Chapter 10

Aircraft Instrument Systems

Introduction

Since the beginning of manned flight, it has been recognized that supplying the pilot with information about the aircraft and its operation could be useful and lead to safer flight. The Wright Brothers had very few instruments on their Wright Flyer, but they did have an engine tachometer, an anemometer (wind meter), and a stop watch. They were obviously concerned about the aircraft's engine and the progress of their flight. From that simple beginning, a wide variety of instruments have been developed to inform flight crews of different parameters. Instrument systems now exist to provide information on the condition of the aircraft, engine, components, the aircraft's attitude in the sky, weather, cabin environment, navigation, and communication. *Figure 10-1* shows various instrument panels from the Wright Flyer to a modern jet airliner.

Figure 10-1. *From top to bottom: instruments of the Wright Flyer, instruments on a World War I era aircraft, a late 1950s/early 1960s Boeing 707 airliner cockpit, and an Airbus A380 glass cockpit.*

The ability to capture and convey all of the information a pilot may want, in an accurate, easily understood manner, has been a challenge throughout the history of aviation. As the range of desired information has grown, so too have the size and complexity of modern aircraft, thus expanding even further the need to inform the flight crew without sensory overload or overcluttering the cockpit. As a result, the old flat panel in the front of the cockpit with various individual instruments attached to it has evolved into a sophisticated computer-controlled digital interface with flat-panel display screens and prioritized messaging. A visual comparison between a conventional cockpit and a glass cockpit is shown in *Figure 10-2.*

Figure 10-2. *A conventional instrument panel of the C-5A Galaxy (top) and the glass cockpit of the C-5B Galaxy (bottom).*

There are usually two parts to any instrument or instrument system. One part senses the situation and the other part displays it. In analog instruments, both of these functions often take place in a single unit or instrument (case). These are called direct-sensing instruments. Remote-sensing requires the information to be sensed, or captured, and then sent to a separate display unit in the cockpit. Both analog and digital instruments make use of this method. *[Figure 10-3]*

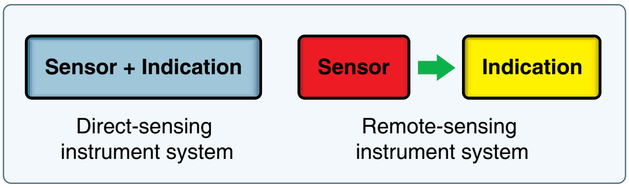


Figure 10-3. *There are two parts to any instrument system—the sensing mechanism and the display mechanism.*

The relaying of important bits of information can be done in various ways. Electricity is often used by way of wires that carry sensor information into the cockpit. Sometimes pneumatic lines are used. In complex, modern aircraft, this can lead to an enormous amount of tubing and wiring terminating behind the instrument display panel. More efficient information transfer has been accomplished via the use of digital data buses. Essentially, these are wires that share message carrying for many instruments by digitally encoding the signal for each. This reduces the number of wires and weight required to transfer remotely sensed information for the pilot's use. Flat-panel computer display screens that can be controlled to show only the information desired are also lighter in weight than the numerous individual gauges it would take to display the same information simultaneously. An added bonus is the increased reliability inherent in these solid-state systems.

It is the job of the aircraft technician to understand and maintain all aircraft, including these various instrument systems. Accordingly, in this chapter, discussions begin with analog instruments and refer to modern digital instrumentation when appropriate.

Classifying Instruments

There are three basic kinds of instruments classified by the job they perform: flight instruments, engine instruments, and navigation instruments. There are also miscellaneous gauges and indicators that provide information that do not fall into these classifications, especially on large complex aircraft. Flight control position, cabin environmental systems, electrical power, and auxiliary power units (APUs), for example, are all monitored and controlled from the cockpit via the use of instruments systems. All may be regarded as position/condition instruments since they usually report the position of a certain moveable component on the aircraft, or the condition of various aircraft components or systems not included in the first three groups.

Flight Instruments

The instruments used in controlling the aircraft's flight attitude are known as the flight instruments. There are basic flight instruments, such as the altimeter that displays aircraft altitude; the airspeed indicator; and the magnetic direction indicator, a form of compass. Additionally, an artificial horizon, turn coordinator, and vertical speed indicator are flight instruments present in most aircraft. Much variation exists for these instruments, which is explained throughout this chapter. Over the years, flight instruments have come to be situated similarly on the instrument panels in most aircraft. This basic T arrangement for flight instruments is shown in *Figure 10-4*. The top center position directly in front of the pilot and copilot is the basic display position for the artificial horizon even in modern glass cockpits (those with solid-state, flat-panel screen indicating systems).

Figure 10-4. *The basic T arrangement of analog flight instruments. At the bottom of the T is a heading indicator that functions as a compass but is driven by a gyroscope and not subject to the oscillations common to magnetic direction indicators.*

Original analog flight instruments are operated by air pressure and the use of gyroscopes. This avoids the use of electricity, which could put the pilot in a dangerous situation if the aircraft lost electrical power. Development of sensing and display techniques, combined with advanced aircraft electrical systems, has made it possible for reliable primary and secondary instrument systems that are electrically operated. Nonetheless, often a pneumatic altimeter, a gyro artificial horizon, and a magnetic direction indicator are retained somewhere in the instrument panel for redundancy. *[Figure 10-5]*

Engine Instruments

Engine instruments are those designed to measure operating parameters of the aircraft's engine(s). These are usually quantity, pressure, and temperature indications. They also include measuring engine speed(s). The most common engine instruments are the fuel and oil quantity and pressure gauges, tachometers, and temperature gauges. *Figure 10-6* contains various engine instruments found on reciprocating and turbine-powered aircraft.

Figure 10-5. *This electrically operated flat screen display instrument panel, or glass cockpit, retains an analog airspeed indicator, a gyroscope-driven artificial horizon, and an analog altimeter as a backup should electric power be lost, or a display unit fails.*

Engine instrumentation is often displayed in the center of the cockpit where it is easily visible to the pilot and copilot. *[Figure 10-7]* On light aircraft requiring only one flight crewmember, this may not be the case. Multiengine aircraft often use a single gauge for a particular engine parameter, but it displays information for all engines through the use of multiple pointers on the same dial face.

Navigation Instruments

Navigation instruments are those that contribute information used by the pilot to guide the aircraft along a definite course. This group includes compasses of various kinds, some of which incorporate the use of radio signals to define a specific course while flying the aircraft en route from one airport to another. Other navigational instruments are designed specifically to direct the pilot's approach to landing at an airport. Traditional navigation instruments include a clock and a magnetic compass. Along with the airspeed indicator and wind information, these can be used to calculate navigational progress. Radios and instruments sending locating information via radio waves have replaced these manual efforts in modern aircraft. Global position systems (GPS) use satellites to pinpoint the location of the aircraft via geometric triangulation. This technology is built into some aircraft instrument packages for navigational purposes.

Reciprocating engines	Turbine engines
Oil pressure	Oil pressure
Oil temperature	Exhaust gas temperature (EGT)
Cylinder head temperature (CHT)	Turbine inlet temperature (TIT) or turbine gas temperature (TGT)
Manifold pressure	Engine pressure ratio (EPR)
Fuel quantity	Fuel quantity
Fuel pressure	Fuel pressure
	Fuel flow
Tachometer	Tachometer (percent calibrated)
	N_1 and N_2 compressor speeds
Carburetor temperature	Torquemeter (on turboprop and turboshaft engines)

Figure 10-6. *Common engine instruments. Note: For example purposes only. Some aircraft may not have these instruments or may be equipped with others.*

Figure 10-7. *An engine instrumentation located in the middle of the instrument panel is shared by the pilot and co-pilot.*

Many of these aircraft navigational systems are discussed in chapter 11 of this handbook. *[Figure 10-8]*

To understand how various instruments work and can be repaired and maintained, they can be classified according to the principle upon which they operate. Some use mechanical methods to measure pressure and temperature. Some utilize magnetism and electricity to sense and display a parameter. Others depend on the use of gyroscopes in their primary workings. Still others utilize solid state sensors and computers to process and display important information. In the following sections, the different operating principles for sensing parameters are explained. Then, an overview of many of the engine, flight, and navigation instruments is given.

Pressure Measuring Instruments

A number of instruments inform the pilot of the aircraft's condition and flight situations through the measurement of pressure. Pressure-sensing instruments can be found in the flight group and the engine group. They can be either direct reading or remote sensing. These are some of the most critical instruments on the aircraft and must accurately inform the pilot to maintain safe operations. Pressure measurement involves some sort of mechanism that can sense changes in pressure. A technique for calibration and displaying the information is then added to inform the pilot. The type of pressure needed to be measured often makes one sensing mechanism more suited for use in a particular instance. The three fundamental pressure-sensing mechanisms used in aircraft instrument systems are the Bourdon tube, the diaphragm or bellows, and the solid-state sensing device.

A Bourdon tube is illustrated in *Figure 10-9*. The open end of this coiled tube is fixed in place and the other end is sealed and free to move. When a fluid that needs to be measured is directed into the open end of the tube, the unfixed portion

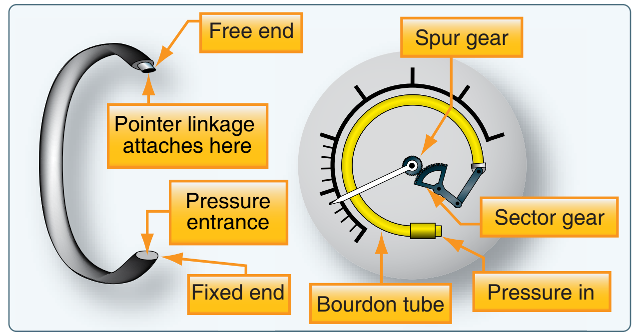


Figure 10-9. *The Bourdon tube is one of the basic mechanisms for sensing pressure.*

of the coiled tube tends to straighten out. The higher the pressure of the fluid, the more the tube straightens. When the pressure is reduced, the tube recoils. A pointer is attached to this moving end of the tube, usually through a linkage of small shafts and gears. By calibrating this motion of the straightening tube, a face or dial of the instrument can be created. Thus, by observing the pointer movement along the scale of the instrument face positioned behind it, pressure increases and decreases are communicated to the pilot.

The Bourdon tube is the internal mechanism for many pressure gauges used on aircraft. When high pressures need to be measured, the tube is designed to be stiff. Gauges used to indicate lower pressures use a more flexible tube that uncoils and coils more readily. Most Bourdon tubes are made from brass, bronze, or copper. Alloys of these metals can be made to coil and uncoil the tube consistently numerous times.

Bourdon tube gauges are simple and reliable. Some of the instruments that use a Bourdon tube mechanism include the engine oil pressure gauge, hydraulic pressure gauge, oxygen tank pressure gauge, and deice boot pressure gauge. Since the pressure of the vapor produced by a heated liquid

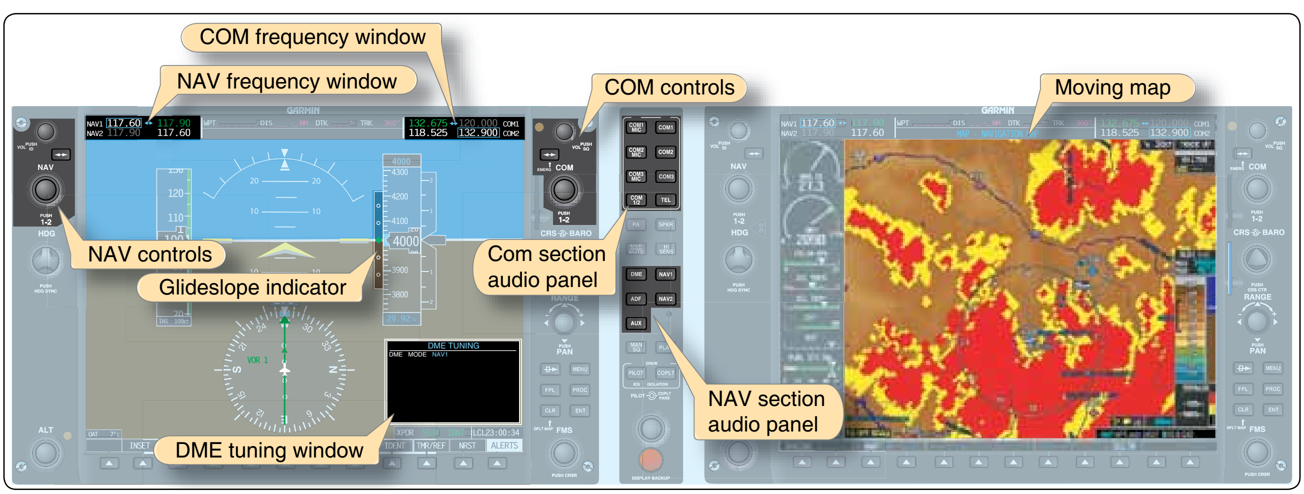


Figure 10-8. *Navigation instruments.*

or gas increases as temperature increases, Bourdon tube mechanisms can also be used to measure temperature. This is done by calibrating the pointer connecting linkage and relabeling the face of the gauge with a temperature scale. Oil temperature gauges often employ Bourdon tube mechanisms. *[Figure 10-10]*

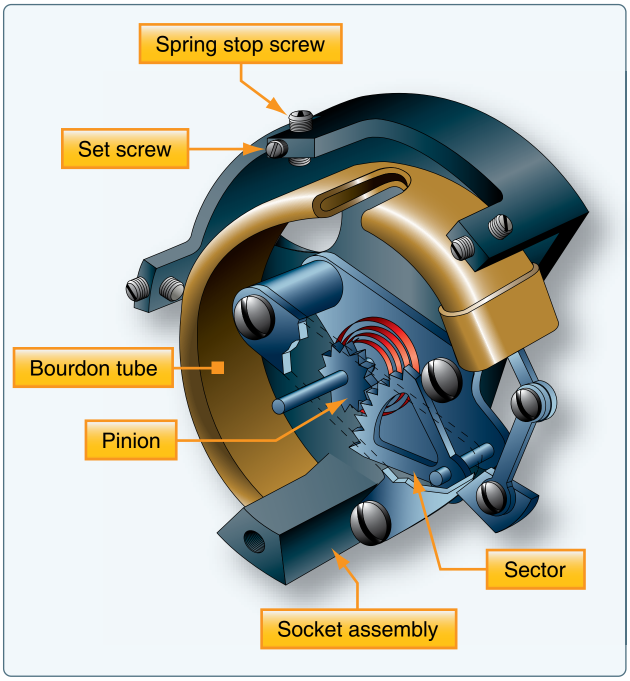


Figure 10-10. *The Bourdon tube mechanism can be used to measure pressure or temperature by recalibrating the pointer's connecting linkage and scaling instrument face to read in degrees Celsius or Fahrenheit.*

Since the sensing and display of pressure or temperature information using a Bourdon tube mechanism usually occurs in a single instrument housing, they are most often direct reading gauges. But the Bourdon tube sensing device can also be used remotely. Regardless, it is necessary to direct the fluid to be measured into the Bourdon tube. For example, a common direct-reading gauge measuring engine oil pressure and indicating it to the pilot in the cockpit is mounted in the instrument panel. A small length of tubing connects a pressurized oil port on the engine, runs though the firewall, and into the back of the gauge. This setup is especially functional on light, single-engine aircraft in which the engine is mounted just forward of the instrument panel in the forward end of the fuselage. However, a remote sensing unit can be more practical on twin-engine aircraft where the engines are a long distance from the cockpit pressure display. Here, the Bourdon tube's motion is converted to an electrical signal and carried to the cockpit display via a wire. This is lighter and more efficient, eliminating the possibility of leaking fluids into the passenger compartment of the aircraft.

The diaphragm and bellows are two other basic sensing mechanisms employed in aircraft instruments for pressure measurement. The diaphragm is a hollow, thin-walled metal disk, usually corrugated. When pressure is introduced through an opening on one side of the disk, the entire disk expands. By placing linkage in contact against the other side of the disk, the movement of the pressurized diaphragm can be transferred to a pointer that registers the movement against the scale on the instrument face. *[Figure 10-11]*

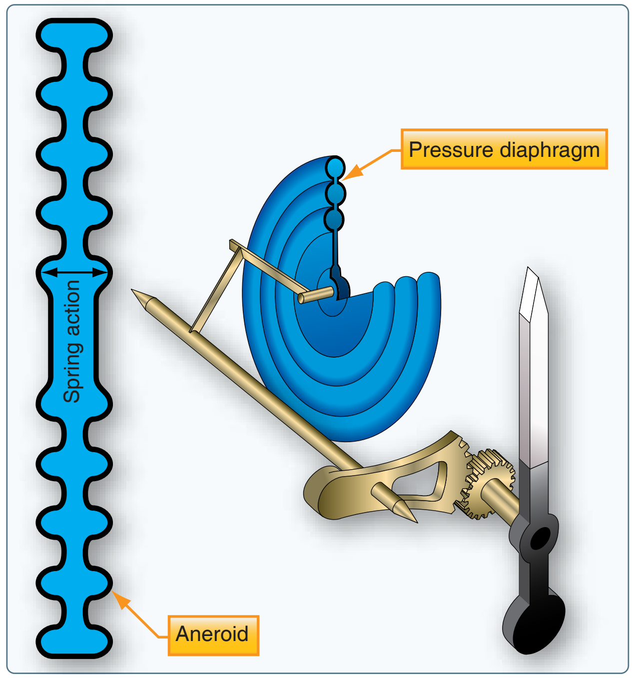


Figure 10-11. *A diaphragm used for measuring pressure. An evacuated sealed diaphragm is called an aneroid.*

Diaphragms can also be sealed. The diaphragm can be evacuated before sealing, retaining absolutely nothing inside. When this is done, the diaphragm is called an aneroid. Aneroids are used in many flight instruments. A diaphragm can also be filled with a gas to standard atmospheric pressure and then sealed. Each of these diaphragms has their uses, which are described in the next section. The common factor in all is that the expansion and contraction of the side wall of the diaphragm is the movement that correlates to increasing and decreasing pressure.

When a number of diaphragm chambers are connected together, the device is called a bellows. This accordion-like assembly of diaphragms can be very useful when measuring the difference in pressure between two gases, called differential pressure. Just as with a single diaphragm, it is the movement of the side walls of the bellows assembly that correlates with changes in pressure and to which a pointer linkage and gearing is attached to inform the pilot. *[Figure 10-12]*

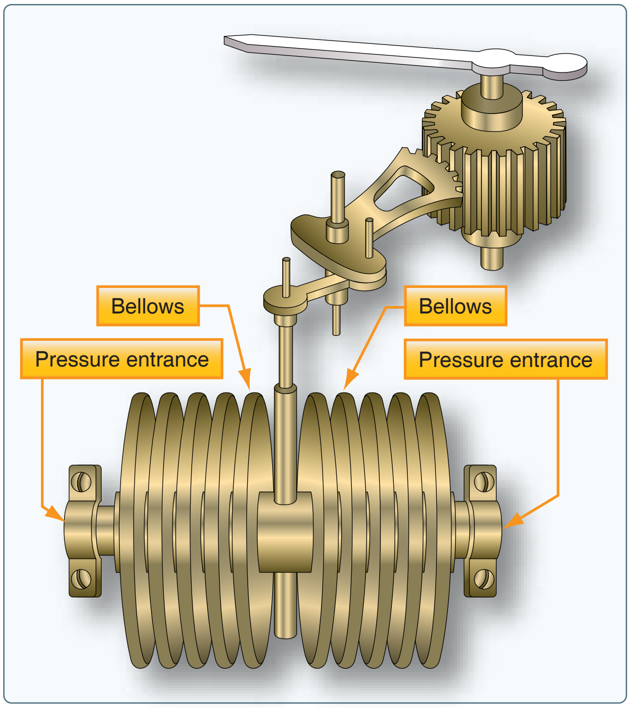


Figure 10-12. *A bellows unit in a differential pressure gauge compares two different pressure values. End movement of the bellows away from the side with the highest pressure input occurs when the pressures in the bellows are not equal. The indicator linkage is calibrated to display the difference.*

Diaphragms, aneroids, and bellows pressure sensing devices are often located inside the single instrument housing that contains the pointer and instrument dial read by the pilot on the instrument panel. Thus, many instruments that make use of these sensitive and reliable mechanisms are direct reading gauges. But, many remote sensing instrument systems also make use of the diaphragm and bellows. In this case, the sensing device containing the pressure sensitive diaphragm or bellows is located remotely on the engine or airframe. It is part of a transducer that converts the pressure into an electrical signal. The transducer, or transmitter, sends the signal to the gauge in the cockpit, or to a computer, for processing and subsequent display of the sensed condition. Examples of instruments that use a diaphragm or bellows in a direct reading or remote sensing gauge are the altimeter, vertical speed indicator, cabin differential pressure gauge (in pressurized aircraft), and manifold pressure gauge.

Solid-state microtechnology pressure sensors are used in modern aircraft to determine the critical pressures needed for safe operation. Many of these have digital output ready for processing by electronic flight instrument computers and other onboard computers. Some sensors send microelectric signals that are converted to digital format for use by computers. As with the analog sensors described above, the key to the function of solid-state sensors is their consistent property changes as pressure changes.

The solid-state sensors used in most aviation applications exhibit varying electrical output or resistance changes when pressure changes occur. Crystalline piezoelectric, piezoresistor, and semiconductor chip sensors are most common. In the typical sensor, tiny wires are embedded in the crystal or pressure-sensitive semiconductor chip. When pressure deflects the crystal(s), a small amount of electricity is created or, in the case of a semiconductor chip and some crystals, the resistance changes. Since the current and resistance changes vary directly with the amount of deflection, outputs can be calibrated and used to display pressure values.

Nearly all of the pressure information needed for engine, airframe, and flight instruments can be captured and/or calculated through the use of solid-state pressure sensors in combination with temperature sensors. But continued use of aneroid devices for comparisons involving absolute pressure is notable. Solid-state pressure-sensing systems are remote sensing systems. The sensors are mounted on the aircraft at convenient and effective locations.

Types of Pressure

Pressure is a comparison between two forces. Absolute pressure exists when a force is compared to a total vacuum, or absolutely no pressure. It is necessary to define absolute pressure, because the air in the atmosphere is always exerting pressure on everything. Even when it seems there is no pressure being applied, like when a balloon is deflated, there is still atmospheric pressure inside and outside of the balloon. To measure that atmospheric pressure, it is necessary to compare it to a total absence of pressure, such as in a vacuum. Many aircraft instruments make use of absolute pressure values, such as the altimeter, the rate-of-climb indicator, and the manifold pressure gauge. As stated, this is usually done with an aneroid.

The most common type of pressure measurement is gauge pressure. This is the difference between the pressure to be measured and the atmospheric pressure. The gauge pressure inside the deflated balloon mentioned above is therefore 0 pounds per square inch (psi). Gauge pressure is easily measured and is obtained by ignoring the fact that the atmosphere is always exerting its pressure on everything. For example, a tire is filled with air to 32 psi at a sea level location and checked with a gauge to read 32 psi, which is the gauge pressure. The approximately 14.7 psi of air pressing on the outside of the tire is ignored. The absolute pressure in the tire is 32 psi plus the 14.7 psi that is needed to balance the 14.7 psi on the outside of the tire. So, the tire's absolute pressure is approximately 46.7 psi. If the same tire is inflated to 32 psi at a location 10,000 feet above sea level, the air pressure on the outside of the tire would only be approximately 10 psi, due to the thinner atmosphere. The pressure inside the tire required to balance this would be 32 psi plus 10 psi, making the absolute pressure of the tire 42 psi. So, the same tire with the same amount of inflation and performance characteristics has different absolute pressure values. Gauge pressure, however, remains the same, indicating the tires are inflated identically. It this case, gauge pressure is more useful in informing us of the condition of the tire.

Gauge pressure measurements are simple and widely useful. They eliminate the need to measure varying atmospheric pressure to indicate or monitor a particular pressure situation. Gauge pressure should be assumed, unless otherwise indicated, or unless the pressure measurement is of a type known to require absolute pressure.

In many instances in aviation, it is desirable to compare the pressures of two different elements to arrive at useful information for operating the aircraft. When two pressures are compared in a gauge, the measurement is known as differential pressure and the gauge is a differential pressure gauge. An aircraft's airspeed indicator is a differential pressure gauge. It compares ambient air pressure with ram air pressure to determine how fast the aircraft is moving through the air. A turbine's engine pressure ratio (EPR) gauge is also a differential pressure gauge. It compares the pressure at the inlet of the engine with that at the outlet to indicate the thrust developed by the engine. Both of these differential pressure gauges and others are discussed further in this chapter and throughout this handbook.

In aviation, there is also a commonly used pressure known as standard pressure. Standard pressure refers to an established or standard value that has been created for atmospheric pressure. This standard pressure value is 29.92 inches of mercury ("Hg), 1,013.2 hectopascal (hPa), or 14.7 psi. It is part of a standard day that has been established that includes a standard temperature of 15 °C at sea level. Specific standard day values have also been established for air density, volume, and viscosity. All of these values are developed averages since the atmosphere is continuously fluctuating. They are used by engineers when designing instrument systems and are sometimes used by technicians and pilots. Often, using a standard value for atmospheric pressure is more desirable than using the actual value. For example, at 18,000 feet and above, all aircraft use 29.92 "Hg as a reference pressure for their instruments to indicate altitude. This results in altitude indications in all cockpits being identical. Therefore, an accurate means is established for maintaining vertical separation of aircraft flying at these high altitudes.

Pressure Instruments

Engine Oil Pressure

The most important instrument used by the pilot to perceive the health of an engine is the engine oil pressure gauge. *[Figure 10-13]* Oil pressure is usually indicated in psi. The normal operating range is typically represented by a green arc on the circular gauge. For exact acceptable operating range, consult the manufacturer's operating and maintenance data. In reciprocating and turbine engines, oil is used to lubricate and cool bearing surfaces where parts are rotating or sliding past each other at high speeds. A loss of pressurized oil to these areas would rapidly cause excessive friction and over temperature conditions, leading to catastrophic engine failure. As mentioned, aircraft using analog instruments often use direct reading Bourdon tube oil pressure gauges. *Figure 10-13* shows the instrument face of a typical oil pressure gauge of this type. Digital instrument systems use an analog or digital remote oil pressure sensing unit that sends output to the computer, driving the display of oil pressure value(s) on the aircraft's cockpit display screens. Oil pressure may be displayed in a circular or linear gauge fashion and may even include a numerical value on screen. Often, oil pressure is grouped with other engine parameter displays on the same page or portion of a page on the display. *Figure 10-14* shows this grouping on a Garmin G1000 digital instrument display system for general aviation aircraft.

Figure 10-13. *An analog oil pressure gauge is driven by a Bourdon tube. Oil pressure is vital to engine health and must be monitored by the pilot.*

Figure 10-14. *Oil pressure indication with other engine-related parameters shown in a column on the left side of this digital cockpit display panel.*

Manifold Pressure

In reciprocating engine aircraft, the manifold pressure gauge indicates the pressure of the air in the engine's induction manifold. This is an indication of power being developed by the engine. The higher the pressure of the fuel air mixture going into the engine, the more power it can produce. For normally aspirated engines, this means that an indication near atmospheric pressure is the maximum. Turbocharged or supercharged engines pressurize the air being mixed with the fuel, so full power indications are above atmospheric pressure.

Most manifold pressure gauges are calibrated in inches of mercury, although digital displays may have the option to display in a different scale. A typical analog gauge makes use of an aneroid described above. When atmospheric pressure acts on the aneroid inside the gauge, the connected pointer indicates the current air pressure. A line running from the intake manifold into the gauge presents intake manifold air pressure to the aneroid, so the gauge indicates the absolute pressure in the intake manifold. An analog manifold pressure gauge, along with its internal workings, is shown in *Figure 10-15*. The digital presentation of manifold pressure is at the top of the engine instruments displayed on the Garmin G1000 multifunctional display in *Figure 10-14.* The aircraft's operating manual contains data on managing manifold pressure in relation to fuel flow and propeller pitch and for achieving various performance profiles during different phases of run-up and flight.

Engine Pressure Ratio (EPR)

Turbine engines have their own pressure indication that relates the power being developed by the engine. It is called the engine pressure ratio (EPR) indicator (EPR gauge). This gauge compares the total exhaust pressure to the pressure of the ram air at the inlet of the engine. With adjustments for temperature, altitude, and other factors, the EPR gauge presents an indication of the thrust being developed by the engine. Since the EPR gauge compares two pressures, it is a differential pressure gauge. It is a remote-sensing instrument that receives its input from an engine pressure ratio transmitter or, in digital instrument systems displays, from a computer. The pressure ratio transmitter contains the bellows arrangement that compares the two pressures and converts the ratio into an electric signal used by the gauge for indication. *[Figure 10-16]*

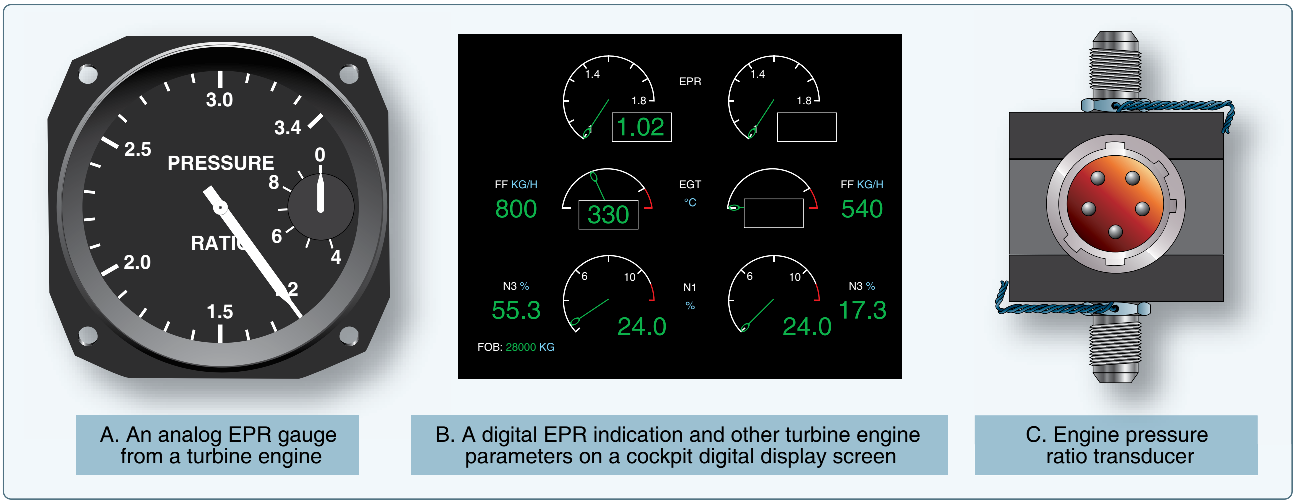


Figure 10-15. *Engine pressure ratio gauges.*

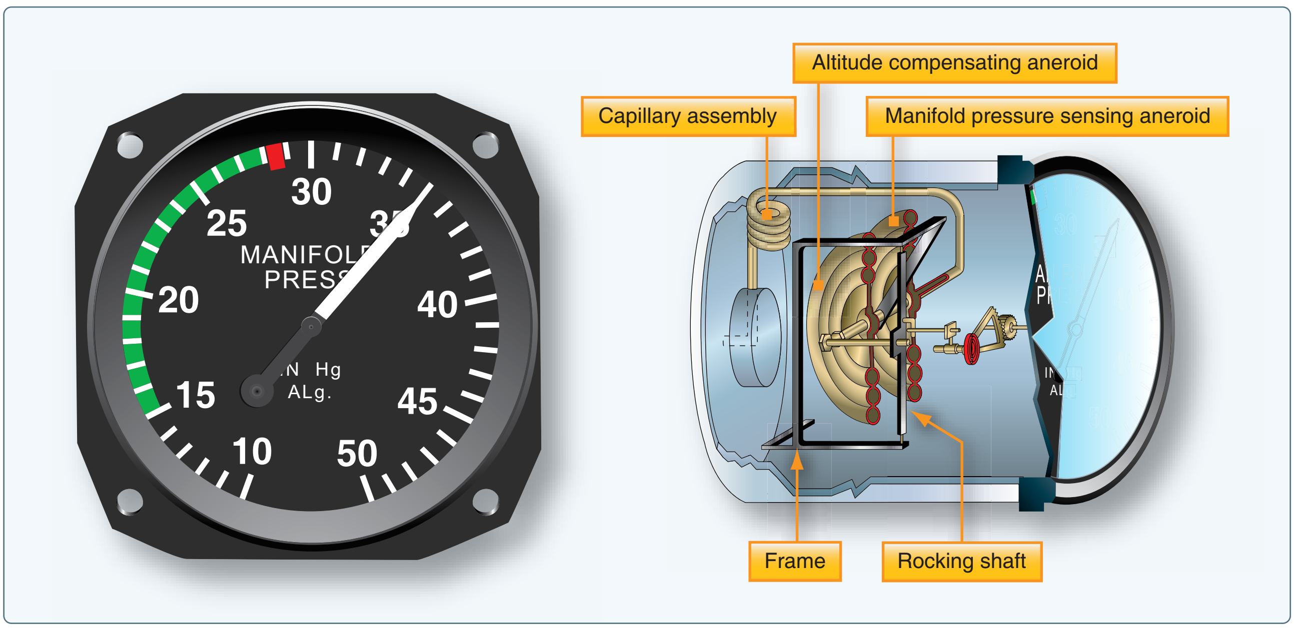


Figure 10-16. *An analog manifold pressure indicator instrument dial calibrated in inches of mercury (left). The internal workings of an analog manifold pressure gauge are shown on the right. Air from the intake manifold surrounds the aneroid causing it to deflect and indicate pressure on the dial through the use of linkage to the pointer (right).*

Fuel Pressure

Fuel pressure gauges also provide critical information to the pilot. *[Figure 10-17]* Typically, fuel is pumped out of various fuel tanks on the aircraft for use by the engines. A malfunctioning fuel pump, or a tank that has been emptied beyond the point at which there is sufficient fuel entering the pump to maintain desired output pressure, is a condition that requires the pilot's immediate attention. While direct-sensing fuel pressure gauges using Bourdon tubes, diaphragms, and bellows sensing arrangements exist, it is particularly undesirable to run a fuel line into the cockpit, due to the potential for fire should a leak develop. Therefore, the preferred arrangement is to have whichever sensing mechanism that is used be part of a transmitter device that uses electricity to send a signal to the indicator in the cockpit. Sometimes, indications monitoring the fuel flow rate are used instead of fuel pressure gauges. Fuel flow indications are discussed in the fuel system chapter of this handbook.

Hydraulic Pressure

Numerous other pressure monitoring gauges are used on complex aircraft to indicate the condition of various support systems not found on simple light aircraft. Hydraulic systems are commonly used to raise and lower landing gear, operate flight controls, apply brakes, and more. Sufficient pressure in the hydraulic system developed by the hydraulic pump(s) is

Figure 10-17. *A typical analog fuel pressure gauge.*

required for normal operation of hydraulic devices. Hydraulic pressure gauges are often located in the cockpit and at or near the hydraulic system servicing point on the airframe. Remotely located indicators used by maintenance personnel are almost always direct reading Bourdon tube type gauges. Cockpit gauges usually have system pressure transmitted from sensors or computers electrically for indication. *Figure 10-18* shows a hydraulic pressure transmitter in place in a high-pressure aircraft hydraulic system.

