1

Advanced Flying Systems

1.1 Introduction General

Modern civil transport aircraft are increasingly fitted with advanced flying control systems which are designed to allow a variety of automatic functions to be carried out in flight and during the landing sequence. Such systems incorporate the use of computers and various other types of electronic devices. Such devices also include the use of advanced instrumentation in what has become known as the 'Glass Cockpit' concept.

In order to understand the operation of such systems, included in this part are chapters explaining such items as Semi-conductors, Logic Circuits, EFIS, EICAS, ECAM, the Automatic Flight Systems, Auto-Land and a variety of items included within such systems.

Chapter One gives an overall general explanation of the basic concepts of automatic flight systems.

It is essential that this part should be read with a good understanding of the Principles of Flight and also in conjunction with the 'Electrics' section of this *The Commercial Pilots Study Manual Series*.

It must be noted that systems do vary from aircraft type to type. The systems within this section are of a general nature and are designed to assist the student in his or her studies for CPL and ATPL levels.

1.2 Automatic Flight and Landing

Introduction

For long periods of flight using manual operation of the flying controls the pilot would become very tired, both physically and mentally. To assist the pilot in this matter, the Automatic Pilot was evolved to take the stress and strain out of the flying. This enables the pilot to concentrate on the other duties associated with flying such as R/T communication, visual scan checks both of the instrumentation and the outside environment. The automatic pilot (more commonly known as the autopilot) has developed, under today's technology into the Automatic Flight and Automatic Landing Systems.

This section is designed to express the basic fundamentals of the autopilot, and its operational facilities. Its emergence into automatic landing will also be discussed, although in-depth knowledge of both should be acquired by the pilot when completing a conversion course onto a specific aircraft type.

1.3 The Autopilot

The automatic pilot discussed in this section is of a basic type from which all other autopilots are derived. A general understanding of the operation and requirements of the autopilot will enable the pilot to understand the aircraft type system more readily.

1.4 Autopilot Requirements

An autopilot is required to fulfil three main functions of aircraft control. These are for aircraft stabilisation, aircraft manoeuvring and facility coupling.

(a) **Aircraft Stabilisation:**
This is to maintain the aircraft in a stable condition with respect to its selected flight path regardless of fast rate or slow rate disturbances. Fast rate disturbances are associated with turbulence, whereas slow rate disturbances could be due to trim changes affected by fuel consumption.

(b) **Aircraft Manoeuvring:**
The autopilot must contain a control unit to allow the aircraft to be displaced in pitch or roll and so to be climbed, dived or turned by selection by the pilot.

(c) **Facility Coupling:**
Certain aircraft navigational facilities or ground facilities (ie ILS, autoland) must be able to be coupled into the system.

1.5 Aircraft Stabilisation

Rate Gyros are used to detect disturbances in the pitch, roll and yaw axes of the aircraft. The axes of rotation are set at 90° to each other. The rate gyros are able to detect disturbances above a certain signal threshold, below which the signal may be too small for detection. To overcome this problem, mercury switch and pendulum monitors are used to detect the finer disturbances. The complete system is designed to be proportional in operation to the initial disturbance. That is to say that a signal output is proportional to the original disturbance, and rate/rate principle is that the rate of control is proportional to the rate of disturbance.

1.6 The Basic Channel

The basic channel comprises four units which are illustrated in Fig 1-1.

(a) Rate Gyro
Comprised of a three-phase hysteresis motor where the rotor is the rotating mass. An 'E' and 'I' bar transformer produces the signal, the signal amplitude being proportional to the rate of disturbance. The 'I' bar is connected to the gimbal assembly, the 'E' bar supplies the signal pick-off, and the phasing will depend upon the direction of the disturbances.

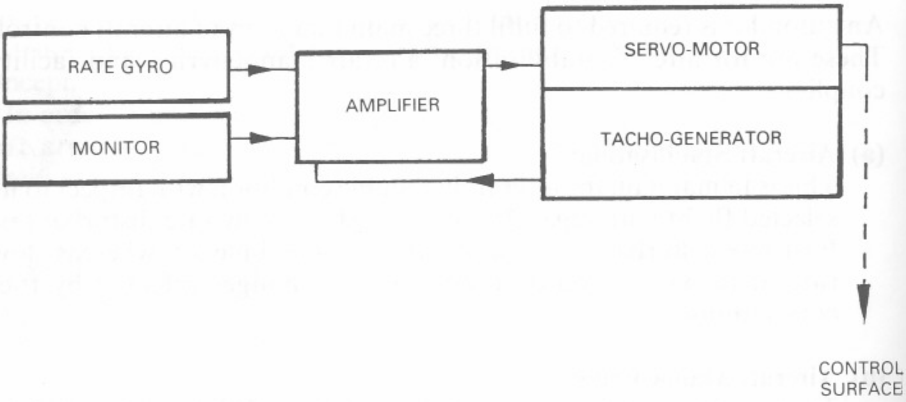


Figure 1–1 Autopilot Basic Channel Circuit.

(b) Monitors
A 'C' and 'Y' bar transformer is used for the roll signal which originates from the aircraft's compass system. A pendulous element provides the originating signal for pitch and yaw. This signal is supplied to a variable inductor which is similar in operation to the 'E' and 'I' bar transformer.

(c) Amplifier
A high gain amplifier is used to amplify and discriminate the disturbance signal, the output of which drives a channel servo-motor.

(d) Servo-motor and Tacho-generator
The control surface is driven by a servo-motor via an electro-magnetic clutch. To provide proportional feedback, a tacho-generator supplies a negative, velocity feedback signal which completes the signal loop.

1.7 Combined Channel Circuit

The combined channel circuit is designed to cover all three primary control surfaces, the rudder, aileron and elevator. Figure 1-2 illustrates the combined channel circuit showing interconnections between rudder to aileron and aileron to rudder. The interconnections of the rudder/aileron and aileron/rudder channel are termed crossfeed.

1.8 Operation in Pitch

If there is an initial disturbance which has the tendency to put the aircraft in a nose down attitude, the pitch gyro displaces the 'E' and 'I' bar causing a signal to be fed to the amplifier unit. After the signal has been amplified, the output is phased according to the direction of the initial disturbance and the resultant is applied to the elevator servo-motor. The servo-motor moves the elevator up and the rotation causes the tacho-generator to give a feedback signal back to the amplifier. This ensures that the rate of correction by the servo-motor is proportional to the initial rate of disturbance.

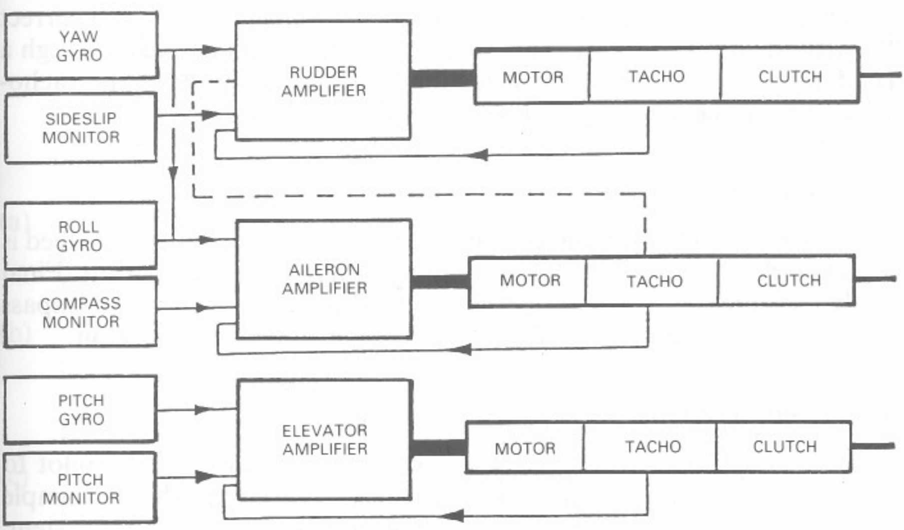


Figure 1–2 Autopilot Combined Channels Circuits.

The elevator movement causes a turning movement to correct the original disturbance. When the opposing torques are equal, the elevator movement will stop. When the original disturbance has ceased, the elevator up position causes a turning movement in the opposite direction creating a disturbance. The pitch gyro detects this change in pitch movement causing a signal to be sent to the servo-motor restoring the neutral position of the elevator. The pendulous element of the monitor detects all the final displacement and adjusts the servo-motor signal to regain level flight in the pitching plane.

1.9 Operation in Yaw

Operation of the autopilot in yaw is similar in operation to the elevator control. A signal is sent from the yaw gyro to the rudder amplifier to move the servo-motor in the correct direction to oppose the initial disturbance. When the opposing torques are equal, further rudder application ceases. Once the initial disturbance has been removed, a signal in the opposite sense causes the servo-motor to remove the rudder deflection to the neutral position.

When a disturbance in yaw is felt and corrective action taken, a disturbance is also felt around the roll axis due to a yaw causing one wing to be leading and one lagging. The changed airflow over both wings induces a lift differential which causes a roll to occur. To overcome this roll tendency and to correct for it, a yaw gyro signal is fed to the aileron channel amplifier which will then oppose the rolling tendency and correct the attitude of the aircraft. This yaw gyro signal is channelled through a rudder/aileron crossfeed and a feedback signal is fed from the tacho-generator on the aileron servo-motor to the rudder amplifier.

1.10 Operation in Roll

This is similar to the yawing condition and an aileron/rudder crossfeed is used in older aircraft which are not fitted with differential ailerons. Final control correction of the roll situation is accomplished by the compass monitor due to the turning effect created by the aileron correction.

1.11 Manoeuvring

With the autopilot engaged it is sometimes required of the pilot to change the heading or the altitude/flight level. To accomplish this a simple turn switch and a pitch switch is incorporated into the autopilot system. These switches cause a signal to be sent to the gyro platforms which apply a false datum. The false datum causes a signal to be sent to the appropriate channel amplifiers and servo-motors which will then turn the aircraft or cause a climb or descent according to the initiating input signal of the switch.

.12 Manoeuvres in Pitch

igure 1-3 and the following text describe the sequence of events to obtain descent using the pitch control on an autopilot. To obtain a climb, the verse order of the control selections should be initiated.

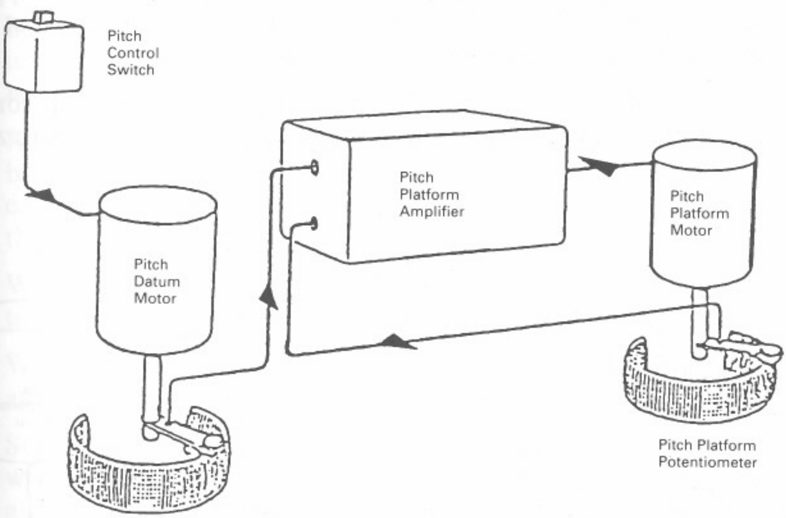


Figure 1–3 Pitch Control Circuit.

) The pitch control switch is pushed forward with the intention of diving the aircraft. Light pressure results in a slow change of attitude, heavy pressure on the switch results in a fast change of attitude.

) The control switch operates the pitch datum motor which rotates the pitch datum potentiometer wiper. Differential signals between the datum potentiometer and the pitch platform are applied to the pitch platform amplifier.

) The amplifier output is applied to the pitch platform motor, thus rotating the pitch platform in the 'nose up' configuration. Platform movement is detected as a disturbance by the pitch gyro which applies corrective elevator to put the aircraft nose down.

) Elevator application ceases when the aircraft is rotating nose down at the same rate as the pitch platform is rotating nose up. The pitch platform is maintained level in space. The aircraft is now rotating nose down, at a constant rate, under the action of the applied elevator.

(e) When the required angle of dive has been reached, the pitch control switch is released. The pitch datum motor stops.

(f) The pitch platform potentiometer has been closely following the datum potentiometer and when the misalignment signal is zero, the platform ceases to rotate.

(g) Further pitching nose down is detected as a disturbance, the applied elevator is removed, and the descent attitude is maintained at that selected when the controller was released.

(h) Levelling of the aircraft is achieved by operating the pitch control switch in the reverse direction until the rate of descent falls to zero.

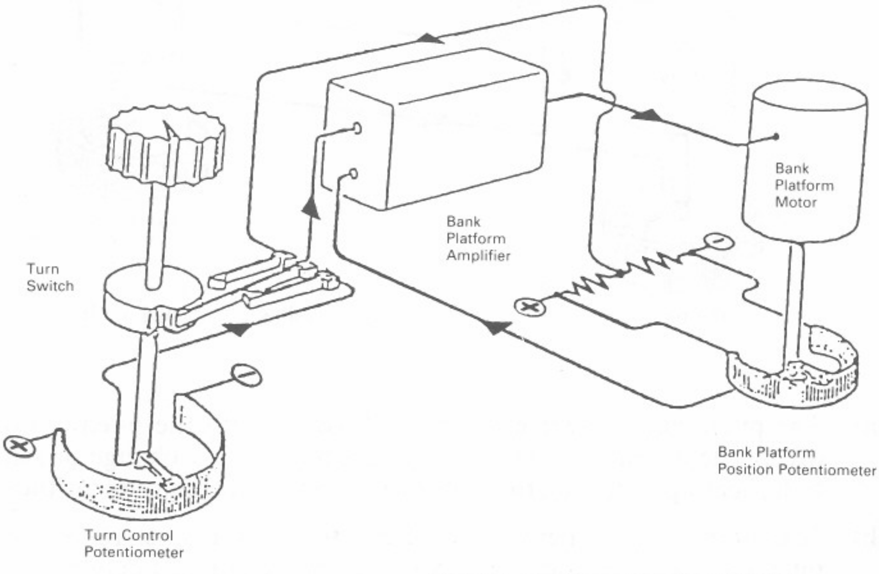


Figure 1–4 Azimuth Control Circuit.

1.13 Manoeuvres in Azimuth

With the aid of Fig 1-4 the following sequence describes a turn to port when selected on the pilot's controller. Maintaining the roll frame level is normally accomplished by the misalignment signal which is developed between the bank platform position potentiometer (BPPP) and the bank datum potentiometer (BDP). By operating the turn switch, a false signal is used on the roll frame which causes an output signal to activate the servo-motor moving the ailerons.

.14 Turn to Port Selection

ı) Offsetting the turn controller to port initially operates the turn switch, disconnecting the BDP and substituting the turn control potentiometer.

›) When the controller is turned, a misalignment signal is introduced between the turn control potentiometer and the BPPP. This signal is applied to the bank platform amplifier, and the output drives the bank platform motor, thereby rotating the roll frame.

:) Rotation of the roll frame is detected by the roll gyro as a disturbance tending to lower the starboard wing. The correction signal causes the starboard aileron to go down raising the starboard wing thereby initiating a turn to port.

l) When the misalignment signal between the turn control potentiometer and the BPPP are equal the platform rotation ceases.

:) Whilst the controller is offset the aileron remains applied and the amount by which the controller is offset determines the rate of turn.

) Suppression of the yaw gyro and compass monitor signals, which would tend to oppose the turn, is achieved by a 1° microswitch operated by the roll frame. When this is made, the compass monitor signal is short circuited and the electro-magnetic clutch is disengaged at the monitor input. The yaw signal is opposed by the pick-off from a turn demand potentiometer, the output of which is determined by the angle of bank.

;) The rudder to aileron crossfeed is disconnected by a further microswitch set at 5°, thereby allowing the sideslip monitor to coordinate the turn.

ı) When the central controller is returned to the central position to stop the turn, the BDP replaces the turn control potentiometer. The aileron is then removed as the misalignment signal between the BDP and BPPP levels the roll frame.

) A manoeuvre in azimuth can only be carried out if the controller was returned to the centre before autopilot engagement.

.15 System Coupling

ltitude Locks

/hen the control (labelled ALT) is pulled out on the switch unit, the rcraft is able to be coupled to a pre-selected pressure altitude. The altitude lock system operation is described below and is shown in Fig 1-5. The sequence of operation described is for an aircraft climbing up to the datum altitude and its subsequent coupling to that altitude.

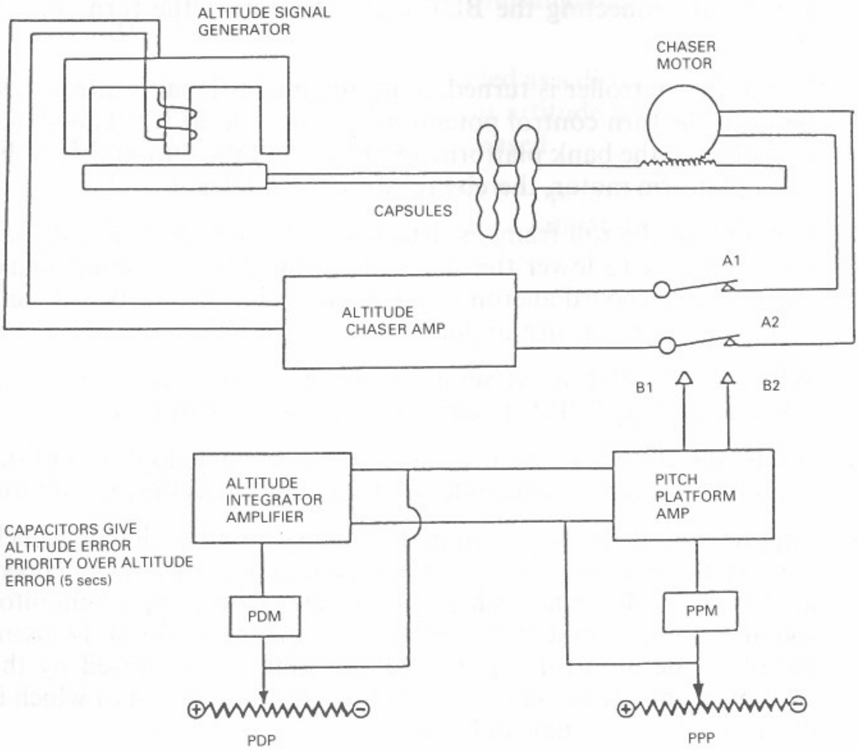


Figure 1–5 Altitude Locking.

(a) An electromagnetic pick-off remains in the sensitive, 'no signal' position due to the chaser motor when the ALT lock is disengaged. The chase rate is sufficient to cope with an altitude change rate of at least 100 ft/sec.

(b) The ALT control is pulled out when the aircraft has reached the datum altitude. The chaser motor is disconnected but the aircraft continues to climb through and above the datum altitude therefore giving an error signal which is then applied to the altitude signal amplifier.

(c) An output is applied to the pitch platform from the altitude signal amplifier causing the platform to be motored 'nose up'. This causes the elevators to be operated which levels the aircraft until the altitude error signal is zero and pitch platform movement ceases.

(d) The altitude control circuit within the Altitude Error Integrating Amplifier, backs off the misalignment signal between the pitch platform potentiometer wiper and the pitch datum potentiometer. A time lag is introduced which enables the aircraft to be locked onto the datum altitude for various conditions of pitch trim altitude.

1.16 Heading Selector

The heading selector incorporates:

(a) Compass monitor

(b) Compass repeater

(c) A pre-select heading facility

All of which are shown in Fig 1-6 and the circuit diagram is illustrated in Fig 1-7.

(a) Compass Monitor
The 'C' and 'Y' type of pick-off is used for developing the compass monitor signal with a change in heading resulting in the 'C' type armature rotating about the 'Y' stator. The error signal resulting from this is applied to the aileron channel. The 'C' bar drive from the synchro is taken via an electromagnetic clutch which is disengaged when the bank platform is rotated by the 1° switch.

(b) Compass Repeater
Synchro heading information is received by a synchro-control transformer stator, a misalignment signal from the rotor is picked off and fed to a chaser amplifier. The output is then fed to a chaser motor, reduction gear train and then to the rotor shaft which backs off the synchro-control transformer output. An indication of heading against a fixed lubber mark on the face of the selector is provided by a compass card attached to, and rotating with, the rotor shaft.

(c) Pre-Select Heading Facility
Friction-loaded to the compass card is a select heading pointer which normally rotates with it. By pressing and turning the select heading knob, the pointer may be rotated independently of the compass card. Rotating the pointer away from the lubber mark also causes the wiper of a heading error potentiometer to be offset. When a new heading is required to be set, pressing of the Set Heading button on the front of the unit feeds the heading error pick-off into the bank platform network. The resultant heading change and synchro-operation

provides the signal to back off the heading error, the 'Alter Heading' button only requires to be momentarily depressed to initiate the heading change.

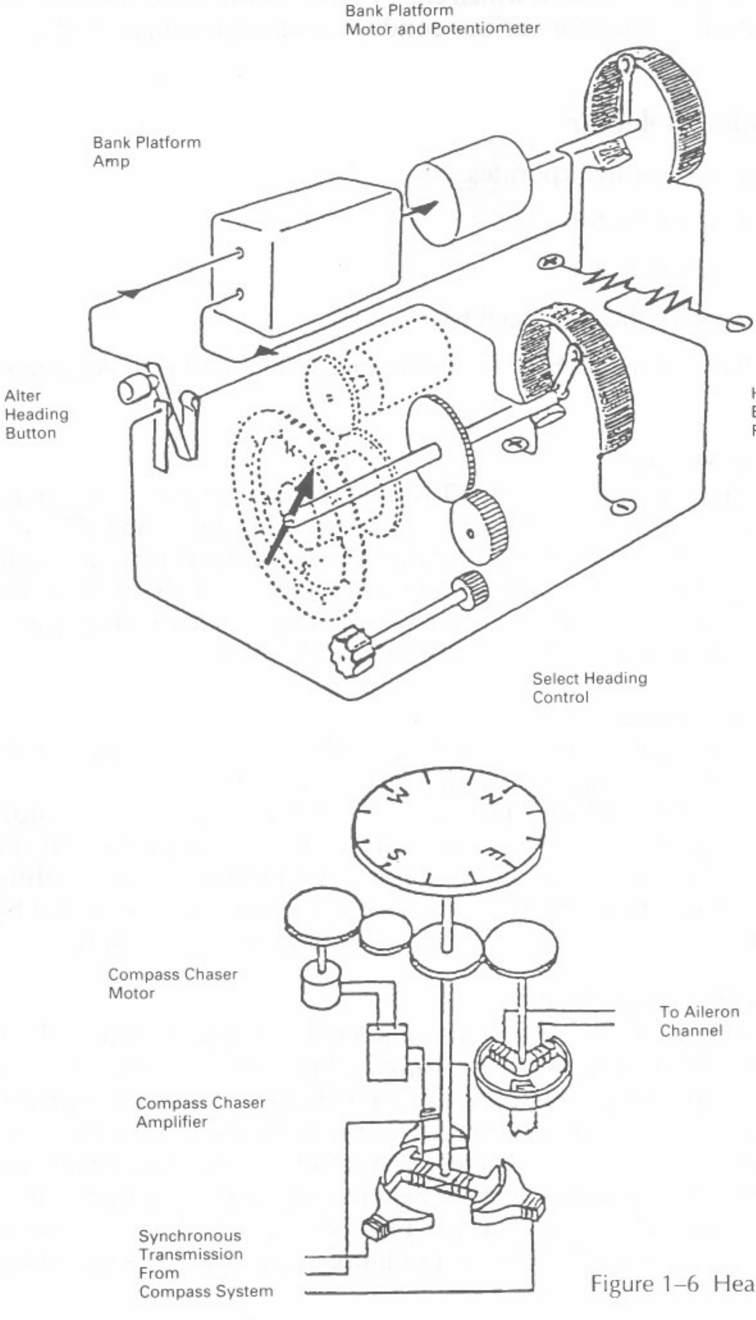


Figure 1–6 Heading Selector.

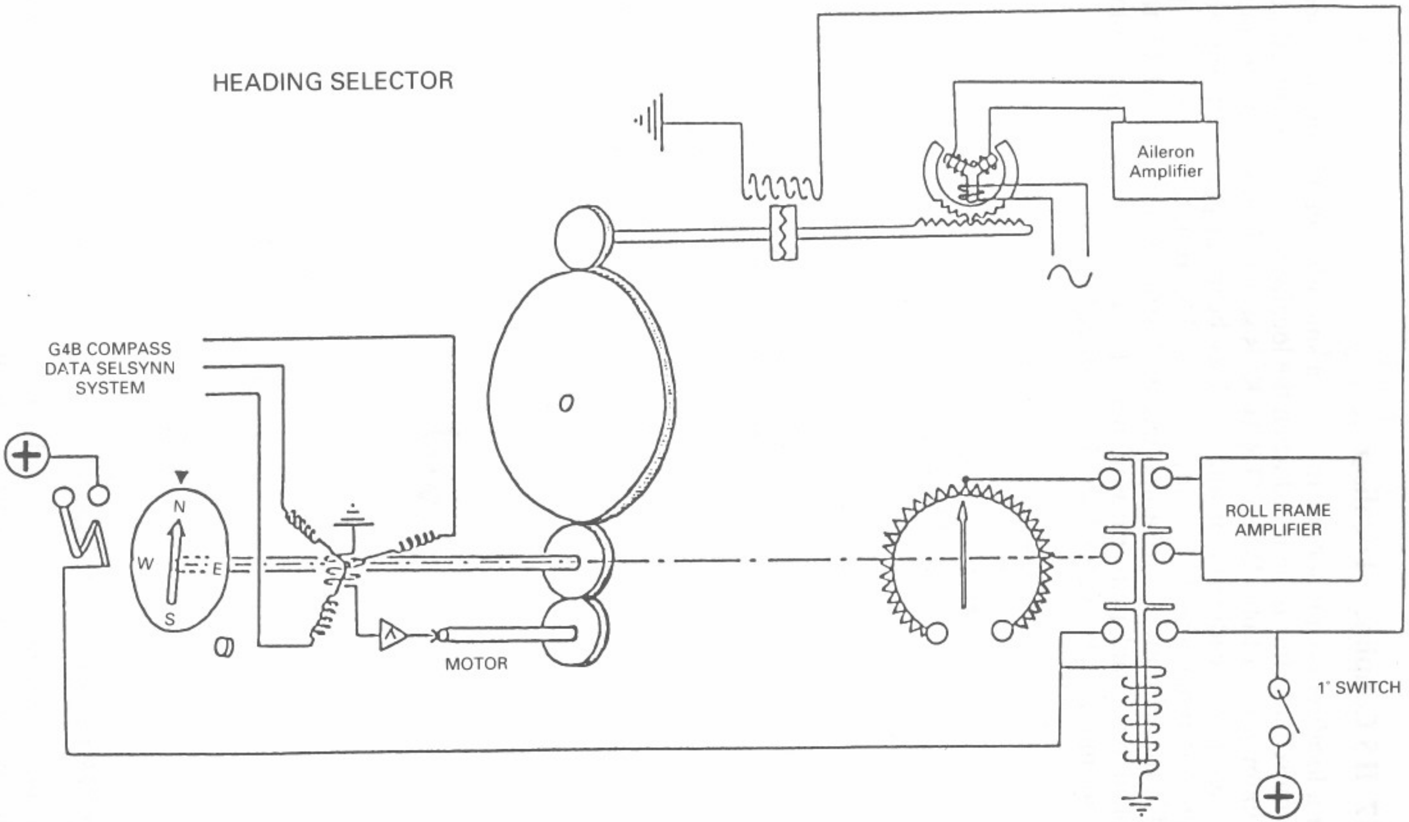


Figure 1–7 Heading Selector Circuits.

1.17 ILS Coupling – Localiser

For a localiser coupling onto the ILS, a smooth join without overshoot is required and this is achieved when the localiser beam is attached at an optimum angle of 60°. When 'TRACK' is selected on the switch unit, a mixing of the heading error and localiser beam displacement signals is permitted giving a resultant output signal. This resultant signal is amplified in the azimuth control amplifier, as illustrated in Fig 1-8, and is then applied to the bank platform amplifier. The ratio of the two signals allows the optimum angle of attack on the localiser beam.

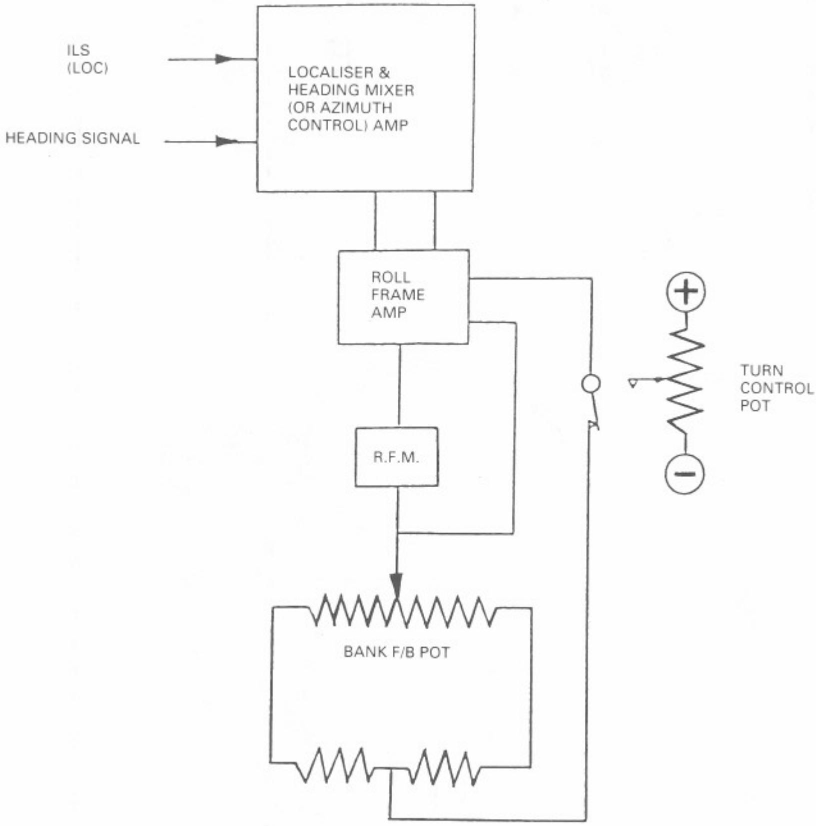


Figure 1–8 Localiser Coupling.

