5 Inertial Navigation Systems (INS)

5.1 Principles and Practical Application

5.1.1 Introduction

Purpose and Application

The purpose of an aircraft inertial navigation system (INS) is to provide accurate worldwide navigation information independent of external aids; the system neither transmits nor receives any signals.

After being supplied with latitude and longitude of the ramp position prior to departure, INS is capable of continuously updating extremely accurate displays of: position, ground speed, attitude and heading. In addition, it may provide guidance or steering information for the autopilot and flight instruments.

Components

The four basic components of an INS unit are *(see fig. IN 5.1)*:

- A stable platform oriented to maintain the accelerometers horizontal to the Earth and to provide azimuth orientation
- The accelerometers arranged on the stable platform to supply specific components of acceleration
- The integrators to receive the output from the accelerometers and to furnish velocity and distance
- A computer to receive the signals from the integrators and to change to distance travelled into latitude and longitude

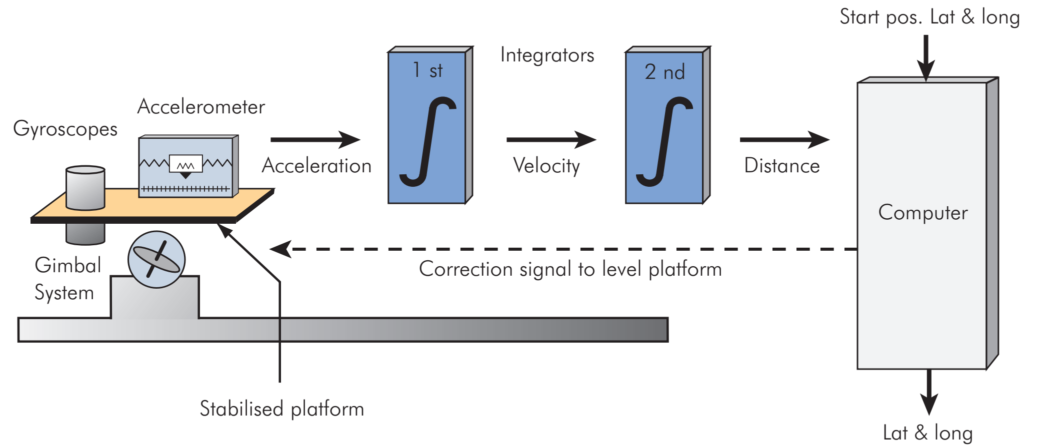

Fig. IN 5.1 Components of simple INS

An additional component, not directly part of the INS system but complimentary to it and necessary for all aircraft, is the navigation computer and display unit.

Most aircraft now fly using triplicate components for safety and reliability. A common aircraft fit would include:

- 3 INS systems
- 3 INS control units, and
- A navigation computer and display.

5.1.2 Accelerometers

Introduction

The basic principles upon which the accelerometers operate are related to Newtons laws regarding motion.
They are:

- A body will continue in a state of rest or maintain a straight line of movement unless compelled to change that state by a force acting upon it
- The acceleration of a body is directly proportional to the applied force causing the change, and takes place in the direction of the applied force
- To every force, there is an equal and opposite reaction

An accelerometer is an essential part of all inertial systems. There are many varieties of this instrument, but they all work on the same basic principle. They can detect accelerations to a thousandth of a G-force, far more sensitive than the human body can detect. In its simplest form, an accelerometer consists of a small weight suspended between two springs, with an electrical pick-off which converts the compression of one of the supporting springs into an output signal *(fig IN. 5.2)*.