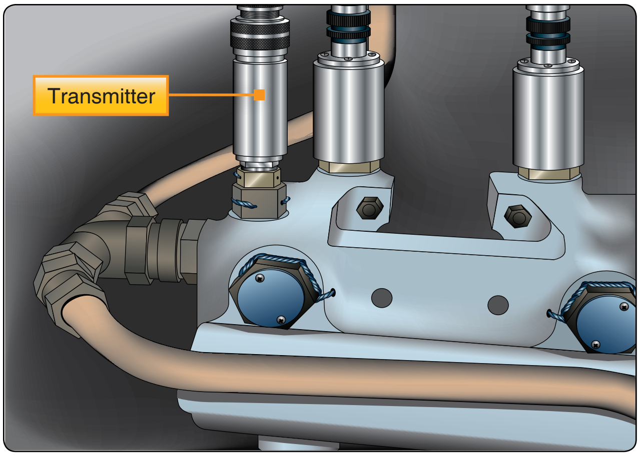


Figure 10-18. *A hydraulic pressure transmitter senses and converts pressure into an electrical output for indication by the cockpit gauge or for use by a computer that analyzes and displays the pressure in the cockpit when requested or required.*

Vacuum Pressure

Gyro pressure gauge, vacuum gauge, or suction gauge are all terms for the same gauge used to monitor the vacuum developed in the system that actuates the air driven gyroscopic flight instruments. Air is pulled through the instruments, causing the gyroscopes to spin. The speed at which the gyros spin needs to be within a certain range for correct operation. This speed is directly related to the suction pressure that is developed in the system. The suction gauge is extremely important in aircraft relying solely on vacuum-operated gyroscopic flight instruments.

Vacuum is a differential pressure indication, meaning the pressure to be measured is compared to atmospheric pressure through the use of a sealed diaphragm or capsule. The gauge is calibrated in inches of mercury. It shows how much less pressure exists in the system than in the atmosphere. *Figure 10-19* shows a suction gauge calibrated in inches of mercury.

Figure 10-19. *Vacuum suction gauge.*

Pressure Switches

In aviation, it is often sufficient to simply monitor whether the pressure developed by a certain operating system is too high or too low, so that an action can take place should one of these conditions occur. This is often accomplished through the use of a pressure switch. A pressure switch is a simple device usually made to open or close an electric circuit when a certain pressure is reached in a system. It can be manufactured so that the electric circuit is normally open and can then close when a certain pressure is sensed, or the circuit can be closed and then opened when the activation pressure is reached. [*Figure 10-20]*

Pressure switches contain a diaphragm to which the pressure being sensed is applied on one side. The opposite side of the diaphragm is connected to a mechanical switching mechanism for an electric circuit. Small fluctuations or a buildup of pressure against the diaphragm move the diaphragm, but not enough to throw the switch. Only when

Figure 10-20. *A pressure switch can be used in addition to, or instead of, a pressure gauge.*

pressure meets or exceeds a preset level designed into the structure of the switch does the diaphragm move far enough for the mechanical device on the opposite side to close the switch contacts and complete the circuit. *[Figure 10-21]* Each switch is rated to close (or open) at a certain pressure, and must only be installed in the proper location.

A low oil pressure indication switch is a common example of how pressure switches are employed. It is installed in an engine so pressurized oil can be applied to the switch's diaphragm. Upon starting the engine, oil pressure increases and the pressure against the diaphragm is sufficient to hold the contacts in the switch open. As such, current does not flow through the circuit and no indication of low oil pressure is given in the cockpit. Should a loss of oil pressure occur, the pressure against the diaphragm becomes insufficient to hold the switched contacts open. When the contacts close, they close the circuit to the low oil pressure indicator, usually a light, to warn the pilot of the situation.

Pressure gauges for various components or systems work similarly to those mentioned above. Some sort of sensing device, appropriate for the pressure being measured or monitored, is matched with an indicating display system. If appropriate, a properly rated pressure switch is installed in the system and wired into an indicating circuit. Further discussion of specific instruments occurs throughout this handbook as the operation of various systems and components are discussed.

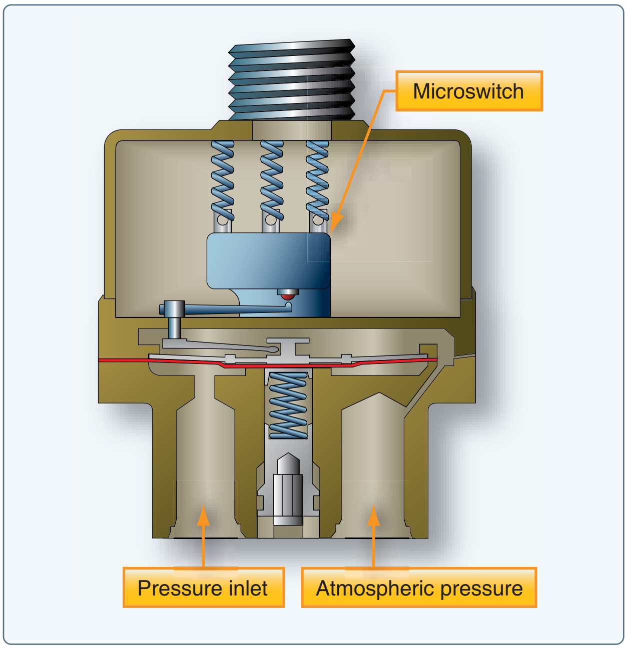


Figure 10-21. *A normally open pressure switch positioned in an electrical circuit causes the circuit to be open as well. The switch closes, allowing electricity to flow when pressure is applied beyond the switch's preset activation point. Normally, closed pressure switches allow electricity to flow through the switch in a circuit but open when pressure reaches a preset activation point, thus opening the electrical circuit.*

Pitot-Static Systems

Some of the most important flight instruments derive their indications from measuring air pressure. Gathering and distributing various air pressures for flight instrumentation is the function of the pitot-static system.

Pitot Tubes and Static Vents

On simple aircraft, this may consist of a pitot-static system head or pitot tube with impact and static air pressure ports and leak-free tubing connecting these air pressure pick-up points to the instruments that require the air for their indications. The altimeter, airspeed indicator, and vertical speed indicator are the three most common pitot-static instruments. *Figure 10-22* illustrates a simple pitot-static system connected to these three instruments.

A pitot tube is shown in *Figure 10-23*. It is open and faces into the airstream to receive the full force of the impact air pressure as the aircraft moves forward. This air passes through a baffled plate designed to protect the system from moisture and dirt entering the tube. Below the baffle, a drain hole is provided, allowing moisture to escape. The ram air is directed aft to a chamber in the shark fin of the assembly. An upright tube, or riser, leads this pressurized air out of the pitot assemble to the airspeed indicator.

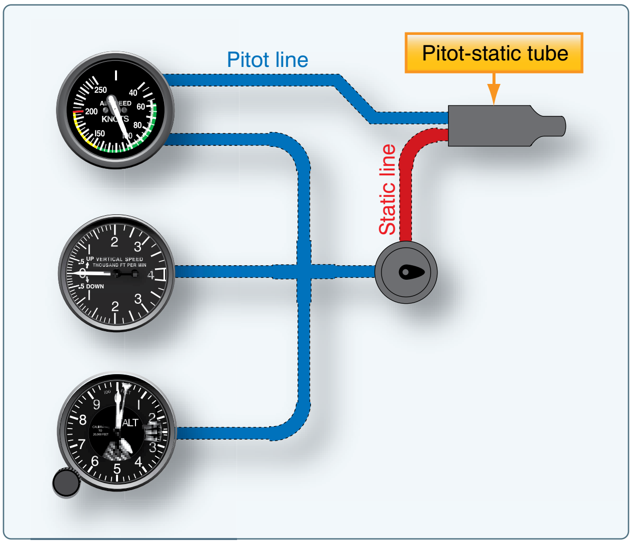


Figure 10-22. *A simple pitot-static system is connected to the primary flight instruments.*

The aft section of the pitot tube is equipped with small holes on the top and bottom surfaces that are designed to collect air pressure that is at atmospheric pressure in a static, or still, condition. *[Figure 10-23]* The static section also contains a riser tube and the air is run out the pitot assembly through tubes and is connected to the altimeter, the airspeed indicator, and the vertical speed indicator.

Many pitot-static tube heads contain heating elements to prevent icing during flight. The pilot can send electric current to the element with a switch in the cockpit when ice-forming conditions exist. Often, this switch is wired through the ignition switch so that when the aircraft is shut down, a pitot tube heater inadvertently left on does not continue to draw current and drain the battery. Caution should be exercised when near the pitot tube, as these heating elements make the tube too hot to be touched without receiving a burn.

The pitot-static tube is mounted on the outside of the aircraft at a point where the air is least likely to be turbulent. It is pointed in a forward direction parallel to the aircraft's line of flight. The location may vary. Some are on the nose of the fuselage and others may be located on a wing. A few may even be found on the empennage. Various designs exist but the function remains the same, to capture impact air pressure and static air pressure and direct them to the proper instruments. *[Figure 10-24]*

Most aircraft equipped with a pitot-static tube have an alternate source of static air pressure provided for emergency use. The pilot may select the alternate with a switch in the cockpit should it appear the flight instruments are not providing accurate indications. On low-flying unpressurized aircraft, the alternate static source may simply be air from

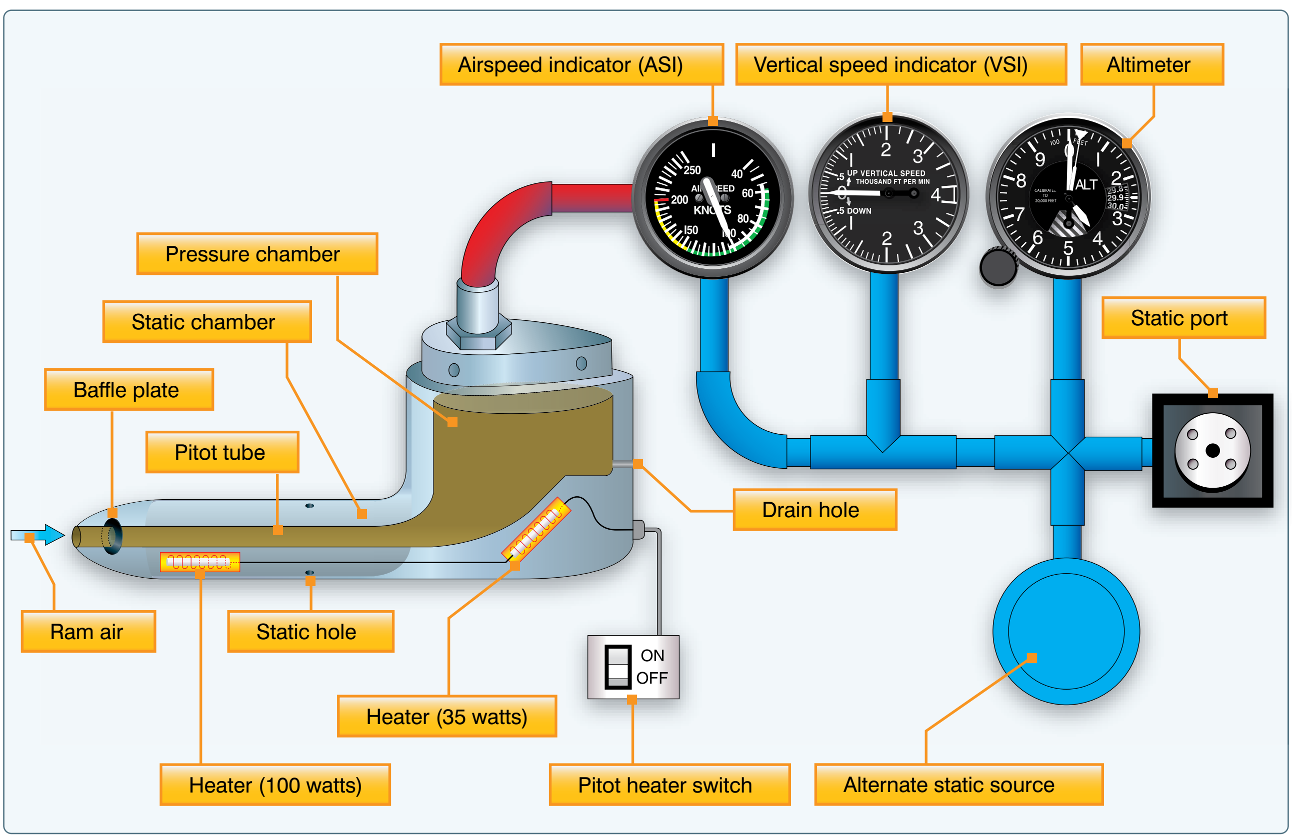


Figure 10-23. *A typical pitot-static system head, or pitot tube, collects ram air and static pressure for use by the flight instruments.*

Figure 10-24. *Pitot-static system heads, or pitot tubes, can be of various designs and locations on airframes.*

the cabin. *[Figure 10-25]* On pressurized aircraft, cabin air pressure may be significantly different than the outside ambient air pressure. If used as an alternate source for static air, instrument indications would be grossly inaccurate. In this case, multiple static vent pickup points are employed. All are located on the outside of the aircraft and plumbed so the pilot can select which source directs air into the instruments. On electronic flight displays, the choice is made for which source is used by the computer or by the flight crew.

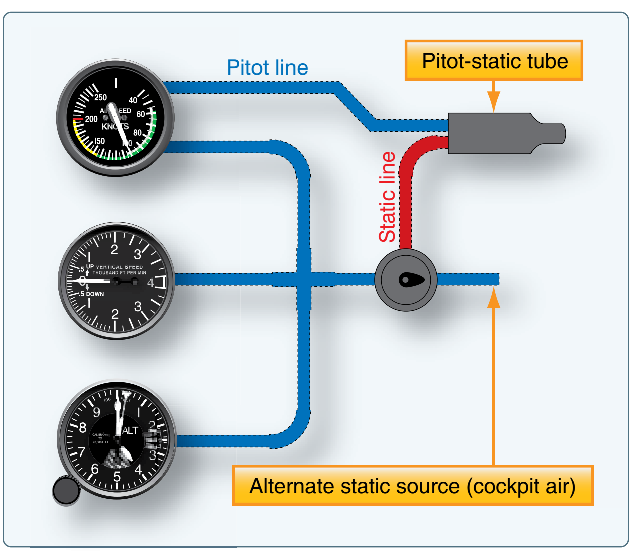


Figure 10-25. *On unpressurized aircraft, an alternate source of static air is cabin air.*

Another type of pitot-static system provides for the location of the pitot and static sources at separate positions on the aircraft. The pitot tube in this arrangement is used only to gather ram air pressure. Separate static vents are used to collect static air pressure information. Usually, these are located flush on the side of the fuselage. *[Figure 10-26]* There may be two or more vents. A primary and alternate source vent is typical, as well as separate dedicated vents for the pilot and first officer's instruments. Also, two primary vents may be located on opposite sides of the fuselage and connected with Y tubing for input to the instruments. This is done to compensate for any variations in static air pressure on the vents due to the aircraft's attitude. Regardless of the number and location of separate static vents, they may be heated as well as the separate ram air pitot tube to prevent icing.

Figure 10-26. *Heated primary and alternate static vents located on the sides of the fuselage.*

The pitot-static systems of complex, multiengine, and pressurized aircraft can be elaborate. Additional instruments, gauges, the autopilot system, and computers may need pitot and static air information. *Figure 10-27* shows a pitot-static system for a pressurized multiengine aircraft with dual analog instrument panels in the cockpit. The additional set of flight instruments for the copilot alters and complicates the pitot-static system plumbing. Additionally, the autopilot system requires static pressure information, as does the cabin pressurization unit. Separate heated sources for static air pressure are taken from both sides of the airframe to feed independent static air pressure manifolds; one each for the pilot's flight instruments and the copilot's flight instruments. This is designed to ensure that there is always one set of flight instruments operable in case of a malfunction.

Air Data Computers (ADC) and Digital Air Data Computers (DADC)

High performance and jet transport category aircraft pitot-static systems may be more complicated. These

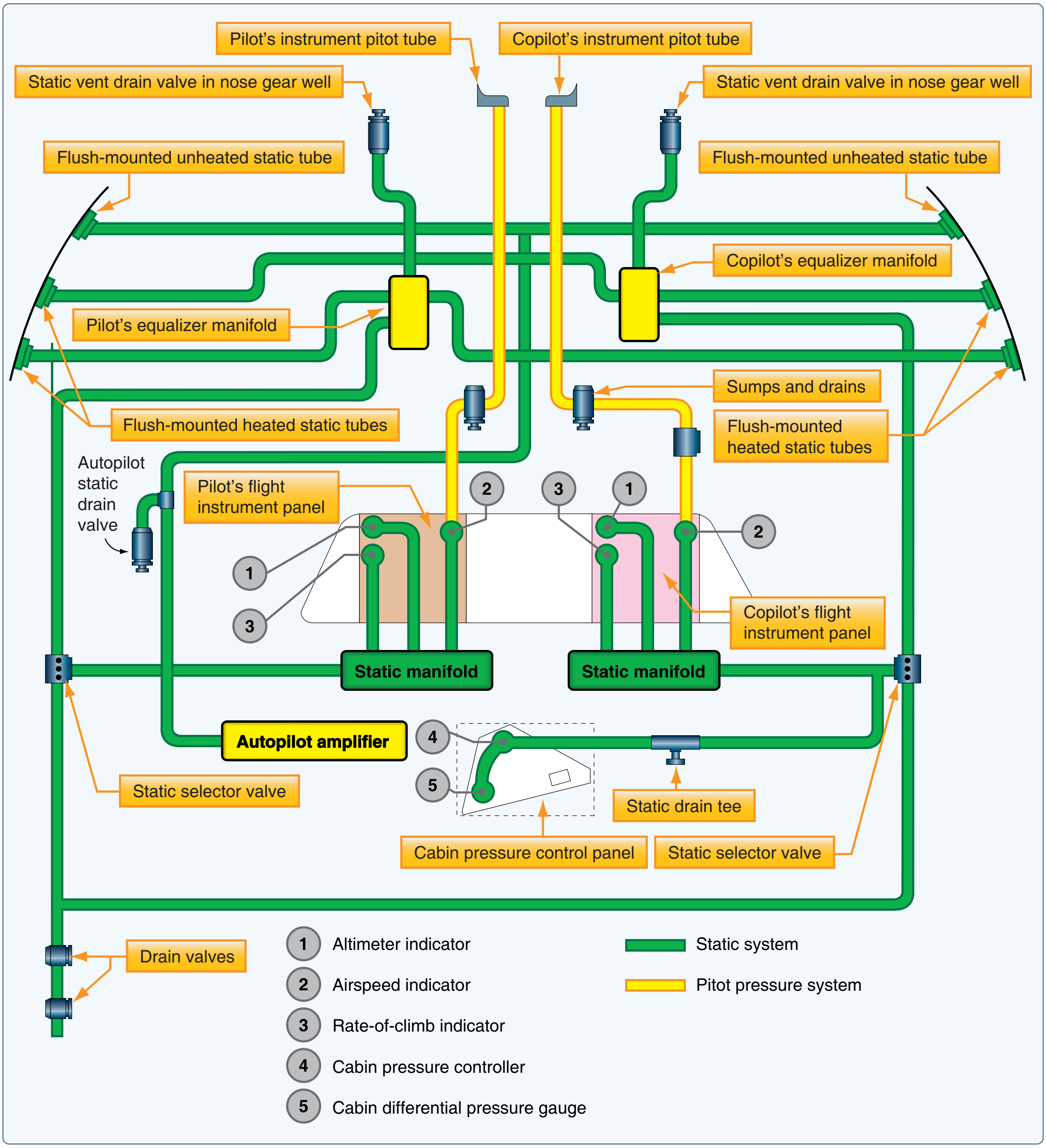


Figure 10-27. *Schematic of a typical pitot-static system on a pressurized multiengine aircraft.*

aircraft frequently operate at high altitude where the ambient temperature can exceed 50 °F below zero. The compressibility of air is also altered at high speeds and at high altitudes. Airflow around the fuselage changes, making it difficult to pick up consistent static pressure inputs. The pilot must compensate for all factors of air temperature and density to obtain accurate indications from instruments. While many analog instruments have compensating devices built into them, the use of an air data computer (ADC) is common for these purposes on high-performance aircraft. Moreover, modern aircraft utilize digital air data computers (DADC). The conversion of sensed air pressures into digital values makes them more easily manipulated by the computer to output accurate information that has compensated for the many variables encountered. *[Figure 10-28]*

Figure 10-28. *Teledyne's 90004 TAS/Plus air data computer (ADC) computes air data information from the pitot-static pneumatic system, aircraft temperature probe, and barometric correction device to help create a clear indication of flight conditions.*

Essentially, all pressures and temperatures captured by sensors are fed into the ADC. Analog units utilize transducers to convert these to electrical values and manipulate them in various modules containing circuits designed to make the proper compensations for use by different instruments and systems. A DADC usually receives its data in digital format. Systems that do not have digital sensor outputs will first convert inputs into digital signals via an analog-to-digital converter. Conversion can take place inside the computer or in a separate unit designed for this function. Then, all calculation and compensations are performed digitally by the computer. Outputs from the ADC are electric to drive servo motors or for use as inputs in pressurization systems, flight control units, and other systems. DADC outputs are distributed to these same systems and the cockpit display using a digital data bus.

There are numerous benefits of using ADCs. Simplification of pitot-static plumbing lines creates a lighter, simpler, system with fewer connections, so it is less prone to leaks and easier to maintain. One-time compensation calculations can be done inside the computer, eliminating the need to build compensating devices into numerous individual instruments or units of the systems using the air data. DADCs can run a number of checks to verify the plausibility of data received from any source on the aircraft. Thus, the crew can be alerted automatically of a parameter that is out of the ordinary. Change to an alternate data source can also be automatic so accurate flight deck and systems operations are continuously maintained. In general, solid-state technology is more reliable and modern units are small and lightweight. *Figure 10-29* shows a schematic of how a DADC is connected into the aircraft's pitot-static and other systems.

Pitot-Static Pressure-Sensing Flight Instruments

The basic flight instruments are directly connected to the pitot-static system on many aircraft. Analog flight instruments primarily use mechanical means to measure and indicate various flight parameters. Digital flight instrument systems use electricity and electronics to do the same. Discussion of the basic pitot-static flight instruments begins with analog instruments to which further information about modern digital instrumentation is added.

Altimeters and Altitude

An altimeter is an instrument that is used to indicate the height of the aircraft above a predetermined level, such as sea level or the terrain beneath the aircraft. The most common way to measure this distance is rooted in discoveries made by scientists centuries ago. Seventeenth century work proving that the air in the atmosphere exerted pressure on the things around us led Evangelista Torricelli to the invention of the barometer. Also in that century, using the concept of this first atmospheric air pressure measuring instrument, Blaise Pascal was able to show that a relationship exists between altitude and air pressure. As altitude increases, air pressure decreases. The amount that it decreases is measurable and consistent for any given altitude change. Therefore, by measuring air pressure, altitude can be determined. *[Figure 10-30]*

Altimeters that measure the aircraft's altitude by measuring the pressure of the atmospheric air are known as pressure altimeters. A pressure altimeter is made to measure the ambient air pressure at any given location and altitude. In aircraft, it is connected to the static vent(s) via tubing in the pitot-static system. The relationship between the measured pressure and the altitude is indicated on the instrument face, which is calibrated in feet. These devises are direct-reading instruments that measure absolute pressure. An aneroid or aneroid bellows is at the core of the pressure altimeter's inner workings. Attached to this sealed diaphragm are the linkages and gears that connect it to the indicating pointer. Static air pressure enters the airtight instrument case and surrounds the aneroid. At sea level, the altimeter indicates zero when this pressure is exerted by the ambient air on the aneroid. As air pressure is reduced by moving the altimeter higher in the atmosphere, the aneroid expands and displays altitude on the instrument by rotating the pointer. As the altimeter is lowered in the atmosphere, the air pressure around the aneroid increases and the pointer moves in the opposite direction. *[Figure 10-31]*

The face, or dial, of an analog altimeter is read similarly to a clock. As the longest pointer moves around the dial, it is registering the altitude in hundreds of feet. One complete revolution of this pointer indicates 1,000 feet of altitude.

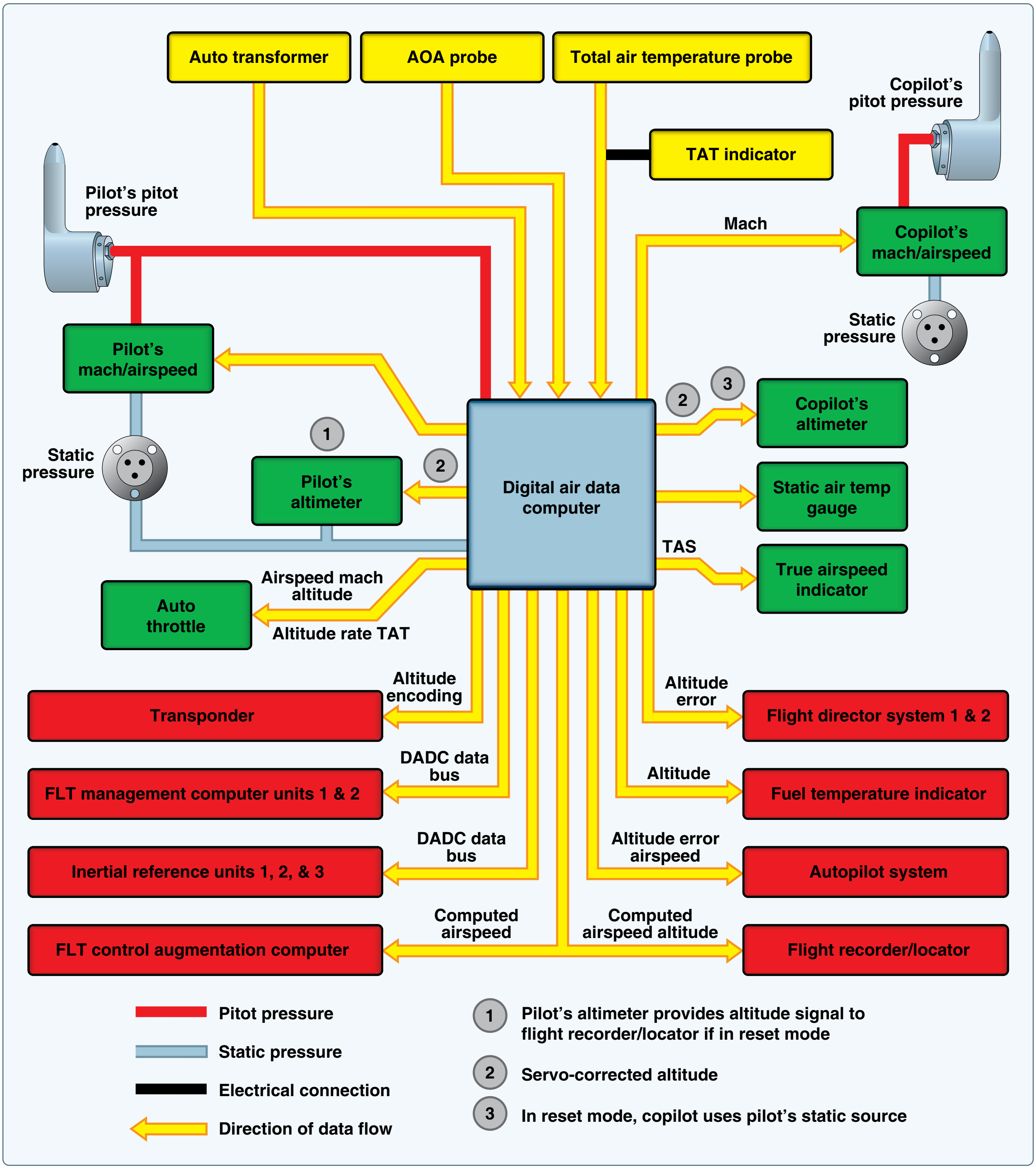


Figure 10-29. *ADCs receive input from the pitot-static sensing devices and process them for use by numerous aircraft systems.*

The second-longest point moves more slowly. Each time it reaches a numeral, it indicates 1,000 feet of altitude. Once around the dial for this pointer is equal to 10,000 feet. When the longest pointer travels completely around the dial one time, the second-longest point moves only the distance between two numerals—indicating 1,000 feet of altitude has been attained. If so equipped, a third, shortest or thinnest pointer registers altitude in 10,000 foot increments. When this pointer reaches a numeral, 10,000 feet of altitude has been attained. Sometimes a black-and-white or red-and-white cross-hatched area is shown on the face on the instrument until the 10,000 foot level has been reached. *[Figure 10-32]*

Atmosphere pressure	
Altitude (ft)	Pressure (psi)
Sea level	14.69
2,000	13.66
4,000	12.69
6,000	11.77
8,000	10.91
10,000	10.10
12,000	9.34
14,000	8.63
16,000	7.96
18,000	7.34
20,000	6.75
22,000	6.20
24,000	5.69
26,000	5.22
28,000	4.77
30,000	4.36
32,000	3.98
34,000	3.62
36,000	3.29
38,000	2.99
40,000	2.72
42,000	2.47
44,000	2.24
46,000	2.04
48,000	1.85
50,000	1.68

Figure 10-30. *Air pressure is inversely related to altitude. This consistent relationship is used to calibrate the pressure altimeter.*

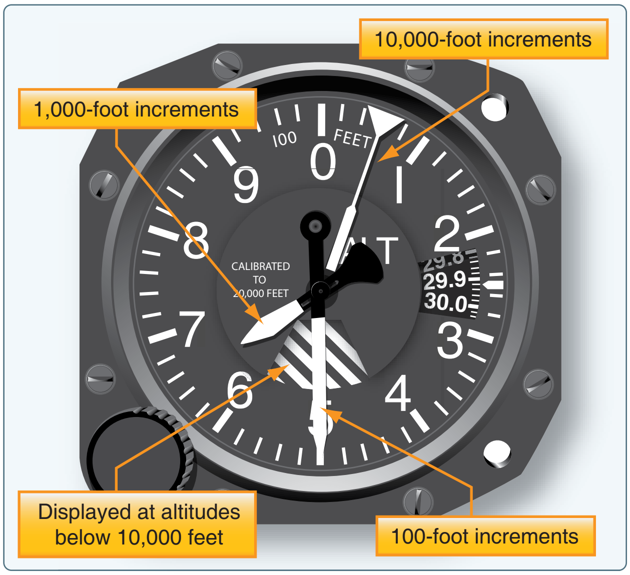


Figure 10-32. *A sensitive altimeter with three pointers and a cross-hatched area displayed during operation below 10,000 feet.*

Many altimeters also contain linkages that rotate a numerical counter in addition to moving pointers around the dial. This quick reference window allows the pilot to simply read the numerical altitude in feet. The motion of the rotating digits or drum-type counter during rapid climb or descent makes it difficult or impossible to read the numbers. Reference can then be directed to the classic clock-style indication. *Figure 10-33* illustrates the inner workings behind this type of mechanical digital display of pressure altitude.

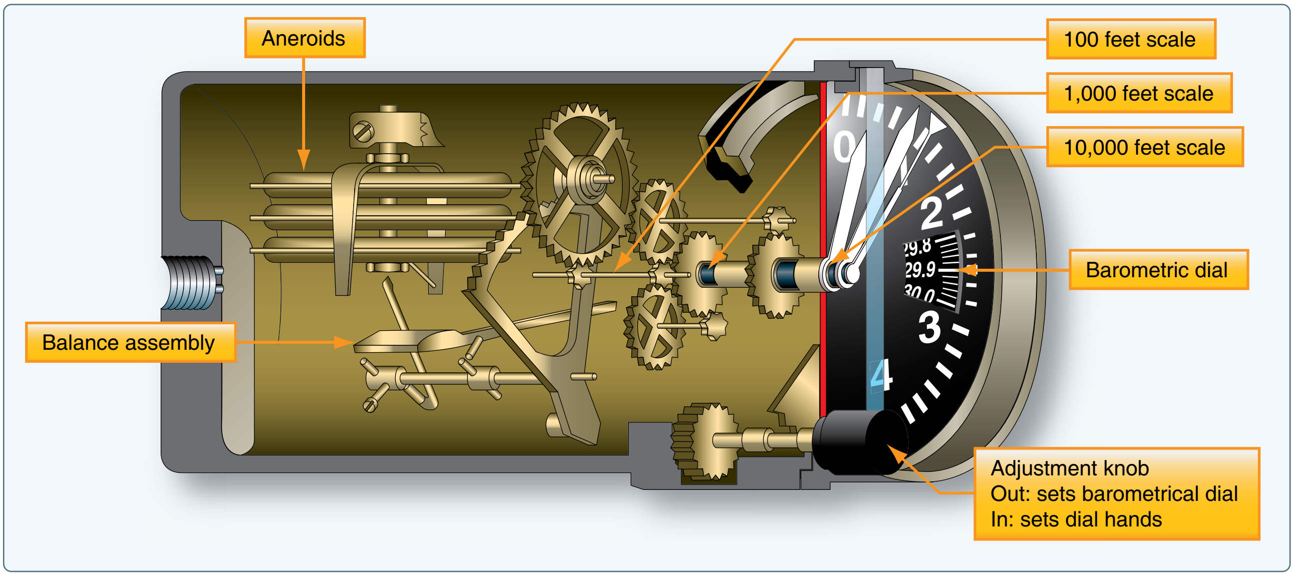


Figure 10-31. *The internal arrangement of a sealed diaphragm pressure altimeter. At sea level and standard atmospheric conditions, the linkage attached to the expandable diaphragm produces an indication of zero. When altitude increases, static pressure on the outside of the diaphragm decreases and the aneroid expands, producing a positive indication of altitude. When altitude decreases, atmospheric pressure increases. The static air pressure on the outside of the diaphragm increases and the pointer moves in the opposite direction, indicating a decrease in altitude.*

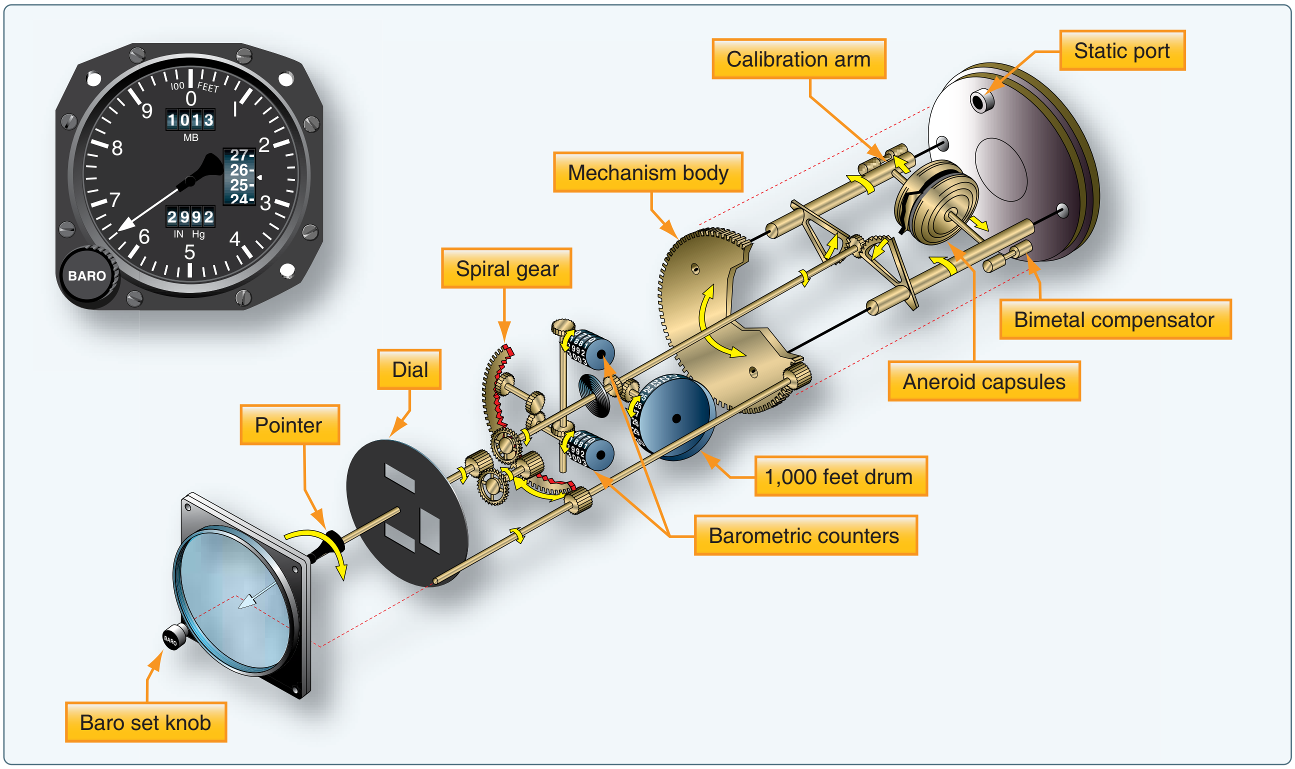


Figure 10-33. *A drum-type counter can be driven by the altimeter's aneroid for numerical display of altitude. Drums can also be used for the altimeter's setting indications.*

True digital instrument displays can show altitude in numerous ways. Use of a numerical display rather than a reproduction of the clock-type dial is most common. Often a digital numeric display of altitude is given on the electronic primary flight display near the artificial horizon depiction. A linear vertical scale may also be presented to put this hard numerical value in perspective. An example of this type of display of altitude information is shown in *Figure 10-34*.