1.18 ILS Coupling – Glidepath

To achieve coupling to the ILS glidepath, an output signal from the glidepath receiver via the glidepath signal amplifier is applied to the pitch platform amplifier as illustrated in Fig 1-9. The present attitude of the aircraft type on an ILS may be superimposed over the glidepath signal and is known as 'GLIDE A'. The adverse effects of the aircraft's pitch changes are overcome with the use of an error integrator amplifier. For the coupling to be achieved, selection of the 'GLIDE' switch must be initiated.

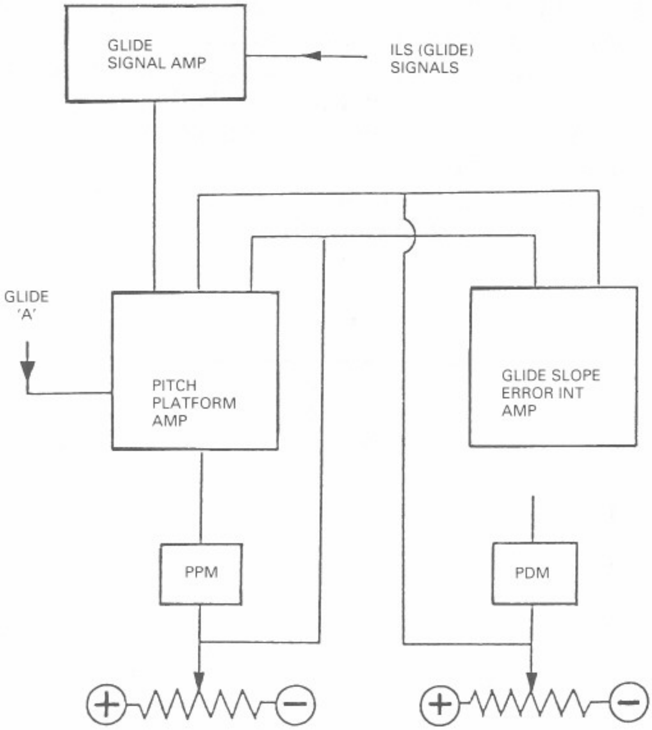


Figure 1–9 Glidepath Coupling.

1.19 Supply and Control

Switch Unit

The switch unit, as illustrated in Fig 1-10, displays several switches to cover TRACK, GLIDE, ALTIMETER as well as the POWER and ENGAGE switches. The power switch supplies power to the autopilot and its associated gyros. The gyros run up to speed and ensure that the platforms are level after 45 to 90 seconds.

The power supplies are 115V 400 Hz 3-phase AC and 28V DC which is routed via a torque switch in the aircraft's control circuit. This ensures that the DC supply is supplied to the autopilot only when the AC is satisfactory.

After the delay switch has operated correctly and the AC and DC supplies are satisfactory the READY flag will appear. When all three channel switches are selected in, the ENGAGE button is pulled and the READY flags disappear from view and the IN flags appear, indicating all three channels are selected in and engaged. If one or two of the channel switches are not selected in when the ENGAGE switch is selected, then the READY flag will still be in view when the IN flag appears. This is an indication that not all three channel switches have been selected.

As maintaining the altitude is a function of elevator control, the DC circuit ensures that the ALT hold-on coil cannot be selected when the elevator servo-motor clutch is de-energised.

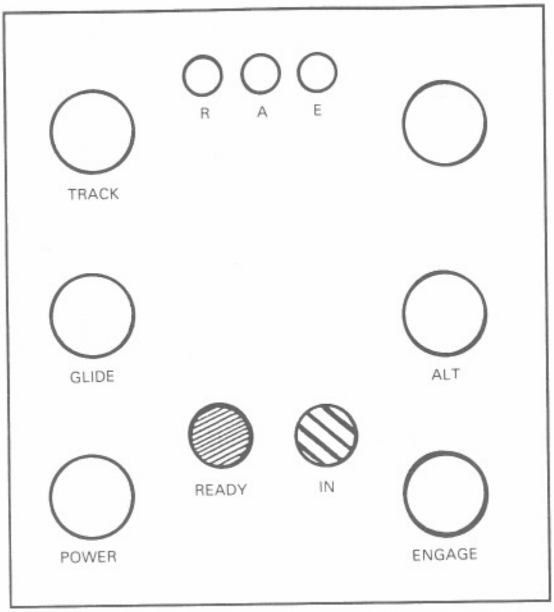


Figure 1–10 Switch Unit..

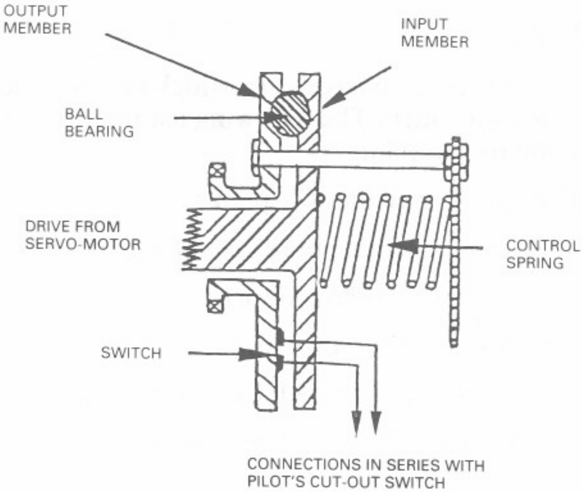


Figure 1–11 Excess Torque Cut-Out.

1.20 Safety Features

(a) Pilot's Instinctive Cut-Out – this is situated on the control column and when selected will ensure instant disengagement.

(b) Roll Error Cut-Out – this cut-out disengages the autopilot if the rate of aileron application is excessive, thereby preventing a dangerous roll attitude in the event of an aileron channel malfunction.

(c) Excess Torque Cut-Out – this is used to limit the torque imparted to the aircraft controls in the event of malfunction, or normal response to a large disturbance of the aircraft. The unit consists of two members, input and output as illustrated in Fig 1-11. The input member is driven by the servo output, the output member drives the control linkage. If the torque level is exceeded, the members move axially as well as radially to each other. This causes the ball bearings to rise up their own cone bush, the axial displacement between members against control spring tension causing contacts in series with the engaging circuit to open.

(d) Shear Linkage – a further safeguard is a weak link in the control linkage from the servos which will shear if the torque exceeds 100lb/ft.

1.21 Interlocks

An autopilot system needs to have an interlock system which allows some conditions to be overridden. The following list indicates some interlocks that are common to autopilots:

(a) Pilot's Controller overrides Co-pilot's

(b) Controlled turns override pre-selected turns

(c) TRACK overrides pre-selected turns

(d) ALT overrides slow pitch control

(e) Fast pitch control overrides ALT control

(f) GLIDE overrides ALT and pitch control

1.22 Miscellaneous Information

Remote Trim Indicator
Provides an indication of sustained loads on the elevator servo-motor associated with an out-of-trim condition. The unit may also incorporate remote Ready and IN flags as illustrated in Fig 1-12.

Engagement
The autopilot may be engaged in a climb or dive, but not in a turn. Whilst the autopilot may be used when flying through turbulence, it is generally recommended that coupling locks (ALT, etc) should not be engaged and that speed is reduced to the turbulence speed for the aircraft type.

Limitations
All altitude and speed limitations must be adhered to, especially the minimum altitude limit.

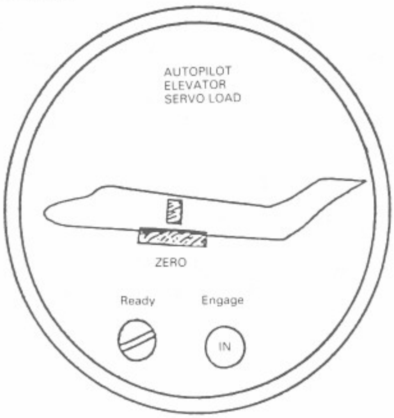


Figure 1–12 Remote Trim Indicator.

With more and later types of electronic and control sophistication being used on the aircraft, scientists and engineers have perfected the autopilot and navigation systems to enable the aircraft to take-off and land automatically. This later development allows an increased accuracy for landing in bad visibility conditions which would otherwise cause an aircraft to divert, and it is known as the Automatic Landing System.

Test Yourself One Advanced Flying Systems

1. In a basic autopilot channel circuit the control surface is driven by:
   (a) a mechanical system.
   (b) the servo-motor.
   (c) the monitor.
   (d) the amplifier.

Ref 1.8.

2. In automatic flight systems the term ALT means:
   (a) aircraft lateral trim.
   (b) aircraft longitudinal trim.
   (c) altitude.
   (d) alert.

Ref 1.15.

3. Proportional feedback is provided in a servo-motor control system to complete the signal loop by the:
   (a) amplifier.
   (b) motor.
   (c) gyro.
   (d) tacho-generator.

Ref 1.6.

4. The heading selector permits:
   (a) real time selection.
   (b) pre selection.
   (c) trim heading only.
   (d) roll trim only.

Ref 1.16.

5. Remove Trim Indication is given in:
   (a) pitch.
   (b) roll.
   (c) yaw.
   (d) roll and pitch.

Ref 1.14.

2

Semiconductors

2.1 Introduction

Before it is possible to take a more detailed look at Semiconductors, a basic knowledge of Resistors, Rectifiers, Capacitors, Transistors, and some selected definitions is necessary for an understanding of Semiconductor materials and Integrated Circuits, the basis of 'Solid State' components used universally in electronics and computers.

2.2 Electric Charge

The unit of electric charge called the coulomb is the quantity of electricity (or number of electrons) transported in one second by a current of one ampere.

2.3 Resistors

Resistance is that property of an electrical circuit which determines, for a given current, the rate at which electric energy is converted into heat or radiant energy. Generally speaking, resistance is in opposition to current flow in a material, and is one of its physical properties.

The unit of resistance is called the OHM, written as Omega from the Greek alphabet (Ω). The definition of resistance is 'that resistance between two points of a conductor when a constant difference of potential of one volt, applied between these two points, produces in this conductor a current of one ampere' (the conductor NOT being the source of any electromotive force).

2.4 Rectifiers

Semiconductor rectifiers are the most used solid state devices in the electronics industry. (The term semiconductor will be explained later). A rectifier basically allows current flow in one direction, and offers a very high resistance to flow in the opposite direction.

2.5 Capacitors

A capacitor basically consists of two plates separated from each other by a thin layer of insulation material (a dielectric). When a source of DC potential is momentarily applied across these plates, they become charged. If the same two plates are then joined together momentarily by means of a switch, the capacitor will discharge.

When the potential was first applied, electrons immediately flowed from one plate to the other through the source of potential. However, the circuit from plate to plate in the capacitor was incomplete (the two plates being separated by the dielectric) and thus the electron flow ceased, meanwhile establishing a shortage of electrons on one plate and a surplus of electrons on the other.

When a deficiency of electrons exists at one end of a conductor, there is always a tendency for the electrons to move about in such a manner as to re-establish a state of balance. In the case of the capacitor, the surplus quantity of electrons on one of the capacitor plates cannot move to the other plate because the circuit has been broken; that is, the battery or DC potential was removed. This leaves the capacitor in a **charged** condition; the capacitor plate with the electron deficiency is **positively** charged, the other being **negatively** charged.

The charge represents a definite amount of electricity, or a given number of electrons. The potential energy possessed by these electrons depends not only on their number, but also on their potential or voltage. For example, a 1 μ F capacitor charged to 1000 volts possesses twice as much potential energy as does a 2 μ F capacitor charged to 500 volts, although the charge (expressed in coulombs) is the same in each case.

The unit of capacitance is the FARAD and is the capacitance of a capacitor between the plates of which there appears a difference of potential of one volt when charged by a quantity of electricity (or number of electrons) equal to one coulomb.

2.6 Construction of Transistors

One of the earliest detection devices used in radio was the galena crystal, a crude example of a **semiconductor** diode. More modern examples of semiconductors are the silicon rectifier, the germanium diode, and numerous varieties of the transistor and integrated circuit (these last two items will be described).

All of these devices offer the interesting property of greater resistance to the flow of electrical current in one direction than in the opposite direction (Rectification principle). The transistor is a three-terminal device which is made in a special way and consists of several layers of semiconductor materials; it offers current amplification and may be used for a wide variety of control functions including amplification, oscillation and frequency conversion.

2.7 Atomic Structure of Germanium and Silicon

Since the mechanism of conduction of a semiconductor is different from that of a vacuum tube, it is well to review briefly the atomic structure of various materials used in the manufacture of solid state devices.

Electrons in an element having a large atomic number are conveniently pictured as being grouped into rings, each ring having a definite number of electrons. Atoms in which these rings are completely filled are termed **inert gases**, of which helium and argon are examples. All other elements have one or more incomplete rings of electrons.

If the incomplete ring is loosely bound, the electrons may be easily removed, the element is called **metallic** and is a conductor of electric current. Copper and iron are examples of conductors.

If the incomplete ring is tightly bound, with only a few electrons missing, the element is called **nonmetallic** and is an insulator (nonconductor) to electric current.

A group of elements, of which germanium, gallium, and silicon are examples, fall between these two sharply defined groups and exhibit both metallic and nonmetallic characteristics. Pure germanium or silicon may be considered good insulators. The addition of certain impurities in carefully controlled amounts to the pure element will alter the conductivity of the material. In addition, the choice of the impurity can change the direction of conductivity through the element, some impurities increasing conductivity to positive potentials, and others increasing conductivity to negative potentials. More about this aspect later.

Early transistors were mainly made of germanium but most modern transistors are made of silicon. Some newer devices are being made of gallium arsenide, which combines some of the desirable features of germanium and silicon, but exhibits faster speed than either.

In consideration of the basic material used in the construction of a diode, namely silicon, this will be described because it is still by far the most popular semiconductor material in use. However, bear in mind that germanium and all other semiconductor materials follow the same general principles.

Like all materials, silicon is made up of atoms. At the centre of the silicon atom is a concentrated mass called the nucleus. The nucleus contains fourteen electrically charged particles called 'protons', plus some neutral particles which can be ignored. Circling the nucleus like little satellites are fourteen other electrically charged particles called 'electrons'.

Protons are positively charged and electrons are negatively charged. Proton and electron charges are not only opposite, but equal. This means that a proton and electron together are electrically neutral, the equal unlike charges neutralize each other. So this combination neither attracts nor repels any other particles. See Fig 2-1.

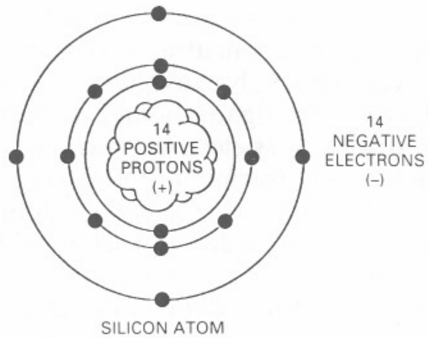


Figure 2–1 Silicon Atom.

Looking at Fig 2-1 we see that ten of the electrons are in the shells close to the nucleus, they are in 'low orbits'. Therefore, counting just the nucleus and the two inner shells, there are ten electrons and fourteen protons, giving a net charge of +4. In the outer shell, there are four electrons, giving that shell a total (negative) charge of –4. So the –4 of the outer shell balances the +4 charge of the core (the nucleus and the inner two shells) leaving the whole atom electrically neutral.

Although the silicon atom has four electrons in its outer orbit, it has what is described as a 'desire' to have eight electrons (this term 'desire' is borrowed from the physicists method of description, and cannot be improved by the author of these notes). This 'desire' is what binds silicon atoms together into a crystal. See Fig 2-2 for a conceptual diagram of a typical section of a silicon crystal.

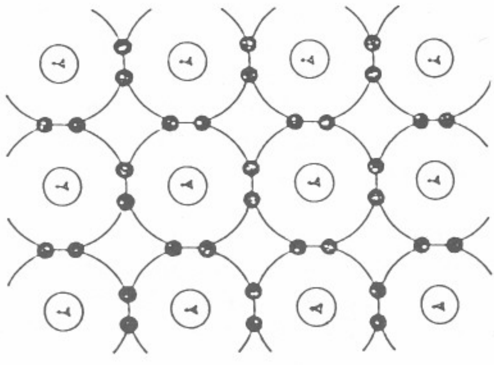


Figure 2–2 Bound Silicon Atoms.

Note that each silicon atom's 'desire' to merge has been satisfied by sharing each of its outer electrons with four neighbours, so the outer orbit of each atom, in effect, interlocks with the outer orbits of four adjoining atoms.

Since the total number of protons now equals the total number of electrons, the crystal is electrically neutral. From an electrical viewpoint, it's not a lot of use in conduction, because in this state, it is a very good insulator. All the electrons are tightly bound in their shared orbits. These electrons cannot flow to carry electrical current.

In the manufacture (or growing) of the silicon crystal, certain impurities are added intentionally. This is called 'doping'. For example the element phosphorus may be added and scattered throughout the silicon lattice. Phosphorus atomic structure is similar to silicon, but has one more proton in its core, and a fifth electron in its outer orbit. This 'spare' electron is free to wander about looking for unfilled orbits.

Doping the silicon raw material with phosphorus provides a means of conduction. Of course the amount of doping will control the degree or ease of conduction, ie, the number of free phosphorus electrons available. Electrons in outer orbits are negative, therefore this process produces 'N' (negative) type semiconductor material.

If this material is used in an electrical circuit, negative electrons being pumped into it will cause the free electrons from the phosphorus atoms to migrate to the other ends of the crystal and out along the wire connection. This is because like charges repel one another. The number of electrons in the **crystal** remains constant; one electron leaves for every one pumped in. This is the concept of electricity flowing in an N-type semiconductor.

If, however, the doping agent is boron, P-type silicon crystals are made. The boron atom has only three electrons in its outer orbit. Instead of donating an extra free electron as the phosphorus did, the boron atom creates a deficiency of one electron in the orbit. This deficiency is called a 'hole'.

Just as the free electrons can wander, so can these holes wander through the crystal lattice. Obviously, a hole is not a physical entity like an electron, but when an electron moves from one place to another, it is just as though the hole it moved to had moved in the **opposite direction**. A hole always represents a positive charge (+1) after it has moved away from the boron atom. So, the hole can be thought of as a freely moving positive charge.

The degree of doping will control the ability of the silicon to conduct. The more boron used creates more holes and therefore the more electrons they can accommodate, the more current the crystal can carry.

Remember: P-Type (positive) conducts electricity only by means of holes, and has **virtually no free electrons**. N-type (negative) conducts **only** by means of free electrons; **it has virtually no holes**.

2.8 Mechanism of Conduction

It has already been stated that there exists in semiconductors both negatively charged electrons and absence of electrons in the lattice (holes), which behave as though they had a positive electrical charge equal in magnitude to the negative charge on the electron. These electrons and holes drift in an electrical field with a velocity which is proportional to the field itself.

In an electric field the holes will drift in a direction opposite to that of the electron, and will have about one-half the velocity, since the hole mobility is about one-half the electron mobility.

A sample of a semiconductor, such as germanium or silicon, which is both chemically pure and mechanically perfect, will contain in it approximately equal number of holes and electrons and is called an **intrinsic** semiconductor.

The intrinsic resistivity of the semiconductor depends strongly on the temperature. As an example, at room temperature germanium is about 50 ohm/cm, and silicon is about 65,000 ohm/cm. Notice this is quoted for cm; actual resistance in the very small component spacing is very much less in a real semiconductor component.

The impurities which contribute electrons are called **donors**. N-type silicon has better conductivity than pure silicon in one direction, and a continuous stream of electrons will flow through the crystal in this direction as long as an external potential of the correct polarity is applied across the crystal.

The impurities which create holes are called acceptors. P-type silicon has better conductivity than pure silicon in one direction. This direction is opposite to that of the N-type material. Either the N-type or the P-type silicon is called **extrinsic** conducting type.

The doped materials have lower resistivities than the pure materials, and doped semiconductor material in the resistivity range of 0.01 to 10 ohm/cm is normally used in the production of transistors. The electrons and holes are called carriers; the electrons are termed majority carriers, and the holes are called minority carriers.

2.9 The PN Junction

The semiconductor diode is a PN junction, or junction diode. This device is one of the simplest semiconductor (solid state) devices and will be described. (A diode is a device which conducts generally in one direction up to a certain current limitation). It has the general electrical characteristic of Fig 2-3.

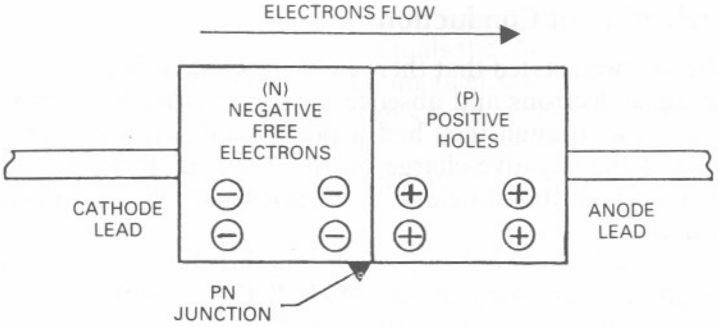


Figure 2–3 PN Junction Diode.

In Fig 2-3, the PN junction diode is made to have N-type material on one side and P-type material on the other. In this example is shown four free electrons in the N material, and four holes in the P material. The dividing line between the two types is called the 'PN junction'. It is the behaviour of the electrons and holes in the vicinity of this junction that gives diodes and other semiconductors their unique properties.

Suppose that in Fig 2-3 electrons are being pumped into the N region from an external generator. These negatively charged electrons repel the free negative electrons already there, forcing them to move towards the PN junction. At the same time, bound electrons are being withdrawn from the P region, creating new holes. The new holes repel the old holes, moving the holes towards the PN junction. So the holes in the P-type silicon and the free electrons in the N-type silicon **are moving towards each other**.

When the holes and free electrons meet at the junction, the free electrons fall into the holes. This conduction process continues as long as there are new holes and free electrons being 'pumped in'.

This is how a diode 'conducts' electricity in one direction, so how can it block current in the opposite direction?

In Fig 2-4 is shown a similar PN junction except that electrons are attempting to flow in the opposite direction, from P to N. This is what happens when an AC generator enters the second half of the alternating-current cycle. Since the electrons are attempting to flow away from P to N, the free electrons in the N region migrate **away** from the PN junction.

In the P region, as bound electrons move in the direction of attempted electron flow, the holes move in the opposite direction **away** from the PN junction. The result is that there are no free electrons or holes anywhere

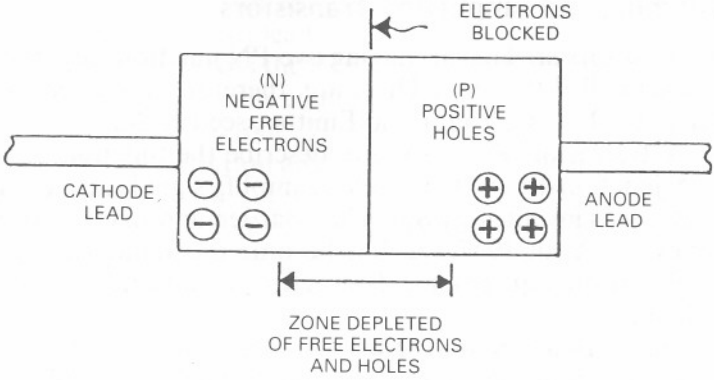


Figure 2–4 PN Junction Diode with Reverse Flow.

near the junction. In effect, this zone is like undoped silicon crystal, which is effectively an insulator **until** the electrons again attempt to flow in the acceptable direction. Electrons can flow from N to P, but not from P to N.

This chip of doped silicon is an electrical conductor under certain conditions, but is an insulator under other conditions – hence the term **'semiconductor'.**

A further definition must be introduced at this point and this is the **avalanche voltage point**. As the applied inverse voltage rises, a potential will be reached at which there will be a breakdown of the current control and a large reverse current and destruction of the diode is more than possible.

Silicon diodes are rated in terms similar to those used for vacuum-tube rectifiers. One of the most important is **Peak Inverse Voltage (PIV)**, which is the maximum reverse voltage that may be applied to a specific diode type before the avalanche breakdown point is reached.

The avalanche voltage point can be used in certain types of diodes as a reference voltage point, or control point as a design feature. In a silicon element operated in the reverse-bias avalanche breakdown region, the breakdown from nonconductance to conductance is very sharp at voltages beyond the breakdown point. The voltage drop across the diode junction becomes essentially constant for a relatively wide range of currents. This is called the zener control region, and diodes which operate utilising the breakdown point are called **zener diodes**. Voltage control in zener diodes is available from 1.8 volts to 200 volts.

2.10 Switching and Amplifying Transistors

Ordinary transistors are **bipolar**, having two PN junctions separated by a very thin layer called the **base**. There are, therefore, three terminals, or connections: the Base, Collector and Emitter, see Fig 2-5.

The word 'transistor' was chosen to describe the function of a three-terminal PN junction device that is able to amplify signal energy (current). The transistor was invented by Shockley, Barden and Brittain at the Bell Laboratories (USA) in 1947 and has become the standard amplifying device in electronic equipment. The action of amplification will be described later.

Some transistors are manufactured so that they operate better as switches, and others are made so they operate better as amplifiers. It is possible that most transistors could be used either to switch or amplify. However, it is not the transistor itself that determines whether it will switch or amplify; rather it is the control circuit, the device that controls the transistor that causes it to function as one or the other. Transistor types are generally classified as amplifiers or switches, but not both.

The study of diode action in semiconductor material will help now in the understanding of other types of semiconductors. In Fig 2-5 is a schematic cross-section of a NPN transistor.

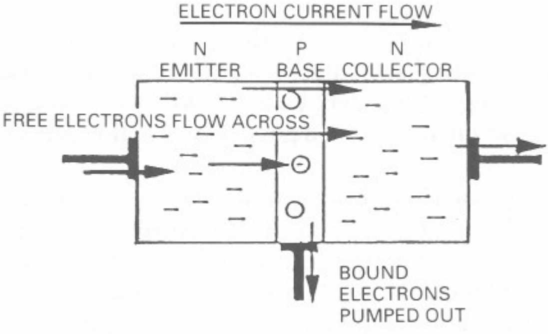


Figure 2–5 Cross-section through an NPN Transistor.

Remember that N-type semiconductor material conducts electricity by means of its supply of free electrons, and that P-type conducts by its supply of positively charged holes. The P region of the transistor is much narrower than the N regions. This P region is much less heavily doped than the N regions; that is, the holes are fewer and farther apart compared to the free electrons in the N regions.

If free electrons from an external generator are pumped from the emitter lead to the collector lead, they continue on their way from the N region of the emitter, across the P region of the base, into the N region of the collector and on down the connecting wire. This process will continue for only a brief instant of time. This may look like a contradiction in the operation of the diode action already discussed, how do the electrons get into the base and pass on to the collector.

It would be expected that these free electrons would be captured in the base area by falling into holes, so that no electrons would pass from base to the collector. In fact the base regions of transistors are very narrow and **lightly doped**, so that the holes are scattered rather sparsely. Most of the electrons (typically 98%) are able to cross the base without falling into a hole.

The few electrons that do fall into holes are stuck there. They accumulate in the base region piling up a negative (repelling) charge in the base. This is what permits the transistor to perform its job of throttling back the emitter-collector working current. The excess bound electrons in the base region repel the free electrons trying to cross through from emitter to collector, making it harder for this current to pass. It does not take long, about 50 nanoseconds for current to be shut off entirely.

Just to recap on this action, as it is the important principle of operation; the nature of the barrier that is shutting off the current, ie the junction between emitter and base, form a PN junction (a diode). In order to get appreciable forward conduction across this diode junction, as with any diode, the electron pressure in the emitter must be greater than the voltage in the base, but the excess electrons that have now accumulated in the base region have **raised** the electron pressure in the base to such a level that the difference becomes less, to the point that no electrons are able to pass on.

The only way to get the working current going again is to withdraw some of the excess bound electrons from the base region. This is done by applying a **lower** voltage pressure of electrons to the base lead which simply allows bound electrons to move out along the path of less electron pressure, ie the control circuit. This creates new holes in the base, tending to restore the proper number of holes.

With this electron pressure barrier lowered, electron current resumes from emitter to collector. For every electron withdrawn from the base, typically 50 electrons cross over from emitter to collector before one falls into a hole. Thus, the small base current proportionally controls the far larger working current. It can now be appreciated how important in manufacture control over the doping levels has to be.

2.11 SCR Devices

Thyristor is a generic term for that family of multilayer semiconductors that comprise **silicon-controlled rectifiers (SCRs), triacs, diacs, four-layer diodes,** and similar devices. The SCR is perhaps the most important member of the family, at least economically, and is used in the control of power. It is the next solid state device in terms of complexity leading to the integrated circuit.

The SCR is a three-terminal, three-junction semiconductor. The SCR will conduct high current in the forward direction with low voltage drop, presenting a high impedance in the reverse direction. The three terminals of an SCR device are **anode, cathode, and gate** (anode is the collector, cathode is the emitter and the gate is the base). Without gate current, the SCR is an open switch in either direction. Sufficient gate current will close the switch in the forward direction only. Forward conduction will continue even with the gate current removed until anode current is reduced below a critical value. At this point the SCR again blocks open. The theory of this action was described earlier, the difference is mainly that SCRs can handle very high current. The SCR is therefore a high speed unidirectional switch capable of being latched in the forward direction.