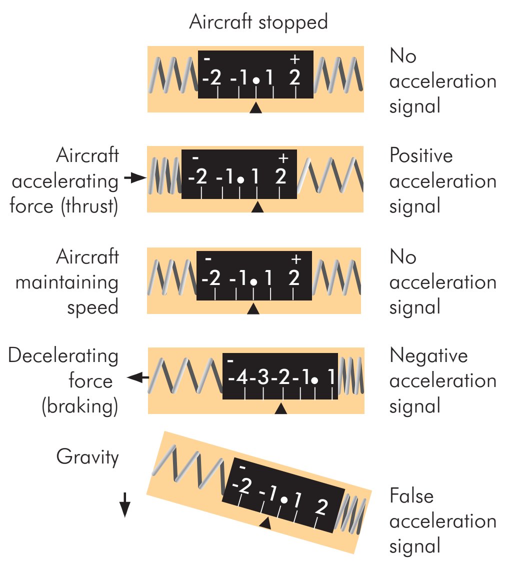

Fig. IN 5.2 Simple spring accelerometer

The accelerometer cannot calculate velocity or distance itself, it quite simply registers the spring displacement, which is directly proportional to the accelerating or decelerating forces. Velocity and distance are computed from sensed acceleration by the application of basic mathematical formulas of integration.

In an inertial navigation system, two or three accelerometers are used. One will measure the aircraft's accelerations in the North-South directions, another will measure the aircraft's accelerations in the East-West directions. The third accelerometer, if fitted, will measure vertical displacement, but is not part of the system described below. A North/South and East/West - orientation of the accelerometers is most common, but note that for polar navigation, another reference might be used.

Pendulum Accelerometer

Accelerometers can, as mentioned earlier, be of various types, but the most common is the pendulum linked to a force feed-back system.

Fig. IN 5.3 shows that the pivot arrangement allows movement in one axis only i.e. north/ south or East/West but not both. It also shows that the greater the acceleration along the swing axis, the more the pendulum will lag behind the pivot and therefore swing from the vertical. This movement is then sensed as a disturbance to the equilibrium of the E and I bar. The E bar is fixed to the stable platform with the legs pointing up, and the I-bar is fixed to the bottom of the pendulum, horizontally above it.

Movement of the pendulum will take the I-bar out of the horizontal which disturbs the relative position of the E and I bar and thus generates an error signal. This signal is fed to the INS computer which will feed a current to the feed-back coils to pull the pendulum back to the vertical and regain the relative position between the E and I bar. This is known as a "Force Re-balance System" or a "Force feedback" system.

The actual strength of the feedback current required to pull the pendulum back to the vertical is directly proportional to the acceleration and is used by the computer to measure the acceleration along its swing axis.

The system's extreme sensitivity enables it to detect even the smallest change of acceleration. To maintain the required accuracy, alignment is critical to the

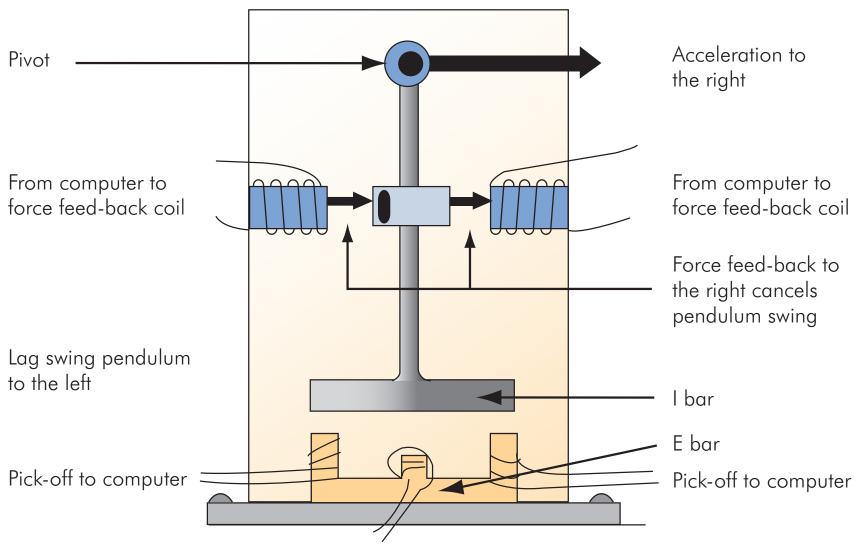

Fig. IN 5.3 Pendulum accelerometer

sensed direction of the acceleration. If the platform is misaligned and accelerated in a North/South direction, the north sensitive accelerometer will not detect the full acceleration and the east accelerometer will detect an unwanted component.