Accurate measurement of altitude is important for numerous reasons. The importance is magnified in instrument flight rules (IFR) conditions. For example, avoidance of tall obstacles and rising terrain relies on precise altitude indication, as does flying at a prescribed altitude assigned by air traffic control (ATC) to avoid colliding with other aircraft. Measuring altitude with a pressure measuring device is fraught with complications. Steps are taken to refine pressure altitude indication to compensate for factors that may cause an inaccurate display.

A major factor that affects pressure altitude measurements is the naturally occurring pressure variations throughout the atmosphere due to weather conditions. Different air masses develop and move over the earth's surface, each with inherent pressure characteristics. These air masses cause the weather we experience, especially at the boundary areas between air masses known as fronts. Accordingly, at sea level, even if the temperature remains constant, air pressure rises and falls as weather system air masses come and go. The values in *Figure 10-30,* therefore, are averages for theoretical purposes.

To maintain altimeter accuracy despite varying atmospheric pressure, a means for setting the altimeter was devised. An adjustable pressure scale visible on the face of an analog altimeter known as a barometric or Kollsman window is set to read the existing atmospheric pressure when the pilot rotates the knob on the front of the instrument. This adjustment is linked through gears inside the altimeter to move the altitude indicating pointers on the dial as well. By putting the current known air pressure (also known as the altimeter setting) in the window, the instrument indicates the actual altitude. This altitude, adjusted for atmospheric pressure changes due to weather and air mass pressure inconsistency, is known as the indicated altitude.

It must be noted that in flight the altimeter setting is changed to match that of the closest available weather reporting station or airport. This keeps the altimeter accurate as the flight progresses.

While there was little need for exact altitude measurement in early fixed wing aviation, knowing one's altitude provided the pilot with useful references while navigating in the three dimensions of the atmosphere. As air traffic grew

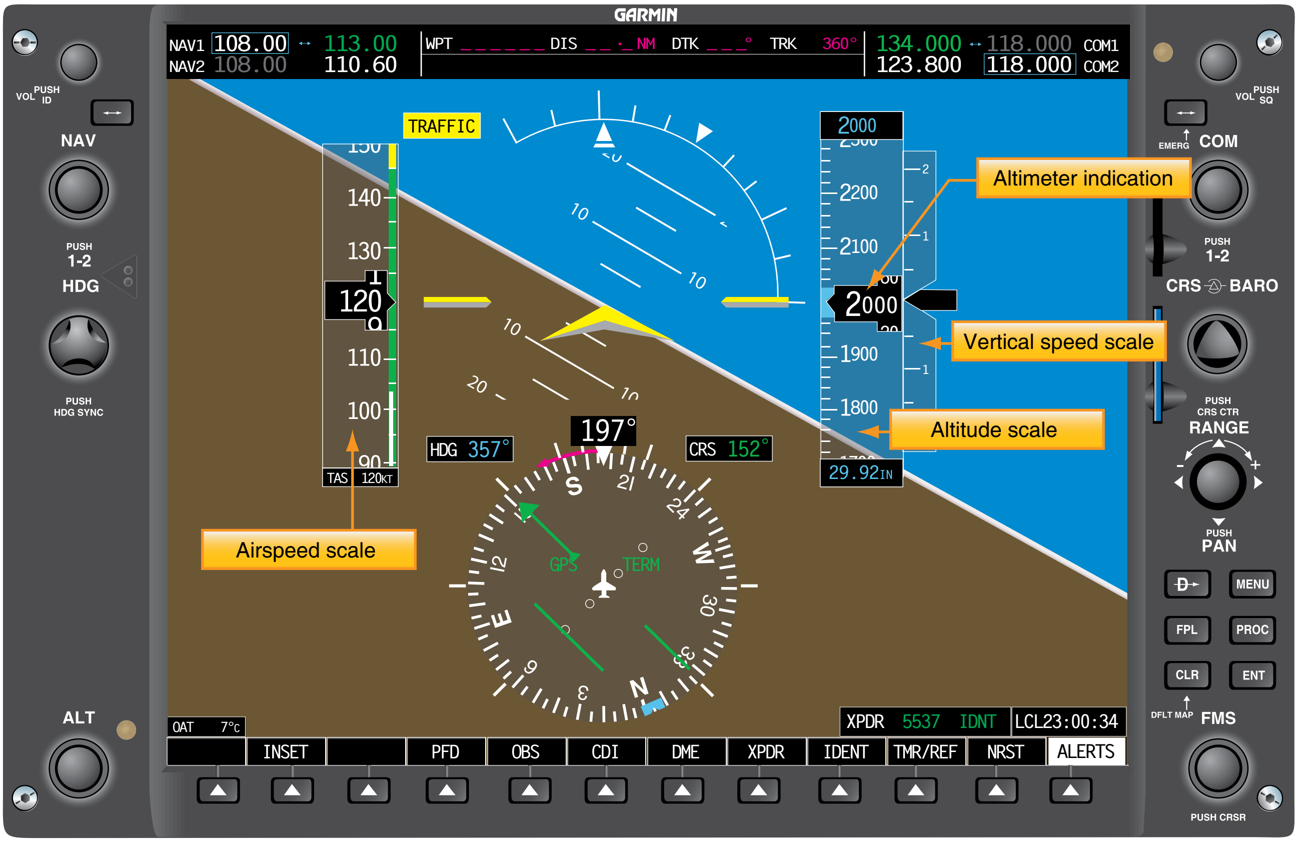


Figure 10-34. *This primary flight display unit of a Garmin 1000 series glass cockpit instrumentation package for light aircraft indicates altitude using a vertical linear scale and a numerical counter. As the aircraft climbs or descends, the scale behind the black numerical altitude readout changes.*

and the desire to fly in any weather conditions increased, exact altitude measurement became more important and the altimeter was refined. In 1928, Paul Kollsman invented the means for adjusting an altimeter to reflect variations in air pressure from standard atmospheric pressure. The very next year, Jimmy Doolittle made his successful flight demonstrating the feasibility of instrument flight with no visual references outside of the cockpit using a Kollsman sensitive altimeter.

The term pressure altitude is used to describe the indication an altimeter gives when 29.92 is set in the Kollsman window. When flying in U.S. airspace above 18,000 feet mean sea level (MSL), pilots are required to set their altimeters to 29.92. With all aircraft referencing this standard pressure level, vertical separation between aircraft assigned to different altitudes by ATC should be assured. This is the case if all altimeters are functioning properly and pilots hold their assigned altitudes. Note that the true altitude or actual height of an aircraft above sea level is only the same as the pressure altitude when standard day conditions exist. Otherwise, all aircraft with altimeters set to 29.92 "Hg could have true altitudes higher or lower than the pressure altitude indicated. This is due to the pressure within the air mass in which they are flying being above or below standard day pressure (29.92). The actual or true altitude is less important than keeping aircraft from colliding, which is accomplished by all aircraft above 18,000 feet referencing the same pressure level (29.92 "Hg). *[Figure 10-35]*

Temperature also affects the accuracy of an altimeter. The aneroid diaphragms used in altimeters are usually made of metal. Their elasticity changes as their temperature changes. This can lead to a false indication, especially at high altitudes when the ambient air is very cold. A bimetallic compensating device is built into many sensitive altimeters to correct for varying temperature. *Figure 10-33* shows one such device on a drum-type altimeter.

Temperature also affects air density, which has great impact on the performance of an aircraft. Although this does not cause the altimeter to produce an errant reading, flight crews must be aware that performance changes with temperature variations in the atmosphere. The term density altitude describes altitude corrected for nonstandard temperature. That is, the density altitude is the standard day altitude (pressure altitude) at which an aircraft would experience similar performance as it would on the non-standard day

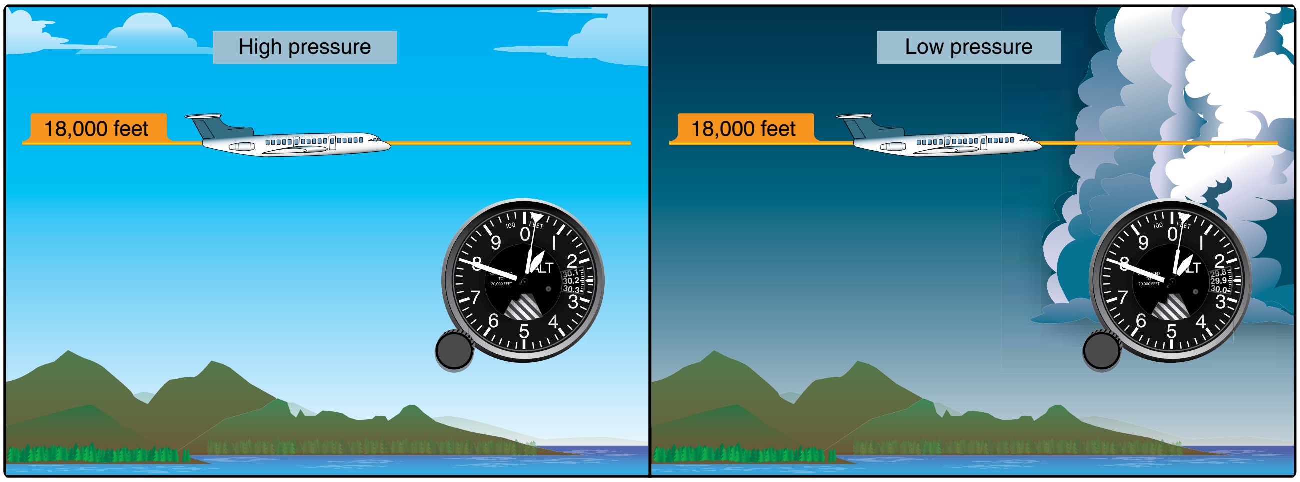


Figure 10-35. *Above 18,000 feet MSL, all aircraft are required to set 29.92 as the reference pressure in the Kollsman window. The altimeter then reads pressure altitude. Depending on the atmospheric pressure that day, the true or actual altitude of the aircraft may be above or below what is indicated (pressure altitude).*

currently being experienced. For example, on a very cold day, the air is denser than on a standard day, so an aircraft performs as though it is at a lower altitude. The density altitude is lower that day. On a very hot day, the reverse is true, and an aircraft performs as though it were at a higher elevation where the air is less dense. The density altitude is higher that day.

Conversion factors and charts have been produced so pilots can calculate the density altitude on any particular day. Inclusion of nonstandard air pressure due to weather systems and humidity can also be factored. So, while the effects of temperature on aircraft performance do not cause an altimeter to indicate falsely, an altimeter indication can be misleading in terms of aircraft performance if these effects are not considered. *[Figure 10-36]*

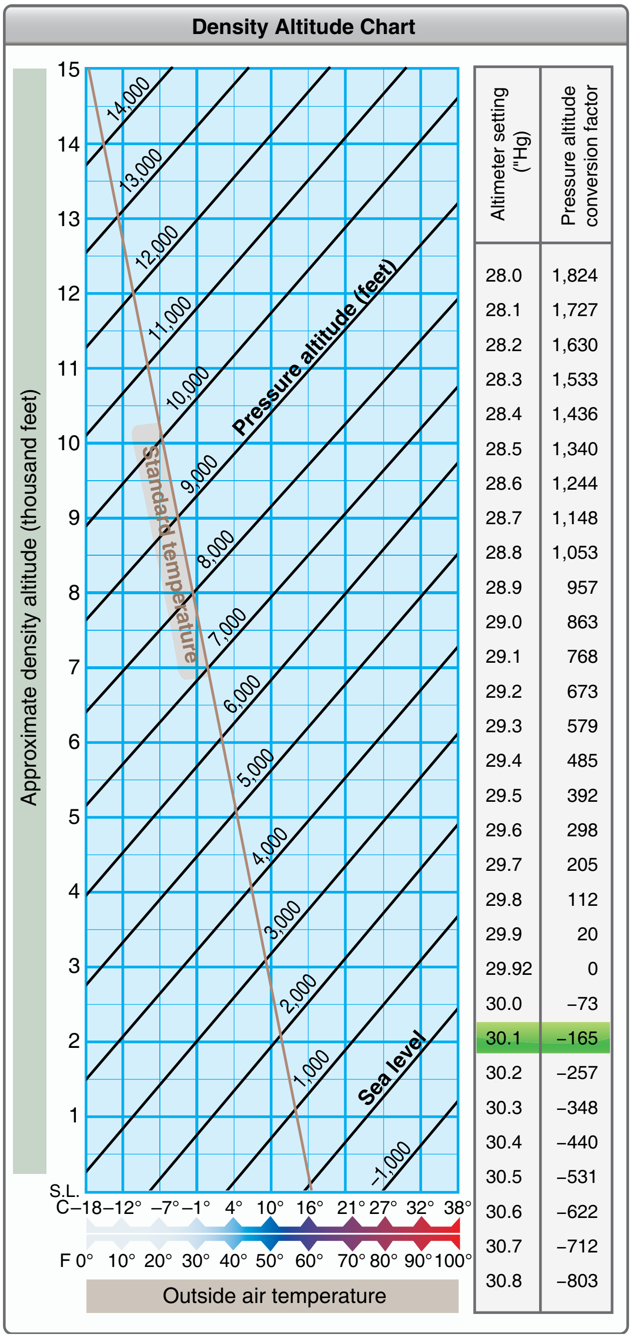
Other factors can cause an inaccurate altimeter indication. Scale error is a mechanical error whereby the scale of the instrument is not aligned so the altimeter pointers indicate correctly. Periodic testing and adjustment by trained technicians using calibrated equipment ensures scale error is kept to a minimum.

The pressure altimeter is connected to the pitot-static system and must receive an accurate sample of ambient air pressure to indicate the correct altitude. Position error, or installation error, is that inaccuracy caused by the location of the static vent that supplies the altimeter. While every effort is made to place static vents in undisturbed air, airflow over the airframe changes with the speed and attitude of the aircraft. The amount of this air pressure collection error is measured in test flights, and a correction table showing the variances can be included with the altimeter for the pilot's use. Normally, location of the static vents is adjusted during these test flights so that the position error is minimal. *[Figure 10-37]* Position error can be removed by the ADC in modern aircraft, so the pilot need not be concerned about this inaccuracy.

Static system leaks can affect the static air input to the altimeter or ADC resulting in inaccurate altimeter indications. It is for this reason that static system maintenance includes leak checks every 24 months, regardless of whether any discrepancy has been noticed. See the instrument maintenance section toward the end of this chapter for further information on this mandatory check. It should also be understood that analog mechanical altimeters are mechanical devices that often reside in a hostile environment. The significant vibration and temperature range swings encountered by the instruments and the pitot static system (i.e., the tubing connections and fittings) can sometime create damage or a leak, leading to instrument malfunction. Proper care upon installation is the best preventive action. Periodic inspection and testing can also insure integrity.

The mechanical nature of the analog altimeter's diaphragm pressure measuring apparatus has limitations. The diaphragm itself is only so elastic when responding to static air pressure changes. Hysteresis is the term for when the material from which the diaphragm is made takes a set during long periods of level flight. If followed by an abrupt altitude change, the indication lags or responds slowly while expanding or contracting during a rapid altitude change. While temporary, this limitation does cause an inaccurate altitude indication.

It should be noted that many modern altimeters are constructed to integrate into flight control systems, autopilots, and altitude monitoring systems, such as those used by ATC. The basic pressure-sensing operation of these altimeters is the same, but a means for transmitting the information is added.



Altimeter setting ("Hg)	Pressure altitude conversion factor
28.0	1,824
28.1	1,727
28.2	1,630
28.3	1,533
28.4	1,436
28.5	1,340
28.6	1,244
28.7	1,148
28.8	1,053
28.9	957
29.0	863
29.1	768
29.2	673
29.3	579
29.4	485
29.5	392
29.6	298
29.7	205
29.8	112
29.9	20
29.92	0
30.0	−73
30.1	−165
30.2	−257
30.3	−348
30.4	−440
30.5	−531
30.6	−622
30.7	−712
30.8	−803

Figure 10-36. *The effect of air temperature on aircraft performance is expressed as density altitude.*

Vertical Speed Indicator

An analog vertical speed indicator (VSI) may also be referred to as a vertical velocity indicator (VVI), or rate-of-climb indicator. It is a direct reading, differential pressure gauge that compares static pressure from the aircraft's static system directed into a diaphragm with static pressure surrounding the diaphragm in the instrument case. Air is free to flow unrestricted in and out of the diaphragm but is made to flow in and out of the case through a calibrated orifice. A pointer attached to the diaphragm indicates zero vertical speed when

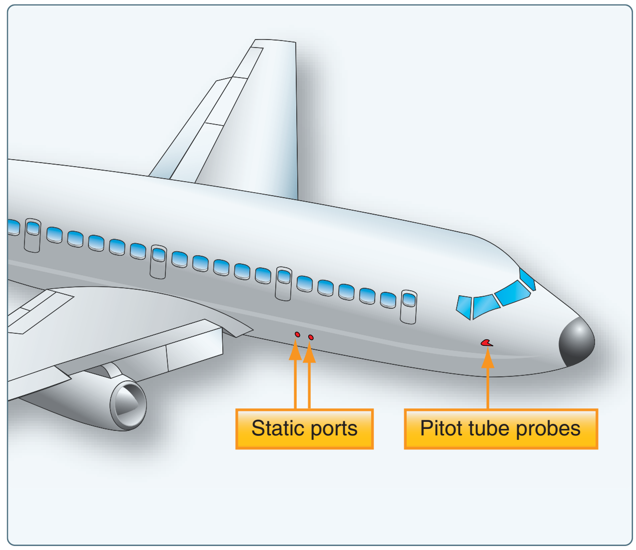


Figure 10-37. *The location of the static vent is selected to keep altimeter position error to a minimum.*

the pressure inside and outside the diaphragm are the same. The dial is usually graduated in 100s of feet per minute. A zeroing adjustment screw, or knob, on the face of the instrument is used to center the pointer exactly on zero while the aircraft is on the ground. *[Figure 10-38]*

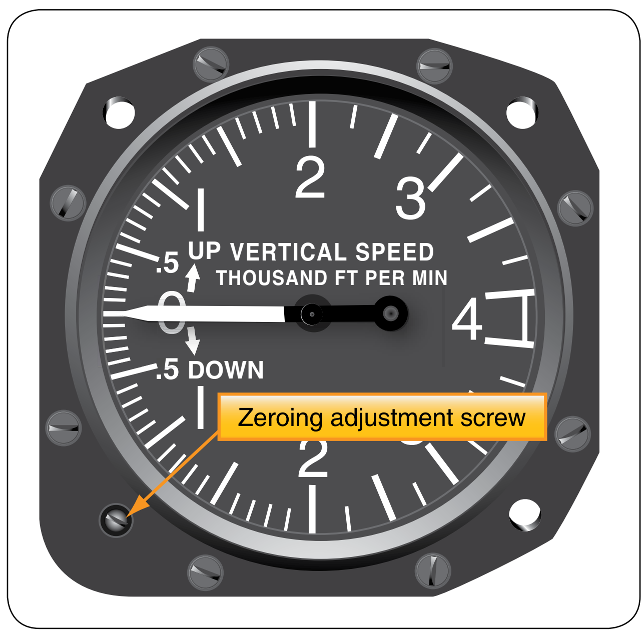


Figure 10-38. *A typical vertical speed indicator.*

As the aircraft climbs, the unrestricted air pressure in the diaphragm lowers as the air becomes less dense. The case air pressure surrounding the diaphragm lowers more slowly, having to pass through the restriction created by the orifice. This causes unequal pressure inside and outside the diaphragm, which in turn causes the diaphragm to contract a bit and the pointer indicates a climb. The process works in reverse for an aircraft in a descent. If a steady climb or descent is maintained, a steady pressure differential is established between the diaphragm and case pressure surrounding it, resulting in an accurate indication of the rate of climb via graduations on the instrument face. *[Figure 10-39]*

A shortcoming of the rate-of-climb mechanism as described is that there is a lag of six to nine seconds before a stable differential pressure can be established that indicates the actual climb or descent rate of the aircraft. An instantaneous vertical speed indicator (IVSI) has a built-in mechanism to reduce this lag. A small, lightly sprung dashpot, or piston, reacts to the direction change of an abrupt climb or descent. As this small accelerometer does so, it pumps air into or out of the diaphragm, hastening the establishment of the pressure differential that causes the appropriate indication. *[Figure 10-40]*

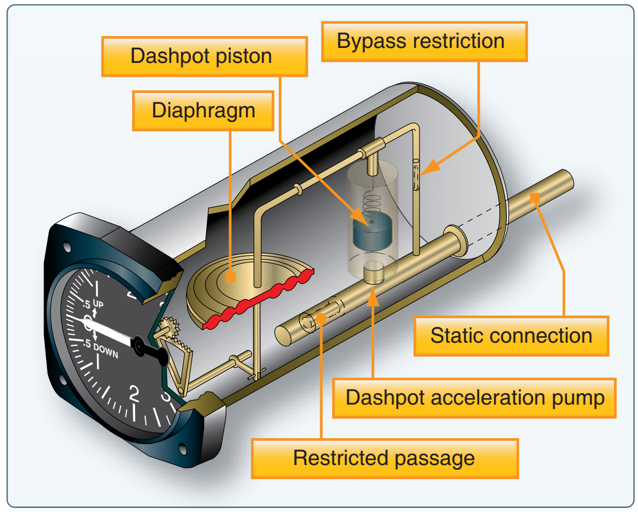


Figure 10-40. *The small dashpot in this IVSI reacts abruptly to a climb or descent pumping air into or out of the diaphragm causing an instantaneously vertical speed indication.*

Gliders and lighter-than-air aircraft often make use of a variometer. This is a differential VSI that compares static pressure with a known pressure. It is very sensitive and gives an instantaneous indication. It uses a rotating vane with a pointer attached to it. The vane separates two chambers. One is connected to the aircraft's static vent or is open to the atmosphere. The other is connected to a small reservoir inside the instrument that is filled to a known pressure. As static air pressure increases, the pressure in the static air chamber increases and pushes against the vane. This rotates the vane and pointer, indicating a descent since the static pressure is now greater than the set amount in the chamber with reservoir pressure. During a climb, the reservoir pressure is greater than the static pressure; the vane is pushed in the opposite direction, causing the pointer to rotate and indicate a climb. *[Figure 10-41]*

The rate-of-climb indication in a digitally displayed instrument system is computed from static air input to the ADC. An aneroid, or solid-state pressure sensor, continuously reacts to changes in static pressure. The digital clock within the computer replaces the calibrated orifice found on an analog instrument. As the static pressure changes, the computer's clock can be used to develop a rate for the change. Using the known lapse rate conversion for air pressure as altitude increases or decreases, a figure for climb or descent in fpm can be calculated and sent to the cockpit. The vertical

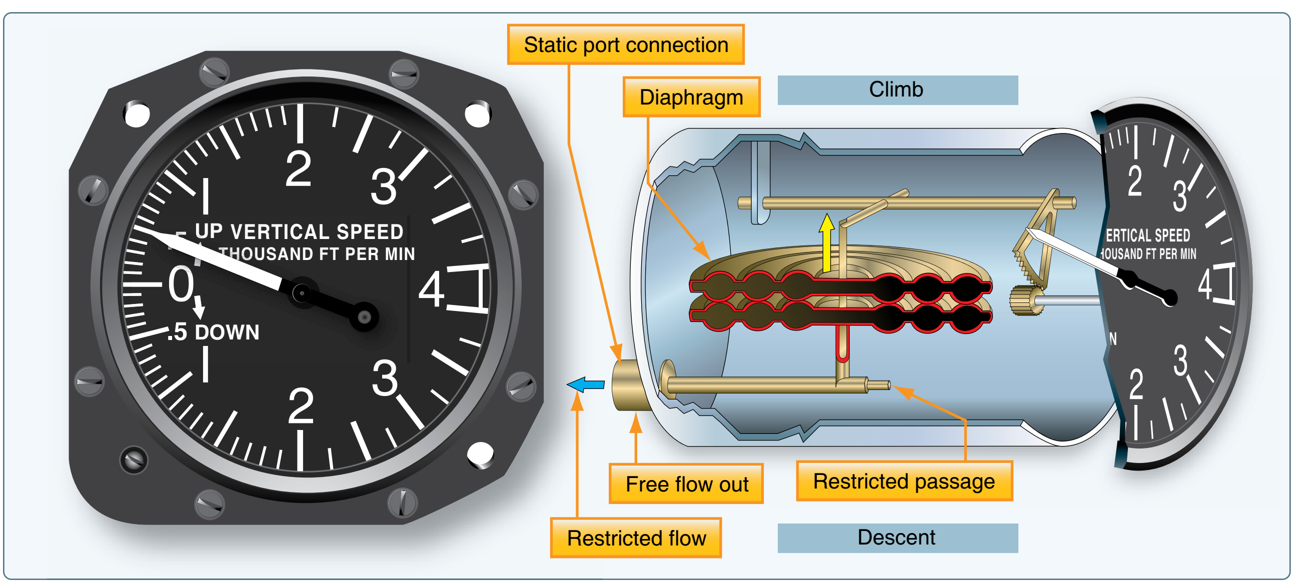


Figure 10-39. *The VSI is a differential pressure gauge that compares free-flowing static air pressure in the diaphragm with restricted static air pressure around the diaphragm in the instrument case.*

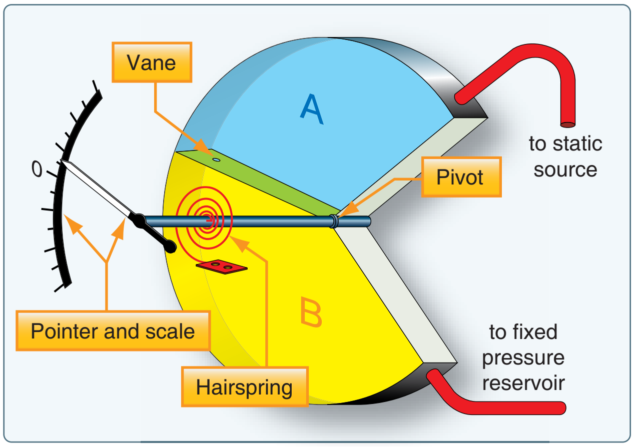


Figure 10-41. *A variometer uses differential pressure to indicate vertical speed. A rotating vane separating two chambers (one with static pressure, the other with a fixed pressure reservoir), moves the pointer as static pressure changes.*

speed is often displayed near the altimeter information on the primary flight display. *[Figure 10-34]*

Airspeed Indicators

The airspeed indicator is another primary flight instrument that is also a differential pressure gauge. Ram air pressure from the aircraft's pitot tube is directed into a diaphragm in an analog airspeed instrument case. Static air pressure from the aircraft static vent(s) is directed into the case surrounding the diaphragm. As the speed of the aircraft varies, the ram air pressure varies, expanding or contracting the diaphragm. Linkage attached to the diaphragm causes a pointer to move over the instrument face, which is calibrated in knots or miles per hour (mph). *[Figure 10-42]*

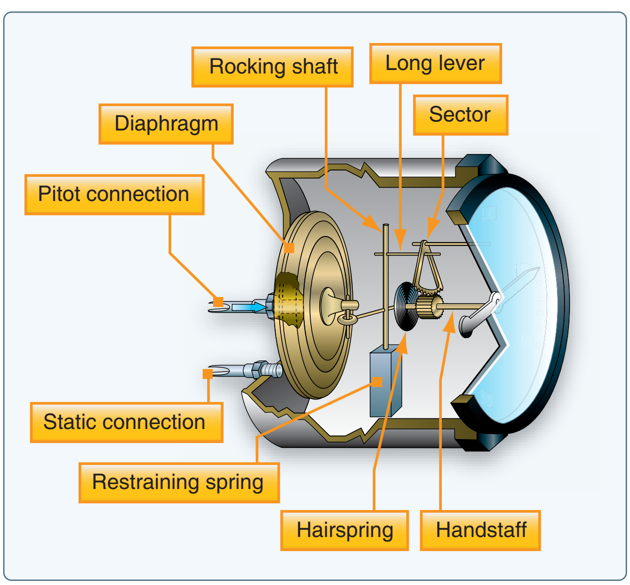


Figure 10-42. *An airspeed indicator is a differential pressure gauge that compares ram air pressure with static pressure.*

The relationship between the ram air pressure and static air pressure produces the indication known as indicated airspeed. As with the altimeter, there are other factors that must be considered in measuring airspeed throughout all phases of flight. These can cause inaccurate readings or indications that are not useful to the pilot in a particular situation. In analog airspeed indicators, the factors are often compensated for with ingenious mechanisms inside the case and on the instrument dial face. Digital flight instruments can have calculations performed in the ADC so the desired accurate indication is displayed.

While the relationship between ram air pressure and static air pressure is the basis for most airspeed indications, it can be more accurate. Calibrated airspeed takes into account errors due to position error of the pitot static pickups. It also corrects for the nonlinear nature of the pitot static pressure differential when it is displayed on a linear scale. Analog airspeed indicators come with a correction chart that allows cross-referencing of indicated airspeed to calibrated airspeed for various flight conditions. These differences are typically very small and often are ignored. Digital instruments have these corrections performed in the ADC.

More importantly, indicated airspeed does not take into account temperature and air pressure differences needed to indicate true airspeed. These factors greatly affect airspeed indication. True airspeed, therefore, is the same as indicated airspeed when standard day conditions exist. But when atmospheric temperature or pressure varies, the relationship between the ram air pressure and static pressure alters. Analog airspeed instruments often include bimetallic temperature compensating devices that can alter the linkage movement between the diaphragm and the pointer movement. There can also be an aneroid inside the airspeed indicator case that can compensate for non-standard pressures. Alternatively, true airspeed indicators exist that allow the pilot to set temperature and pressure variables manually with external knobs on the instrument dial. The knobs rotate the dial face and internal linkages to present an indication that compensates for non-standard temperature and pressure, resulting in a true airspeed indication. *[Figure 10-43]*

Digital flight instrument systems perform all of the calculations for true airspeed in the ADC. Ram air from the pitot tube and static air from the static vent(s) are run into the sensing portion of the computer. Temperature information is also input. This information can be manipulated and calculations performed so a true airspeed value can be digitally sent to the cockpit for display. Refer to *Figure 10-34* for the display of airspeed information on the primary flight display on a light aircraft. Note that similar to its position in the standard T configuration of an analog cockpit, the airspeed indication is just left of the artificial horizon display.

Figure 10-43. *An analog true airspeed indicator. The pilot manually aligns the outside air temperature with the pressure altitude scale, resulting in an indication of true airspeed.*

Complications continue when considering airspeed indications and operating limitations. It is very important to keep high-speed aircraft from traveling faster than the speed of sound if they are not designed to do so. Even as an aircraft approaches the speed of sound, certain parts on the airframe may experience airflows that exceed it. The problem with this is that near the speed of sound, shock waves can develop that can affect flight controls and, in some cases, can literally tear the aircraft apart if not designed for supersonic airflow. A further complication is that the speed of sound changes with altitude and temperature. So a safe true airspeed at sea level could put the aircraft in danger at altitude due to the lower speed of sound. *[Figure 10-44]*

In order to safeguard against these dangers, pilots monitor airspeed closely. A maximum allowable speed is established for the aircraft during certification flight testing. This speed is known the critical Mach number or Mcrit. Mach is a term for the speed of sound. The critical Mach number is expressed as a decimal of Mach such as 0.8 Mach. This means $^{8}/_{10}$ of the speed of sound, regardless of what the actual speed of sound is at any particular altitude.

Many high performance aircraft are equipped with a Machmeter for monitoring Mcrit. The Machmeter is essentially an airspeed instrument that is calibrated in relation to Mach on the dial. Various scales exist for subsonic and supersonic aircraft. *[Figure 10-45]* In addition to the ram air/static air diaphragm arrangement, Machmeters also contain an altitude sensing diaphragm. It adjusts the input to the pointer so changes in the speed of sound due to altitude are incorporated into the indication. Some aircraft use a Mach/airspeed indicator as shown in *Figure 10-46*. This two-in-one instrument contains separate mechanisms to display the airspeed and Mach number. A standard white pointer is used to indicate airspeed in knots against one scale. A red and white

Standard Altitude, Temperature, and the Speed of Sound		
Altitude (feet)	Temperature (°F)	Speed of sound (knots)
Sea level	59	661
2,000	52	657
4,000	48	652
6,000	38	648
8,000	30	643
10,000	23	638
12,000	16	633
14,000	9	629
16,000	2	624
18,000	–5	619
20,000	–12	614
22,000	–19	609
24,000	–27	604
26,000	–34	599
28,000	–41	594
30,000	–48	589
32,000	–55	584
34,000	–62	579
36,000	–69	574
38,000	–70	574
40,000	–70	574
42,000	–70	574
44,000	–70	574
46,000	–70	574
48,000	–70	574
50,000	–70	574

Figure 10-44. *As temperatures fall at higher altitudes, the speed of sound is reduced.*

Figure 10-45. *A Machmeter indicates aircraft speed relative to the speed of sound.*

Figure 10-46. *A combination Mach/airspeed indicator shows airspeed with a white pointer and Mach number with a red and white striped pointer. Each pointer is driven by separate internal mechanisms.*

striped pointer is driven independently and is read against the Mach number scale to monitor maximum allowable speed.

