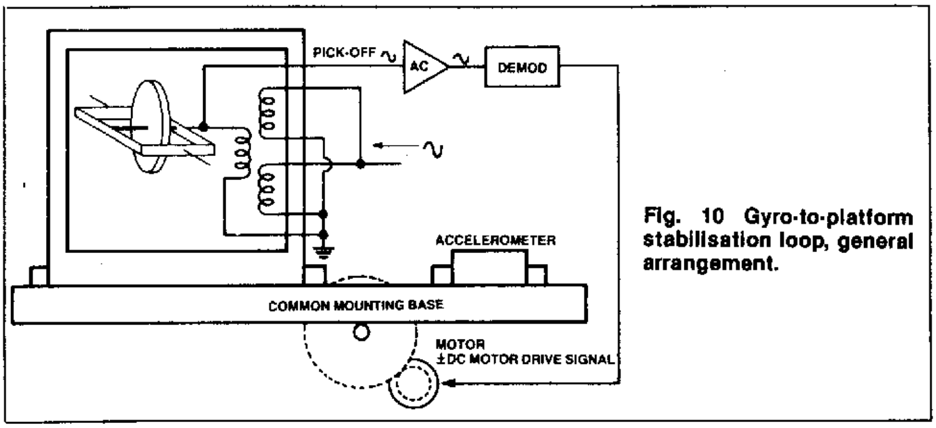


Fig. 10 Gyro-to-platform stabilisation loop, general arrangement.

Platform corrections

When used for terrestrial navigation, an INS is subject to two major forms of error, coriolis error and centripetal error. Coriolis error is due to the rotation of the Earth, which acts upon the gyros, and centripetal error is brought about when the platform moves over the surface of the Earth between poles.

Compensation for coriolis error is achieved by the application of the Earth's rotation rate (approximately 15 degrees of arc per hour at the equator) to the platform. However, the rate varies with respect to latitude angle and is produced from a resolution of vector, as shown in Figure 11. These vectors are calculated from the following equation:

$$\text{Horizontal vector} = \Omega \cos \varnothing$$
$$\text{Vertical vector} = \Omega \sin \varnothing$$

where omega ohm is full Earth rate (15 degrees) and phi is latitude angle.

Centripetal correction is only applied to the horizontal (X and Y) axes of the platform, as the vertical (Z) axis is insensitive to centripetal accelerations.

If the platform is held tangential to the curvature of the Earth, moves at a constant velocity, shares the Earth's centre of gravity, and moves over a great circle path (one whose axis passes through the centre of the earth), then the X and Y axes will sense the path of travel as a straight line and not require centripetal correction. However, any other path requires correction, which takes the form of a constant southward acceleration applied to the X and Y axis accelerometers. This correction is required, as the system, which is north-seeking, possesses an inherent northward drift when moving. The net result of the drift and correction is a zero velocity component applied to the accelerometers. The correction is generated within the system computer.

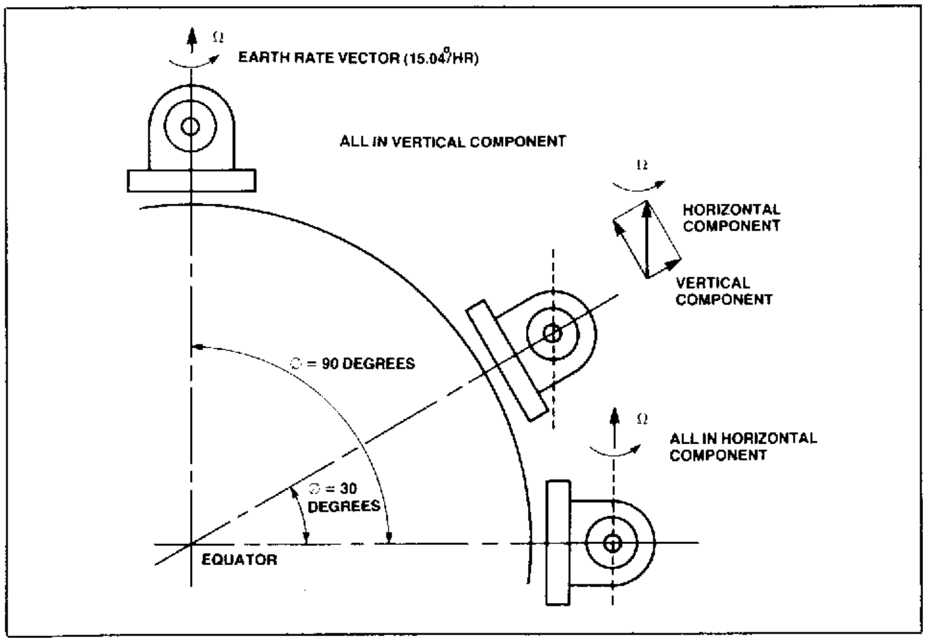


Fig. 11 Resolution of vectors in coriolis correction.