5.1.3 Integrators

Integration is a function that can be viewed as a multiplication by time. For example, a vehicle accelerating at three ft per second squared would be travelling at a velocity of 30 ft per second after 10 seconds have passed. Note that acceleration was simply multiplied by time to get a velocity.

The microprocessor also integrates the calculated velocity to determine position. For example, a vehicle travelling at a velocity of 30 ft per second for 10 seconds will have changed position by 300 ft. Velocity was simply multiplied by time to determine the position.

All an integrator does is to produce an output which is the mathematical integral of the input, or in other words, the input signal multiplied by the time it was present.

There are, as mentioned above, two stages of integration: first and second stage. There are 4 integrators in all per system: 2 to the North/South channel and 2 to the East/West channel. The first stage integrator takes an input voltage proportional to acceleration (i.e. ft per second squared) from an accelerometer and integrates it, thus producing an output voltage proportional to velocity, North/South or East/West (ft per second). In *fig. IN 5.4* the velocity is North.

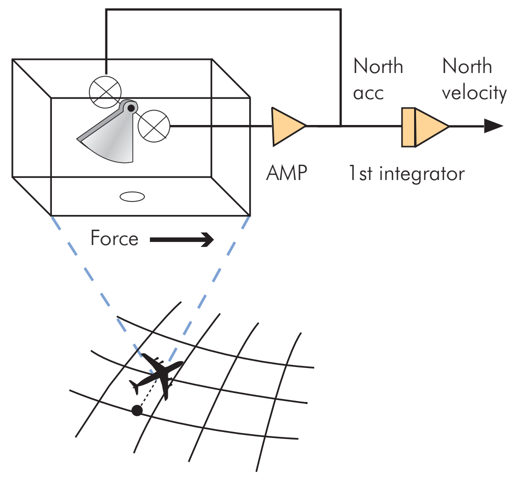

Fig. IN 5.4 1st integrator

The signal is then sent through a second integrator and again it is a time multiplier *(fig. IN 5.5).* With an output of ft per second, which is multiplied by time, the result is a distance in ft or miles, in this example 221 miles.

The computer associated with the Inertial System knows the latitude and the longitude of the takeoff position and calculates that the aircraft has travelled so far in a North – South direction and so far in an East – West direction. It now becomes simple for a digital computer to continuously compute the new present position of the aircraft.

The integration process is completed several hundred times a second, and will thus give a nearly continuous information on distance travelled in the direction the particular accelerometer is aligned with.