Remote Sensing and Indication

It is often impractical or impossible to utilize direct reading gauges for information needed to be conveyed in the cockpit. Placing sensors at the most suitable location on the airframe or engine and transmitting the collected data electrically through wires to the displays in the cockpit is a widely used method of remote-sensing and indicating on aircraft. Many remote sensing instrument systems consist simply of the sensing and transmitter unit and the cockpit indicator unit connected to each other by wires. For pressure flight instruments, the ADC and pickup devices (pitot tubes, static vents, etc.) comprise the sensing and transmitter unit. Many aircraft collect sensed data in dedicated engine and airframe computers. There, the information can be processed. An output section of the computer then transmits it electrically or digitally to the cockpit for display. Remote-sensing instrument systems operate with high reliability and accuracy. They are powered by the aircraft's electrical system.

Small electric motors inside the instrument housings are used to position the pointers, instead of direct-operating mechanical linkages. They receive electric current from the output section of the ADC or other computers. They also receive input from sensing transmitters or transducers that are remotely located on the aircraft. By varying the electric signal, the motors are turned to the precise location needed to reflect the correct indication. Direct electric transmission of information from different types of sensors is accomplished with a few reliable and relatively simple techniques. Note that digital cockpit displays receive all of their input from a DADC and other computers, via a digital data bus and do not use electric motors. The data packages transmitted via the bus contain the instructions on how to illuminate the display screen.

Synchro-Type Remote-Indicating Instruments

A synchro system is an electric system used for transmitting information from one point to another. The word "synchro" is a shortened form of the word "synchronous," and refers to any one of a number of similarly operating two-unit electrical systems capable of measuring, transmitting, and indicating a certain parameter on the aircraft. Most position-indicating instruments are designed around a synchro system, such as the flap position indicator. Fluid pressure indicators also commonly use synchro systems. Synchro systems are used as remote position indicators for landing gear, autopilot systems, radar, and many other remote-indicating applications. The most common types of synchro system are the autosyn, selsyn, and magnesyn synchro systems.

These systems are similar in construction, and all operate by exploiting the consistent relationship between electricity and magnetism. The fact that electricity can be used to create magnetic fields that have definite direction, and that magnetic fields can interact with magnets and other electromagnetic fields, is the basis of their operation.

DC Selsyn Systems

On aircraft with direct current (DC) electrical systems, the DC selsyn system is widely used. As mentioned, the selsyn system consists of a transmitter, an indicator, and connecting wires. The transmitter consists of a circular resistance winding and a rotatable contact arm. The rotatable contact arm turns on a shaft in the center of the resistance winding. The two ends of the arm are brushes and always touch the winding on opposite sides. *[Figure 10-47]* On position

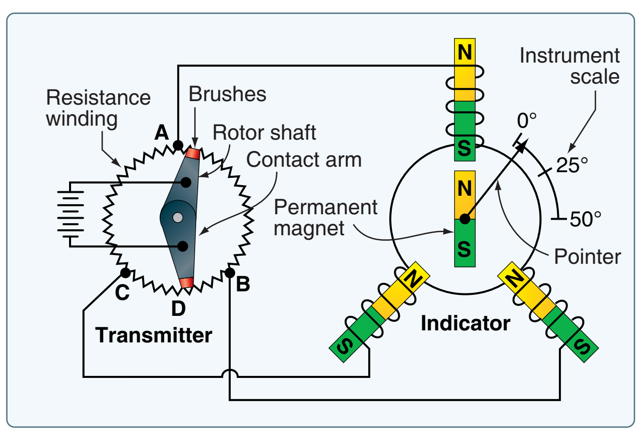


Figure 10-47. *A schematic of a DC selsyn synchro remote indicating system.*

indicating systems, the shaft to which the contact arm is fastened protrudes through the end of transmitter housing and is attached to the unit whose position is to be transmitted (e.g., flaps, landing gear). The transmitter is often connected to the moving unit through a mechanical linkage. As the unit moves, it causes the transmitter shaft to turn. The arm is turned so that voltage is applied through the brushes to any two points around the circumference of the resistance winding. The rotor shaft of DC selsyn systems, measuring other kinds of data, operates the same way, but may not protrude outside of the housing. The sensing device, which imparts rotary motion to the shaft, could be located inside the transmitter housing.

Referring to *Figure 10-47*, note that the resistance winding of the transmitter is tapped off in three fixed places, usually 120° apart. These taps distribute current through the toroidial windings of the indicator motor. When current flows through these windings, a magnetic field is created. Like all magnetic fields, a definite north and south direction to the field exists. As the transmitter rotor shaft is turned, the voltage-supplying contact arm moves. Because it contacts the transmitter resistance winding in different positions, the resistance between the supply arm and the various tapoffs changes. This causes the voltage flowing through the tapoffs to change as the resistance of sections of the winding become longer or shorter. The result is that varied current is sent via the tapoffs to the three windings in the indicator motor.

The resultant magnetic field created by current flowing through the indicator coils changes as each receives varied current from the tapoffs. The direction of the magnetic field also changes. Thus, the direction of the magnetic field across the indicating element corresponds in position to the moving arm in the transmitter. A permanent magnet is attached to the centered rotor shaft in the indicator, as is the indicator pointer. The magnet aligns itself with the direction of the magnetic field and the pointer does as well. Whenever the magnetic field changes direction, the permanent magnet and pointer realign with the new position of the field. Thus, the position of the aircraft device is indicated.

Landing gear contain mechanical devices that lock the gear up, called an up-lock, or down, called a down-lock. When the DC selsyn system is used to indicate the position of the landing gear, the indicator can also show that the up-lock or down-lock is engaged. This is done by again varying the current flowing through the indicator's coils. Switches located on the actual locking devices close when the locks engage. Current from the selsyn system described above flows through the switch and a small additional circuit. The circuit adds an additional resistor to one of the transmitter winding sections created by the rotor arm and a tapoff. This changes the total resistance of that section. The result is a change in the current flowing through one of the indicator's motor coils. This, in turn, changes the magnetic field around that coil. Therefore, the combined magnetic field created by all three motor coils is also affected, causing a shift in the direction of the indicator's magnetic field. The permanent magnet and pointer align with the new direction and shift to the locked position on the indicator dial. *Figure 10-48* shows a simplified diagram of a lock switch in a three-wire selsyn system and an indicator dial.

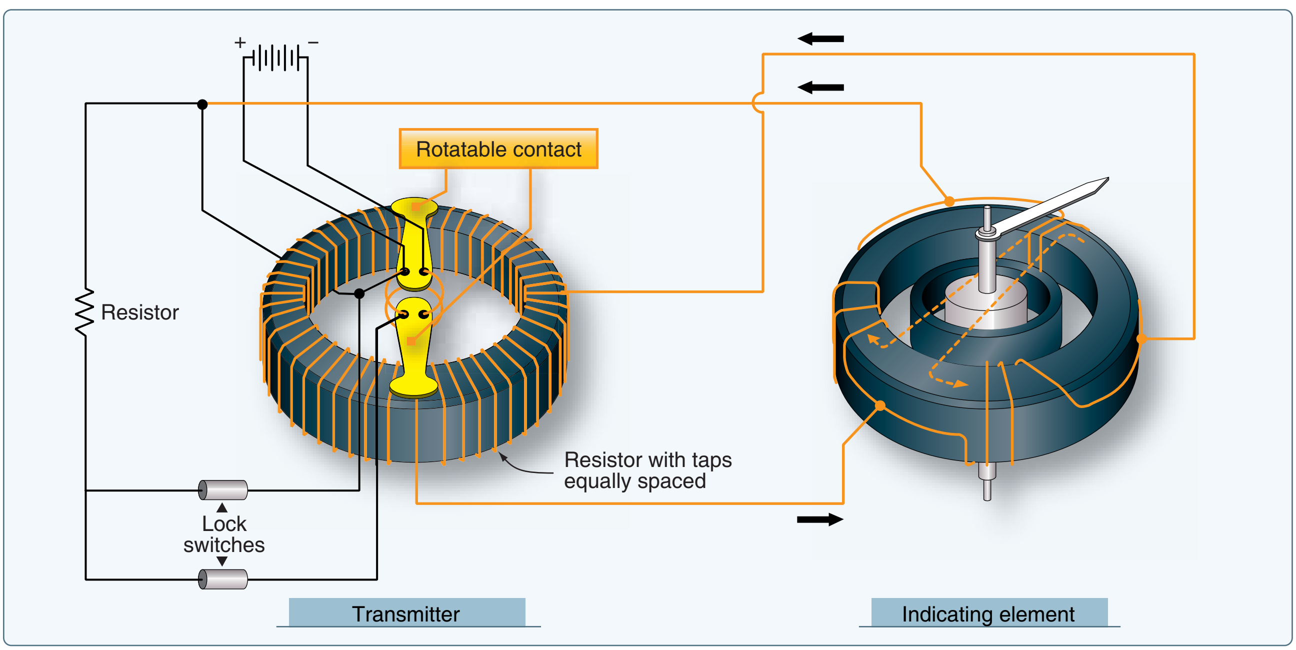


Figure 10-48. *A lock switch circuit can be added to the basic DC selsyn synchro system when used to indicate landing gear position and up- and down-locked conditions on the same indicator.*

AC Synchro Systems

Aircraft with alternating current (AC) electrical power systems make use of autosyn or magnasysn synchro remote indicating systems. Both operate in a similar way to the DC selsyn system, except that AC power is used. Thus, they make use of electric induction, rather than resistance current flows defined by the rotor brushes. Magnasyn systems use permanent magnet rotors such a those found in the DC selsyn system. Usually, the transmitter magnet is larger than the indicator magnet, but the electromagnetic response of the indicator rotor magnet and pointer remains the same. It aligns with the magnetic field set up by the coils, adopting the same angle of deflection as the transmitter rotor. *[Figure 10-49]*

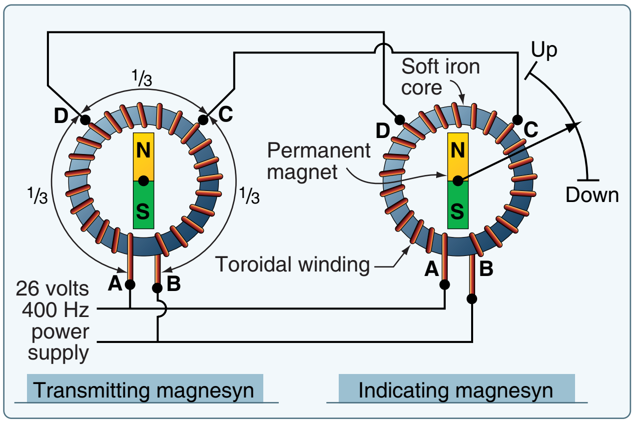


Figure 10-49. *A magnasysn synchro remote-indicating system uses AC. It has permanent magnet rotors in the transmitter and indictor.*

Autosyn systems are further distinguished by the fact that the transmitter and indicator rotors used are electro-magnets rather than permanent magnets. Nonetheless, like a permanent magnet, an electro-magnet aligns with the direction of the magnetic field created by current flowing through the stator coils in the indicator. Thus, the indicator pointer position mirrors the transmitter rotor position. *[Figure 10-50]*

AC synchro systems are wired differently than DC systems. The varying current flows through the transmitter and indicator stator coils are induced as the AC cycles through zero and the rotor magnetic field flux is allowed to flow. The important characteristic of all synchro systems is maintained by both the autosyn and magnasyn systems. That is, the position of the transmitter rotor is mirrored by the rotor in the indicator. These systems are used in many of the same applications as the DC systems and more. Since they are usually part of instrumentation for high performance aircraft, adaptations of autosyn and magnasyn synchro systems are frequently used in directional indicators and in autopilot systems.

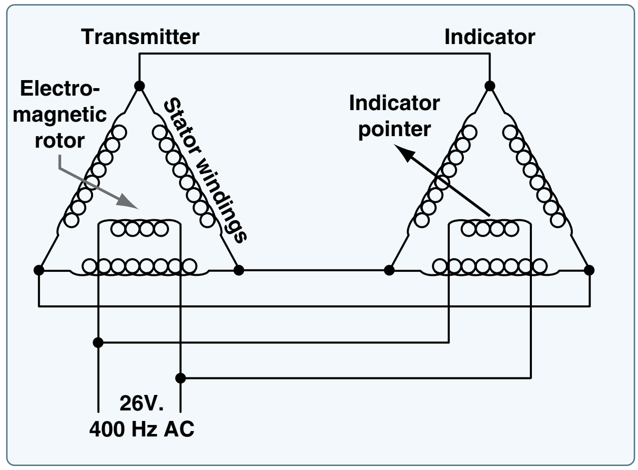


Figure 10-50. *An autosyn remote-indicating system utilizes the interaction between magnetic fields set up by electric current flow to position the indicator pointer.*

Remote Indicating Fuel and Oil Pressure Gauges

Fuel and oil pressure indications can be conveniently obtained through the use of synchro systems. As stated previously, running fuel and oil lines into the cabin to direct reading gauges is not desirable. Increased risk of fire in the cabin and the additional weight of the lines are two primary deterrents.

By locating the transmitter of a synchro system remotely, fluid pressure can be directed into it without a long tubing run. Inside the transmitter, the motion of a pressure bellows can be geared to the transmitter rotor in such a way as to make the rotor turn. *[Figure 10-51]* As in all synchros, the transmitter rotor turns proportional to the pressure sensed, which varies the voltages set up in the resistor windings of the synchro stator. These voltages are transmitted to the indicator coils that develop the magnetic field that positions the pointer.

Often on twin-engine aircraft, synchro mechanisms for each engine can be used to drive separate pointers on the same indicator. By placing the coils one behind the other, the pointer shaft from the rear indicator motor can be sent through the hollow shaft of the forward indicator motor. Thus, each pointer responds with the magnet's alignment in its own motor's magnetic field while sharing the same gauge housing. Labeling the pointer's engine 1 or 2 removes any doubt about which indicator pointer is being observed. A similar principle is employed in an indicator that has side-by-side indications for different parameters, such as oil pressure and fuel pressure in the same indicator housing. Each parameter has its own synchro motor for positioning its pointer.

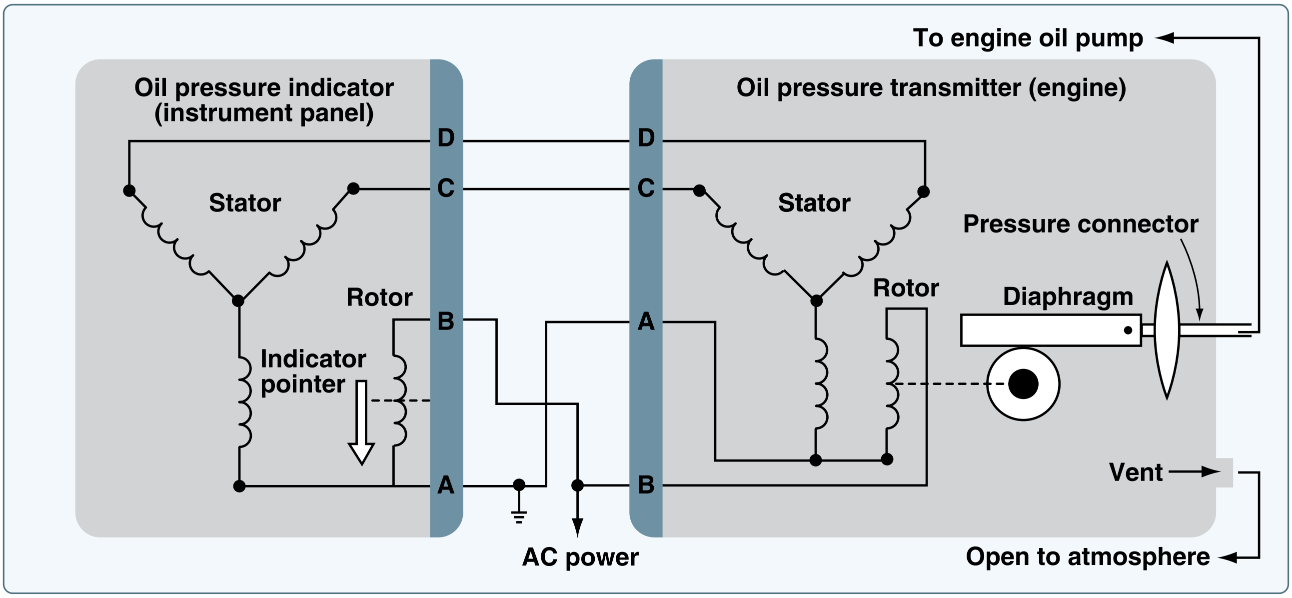


Figure 10-51. *Remote pressure sensing indicators change linear motion to rotary motion in the sensing mechanism part of the synchro transmitter.*

Aircraft with digital instrumentation make use of pressure-sensitive solid-state sensors that output digital signals for collection and processing by dedicated engine and airframe computers. Others may retain their analog sensors, but may forward this information through an analog to digital converter unit from which the appropriate computer can obtain digital information to process and illuminate the digital display. Many more instruments utilize the synchro remote-indicating systems described in this section or similar synchros. Sometimes simple, more suitable, or less expensive technologies are also employed.

Mechanical Movement Indicators

There are many instruments on an aircraft that indicate the mechanical motion of a component, or even the aircraft itself. Some utilize the synchro remote-sensing and indicating systems described above. Other means for capturing and displaying mechanical movement information are also used. This section discusses some unique mechanical motion indicators and groups instruments by function. All give valuable feedback to the pilot on the condition of the aircraft in flight.

Tachometers

The tachometer, or tach, is an instrument that indicates the speed of the crankshaft of a reciprocating engine. It can be a direct- or remote-indicating instrument, the dial of which is calibrated to indicate revolutions per minutes (rpm). On reciprocating engines, the tach is used to monitor engine power and to ensure the engine is operated within certified limits.

Gas turbine engines also have tachometers. They are used to monitor the speed(s) of the compressor section(s) of the engine. Turbine engine tachometers are calibrated in percentage of rpm with 100 percent corresponding to optimum turbine speed. This allows similar operating procedures despite the varied actual engine rpm of different engines. *[Figure 10-52]*

In addition to the engine tachometer, helicopters use a tachometer to indicator main rotor shaft rpm. It should also be noted that many reciprocating-engine tachometers also have built-in numeric drums that are geared to the rotational mechanism inside. These are hour meters that keep track of the time the engine is operated. There are two types of tachometer system in wide use today: mechanical and electrical.

Mechanical Tachometers

Mechanical tachometer indicating systems are found on small, single-engine light aircraft in which a short distance exists between the engine and the instrument panel. They consist of an indicator connected to the engine by a flexible drive shaft. The drive shaft is geared into the engine so that when the engine turns, so does the shaft. The indicator contains a flyweight assembly coupled to a gear mechanism that drives a pointer. As the drive shaft rotates, centrifugal force acts on the flyweights and moves them to an angular position. This angular position varies with the rpm of the engine. The amount of movement of the flyweights is transmitted through the gear mechanism to the pointer. The pointer rotates to indicate this movement on the tachometer indicator, which is directly related to the rpm of the engine. *[Figure 10-53]*

Figure 10-52. *A tachometer for a reciprocating engine is calibrated in rpm. A tachometer for a turbine engine is calculated in percent of rpm.*

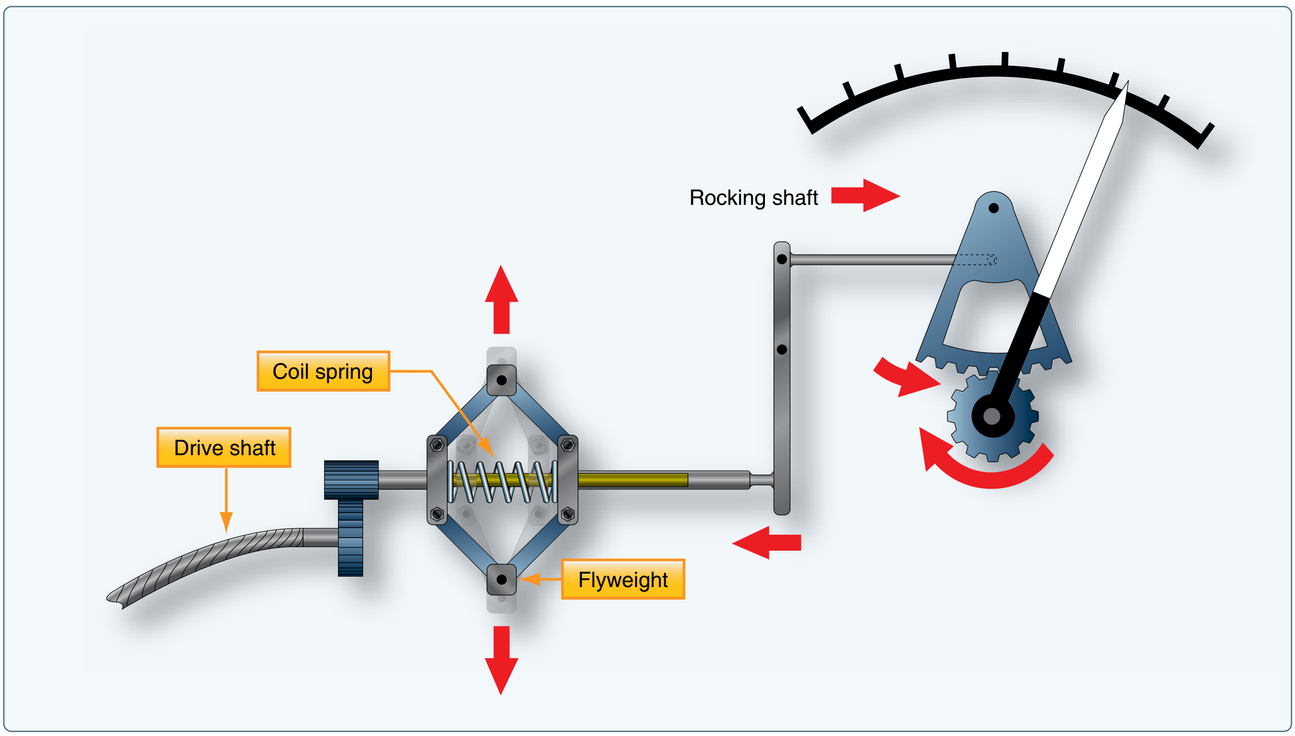


Figure 10-53. *The simplified mechanism of a flyweight type mechanical tachometer.*

A more common variation of this type of mechanical tachometer uses a magnetic drag cup to move the pointer in the indicator. As the drive shaft turns, it rotates a permanent magnet in a close-tolerance aluminum cup. A shaft attached to the indicating point is attached to the exterior center of the cup. As the magnet is rotated by the engine flex drive cable, its magnetic field cuts through the conductor surrounding it, creating eddy currents in the aluminum cup. This current flow creates its own magnetic field, which interacts with the rotating magnet's flux field. The result is that the cup tends to rotate, and with it, the indicating pointer. A calibrated restraining spring limits the cup's rotation to the arc of motion of the pointer across the scale on the instrument face. *[Figure 10-54]*

Electric Tachometers

It is not practical to use a mechanical linkage between the engine and the rpm indicator on aircraft with engines not mounted in the fuselage just forward of the instrument panel. Greater accuracy with lower maintenance is achieved through the use of electric tachometers. A wide variety of electric tachometer systems can be employed, so manufacturer's

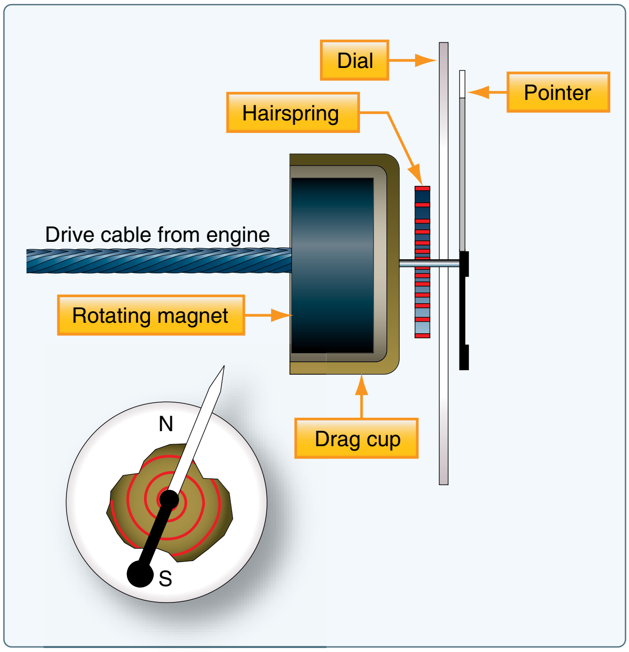


Figure 10-54. *A simplified magnetic drag cup tachometer indicating device.*

instructions should be consulted for details of each specific tachometer system.

A popular electric tachometer system makes use of a small AC generator mounted to a reciprocating engine's gear case or the accessory drive section of a turbine engine. As the engine turns, so does the generator. The frequency output of the generator is directly proportional to the speed of the engine. It is connected via wires to a synchronous motor in the indicator that mirrors this output. A drag cup, or drag disk link, is used to drive the indicator as in a mechanical tachometer. *[Figure 10-55]* Two different types of generator units, distinguished by their type of mounting system, are shown in *Figure 10-56*.

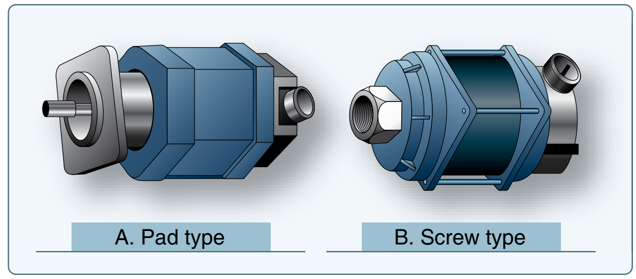


Figure 10-56. *Different types of tach generators.*

The dual tachometer consists of two tachometer indicator units housed in a single case. The indicator pointers show simultaneously, on one or two scales, the rpm of two engines. A dual tachometer on a helicopter often shows the rpm of the engine and the rpm of the main rotor. A comparison of the voltages produced by the two tach generators of this type of helicopter indicator gives information concerning clutch slippage. A third indication showing this slippage is sometimes included in the helicopter tachometer. [*Figure 10-57]*

Some turbine engines use tachometer probes for rpm indication, rather than a tach generator system. They provide a great advantage in that there are no moving parts. They are sealed units that are mounted on a flange and protrude into the compressor section of the engine. A magnetic field is set up inside the probe that extends through pole pieces and out the end of the probe. A rotating gear wheel, which moves at the same speed as the engine compressor shaft, alters the magnetic field flux density as it moves past the pole pieces at close proximity. This generates voltage signals in coils inside the probe. The amplitude of the EMF signals vary directly with the speed of the engine.

The tachometer probe's output signals need to be processed in a remotely located module. They must also be amplified to drive a servo motor type indicator in the cockpit. They may

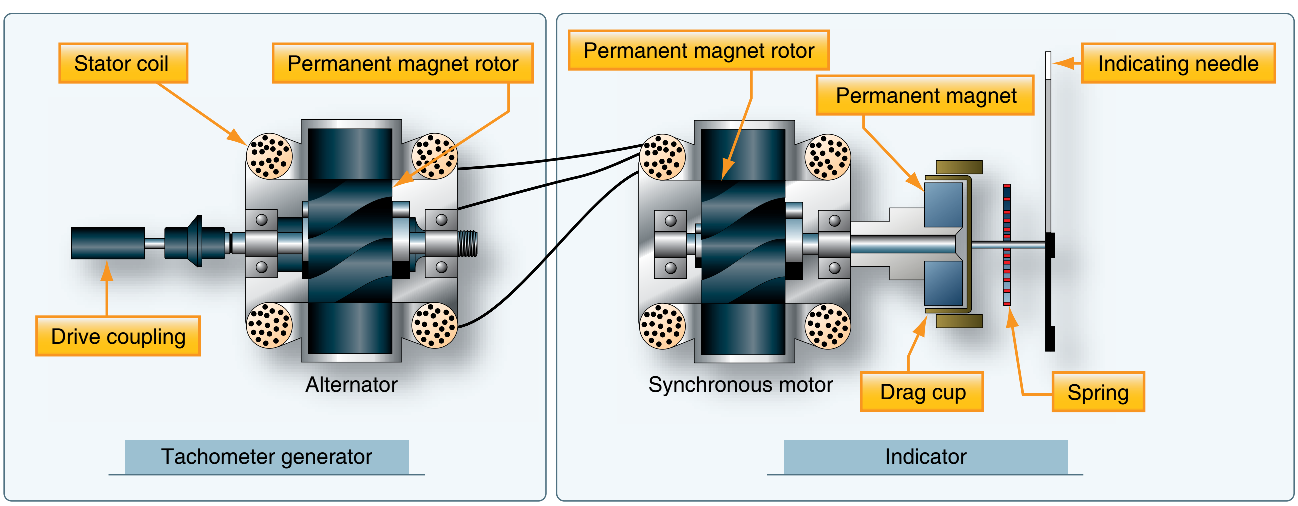


Figure 10-55. *An electric tachometer system with synchronous motors and a drag cup indicator.*

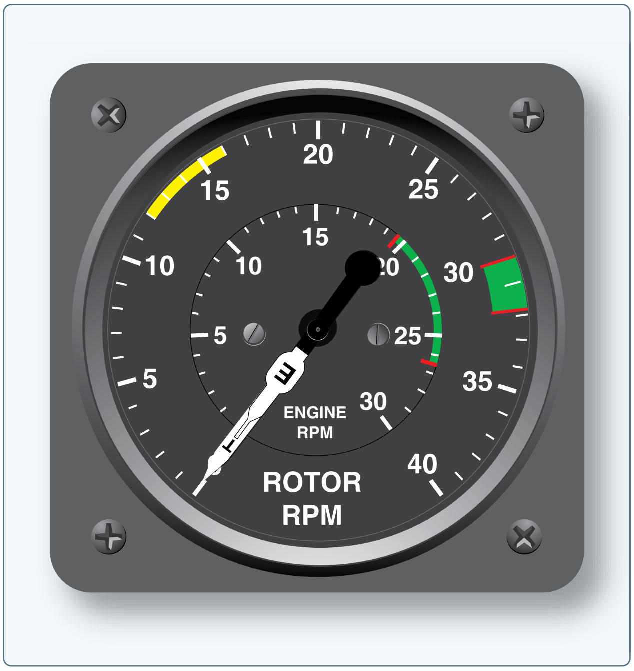


Figure 10-57. *A helicopter tachometer with engine rpm, rotor rpm, and slippage indications.*

also be used as input for an automatic power control system or a flight data acquisition system. *[Figure 10-58]*

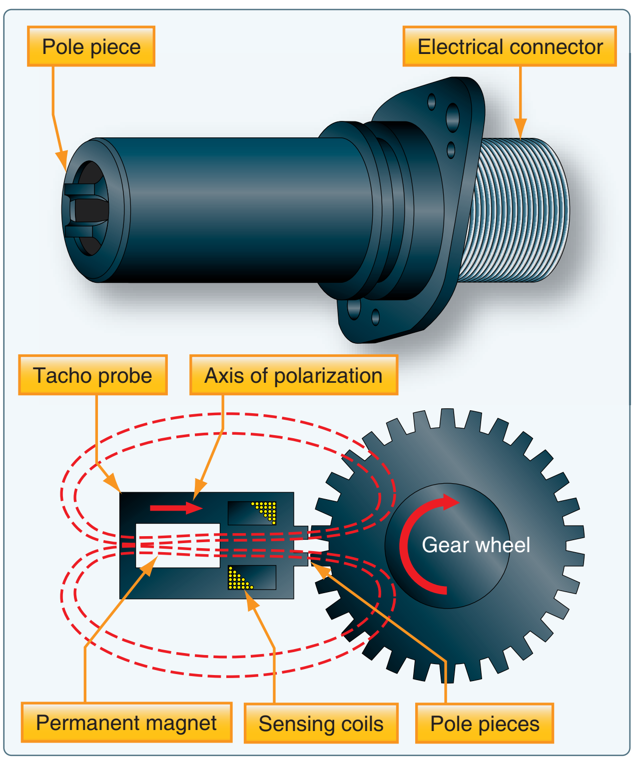


Figure 10-58. *A tacho probe has no moving parts. The rate of magnetic flux field density change is directly related to engine speed.*

Synchroscope

The synchroscope is an instrument that indicates whether two or more rotating devices, such as engines, are synchronized. Since synchroscopes compare rpm, they utilize the output from tachometer generators. The instrument consists of a small electric motor that receives electrical current from the generators of both engines. Current from the faster running engine controls the direction in which the synchroscope motor rotates.

If both engines are operating at exactly the same speed, the synchroscope motor does not operate. If one engine operates faster that the other, its tach generator signal causes the synchroscope motor to turn in a given direction. Should the speed of the other engine then become greater than that of the first engine, the signal from its tach generator causes the synchroscope motor to reverse itself and turn in the opposite direction. The pilot makes adjustments to steady the pointer so it does not move.

One use of synchroscope involve designating one of the engines as a master engine. The rpm of the other engine(s) is always compared to the rpm of this master engine. The dial face of the synchroscope indicator looks like *Figure 10-59*. "Slow" and "fast" represent the other engine's rpm relative to the master engine, and the pilot makes adjustments accordingly.

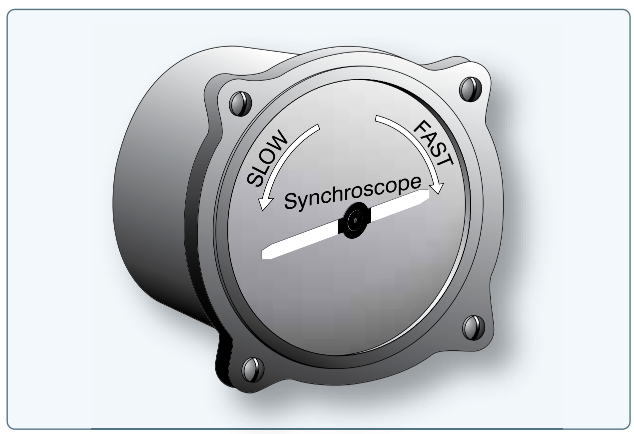


Figure 10-59. *This synchroscope indicates the relative speed of the slave engine to the master.*

Accelerometers

An accelerometer is an instrument that measures acceleration. It is used to monitor the forces acting upon an airframe. Accelerometers are also used in inertial reference navigation systems. The installation of accelerometers is usually limited to high-performance and aerobatic aircraft.