The gate signal used to trigger an SCR may be an AC wave, and the SCR may be used for dimming lights or speed control of small AC universal series-wound motors, such as those commonly used in power tools.

2.12 Power Amplification

It has already been stated that transistors are used (among other things) for power amplification, and a brief description of how this is achieved follows. The Base, Collector and Emitter can be compared to the Grid, Anode and Cathode of a triode valve.

Because the collector is biased in the back direction, the collector-to-base resistance is high. On the other hand, the emitter and collector currents are substantially equal, so the power in the collector circuit is larger than the power in the emitter circuit. From Ohm's law $P=I^2R$, so the powers are proportional to the respective resistances if the currents are the same. In practical transistors, emitter resistance is in the order of a few Ohms, while the collector resistance is hundreds or thousands of times higher, so power gains of 20 to 40 dB or even higher are possible.

2.13 Transistor Types

The transistor may be one of the types shown in Fig 2-3. The assembly of P- and N-type materials may be reversed, so that PNP and NPN transistors are both possible. The first two letters of the NPN and PNP designations indicate the respective polarities of the voltages applied to the emitter and collector in normal operation. See Fig 2-6 for the symbols used in transistors.

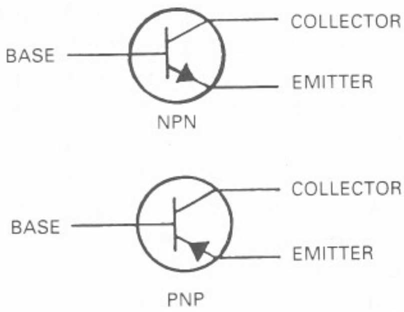


Figure 2–6 Symbols used for NPN and PNP type transistors.

In a PNP transistor, for example, the emitter is made positive with respect to both the collector and the base, and the collector is made negative with respect to both the emitter and the base.

Most modern transistors are of the junction variety. Various names have been given to the several types, some of which are junction alloy, mesa and planar. Though their characteristics may differ slightly, they are basically of the same family and simply represent different physical properties and manufacturing techniques.

2.14 Bipolar Transistor Switches

Our present day technology includes the use of solid-state switches as practical alternatives to mechanical switches. When a bipolar transistor is used in a switching application it is either in an ON or OFF state. In the ON state a forward bias is applied to the transistor, sufficient in level to saturate the device. The common emitter format is used for nearly all transistor switches.

2.15 Integrated Circuits

There are two general types of integrated circuits (ICs): linear and digital. Dealing first with Linear ICs (sometimes called microcircuits or chips): they respond to continuously variable signals and contain many active and passive components. Some ICs have only a single type of component (diodes or transistors), while others have a combination of capacitors, diodes, resistors and transistors. Modern Linear ICs contain hundreds or thousands of active and passive components.

Digital ICs respond only to ON and OFF states, and are mainly confined to computers. The basic IC is formed on a uniform wafer of N-type or P-type silicon. Circuit designs using linear and digital ICs generally have two advantages over their counterparts made from discrete components. The first is that all similar components on the substrate have nearly identical performance characteristics, a condition impossible to realize without very closely matched discrete components. The second advantage is that equipment designed with ICs does not require as much space on a printed circuit board as one using all discrete components. This leads to more compact equipment.

ICs are available in a variety of packages. The most popular style is the moulded plastic duel inline package (DIP) having 8, 14, 16, 18, 20 or 22 pins. Another style is the TO–5 metal can package having 8, 10 or 12 leads. Use of this style is declining, however, because it does not provide enough leads for many modern ICs. See Fig 3-37 and 3-38 which shows in schematic form 14-pin DIL ICs used in computer logic circuits (the significance of the symbols used is discussed in the next chapter on logic circuits).

Test Yourself Two Semiconductors

1. A Rectifier is a device which:
   (a) offers equal resistance to electrical current in both directions.
   (b) allows current flow in both directions.
   (c) allows current flow in one direction.
   (d) allows no current flow in either direction.

Ref 2.4.

2. The unit of Capacitance is the:
   (a) Farad.
   (b) Volt.
   (c) Amp.
   (d) Hertz.

Ref 2.5.

3. The two general types of Integrated Circuits are:
   (a) linear and rotary.
   (b) AC and DC.
   (c) linear and digital.
   (d) digital and directional.

Ref 2.15.

4. Within the silicon atom Protons are:
   (a) not changed.
   (b) positively charged.
   (c) negatively charged.
   (d) constantly alternating their state of charge.

Ref 2.8.

5. Digital ICs respond to:
   (a) ON and OFF states.
   (b) circuits not involving computers.
   (c) no variation of voltage input.
   (d) multi input values.

Ref 2.15.

3

Logic Circuit

3.1 Introduction

The study of simple logic circuits will allow the student to understand how computers make decisions. There are basically two types of computer: Digital and Analogue. Information (suitably encoded) can be handled by either, and manipulated, processed and used to display answers on a visual display unit, or to control equipment like opening and shutting a door, or flying an aeroplane.

Dealing firstly with an analogue computer, there is a tremendous variety of electrical systems that use voltage analogue to transmit information. Most old-fashioned car fuel gauges worked this way with a float in a tank controlling a variable resistor. As the level of petrol changes, the voltage going to the petrol gauge changes. Such a gauge is really a voltmeter whose dial is marked from empty to full, instead of in volts.

Another example of voltage analogue computers (where voltage stands for numbers or mathematical functions of numbers) is in telephones, the voltage standing for fluctuating air pressure, which the ear interprets as sound.

Measurements other than voltage can be used to transmit information. Current analogue systems, for example, operate the same way as voltage analogue systems except that they depend on measurements of current, or Amps instead of voltage.

The codes used in this type of computer are continuous waves and are 'modulated' in the same way as that used in radio modulation systems. The two basic systems are Amplitude Modulation (AM) and Frequency Modulation (FM). An AM system would use the height of the waves to indicate the numbers that may be transmitted. With FM systems the frequency, for example, could vary from 5 Hertz to 10 Hertz, then there is a method of transmitting the numbers from 5 to 10.

There are many analogue methods available, but in summary, it can be stated that all analogue methods are based on regulating various properties of electricity. Conversely digital methods are based on switching electricity on and off, and it is the digital system that will be described.

.2 Electronic Counting

\n understanding of the methods of counting must first of all be looked t because computers use more efficient methods than using the base of en (fingers).

.3 Computer Arithmetic

Ve are used to the decimal numbering system, ie that in which we count n powers of ten. This may well have originated from counting on ten ingers. However, for reasons which should become clear later, it is not onvenient for electronic digital computers to use the decimal system. We nay input information into a computer in this manner, but its process of omputation and manipulation is done using other counting methods, nd again, the output could well be in terms of decimal to be readily nderstood by the human operator. Computers can use the decimal ystem, but the electronics become even more unwieldy and therefore neconomic.

In computer arithmetic there are three counting systems:

1 The Octal System

2 The Hexadecimal System

3 The Binary System

It is necessary to review the decimal numbering system first of all because the process of analysis is similar. When we write the number 147 as an example, it is the conventional shorthand way of expressing a decimal number. The longhand way of writing the same number is:

$$(1\times10^2) + (4\times10^1) + (7\times10^0) = 147_{10}$$

The ten (printed as a subscript) is known as the BASE, or RADIX, of the system and the indices (printed as superscript) indicate the power to which the base is raised. The base and the particular index to which it is raised are called the WEIGHT; that is, the least significant weight is 10^0 which is 1, the next is 10^1 which is 10 and so on. The numbers by which each weight is multiplied are called digits. In practice, only the digits of the system are written, the weights are implied.

Another way of representing the decimal system follows as we will be able to use the same approach in other systems. Taking a bigger figure of 5738 (decimal) of 5738^{10} it can be written as below:

1000s	100s	10s	1s
5	7	3	8

In other words, we mean:

$$(5\times10^3) + (7\times10^2) + (3\times10^1) + (8\times10^0) = 5738_{10}$$

$$\text{or } (5\times1000) + (7\times100) + (3\times10) + (8\times1) = 5738$$

The OCTAL System of numbering is often used in digital computers to control the input and output units. The digital computer uses the BINARY System for its basic method of computation, but octal is used in certain steps in some devices that are being controlled because it requires far fewer digits than does the binary system.

The octal system of numbers uses the base or radix of eight. This means that each digit position in the octal system represents a power of eight. Octal counting proceeds from 0 to 7 just as the decimal system. The digits 8 and 9 do not exist in octal, and to progress from 7 requires a carry operation. An octal number of 1264, (1264_8) for example, could be written as follows:

8^3	(512s)	8^2	(64s)	8^1	(8s)	8^0	(1s)
	1		2		6	4	

Which in decimal is:

$$512 \quad + \quad 128 \quad + \quad 48 \quad + \quad 4 = 692_{10}$$

Therefore the octal number of 1264 = 692 decimal.

Notice the columns are headed by 8 multiplied by the power of 8 the appropriate number of times, for example, the column headed by 512s = 8×8×8, so the next column would be 8×8×8×8 = 4096s. The column headed by 1s is the same as decimal up to 7. Remember 8 and 9 do not exist in octal.

We know that any decimal number can be represented with ten digits 0, 1, 2, 3, 4, 5, 6, 7, 8, 9. Similarly, any octal number may be represented by the eight digits 0, 1, 2, 3, 4, 5, 6, 7. The highest octal number of 4 digits if 7777_8 or $(7\times512) + (7\times64) + (7\times8) = (7\times1) = 4095_{10}$.

In the HEXADECIMAL system of numbering we require sixteen different digits or symbols (base or radix being sixteen) and we therefore require another six in addition to the digits 0 to 9. To fulfil this requirement we use the letters of the alphabet A, B, C, D, E, F to represent the equivalent numbers 10, 11, 12, 13, 14, 15 respectively. This system is unique in having the ten decimal digits 0 to 9. Furthermore, another feature is that each digit is equal to 4 bits, a term used in the binary system.

A number such as 183 hexadecimal (183_{16}) is

16^2	(256s)	16^1	(16s)	16^0	(1s)		
	1		8		3		
or	(1×256)	+	(8×16)	+	(3×1)		
	256	+	128	+	3	=	387_{10}

To take this a step further, the decimal equivalent of $2A9D_{16}$ is:

16^3	(4096s)	16^2	(256s)	16^1	(16s)	16^0	(1s)
	2	A		9			D
=	(2×4096s) +		(10×256) +		(9×16) +		(13×1)

= $10{,}909_{10}$ (decimal)

(Remember A = 10 and D = 13 in decimal: see Fig 3-1).
The highest hexadecimal number using 4 digits is $FFFF_{16}$

or (15×4096) + (15×256) + (15×16) + (15×1) = $65{,}535_{10}$

The BINARY System of counting is a digital computer's working language. It is possible to represent very large numbers in binary notation, with just the digits 1 and 0. These binary digits are frequently referred to as bits.

As the binary numbering system uses two symbols only, 1 and 0, it is a convenient system for digital computers to use since electronic logic circuits have two distinct states of operation (these circuits are introduced later) but we see that a binary number may be represented by a row of switches (open or closed) or a row of lamps (on or off).

The binary system of counting has a radix of 2. This means that each digit position of a binary number represents a power of 2. Consequently the only symbols we require to express a number in the binary system are 0 and 1 since the next highest digit we are familiar with, 2, will be carried over to the next column. For example, 1001 (binary) means:

2^3 (8s)	2^2 (4s)	2^1 (2s)	2^0 (1s)
1	0	0	1
or (1x8) +	(0x4) +	(0x2) +	(1x1) = 9_{10}

Remember that writing 1001 (binary) is equivalent to writing 1001_2.
Figure 3-1 lists counting in decimal, octal, hexadecimal and binary.

Decimal	Octal	Hexadecimal	Binary
1	1	1	1
2	2	2	10
3	3	3	11
4	4	4	100
5	5	5	101
6	6	6	110
7	7	7	111
8	10	8	1000
9	11	9	1001
10	12	A	1010
11	13	B	1011
12	14	C	1100
13	15	D	1101
14	16	E	1110
15	17	F	1111
16	20	10	10000
17	21	11	10001
18	22	12	10010
19	23	13	10011
20	24	14	10100
21	25	15	10101
22	26	16	10110
23	27	17	10111
24	30	18	11000
25	31	19	11001
26	32	1A	11010
27	33	1B	11011
28	34	1C	11100
29	35	1D	11101
30	36	1E	11110
31	37	1F	11111
32	40	20	100000

Figure 3–1 Counting in Decimal, Octal, Hexadecimal and Binary.

Although it is quite easy for computers to understand and manipulate binary numbers, it is not so easy for human beings, because of the number of 1s and 0s needed to represent large decimal numbers. Also they are rather awkward to pronounce if we want to communicate them to other people.

Electronic circuits which convert binary numbers to decimal numbers are very complex and so we need an easier way for the computer to express binary numbers so that they are more readily understood. Figure 3-2 shows the powers of 2, 8 and 16 which are implied when we write numbers in the binary, octal and hexadecimal systems respectively.

2^n	Power of 2	Power of 8	Power of 16
1	0	0	0
2	1		
4	2		
8	3	1	
16	4		1
32	5		
64	6	2	
128	7		
256	8		2
512	9	3	
1024	10		
2048	11		
4096	12	4	3
8192	13		
16384	14		
32768	15	5	
65536	16		4

Figure 3–2 Powers of 2, 8 and 16.

3.4 Binary–Octal Conversion

We can see quite clearly from Fig 3-2 that powers of 8 and 16 are also powers of 2. It seems logical therefore that binary numbers can be very easily converted to octal or hexadecimal and vice versa. This is why computers, although working in binary, frequently accept and display numbers in octal or hexadecimal.

The rules for converting binary whole numbers to octal are very simple, eg consider the binary number: 10100111011

(i) Divide the number into groups of 3 bits starting from the least significant figure, ie the right-hand end. The above number is then written as 10 100 111 011

(ii) Now convert each group of three bits to the equivalent decimal number, ie:

	10	100	111	011
becomes:	2	4	7	3

(iii) Put the converted digits together to give the equivalent octal number, ie 2473_8

3.5 Octal–Binary Conversion

To convert octal whole numbers to binary we reverse the rules used above; eg to convert the octal number 3072^8 to binary we write down the binary code for each digit in the octal number, ie:

	3	0	7	2
becomes:	011	000	111	010

We then group these digits together to form the equivalent binary number, ie 11000111010; notice we have dropped the 0 at the most significant figure, ie the left-hand end.

3.6 Binary–Hexadecimal Conversion

The rules for converting binary whole numbers to hexadecimal numbers are very similar to those for converting to octal, the main difference being that the binary number must be divided into groups of four bits rather than three, eg:

To convert binary 110110110011110 to hexadecimal:

(i) Divide the binary number into groups of four bits starting from the least significant end. The above number then becomes:

110 1101 1001 1110

(ii) Next convert each group to the equivalent decimal number. The number in the above example becomes:

110	1101	1001	1110
6	13	9	14

(iii) The next step is to convert any number greater than 9 resulting from the above step to the equivalent hexadecimal symbol (refer to Fig 3-1), before grouping all the digits together to give the equivalent hexadecimal number. In the above example this becomes $6D9E_{16}$.

3.7 Hexadecimal–Binary Conversion

The reverse of the above applies when converting hexadecimal whole numbers to binary, eg to convert the number $D39A_{16}$ to binary:

(i) First convert the hexadecimal symbols to decimal so that the number becomes:

D	3	9	A
13	3	9	10

(ii) Then write the binary equivalents for each of these numbers:

13	3	9	10
1101	0011	1001	1010

(iii) Finally, group the numbers together to form the binary result, ie: 1101001110011010

These conversions are applicable to whole numbers; the conversion of fractions is beyond the scope of this syllabus.

3.8 Digital Information

It has been shown that the working language of a digital computer is binary, and in this section, it will be shown how intelligence can be sent by digital means. The binary system is a two-state system, and basically digital computers use high speed switches which are either open or closed (two-state).

To see how it is possible for such techniques to be used in computers, consider the simple circuit in Fig 3-3. This is a schematic of a simple old-fashioned telegraph circuit.

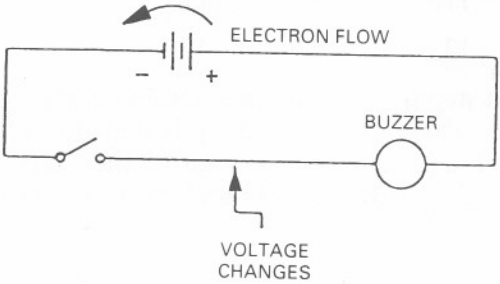


Figure 3–3 Simple Telegraph Circuit.

The power supply is a battery which 'pumps' electrons to a higher voltage on one side of the circuit than the other. The switch in the schematic is the telegrapher's transmitter key, and there is a simple buzzer as a receiver. In the schematic, the switch is in the off (or open) position. Since the voltage on both sides of the buzzer is the same, the receiver is silent. When the key is pressed, turning the switch on, the voltage on the switch side of the receiver goes high, increasing the current flow and causing the buzzer to operate. When the switch is returned to the off position, the current flow stops and the buzzer becomes silent.

It can be said it is the change in voltage in the wire that carries the information and can be visualized as shown in Fig 3-4. The level of the bottom horizontal lines represents zero voltage, meaning that the switch is off.

Figure 3-4 Switched Voltage Curve Showing an 'A' in Morse Code.

When the switch is turned on, the voltage rises to a higher level indicated by the upper horizontal lines. If the switch is closed for a short time, we get a dot in Morse code. If it's held closed for a longer period we get a dash. The curve shown gives a dot–dash, which is an 'A' in Morse code. This is the simplest digital system, switch on and switch off. A point in passing, the Morse code is one of the very few digital systems that can be decoded by the human brain. It normally decodes analogue inputs.

The Morse code requires a cumbersome five characters for each digit, but computers use a more efficient code, the binary number code. In a digital computer, it is usual to let a low voltage represent a zero, and a higher voltage to represent a one. Figure 3-5 shows the voltage curve.

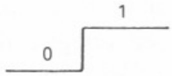


Figure 3–5 Voltage Curve in a Two-State Binary Counting System.

Since all that can be transmitted in a binary code is zeros and ones, how is it possible to extract intelligence from the code? In Fig 3-6 is a five-bit word; each zero or one is called a BIT and a given number of bits makes up a word. This five-bit word will serve as an example, even though typical computers use 32-bit words (and higher). To read this word as a number in binary code, the first bit reading from the right stands for one; the second bit for two; the third bit for four; the fourth for eight; and the fifth for sixteen.

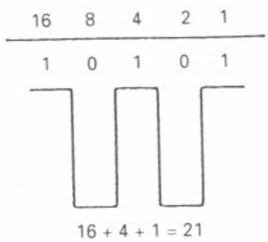


Figure 3–6 A Five-Bit Word in Binary Code.

Now thinking of zeros as standing for NO and the ones for YES it is possible to read the word from right to left in the following way: YES, we have a one; NO, we don't have a two. YES we have a four; NO we don't have an eight. YES we have a sixteen. Add up the values we do have, as we have done on the bottom line of Fig 3-6, and you get twenty-one. So twenty-one is the number represented by this word: 10101 in the binary code.

It is now easy to see how it is possible to add more bits to the left. The next bit would represent thirty-two, the next would be sixty-four, the next one hundred and twenty-eight, etc. In this way it is possible to send numbers as large as is necessary. It is also possible to encode decimal fractions.

Digital computers use many other codes, such as binary-coded decimal (BCD), Grey code, and for letters, the Hollerith code, but all these codes use just zeros and ones, so they are all binary codes. (Binary means 'two-state', on or off).

This simple principle of transmitting digital information has remained the same from the old-fashioned telegraph system through to today's most modern and powerful digital computers.

3.9 Digital Decisions

As it was possible to see how detailed information can be communicated using only the words YES and NO, or in electrical terms – HIGH or LOW voltages, how is it possible for digital systems to make decisions? Before this can be described, it is first necessary to understand some aspects of Boolean Functions because the analysis of switching circuits (Logic Gates) are universally described by this method, and some practical applications will help in the understanding of how decisions are made.

Boolean algebra was introduced by George Boole, an English mathematician in 1847. The algebra was intended as a shorthand notation for the system of logic originally set forth by Aristotle. Aristotle's system dealt with statements which were considered to be either true or false. Boole's algebra deals with variables which may have two discrete possible states or values (often referred to as true or false).

Until the coming of digital electronics and digital computers, Boolean algebra had very little practical use. Now it is extensively used for handling any digital problem. We have already seen that digital computers use the binary numbering system which has only two states, 0 and 1. Boolean algebra is therefore ideally suited to dealing with problems of binary arithmetic and electronic digital systems.

The binary states of Boolean variables may be conveniently illustrated by referring to a simple switch. Here the two states are switch open and switch closed. Let us say that an open switch is equivalent to a 0 and a closed switch is equivalent to a 1. (See Fig 3-7.)

Figure 3–7 Simple switch (a) open, (b) closed.

In diagram (a) the switch is open and so there is no connection between points X and Y (0 condition). In diagram (b) the switch is closed and so there is a connection between points X and Y (1 condition). Further use of the switch analogy will be made later. It is important to understand the first basic examples of Boolean algebra, these being OR and AND. They are referred to as the 'OR function' and the 'AND function'.

3.10 The OR Function

This is obeyed in a situation with Boolean variables when a desired result will occur after at **least** one of two (or more) conditions are satisfied. A 'Boolean variable' is a variable with just two possible states such as on or off, open or shut, etc.

To examine the Boolean OR function, the following problem will be considered: assume that a burglar alarm system is fitted to a building; the building has one door and one window, each will cause the alarm to sound if opened ie: alarm sounds if door open OR window open

The alarm has two states – on or off

The door has two states – open or closed

The window has two states – open or closed

The door, the window and the alarm have each got two states and are, therefore, Boolean variables. Since all variables in the problem are Boolean, the problem can be expressed in Boolean algebra. In the statement above, the word OR is used to describe the alarm's dependence on the states of the door and window; OR is called a logical connective. The + symbol is used for the OR function. Thus we can write a Boolean equation to represent the alarm system:

(door open) + (window open) = (alarm sounding)

Note that the + sign is used here quite differently from the way it is used in ordinary mathematics. Before being introduced to the Boolean OR function it was possible to interpret the equation as: 'door open and window open equals alarm sounding' – this is not the same thing at all, although it is also true.

Referring to the switch analogy mentioned earlier, the OR function may be represented as shown in Fig 3-8.

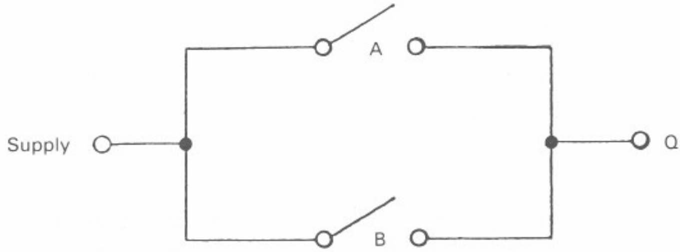


Figure 3–8 The OR function representation.

In Fig 3-8, the switch 'A' could be operated by the door, and switch 'B' could be operated by the window. The Q connection is the burglar alarm.

For a connection to be made between the supply and point Q (the burglar alarm), either switch A (the door) OR switch B (the window) must be closed, ie: Connection (Q) = A+B

It is now possible to construct a table with all possible combinations of states A and B, showing which conditions cause a connection to Q. (Fig 3-9).

A	B	(Q) Connection
Open	Open	No
Open	Closed	Yes
Closed	Open	Yes
Closed	Closed	Yes

Figure 3–9 Basis of a 'Truth Table'.

Reconsider now the case of the two switches represented by the OR function. A closed switch is represented by a 1 and an open switch with a 0. The condition is also represented when a connection (Q) is made with a 1 and the condition when a connection is not made with a 0. The truth table now becomes as in Fig 3-10.

A	B	Q
0	0	0
0	1	1
1	0	1
1	1	1

Figure 3–10 Simple Truth Table.

This is the binary truth table for the Boolean OR function, ie: Q = A=B

The truth table is the same for any OR function of two binary variables and is known as the OR truth table.

Note that Q = 1 if either A = 1 OR B = 1

Taking this a stage further, consider a three-switch circuit as shown in Fig 3-11, and the equivalent truth table in Fig 3-12.

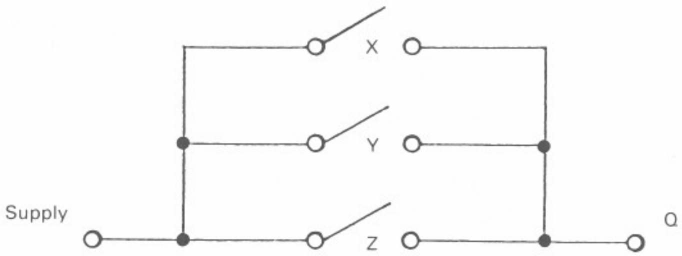


Figure 3–11 A three-switch circuit, X Y and Z.

X	Y	Z	Connection (Q)
0	0	0	0
0	0	1	1
0	1	0	1
0	1	1	1
1	0	0	1
1	0	1	1
1	1	0	1
1	1	1	1

Figure 3–12 Truth table for a three-switch circuit.

This is the connection if switch X or Y or Z is closed, ie: X+Y+Z = Q.

3.11 The AND Function

This is the second of the Boolean functions. If a situation which may be described with Boolean variables gives a desired result when all of several external conditions are satisfied, then that situation is said to obey the Boolean AND function.

The following example explains the AND function in simple terms. Consider a gas-fired central heating system in a building. Figure 3-13 illustrates a schematic for such a thermostatically-controlled system.

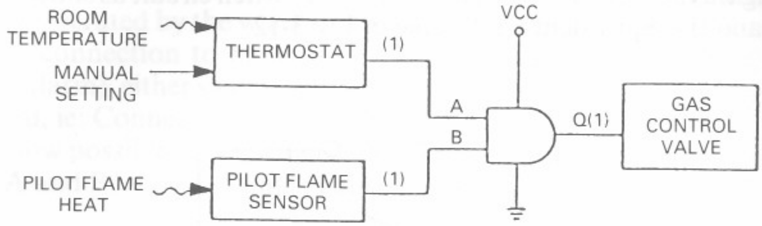


Figure 3–13 Thermostatically-Controlled Gas-Fired Central Heating System.

The thermostat on the wall compares actual room temperature with the desired temperature setting which was manually set. The output wire from the thermostat carries digital information. A high voltage means 'Yes, the room needs more heat'. A low voltage means 'No, the room does not need heat'. This signal is sufficient to turn the gas valve on or off at the proper time.

However, as a safety factor, the system must incorporate a second stream of information. We need a temperature sensor next to the pilot flame which will determine whether this flame is on or not, because we depend upon it to ignite the main burner. In an all-electronic system, the information from this sensing function would be either a high voltage saying 'Yes, the pilot flame is burning', or a low voltage saying 'No, it is not burning'.

ie, **The main burner will be ignited if the thermostat is on AND the pilot flame sensor is on.**

The main burner has two states – on or off

The thermostat has two states – on or off

The pilot flame sensor has two states – on or off

Referring to the switch analogy mentioned earlier, the AND function may be represented as shown in Fig 3-14 where switch A could be the wall thermostat and switch B could be the pilot flame sensor.

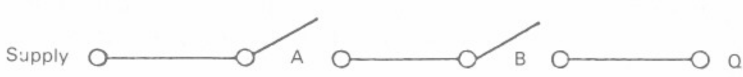


Figure 3–14 The AND switch analogy.

The AND gate has an output which goes to the gas valve control. If the thermostat says 'Yes, we need heat', AND the pilot sensor says 'Yes, the pilot flame is burning', THEN the AND gate decides 'Yes, turn on the gas valve'. On the other hand, if we get a 'No' at EITHER of these inputs, then the output will be 'NO'. Using an AND gate, we get a 'Yes' output ONLY if BOTH inputs are 'Yes'.

Consequently, Boolean algebra may be used to express this situation as: (Thermostat on). (Pilot-flame sensor on) = main gas valve on.

The word AND is the Boolean logical connective for the AND function. In practice the full stop symbol (.) is used for this connective.

The truth table for the thermostatically-controlled gas-fired central heating system is given in Fig 3-15.

Thermostat On	Pilot Flame On	Burner Ignites
No	No	No
No	Yes	No
Yes	No	No
Yes	Yes	Yes

Figure 3–15 The central heating Truth Table.

If we now look at the switch analogy of the AND function and adopt the convention as before, that an open switch is represented by an 0, a closed switch by a 1, a connection (Q) is represented by a 1 and a no connection by a 0, then the truth table is as shown in Fig 3-16.

A	B	C
0	0	0
0	1	0
1	0	0
1	1	1

Figure 3–16 The binary truth table for the Boolean AND function.

The truth table is the same for any AND function of two binary variables and is known as the AND truth table. Note that Q = 1 only if A = 1 AND B = 1. (Q = A.B)

To take this a stage further, using the switch circuit in Fig 3-17, we obtain the corresponding truth table set out in Fig 3-18.

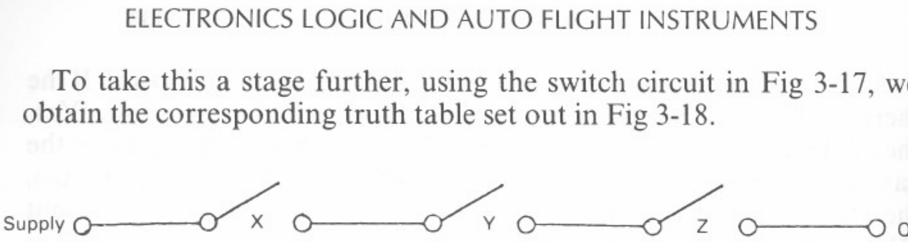


Figure 3–17 The AND switch analogy.

For a connection to be made to Q all three switches X AND·Y AND Z must be closed.

X	Y	Z	Q
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	0
1	0	0	0
1	0	1	0
1	1	0	0
1	1	1	1

Figure 3–18 Connection if switches X, Y and Z are closed, ie Q = X.Y.Z.