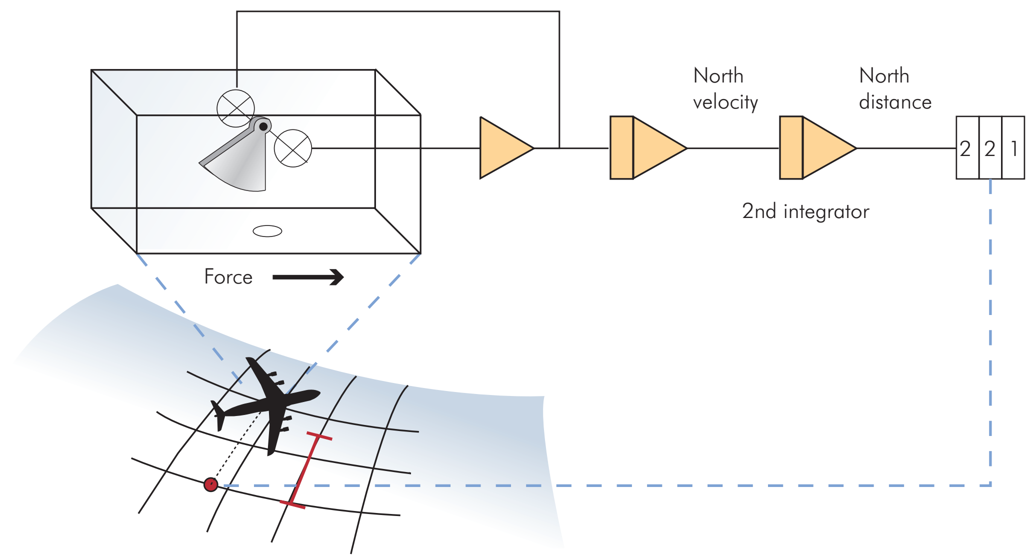

Fig. IN 5.5 2nd integrator

5.1.4 The Platform

The platform provides the mounting for the accelerometers and gyroscopes. In order that accelerometers can measure accelerations along two independent axes, namely North/South and East/West, the platform must be kept level and aligned by a gimbal system. The function of the platform is to maintain the accelerometers level and aligned to the Earth's North/South and East/West axes.

5.1.5 Gimbal System

A three gimbal system is normally used, each gimbal having a pick-off and a gimbal torquer. Pick-offs are used to provide pitch, roll, and heading information to the main flight instruments. Gimbal torquers are follow-up motors used to drive the gimbal to maintain the platform level and aligned to north in the presence of aircraft manoeuvres:

- The pitch torquer is fixed to the pitch gimbal and the roll gimbal
- The roll torquer is fixed to the pitch gimbal and the aircraft
- The azimuth torquer is fixed to the pitch gimbal and the platform.

The torque motors signalled by the levelling and azimuth gyroscopes automatically control the gimbals. If the aircraft rolls, the roll is instantly passed to the platform through the gimbals. The levelling gyros will be caused to precess, producing output voltages which are passed to the roll torquer motor which drives the roll gimbal, returning the platform to its start position in the horizontal. In practice the platform remains level, driven by the gimbals and torquer motors. The angle the roll gimbal has been moved to keep the platform level is termed roll angle. This is sensed by the pick-off and is passed to the relevant instrument displaying roll angle.

5.1.6 Gyroscopes

There are two levelling gyroscopes: one set up sensitive to rotations about the North/South axis; the other about the East/West axis. The third gyro, or azimuth gyro, is sensitive to rotations around the vertical axis. All platform gyros are rate integrating gyros and if turned around their sensitive axes will precess producing an output voltage from electrical pick-offs.

The levelling gyros are usually vertical gyros while the azimuth gyro is a horizontal gyro.

The rate integrating gyroscope is a gyro mounted inside two concentric cans. The inner can forms a gimbal by rotating within an outer can. The outer can is fixed to the INS platform. It can be seen from the *fig. IN 5.6* that the gyro's sensitive axis is at right angles to both the output and spin axis.

The outer can is filled with a viscous fluid, which produces a resistance, or damping to stop the inner can from toppling. If the gyro is rotated about its sensitive axis Z a torque/force will be applied to the spin axis producing a precession about its output axis Y. The rotation about Y will continue until the viscous restraint of the oil equals the precessional torque.

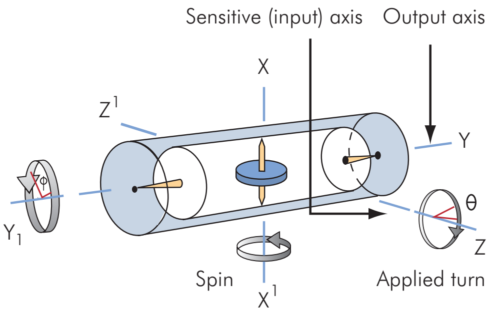

Fig. IN 5.6 Levelling gyroscope

The gimbal or gyro precession around the output axis is thus proportional to the rate of rotation producing it. The pick-off measures this precession and passes a voltage proportional to the precession to the relevant gimbal torquer, which drives the gimbals to keep the platform level and aligned. In addition each gyroscope has a gyro torquer which is used to apply forces to the output axis to correct for apparent drift and topple.