Simple accelerometers are mechanical, direct-reading instruments calibrated to indicate force in Gs. One G is equal to one times the force of gravity. The dial face of an accelerometer is scaled to show positive and negative forces. When an aircraft initiates a rapid climb, positive G force tends to push one back into one's seat. Initiating a rapid decent causes a force in the opposite direction, resulting in a negative G force.

Most accelerometers have three pointers. One is continuously indicating the acceleration force experienced. The other two contain ratcheting devices. The positive G pointer follows the continuous pointer and stay at the location on the dial where the maximum positive force is indicated. The negative G pointer does the same for negative forces experienced. Both max force pointers can be reset with a knob on the instrument face.

The accelerometer operates on the principle of inertia. A mass, or weight, inside is free to slide along a shaft in response to the slightest acceleration force. When a maneuver creates an accelerating force, the aircraft and instrument move, but inertia causes the weight to stay at rest in space. As the shaft slides through the weight, the relative position of the weight on the shaft changes. This position corresponds to the force experienced. Through a series of pulleys, springs, and shafts, the pointers are moved on the dial to indicate the relative strength of the acceleration force. [*Figure 10-60*] Forces can act upon an airframe along the three axes of flight. Single and multi-axis accelerometers are available, although most cockpit gauges are of the single-axis type. Inertial reference navigation systems make use of multi-axis accelerometers to continuously, mathematically calculate the location of the aircraft in a three dimensional plane.

Electric and digital accelerometers also exist. Solid-state sensors are employed, such as piezoelectric crystalline devices. In these instruments, when an accelerating force is applied, the amount of resistance, current flow, or capacitance changes in direct relationship to the size of the force. Micro-electric signals integrate well with digital computers designed to process and display information in the cockpit.

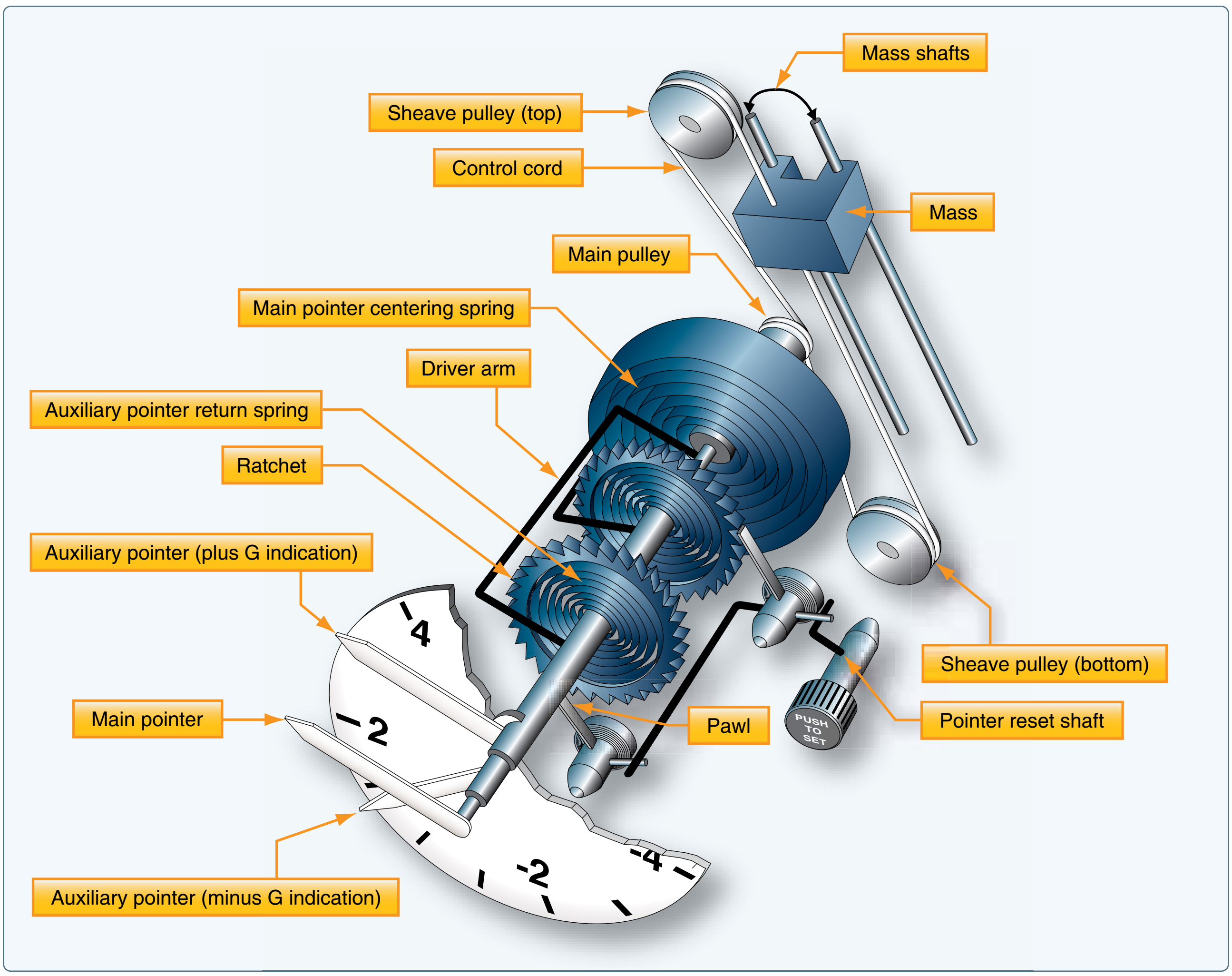


Figure 10-60. *The inner workings of a mass-type accelerometer.*

Stall Warning and Angle of Attack (AOA) Indicators

An aircraft's angle of attack (AOA) is the angle formed between the wing cord centerline and the relative wind. At a certain angle, airflow over the wing surfaces is insufficient to create enough lift to keep the aircraft flying, and a stall occurs. An instrument that monitors the AOA allows the pilot to avoid such a condition.

The simplest form of AOA indicator is a stall warning device that does not have a gauge located in the cockpit. It uses an aural tone to warn of an impending stall due to an increase in AOA. This is done by placing a reed in a cavity just aft of the leading edge of the wing. The cavity has an open passage to a precise point on the leading edge.

In flight, air flows over and under a wing. The point on the wing leading edge where the oncoming air diverges is known as the point of stagnation. As the AOA of the wing increases, the point of stagnation moves down below the open passage that leads inside the wing to the reed. Air flowing over the curved leading edge speeds up and causes a low pressure. This causes air to be sucked out of the inside of the wing through the passage. The reed vibrates as the air rushes by making a sound audible in the cockpit. *[Figure 10-61]*

Another common device makes use of an audible tone as the AOA increases to near the point where the aircraft will stall. This stall warning device includes an electric switch that opens and closes a circuit to a warning horn audible in the cockpit. It may also be wired into a warning light circuit.

Figure 10-61. *A reed-type stall warning device is located behind this opening in the leading edge of the wing. When the angle of attack increases to near the point of a stall, low-pressure air flowing over the opening causes a suction, which audibly vibrates the reed.*

The switch is located near the point of stagnation on the wing leading edge. A small lightly sprung tab activates the switch. At normal AOA, the tab is held down by air that diverges at the point of stagnation and flows under the wing. This holds the switch open so the horn does not sound nor the warning light illuminate. As the AOA increases, the point of stagnation moves down. The divergent air that flows up and over the wing now pushes the tab upward to close the switch and complete the circuit to the horn or light. *[Figure 10-62]*

A true AOA indicating system detects the local AOA of the aircraft and displays the information on a cockpit indicator. It also may be designed to furnish reference information to other systems on high-performance aircraft. The sensing

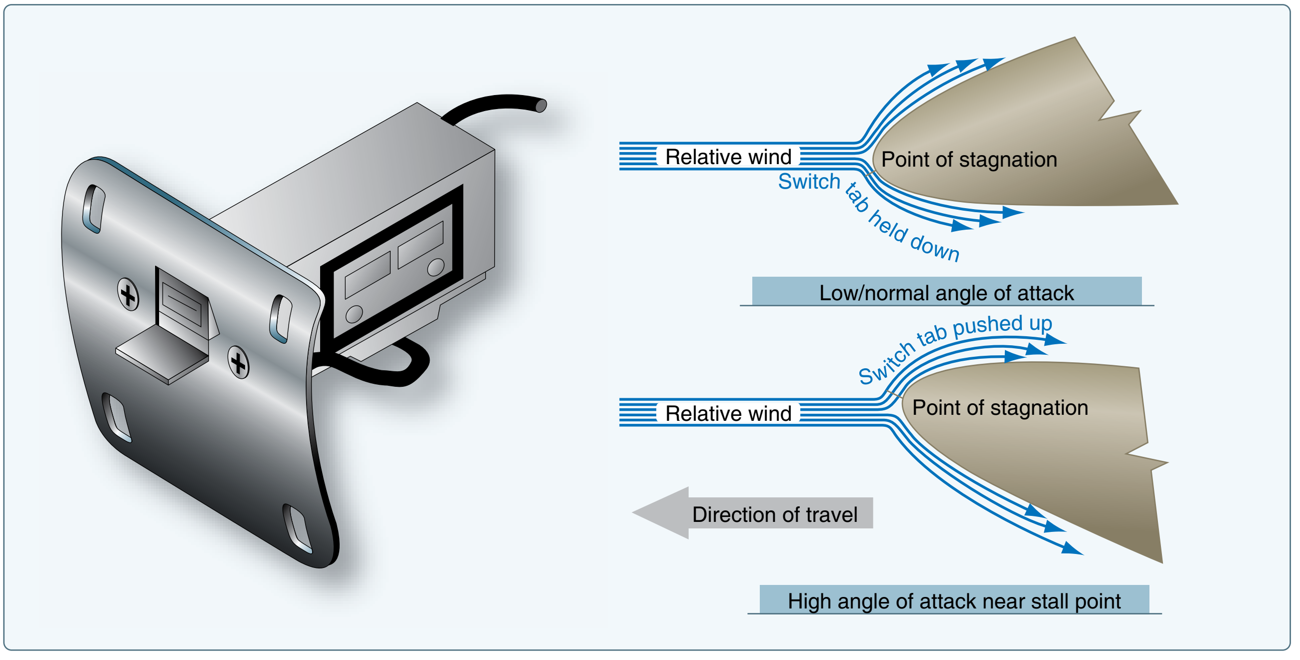


Figure 10-62. *A popular stall warning switch located in the wing leading edge.*

mechanism and transmitter are usually located on the forward side of the fuselage. It typically contains a heating element to ensure ice-free operation. Signals are sent from the sensor to the cockpit or computer(s) as required. An AOA indicator may be calibrated in actual angle degrees, arbitrary units, percentage of lift used, symbols, or even fast/slow. *[Figure 10-63]*

Figure 10-63. *Angle of attack indicator.*

There are two main types of AOA sensors in common use. Both detect the angular difference between the relative wind and the fuselage, which is used as a reference plane. One uses a vane, known as an alpha vane, externally mounted to the outside of the fuselage. It is free to rotate in the wind. As the AOA changes, air flowing over the vane changes its angle. The other uses two slots in a probe that extends out of the side of the fuselage into the airflow. The slots lead to different sides of movable paddles in a chamber of the unit just inside the fuselage skin. As the AOA varies, the air pressure ported by each of the slots changes and the paddles rotate to neutralize the pressures. The shaft upon which the paddles rotate connects to a potentiometer wiper contact that is part of the unit. The same is true of the shaft of the alpha vane. The changing resistance of the potentiometer is used in a balanced bridge circuit to signal a motor in the indicator to move the pointer proportional to the AOA. *[Figures 10-64* and *10-65]*

Modern aircraft AOA sensor units send output signals to the ADC. There, the AOA data is used to create an AOA indication, usually on the primary flight display. AOA information can also be integrated with flap and slat position information to better determine the point of stall. Additionally, AOA sensors of the type described are subject to position error since airflow around the alpha vane and slotted

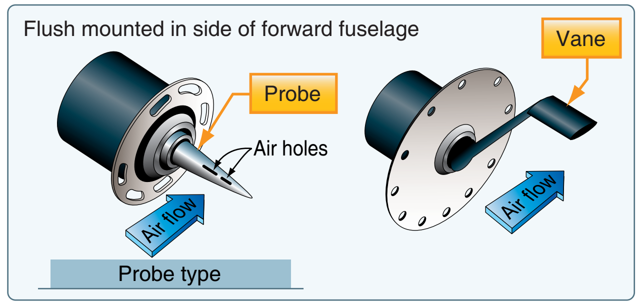


Figure 10-64. *A slotted AOA probe and an alpha vane.*

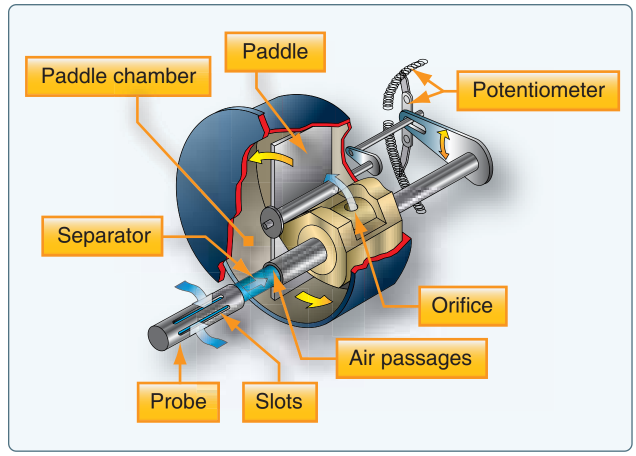


Figure 10-65. *The internal structure of a slotted probe airstream direction detector.*

probe changes somewhat with airspeed and aircraft attitude. The errors are small, but can be corrected in the ADC.

To incorporate a warning of an impending stall, many AOA systems signal a stick shaker motor that literally shakes the control column to warn the pilot as the aircraft approaches a stall condition. Electrical switches are actuated in the AOA indicator at various preset AOA to activate the motor that drives an unbalanced weighted ring, causing the column to shake. Some systems include a stick pusher actuator that pushes the control yoke forward, lowering the nose of the aircraft when the critical AOA is approached. Regardless of the many existing variations for warning of an impending stall, the AOA system triggers all stall warnings in high performance aircraft.

Temperature Measuring Instruments

The temperature of numerous items must be known for an aircraft to be operated properly. Engine oil, carburetor mixture, inlet air, free air, engine cylinder heads, heater ducts, and exhaust gas temperature of turbine engines are all items requiring temperature monitoring. Many other temperatures must also be known. Different types of thermometers are used to collect and present temperature information.

Non-Electric Temperature Indicators

The physical characteristics of most materials change when exposed to changes in temperature. The changes are consistent, such as the expansion or contraction of solids, liquids, and gases. The coefficient of expansion of different materials varies and it is unique to each material. Most everyone is familiar with the liquid mercury thermometer. As the temperature of the mercury increases, it expands up a narrow passage that has a graduated scale upon it to read the temperature associated with that expansion. The mercury thermometer has no application in aviation.

A bimetallic thermometer is very useful in aviation. The temperature sensing element of a bimetallic thermometer is made of two dissimilar metals strips bonded together. Each metal expands and contracts at a different rate when temperature changes. One end of the bimetallic strip is fixed, the other end is coiled. A pointer is attached to the coiled end which is set in the instrument housing. When the bimetallic strip is heated, the two metals expand. Since their expansion rates differ and they are attached to each other, the effect is that the coiled end tries to uncoil as the one metal expands faster than the other. This moves the pointer across the dial face of the instrument. When the temperature drops, the metals contract at different rates, which tends to tighten the coil and move the pointer in the opposite direction.

Direct reading bimetallic temperature gauges are often used in light aircraft to measure free air temperature or outside air temperature (OAT). In this application, a collecting probe protrudes through the windshield of the aircraft to be exposed to the atmospheric air. The coiled end of the bimetallic strip in the instrument head is just inside the windshield where it can be read by the pilot. *[Figures 10-66 and 10-67]*

A bourdon tube is also used as a direct reading non-electric temperature gauge in simple, light aircraft. By calibrating the dial face of a bourdon tube gauge with a temperature scale, it can indicate temperature. The basis for operation is the consistent expansion of the vapor produced by a volatile liquid in an enclosed area. This vapor pressure changes directly with temperature. By filling a sensing bulb with such a volatile liquid and connecting it to a bourdon tube, the tube causes an indication of the rising and falling vapor pressure due to temperature change. Calibration of the dial face in degrees Fahrenheit or Celsius, rather than psi, provides a temperature reading. In this type of gauge, the sensing bulb is placed in the area needing to have temperature measured. A long capillary tube connects the bulb to the bourdon tube in the instrument housing. The narrow diameter of the capillary tube ensures that the volatile liquid is lightweight and stays primarily in the sensor bulb. Oil temperature is sometimes measured this way.

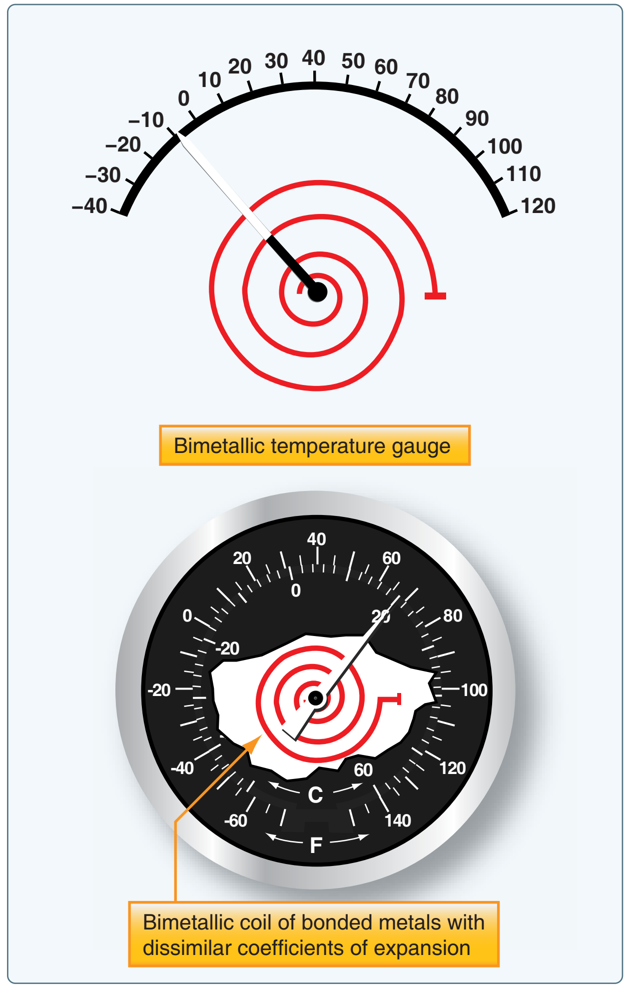


Figure 10-66. *A bimetallic temperature gauge works because of the dissimilar coefficients of expansion of two metals bonded together. When bent into a coil, cooling or heating causes the dissimilar metal coil to tighten, or unwind, moving the pointer across the temperature scale on the instrument dial face.*

Electrical Temperature Measuring Indication

The use of electricity in measuring temperature is very common in aviation. The following measuring and indication systems can be found on many types of aircraft. Certain temperature ranges are more suitably measured by one or another type of system.

Electrical Resistance Thermometer

The principle parts of the electrical resistance thermometer are the indicating instrument, the temperature-sensitive element (or bulb), and the connecting wires and plug connectors. Electrical resistance thermometers are used widely in many types of aircraft to measure carburetor air, oil, free air temperatures, and more. They are used to measure low and medium temperatures in the –70 °C to 150 °C range.

Figure 10-67. *A bimetallic outside air temperature gauge and its installation on a light aircraft.*

For most metals, electrical resistance changes as the temperature of the metal changes. This is the principle upon which a resistance thermometer operates. Typically, the electrical resistance of a metal increases as the temperature rises. Various alloys have a high temperature-resistance coefficient, meaning their resistance varies significantly with temperature. This can make them suitable for use in temperature sensing devices. The metal resistor is subjected to the fluid or area in which temperature needs to be measured. It is connected by wires to a resistance measuring device inside the cockpit indicator. The instrument dial is calibrated in degrees Fahrenheit or Celsius as desired rather than in ohms. As the temperature to be measured changes, the resistance of the metal changes and the resistance measuring indicator shows to what extent.

A typical electrical resistance thermometer looks like any other temperature gauge. Indicators are available in dual form for use in multiengine aircraft. Most indicators are self-compensating for changes in cockpit temperature. The heat-sensitive resistor is manufactured so that it has a definite resistance for each temperature value within its working range. The temperature-sensitive resistor element is a length or winding made of a nickel/manganese wire or other suitable alloy in an insulating material. The resistor is protected by a closed-end metal tube attached to a threaded plug with a hexagonal head. *[Figure10-68]* The two ends of the winding are brazed, or welded, to an electrical receptacle designed to receive the prongs of the connector plug.

Figure 10-68. *An electric resistance thermometer sensing bulb.*

The indicator contains a resistance-measuring instrument. Sometimes it uses a modified form of the Wheatstone-bridge circuit. The Wheatstone-bridge meter operates on the principle of balancing one unknown resistor against other known resistances. A simplified form of a Wheatstone-bridge circuit is shown in *Figure 10-69*. Three equal values of resistance *[Figure 10-69A, B,* and *C]* are connected into a diamond shaped bridge circuit. A resistor with an unknown value *[Figure 10-69D]* is also part of the circuit. The unknown resistance represents the resistance of the temperature bulb of the electrical resistance thermometer system. A galvanometer is attached across the circuit at points X and Y.

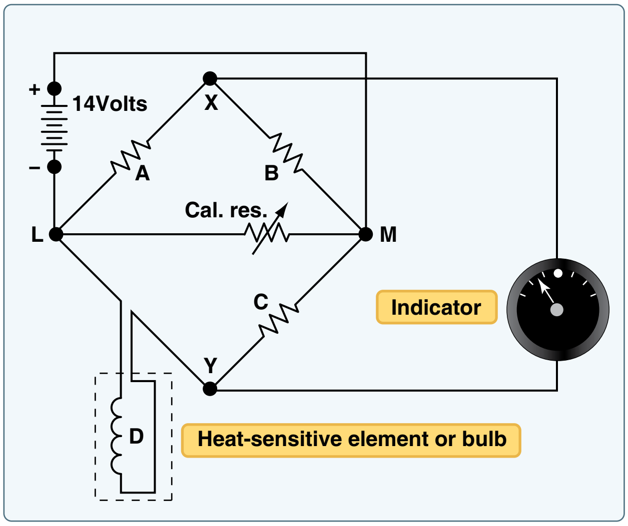


Figure 10-69. *The internal structure of an electric resistance thermometer indicator features a bridge circuit, galvanometer, and variable resistor, which is outside the indicator in the form of the temperature sensor.*

When the temperature causes the resistance of the bulb to equal that of the other resistances, no potential difference exists between points X and Y in the circuit. Therefore, no current flows in the galvanometer leg of the circuit. If the temperature of the bulb changes, its resistance also changes, and the bridge becomes unbalanced, causing current to flow through the galvanometer in one direction or the other. The galvanometer pointer is actually the temperature gauge pointer. As it moves against the dial face calibrated in degrees, it indicates temperature. Many indicators are provided with a zero adjustment screw on the face of the instrument. This adjusts the zeroing spring tension of the pointer when the bridge is at the balance point (the position at which the bridge circuit is balanced and no current flows through the meter).

Ratiometer Electrical Resistance Thermometers

Another way of indicating temperature when employing an electric resistance thermometer is by using a ratiometer. The Wheatstone-bridge indicator is subject to errors from line voltage fluctuation. The ratiometer is more stable and can deliver higher accuracy. As its name suggests, the ratiometer electrical resistance thermometer measures a ratio of current flows.

The resistance bulb sensing portion of the ratiometer electric resistance thermometer is essentially the same as described above. The circuit contains a variable resistance and a fixed resistance to provide the indication. It contains two branches for current flow. Each has a coil mounted on either side of the pointer assembly that is mounted within the magnetic field of a large permanent magnet. Varying current flow through the coils causes different magnetic fields to form, which react with the larger magnetic field of the permanent magnet. This interaction rotates the pointer against the dial face that is calibrated in degrees Fahrenheit or Celsius, giving a temperature indication. *[Figure 10-70]*

The magnetic pole ends of the permanent magnet are closer at the top than they are at the bottom. This causes the magnetic field lines of flux between the poles to be more concentrated at the top. As the two coils produce their magnetic fields, the stronger field interacts and pivots downward into the weaker, less concentrated part of the permanent magnet field, while the weaker coil magnetic field shifts upward toward the more concentrated flux field of the large magnet. This provides a balancing effect that changes but stays in balance as the coil field strengths vary with temperature and the resultant current flowing through the coils.

For example, if the resistance of the temperature bulb is equal to the value of the fixed resistance (R), equal values of current flow through the coils. The torques, caused by the magnetic field each coil creates, are the same and cancel

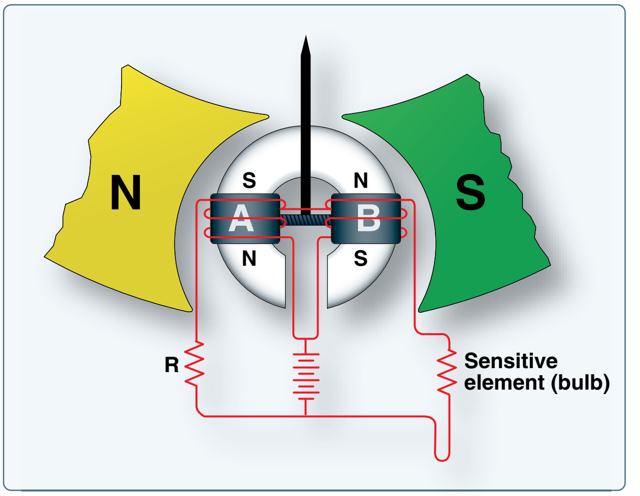


Figure 10-70. *A ratiometer temperature measuring indicator has two coils. As the sensor bulb resistance varies with temperature, different amounts of current flow through the coils. This produces varying magnetic fields. These fields interact with the magnetic field of a large permanent magnet, resulting in an indication of temperature.*

any movement in the larger magnetic field. The indicator pointer will be in the vertical position. If the bulb temperature increases, its resistance also increases. This causes the current flow through coil A circuit branch to increase. This creates a stronger magnetic field at coil A than at coil B. Consequently, the torque on coil A increases, and it is pulled downward into the weaker part of the large magnetic field. At the same time, less current flows through the sensor bulb resistor and coil B, causing coil B to form a weaker magnetic field that is pulled upward into the stronger flux area of the permanent magnet's magnetic field. The pointer stops rotating when the fields reach a new balance point that is directly related to the resistance in the sensing bulb. The opposite of this action would take place if the temperature of the heat-sensitive bulb should decrease.

Ratiometer temperature measuring systems are used to measure engine oil, outside air, carburetor air, and other temperatures in many types of aircraft. They are especially in demand to measure temperature conditions where accuracy is important, or large variations of supply voltages are encountered.

Thermocouple Temperature Indicators

A thermocouple is a circuit or connection of two unlike metals. The metals are touching at two separate junctions. If one of the junctions is heated to a higher temperature than the other, an electromotive force is produced in the circuit. This voltage is directly proportional to the temperature. So, by measuring the amount of electromotive force, temperature can be determined. A voltmeter is placed across the colder of the two junctions of the thermocouple. It is calibrated in degrees Fahrenheit or Celsius, as needed. The hotter the high-temperature junction (hot junction) becomes, the greater the electromotive force produced, and the higher the temperature indication on the meter. *[Figure 10-71]*

Thermocouples are used to measure high temperatures. Two common applications are the measurement of cylinder head temperature (CHT) in reciprocating engines and exhaust gas temperature (EGT) in turbine engines. Thermocouple leads are made from a variety of metals, depending on the maximum temperature to which they are exposed. Iron and constantan, or copper and constantan, are common for CHT measurement. Chromel and alumel are used for turbine EGT thermocouples.

The amount of voltage produced by the dissimilar metals when heated is measured in millivolts. Therefore, thermocouple leads are designed to provide a specific amount of resistance in the thermocouple circuit (usually very little). Their material, length, or cross-sectional size cannot be altered without compensation for the change in total resistance that would result. Each lead that makes a connection back to the voltmeter must be made of the same metal as the part of the thermocouple to which it is connected. For example, a copper wire is connected to the copper portion of the hot junction and a constantan wire is connected to the constantan part.

The hot junction of a thermocouple varies in shape depending on its application. Two common types are the gasket and the bayonet. In the gasket type, two rings of the dissimilar metals are pressed together to form a gasket that can be installed under a spark plug or cylinder hold down nut. In the bayonet type, the metals come together inside a perforated protective sheath. Bayonet thermocouples fit into a hole or well in a cylinder head. On turbine engines, they are found mounted on the turbine inlet or outlet case and extend through the case into the gas stream. Note that for CHT indication, the cylinder chosen for the thermocouple installation is the one that runs the hottest under most operating conditions. The location of this cylinder varies with different engines. *[Figure 10-72]*

The cold junction of the thermocouple circuit is inside the instrument case. Since the electromotive force set up in the circuit varies with the difference in temperature between the hot and cold junctions, it is necessary to compensate the indicator mechanism for changes in cockpit temperature which affect the cold junction. This is accomplished by using a bimetallic spring connected to the indicator mechanism. This actually works the same as the bimetallic thermometer described previously. When the leads are disconnected from the indicator, the temperature of the cockpit area around the instrument panel can be read on the indicator dial. *[Figure 10-73]* Numeric LED indictors for CHT are also common in modern aircraft.

Turbine Gas Temperature Indicating Systems

EGT is a critical variable of turbine engine operation. The EGT indicating system provides a visual temperature indication in the cockpit of the turbine exhaust gases as

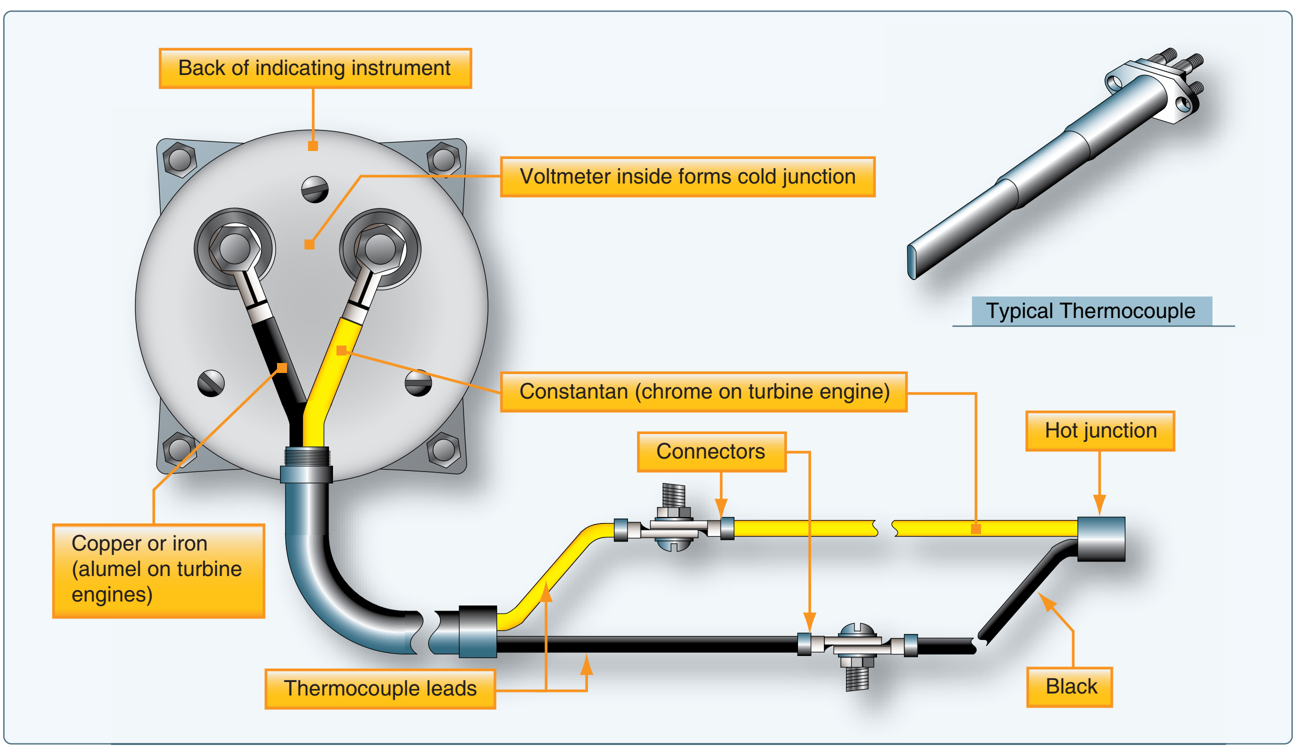


Figure 10-71. *Thermocouples combine two unlike metals that cause current flow when heated.*

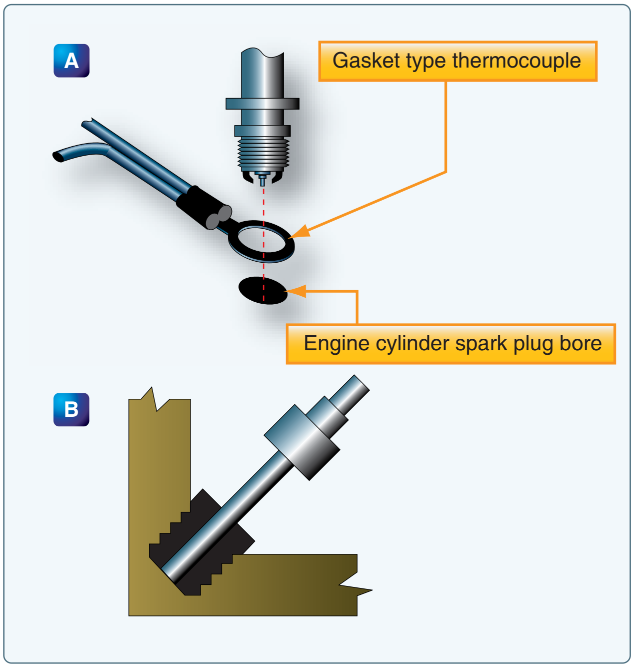


Figure 10-72. *A cylinder head temperature thermocouple with a gasket type hot junction is made to be installed under the spark plug or a cylinder hold down nut of the hottest cylinder (A). A bayonet type thermocouple is installed in a bore in the cylinder wall (B).*

they leave the turbine unit. In certain turbine engines, the temperature of the exhaust gases is measured at the entrance to the turbine unit. This is referred to as a turbine inlet temperature (TIT) indicating system.

Several thermocouples are used to measure EGT or TIT. They are spaced at intervals around the perimeter of the engine turbine casing or exhaust duct. The tiny thermocouple voltages are typically amplified and used to energize a servomotor that drives the indicator pointer. Gearing a digital drum indication off of the pointer motion is common. *[Figure 10-74]* The EGT indicator shown is a hermetically sealed unit. The instrument's scale ranges from 0 °C to 1,200 °C, with a vernier dial in the upper right-hand corner and a power off warning flag located in the lower portion of the dial.