3.12 The AND – OR Combination

It is possible to have Boolean algebra expressions which are more complex than just a single AND or OR function. A convenient way of becoming familiar with these is to continue with the switch analogies given in Fig 3-19.

A condition Q is defined where Q = 1, when there is a connection between the supply and Q, Q = 0 where there is no connection. There are two ways of tackling the problem in order to obtain a Boolean equation for Q. The first is to look at the diagram, and see that there is a connection to Q if both A and B are closed or if both A and C are closed, ie: Q = (A AND B) OR (A AND C)

$$Q = A.B + A.C$$

Electrons at the inputs can move only into the inputs, and not out of them, because of the one-way quality of the diodes. Assume a 1 at input A, and a 0 at input B. Electrons would flow from the high electron voltage at the input to produce a high voltage (1) at the output. The only way to get a 0 at the output is to have 0s at both inputs.

This very simple concept poses the question, why have diodes at all – why not just let the electrons flow through the wires? To answer that, consider what would happen if we had a 1 at input A and a 0 at B. Without the diode on the input path to block outgoing electron current, we would have a short-circuit path, and electrons would run out through this path, rather than through the output. The output voltage would then lie at some indefinite point between high and low. The output would not be a clear cut YES or NO, which is what the computer wants, nor a 'maybe' otherwise the computer will not work. So we need diodes to build this kind of simple logic gate.

If the diodes are turned around so that they block current from coming into the inputs, we would have an AND gate. All the gates described and others later, use a diode matrix arranged in such a manner as to produce the required switching.

There are a number of variations of symbols used for logic gates, and those used in these notes are to MIL standard 806. The basic symbols are shown in Fig 3-21.

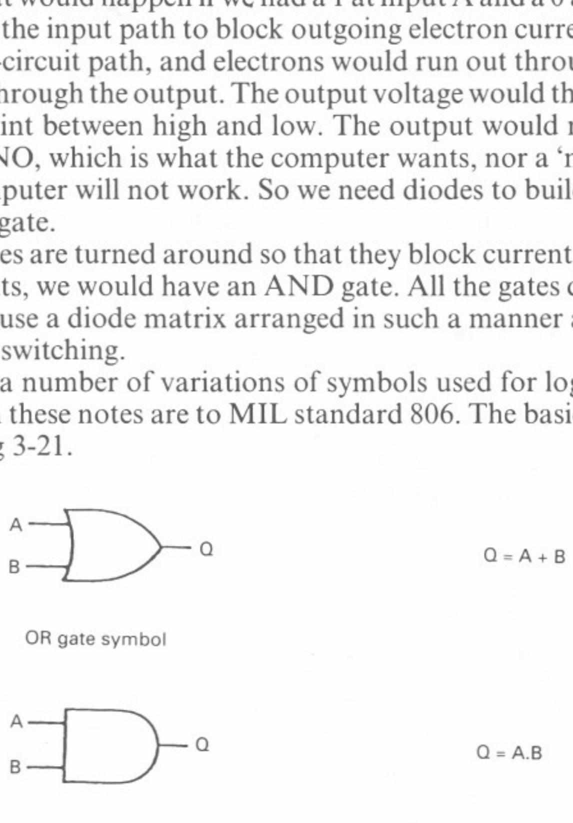


Figure 3–21 Symbols used for logic gates.

We have already seen how to use switches to perform logic functions. In fact the very early computers did actually use electronically controlled electro-magnetic switching, which used coils, a lot of power, and were very slow. Modern computers use thousands of logic gates and although they are associated with circuits that provide power, are becoming very fast indeed.

The AND or OR gates introduced earlier, may be interconnected to perform a variety of Boolean functions, the binary output voltage patterns of gates being the input information to other gates, as shown at Fig 3-22.

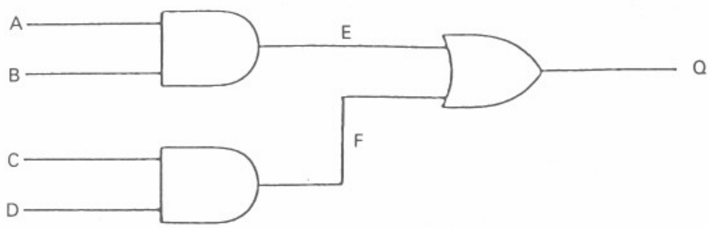


Figure 3–22 Interconnection of AND gates and OR gate to perform more complex logic states.

In Fig 3-22 we see that the logic is:

E = A.B

and F = C.D

also that Q = E+F

Therefore Q = A.B + C.D

So for the logic diagram shown in Fig 3-22, the Boolean equation for the output Q in terms of the input A, B, C and D is:

Q = A.B + C.D

When designing logic circuits, the process is generally the reverse of that shown in Fig 3-22, ie we would first have to formulate a Boolean expression which adequately described the problem and then the expression would need to be translated into a logic diagram.

For example, suppose a certain item of machinery is to have an electronic control circuit to switch off the machine or reduce inputs when certain parameters reach critical values. Assume that there are four parameters, their critical values being indicated by electronic signals W, X, Y and Z. The machine must be stopped if W and X become critical at the same time, or if W, Y and Z become critical together.

To check the requirement, the machine must be stopped if **W and X** are critical, or if **W and Y and Z** are critical. This suggests the Boolean expression: W.X + W.Y.Z which may be simplified to W.(X+Y.Z). It now remains to construct a logic diagram, and it is best to start from the output, and also from within the brackets of the expression and working outwards, we then obtain the diagram shown in Fig 3-23.

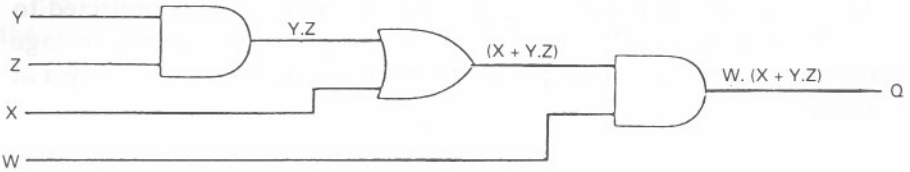


Figure 3–23 A logic diagram.

3.14 The NOT Function

So far there is one important Boolean function which has not been introduced. This is the NOT function.

The NOT function is used, just as it sounds, to describe the INVERSE of an expression, ie:

If A means:	switch A is closed
	Lock A is secure
	point A is at a positive voltage etc
Then NOT A means:	switch A is open
	Lock A is not secure
	point A is at a negative voltage or zero volts etc.

NOT A is written $\bar{A}$ and is pronounced in many ways including NOT A, bar A, A barred, the complement of A, the inverse of A etc.

If the NOT function is applied again, ie to $\bar{A}$, the result is NOT A written $\bar{\bar{A}}$, which is the equivalent of A again, since the inversion becomes the original. The symbol for an electronic NOT gate, more commonly now called an INVERTOR is shown in Fig 3-24.

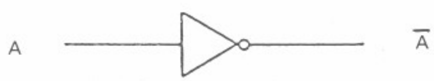


Figure 3–24 Symbol for an Electronic NOT gate (an invertor).

3.15 The Exclusive–OR Function (EX–OR) or (XOR)

The Exclusive–OR function is a Boolean function which differs slightly from the normal OR function already introduced. (The normal OR function is often called the Inclusive-OR function). The differences may be seen from the truth tables in Fig 3-25 and 3-26.

Input A	Input B	Output
0	0	0
0	1	1
1	0	1
1	1	0

Figure 3–25 Exclusive-OR truth table.

Input A	Input B	Output
0	0	0
0	1	1
1	0	1
1	1	1

Figure 3–26 Inclusive-OR truth table.

Notice that whereas the NORMAL OR function (Inclusive–OR) gives a 1 output if any input is a 1, the Exclusive–OR function gives a 1 output if either input is at a 1 but not if both inputs are at 1. A device which performs the Exclusive–OR function is called an Exclusive–OR gate, sometimes referred to as a non-equivalence gate, since if the inputs are not equivalent then the output is a 1. See the appropriate symbol in Fig 3-27.

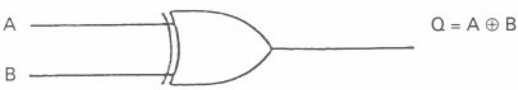


Figure 3–27 The symbol for an Exclusive-OR gate.

There is a new Boolean symbol introduced in Fig 3-27 (⊕). This symbol represents the XOR operation (also it will be seen later in the XNOR) operation. To find the output (Q) of these devices, refer to the truth tables.

More often than not when designing logic circuits we only have the normal OR and AND functions and invertors available. Therefore if we require the Exclusive–OR function we must first know how to implement them with these devices. To do this it must first be expressed in a Boolean algebraic form which is best derived from a study of the truth table. There is a 1 output (Q) when:

A = 1, B = 0 or when A = 0, B = 1

The Boolean representation for the condition A = 1, B = 0 is $A.\bar{B}$ ie, A AND (NOT B).

The Boolean representation for the condition A = 0, B = 1 is $\bar{A}.B$ ie, (NOT A) AND B.

Therefore Q = 1 for $A.\bar{B}$ OR $\bar{A}.B$

ie, $Q = A.\bar{B} + \bar{A}.B$ (written as Q = A + B)

This is the Boolean representation of the Exclusive–OR function.

3.16 The NAND Function

This is a Boolean function which is simply a combination of the NOT function (invertor) and the AND function, ie NOT AND is abbreviated to NAND. Consequently the NAND function may be represented as in the circuit in Fig 3-28.

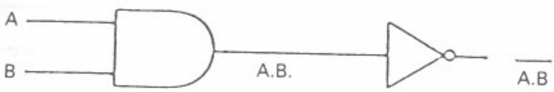


Figure 3–28 The symbol for the NAND circuit.

The NAND of two variables A and B represented in Boolean algebra as A.B. meaning the NOT (or inversion) of A.B. The symbol for the single gate which performs the NAND function is shown in Fig 3-29, and the truth table in Fig 3-30.

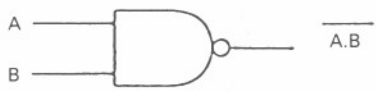


Figure 3–29 The symbol for the NAND function.

As with an invertor, the small circle on the output of the gate indicates an inverted output.

A	B	$\overline{A.B}$
0	0	1
0	1	1
1	0	1
1	1	0

Figure 3–30 Truth table for a two input NAND gate.

3.17 The NOR Function

It has been seen that NAND means the NOT AND function, similarly the NOR function is the NOT OR function and a circuit is shown in Fig 3-31.

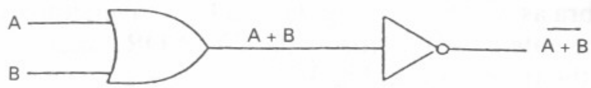


Figure 3–31 The symbols for the NOR circuit.

The NOR function of two variables A and B is represented in Boolean algebra as $\overline{A + B}$ meaning the NOT (or inversion) of A + B. The symbol for a gate which performs the NOR function is shown in Fig 3-32, and the truth table in Fig 3-33.

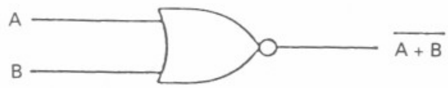


Figure 3–32 The symbol for the NOR function.

As with an invertor, the small circle on the output of the gate indicates an inverted output.

A	B	$\overline{A \oplus B}$
0	0	1
0	1	0
1	0	0
1	1	0

Figure 3–33 Truth table for a two input NOR gate.

3.18 The Exclusive–NOR Function (Ex–NOR)

This is the inverse function of Exclusive–OR (EX–OR). It was pointed out earlier that the EX–OR gate is sometimes called a 'non-equivalence' gate. Consequently the EX–NOR gate may be called an 'Equivalence gate', since the output will be 1 if the inputs are identical (equivalent). The EX–NOR function may be performed by the circuit in Fig 3-34.

Figure 3–34 The symbols for the EX-NOR circuit.

The EX–NOR function of the two variables A and B is represented in Boolean algebra as $\overline{A \oplus B}$, meaning the NOT (or inversion) of A + B. The symbol for the gate which performs the EX–NOR function is shown in Fig 3-35 and the truth table in Fig 3-36.

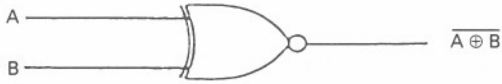


Figure 3–35 The symbol for the EX-NOR function.

As with the invertor, the small circle on the output of the gate indicates an inverted output.

A	B	$\overline{A \oplus B}$
0	0	1
0	1	0
1	0	0
1	1	1

Figure 3–36 Truth table for the Equivalence gate (EX-NOR gate).

NAND and NOR gates can also perform respectively the AND and OR functions, but in such cases this is achieved by additional inversion (the effect of one inversion is always cancelled by adding a second) at the output. It is also possible for a NAND gate to perform an OR function and a NOR gate to perform an AND function, and this can be done by inverting the inputs and outputs. Thus, any of the three basic logic functions can be performed with either a NAND gate or a NOR gate, permitting some economy to be achieved in applying them to certain digital circuits.

Logic gates are fabricated as Integrated Circuit packs (ICs) either in dual, triple or quadruple circuit arrangements. Figure 3-37 and 3-38 show typical arrangements contained in a dual-in-line (DIL) pack monolithic IC. The numbered squares represent the connecting pins. (TTL means Transistor-Transistor-Logic).

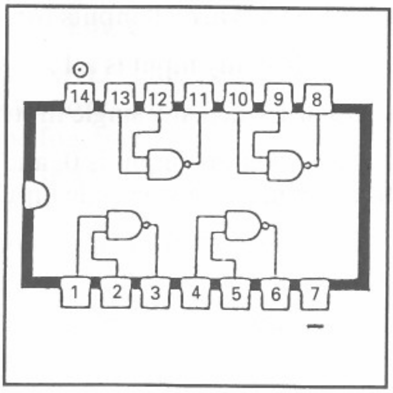


Figure 3–37 DIL type 7400 TTL quadruple 2–input NAND gates.

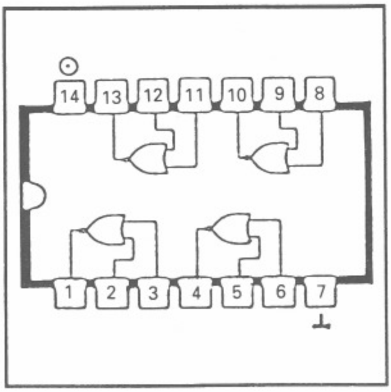


Figure 3–38 DIL type 7402 TTL quadruple 2-input NOR gates.

3.19 Summary of Boolean Functions and Logic Gates

At this point it is useful to summarise the work covered in this chapter. We have seen what is meant by the Boolean functions: AND; OR; EX–OR; NOT; NAND; NOR; EX–NOR. The definitions of these functions are restated below. Also, we have discussed their implementation and use as logic gates. Figure 3-39 shows a summary of Boolean functions, logic gates and truth tables.

the **AND** function gives a 1 only when all inputs (or variables) are 1

The **OR** function gives a 1 when any input is a 1

The **EX–OR** function gives a 1 when any single input is a 1

The **NOT** function gives a 1 when the input is 0, and a 0 when the input is a 1. The NOT function can have only a single input (variable)

The **NAND** function gives a 0 only when all inputs are 1, being the inverse of AND (NOT AND)

The **NOR** function gives a 0 when any input is a 1, being the inverse of OR (NOT OR)

The **EX–NOR** function gives a 0 when any single input only is 1, being the inverse of EX–OR (EX–NOT–OR).

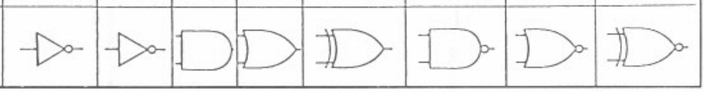
A	B	NOT A $\bar{A}$	NOT B $\bar{B}$	AND A.B	OR A + B	EX-OR $A \oplus B$	NAND $\overline{A.B.}$	NOR $\overline{A + B}$	EX-NOR $\overline{A \oplus B}$
0	0	1	1	0	0	0	1	1	1
0	1	1	0	0	1	1	1	0	0
1	0	0	1	0	1	1	1	0	0
1	1	0	0	1	1	0	0	0	1
SYMBOL									

Figure 3–39 Summary of Boolean functions, logic gates and truth tables.

Test Yourself Three Logic Circuits

1. The Output of an AND Gate:
   (a) has three functions.
   (b) has only one function.
   (c) has four functions.
   (d) has two functions.

   Ref 3.11.

2. A NOT gate is more commonly known as:
   (a) an Invertor.
   (b) a NAND Gate.
   (c) a NOR Gate.
   (d) a Non Gate.

   Ref 3.14.

3. The NAND Function is achieved with the use of:
   (a) a NOT Gate and an OR Gate.
   (b) a reversed AND Gate.
   (c) a NOT Gate and an AND Gate.
   (d) an AND Gate and an OR Gate.

   Ref 3.16.

4. The Logic NOR Function employs the use of:
   (a) an AND and OR Gate.
   (b) an AND and NAND Gate.
   (c) a NOT and OR Gate.
   (d) a NOT and NOR Gate.

   Ref 3.17.

5. Switching within logic gates is normally achieved with the use of:
   (a) Relays.
   (b) CBs.
   (c) BTBs.
   (d) Diodes.

   Ref 3.13.

4

Electronic Instrument Display Systems

4.1 Introduction

It is necessary for students to have an understanding of the modern cockpit displays using Cathode Ray Tubes (CRTs) coming into regular use in the airlines. Before looking at particular systems, it will be useful to understand why the technology has moved in this direction, and some background information is given. There are also a number of new abbreviations which are now in common use, and will be seen on the diagrams.

The introduction of CRT technology for the display of flight systems information represented a milestone in the evolution of the flight deck. The so-called glass cockpit provided a release from the many constraints of earlier electro-mechanical displays; it also permitted the integration of displays, a more effective utilization of high priority panel space, and greater flexibility.

The cathode ray tube used in aircraft has been developed to the stage of presenting to the pilot pictorial colour images of the aircraft systems (more later). Valuable development work was carried out in the 1970s by British Aerospace and Smiths Industries at Weybridge in England on what is known as the AFD or Advanced Flight Deck. At the same time,the technology of producing a satisfactory colour CRT was progressing, particularly in Japan.

It was in the early 1980s that the all-digital Airbus A310 and Boeing 757/767 introduced CRT flight displays in civil aviation and this marked the watershed in the evolution of the glass cockpit. While the technology employed in the displays was not significantly different, conceptually the A310 and A300-600 displays were more advanced than those of the Boeing aircraft.

Boeing used an Electronic Attitude Director Indicator (EADI), the display details of which were similar to those of the electro-mechanical ADI which it replaced. On the other hand, Airbus took advantage of the research on the Weybridge AFD and elected to introduce a Primary Flight Display (PFD) which incorporated the main airspeed indication, selected altitude and deviation, full flight mode annunciation and various other items of information. The A310 flight director was conventional but could, on selection, be changed to a flight path vector display.

There was little difference between the CRT Navigation Display (ND) on these aircraft, providing a map mode, a reproduction of the conventional Horizontal Situation Indicator (HSI) and superimposition of weather radar. However, the concept of system display was quite different. The Airbus Electronic Centralised Aircraft Monitoring (ECAM) system employed two CRTs, one for warning displays and the other for systems. The systems display automatically related to phase of flight but had to be manually selected.

Airbus continued to use conventional dial engine indicators. The Engine Indicating and Crew Alerting System (EICAS) of Boeing used the upper of two CRTs for primary engine parameters with secondary information on the lower screen. No systems diagrams or guidance on corrective actions were displayed on these CRTs, as were available on the Airbus ECAM.

The use of CRTs for flight instrument displays is just one of three flight deck functions for the application of this technology. A second is for the display of systems information. This involves engine data as well as other aircraft systems. The flexibility of this time-sharing form of display enables systems information to be presented only when required, either because of the phase of the operation (such as engine starting) or when a system deviates from its normal operating range. This function includes use as part of the warning system.

The third use of CRTs on the flight deck is for the Flight Management System (FMS). These systems are increasingly being installed, particularly to optimise operating efficiency with a primary objective of reducing fuel consumption. The FMS interfaces with the navigation system.

Introduction of the digital FMS is easier on all the new all-digital aircraft. Retro-fitting on earlier analogue aircraft such as the Boeing 747 is expensive, but in certain cases it has proved cost-effective in fuel saving. A distinction should be made between retro-fitting FMS devices to aircraft already in service, and the more complex versions of FMS designed into new aircraft. The latter can typically ensure reduced workload, compile complicated lateral and vertical profiles and supply data for the electronic flight guidance system.

The CRTs used on the flight deck of modern aircraft can display information to the pilot that in former times was impossible. Furthermore, the old style instrumentation cluttered up practically all available areas in the cockpit. The flight engineer had a vast array of instrumentation to monitor during flight, and modern aircraft using a two pilot crew are able to (electronically) monitor not only the navigation and flying conditions, but engine and aircraft systems.

A further very important area, and in some respects because of the design features of glass cockpits, there is the Warning, Advisory and Alerting systems. In early times, a fire bell and a few lights were all that were fitted, but even in the jet age, warnings increased from 172 on the DC-8 to 418 on the DC-10, and from 188 on the Boeing 707 to 455 on the 747. The glass cockpit display is able not only to alert the crew and call for their attention, but report the nature of the condition and **guide the crew in the appropriate corrective procedure**.

4.2 Cathode Ray Tube (CRT)

The cathode ray tube is still currently the preferred method of presenting the information to the pilot as described in the earlier section. However, the modern CRT is more complex than the earlier monochrome CRTs used in weather radar, as apart from being able to generate colour displays, it is also able to present alpha-numeric data, aircraft system line drawings, pictorial instrumentation and moving weather displays.

A CRT is a thermionic device, ie one in which electrons are liberated as a result of heating. Figure 4-1 shows a schematic of a single electron 'gun' CRT. To generate colour, a three-gun CRT is used and this will be described later.

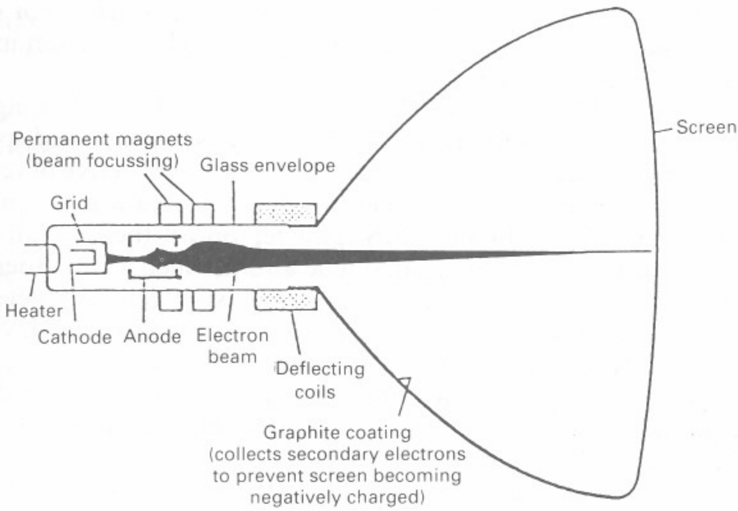


Figure 4–1 Schematic of a single electron 'gun' CRT.

The CRT consists of an evacuated glass envelope, inside which are positioned an electron 'gun' and beam focusing and beam deflection systems. The inside surface of the screen is coated with a phosphor which 'luminesces' when the electron beam strikes it. Control of the electron beam will produce 'pictures' that can be viewed by the pilot.

The electron gun consists of an indirectly heated cathode biased negatively with respect to the screen, a cylindrical grid surrounding the cathode, and two (sometimes three) anodes. When the cathode is heated, negative electrons are liberated and in passing through the anodes they are squeezed to form a beam by negative potential applied to the anodes. Modulation of the beam is also effected by one of the anodes, ie it can be controlled in size (focus) and cut off.

In order to 'trace out' a luminescent display, it is necessary for the spot of light to be deflected about the horizontal and vertical axes, and for this purpose a beam-deflection system is also provided. Deflection systems can be either electrostatic or electro-magnetic, but in aircraft display systems, the electro-magnetic method is used.

An electron beam can be forced to move when subjected to electro-magnetic fields acting across the space within the tube, and coils are therefore mounted around the neck of the tube and are configured so that fields are produced horizontally (X-axis fields) and vertically (Y-axis fields). The coils are connected to the signal sources whose variables are to be displayed, and the electron beam can be deflected to the left or right, up and down, or along some resulting direction depending on the polarities produced by the coils, and on whether one alone is energised, or both are energised simultaneously.

4.3 Colour CRT Displays

Colour CRTs are also used in weather radar display units. In these units, weather data is integrated with the other data displays. The video data received from a radar antenna corresponds to the 'sweeping' movement of the antenna as it is driven by its motor. In a colour display indicator, the scanning of data is somewhat similar to that adopted in the tube of a television receiver, ie 'raster' scanning in horizontal lines, and the data received is converted into an X-Y co-ordinate format. This format also permits the display of other data in areas of the screen where weather data is not displayed. The other scanning technique is called 'stroke' scanning which produces the symbols and alpha-numeric data also presented on the same screen, and this will be described later.

Each time the radar transmitter transmits a pulse, the receiver begins receiving return echoes from 'targets' at varying distances from the transmitter. This data is digitized to provide output levels in binary-coded form, and is supplied to the indicator on two data lines (one data line can supply two states, and two data lines can supply four states).

The binary-coded data can represent four conditions corresponding to the level of return echoes which, in turn, are related to the weather conditions prevailing at the range in nautical miles preselected on the indicator. The data is stored in memories which, on being addressed as the CRT is scanned, will, at the proper time, permit the weather conditions to be displayed. The four conditions are displayed as follows:

Blank screen:	Zero, or low-level returns.
Green:	Low returns (lowest rainfall rate)
Yellow:	Moderate returns (moderate rainfall rate)
Red:	Strong returns (high density rainfall rate)

4.4 Colour Generation

A colour CRT has three electron guns, each of which can direct an electron beam at the screen which is coated with different kinds of phosphor material. The colours are a function of the type of phosphor, the electron guns are virtually identical and it is the method of control of the three beams that determines which of the phosphors are energised.

The phosphors luminesce in each of three colours, red, green and blue. The screen is divided into a large number of small areas or dots, each of which contains a phosphor of each kind as shown in Fig 4-2. The smaller the dot size, the better the resolution of the final picture, within the limitations of manufacturing tolerances.

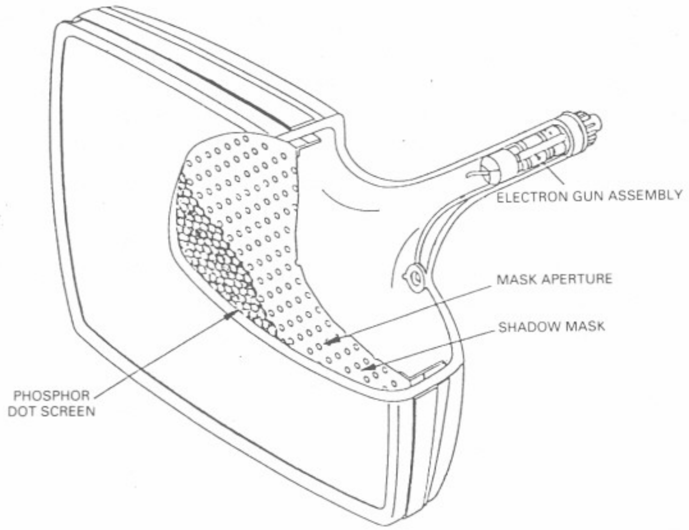


Figure 4–2 A Colour CRT.

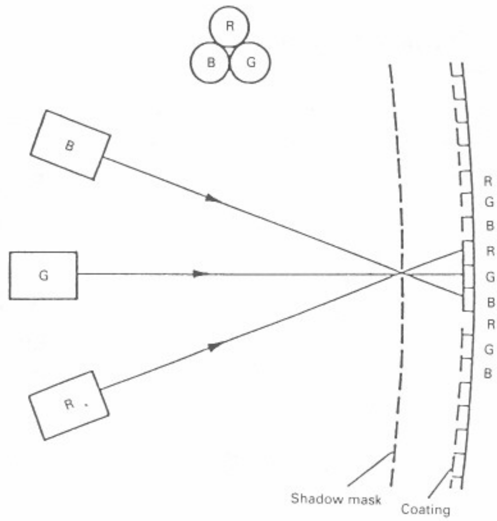


Figure 4–3 Shadow Mask Principle in a Colour CRT.

The beam from a particular gun must be made only to strike screen elements of one colour, and to achieve this in aircraft type CRTs, a perforated steel sheet called a 'shadow mask' is very accurately placed adjacent to the coating of the screen. The perforations are arranged in a regular pattern, and their number depends on the size of the screen; 330,000 is a typical number.

Beams from the three guns pass through the perforations in the mask and they cause the phosphor dots in the coating to luminesce in the appropriate colour, ie the red gun emission will pass through the holes in the shadow mask that are in line with the red phosphor dots, and only red will luminesce. After a full raster sweep of the screen, the eye will perceive a totally red screen as a function of the persistence of vision by the human eye.

For colours other than red, green and blue, control of the electron beams by independent circuitry can effect a kind of 'electronic paint mixing' producing the required colour.

Returning to weather radar displays, the data readout from the memory, apart from being presented at the appropriate location of the CRT screen, must also be displayed in the colours corresponding to the weather conditions prevailing. In order to achieve this, the data is decoded to produce outputs which, after amplification, will turn on the required colour guns.

The output from the memory, which were in two-bit binary, is supplied to a data decoder whose output is three-bit words corresponding to the colours to be displayed, as shown in Fig 4-4.

Outputs to guns			
B_1 Green	B_0 Blue	B_2 Red	Resulting Colours
1	1	1	Black (off)
0	0	0	White
0	0	1	Yellow
0	1	1	Red
1	0	0	Light blue
1	0	1	Green

Figure 4–4 Three-bit words determines the colours.

The three-bit word outputs from the data decoder are then applied to a colour decoder and primary decoder circuit, and this in turn provides three outputs, each of which corresponds to one of the colour guns as shown in the data flow in Fig 4-5.