INS - Principle of Operation

Accelerometers on the INS platform measure vehicle accelerations in the North/South and East/West planes. The acceleration information are then integrated twice in a computer, and compared with a timing signal to produce distance gone in two channels - North/South and East/West. The platform is kept level and aligned to true north by a gimbal system stabilised by gyroscopes, and a platform control unit. The relative position of the aircraft axes and the INS platform axes provides information on aircraft pitch, roll and heading.

Measurement Axes

Acceleration must be measured along two axes, usually orthogonal, if vehicle velocity and displacement are to be defined in a given plane. Since most accelerometers are designed to measure acceleration along one axis only, two accelerometers are required for inertial navigation in a two dimensional plane. In aircraft systems the accelerometers are usually mounted with their input axes aligned with north and east, and this alignment must be maintained if the correct accelerations are to be measured. Moreover, the sensitive axes must be kept perpendicular to the gravity vertical, otherwise, the accelerometers sense part of the gravity acceleration *(fig. IN 5.7)*. The reference frame defined by these directions, i.e. local North, local East, and local Vertical, is called the Local Vertical Reference Frame. Other reference frames can be used, but the local vertical is the fundamental mechanisation used.

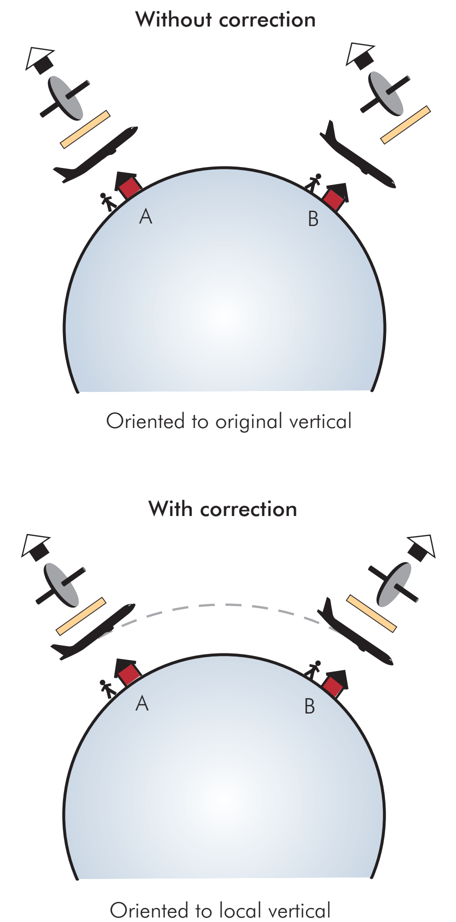

Fig. IN 5.7 Local vertical

Gyro Stabilisation

Once the accelerometers have been aligned in the chosen reference frame, they must be capable of maintaining that orientation during aircraft manoeuvres. The accelerometers are therefore mounted on a platform, which is suspended in a gimbal system that isolates the accelerometers from aircraft manoeuvres *see fig. IN 5.8)*.

However, this platform is not inherently stable, and any tendency for the platform to rotate with the aircraft must be detected and opposed. Gyros are therefore mounted on the platform to detect platform rotation and control platform attitude. Three single degree of freedom gyros are normally used; one gyro detects rotation about the North axis, another rotation about East, and the third rotation about the vertical.

The platform rotations detected by the gyros are used to generate error signals, proportional to change in platform attitude, which are used to motor the platform back to its correct orientation.