A TIT indicating system provides a visual indication at the instrument panel of the temperature of gases entering the turbine. Numerous thermocouples can be used with the average voltage representing the TIT. Dual thermocouples exist containing two electrically independent junctions within a single probe. One set of these thermocouples is paralleled to transmit signals to the cockpit indicator. The other set of parallel thermocouples provides temperature signals to engine monitoring and control systems. Each circuit is electrically independent, providing dual system reliability.

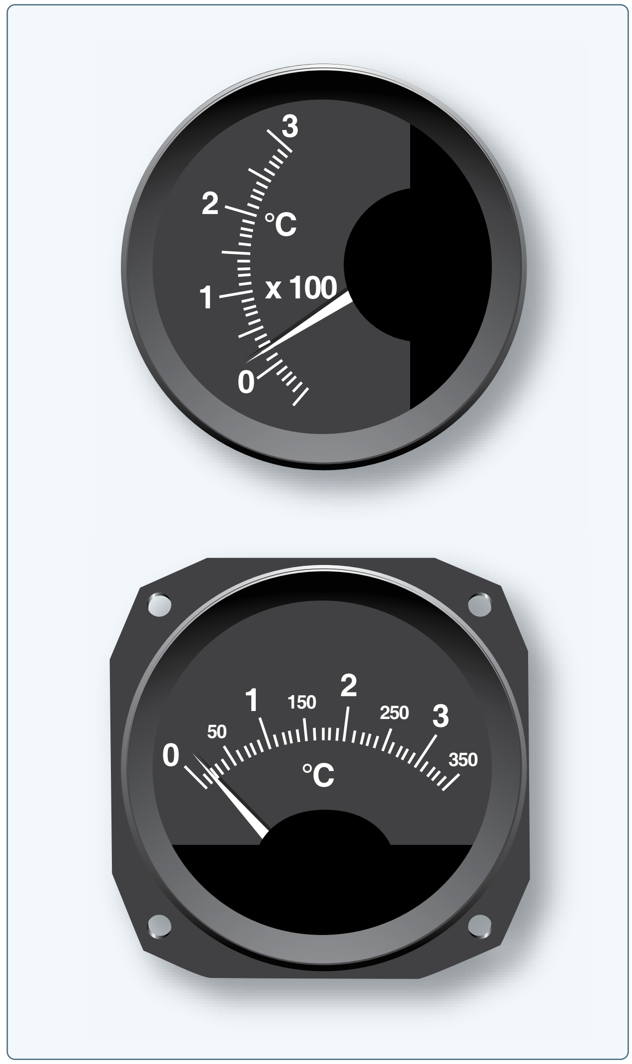


Figure 10-73. *Typical thermocouple temperature indicators.*

A schematic for the turbine inlet temperature system for one engine of a four-engine turbine aircraft is shown in *Figure 10-75*. Circuits for the other three engines are identical to this system. The indicator contains a bridge circuit, a chopper circuit, a two-phase motor to drive the pointer, and a feedback potentiometer. Also included are a voltage reference circuit, an amplifier, a power-off flag, a power supply, and an over temperature warning light. Output of the amplifier energizes the variable field of the two-phase motor that positions the indicator main pointer and a digital indicator. The motor also drives the feedback potentiometer to provide a humming signal to stop the drive motor when the correct pointer position, relative to the temperature signal, has been reached. The voltage reference circuit provides a closely regulated reference voltage in the bridge circuit to preclude error from input voltage variation to the indicator power supply.

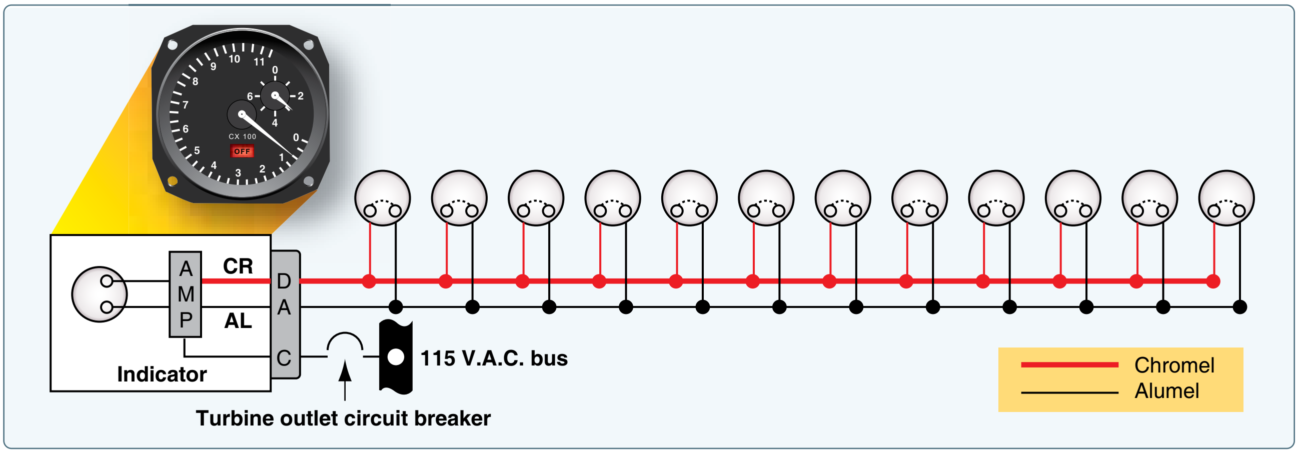


Figure 10-74. *A typical exhaust gas temperature thermocouple system.*

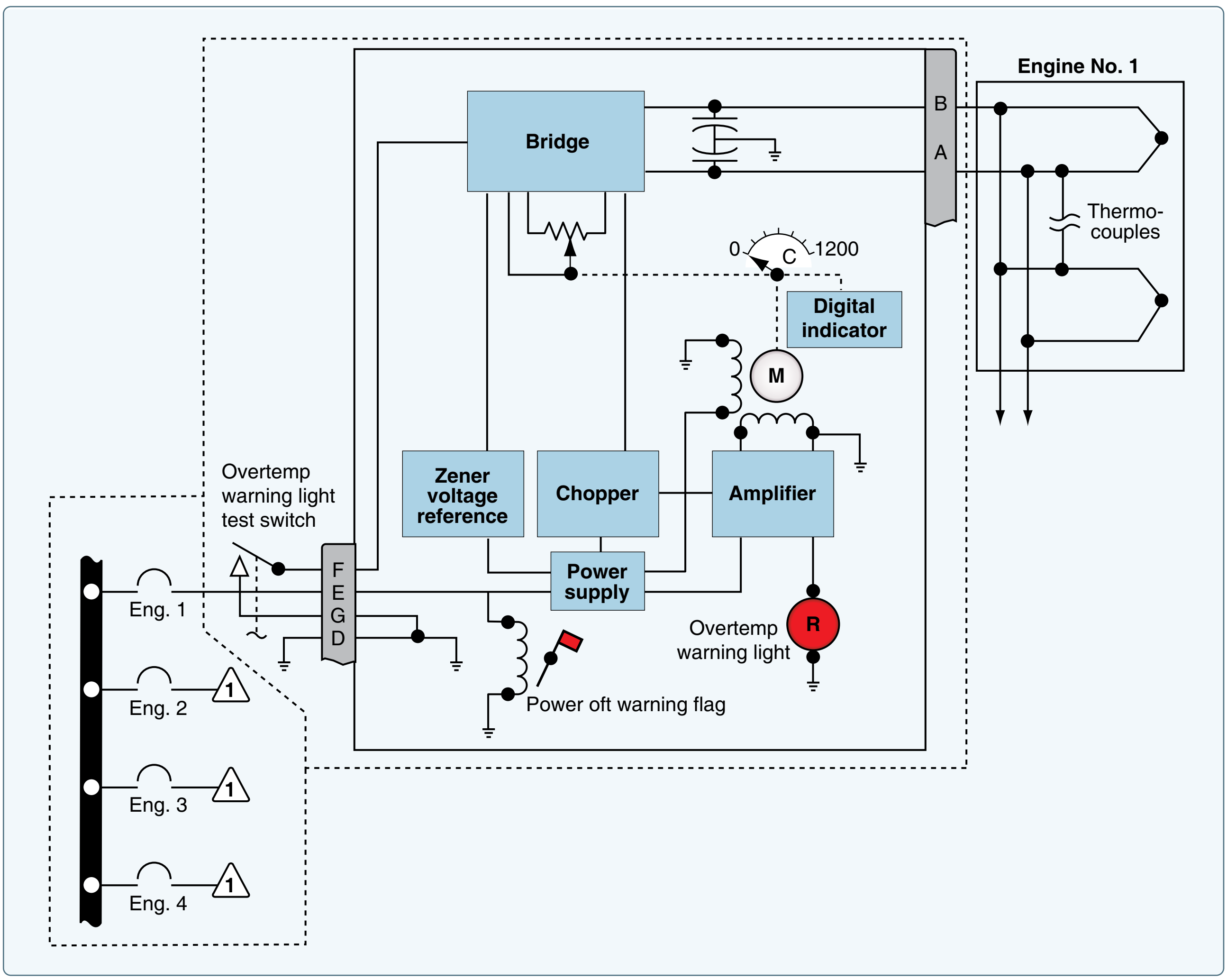


Figure 10-75. *A typical analog turbine inlet temperature indicating system.*

The overtemperature warning light in the indicator illuminates when the TIT reaches a predetermined limit. An external test switch is usually installed so that over temperature warning lights for all the engines can be tested at the same time. When the test switch is operated, an overtemperature signal is simulated in each indicator temperature control bridge circuit.

Digital cockpit instrumentation systems need not employ resistance-type indicators and adjusted servo-driven thermocouple gauges to provide the pilot with temperature information. Sensor resistance and voltage values are input to the appropriate computer, where they are adjusted, processed, monitored, and output for display on cockpit display panels. They are also sent for use by other computers requiring temperature information for the control and monitoring of various integrated systems.

Total Air Temperature Measurement

Air temperature is a valuable parameter that many performance monitoring and control variables depend on. During flight, static air temperature changes continuously and accurate measurement presents challenges. Below 0.2 Mach, a simple resistance-type or bimetallic temperature gauge can provide relatively accurate air temperature information. At faster speeds, friction, the air's compressibility, and boundary layer behavior make accurate temperature capture more complex. Total air temperature (TAT) is the static air temperature plus any rise in temperature caused by the high-speed movement of the aircraft through the air. The increase in temperature is known as ram rise. TAT-sensing probes are constructed specifically to accurately capture this value and transmit signals for cockpit indication, as well as for use in various engine and aircraft systems.

Simple TAT systems include a sensor and an indicator with a built-in resistance balance circuit. Air flow through the sensor is designed so that air with the precise temperature impacts a platinum alloy resistance element. The sensor is engineered to capture temperature variations in terms of varying the resistance of the element. When placed in the bridge circuit, the indicator pointer moves in response to the imbalance caused by the variable resistor.

More complex systems use signal correction technology and amplified signals sent to a servo motor to adjust the indicator in the cockpit. These systems include closely regulated power supply and failure monitoring. They often use numeric drum type readouts, but can also be sent to an LCD driver to illuminate LCD displays. Many LCD displays are multifunctional, capable of displaying static air temperature and true airspeed. In fully digital systems, the correction signals are input into the ADC. There, they can be manipulated appropriately for cockpit display or for whichever system requires temperature information. *[Figure 10-76]*

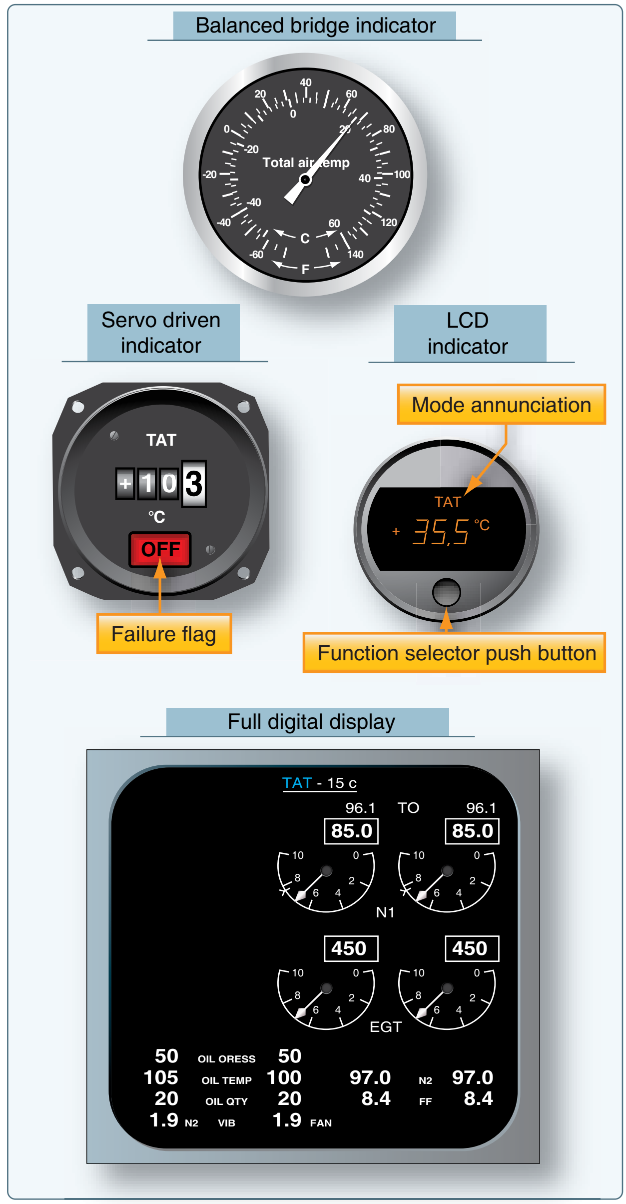


Figure 10-76. *Different cockpit TAT displays.*

TAT sensor/probe design is complicated by the potential of ice forming during icing conditions. Left unheated, a probe may cease to function properly. The inclusion of a heating element threatens accurate data collection. Heating the probe must not affect the resistance of the sensor element. *[Figure 10-77]*

Close attention is paid to airflow and materials conductivity during the design phase. Some TAT sensors channel bleed air through the units to affect the flow of outside air, so that it flows directly onto the platinum sensor without gaining added energy from the probe heater.

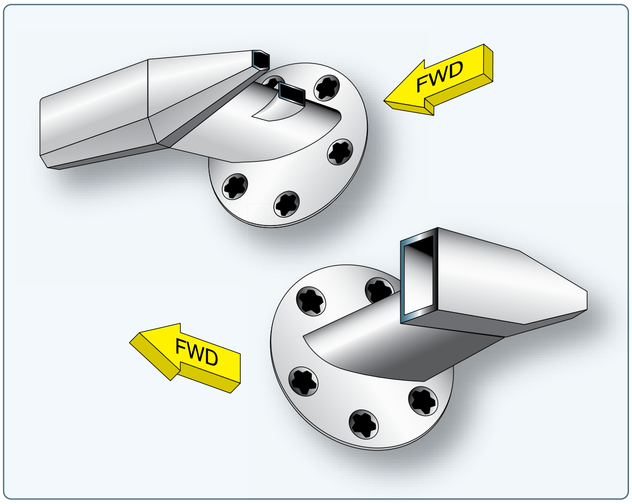


Figure 10-77. *Total air temperature (TAT) probes.*

Direction Indicating Instruments

A myriad of techniques and instruments exist to aid the pilot in navigation of the aircraft. An indication of direction is part of this navigation. While the next chapter deals with communication and navigation, this section discusses some of the magnetic direction indicating instruments. Additionally, a common, reliable gyroscopic direction indicator is discussed in the gyroscopic instrument section of this chapter.

Magnetic Compass

Having an instrument on board an aircraft that indicates direction can be invaluable to the pilot. In fact, it is a requirement that all certified aircraft have some sort of magnetic direction indicator. The magnetic compass is a direction finding instrument that has been used for navigation for hundreds of years. It is a simple instrument that takes advantage of the earth's magnetic field.

Figure 10-78 shows the earth and the magnetic field that surrounds it. The magnetic north pole is very close to the geographic North Pole of the globe, but they are not the same. An ordinary permanent magnet that is free to do so, aligns itself with the direction of the earth's magnetic field. Upon this principle, an instrument is constructed that the pilot can reference for directional orientation. Permanent magnets are attached under a float that is mounted on a pivot so it is free to rotate in the horizontal plane. As such, the magnets align with the earth's magnetic field. A numerical compass card, usually graduated in 5° increments, is constructed around the perimeter of the float. It serves as the instrument dial. The entire assembly is enclosed in a sealed case that is filled with a liquid similar to kerosene. This dampens vibration and oscillation of the moving float assembly and decreases friction.

On the front of the case, a glass face allows the numerical compass card to be referenced against a vertical lubber line.

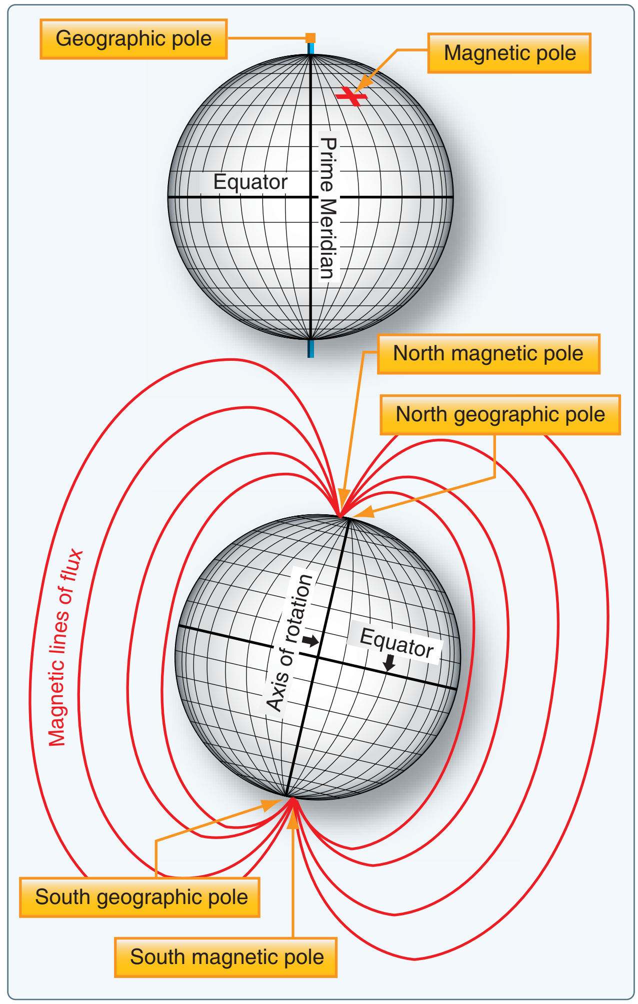


Figure 10-78. *The earth and its magnetic field.*

The magnetic heading of the aircraft is read by noting the graduation on which the lubber line falls. Thus, direction in any of 360° can be read off the dial as the magnetic float compass card assembly holds its alignment with magnetic north, while the aircraft changes direction.

The liquid that fills the compass case expands and contracts as altitude changes and temperature fluctuates. A bellows diaphragm expands and contracts to adjust the volume of the space inside the case so it remains full. *[Figure 10-79]*

There are accuracy issues associated with using a magnetic compass. The main magnets of a compass align not only with the earth's magnetic field, they actually align with the composite field made up of all magnetic influences around them, meaning local electromagnetic influence from metallic structures near the compass and operation aircraft's electrical system. This is called magnetic deviation. It causes a magnet's alignment with the earth's magnetic field to be altered. Compensating screws are turned, which move small permanent magnets in the compass case to correct for this

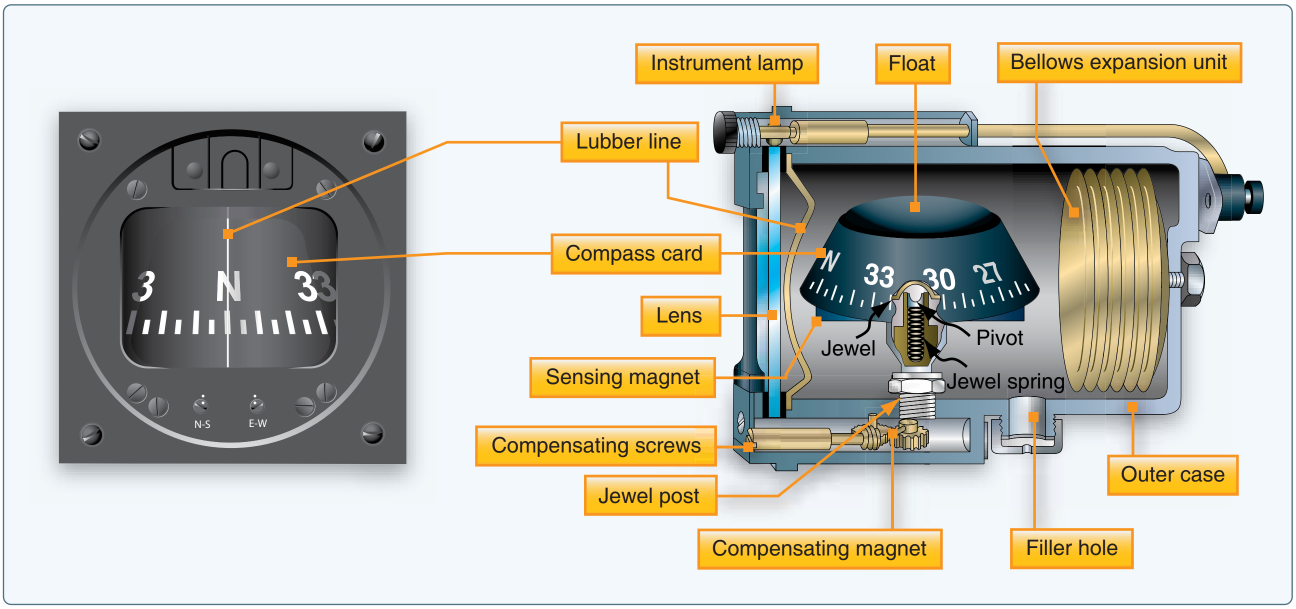


Figure 10-79. *The parts of a typical magnetic compass.*

magnetic deviation. The two set-screws are on the face of the instrument and are labeled N-S and E-W. They position the small magnets to counterbalance the local magnetic influences acting on the main compass magnets.

The process for knowing how to adjust for deviation is known as swinging the compass. It is described in the instrument maintenance pages near the end of this chapter. Magnetic deviation cannot be overlooked. It should never be more than 10°. Using nonferrous mounting screws and shielding or twisting the wire running to the compass illuminating lamp are additional steps taken to keep deviation to a minimum.

Another compass error is called magnetic variation. It is caused by the difference in location between the earth's magnetic poles and the geographic poles. There are only a few places on the planet where a compass pointing to magnetic north is also pointing to geographic North. A line drawn through these locations is called the Agonic line. At all other points, there is some variation between that which a magnetic compass indicates is north and geographic (true) North. Isogonic lines drawn on aeronautical charts indicate points of equal variation. Depending on the location of the aircraft, airmen must add or subtract degrees from the magnetic indication to obtain true geographic location information. *[Figure 10-80]*

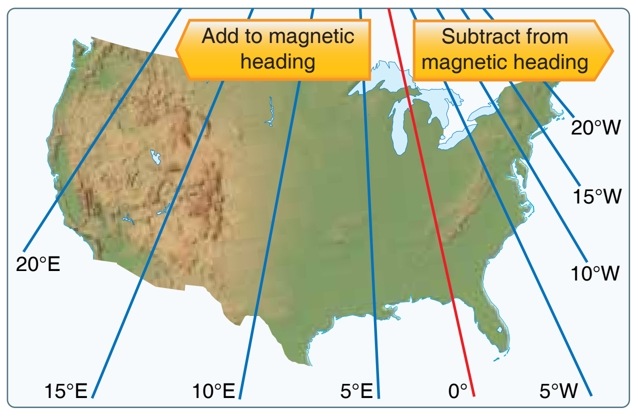


Figure 10-80. *Aircraft located along the agonic line have 0° of variation between magnetic north and true north. Locations on and between the isogonic lines require addition or subtraction, as shown, to magnetic indications to arrive at a true geographic direction.*

The earth's magnetic field exits the poles vertically and arches around to extend past the equator horizontally or parallel to the earth's surface. *[Figure 10-78]* Operating an aircraft near the magnetic poles causes what is known as dip error. The compass magnets pull downward toward the pole, rather than horizontally, as is the case near the equator. This downward motion causes inaccuracy in the indication. Although the compass float mechanism is weighted to compensate, the closer the aircraft is to the north or south magnetic poles, the more pronounced the errors.

Dip errors manifest themselves in two ways. The first is called acceleration error. If an aircraft is flying on an east-west path and simply accelerates, the inertia of the float mechanism causes the compass to swing to the north. Rapid deceleration causes it to swing southward. Second, if flying toward the North Pole and a banked turn is made, the downward pull of the magnetic field initially pulls the card away from the direction of the turn. The opposite is true if flying south from the North Pole and a banked turn is initiated. In this case, there is initially a pull of the compass indicator toward the direction of the turn. These kinds of movements are called turning errors.

Another peculiarity exists with the magnetic compass that is not dip error. Look again at the magnetic compass in *Figure 10-79*. If flying north or toward any indicated heading, turning the aircraft to the left causes a steady decrease in the heading numbers. But, before the turn is made, the numbers to the left on the compass card are actually increasing. The numbers to the right of the lubber line rotate behind it on a left turn. So, the compass card rotates opposite to the direction of the intended turn. This is because, from the pilot's seat, you are actually looking at the back of the compass card. While not a major problem, it is more intuitive to see the 360° of direction oriented as they are on an aeronautical chart or a hand-held compass.

Vertical Magnetic Compass

Solutions to the shortcomings of the simple magnetic compass described above have been engineered. The vertical magnetic compass is a variation of the magnetic compass that eliminates the reverse rotation of the compass card just described. By mounting the main indicating magnets of the compass on a shaft rather than a float, through a series of gears, a compass card can be made to turn about a horizontal axis. This allows the numbers for a heading, towards which the pilot wants to turn, to be oriented correctly on the indicating card. In other words, when turning right, increasing numbers are to the right; when turning left, decreasing numbers rotate in from the left. *[Figure 10-81]* Many vertical magnetic compasses have also replaced the liquid-filled instrument housing with a dampening cup that uses eddy currents to dampen oscillations. Note that a vertical magnetic compass and a directional gyro look very similar and are often in the lower center position of the instrument panel basic T. Both use the nose of an aircraft as the lubber line against which a rotating compass card is read. Vertical magnetic compasses are characterized by the absence of the hand adjustment knob found on DGs, which is used to align the gyro with a magnetic indication.

Remote Indicating Compass

Magnetic deviation is compensated for by swinging the compass and adjusting compensating magnets in the instrument housing. A better solution to deviation is to remotely locate the magnetic compass in a wing tip or vertical stabilizer where there is very little interference with the earth's magnetic field. By using a synchro remote indicating system, the magnetic compass float assembly can act as the rotor of the synchro system. As the float mechanism rotates to align with magnetic north in the remotely located compass, a varied electric current can be produced in the transmitter. This alters the magnetic field produced by the coils of the indicator in the cockpit, and a magnetic indication relatively free from deviation is displayed. Many of these systems are of the magnesyn type.

Figure 10-81. *A vertical magnetic direction indicator provides a realistic reference of headings.*

Remote Indicating Slaved Gyro Compass (Flux Gate Compass)

An elaborate and very accurate method of direction indication has been developed that combines the use of a gyro, a magnetic compass, and a remote indicating system. It is called the slaved gyro compass or flux gate compass system. A study of the gyroscopic instruments section of this chapter assists in understanding this device.

A gyroscopic direction indicator is augmented by magnetic direction information from a remotely located compass. The type of compass used is called a flux valve or flux gate compass. It consists of a very magnetically permeable circular segmented core frame or spider. The earth's magnetic field flows through this iron core and varies its distribution through segments of the core as the flux valve is rotated via the movement of the aircraft. Pickup coil windings are located on each of the core's spider legs that are positioned 120° apart. *[Figure 10-82]*

The distribution of earth's magnetic field flowing through the legs is unique for every directional orientation of the aircraft. A coil is placed in the center of the core and is energized by AC current. As the AC flow passes through zero while changing direction, the earth's magnetic field is allowed to flow through the core. Then, it is blocked or gated as the magnetic field of the core current flow builds to its peak again. The cycle is repeated at the frequency of

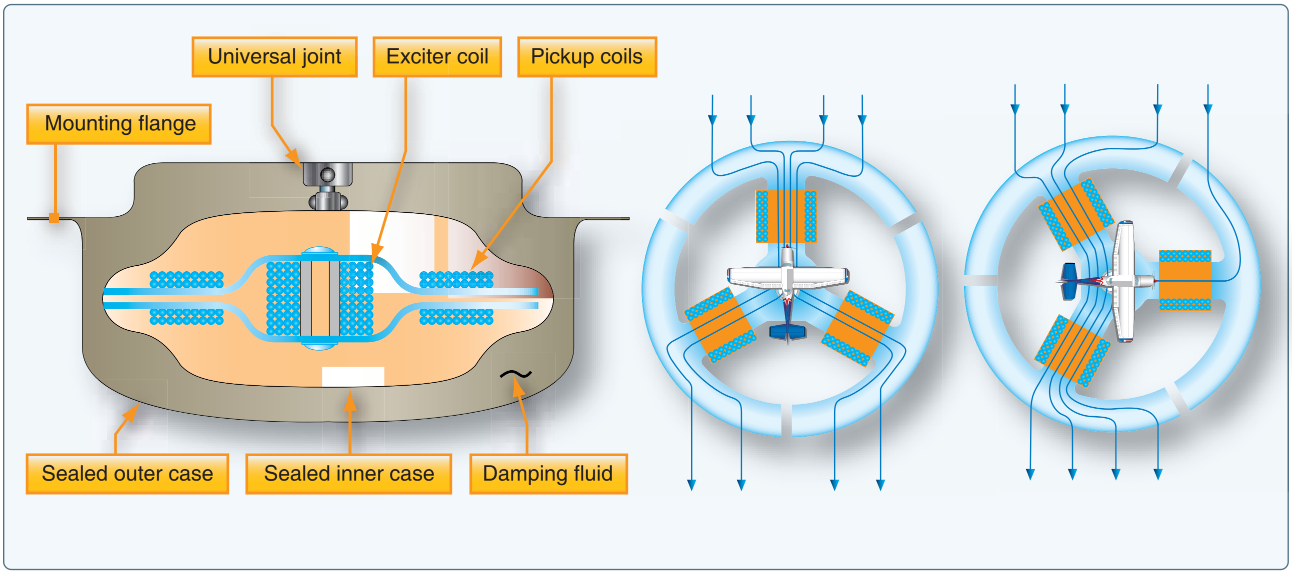


Figure 10-82. *As the aircraft turns in the earth's magnetic field, the lines of flux flow lines vary through the permeable core of flux gate, creating variable voltages at the three pickoffs.*

the AC supplied to the excitation coil. The result is repeated flow and nonflow of the earth's flux across the pickup coils. During each cycle, a unique voltage is induced in each of the pickup coils reflecting the orientation of the aircraft in the earth's magnetic field.

The electricity that flows from each of the pickup coils is transmitted out of the flux valve via wires into a second unit. It contains an autosyn transmitter, directional gyro, an amplifier, and a triple wound stator that is similar to that found in the indicator of a synchro system. Unique voltage is induced in the center rotor of this stator which reflects the voltage received from the flux valve pickup coils sent through the stator coils. It is amplified and used to augment the position of the DG. The gyro is wired to be the rotor of an autosyn synchro system, which transmits the position of the gyro into an indicator unit located in the cockpit. In the indicator, a vertical compass card is rotated against a small airplane type lubber line like that in a vertical magnetic compass. *[Figure 10-83* and *84]*

Further enhancements to direction finding systems of this type involving the integration of radio navigation aids are common. The radio magnetic indicator (RMI) is one such variation. *[Figure 10-85]* In addition to the rotating direction indicator of the slaved gyro compass, it contains two pointers. One indicates the bearing to a very high frequency (VHF) omnidirectional range (VOR) station and the other indicates the bearing to a nondirectional automatic direction finder (ADF) beacon. These and other radio navigation aids are discussed further in the communications and navigation chapter of this handbook. It should also be noted that integration of slaved gyro direction indicating system information into auto-pilot systems is also possible.

Solid State Magnetometers

Solid state magnetometers are used on many modern aircraft. They have no moving parts and are extremely accurate. Tiny layered structures react to magnetism on a molecular level resulting in variations in electron activity. These low power consuming devices can sense not only the direction to the earth's magnetic poles, but also the angle of the flux field. They are free from oscillation that plagues a standard magnetic compass. They feature integrated processing algorithms and easy integration with digital systems. *[Figure 10-86]*

Sources of Power for Gyroscopic Instruments

Gyroscopic instruments are essential instruments used on all aircraft. They provide the pilot with critical attitude and directional information and are particularly important while flying under IFR. The sources of power for these instruments can vary. The main requirement is to spin the gyroscopes at a high rate of speed. Originally, gyroscopic instruments were strictly vacuum driven. A vacuum source pulled air across the gyro inside the instruments to make the gyros spin. Later, electricity was added as a source of power. The turning armature of an electric motor doubles as the gyro rotor. In some aircraft, pressure, rather than vacuum, is used to induce the gyro to spin. Various systems and powering configurations have been developed to provide reliable operation of the gyroscopic instruments.