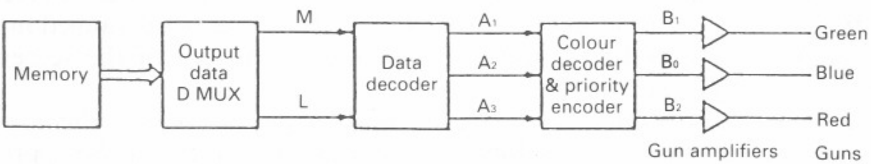


Figure 4–5 Data Flow for Selection of Colour Guns.

The 'Low' state outputs turn on the guns, and it can be seen from Fig 4-4 how simultaneous gun operation produces other colours from a mix of the basic colours. Figure 4-6 shows a typical weather data display together with associated alpha-numeric data, namely ranges in nm, and the operating mode, which in this case is WX signifying 'weather' mode.

4.5 Alpha-numeric Displays

The display of data, in alpha-numeric and symbolic form is wide-ranging. For example, in a weather radar indicator is it usually only required for range information and which modes are selected, while in systems designed to perform functions within the realm of flight management, a very much higher proportion of information must be 'written' on the screens of the appropriate display unit.

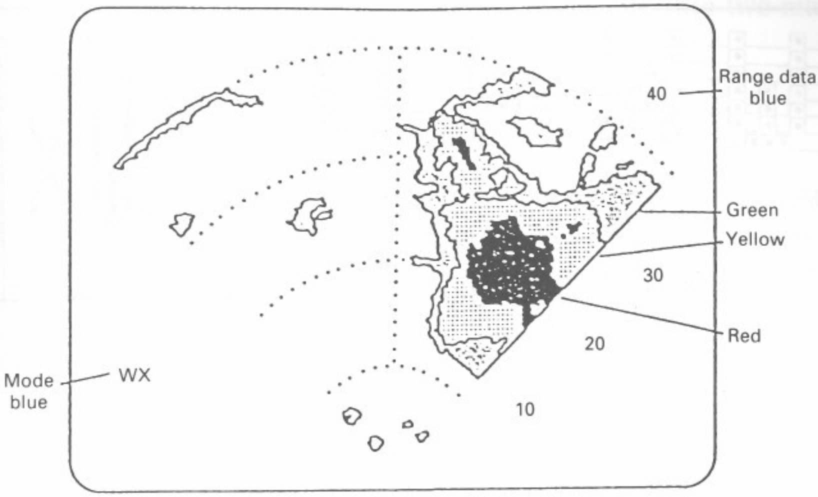


Figure 4–6 Weather Data Display.

This is accomplished in a manner similar to that adopted for the display of weather data, but additional memory circuits, decoders, character and symbol generator circuits are required.

Raster scanning is also used, but where datum marks, arcs (eg engine instrument scales) are to be displayed, a 'stroke pulse' method of scanning is used. The position of each character on the screen is predetermined and stored in a memory.

Figure 4-7 illustrates how the letters WX and the number 40 are formed on the screen of the weather radar display in Fig 4-6. One line of dots is written at a time for the area in which the characters are to be displayed, and it can be seen in Fig 4-7 that seven image lines are required to write the complete characters and/or row of characters, and they have a three dot spacing.

It will be noted also from Fig 4-6 that the mode indication (WX) is displayed in blue, so only the blue electron gun is active in producing these letters.

This particular CRT permits the display of 12 rows each of 32 characters. The CRT display units of more comprehensive electronic instrument systems operate on the same fundamental principles as those just described, but in applying them, more extensive microprocessor circuitry is required in order to process and display far greater amounts of data.

There are symbol generators which supply signals to the beam deflection and colour gun circuits of the CRT, such that its beams are raster and stroke scanned to present the data at the relevant parts of the screen, and in the required colour.

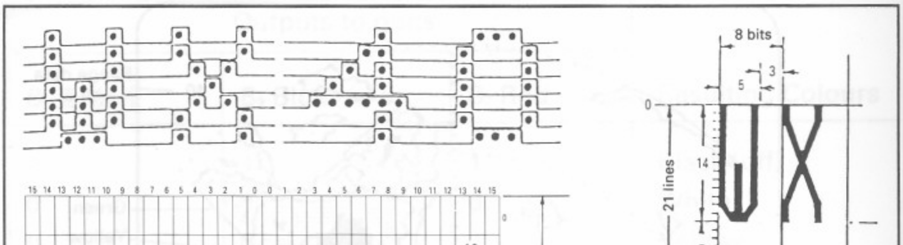


Figure 4–7 Alpha-numeric Display.

The displayed data is in two basic forms: fixed and moving. Fixed data relate in particular to such presentations as symbols, scale markings, names of systems, datum marks, names of parameters being measured, etc. Moving data are in the majority, as they measure changes occurring in the measurement of all parameters essential for in-flight management. The changes are indicated by the movement of symbolic pointers, index marks, digital counter presentations, and system status messages and there are, of course, more.

4.6 Flight Deck Displays

The flight deck displays as shown by the CRTs, are displays necessary for the in-flight operation of the aircraft and its systems, and also for their maintenance. The data is processed by high storage capacity computers, and originates as signals (analogue and/or digital) generated by sensors associated with each individual major system in the aircraft.

The information passed from sensors to displays, falls into two main areas:

(a) Flight Path and Navigational.

(b) Engine and Airframe systems operation.

Appropriate electronic display systems are therefore designed for each of these areas and are known respectively as an Electronic Flight Instrument System (EFIS) and either an Electronic Centralized Aircraft Monitor (ECAM) system, or an Engine Indicating and Crew Alerting System (EICAS). See Fig 4-8 for a flight deck layout of the CRTs, in this example, the Airbus A320.

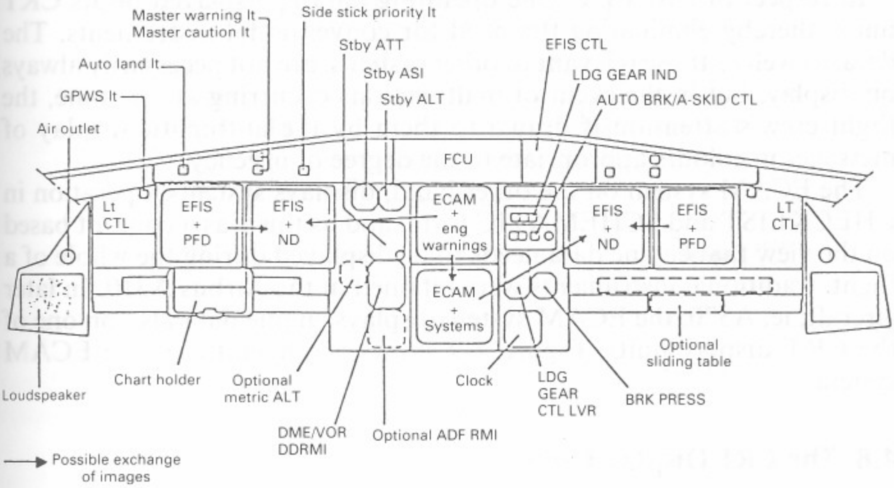


Figure 4–8 EFIS and ECAM CRTs on the Flight Deck of the Airbus A320.

The EFIS installation is made up of left (Captain) and right (First Officer) systems. Each system is made up of two display units. There are certain differences in the terminology used in some modern all glass cockpits; some displays are called Electronic Attitude Director Indicator (EADI) and Electronic Horizontal Situation Indicator (EHSI) whilst the Airbus A320 display (Fig 4-8) is labelled PFD (Primary Flight Display) and ND (Navigation Display).

The flight deck display system also has a control panel, a symbol generator (SG) and a remote light sensor unit. A third (centre) SG is also incorporated so that drive signals may be switched either to the left or the right display units in the event of failure of the corresponding SGs. In

Fig 4-8, the arrows drawn between the EFIS and ECAM displays show how these displays may be switched.

As far as electrical systems are concerned, the operational monitoring is handled either by an ECAM system or by EICAS.

The main presentations of ECAM, EICAS and EFIS will now be described.

4.7 The ECAM and EICAS Systems

The ECAM system (Electronic Centralized Aircraft Monitoring) was introduced in the Airbus A310, and the EICAS system (Engine Indicating and Crew Alerting System) was introduced in Boeing 757 and 767 aircraft.

In respect of EICAS, engine operating data is displayed on its CRT units, thereby eliminating the need for conventional instruments. The data, as well as those relevant to other systems, are not necessarily always on display, but in the event of malfunctions occurring at any time, the flight crew's attention is drawn to them by the automatic display of messages in colours appropriate to the degree of urgency.

The ECAM system on the other hand, displays systems' operation in CHECKLIST and SCHEMATIC form, and as this was a concept based on the view that engine data needs to be displayed during the whole of a flight, traditional instruments were retained in the Airbus A310. In later aircraft, ie, A320, the ECAM system displays engine data also on one of the CRT display units. Figure 4-9 shows a schematic of the ECAM system.

4.8 The CRT Display Units

Units are mounted side by side so that the left-hand unit is dedicated to information in message form on systems' status, warnings and corrective action required, while the right-hand unit is dedicated to associated information in diagrammatic form (sometimes referred to as synoptic format).

There are four modes of display, three of which are automatically selected and referred to as: Flight Phase-Related, Advisory and Failure Related. The fourth mode is manual and permits the selection of diagrams relating to any of the aircraft's systems for routine checking and also the selection of status messages. The selections are made on the ECAM control panel. (See Fig 4-10.)

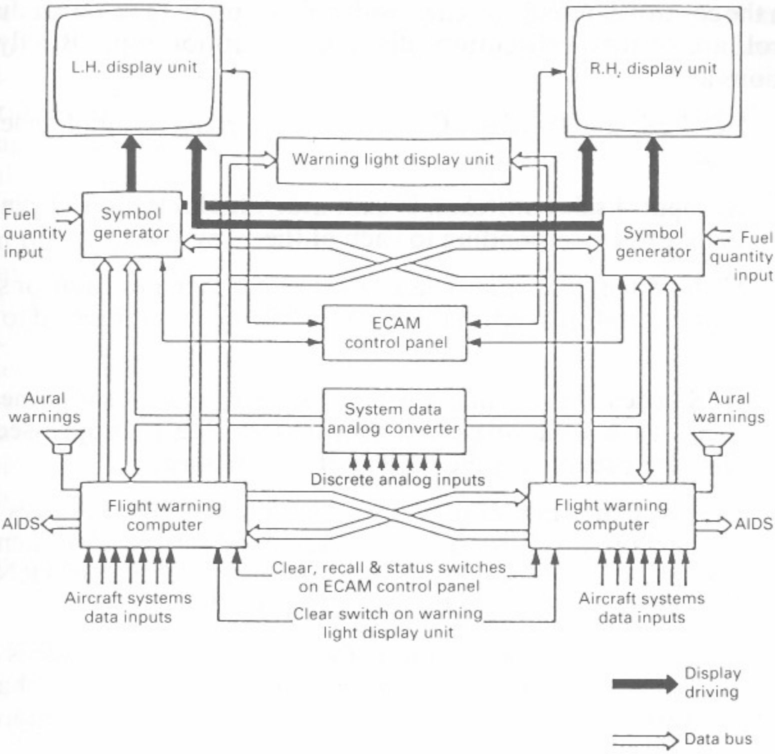


Figure 4–9 Schematic Functional Diagram of the ECAM system.

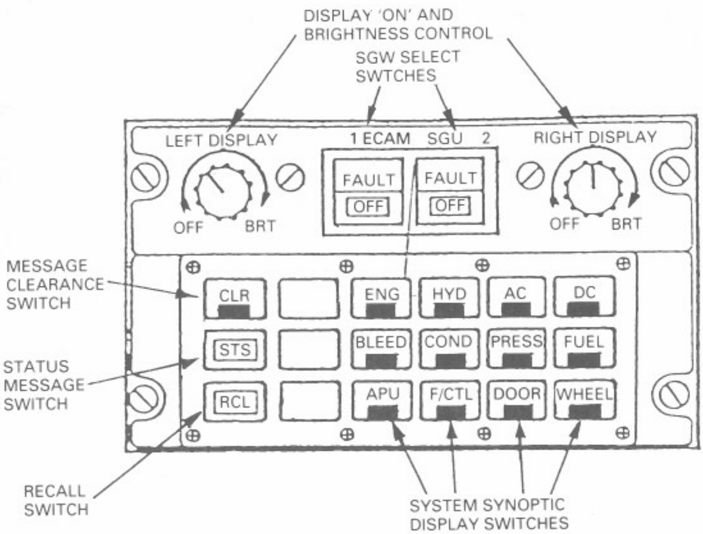


Figure 4–10 ECAM Control Panel.

On the control panel all switches, with the exception of those for display control, are of the push-button, illuminated caption type. Briefly, the functions are:

1 **SGU selector switches**. Control the respective symbol generator units.

2 **Synoptic display switches**. Permit individual selection of synoptic diagrams corresponding to each of the 12 systems.

3 **CLR switch**. Light illuminated white whenever a warning or status message is displayed on the left-hand display unit. Pressed to clear messages.

4 **STS switch**. Permits manual selection of an aircraft status message if no warning is displayed. Status message is suppressed if a warning occurs or if the CLR switch is pressed.

5 **RCL switch**. Enables previously cleared warning messages to be recalled provided the failure conditions which initiated them still exist. If a failure no longer exists the message 'NO WARNING PRESENT' is displayed on the left-hand display unit.

In normal operation the automatic flight phase-related mode is used, and in this case the displays are appropriate to the current phase of aircraft operation, ie pre-flight, take-off, climb, cruise, descent, approach, and after landing.

An example of a pre-flight phase is shown in Fig 4-11; the left-hand display unit shows an advisory memo mode, and the right-hand unit shows a diagram of the aircraft's fuselage doors and arming of the escape slides deployment system.

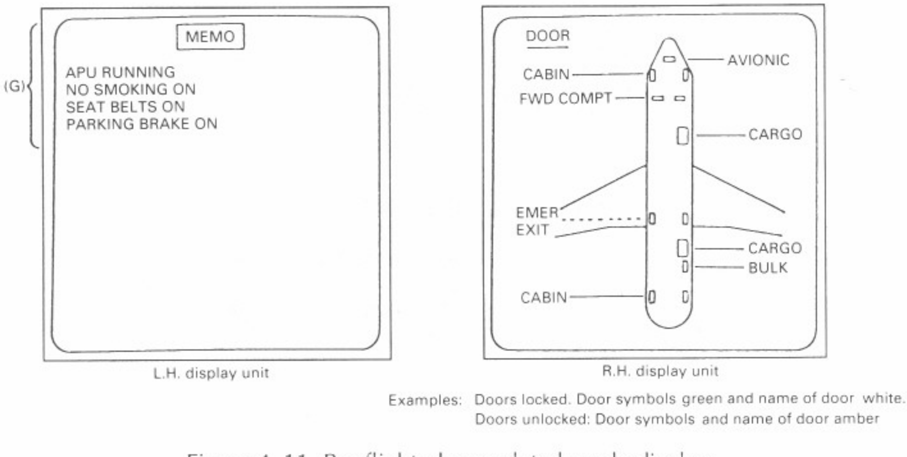


Figure 4–11 Pre-flight phase-related mode display.

The failure-related mode takes precedence over the other two modes and the manual mode. An example of a failure-related mode is shown in Fig 4-12. In this case there is problem associated with the number one generator. The left-hand display unit shows the affected system in message form, and in red or amber depending on the degree of urgency, and also the corrective action required in blue.

At the same time, a diagram is displayed on the right-hand display unit. When the number one generator has been switched off, the light in the relevant push-button switch on the flight deck overhead panel is illuminated, and simultaneously, the blue instruction on the left-hand display unit changes to white.

The diagram on the right-hand display unit is also 'redrawn' to depict by means of an amber line that the number one generator is no longer available, and that number two generator is supplying the busbar system.

This is displayed in green, which is the normal operating colour of the displays. After corrective action has been taken, the message on the left-hand unit can be removed by operating a 'clear' button switch located on the ECAM control panel.

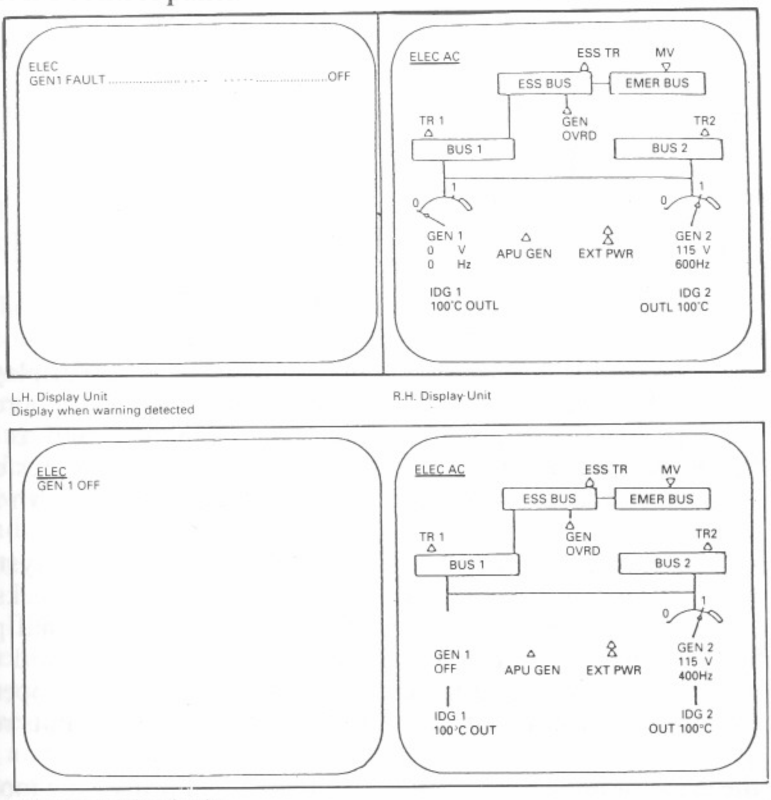


Figure 4–12 ECAM Displays showing number one generator fault.

In the event of a single system malfunction, by convention such warnings are signified by under-lining the system title displayed. In Fig 4-11, the fault is electrical in the AC generator and ELEC is shown underlined in the left-hand display and ELEC AC is shown underlined in the right-hand display.

In cases where a failure can affect other sub-systems, the title of the sub-system is shown **'boxed'**, as shown in Fig 4-13. Warnings and the associated lights are cleared by means of CLEAR push-button switches either on the ECAM control panel or the warning light display panel.

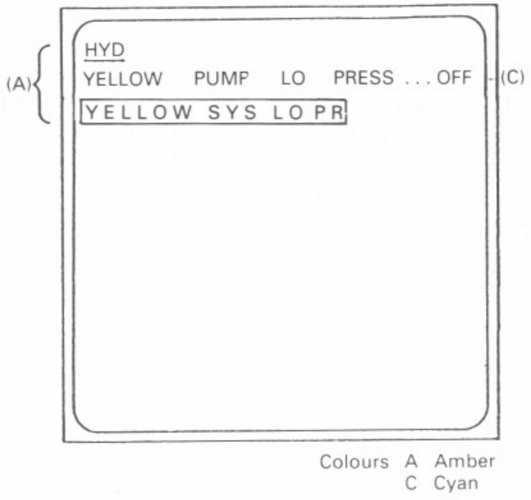


Figure 4–13 Display of Failure Affecting a sub-system.

Status messages, which are also displayed on the left-hand display unit, provide the flight crew with an operational summary of the aircraft's condition, possible downgrading of autoland capability, and as far as possible, indications of the aircraft status following all failures except those that do not affect the flight. An example display is shown in Fig 4-14.

System testing. Each flight warning computer of the system is equipped with a monitoring module which automatically checks data acquisition and processing modules, memories, and internal power supplies as soon as the aircraft's main power supply is applied to the system. A power-on test routine is also carried out for correct operation of the symbol generator units. During the test, the display units remain blank.

In the event of failure of the data acquisition and processing modules, or of any of the warning light display panel, a FAILURE WARNING

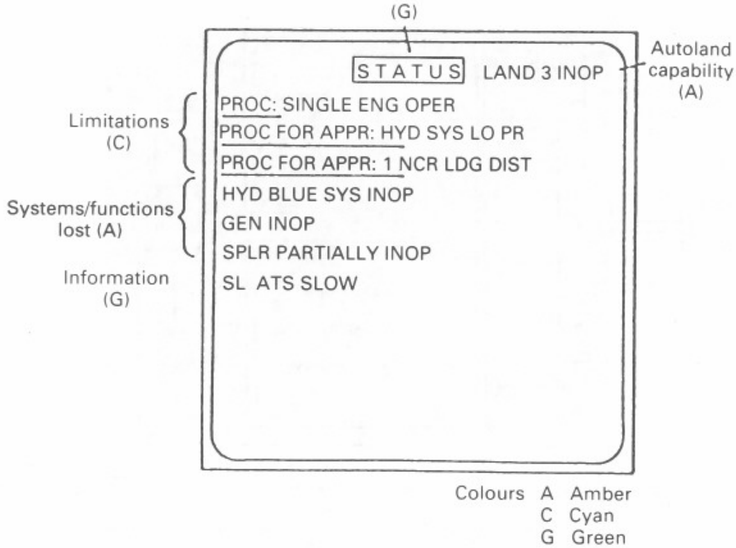


Figure 4–14 Example of a Status Display.

SYSTEM LIGHT on the panel is illuminated. Failure of a computer causes a corresponding annunciator light on the maintenance panel captioned FWC FAULT to illuminate. An SG unit failure causes a FAULT caption on the appropriate push-button switch on the system control panel to illuminate.

4.9 The EICAS System comprises two display units, a control panel, and two computers supplied with analog and digital signals from engine and system sensors as shown in the schematic in Fig 4-15.

Operating in conjunction with the system are discrete caution and warning lights, standby engine indicators and a remotely-located panel for selecting maintenance data displays. The system provides the flight crew with information on primary engine parameters (full-time), with secondary engine parameters and advisory/caution/warning alert messages displayed as required.

4.10 Display units provide a wide variety of information relevant to engine operation, and the operation of other automated systems. The display units are mounted one above the other, as in Fig 4-16.

The upper unit displays the primary engine parameters N_1, speed, EGT, and warning and caution messages. In some cases this unit can also display EPR depending on the type of engines installed. The lower unit

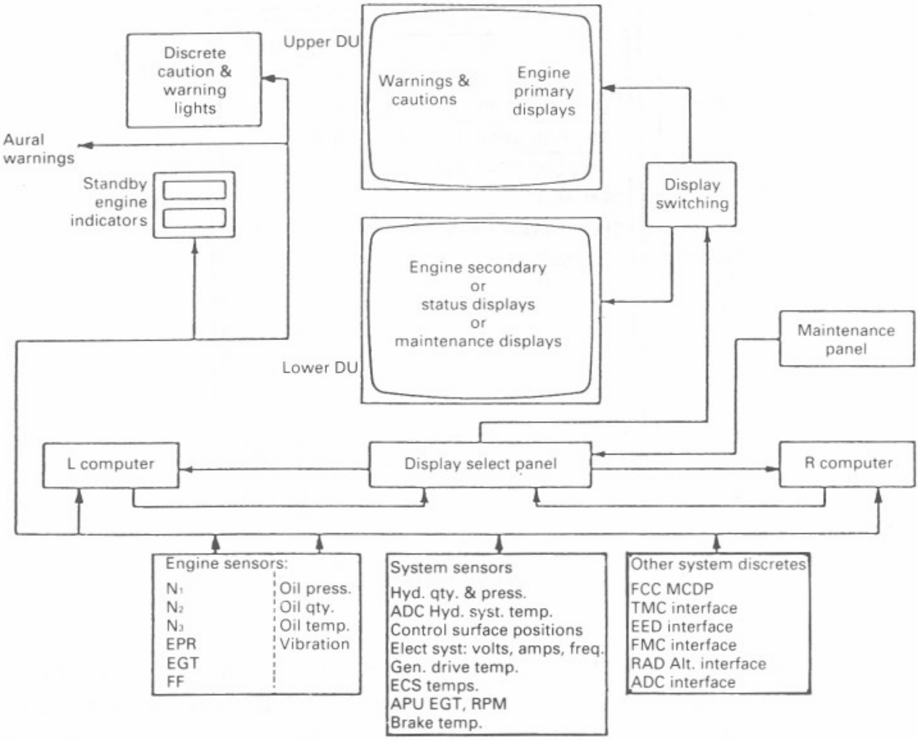


Figure 4–15 EICAS functional schematic.

displays secondary engine parameters, ie N_2 speed, fuel flow, oil quantity, pressure and temperature, and engine vibration. In addition, the status of non-engine systems, ie flight control surface position, hydraulic system, APU, etc. It can also be displayed together with aircraft configuration and maintenance data.

Referring to Fig 4-16, the row of 'V's shown on the upper display unit only appear when secondary information is being displayed on the lower unit.

Seven colours are produced by the CRTs and they are used as follows:

White All scales, normal operating range of pointers, digital readouts.

Red Warning messages, maximum operating limit marks on scales, digital readouts.

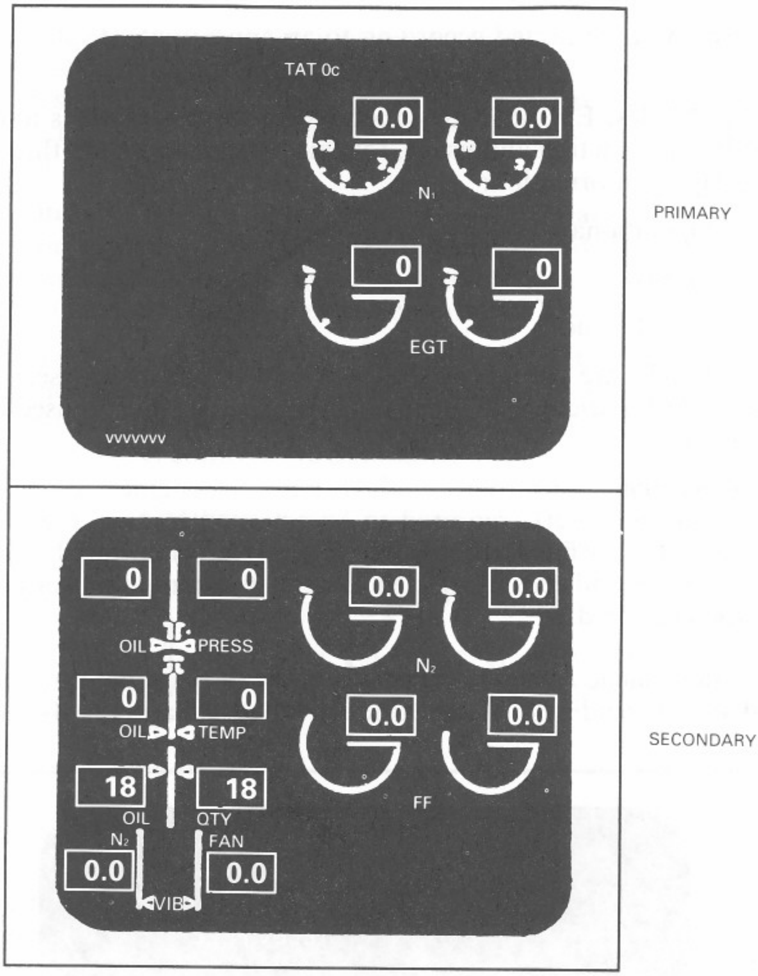


Figure 4–16 EICAS: engine data displays.

Green Thrust mode readout and selected EPR/N_1 speed marks or target cursors.

Blue Testing of system only.

Yellow Caution and advisory messages, caution limit marks on scales, digital readouts.

Magenta During in-flight engine starting, and for cross-bleed messages.

Cyan Names of all parameters being measured (eg N_1 oil pressure, TAT, etc) and status marks or cues.

The displays are selected according to an appropriate display selection mode.

Display Modes. EICAS is designed to categorize displays and alerts according to function and usage, for this purpose there are three modes of displaying information:

1 Operational

2 Status

3 Maintenance.

Modes 1 and 2 are selected by the flight crew on the display select panel, while mode 3 is selected on the maintenance panel which is used by engineers only.

4.11 Operational mode. This mode displays the engine operating information and any alerts required to be actioned by the crew in flight. Normally only the upper display unit presents information, the lower one remains blank and can be selected to display secondary information as and when required.

4.12 Status mode. When selected this mode displays data to determine the dispatch readiness of the aircraft. The display (Fig 4-17) shows

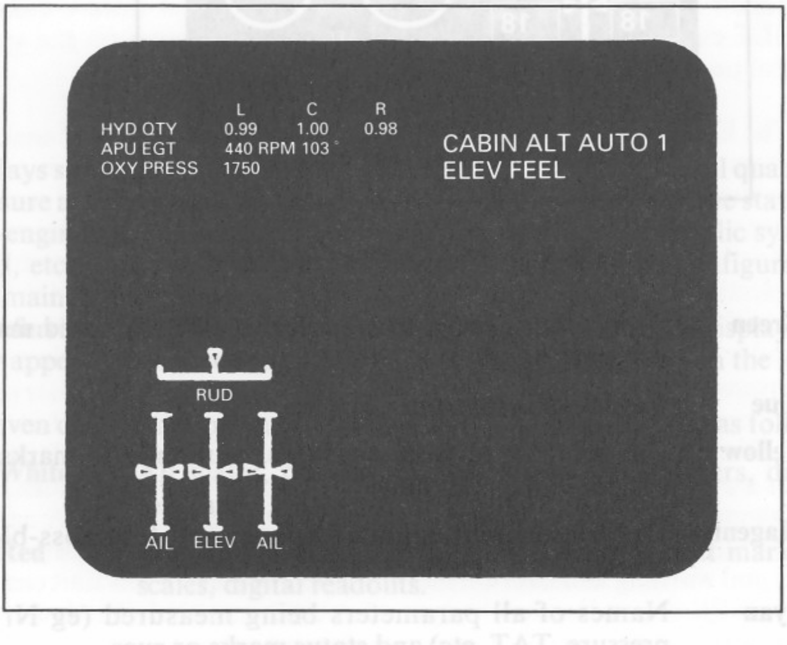


Figure 4–17 Status Mode Display.

position of flight control surfaces against vertical scales (rudder against a horizontal scale). Other items are shown such as selected sub-systems and equipment status. Selection is normally done on the ground as part of the pre-flight checks, or just before shut-down to help the crew complete the aircraft technical log.