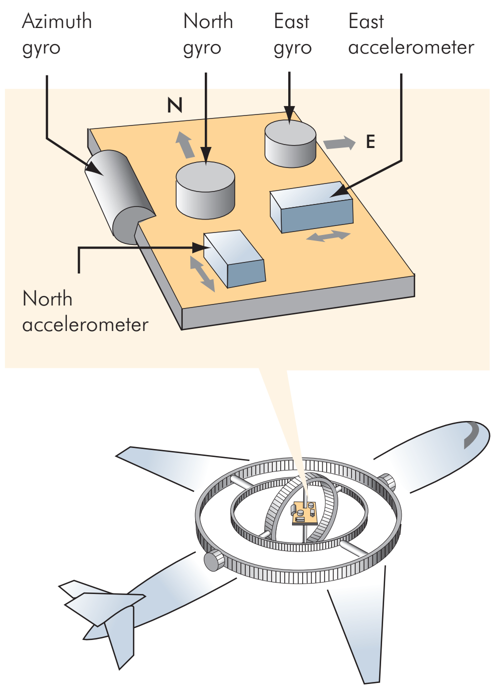

Fig. IN 5.8 Simplified INS platform

Effect of Earth Rotation and Vehicle Movement

An INS operating in the local vertical reference frame must maintain its alignment relative to Earth directions. The gyros used to stabilise the platform are rigid in space and must therefore be corrected for Earth rate and transport wander to make them "Earth stable". Additionally, the accelerometers must be corrected for the effects of Coriolis and the centripetal acceleration caused by rotating the platform to maintain alignment with the local vertical reference frame.

Platform Control

The platform control unit computes and applies the gyro and accelerometer correction terms from calculated values of ground speed and latitude and stored values of Earth radius and Earth rotation rate, *see fig. IN 5.9.*

Output

The outputs of the INS system are distance gone North/South (Change in latitude) & East/West (Change in longitude from departure formula), pitch, roll, and true heading. The INS and navigation computer combine to give outputs of distance gone, groundspeed, drift, and track.

5.1.7 Platform Control

The platform must remain level and aligned to true North in the presence of Earth rotation and aircraft movement. These movements must be corrected in order that the accelerometers will only measure accelerations N/S and E/W, and the following terms for drift and topple must be made ***(see table IN 5.1).***

It is the function of the platform control to calculate these corrections and pass them as correcting currents to the relevant gyro torquers. The torquers produce forces on the gyro spin axes causing correcting precessions. Correction voltages are also passed by the platform control to correct or bias the output voltages of the accelerometers to correct for Coriolis and centripetal acceleration errors.