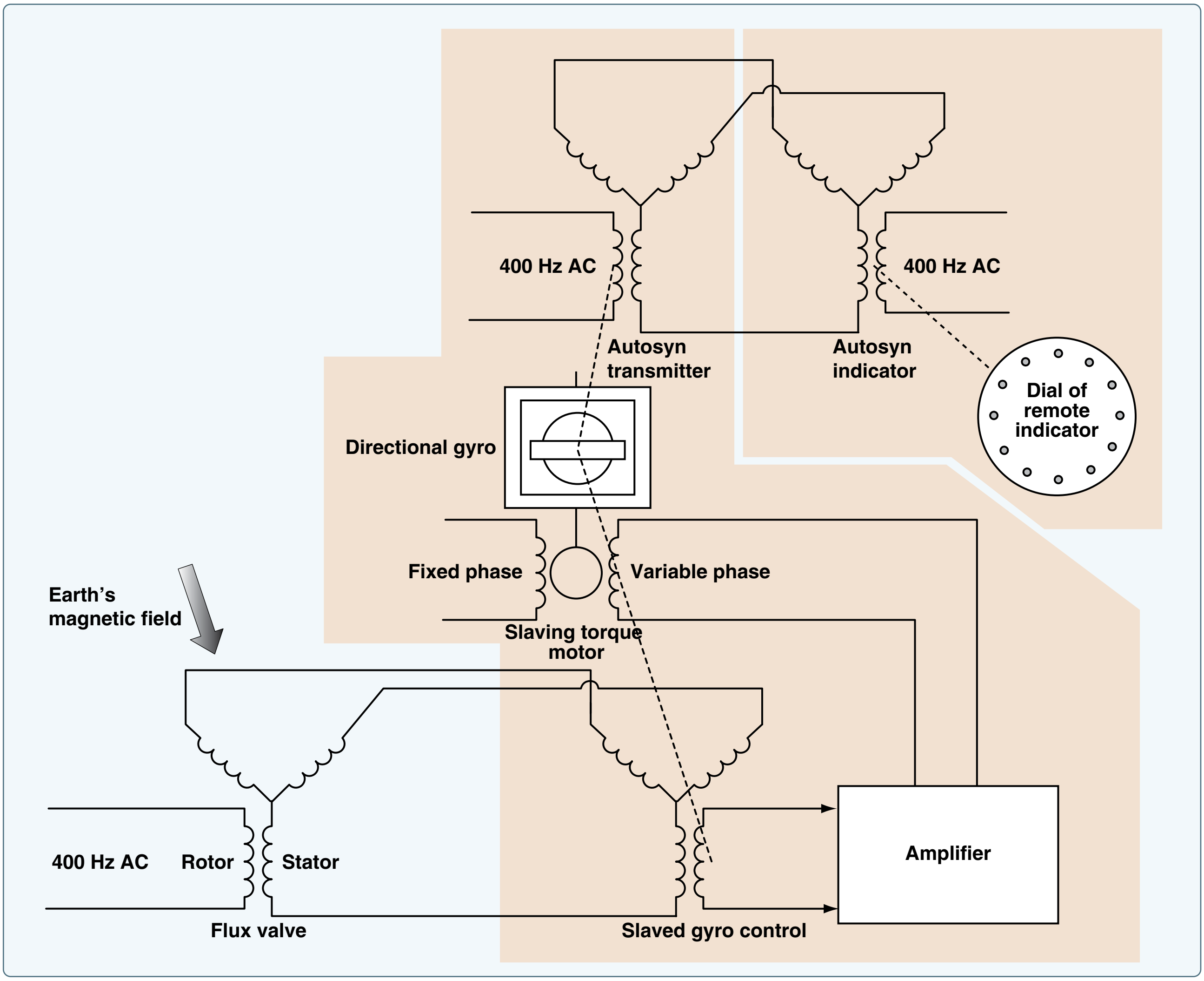


Figure 10-83. *A simplified schematic of a flux gate, or slaved gyro, compass system.*

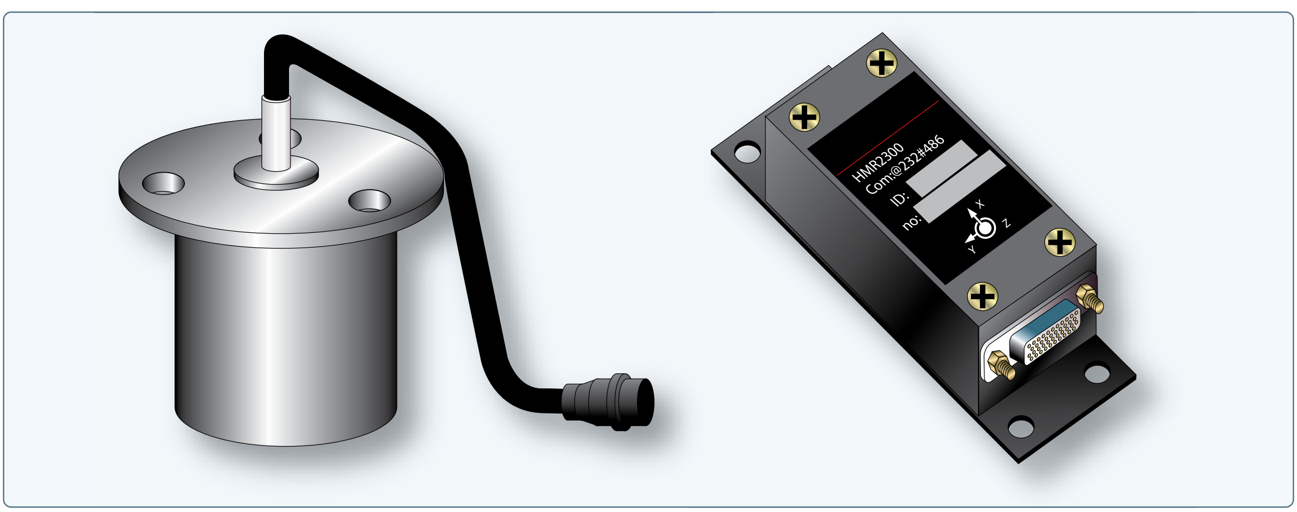


Figure 10-84. *Solid state magnetometer units.*

Figure 10-85. *A radio magnetic indicator (RMI) combines a slaved gyro heading indication (red triangle at top of gauge) with magnetic bearing information to a VOR station (solid pointer) and an ADF station (hollow pointer).*

Vacuum Systems

Vacuum systems are very common for driving gyro instruments. In a vacuum system, a stream of air directed against the rotor vanes turns the rotor at high speed. The action is similar to a water wheel. Air at atmospheric pressure is first drawn through a filter(s). It is then routed into the instrument and directed at vanes on the gyro rotor. A suction line leads from the instrument case to the vacuum source. From there, the air is vented overboard. Either a venturi or a vacuum pump can be used to provide the vacuum required to spin the rotors of the gyro instruments.

The vacuum value required for instrument operation is usually between 3½ inches to 4½ inches of mercury. It is usually adjusted by a vacuum relief valve located in the supply line. Some turn-and-bank indicators require a lower vacuum setting. This can be obtained through the use of an additional regulating valve in the turn and bank vacuum supply line.

Venturi Tube Systems

The velocity of the air rushing through a venturi can create sufficient suction to spin instrument gyros. A line is run from the gyro instruments to the throat of the venturi mounted on the outside of the airframe. The low pressure in the venturi tube pulls air through the instruments, spins the gyros, and expels the air overboard through the venturi. This source of gyro power is used on many simple, early aircraft.

A light, single-engine aircraft can be equipped with a 2-inch venturi (2 inches of mercury vacuum capacity) to operate the turn and bank indicator. It can also have a larger 8-inch venturi to power the attitude and heading indicators. Simplified illustrations of these venturi vacuum systems are shown in *Figure 10-87*. Normally, air going into the instruments is filtered.

The advantages of a venturi as a suction source are its relatively low cost and its simplicity of installation and operation. It also requires no electric power. But there are serious limitations. A venturi is designed to produce the desired vacuum at approximately 100 mph at standard sea level conditions. Wide variations in airspeed or air density cause the suction developed to fluctuate. Airflow can also be hampered by ice that can form on the venturi tube. Additionally, since the rotor does not reach normal operating speed until after takeoff, preflight operational checks of venturi powered gyro instruments cannot be made. For these reasons, alternate sources of vacuum power were developed.

Engine-Driven Vacuum Pump

The vane-type engine-driven pump is the most common source of vacuum for gyros installed in general aviation,

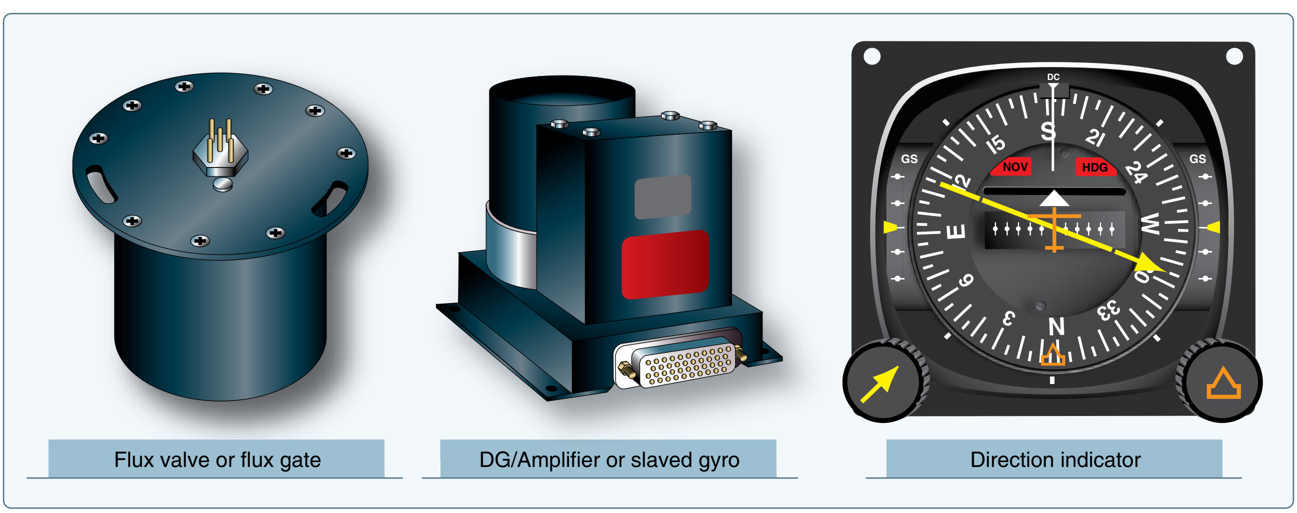


Figure 10-86. *Solid state magnetometers.*

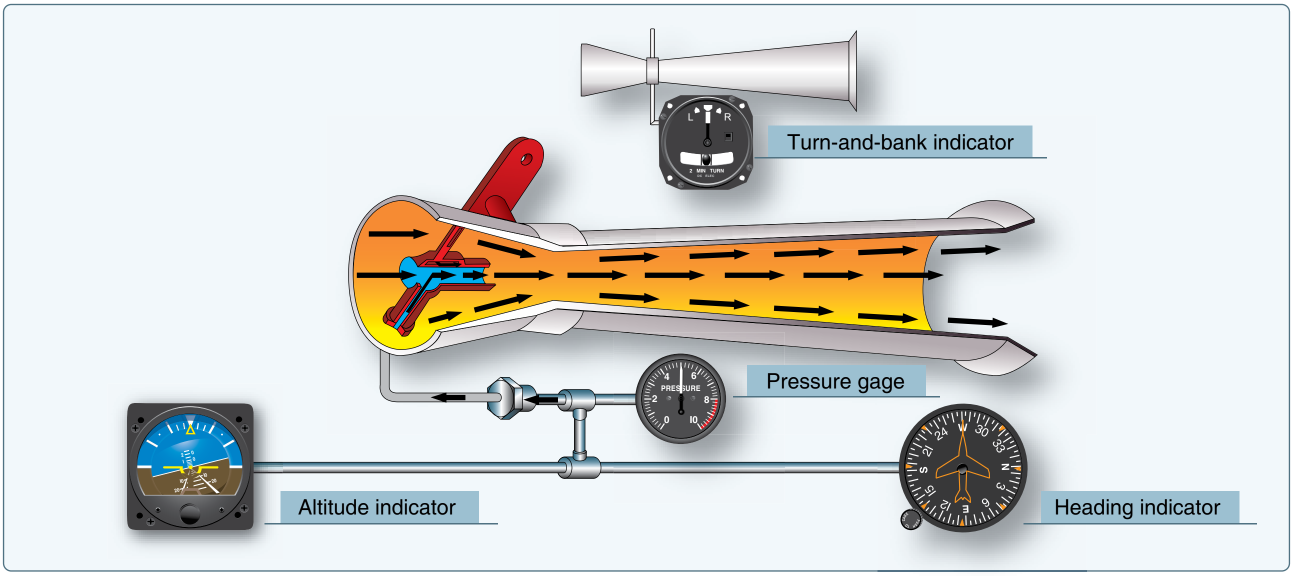


Figure 10-87. *Simple venturi tube systems for powering gyroscopic instruments.*

light aircraft. One type of engine-driven pump is geared to the engine and is connected to the lubricating system to seal, cool, and lubricate the pump. Another commonly used pump is a dry vacuum pump. It operates without external lubrication and installation requires no connection to the engine oil supply. It also does not need the air oil separator or gate check valve found in wet pump systems. In many other respects, the dry pump system and oil lubricated system are the same. *[Figure 10-88]*

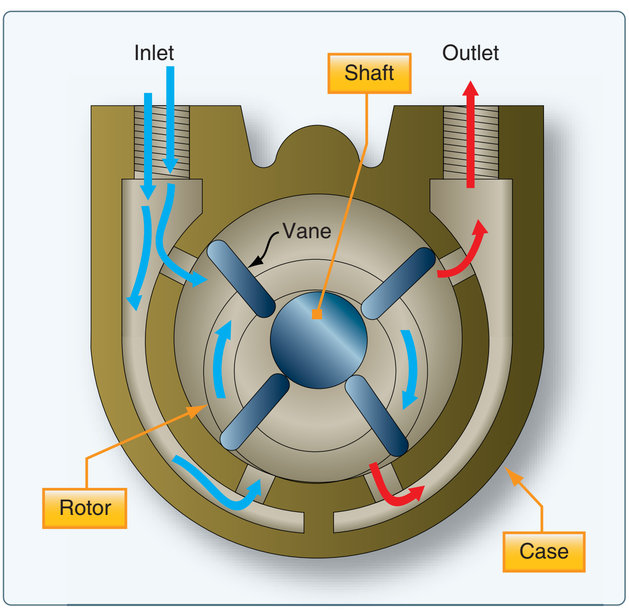


Figure 10-88. *Cutaway view of a vane-type engine-driven vacuum pump used to power gyroscopic instruments.*

When a vacuum pump develops a vacuum (negative pressure), it also creates a positive pressure at the outlet of the pump. This pressure is compressed air. Sometimes, it is utilized to operate pressure gyro instruments. The components for pressure systems are much the same as those for a vacuum system as listed below. Other times, the pressure developed by the vacuum pump is used to inflate de-ice boots or inflatable seals or it is vented overboard.

An advantage of engine-driven pumps is their consistent performance on the ground and in flight. Even at low engine rpm, they can produce more than enough vacuum so that a regulator in the system is needed to continuously provide the correct suction to the vacuum instruments. As long as the engine operates, the relatively simple vacuum system adequately spins the instrument gyros for accurate indications. However, engine failure, especially on single-engine aircraft, could leave the pilot without attitude and directional information at a critical time. To thwart this shortcoming, often the turn and bank indicator operates with an electrically driven gyro that can be driven by the battery for a short time. Thus, when combined with the aircraft's magnetic compass, sufficient attitude and directional information is still available.

Multiengine aircraft typically contain independent vacuum systems for the pilot and copilot instruments driven by separate vacuum pumps on each of the engines. Should an engine fail, the vacuum system driven by the still operating engine supplies a full complement of gyro instruments. An interconnect valve may also be installed to connect the failed instruments to the still operational pump.

Typical Pump-Driven System

The following components are found in a typical vacuum system for gyroscopic power supply. A brief description is given of each. Refer to the figures for detailed illustrations.

Air-oil separator—oil and air in the vacuum pump are exhausted through the separator, which separates the oil from the air; the air is vented overboard and the oil is returned to the engine sump. This component is not present when a dry-type vacuum pump is used. The self-lubricating nature of the pump vanes requires no oil.

Vacuum regulator or suction relief valve—since the system capacity is more than is needed for operation of the instruments, the adjustable vacuum regulator is set for the vacuum desired for the instruments. Excess suction in the instrument lines is reduced when the spring-loaded valve opens to atmospheric pressure. *[Figure 10-89]*

Figure 10-89. *A vacuum regulator, also known as a suction relief valve, includes a foam filter. To relieve vacuum, outside air of a higher pressure must be drawn into the system. This air must be clean to prevent damage to the pump.*

Gate check valve—prevents possible damage to the instruments by engine backfire that would reverse the flow of air and oil from the pump. *[Figure 10-90]*

Pressure relief valve—since a reverse flow of air from the pump would close both the gate check valve and the suction relief valve, the resulting pressure could rupture the lines. The pressure relief valve vents positive pressure into the atmosphere.

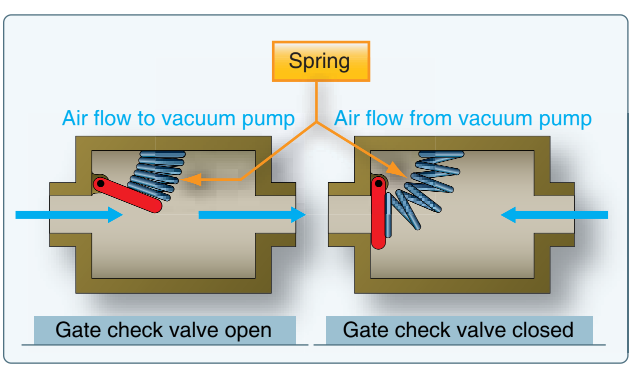


Figure 10-90. *Gate check valve used to prevent vacuum system damage from engine backfire.*

Selector valve—In twin-engine aircraft having vacuum pumps driven by both engines, the alternate pump can be selected to provide vacuum in the event of either engine or pump failure, with a check valve incorporated to seal off the failed pump.

Restrictor valve—Since the turn needle of the turn and bank indicator operates on less vacuum than that required by the other instruments, the vacuum in the main line must be reduced for use by this instrument. An in-line restrictor valve performs this function. This valve is either a needle valve or a spring-loaded regulating valve that maintains a constant, reduced vacuum for the turn-and-bank indicator.

Air filter—A master air filter screens foreign matter from the air flowing through all the gyro instruments. It is an extremely import filter requiring regular maintenance. Clogging of the master filter reduces airflow and causes a lower reading on the suction gauge. Each instrument is also provided with individual filters. In systems with no master filter that rely only upon individual filters, clogging of a filter does not necessarily show on the suction gauge.

Suction gauge—a pressure gauge which indicates the difference between the pressure inside the system and atmospheric or cockpit pressure. It is usually calibrated in inches of mercury. The desired vacuum and the minimum and maximum limits vary with gyro system design. If the desired vacuum for the attitude and heading indicators is 5 inches and the minimum is 4.6 inches, a reading below the latter value indicates that the airflow is not spinning the gyros fast enough for reliable operation. In many aircraft, the system provides a suction gauge selector valve permitting the pilot to check the vacuum at several points in the system.

Suction/vacuum pressures discussed in conjunction with the operation of vacuum systems are actually negative pressures, indicated as inches of mercury below that of atmospheric pressure. The minus sign is usually not presented, as the importance is placed on the magnitude of the vacuum developed. In relation to an absolute vacuum (0 psi or 0 "Hg), instrument vacuum systems have positive pressure.

Figure 10-91 shows a typical engine-driven pump vacuum system containing the above components. A pump capacity of approximately 10"Hg at engine speeds above 1,000 rpm is normal. Pump capacity and pump size vary in different aircraft, depending on the number of gyros to be operated.

Twin-Engine Aircraft Vacuum System Operation

Twin-engine aircraft vacuum systems are more complicated. They contain an engine-driven vacuum pump on each engine. The associated lines and components for each pump are

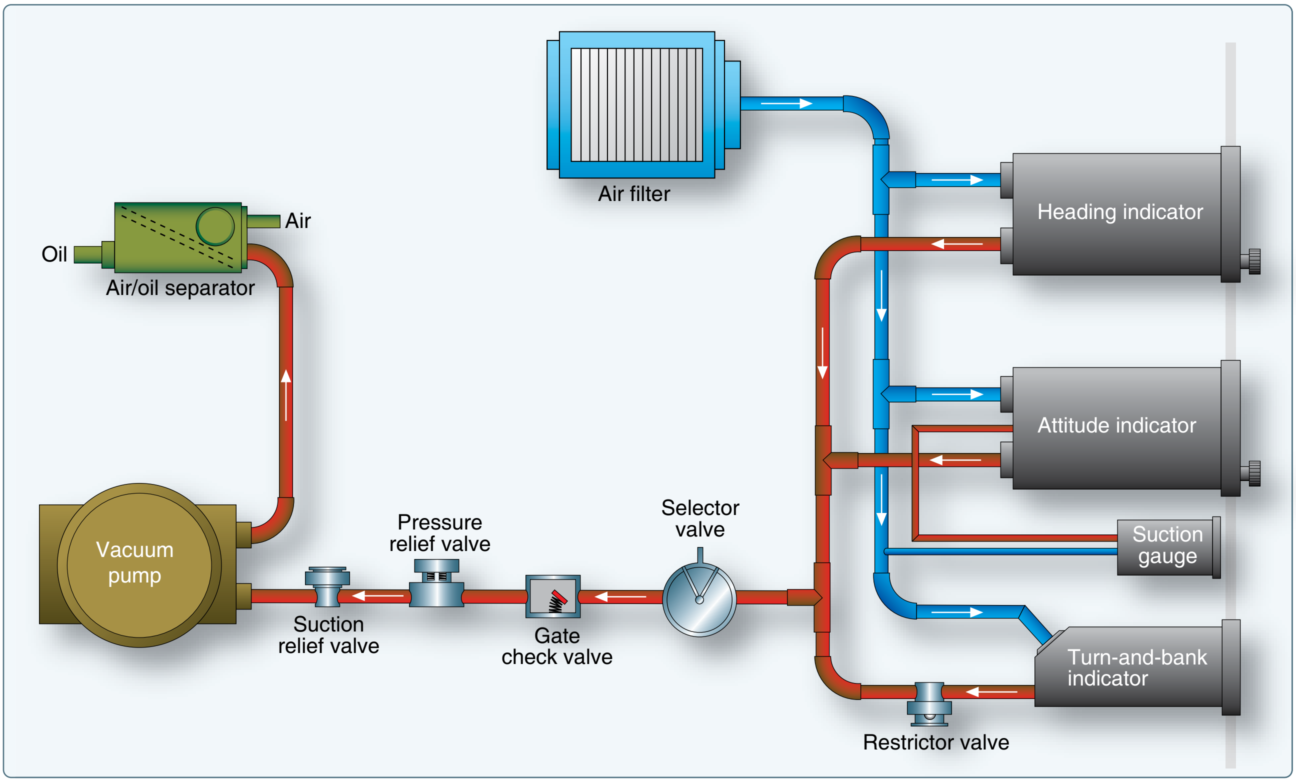


Figure 10-91. *A typical pump-driven vacuum system for powering gyroscopic instruments.*

isolated from each other and act as two independent vacuum systems. The vacuum lines are routed from each vacuum pump through a vacuum relief valve and through a check valve to the vacuum four-way selector valve. The four-way valve permits either pump to supply a vacuum manifold. From the manifold, flexible hoses connect the vacuum-operated instruments into the system. To reduce the vacuum for the turn and bank indicators, needle valves are included in both lines to these units. Lines to the artificial horizons and the directional gyro receive full vacuum. From the instruments, lines are routed to the vacuum gauge through a turn and bank selector valve. This valve has three positions: main, left turn and bank (T&B), and right T&B. In the main position, the vacuum gauge indicates the vacuum in the lines of the artificial horizons and directional gyro. In the other positions, the lower value of vacuum for the turn and bank indicators can be read.

A schematic of this twin-engine aircraft vacuum system is shown in *Figure 10-92*. Note the following components: two engine-driven pumps, two vacuum relief valves, two flapper type check valves, a vacuum manifold, a vacuum restrictor for each turn and bank indicator, an engine four-way selector valve, one vacuum gauge, and a turn-and-bank selector valve. Not shown are system and individual instrument filters. A drain line may also be installed at the low point in the system.

Pressure-Driven Gyroscopic Instrument Systems

Gyroscopic instruments are finely balanced devices with jeweled bearings that must be kept clean to perform properly. When early vacuum systems were developed, only oil-lubricated pumps were available. Even with the use of air-oil separators, the pressure outputs of these pumps contain traces of oil and dirt. As a result, it was preferred to draw clean air through the gyro instruments with a vacuum system, rather than using pump output pressure that presented the risk of contamination. The development of self-lubricated dry pumps greatly reduced pressure output contaminates. This made pressure gyro systems possible.

At high altitudes, the use of pressure-driven gyros is more efficient. Pressure systems are similar to vacuum systems and make use of the same components, but they are designed for pressure instead of vacuum. Thus, a pressure regulator is used instead of a suction relief valve. Filters are still extremely important to prevent damage to the gyros. Normally, air is filtered at the inlet and outlet of the pump in a pressure gyro system.

Electrically-Driven Gyroscopic Instrument Systems

A spinning motor armature can act as a gyroscope. This is the basis for electrically driven gyroscopic instruments in which the gyro rotor spin is powered by an electric motor.

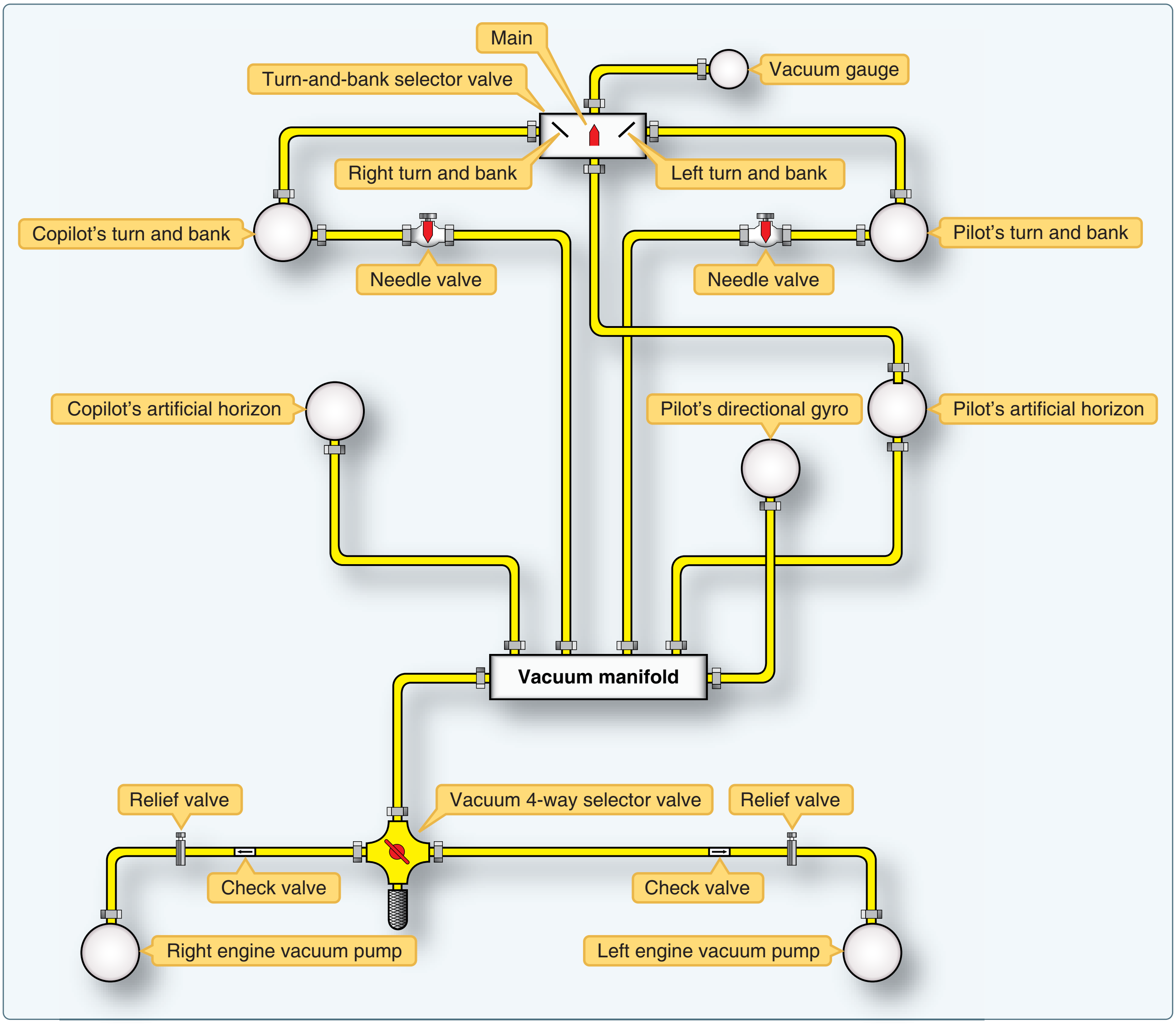


Figure 10-92. *An example of a twin-engine instrument vacuum system.*

Electric gyros have the advantage of being powered by battery for a limited time if a generator fails or an engine is lost. Since air is not sent through the gyro to spin the rotor, contamination worries are also reduced. Also, elimination of vacuum pumps, plumbing, and vacuum system components saves weight.

On many small, single-engine aircraft, electric turn-and-bank or turn coordinators are combined with vacuum-powered attitude and directional gyro instruments as a means for redundancy. The reverse is also possible. By combining both types of instruments in the instrument panel, the pilot has more options. On more complex multiengine aircraft, reliable, redundant electrical systems make use of all electric-powered gyro instruments possible.

It should be noted that electric gyro instruments have some sort of indicator on the face of the dial to show when the instrument is not receiving power. Usually, this is in the form of a red flag or mark of some sort often with the word "off" written on it.

Principles of Gyroscopic Instruments

Mechanical Gyros

Three of the most common flight instruments, the attitude indicator, heading indicator, and turn needle of the turn-and-bank indicator, are controlled by gyroscopes. To understand how these instruments operate, knowledge of gyroscopic principles and instrument power systems is required.

A mechanical gyroscope, or gyro, is comprised of a wheel or rotor with its mass concentrated around its perimeter. The rotor has bearings to enable it to spin at high speeds. *[Figure 10-93A]*

Different mounting configurations are available for the rotor and axle, which allow the rotor assembly to rotate about one or two axes perpendicular to its axis of spin. To suspend the rotor for rotation, the axle is first mounted in a supporting ring. *[Figure 10-93B]* If brackets are attached 90° around the supporting ring from where the spin axle attached, the supporting ring and rotor can both move freely 360°. When in this configuration, the gyro is said to be a captive gyro. It can rotate about only one axis that is perpendicular to the axis of spin. *[Figure 10-93C]*

The supporting ring can also be mounted inside an outer ring. The bearing points are the same as the bracket just described, 90° around the supporting ring from where the spin axle attached. Attachment of a bracket to this outer ring allows the rotor to rotate in two planes while spinning. Both of these are perpendicular to the spin axis of the rotor. The plane that the rotor spins in due to its rotation about its axle is not counted as a plane of rotation.

A gyroscope with this configuration, two rings plus the mounting bracket, is said to be a free gyro because it is free to rotate about two axes that are both perpendicular to the rotor's spin axis. *[Figure 10-93D]* As a result, the supporting ring with spinning gyro mounted inside is free to turn 360° inside the outer ring.

Unless the rotor of a gyro is spinning, it has no unusual properties; it is simply a wheel universally mounted. When the rotor is rotated at a high speed, the gyro exhibits a couple of unique characteristics. The first is called gyroscopic rigidity, or rigidity in space. This means that the rotor of a free gyro always points in the same direction no matter which way the base of the gyro is positioned. *[Figure 10-94]*

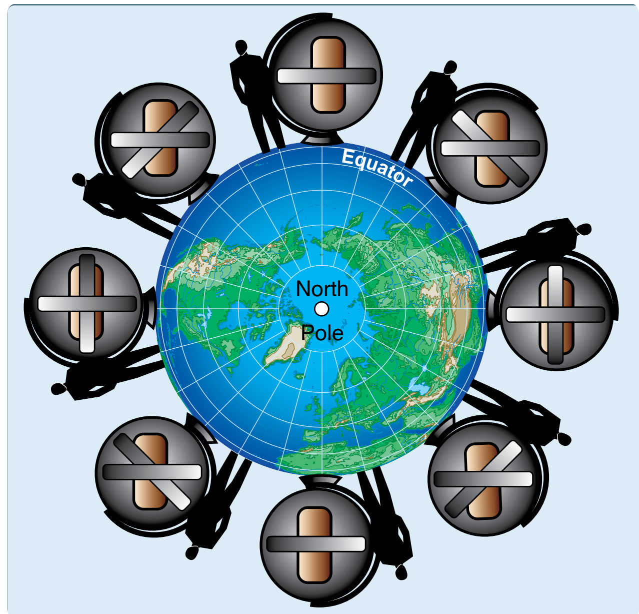


Figure 10-94. *Once spinning, a free gyro rotor stays oriented in the same position in space despite the position or location of its base.*

Gyroscopic rigidity depends upon several design factors:

1. Weight—for a given size, a heavy mass is more resistant to disturbing forces than a light mass.
2. Angular velocity—the higher the rotational speed, the greater the rigidity or resistance is to deflection.
3. Radius at which the weight is concentrated—maximum effect is obtained from a mass when its principal weight is concentrated near the rim, rotating at high speed.
4. Bearing friction—any friction applies a deflecting force to a gyro. Minimum bearing friction keeps deflecting forces at a minimum.

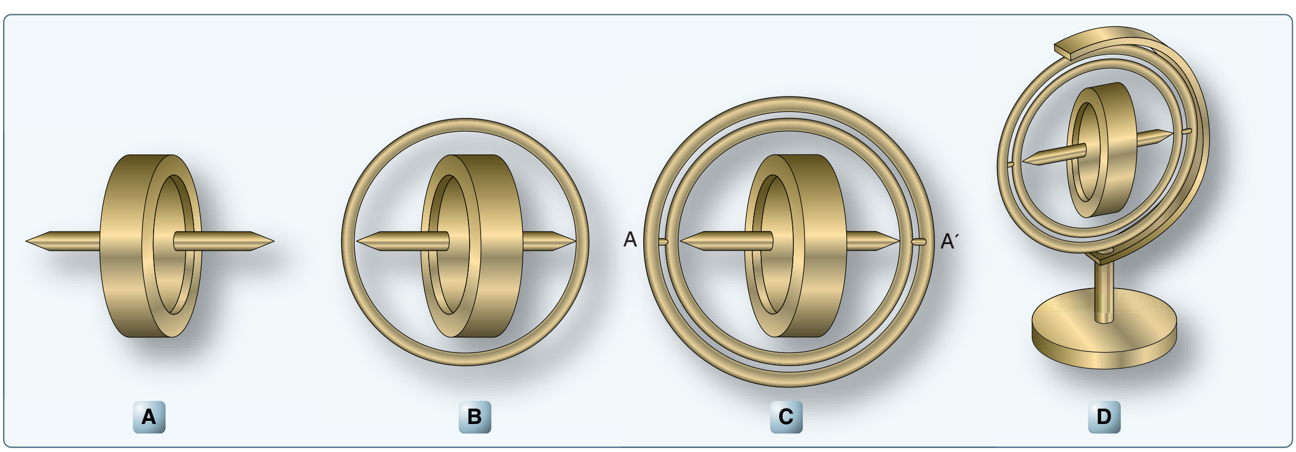


Figure 10-93. *Gyroscopes.*

This characteristic of gyros to remain rigid in space is exploited in the attitude-indicating instruments and the directional indicators that use gyros.

Precession is a second important characteristic of gyroscopes. By applying a force to the horizontal axis of the gyro, a unique phenomenon occurs. The applied force is resisted. Instead of responding to the force by moving about the horizontal axis, the gyro moves in response about its vertical axis. Stated another way, an applied force to the axis of the spinning gyro does not cause the axis to tilt. Rather, the gyro responds as though the force was applied 90° around in the direction of rotation of the gyro rotor. The gyro rotates rather than tilts. *[Figure 10-95]* This predictable controlled precession of a gyroscope is utilized in a turn and bank instrument.