4.13 Maintenance mode. This mode provides maintenance engineers with information in five different display formats to aid them in trouble-shooting and verification testing of major sub systems. The displays are presented on the lower display unit. They are NOT available in flight.

4.14 Display select panel. This permits control of EICAS functions and displays and can be used both in flight and on the ground. It is normally located on the centre pedestal of an aircraft's flight deck. See Fig 4-18. Display select panel controls are as follows:

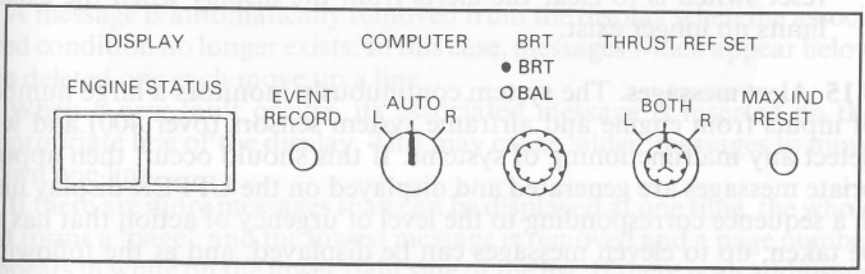


Figure 4–18 EICAS display select panel.

1. **Engine display switch.** This is of the momentary-push type for removing or presenting the display of secondary information on the lower display unit.
2. **Status display switch**. Also of the momentary-push type, this is used to display the status mode information as already described, see Fig 4-14 for an example.
3. **Event record switch.** This is a momentary-push type and is used in the air, or on the ground, to activate the recording of fault data relevant to the environmental control system, electrical power, hydraulic system, performance of APU. Normally, if any malfunction occurs in a system, it is recorded automatically (called an '**auto event**') and stored in memory of the EICAS computer. The push switch also enables the flight crew to record a suspect malfunction for storage, and is called a '**manual event**'. The relevant data can only be retrieved from memory and displayed when the aircraft is on the ground and by operating switches on the maintenance control panel.

4. **Computer select switch.** In the AUTO position it selects the left, or primary, computer and automatically switches to the other computer in the event of failure. The other positions are for the manual selection of left or right computers.

5. **Display brightness control.** The inner knob controls the intensity of the two displays, and the outer knob controls the brightness balance between the two displays.

6. **Thrust reference set switch.** Pulling and rotating the inner knob positions the reference cursor on the thrust indicator display (either EPR or N_1) for the engine(s) selected by the cursor.

7. **Maximum indicator reset switch.** If any one of the measured parameters, eg oil pressure, EGT, should exceed normal operating limits, this will be automatically alerted on the display units. The purpose of the reset switch is to clear the alerts from the display when the excess limits no longer exist.

4.15 Alert messages. The system continuously monitors a large number of inputs from engine and airframe system sensors (over 400) and will detect any malfunctioning of systems. If this should occur, then appropriate messages are generated and displayed on the UPPER display unit in a sequence corresponding to the level of urgency of action that has to be taken; up to eleven messages can be displayed, and at the following levels:

Level A Warning requiring immediate corrective action. Displayed in red. Master warning lights are also illuminated, and an aural warning (eg fire bell) from a central warning system is given.

Level B Cautions requiring immediate crew awareness and possible action. Displayed in amber, and also by message caution lights. An aural tone is also repeated twice.

Level C Advisories requiring crew awareness, also displayed in amber. No caution lights or aural tones are associated with this level.

The messages appear on the top line at the left of the display screen as shown in Fig 4-19. In order to differentiate between a caution and an advisory, an advisory message is indented one space to the right.

The master warning and caution lights are located adjacent to the display units together with a Cancel switch and a Recall switch. Pushing the Cancel switch removes only the caution and advisory messages from the display. Warning messages cannot be cancelled. The Recall switch is used to bring back the caution and advisory messages into the display, at the same time, the word RECALL appears at the bottom of the display.

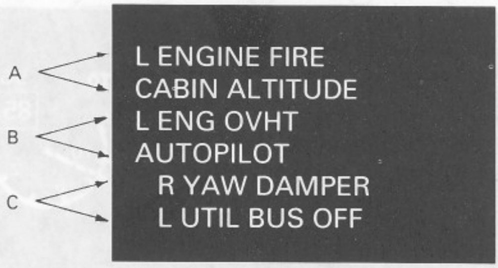


Figure 4–19 Alert Message Levels.

A message is automatically removed from the display when the associated condition no longer exists. In this case, messages which appear below the deleted one each move up a line.

When a new fault occurs, its associated message is inserted on the appropriate line of the display. This may cause 'older' messages to move down one line.

If there are more messages than can be displayed at one time, the whole list forms a 'page', and the lowest message is removed and a page number appears in white on the lower right side of the list. If there is an additional page of messages it can be displayed by pushing the Cancel switch. Warning messages are carried over from the previous page.

4.16 Display unit failure. If the lower display unit should fail when secondary information is being displayed on it, an amber alert message appears at the top left of the upper display unit, and the information is transferred to it as shown in Fig 4-20. The format of this display is referred to as COMPACT, and may be removed by pressing the ENGINE switch on the display select panel. (Fig 4-16). Failure of a display unit causes the function of the display select panel STATUS switch to be inhibited so that the status page format cannot be displayed.

4.17 Display select panel failure. If this panel fails the advisory message 'EICAS CONTROL PANEL' appears at the top left of the upper display unit together with the primary information, and the secondary information automatically appears on the lower display unit. The cancel/recall switches do not operate in this failure condition.

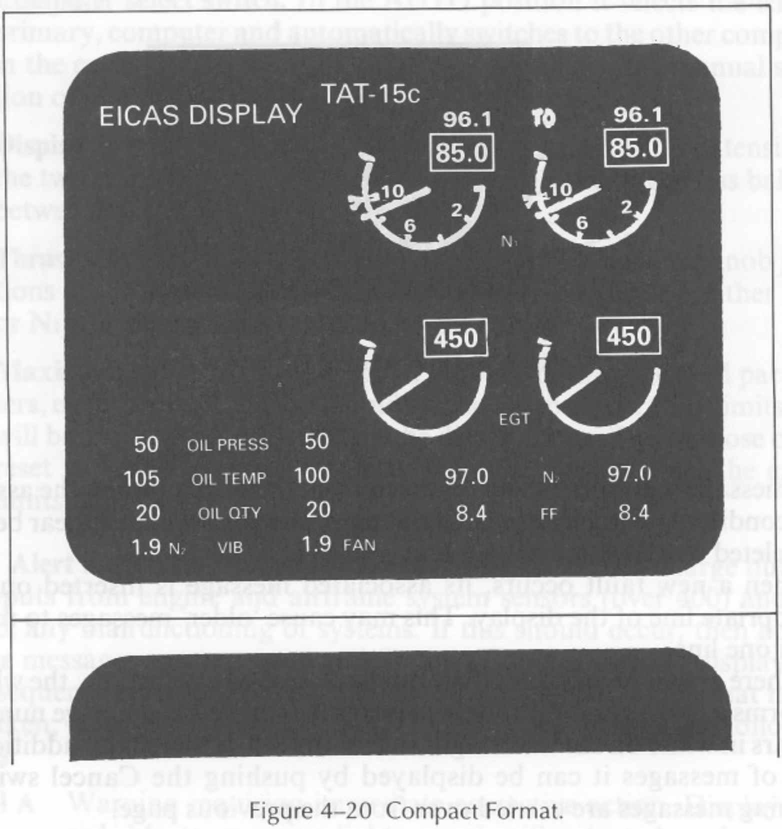


Figure 4–20 Compact Format.

4.18 Standby engine indicator. This indicator provides primary engine information in the event that a total loss of the EICAS displays occurs (see Fig 4-21). The information relates to N_1 and N_2 speeds and EGT, the displays are of the LCD type. Operating limit values are also displayed.

The display control switch has two positions ON and AUTO. In the ON position, the displays are permanently on. In the AUTO position the internal circuits are functional, but the displays will automatically be presented when the EICAS displays are lost due to failure of both displays, or failure of both computers. There is a test switch which selects either of two power supplies.

4.19 Maintenance control panel. This panel is used by maintenance engineers for the purpose of displaying data stored in system computer memories during flight or ground operations. (See Fig 4-22).

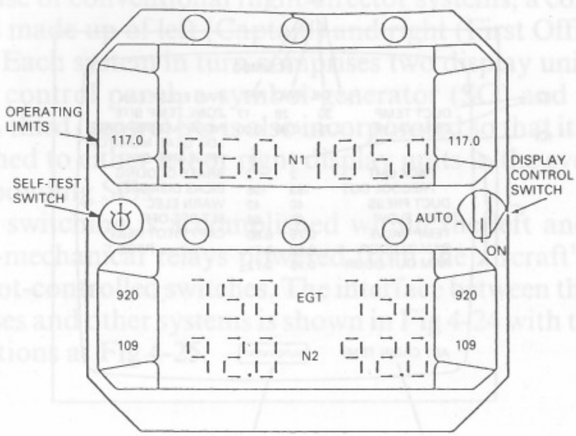


Figure 4–21 Standby Engine Indicator.

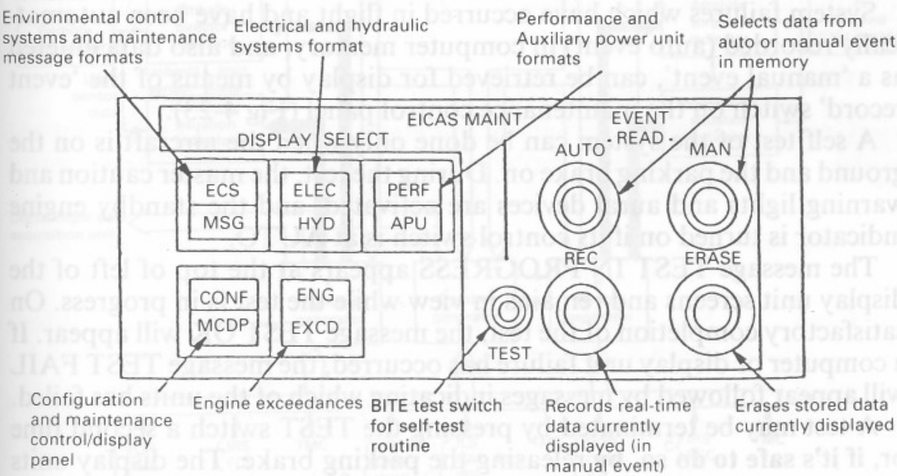


Figure 4–22 Maintenance control panel.

When a switch is activated, a corresponding maintenance display page appears on the lower display unit screen. The pages are listed together with two example displays in Fig 4-23. The upper display unit displays data in the compact format (see Fig 4-20) and has the message PARKING BRAKE at the top of the screen.

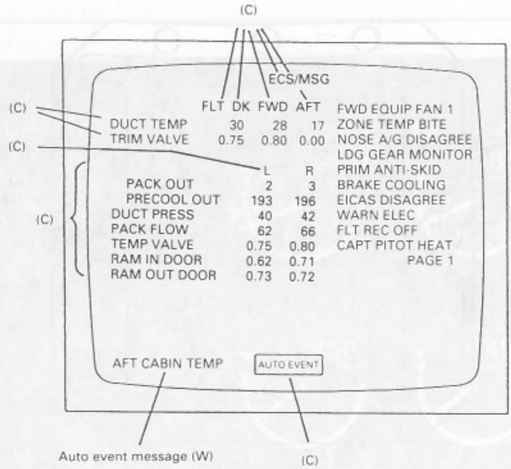


Figure 4–23 Examples of maintenance mode displays.

System failures which have occurred in flight and have been automatically recorded (auto event) in computer memory, and also data entered as a 'manual event', can be retrieved for display by means of the 'event record' switch on the maintenance control panel (Fig 4-23).

A self test of the system can be done only when the aircraft is on the ground and the parking brake on. During the test, the master caution and warning lights and aural devices are activated, and the standby engine indicator is turned on if its control switch is at AUTO.

The message TEST IN PROGRESS appears at the top of left of the display unit screens and remains in view while the test is in progress. On satisfactory completion of the test, the message TEST OK will appear. If a computer or display unit failure has occurred, the message TEST FAIL will appear followed by messages indicating which of the units has failed.

A test may be terminated by pressing the TEST switch a second time or, **if it's safe to do so**, by releasing the parking brake. The display units revert to their normal primary and secondary information displays.

4.20 The EFIS System

The EFIS system (Electronic Flight Instrument System) is fully integrated with digital computer-based navigation systems, and utilizes colour CRT type of EADI (Electronic Attitude Director Indicator) and EHSI (Electronic Horizontal Situation Indicator). The system is far more sophisticated than former flight director systems, not only in terms of physical construction, but also in the extent to which it can present attitude and navigational data to the flight crew.

As in the case of conventional flight director systems, a complete EFIS installation is made up of left (Captain) and right (First Officer) systems (see Fig 4-8). Each system in turn comprises two display units: an EADI and EHSI, a control panel, a symbol generator (SG) and remote light sensor unit. A third (centre) SG is also incorporated so that it drive signals may be switched to either left or right display units in the event of failure of the corresponding SGs.

The signal switching is accomplished within the left and right SGs, using electro-mechanical relays powered from the aircraft's DC power supply via pilot-controlled switches. The interface between the EFIS units and data busses and other systems is shown in Fig 4-24 with the acronyms and abbreviations at Fig 4-25.

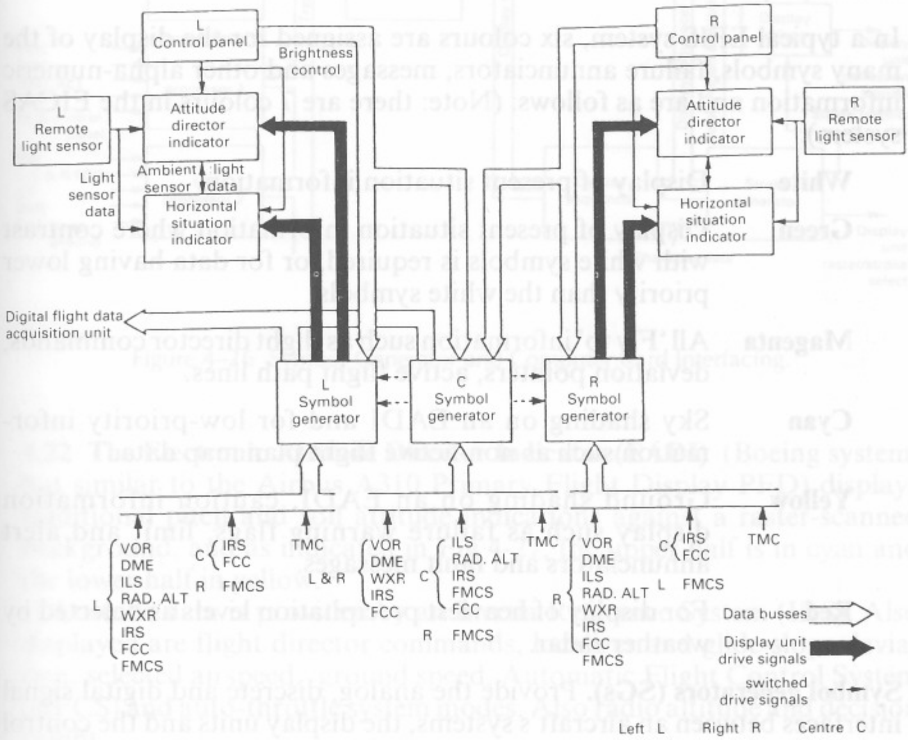


Figure 4–24 EFIS units and signal interfacing.

VOR	Very high frequency Omnidirectional Range
DME	Distance Measuring Equipment
ILS	Instrument Landing System
RAD.ALT	Radio Altimeter
WXR	Weather Radar transceiver
IRS	Inertial Reference System
FCC	Flight Control Computer
FMCS	Flight Management Computer System
TMC	Thrust Management Computer

Figure 4–25 Inputs to data busses: Acronyms and Abbreviations.

In a typical EFIS system, six colours are assigned for the display of the many symbols, failure annunciators, messages and other alpha-numeric information and are as follows: (Note: there are 7 colours in the EICAS system).

White Display of present situation information.

Green Display of present situation information where contrast with white symbols is required, or for data having lower priority than the white symbols.

Magenta All 'Fly to' information such as flight director commands, deviation pointers, active flight path lines.

Cyan Sky shading on an EADI and for low-priority information such as non-active flight plan map data.

Yellow Ground shading on an EADI, caution information display such as failure warning flags, limit and alert annunciators and fault messages.

Red For display of heaviest precipitation levels as detected by weather radar.

Symbol generators (SGs). Provide the analog, discrete and digital signal interfaces between an aircraft's systems, the display units and the control panel, and they also perform symbol generation, system monitoring, power control and the main control functions of the EFIS overall. The interfacing between the computer card modules of an SG is shown in Fig 4-26.

4.21 Remote Light Sensor. There is a photodiode which responds to flight deck ambient light conditions and automatically adjusts the brightness of the CRT displays to a compatible level.

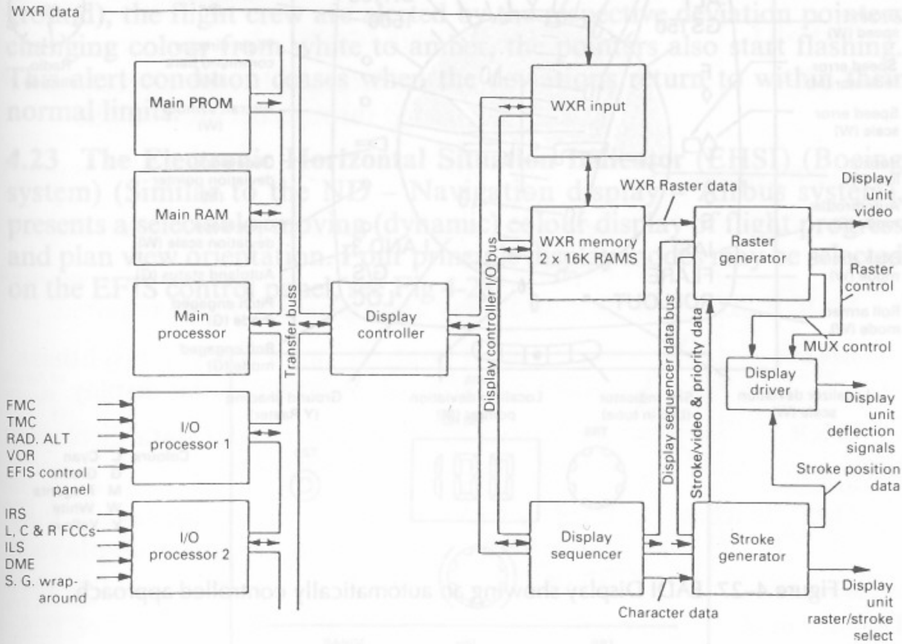


Figure 4–26 Symbol Generator and Computer Card Interfacing.

4.22 The Electronic Attitude Director Indicator (EADI) (Boeing system, but similar to the Airbus A310 Primary Flight Display PFD) displays traditional pitch and roll attitude indications against a raster-scanned background, and as indicated in Fig 4-27, the upper half is in cyan and the lower half in yellow.

Attitude data is provided by an Inertia Reference System (IRS). Also displayed are flight director commands, localizer and glide-slope deviation, selected airspeed, ground speed, Automatic Flight Control System (AFCS) and auto-throttle system modes. Also radio altitude and decision height.

Figure 4-27 shows a representation of an automatically controlled approach-to-land situation, together with the colours of the symbols and alpha-numeric data produced via the EFIS control panel and SGs.

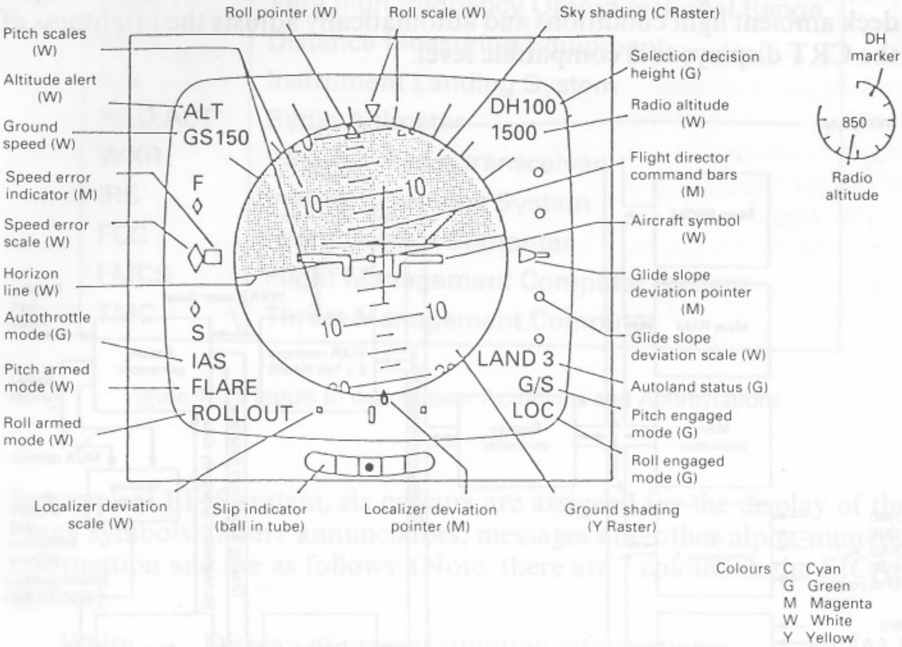


Figure 4–27 EADI Display showing an automatically controlled approach.

The auto-land status, pitch, roll-armed and engage modes are selected on the AFCS control panel, and the decision height is selected on the EFIS control panels. Radio altitude is digitally displayed during an approach when the aircraft is between 2500 and 1000 feet above the ground. When the aircraft is below 1000 feet, the display automatically changes to a white circular scale calibrated in increments of 100 feet, and the selected decision height is then displayed as a magenta-coloured marker on the outer scale.

The radio altitude also appears within the scale as a digital readout. As the aircraft descends, segments of the altitude scale are simultaneously erased so that the scale continuously diminishes in length in an anti-clockwise direction.

At the selected decision height plus 50 feet, an aural alert chime sounds at an increasing rate until decision height is reached. At the decision height, the circular scale changes from white to amber, and the marker changes from magenta to amber, both the scale and the marker also flash for several seconds.

A reset button is provided on the control panel and when pressed, it stops the flashing and causes the scale and marker to change from amber back to their normal colour. The EFIS control panel is shown in Fig 4-28.

If during the approach the aircraft deviates beyond the normal ILS glide slope and/or localizer limits (and when below 500 feet above the ground), the flight crew are alerted by the respective deviation pointers changing colour from white to amber, the pointers also start flashing. This alert condition ceases when the deviations return to within their normal limits.

4.23 The Electronic Horizontal Situation Indicator (EHSI) (Boeing system) (Similar to the ND – Navigation display – Airbus system), presents a selectable, moving (dynamic) colour display of flight progress and plan view orientation. Four principle display modes may be selected on the EFIS control panel, see Fig 4-28.

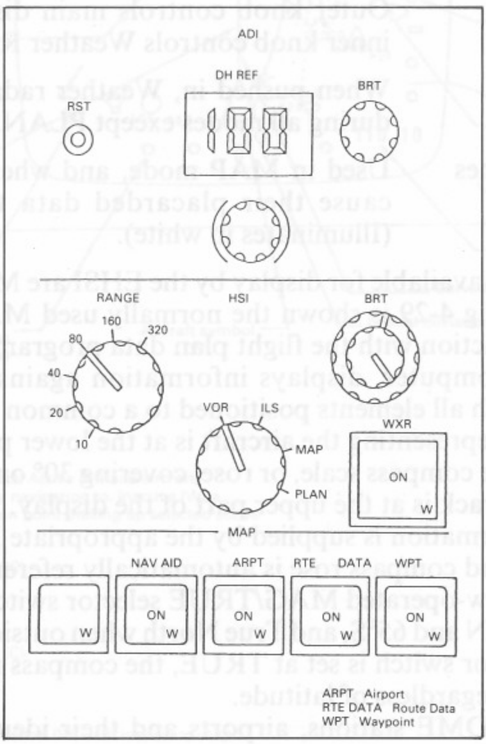


Figure 4–28 EFIS Control Panel.

Referring to Fig 4-28, the following list identifies the switch functions for both sections, EADI and EHSI:

Switch	Function
EADI section:	
BRT	Controls levels of display brightness.
DH SET	Setting of decision height.
RST	Manually resets decision height circuits after aircraft has passed through decision height.
EHSI section:	
RANGE	Selects range for displayed Weather Radar display.
MODE SELECT	Selects display appropriate to mode required.
BRT	Outer knob controls main display brightness: inner knob controls Weather Radar display.
WXR	When pushed in, Weather radar data displayed during all modes except PLAN.
MAP switches	Used in MAP mode, and when pushed in they cause their placarded data to be displayed. (Illuminates in white).

The four modes available for display by the EHSI are MAP, PLAN, ILS, and VOR. In Fig 4-29 is shown the normally used MAP mode display which in conjunction with the flight plan data programmed into a flight management computer, displays information against a moving map background with all elements positioned to a common scale.

The symbol representing the aircraft is at the lower part of the display and an arc of the compass scale, or rose, covering 30° on either side of the instantaneous track is at the upper part of the display.

Heading information is supplied by the appropriate Inertia Reference System (IRS) and compass rose is automatically referenced to Magnetic North (via a crew-operated MAG/TRUE selector switch) when between the latitudes 73°N and 65°S, and True North when outside these latitudes. When the selector switch is set at TRUE, the compass rose is referenced to True North regardless of latitude.

Tuned VOR/DME stations, airports and their identification letters, and the flight plan entered into the flight management system computer are all correctly orientated with respect to the positions and track of the aircraft, and to the range scale (nm/in) selected on the EFIS control panel. Weather radar 'returns' may also be selected and displayed when required, at the *same scale* and orientation as the map.

Indications of other data such as wind speed and direction, lateral and

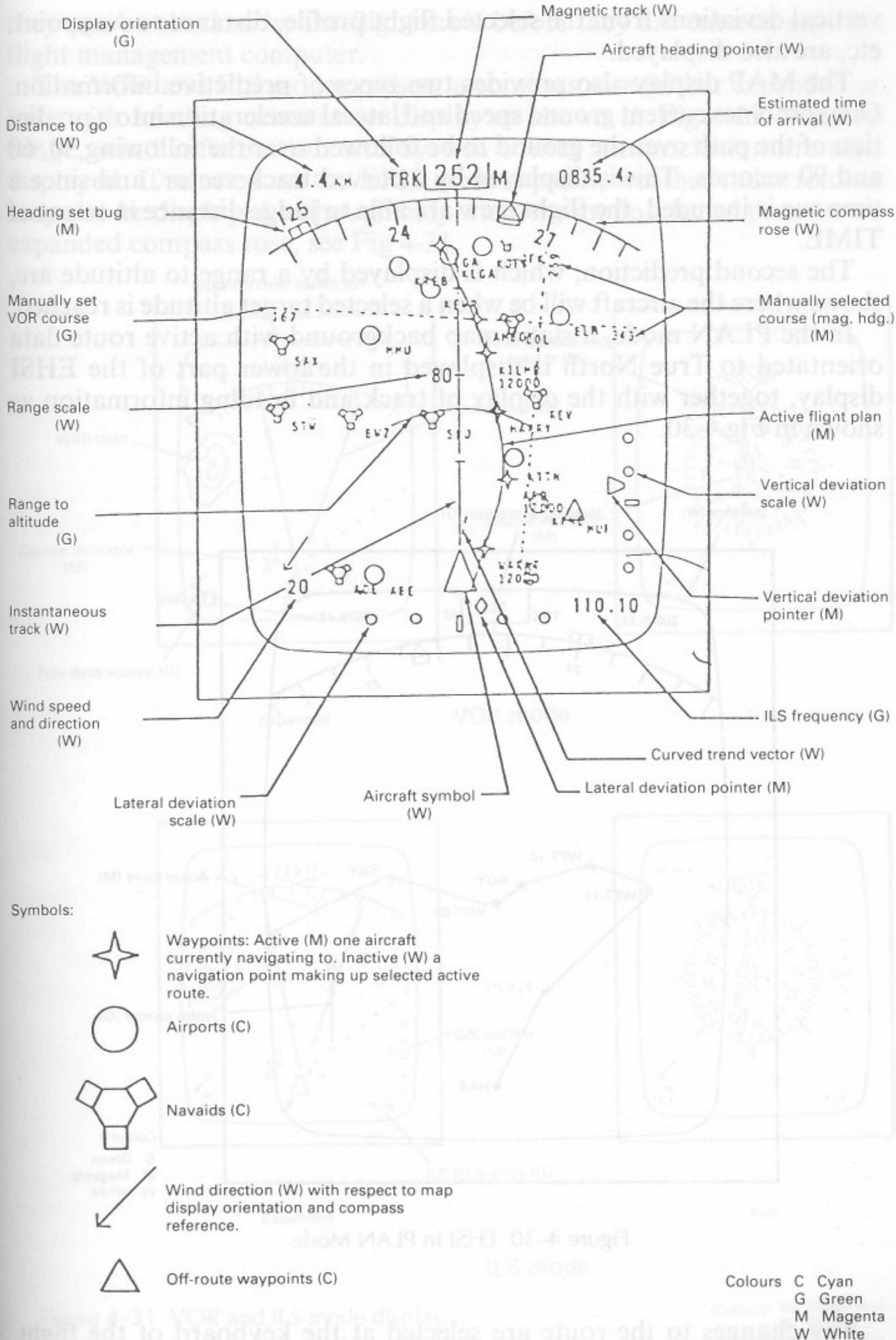


Figure 4–29 EHSI in MAP Mode.

vertical deviations from the selected flight profile, distance to waypoint, etc, are also displayed.