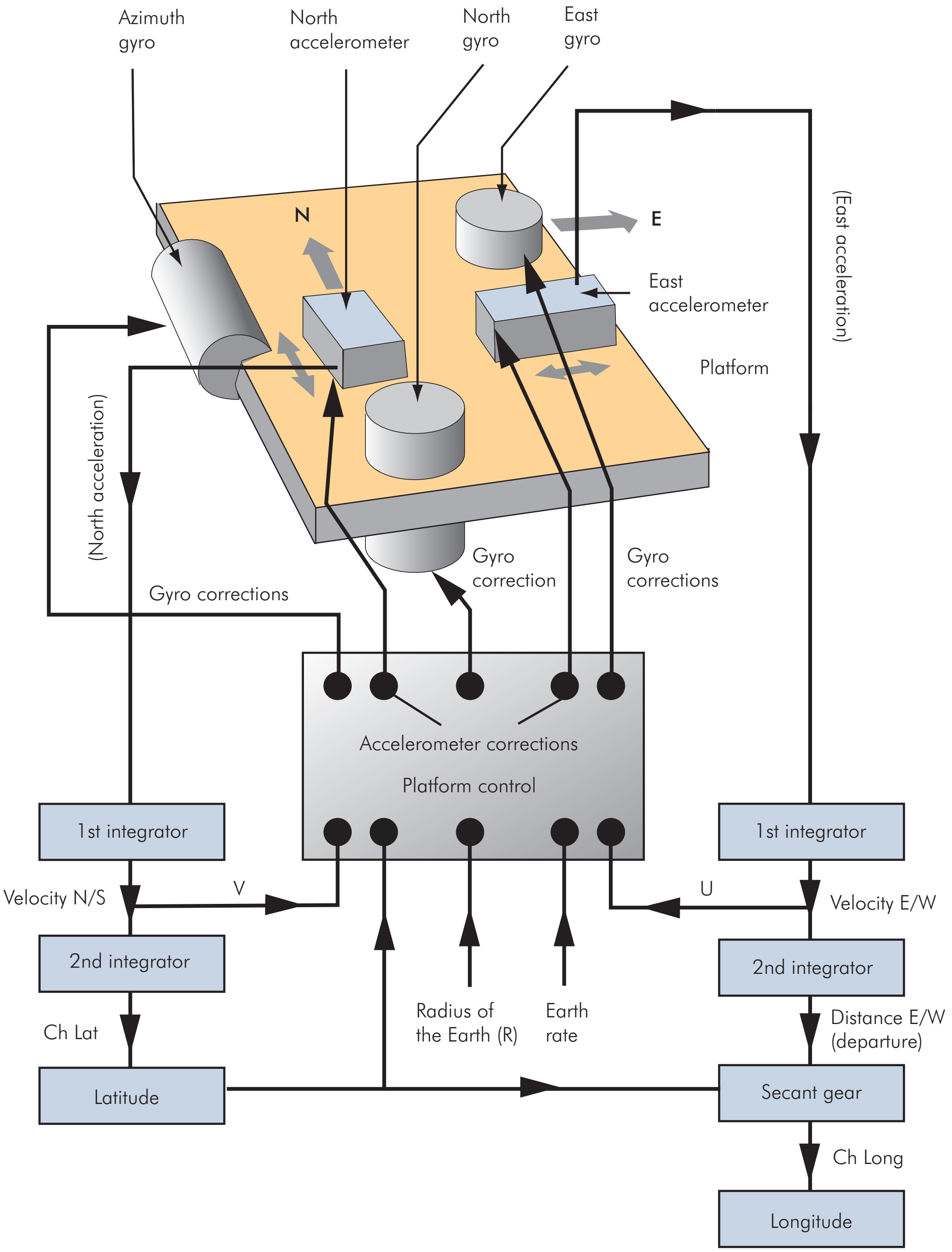

Fig. IN 5.9 Simple inertial navigation system

Component	Correction for	Correction value
E/W levelling gyro	Apparent topple around E/W axis	$-\frac{V}{R}$
N/S levelling gyro	Apparent topple around N/S axis	$\Omega \cos \lambda + \frac{U}{R}$
Azimuth gyro	Apparent drift in azimuth	$\Omega \sin \lambda + \frac{U \tan \lambda}{R}$
E/W accelerometer	Coriolis and centripetal accelerations	$2\Omega V \sin \lambda + \frac{UV \tan \lambda}{R}$
N/S accelerometer	Coriolis and centripetal accelerations	$2\Omega V \sin \lambda + \frac{U2 \tan \lambda}{R}$

Table IN 5.1

Platform Operation

A typical platform mounting in the aircraft is shown in *fig. IN 5.10.* Gyroscopes and accelerometers are corrected for drift and topple by the platform control unit, but are not shown.

If the aircraft is flying north as shown, any pitch manoeuvre will cause the gimbals to pitch the platform. The pitch rotation will be sensed by the East/West levelling gyro. It will precess and pass an output signal to the pitch torque motor to level the platform. Flying north, the East/West gyro signals the pitch torque motor.