A servo system in conjunction with the system computer simulates the effect of the platform sharing the Earth's centre of gravity. This is called the Schuler pendulum effect, after the scientist who demonstrated the effect of Earth rotation.

To allow for radial accelerations in the Z-axis, the accelerometer is corrected for ground velocity over a curved surface given by the following equation:

$$\text{radial acceleration} = \frac{\text{velocity}^2 \times \text{gravity}}{\text{Earth's radius}}$$

The necessary functions are generated within the system computer.

System alignment

The operation of an inertial navigation system uses the mathematical integration of acceleration to obtain velocity and positional information. To implement any integration process, an accurate initial reference must be established, in this case velocity and position. The establishment of these references is called system alignment.

The alignment procedures entail the matching of platform and computer axes to external or interna known references. External references can be terrestrial, celestial or inertial. Terrestrial reference systems employ surveyed lines, benchmarks, plumb-bobs and bubble gauges. These devices can provide level accuracies in the order of ten seconds of arc and heading accuracies to three minutes of arc.

Celestial reference systems obtain information from star trackers and radio sextants. Accuracies are similar to those for terrestrial devices.

Inertial references comprise some form of portable inertial platform. However, accuracies are only as good as the last equipment calibration, which could have been months previous to their use.

An external reference system uses some form of interface unit to connect to the INS under test. These interfaces take the form of optical couplers, synchro devices, electrical transducers, digital-to-analogue or analogue-to-digital converters, or some form of logic conversion circuit.

Internal or self-alignment systems use the sensors on the platform to sense the physical deviation from a fixed position to align the platform using its servo systems.

To determine the orientation of a three-axis, right-angled co-ordinate system (INS), at least two reference vectors are required. The Earth's spin and gravitational vectors are used for this purpose when implementating a self-alignment procedure. Using these vectors reduces computer requirements because the accelerometer outputs do not require resolution into gravity and vehicle acceleration components. Also, as the accelerometers and gyros share the same platform, their relative positions do not require computing.

A self-alignment is divided into three inter-related modes. The first is coarse alignment, or caging, followed by fine alignment, or levelling, culminating in an operation called gyro-compassing.

Coarse alignment involves slaving the gyro gimbals to their own servo output signals, or to some external source possessing a particular orientation with respect to the vehicle in which the platform is fitted. The caging sequence is automatically implementated by a timing circuit and lasts for about 30 seconds after system switch-on.

Fine alignment, together with gyro-compasssing circuit configuration, is shown in Figure 12. The top feedback loop identifies levelling. This involves setting the pendulums of each accelerometer to the null position, each pendulum at 90° with respect to the other two. This is implemented by connecting the X-axis accelerometer output, via a function generator (G), to the Y-axis gyro and vice-versa. When the errors between the X and Y axes are zero, the Z or gravity axis is automatically in alignment. This provides one of the unknown vectors; gyro-compassing provides the other.

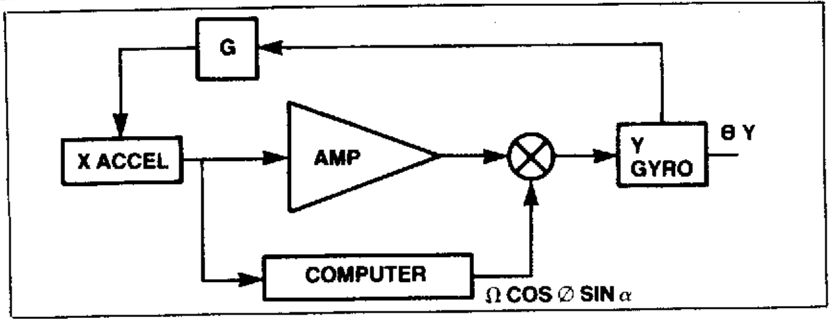


Fig. 12 System alignment servo loops.

The bottom feedback loop in Figure 12 identifies the gyro-compassing circuit configuration. If left uncorrected, the platform Y-axis gyro would tilt under the influence of the Earth's spin vector. The angle of tilt is called the 'wander angle' or alph (x). The system computer produces a set of acceleration corrections to the Y-axis gyro for a range of values for alpha, using a modification of the coriolis correction information detailed in Figure 11. The acceleration correction is given by the following equation:

$$\text{acceleration correction} = \cos \emptyset \sin\alpha$$

When the output of the X-axis accelerometer is zero, the platform has been aligned in the present position and no further system alignment is required. The Y-axis gyro and X-axis accelerometer are then connected in their normal operational configurations (X-axis accelerometer with X-axis gyro).

System computer

The system computer consists of a standard type of digital computer using microprocessor chips for control and computation purposes. The majority of program and mathematical information is held in EPROM memories. Access to the computer control circuits is via an operator-orientated keyboard. A set of digital readout units provides navigational and other data.