The MAP display also provides two types of predictive information. One combines current ground speed and lateral acceleration into a prediction of the path over the ground to be followed over the following 30, 60 and 90 seconds. This is displayed by a curved track vector, and since a time cue is included, the flight crew are able to judge distance in terms of TIME.

The second prediction, which is displayed by a range to altitude arc, shows where the aircraft will be when a selected target altitude is reached.

In the PLAN mode, a static map background with active route data orientated to True North is displayed in the lower part of the EHSI display, together with the display of track and heading information as shown in Fig 4-30.

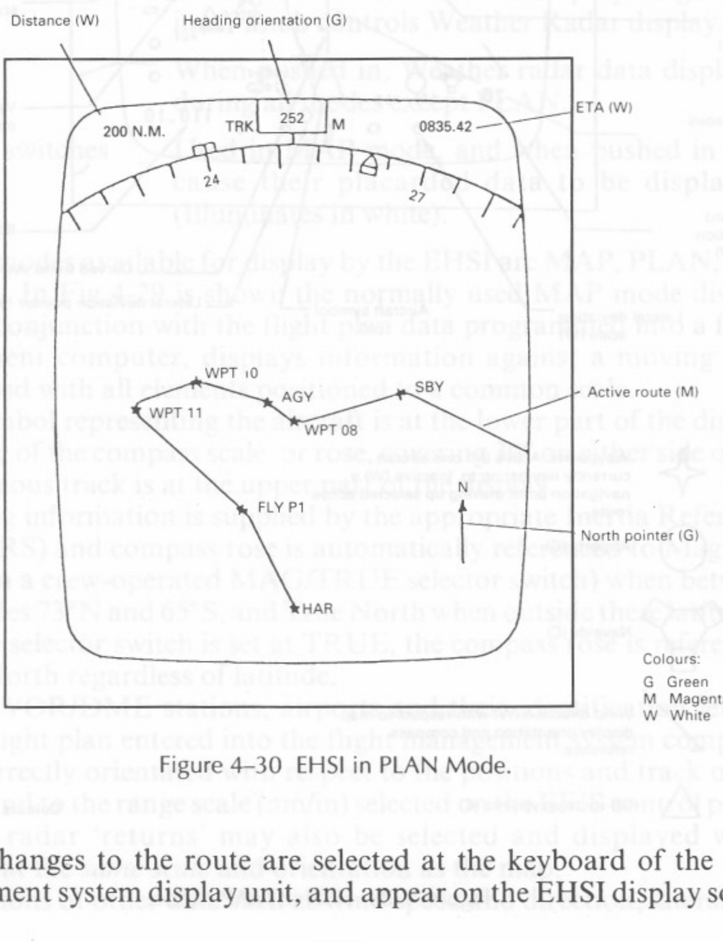


Figure 4–30 EHSI in PLAN Mode.

Any changes to the route are selected at the keyboard of the flight management system display unit, and appear on the EHSI display so that they can be checked by the flight crew before they are entered into the flight management computer.

The VOR and ILS modes present a compass rose (either expanded or full) with heading orientation display as shown in Fig 4-29. Selected range, wind information and system source annunciation are also displayed. If selected on the EFIS control panel, weather radar returns may also be displayed, although only when the mode selected presents an expanded compass rose, see Fig 4-31.

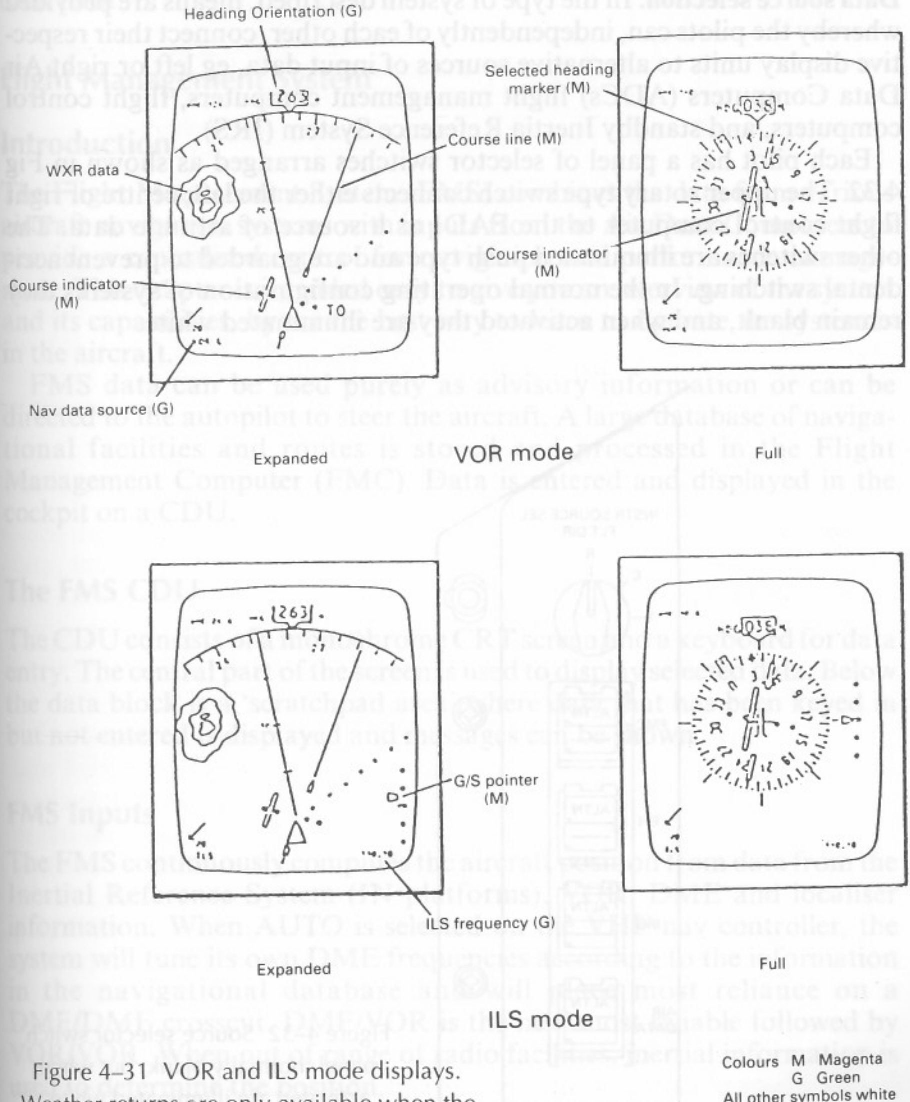


Figure 4–31 VOR and ILS mode displays. Weather returns are only available when the compass rose is in expanded format.

Failure annunciation: Failure of data signals from such systems as the ILS and radio altimeter are displayed on each EADI and EHSI in the form of yellow flags 'painted' at specific matrix locations on the CRT screens. In addition, fault messages may also be displayed: for example, if the associated flight management computer and weather radar range disagree with the control panel range data, the discrepancy message –

'WXR/MAP RANGE DISAGREE' appears on the EHSI.

Data source selection: In the type of system described, means are provided whereby the pilots can, independently of each other, connect their respective display units to alternative sources of input data, eg left or right Air Data Computers (ADCs) flight management computers, flight control computers, and standby Inertia Reference System (IRS).

Each pilot has a panel of selector switches arranged as shown in Fig 4-32. The upper rotary type switch connects either the left, centre or right flight control computer to the EADI as a source of attitude data. The other switches are illuminated push type and are guarded to prevent accidental switching. In the normal operating configuration of systems they remain blank, and when activated they are illuminated white.

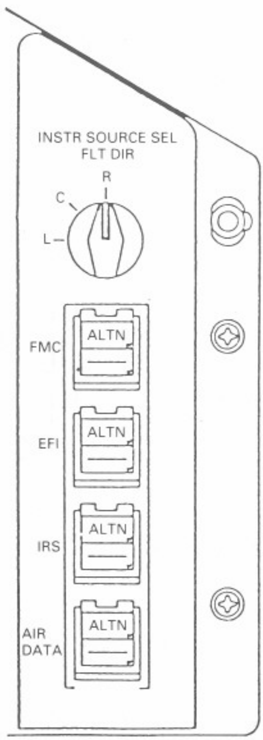


Figure 4–32 Source selector switch panel, normally blank, but when activated are illuminated white.

Display of air data: In a number of EFIS applications, the display of such air data as altitude, airspeed and vertical speed is provided in the conventional manner, ie separate indicators servo-operated from ADCs are mounted adjacent to the EFIS display units in the former basic 'T' arrangement. With continued development of display technology, however, CRTs with much bigger screen areas have already been produced and fitted to Boeing 747–400 aircraft, such displays make it unnecessary to provide conventional primary air data instruments for each pilot.

Flight Management System

Introduction

The Flight Management System (FMS) combines the data from various aircraft navigation systems with inputs from the Air Data Computers to provide a centralised control for navigation and performance management. This chapter is intended only to give you an overview of the system and its capabilities, by far the best way to learn to operate the system is in the aircraft.

FMS data can be used purely as advisory information or can be directed to the autopilot to steer the aircraft. A large database of navigational facilities and routes is stored and processed in the Flight Management Computer (FMC). Data is entered and displayed in the cockpit on a CDU.

The FMS CDU

The CDU consists of a monochrome CRT screen and a keyboard for data entry. The central part of the screen is used to display selected data. Below the data block is a 'scratchpad area' where data that has been keyed in but not entered is displayed and messages can be shown.

FMS Inputs

The FMS continuously computes the aircraft position from data from the Inertial Reference System (IN platforms), VOR, DME and localiser information. When AUTO is selected on the VHF nav controller, the system will tune its own DME frequencies according to the information in the navigational database and will place most reliance on a DME/DME crosscut. DME/VOR is the next most reliable followed by VOR/VOR. When out of range of radio facilities, inertial information is used to determine the position.

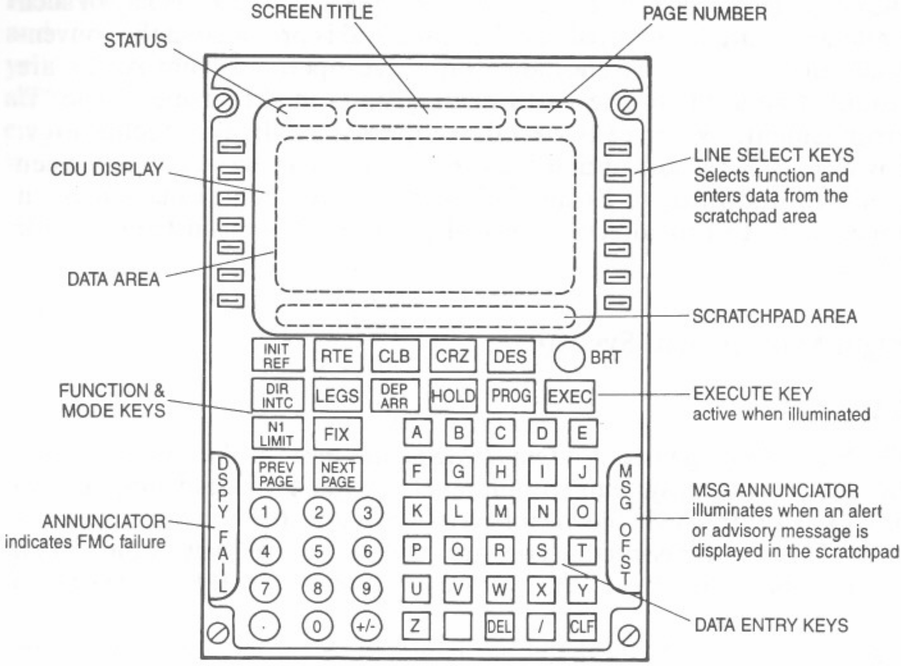


Figure 4–33 Flight Management Computer Cockpit Display Unit.

LNAV and VNAV

Pre-determined or custom-made routes in the database can be selected and flown. This is known as LNAV, short for Lateral Navigation. LNAV is available from take-off to localiser capture. Vertical Navigation or VNAV controls the altitude of the aircraft and the climb and descent profiles. A stored company route will contain a complete lateral and vertical flight profile, this can be amended by the crew, or left untouched. Standard instrument departure and arrival procedures are also stored in the database. The RTE key leads into the route selection procedure and the DEP ARR key into the SIDs and STARs. Figure 4-34 shows the display indicating a route from Heathrow (EGLL) to Hannover (EDVV). Runway 09R has been selected for Heathrow with a Dover 3K departure to Detling then via airway G1 to Dover.

Once the aircraft is airborne the FMS screen shows the active waypoint, that is to say the next one, in reverse video and gives course and distance between waypoints together with the speed and altitude at the waypoints. Speed and altitude may be restrictions built in to the route in

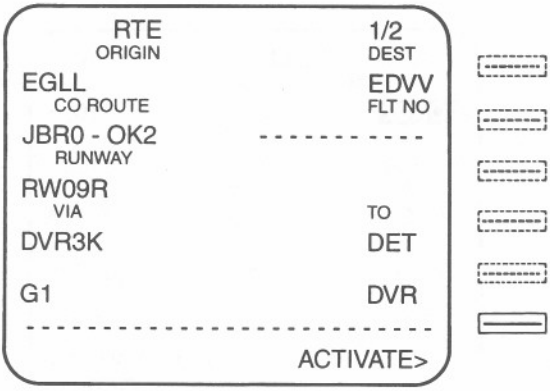


Figure 4–34 A
Route Selected.

which case they are shown in large characters, or they may be computed figures. Legs that require a heading rather than a course to be flown are suffixed HDG or H. Figure 4-35 shows the FMS display for the early part of the departure with the SID itself.

Performance Management

Once the route is loaded the FMS invites the pilot to feed in performance data, temperature and winds so that power settings and speeds can be calculated and the vertical profile can be assessed correctly. Performance management will optimise speeds for the minimum cost taking into account factors such as the price of fuel at departure and destination. This is collectively known as the cost index for a route and is part of stored company routes.

The following entries are required:

1 Either gross weight or zero fuel weight
2 Fuel reserves
3 Cost Index, if not using or overriding a stored route
4 Cruise altitude
5 Transition altitude
6 ISA deviation
7 Winds at height

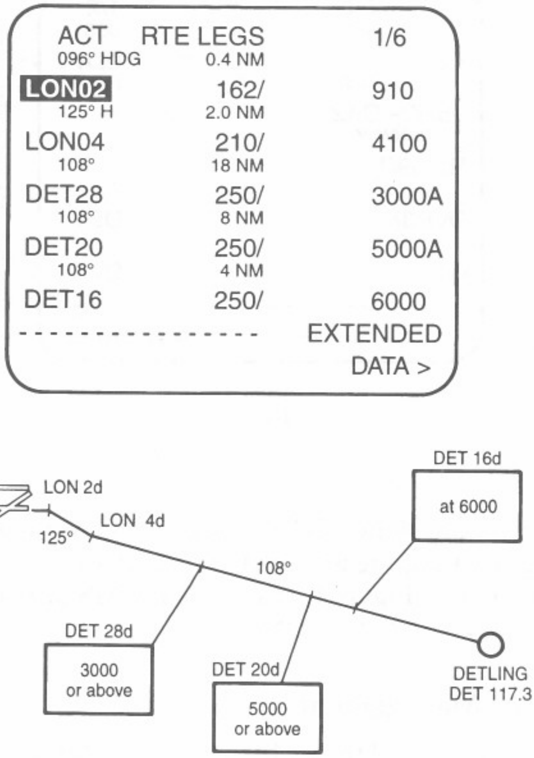


Figure 4–35 FMS Display for Early Parts of Departure.

If the transition altitude is not entered it will default to 18,000ft. If winds are not entered the route will be calculated with observed wind to the next waypoint and for zero wind subsequently. In addition to the above the pilot may also enter low or high speed restrictions for any phase of flight.

Advanced FMS computers will provide take-off information to the pilots. The runway in use is known from the route selection page. Extra data required is the OAT, the surface wind, runway direction, runway condition (dry or wet), slope and C of G position. The FMS will compute trim setting, V1, Vr, V2 and take-off thrust and can provide reduced thrust settings for take-off if performance is not limiting.

Test Yourself Four Electronic Instrument Display Systems

1. A CRT is a:
   (a) Cathode Ray Tube.
   (b) Cathode Relay Tube.
   (c) Compilation Relay Tube.
   (d) Component Rectifier Tube.

Ref 4.1.

2. EICAS is the:
   (a) Engine Indicating and Central Alerting System.
   (b) Engine Indicating and Crew Alerting System.
   (c) Electronic Indication and Central Alerting System.
   (d) Electronic Indicating and Central Alternating System.

Ref 4.1.

3. ECAM is the:
   (a) Electronic Central Aircraft Management system.
   (b) Electronic Central Aircraft Manager.
   (c) Electronic Centralised Aircraft Monitoring.
   (d) Electric Controlled Aircraft Mandate.

Ref 4.1.

4. The EFIS Display primarily consists of the:
   (a) ADI and HSI.
   (b) EICAS and ECAM.
   (c) EICAS and HSI.
   (d) ECAM, ADI and HSI.

Ref 4.6.

5. The Upper Display Unit of the EICAS system indicates:
   (a) primary engine functions.
   (b) primary and secondary engine functions.
   (c) secondary and alert status information.
   (d) primary and secondary engine functions.

Ref 4.9.

5

Automatic Flight

5.1 Fly-by-Wire System

The fly-by-wire control system, although not a new concept in aviation, has had to be re-developed in recent years to control ever more sophisticated types of aeroplanes coming into service. The problems of such sophistication has introduced even more complexity into the mechanical control linkages to operate the flight control system. The fly-by-wire system, as the description suggests, is therefore, where the mechanical linkages are dispensed with, and control wires carrying electrical signals from the pilot's controls replace them. Electrical or hydraulic servo-actuators do the actual movement of control surfaces, but the signals are electrical.

The pilot's controls are connected to electrical transducers which essentially measure the forces applied by the pilot; these forces are then translated in terms of electrical signals, which are amplified and relayed to the appropriate hydraulic servo-actuator directly connected to the flight control surface. In Fig 5-1 the system used by the Boeing 767 spoiler control panel is illustrated.

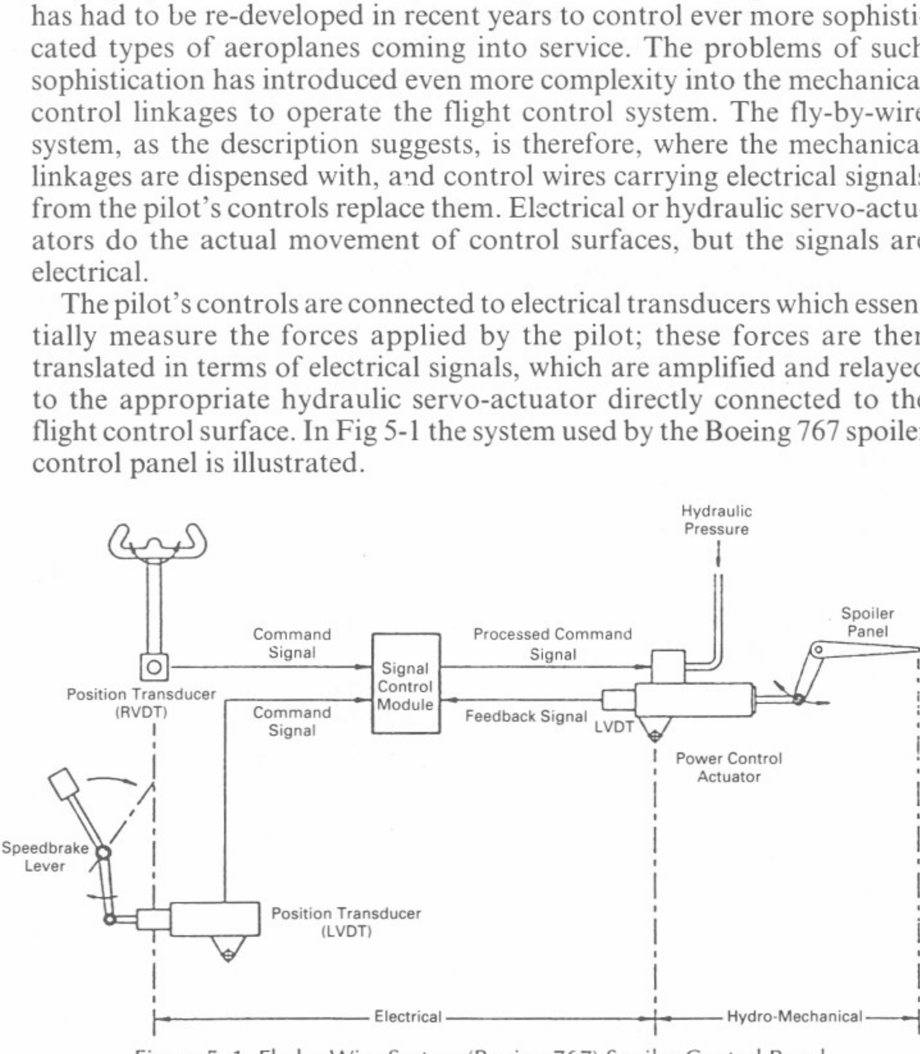


Figure 5–1 Fly-by-Wire System (Boeing 767) Spoiler Control Panel.

In considering lateral control, the deployment of the panels is initiated by the pilot moving the control wheel to the left or right. This movement operates position transducers, called Rotary Variable Differential Transformers (RVDTs) through mechanical gear drives from the control wheel. The RVDTs produce command voltage signals proportional to control wheel position and these signals are fed into a spoiler control module for processing and channel selection.

The spoiler control module output signals are then supplied to a solenoid valve forming an integral part of a hydraulic power control actuator. The valve directs hydraulic fluid under pressure to one or other side of the actuator piston which then raises or lowers the spoiler panel.

As the actuator rod moves, it also actuates a position transducer of the Linear Variable Differential Transformer (LVDT) type, and this produces a voltage feedback signal proportional to the spoiler panel position. When the feedback signal equals the command signal, a null condition is reached and the spoiler panel movement stops.

Deployment of spoiler panels for the purpose of acting as speedbrakes is initiated by movement of a speedbrake lever. The lever operates an LVDT type of transducer which produces a command voltage signal for processing by the signal control module. The output signal operates the actuator in the same way as for lateral control except that the spoiler panels are deployed to their fullest extent. Nulling of the command signal is also produced in the same way. Lateral control and speedbrake signals are mixed in the signal control module to provide the proper ratio of simultaneous operation.

A further advance in the fly-by-wire concept, is the use of fibre optic cables for conveying the flight commands to control surfaces. The great advantage of fibre optic cables is the enormous potential of signal carrying, and immunity to electro-magnetic interference, which means it is not necessary to use heavy shielding as in normal signal wires.

With fibre optics, only the commands are transmitted by light through the glass fibres of the conductor; the signal processing is done electronically after passing through a light to electronic transducer. All signal processing is done electronically within the aircraft's control system computers.

5.2 Servo-Mechanisms and Automatic Control Fundamentals

Introduction

With manual controlled flight, the pilot and the flight control system of his aircraft together comprise what may be termed a **closed-loop servo system**. Should the pilot wish to change heading or altitude the controls are manually moved in a way such as to produce the change. Looking closer at a change of altitude, say a descent, the pilot would move the control column forward to apply downward movement to the elevators, thus causing a nose-down attitude of the aircraft and initiate the descent.

Since the descent must be made at a certain angle and rate of change, the pilot will also monitor his primary flight instruments which detect and indicate attitude changes, namely gyro horizon, vertical speed indicator, altimeter and airspeed indicator, and then start returning the elevators to their neutral position by pulling back on the control column.

In order to level out at the new altitude, the control column will first be pulled farther back, thereby applying upward movement of the elevators to produce a nose-up attitude of the aircraft, and then moved forward again to position the elevators in neutral, to fly into the new level flight attitude.

This is a simplified explanation of how an attitude change is effected, and the particular point to be noted is that a pilot must always 'follow-up' his initial control input by applying secondary opposing inputs, thereby progressively removing control so that the attitude changes are made as smoothly and as accurately as possible, and without exceeding those changes commanded by the input.

Such a closed-loop servo-mechanism technique is applied to automatic flight control systems, and the 'follow-up' action in this connection is referred to as **feedback**.

5.3 Servo-Mechanisms

A servo-mechanism may be described in broad terms as a closed-loop system whereby a small powered input controls a much larger powered output while still retaining the proportional movements. In the application of such a system in an aircraft's automatic control, the system must be capable of continuous operation and have the ability to:

(1) Detect the difference between an input and an output (error detection).

(2) Amplify the error signals.

(3) Control the closing of the servo loop by providing **feedback**.

There are two main classes of servo-mechanism:

(a) Position control.

(b) Speed control.

Both classes may be independently applied to automatic flight control systems depending respectively on whether they are of the **displacement** type or the **rate-sensing** type. Some control systems use both types in conjunction.

Position type control mechanisms often utilize potentiometers to register angular position. The input controlling shaft also moves the wiper arm of a potentiometer whose output is fed to a servo-motor after amplification. A second potentiometer is used to measure the output angle whose wiper arm is mechanically coupled to the output shaft. The potentiometers are electrically coupled such that when both wiper arms are in the same angular position, a null or zero signal condition exists.

When it is required to move the load to a particular angular position, the controlling shaft is rotated through the appropriate number of degrees. As there is now a signal generated because of the difference in angular position of the potentiometers, ie they have moved away from null or equal position state, a signal is generated, and also the direction of movement is represented by signal polarity. The servo-motor is energised to move the load shaft in the direction of the new position set by the controlling shaft. The error signal is fed back to the amplifier, thereby reducing the input error signal. When both the load shaft and input shaft are in the same angular position, both potentiometers register a null, or zero signal, and the servo-motor is de-energised.

The **Speed control servo-mechanism** is a method of controlling the output speed of a system by simple comparison of voltages corresponding to input and output speeds. The signals are used to control the speed of the servo-motor and load. The difference between this system and that of the position control system is that the servo-motor also drives a device called a **tachogenerator**.

A tachogenerator, sometimes called a velodyne, produces a voltage which is proportional to the speed of rotation. A voltage setting at the input is compared to the voltage generated by the tachogenerator, any difference producing an error signal which is used to allow the load (the output) to speed up (or slow down) depending on the sign of the error signal compared to the input signal. When the load tachogenerator output voltage matches the input setting, a null or zero voltage exists, and the servo-motor will run at a constant speed. Speed control of the servo-motor is maintained by differences in voltages, and will speed up or slow down until the difference is zero.

5.4 Automatic Control Fundamentals

The closed-loop servo technique is applied in the automatic flight control system of an aircraft. In Fig 5-2 is shown a functional diagram of a closed-loop system which is the basis of all classes of automatic flight control systems. There are four principle elements which together are allocated the task of coping with what is generally termed 'inner-loop' stabilization, the individual functions of the elements are as follows:

(a) Sensing of attitude changes of the aircraft about its principle axes by means of stable reference devices: eg gyroscopes and/or accelerometers.

(b) Sensing of attitude changes in terms of error signals and the transmission of such signals.

(c) Processing of error signals and their conversion into a form suitable for operation of the servo-motors forming the output stage.

(d) Conversion of processed signals into movement of the aircraft's flight control surfaces.

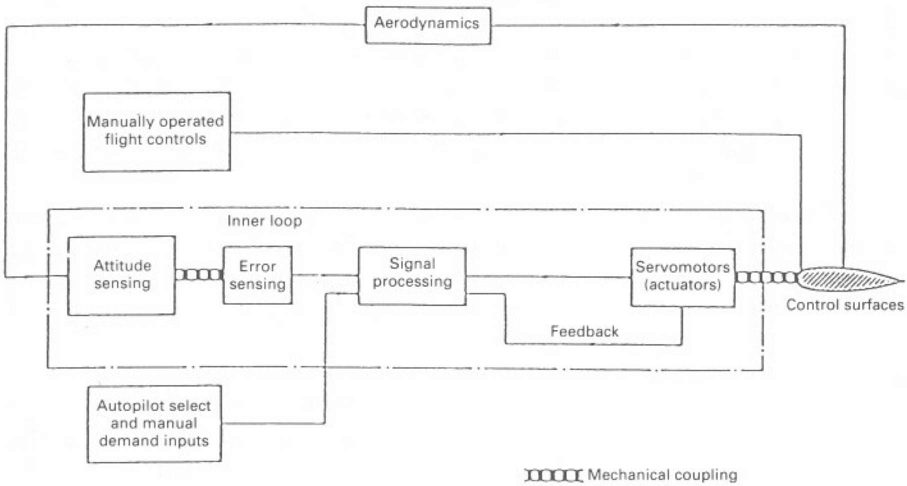


Figure 5–2 Inner-loop Stabilisation.

The number of control loops, or channels, comprising an automatic control system is dependent on the number of axes about which control is to be effected.

5.5 Classification of systems is done on the basis of the number of axes that require control, and are:

(a) **Single-axis** in which attitude control is normally about the roll axis only. The control surfaces forming part of the one and only control loop are, therefore, the ailerons. Such a control system is the most basic type, and is used in a number of types of small fixed-wing aircraft for lateral stabilization, or wing-levelling as it's often called. The pilot can inject command signals into the control loop thereby enabling him to turn the aircraft automatically. In some cases, signals from a compass system and from radio navigation equipment are also injected into the loop so that magnetic headings, and tracking capability can be automatically maintained. Such operating modes are known as heading-hold and radio-coupling respectively, and form part of the **outer-loop control**.

(b) **Two-axis** in which attitude control is, in most cases, about the roll and pitch axes; the control surfaces forming parts of the two loops are, therefore, the ailerons and elevators. Manual turn control, heading-hold and radio-coupling facilities are normally standard features in any one design with, in some cases, an additional facility for selecting and holding a specific altitude. The two-axis automatic control system consists of: Directional gyro, Attitude gyro, Computer amplifier, Pitch and Roll actuators which are integrated with an attitude director indicator (ADI) and horizontal situation indicator (HSI) of a flight director system.