Consider flying east as shown in *fig. IN 5.11.* Pitch manoeuvres this time will be sensed by the N/S levelling gyro. To correct for pitch manoeuvres when flying east the North/South gyro signals the pitch torquer motor. In both cases the pitch torque motor drives the platform in the presence of pitch changes to re-level the platform, but is signalled by either the North/South or East/West levelling gyro, *see table IN 5.2.*

Pitch and Roll Correction

Pitch and roll aircraft manoeuvres passed to the platform are corrected by the pitch and roll gimbal torque motors. However, the detection of pitch and roll manoeuvres

Heading	Manoeuvre	Sensing gyro	Correcting gyro
North/south	Yaw	Azimuth	Azimuth
	Pitch	East	Pitch
	Roll	North	Roll
East/west	Yaw	Azimuth	Azimuth
	Pitch	North	Pitch
	Roll	East	Roll

Table IN 5.2

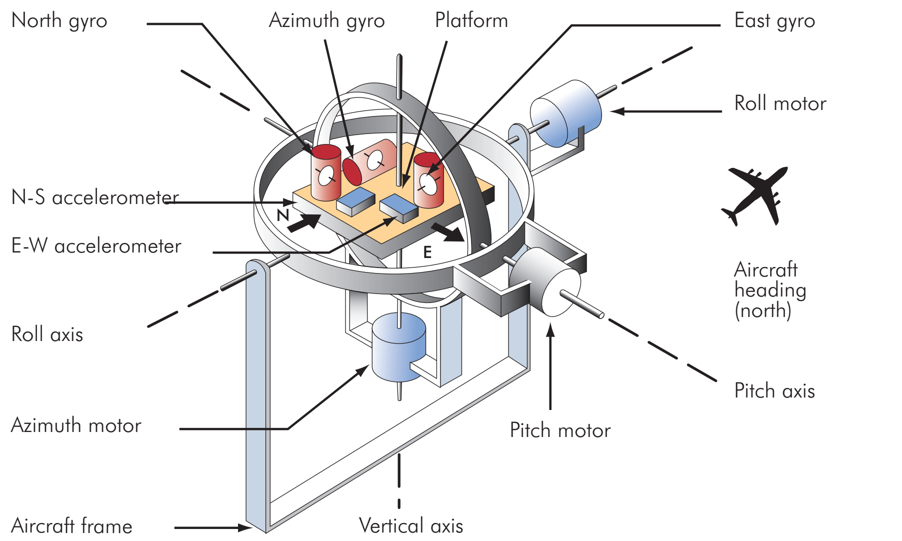

Fig. IN 5.10 Platform arrangement-aircraft heading north

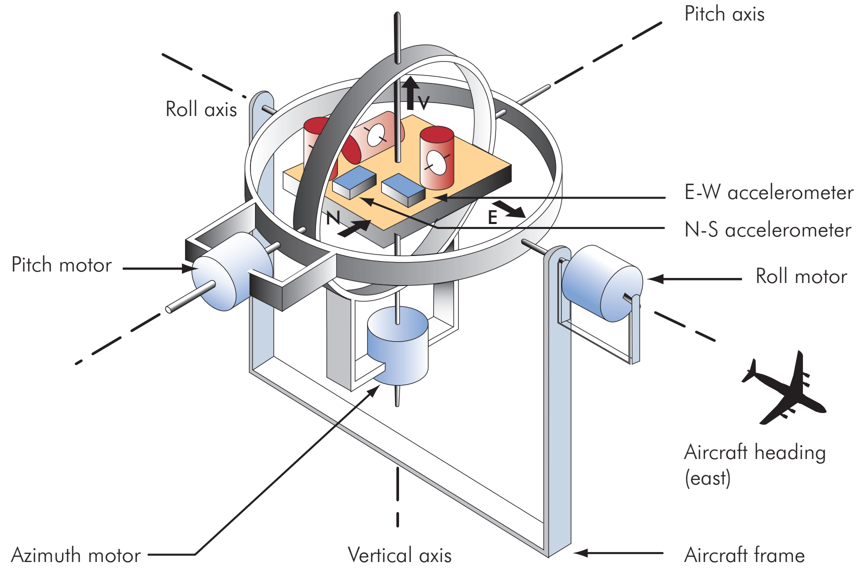

Fig. IN 5.11 Platform arrangement - aircraft heading east