Such integration permits the sharing of common basic attitude and navigation data, and servo-mechanism loops, and by virtue of the indicators' display presentations, it enables a flight crew to initiate precise flight guidance commands to the automatic control system.

Note: Rudder control is carried out by means of a yaw damper system and does not imply that the automatic control system should therefore be classified as a three-axis system, and not a two-axis system as already described. The reason for this is that a yaw damper system is always separate, and can be operated to apply rudder control regardless of whether or not the automatic control system is engaged.

(c) **Three-axis** in which attitude control about all three axes is carried out by specifically related control channels of an automatic flight control system (AFCS).

5.6 Trimming and Synchronisation

It must be ensured that when the automatic control system is engaged, the system takes over without 'snatching' of the aircraft's control system, ie it must be effected smoothly. This means that the aircraft must be trimmed for the desired flight attitude before engagement, and the automatic control system must be synchronised to maintain that attitude when engaged. Auto-trim is normally a function of pitch only.

When power is applied to the automatic control system, the attitude sensing elements are in operation so will always detect the aircraft's attitude and, therefore, supply any necessary control command signals to the servo-motors. At the same time, any signals will be supplied to the appropriate channels of a trim indicating system, or out-of-trim light system.

As an example, if before control system engagement the aircraft is in a climb, or has been trimmed to fly in a nose-up attitude, the pitch attitude sensing element will detect this, and will supply a signal to the elevator servo-motor commanding it to rotate in a direction corresponding to 'elevator down', such as would be shown on the trim indicator.

Because the signal in this case is a standing one, assuming for the moment that it has no opposition, the servo-motor will continue to rotate, and if the clutch were engaged at any one movement the elevators would be snatched from the trimmed position and so cause a nose-down attitude change.

The aerodynamic load acting on the elevators would be felt by the servo-motor, thereby helping to retard its rotation. As soon as the sensing element of the pitch attitude detector responded to the attitude change, the opposing signal produced would then eventually stop the motor and rotate it in the opposite direction. Thus, control would be of an oscillatory nature and the aircraft would take up the pitch attitude determined by the attitude detector and not that which it was desired the control system should maintain, ie in the example considered, a climb or nose-up trim condition.

It is therefore necessary to oppose the standing signal and reduce it to zero before engaging the control system, thereby stopping the servo-motor in a position which is synchronised with the datum attitude detected by the sensing element, such position being indicated by the return of the trim indicator pointer to its central position.

The manner in which synchronising is effected depends on the type of automatic control system and the signal processing circuit arrangements adopted.

5.7 Gain and Gain Programming

Different aircraft respond at different rates to displacement of their flight control surfaces. In particular they vary with altitude, speed, aircraft load, configuration and rate of manoeuvre. It is because of these differing basic handling characteristics that 'gearing' is incorporated in flight control systems and thereby reduce the effects which variations in flight parameters can have on handling characteristics.

Similarly, in applying particular types of automatic flight control systems to individual aircraft control systems, it is necessary to provide facilities for altering the response of an automatic system to any given level of input signal, thereby obtaining a signal ratio best suited to the operation of the systems when working in combination. Such a ratio is known as **gain** and may be considered as having a function similar to the changing gear ratios in a mechanical gearing system.

Figure 5-3 shows a closed-loop control system in simple form. The signal path fròm error to response, measured amplification ratio, is the **loop gain**.

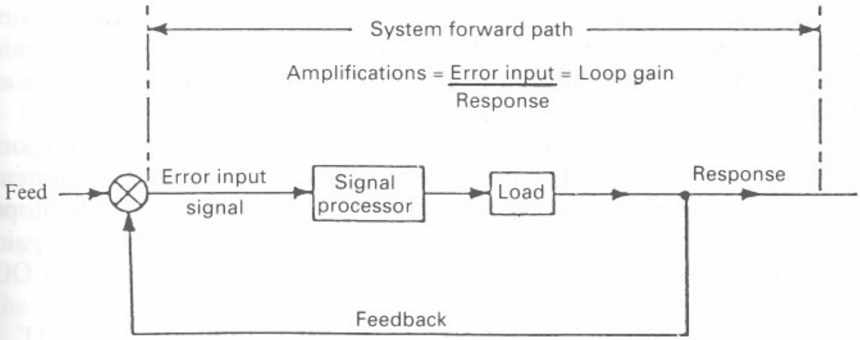


Figure 5–3 Simplified closed-loop system.

Within limits, increased gain improves performance in two ways:

(a) Residual error in steady state is reduced and so improves long-term accuracy.

(b) Initial response to a given command is more rapid.

The limit on these improvements arises from the need for adequate dynamic stability of the system. If, for example, loop gain is increased to some excessive value, then dynamic instability will be produced so that response is grossly oscillatory and never settles to a steady state.

Even before instability is reached, excessive loop gain reduces dynamic stability to an extent that it would take too long for a response to settle at a steady rate: furthermore, it would initially overshoot and then hunt about a steady-state value.

Satisfactory closed-loop performance depends on determining a loop gain which compromises between long-term accuracy plus initial response, and acceptable settling time plus limited overshoot. These factors, in turn, require sufficient inherent damping in the load.

Certain adjustments of command and feedback signals can be pre-set within amplifier and/or computer units in order to produce gain factors which establish a basic 'match' between an automatic control system and the aircraft's characteristics.

Adjustments are based on the variation of electrical resistance at appropriate sections of signal circuits, and as in several types of control system, this is accomplished by means of potentiometers located on a calibration panel that forms an integral part of an amplifier or computer unit.

Further to this, it is also necessary, particularly when the control system is operating in any of the outer-loop control modes, for the gain factor to be altered automatically to offset variations in handling characteristics resulting from changing flight conditions. This process is called **gain programming or scheduling**, and is part of a technique referred to as **adaptive control**.

An example of gain programming relates to an approach to an airport runway when the automatic control system is coupled to the Instrument Landing System (ILS) that is, coupled to the Localiser and Glide Slope modes. The purpose of gain programming in this case is to reduce the gain of beam deviation signals and thereby allow for convergence of the LOC and GS beams.

5.8 Outer-Loop Control

Over and above the primary task of stabilisation performed by an automatic flight control system, it can also be developed to perform the tasks of modifying the stabilised attitude of an aircraft by computing the necessary manoeuvres from inputs such as airspeed, altitude, magnetic heading, interception of radio beams from ground based aids, etc. Such data inputs constitute **outer-loop control**. See Fig 5-4.

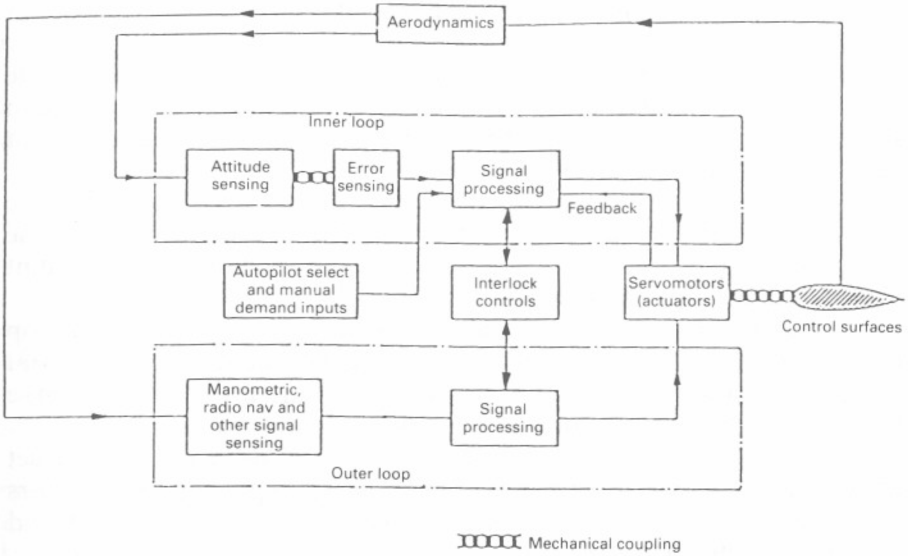


Figure 5–4 Inner-loop stabilisation and outer-loop control.

The provision of raw data inputs relevant to a particular flight-path is referred to as **coupling** or as a **mode of operation**, the selection of each mode being made by the pilot via appropriate control panel switching devices.

Other terms commonly used in connection with operating modes are: **Hold, Lock and Capture**. For example, an aircraft flying automatically at a selected altitude is said to be in the **altitude hold** or **height lock mode**. The term **capture** relates principally to modes associated with the selection and interception of beams from ground-based radio navigation aids, for example, **glide-slope capture**.

In some cases, mode switching is automatic, therefore to switch from intercepting a beam or a heading to tracking the beam on reaching it, a beam sensor is installed. This device senses beam deviation and switches modes automatically when the aircraft flies into the beam. Glide-slope capture can also take place automatically, in this case the pitch control channel is switched from 'altitude hold' mode to glide-slope track when the aircraft flies into the glide-slope beam.

The raw data is supplied from sensors which convert the data into appropriate electrical signals that can be mixed in with inner-loop signal data to produce the changes to the aircraft's flight path. The traditional raw data instrument displays are used by the pilot for monitoring, and programming management. The outer-loop control modes that can be incorporated into a control system are listed in Fig 5-5. Modes actually used are dependent on the type of aircraft and its control system.

In a single-engine light aircraft having a basic wing-levelling control system for example, only altitude and heading modes might comprise the outer-loop control, whereas in a more complex larger type of passenger-carrying aircraft using a flight guidance system, and having automatic landing capability, the outer-loop comprises all the modes listed in Fig 5-5.

5.9 Manometric or Air Data

Raw data inputs which come under this heading are those associated with **altitude, airspeed, vertical speed, and speed in terms of Mach number**, each providing outer-loop control about the pitch axis of an aircraft. Sensing may be carried out either by independent sensor units, or by a central air data computer.

The sensors operate on the same fundamental principles as the basic pilot-static flight instruments, the measuring elements being coupled to appropriate types of electrical pick-off elements in lieu of indicating pointer mechanisms.

Pitch Axis	Roll Axis
Manometric or air data: Altitude select and hold Vertical speed Airspeed select and hold Mach hold Pitch hold Pitch trim Turbulence penetration Vertical navigation	Heading select and hold Bank hold Radio navigation VOR Back Beam Area navigation: Doppler Inertial
Instrument Landing System	
Glide-Slope	Localiser
Autoland	
Approach Flare	Runway align Roll-out
Control wheel steering Touch control steering	

Figure 5–5 Outer-loop control modes.

5.10 Altitude Hold

Any change of aircraft attitude about its pitch axis while in straight and level flight, will be detected by the pitch attitude sensing element of the automatic control system, and the changes will be accordingly corrected; however, after correction the aircraft could be at a new altitude, either above or below that which is desired. Attitude sensing on its own cannot detect altitude changes, and neither can it maintain a required altitude. What is necessary is a means of locking on the altitude selected; also, a means of levelling off at any desired altitude.

An altitude hold, or lock sensor is employed. An altitude hold system employs its own pressure-sensitive capsule, which measures static pressure changes. Any deviations from a selected altitude will result in a signal being applied to the pitch servo-motor to return the aircraft to the selected altitude.

5.11 Airspeed Hold

In an airspeed hold or lock sensor, there is also a capsule, but measurements are taken from the differences in dynamic and static pressure. The assembly expands or contracts under the influence of a pressure differential created by a change of airspeed. The electronics used to pick-off the pressure differential are similar to the electronics used in the altitude hold sensor, the signal then being applied to the pitch servo-control channel. The capsule assembly is usually housed in the same chamber as the altitude capsule assembly.

5.12 Mach Hold

There is a requirement in high performance aircraft to fly at given Mach Numbers at high speed and high altitude, so that both airspeed hold and Mach hold modes are required under automatically controlled flight. The airspeed hold is the more commonly used during the low altitude cruise phase of flight, and Mach hold during the high altitude phase.

Since Mach Number varies with airspeed and altitude, the signal outputs from independent sensors can be integrated to provide required Mach Number signal output. This is accomplished by incorporating all sensors in a unit called a Central Air Data Computer (CADC).

5.13 Vertical Speed Selection and Hold

After taking-off, it is necessary to climb at a particular rate, or at a particular speed in automatic flight, therefore, a vertical speed reference must be incorporated into the system. The rate signal is originated by a tachogenerator driven by the altitude sensor of a central air data computer, and is supplied to the pitch channel of the control system through a vertical speed mode select circuit which forms part of the pilot's control unit.

Signals from this unit are fed to the pitch servo-amplifier and servomotor to displace the pitch control surfaces in the appropriate direction for restoring the aircraft attitude and vertical speed to that prevailing at the time of engagement of the control system.

5.14 Heading Hold

This system will hold the aircraft in automatic flight on a pre-selected magnetic heading. Since turning the aircraft is carried out by displacement of the ailerons, the heading hold mode relates to control about the roll axis, and heading error signals are applied to the roll control channel of the flight control system.

In most aircraft, heading data is supplied either from a remote-indicating compass or from a flight director system. Since the 'heading select' facility of the compass system provides automatic turn control, it is comparable in function to the turn control provided on a pilot's control panel. It is necessary, therefore to incorporate an interlock circuit between the two to prevent their signals from opposing each other.

5.15 Turbulence Penetration

When flying in turbulent air conditions, varying loads are imposed on the aircraft structure. It is normal for the pilot to adjust the power and the speed and to operate the flight control system in a manner compatible with the flight conditions prevailing.

In an aeroplane under automatic flight control, the control system senses the turbulence as disturbances to aircraft attitude, but in applying corrective control it is possible for additional structural loads to be imposed. The reason for this is that the rate of control system response tends to get out of phase with the rate at which the disturbances occur, the result being that control responses tend to become 'stiffer'.

In turbulent conditions, it is normal to disengage the automatic flight control system. In some current systems, however, turbulence penetration may be an optional selection mode. Under this mode of operation, the gain of both pitch and roll channels is reduced thereby 'softening' flight control system response to turbulence.

5.16 Control Wheel Steering

Some automatic flight control systems are fitted with Control Wheel Steering (CWS). The purpose of CWS is to allow the pilot to manoeuvre his aircraft in pitch and roll by applying inputs to the automatic flight control system, this being achieved by operation of the wheel in a similar manner to the operation of the conventional control column. When the control wheel is released, the automatic flying control system maintains the attitude of the aircraft in the newly selected position.

In some aircraft systems limits are imposed as to the degree of manoeuvring that may be carried out by the CWS.

5.17 Touch Control Steering

Touch Control Steering (TCS), in a similar manner to Control Wheel Steering, will permit the pilot to manoeuvre his aircraft. In this system, unlike the CWS system, the appropriate control channels and servos are disengaged while the aircraft is flown to its new attitude and heading. Release of the Touch Control Steering switch will re-engage normal channels and servos.

Test Yourself Five Automatic Flight

1. In a Fly-by-Wire control system the Pilot's Control inputs are connected to:
   (a) mechanical linkages to the Power Control Actuator.
   (b) transducers.
   (c) transformers.
   (d) servo amplifiers.

   Ref 5.1.

2. A Two-Axis Automatic Control System normally provides attitude control in the:
   (a) roll axis only.
   (b) roll and yaw axis.
   (c) yaw and pitch axis.
   (d) roll and pitch axis.

   Ref 5.5

3. Auto Trim is normally a function of:
   (a) yaw and pitch.
   (b) roll.
   (c) yaw.
   (d) pitch.

   Ref 5.6.

4. Primary Automatic Control Stabilisation is provided by:
   (a) outer loop.
   (b) inner and outer loop.
   (c) inner loop.
   (d) mechanical inputs only.

   Ref 5.8.

5. Vertical Speed is a function of:
   (a) pitch and yaw axis.
   (b) roll axis.
   (c) pitch axis.
   (d) roll and yaw axis.

   Ref 5.8.

6

Automatic Landing

6.1 Central Air Data Computer (CADC)

Pressure from static vents and pitot tubes are transmitted to the primary flight instruments, ie airspeed indicator, altimeter and vertical speed indicator, via pipelines, the length and quantity of which will vary according to the size of the aircraft, and the number of stations within the aircraft at which relevant indications are required.

In order to reduce the 'pressure plumbing' arrangements, the pressures are supplied to a central location from which they can be transmitted to any number of stations, and in the form of synchronous signal data links. This central facility is called a Central Air Data Computer.

6.12 Automatic Landing

Introduction

Automatic landing is one of the most demanding of the automatic control flight phases. In order to achieve a safe landing, the aeroplane has to be controlled in a manner such that its wheels make contact with the runway within a fairly narrow longitudinal limits along it, and at a low sinking rate, something like 1 to 2 feet per second. The speed at touch-down should have been reduced from the approach margin of about 30% above the stall to about half of this value by progressive reduction of engine power during the landing flare.

The wings should have been levelled prior to the actual landing, and the aircraft yawed to bring its longitudinal axis parallel to the runway centre-line to remove any drift angle due to cross-wind, this manoeuvre being known as 'decrabbing', or 'kick-off'.

Control is therefore required about all three axes simultaneously, as well as the control of airspeed through engine power changes. This is a demanding requirement for the pilot in a manually controlled landing. The control function during the approach and landing manoeuvre is required on a highly repetitive basis, and although a number of parameters are to be controlled simultaneously, such control is only necessary for a comparatively short period of time, and is therefore most suited to automatic control.

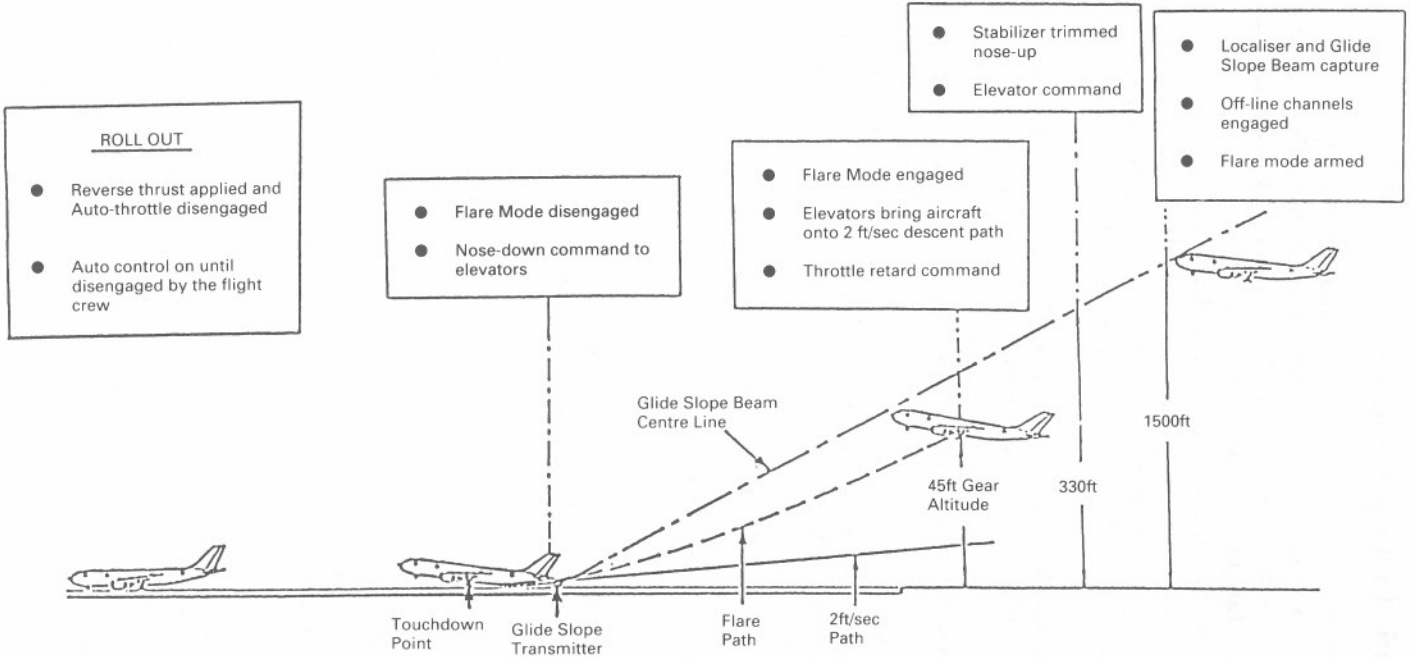


Figure 6–1 Automatic Approach, Flare and Land.

6.3 Automatic Landing Sequence

Figure 6-1 shows the flight profile of an automatic approach, flare and touchdown. This is based on a system that utilises triple digital flight control computer channels, allowing for redundancy to operate in the **fail operational** and **fail passive conditions**.

Fail operational means a system in which one failure (sometimes more) can occur, but leaves the overall system still functioning, and without causing degradation of performance beyond the limits required for automatic landing and roll-out. (Alternative terms are: fail-active and fail-survival).

Fail-passive (USA terminology: or Fail-soft in UK) means the ability of a system to withstand a failure without endangering passenger safety, and without excessive deviations from the flight path.

Depending on the number of channels that are armed and engaged, the system performs what are termed a LAND 2 status or LAND 3 status autoland. LAND 2 signifies there is dual redundancy of engaged flight control computers, sensors and servos (fail-passive operation) whereas LAND 3 signifies triple redundancy of power sources, engaged flight control computers, sensors and servos (fail-operational). Each status is displayed on an autoland status annunciator.

During the cruise and initial stages of approach to land, the control system operates as a single channel system, controlling the aircraft about its pitch and roll axes and providing the appropriate flight director commands. Since multichannel operation is required for automatic landing, at a certain stage of the approach the remaining two channels are armed by pressing an APPR (Approach) switch on the flight control panel.

The operation of the switch also arms the localiser and glide slope modes. Both of the 'off-line' channels are continually supplied with the relevant outer-loop control signals and operate on a **comparative basis** the whole time.

Altitude information, essential for vertical guidance to touchdown, is always provided by signals from a radio altimeter that become effective as soon as the aircraft's altitude is within the altimeter's operating range, typically 2500 feet.

When the aircraft has descended to 1500 feet radio altitude, the localiser and glide slope beams are captured and the armed 'off-line' control channels are then automatically engaged. The localiser and glide slope beam signals control the aircraft about the roll and pitch axes so that any deviations are automatically corrected to maintain alignment with the runway.

At the same time, the autoland status annunciator displays LAND 2 or LAND 3 depending on the number of channels 'voted into operation' for landing the aircraft, and computerised control of flare is also armed.

At a radio altitude of 300 feet, the aircraft's horizontal stabiliser is automatically repositioned to begin trimming the aircraft to a nose-up attitude. The elevators are also deflected to counter the trim and to provide subsequent pitch control in the trimmed attitude.

When an altitude is reached at which the landing gear is 45 feet above the ground (referred to as gear height) the flare mode is automatically engaged. The gear altitude calculation, which is pre-programmed into the computer, is based upon radio altitude, pitch attitude and known distance between the landing gear, the fuselage and radio altimeter antenna.

The flare mode takes over pitch attitude control from the glide slope, and generates a pitch command to bring the aircraft onto a 2 feet per second descent path, at the same time, a 'throttle retard' command signal is supplied to the auto-throttle system to reduce engine thrust to the limits compatible with the flare path.

Prior to touchdown, and at about 5 feet gear altitude, the flare mode is disengaged and there is a transition to the touchdown and roll-out mode. At about 1 foot gear altitude, the pitch attitude of the aircraft is decreased to 2° and at touchdown, a command signal is supplied to the elevators to lower the aircraft's nose and so bring the nose landing gear wheels in contact with the runway and hold them there during the roll-out.

When reverse thrust is applied, the auto-throttle system is automatically disengaged. The automatic flight control system remains on until disengaged by the flight crew.

Key Points

Electrics

1. Generators are normally AIR cooled.
2. As loads are increased in a SHUNT-WOUND GENERATOR supply system current increases and voltage decreases.
3. Loads are normally connected to the bus-bar in parallel to allow load shedding to take place.
4. When FIELD FLASHING is carried out, the polarity of the magnets of the generator reverse.
5. When a shunt-wound generator is over-volting, field current is reduced.
6. In normal flight the lower screen of an EICAS is blank.

7. The HSI of the EFIS has four modes – MAP, PLAN, ILS & VOR.
8. LAND 3 on the ADI indicates FAIL OPERATIONAL
9. Aircraft attitude in AUTOFLIGHT is a function of the INNER LOOP.
10. Failure annunciations on the EFIS are indicated by yellow flags.
11. Engine vibration is indicated on the EICAS Lower Display.
12. Caution messages are indicated on the EICAS Upper Display Left-Hand Side.
13. LAND 2 is fail passive.
14. The RAD ALT is shown on the ADI at 1 o'clock.
15. The RAD ALT changes to a circular scale at 1000ft.

Test Yourself Six Automatic Landing

1. Fail operational is also known as:
   (a) fail active.
   (b) fail passive.
   (c) fail soft.
   (d) serviceable.

Ref 6.3.

2. During the autoland sequence the horizontal stabiliser automatically commences to trim the aircraft Nose Up at:
   (a) 1000ft.
   (b) 100ft.
   (c) 300ft.
   (d) 3000ft.

Ref 6.3.

3. Just prior to touchdown the aircraft's rate of descent should be reduced to:
   (a) 10ft per second.
   (b) 2ft per second.
   (c) 8ft per second.
   (d) 5ft per second.

Ref 6.3.

4. On touch-down in autoland a command signal is supplied to the elevators to:
   (a) maintain flare attitude.
   (b) increase Nose Up by 2°.
   (c) lower the nose.
   (d) increase Nose Up by 5°.

Ref 6.3.

5. Auto-throttle is automatically disengaged when:
   (a) the main undercarriage touches the runway.
   (b) the nose undercarriage touches the runway.
   (c) selected OFF only.
   (d) reverse thrust is selected.

Ref 6.3.

Test Yourself Final Practice Questions

1. Normally the EICAS Upper Display Unit displays:
   (a) FF, EPR and Vibration.
   (b) FF, EGT and EPR.
   (c) EGT, EPR and N1 speed.
   (d) N1, N2 and N3 speeds.

Ref 4.10.

2. Warning messages on the EICAS Upper Display Units are indicated in:
   (a) Yellow.
   (b) Amber.
   (c) White.
   (d) Red.

Ref 4.10.

3. If the Lower Display Unit of the EICAS fails during operation then a warning display is illuminated in:
   (a) the form of a red warning light.
   (b) the upper display unit in amber.
   (c) the upper display unit in red.
   (d) the lower display unit top left corner in red.

Ref 4.15.

4. In the event of total failure of the EICAS, information is:
   (a) displayed on the Standby Engine Indicator.
   (b) displayed on conventional instruments.
   (c) by a system of warning lights.
   (d) by a standby image generator.

Ref 4.18.

5. The ADI of the EFIS RAD ALT is displayed on the instrument's face at:
   (a) 1 o'clock position.
   (b) 6 o'clock position.
   (c) 7 o'clock position.
   (d) 9 o'clock position.

Ref 4.22.

6. The HSI of the EFIS consists of:
   (a) Three Modes.
   (b) Two Modes.
   (c) Four Modes.
   (d) Six Modes.

Ref 4.23.

7. The HSI displays a dynamic map background in:
   (a) Map and Plan Modes.
   (b) Map Mode.
   (c) Map, Plan and VOR Modes.
   (d) Map, Plan and ILS Modes.

Ref 4.23.

8. Failure of DATA Signals on the HSI is shown as:
   (a) red warning lights.
   (b) red flags.
   (c) yellow flags.
   (d) amber warning lights.

Ref 4.23.

9. Weather returns are available on the HSI:
   (a) in all modes at all times.
   (b) in MAP and PLAN modes only.
   (c) on VOR and ILS in expanded Mode only.
   (d) on the MAP Mode only.

Ref 4.23.

10. The RAD ALT is displayed below 1000ft as a circular scale in increments of:
    (a) 100ft.
    (b) 50ft.
    (c) 500ft.
    (d) 250ft.

Ref 4.22.

11. In the HSI PLAN Mode the active route date is orientated to:
    (a) Magnetic North.
    (b) True North.
    (c) True or Magnetic North.
    (d) a diagramatic heading.

Ref 4.23.

12. An aural alarm is sounded on the ADI when the:
    (a) DH is reached.
    (b) DH + 50ft is reached.
    (c) height of 50ft above the ground is reached.
    (d) DH minus 50ft is reached.

Ref 4.22.

13. The Circular Scale of the RAD ALT changes from magenta to amber at:
    (a) DH + 50ft.
    (b) DH.
    (c) DH –50ft.
    (d) 50ft above the ground.

Ref 4.22.

14. The DH Marker of the ADI RAD ALT is positioned on the scale at:
    (a) 1 o'clock.
    (b) 6 o'clock.
    (c) 12 o'clock.
    (d) 7 o'clock.

Ref 4.22.

15. Decision height is selected on the:
    (a) EFIS control panel.
    (b) ADI Instrument.
    (c) HSI Instrument.
    (d) AFCS control panel.

Ref 4.22.

16. Radio Altitude is indicated above 1000ft on the ADI at:
    (a) 1 o'clock.
    (b) 6 o'clock.
    (c) 12 o'clock.
    (d) 7 o'clock.

Ref 4.22.

17. When Automatic Flight is employed with a single axis system automatic stabilisation is normally provided in the:
    (a) roll and yaw axis.
    (b) yaw axis.
    (c) pitch axis.
    (d) roll axis.

Ref 5.5.

18. Auto Trim is normally a function of:
    (a) Pitch and Roll.
    (b) Pitch and Yaw.
    (c) Roll and Yaw.
    (d) Pitch only.

Ref 5.6.

19. Primary Control Functions of Automatic Flight are controlled within the:
    (a) Outer Loop.
    (b) Inner and Outer Loop.
    (c) Inner Loop.
    (d) Auxiliary and Inner Loop.

Ref 5.4.

20. Raw Air Data to the Outer Loop is termed:
    (a) Outer Loop Data.
    (b) Air Data.
    (c) Pressure Data.
    (d) Manometric Data.

Ref 5.9.