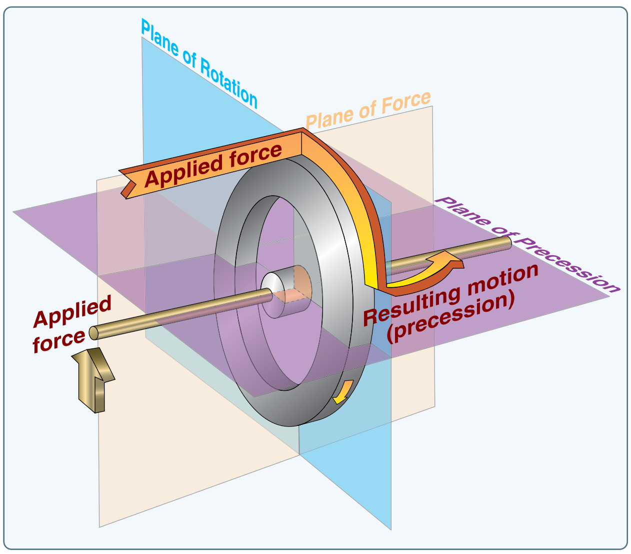


Figure 10-95. *When a force is applied to a spinning gyroscope, it reacts as though the force came from 90° further around the rotor in the direction it is spinning. The plane of the applied force, the plane of the rotation, and the plane in which the gyro responds (known as the plane of precession), are all perpendicular to each other.*

Solid State Gyros and Related Systems

Improved attitude and direction information is always a goal in aviation. Modern aircraft make use of highly accurate solid-state attitude and directional devices with no moving parts. This results in very high reliability and low maintenance.

Ring Laser Gyros (RLG)

The ring laser gyro (RLG) is widely used in commercial aviation. The basis for RLG operation is that it takes time for light to travel around a stationary, nonrotating circular path. Light takes longer to complete the journey if the path is rotating in the same direction as the light is traveling. And, it takes less time for the light to complete the loop if the path is rotating in the direction opposite to that of the light. Essentially, the path is made longer or shorter by the rotation of the path. *[Figure 10-96]* This is known as the Sagnac effect.

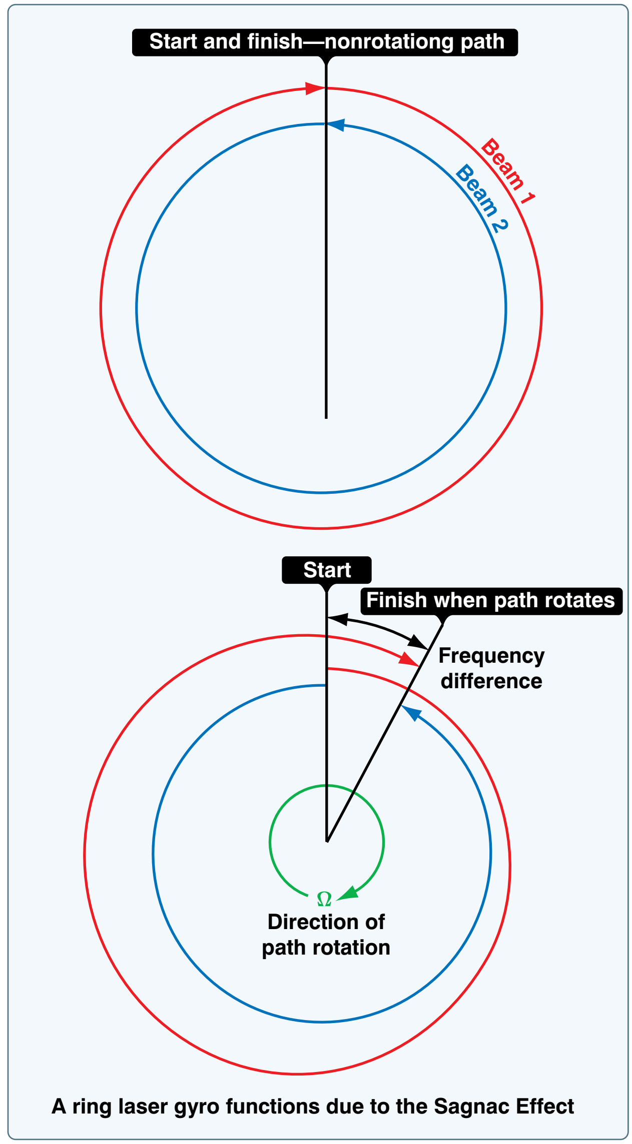


Figure 10-96. *Light traveling in opposite directions around a non-rotating path arrives at the end of the loop at the same time (top). When the path rotates, light traveling with the rotation must travel farther to complete one loop. Light traveling against the rotation completes the loop sooner (bottom).*

A laser is light amplification by stimulated emission of radiation. A laser operates by exciting atoms in plasma to release electromagnetic energy, or photons. A ring laser gyro produces laser beams that travel in opposite directions around a closed triangular cavity. The wavelength of the light traveling around the loop is fixed. As the loop rotates, the path the lasers must travel lengthens or shortens. The light wavelengths compress or expand to complete travel around the loop as the loop changes its effective length. As the wavelengths change, the frequencies also change.

By examining the difference in the frequencies of the two counterrotating beams of light, the rate at which the path is rotating can be measured. A piezoelectric dithering motor in the center of the unit vibrates to prevent lock-in of the output signal at low rotational speeds. It causes units installed on aircraft to hum when operating. *[Figure 10-97]*

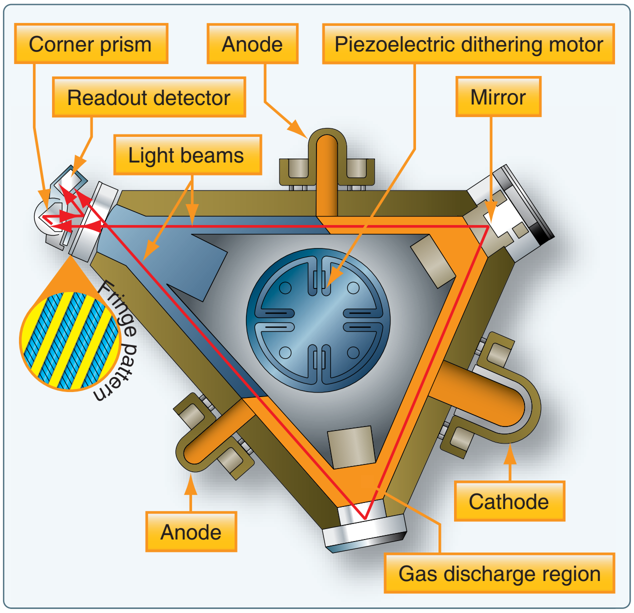


Figure 10-97. *The ring laser gyro is rugged, accurate, and free of friction.*

An RLG is remotely mounted so the cavity path rotates around one of the axes of flight. The rate of frequency phase shift detected between the counterrotating lasers is proportional to the rate that the aircraft is moving about that axis. On aircraft, an RLG is installed for each axis of flight. Output can be used in analog instrumentation and autopilot systems. It is also easily made compatible for use by digital display computers and for digital autopilot computers.

RLGs are very rugged and have a long service life with virtually no maintenance due to their lack of moving parts. They measure movement about an axis extremely quickly and provide continuous output. They are extremely accurate and generally are considered superior to mechanical gyroscopes.

Microelectromechanical Based Attitude and Directional Systems

On aircraft, microelectromechanical systems (MEMS) devices save space and weight. Through the use of solid-state MEMS devices, reliability is increased primarily due to the lack of moving parts. The development of MEMS technology for use in aviation instrumentation integrates with the use of ADCs. This newest improvement in technology is low cost and promises to proliferate through all forms of aviation.

MEMS for gyroscopic applications are used in small, general aviation aircraft, as well as larger commercial aircraft. Tiny vibration-based units with resistance and capacitance measuring pick-offs are accurate and reliable and only a few millimeters in length and width. They are normally integrated into a complete micro-electronic solid-state chip designed to yield an output after various conditioning processes are performed. The chips, which are analogous to tiny circuit boards, can be packaged for installation inside a dedicated computer or module that is installed on the aircraft.

While a large mechanical gyroscope spins in a plane, its rigidity in space is used to observe and measure the movement of the aircraft. The basis of operation of many MEMS gyroscopes is the same despite their tiny size. The difference is that a vibrating or oscillating piezoelectric device replaces the spinning, weighted ring of the mechanical gyro. Still, once set in motion, any out-of-plane motion is detectable by varying microvoltages or capacitances detected through geometrically arranged pickups. Since piezoelectric substances have a relationship between movement and electricity, microelectrical stimulation can set a piezoelectric gyro in motion and the tiny voltages produced via the movement in the piezo can be extracted. They can be input as the required variables needed to compute attitude or direction information. *[Figure 10-98]*

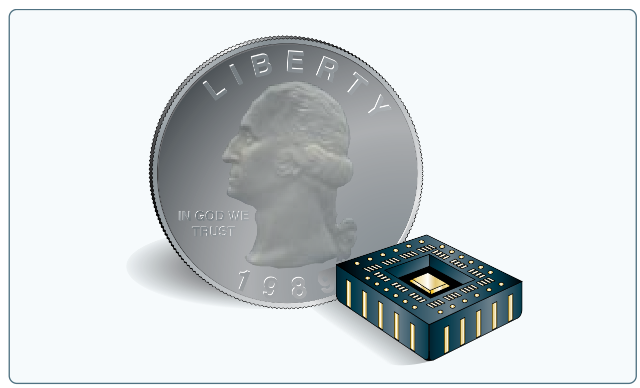


Figure 10-98. *The relative scale size of a MEMS gyro.*

Other Attitude and Directional Systems

In modern aircraft, attitude heading and reference systems (AHRS) have taken the place of the gyroscope and other individual instruments. While MEMS devices provide part of the attitude information for the system, GPS, solid state magnetometers, solid state accelerometers, and digital air data signals are all combined in an AHRS to compute and output highly reliable information for display on a cockpit panel. *[Figure 10-99]*

Figure 10-99. *Instrumentation displayed within a glass cockpit using an attitude heading and reference system (AHRS) computer.*

Common Gyroscopic Instruments

Vacuum-Driven Attitude Gyros

The attitude indicator, or artificial horizon, is one of the most essential flight instruments. It gives the pilot pitch and roll information that is especially important when flying without outside visual references. The attitude indicator operates with a gyroscope rotating in the horizontal plane. Thus, it mimics the actual horizon through its rigidity in space. As the aircraft pitches and rolls in relation to the actual horizon, the gyro gimbals allow the aircraft and instrument housing to pitch and roll around the gyro rotor that remains parallel to the ground. A horizontal representation of the airplane in miniature is fixed to the instrument housing. A painted semisphere simulating the horizon, the sky, and the ground is attached to the gyro gimbals. The sky and ground meet at what is called the horizon bar. The relationship between the horizon bar and the miniature airplane are the same as those of the aircraft and the actual horizon. Graduated scales reference the degrees of pitch and roll. Often, an adjustment knob allows pilots of varying heights to place the horizon bar at an appropriate level. *[Figure 10-100]*

In a typical vacuum-driven attitude gyro system, air is sucked through a filter and then through the attitude indicator in a manner that spins the gyro rotor inside. An erecting mechanism is built into the instrument to assist in keeping the gyro rotor rotating in the intended plane. Precession caused by bearing friction makes this necessary. After air engages the scalloped drive on the rotor, it flows from the instrument to the vacuum pump through four ports. These ports all exhaust the same amount of air when the gyro is rotating in plane. When the gyro rotates out of plane, air tends to port out of one side more than another. Vanes close to prevent this, causing more air to flow out of the opposite side. The force from this unequal venting of the air re-erects the gyro rotor. *[Figure 10-101]*

Early vacuum-driven attitude indicators were limited in how far the aircraft could pitch or roll before the gyro gimbals contacted stops, causing abrupt precession and tumbling of the gyro. Many of these gyros include a caging device. It is used to erect the rotor to its normal operating position prior to flight or after tumbling. A flag indicates that the gyro must be uncaged before use. More modern gyroscopic instruments are built so they do not tumble, regardless of the angular movement of the aircraft about its axes.

In addition to the contamination potential introduced by the air-drive system, other shortcomings exist in the performance of vacuum-driven attitude indicators. Some are induced by the erection mechanism. The pendulous vanes that move to direct airflow out of the gyro respond not only to forces caused by a deviation from the intended plane of rotation, but centrifugal force experienced during turns also causes the vanes to allow asymmetric porting of the gyro vacuum air. The result is inaccurate display of the aircraft's attitude, especially in skids and steep banked turns. Also, abrupt acceleration and deceleration imposes forces on the gyro rotor. Suspended in its gimbals, it acts similar to an accelerometer, resulting in a false nose-up or nose-down indication. Pilots must learn to recognize these errors and adjust accordingly.

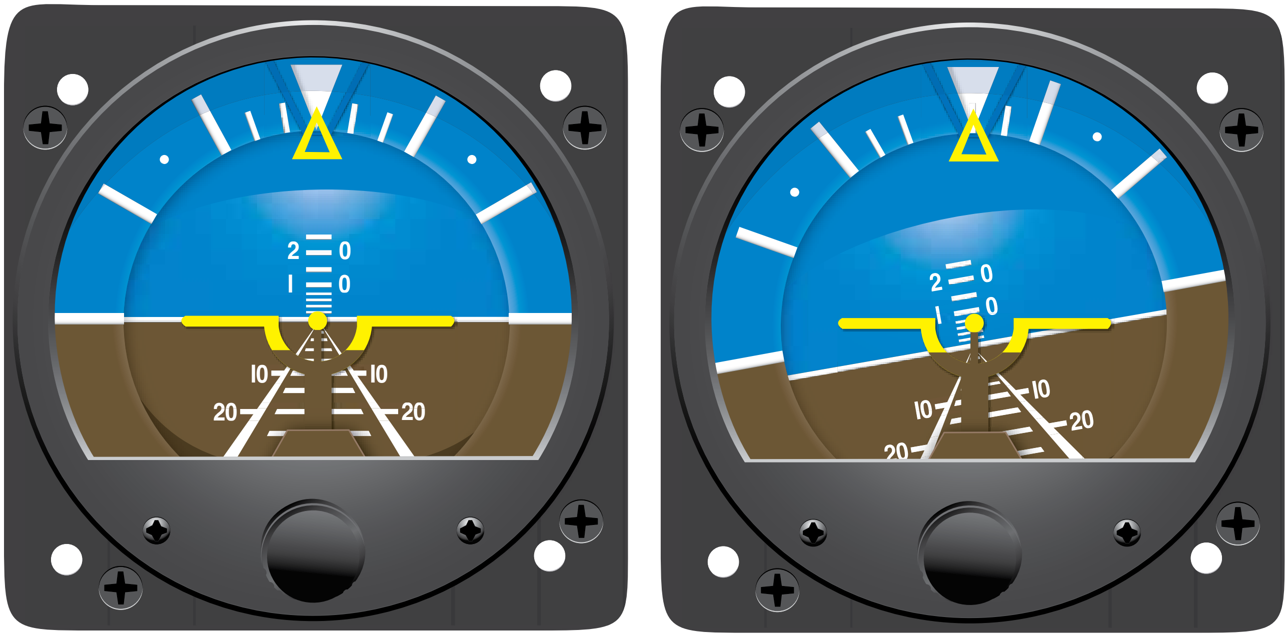


Figure 10-100. *A typical vacuum-driven attitude indicator shown with the aircraft in level flight (left) and in a climbing right turn (right).*

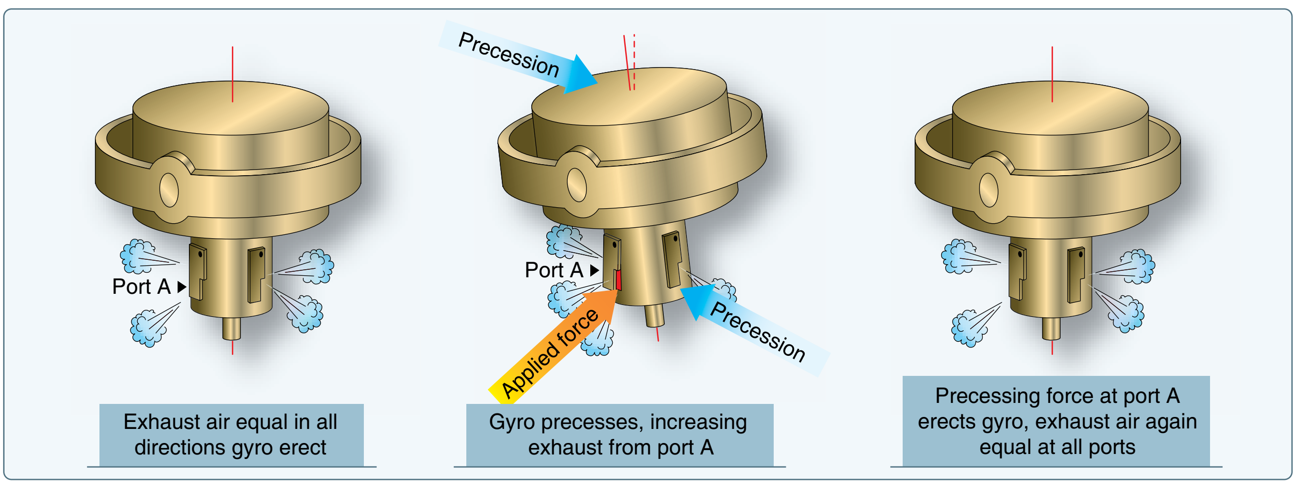


Figure 10-101. *The erecting mechanism of a vacuum-driven attitude indicator.*

Electric Attitude Indicators

Electric attitude indicators are very similar to vacuum-driven gyro indicators. The main difference is in the drive mechanism. Inside the gimbals of an electric gyro, a small squirrel cage electric motor is the rotor. It is typically driven by 115-volt, 400-cycle AC. It turns at approximately 21,000 rpm.

Other characteristics of the vacuum-driven gyro are shared by the electric gyro. The rotor is still oriented in the horizontal plane. The free gyro gimbals allow the aircraft and instrument case to rotate around the gyro rotor that remains rigid in space. A miniature airplane fixed to the instrument case indicates the aircraft's attitude against the moving horizon bar behind it.

Electric attitude indicators address some of the shortcomings of vacuum-driven attitude indicators. Since there is no air flowing through an electric attitude indicator, air filters, regulators, plumbing lines and vacuum pump(s) are not needed. Contamination from dirt in the air is not an issue, resulting in the potential for longer bearing life and less precession. Erection mechanism ports are not employed, so pendulous vanes responsive to centrifugal forces are eliminated.

It is still possible that the gyro may experience precession and need to be erected. This is done with magnets rather than vent ports. A magnet attached to the top of the gyro shaft spins at approximately 21,000 rpm. Around this magnet, but not attached to it, is a sleeve that is rotated by magnetic attraction at approximately 44 to 48 rpm. Steel balls are free to move around the sleeve. If the pull of gravity is not aligned with the axis of the gyro, the balls fall to the low side. The resulting precession re-aligns the axis of rotation vertically.

Typically, electric attitude indicator gyros can be caged manually by a lever and cam mechanism to provide rapid erection. When the instrument is not getting sufficient power for normal operation, an off flag appears in the upper right hand face of the instrument. *[Figure 10-102]*

Gyroscopic Direction Indicator or Directional Gyro (DG)

The gyroscopic direction indicator or directional gyro (DG) is often the primary instrument for direction. Because a magnetic compass fluctuates so much, a gyro aligned with the magnetic compass gives a much more stable heading indication. Gyroscopic direction indicators are located at the center base of the instrument panel basic T.

A vacuum-powered DG is common on many light aircraft. Its basis for operation is the gyro's rigidity in space. The gyro rotor spins in the vertical plane and stays aligned with the direction to which it is set. The aircraft and instrument case moves around the rigid gyro. This causes a vertical compass card that is geared to the rotor gimbal to move. It is calibrated in degrees, usually with every 30 degrees labeled. The nose of a small, fixed airplane on the instrument glass indicates the aircraft's heading. *[Figure 10-103]*

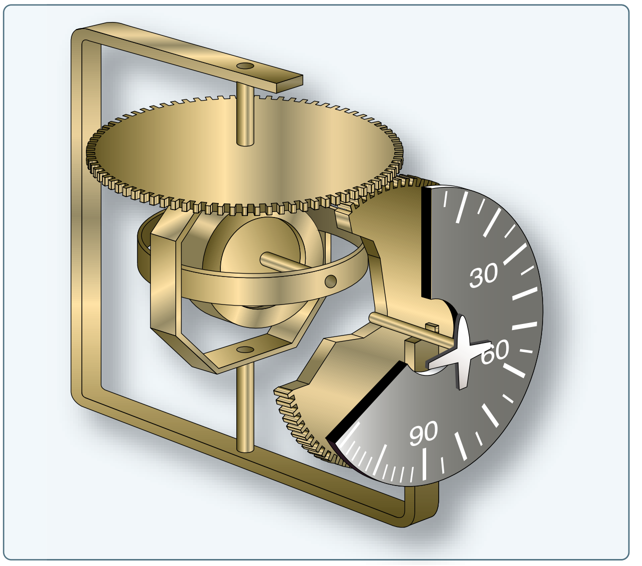


Figure 10-103. *A typical vacuum-powered gyroscopic direction indicator, also known as a directional gyro.*

Vacuum-driven direction indicators have many of the same basic gyroscopic instrument issues as attitude indicators. Built-in compensation for precession varies and a caging device is usually found. Periodic manual realignment with the magnetic compass by the pilot is required during flight.

Turn Coordinators

Many aircraft make use of a turn coordinator. The rotor of the gyro in a turn coordinator is canted upwards 30°. As such, it responds not only to movement about the vertical axis, but also to roll movements about the longitudinal axis. This is useful because it is necessary to roll an aircraft to turn it about the vertical axis. Instrument indication of roll, therefore, is the earliest possible warning of a departure from straight-and-level flight.

Typically, the face of the turn coordinator has a small airplane symbol. The wing tips of the airplane provide the indication of level flight and the rate at which the aircraft is turning. *[Figure 10-104]*

Turn-and-Slip Indicator

The turn-and-slip indicator may also be referred to as the turn-and-bank indicator, or needle-and-ball indicator. Regardless, it shows the correct execution of a turn while banking the aircraft and indicates movement about the vertical axis of the aircraft (yaw). Most turn-and-slip indicators are located below the airspeed indicator of the instrument panel basic T, just to the left of the direction indicator.

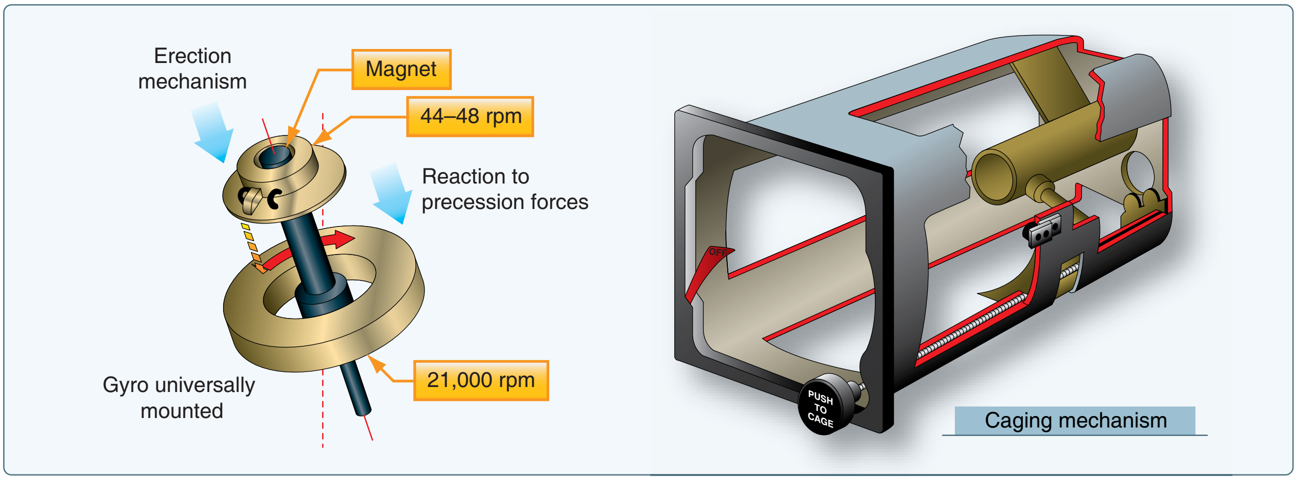


Figure 10-102. *Erecting and caging mechanisms of an electric attitude indicator.*

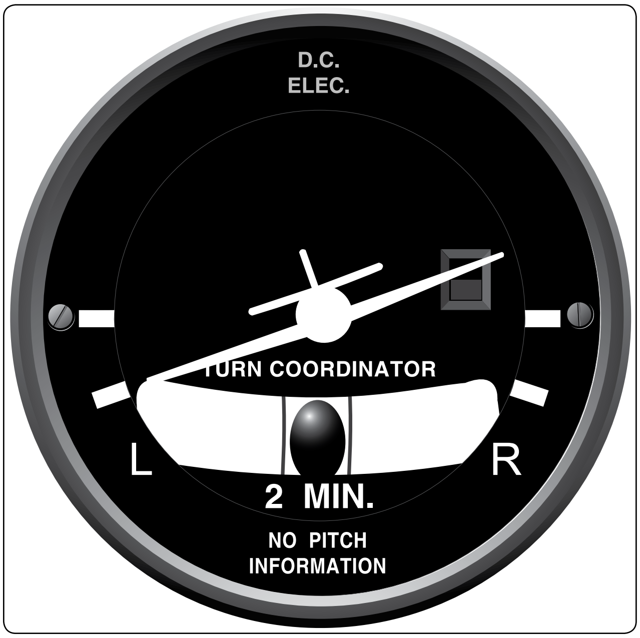


Figure 10-104. *A turn coordinator senses and indicates the rate of both roll and yaw.*

The turn-and-slip indicator is actually two separate devices built into the same instrument housing: a turn indicator pointer and slip indicator ball. The turn pointer is operated by a gyro that can be driven by a vacuum, air pressure, or by electricity. The ball is a completely independent device. It is a round agate, or steel ball, in a glass tube filled with dampening fluid. It moves in response to gravity and centrifugal force experienced in a turn.

Turn indicators vary. They all indicate the rate at which the aircraft is turning. Three degrees of turn per second cause an aircraft to turn 360° in 2 minutes. This is considered a standard turn. This rate can be indicated with marks right and left of the pointer, which normally rests in the vertical position. Sometimes, no marks are present and the width of the pointer is used as the calibration device. In this case, one pointer width deflection from vertical is equal to the 3° per second standard 2-minute turn rate. Faster aircraft tend to turn more slowly and have graduations or labels that indicate 4-minute turns. In other words, a pointer's width or alignment with a graduation mark on this instrument indicates that the aircraft is turning a 1½° per second and completes a 360° turn in 4 minutes. It is customary to placard the instrument face with words indicating whether it is a 2-or 4-minute turn indicator. *[Figure 10-105]*

The turn pointer indicates the rate at which an aircraft is turning about its vertical axis. It does so by using the precession of a gyro to tilt a pointer. The gyro spins in a vertical plane aligned with the longitudinal axis of the aircraft. When the aircraft rotates about its vertical axis during a turn,

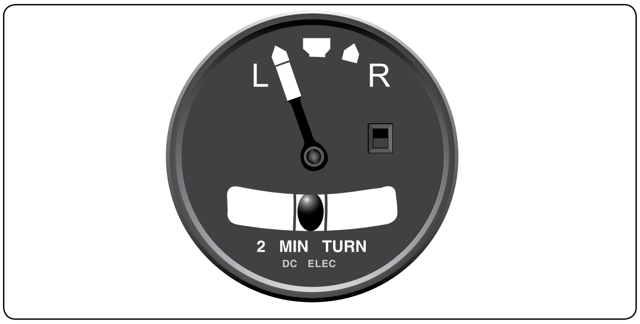


Figure 10-105. *Turn-and-slip indicator.*

the force experienced by the spinning gyro is exerted about the vertical axis. Due to precession, the reaction of the gyro rotor is 90° further around the gyro in the direction of spin. This means the reaction to the force around the vertical axis is movement around the longitudinal axis of the aircraft. This causes the top of the rotor to tilt to the left or right. The pointer is attached with linkage that makes the pointer deflect in the opposite direction, which matches the direction of turn. So, the aircraft's turn around the vertical axis is indicated around the longitudinal axis on the gauge. This is intuitive to the pilot when regarding the instrument, since the pointer indicates in the same direction as the turn. *[Figure 10-106]*

The slip indicator (ball) part of the instrument is an inclinometer. The ball responds only to gravity during coordinated straight-and-level flight. Thus, it rests in the lowest part of the curved glass between the reference wires. When a turn is initiated and the aircraft is banked, both gravity and the centrifugal force of the turn act upon the ball. If the turn is coordinated, the ball remains in place. Should a skidding turn exist, the centrifugal force exceeds the force of gravity on the ball and it moves in the direction of the outside of the turn. During a slipping turn, there is more bank than needed, and gravity is greater than the centrifugal force acting on the ball. The ball moves in the curved glass toward the inside of the turn.

As mentioned previously, often power for the turn-and-slip indicator gyro is electrical if the attitude and direction indicators are vacuum powered. This allows limited operation off battery power should the vacuum system and the electric generator fail. The directional and attitude information from the turn-and-slip indicator, combined with information from the pitot static instruments, allow continued safe emergency operation of the aircraft.

Electrically powered turn-and-slip indicators are usually DC powered. Vacuum-powered turn-and-slip indicators are usually run on less vacuum (approximately 2 "Hg) than fully gimbaled attitude and direction indicators. Regardless, proper vacuum must be maintained for accurate turn rate information to be displayed.

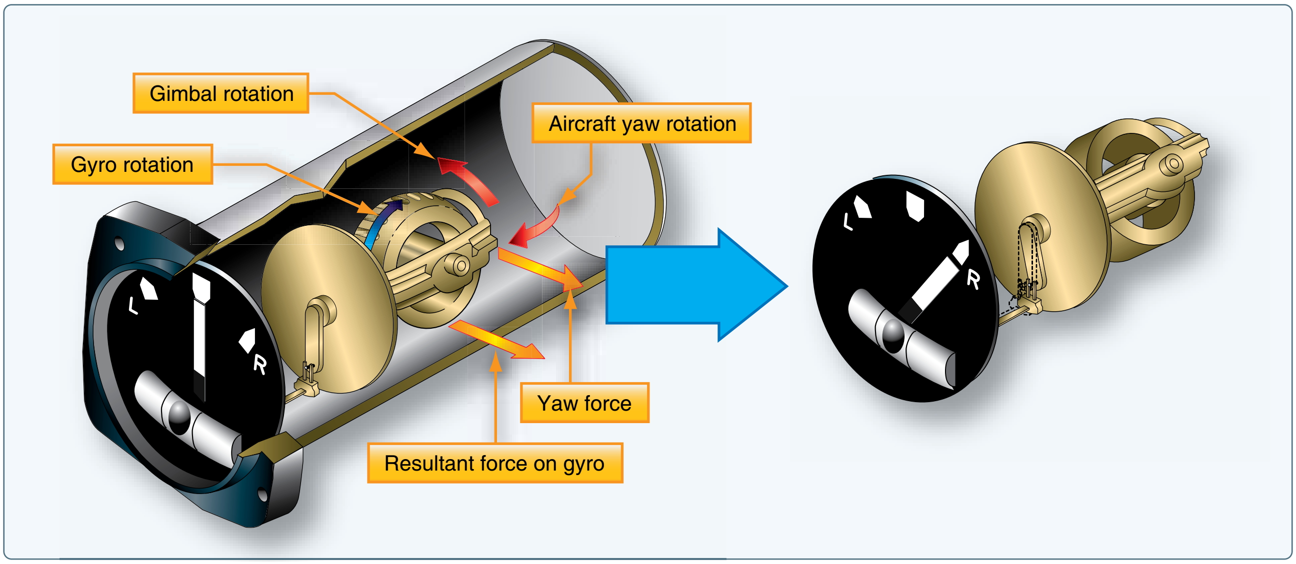


Figure 10-106. *The turn-and-slip indicator's gyro reaction to the turning force in a right hand turn. The yaw force results in a force on the gyro 90° around the rotor in the direction it is turning due to precession. This causes the top of the rotor to tilt to the left. Through connecting linkage, the pointer tilts to the right.*

Autopilot Systems

An aircraft automatic pilot system controls the aircraft without the pilot directly maneuvering the controls. The autopilot maintains the aircraft's attitude and/or direction and returns the aircraft to that condition when it is displaced from it. Automatic pilot systems are capable of keeping aircraft stabilized laterally, vertically, and longitudinally.

The primary purpose of an autopilot system is to reduce the work strain and fatigue of controlling the aircraft during long flights. Most autopilots have both manual and automatic modes of operation. In the manual mode, the pilot selects each maneuver and makes small inputs into an autopilot controller. The autopilot system moves the control surfaces of the aircraft to perform the maneuver. In automatic mode, the pilot selects the attitude and direction desired for a flight segment. The autopilot then moves the control surfaces to attain and maintain these parameters.

Autopilot systems provide for one-, two-, or three-axis control of an aircraft. Those that manage the aircraft around only one axis control the ailerons. They are single-axis autopilots, known as wing leveler systems, usually found on light aircraft. *[Figure 10-107]* Other autopilots are two-axis systems that control the ailerons and elevators. Three-axis autopilots control the ailerons, elevators, and the rudder. Two-and three-axis autopilot systems can be found on aircraft of all sizes.

There are many autopilot systems available. They feature a wide range of capabilities and complexity. Light aircraft typically have autopilots with fewer capabilities than high-performance and transport category aircraft. Integration of navigation functions is common, even on light aircraft autopilots. As autopilots increase in complexity, they not only manipulate the flight control surfaces, but other flight parameters as well.

Some modern small aircraft, high-performance, and transport category aircraft have very elaborate autopilot systems known as automatic flight control systems (AFCS). These three-axis systems go far beyond steering the airplane. They control the aircraft during climbs, descents, cruise, and approach to landing. Some even integrate an auto-throttle function that automatically controls engine thrust that makes auto-landings possible.

For further automatic control, flight management systems have been developed. Through the use of computers, an entire flight profile can be programmed ahead of time allowing the pilot to supervise its execution. An FMS computer coordinates nearly every aspect of a flight, including the autopilot and auto throttle systems, navigation route selection, fuel management schemes, and more.

Basis for Autopilot Operation

The basis for autopilot system operation is error correction. When an aircraft fails to meet the conditions selected, an error is said to have occurred. The autopilot system automatically corrects that error and restores the aircraft to the flight attitude desired by the pilot. There are two basic ways modern autopilot systems do this. One is position based and the other is rate based. A position based autopilot manipulates the aircraft's controls so that any deviation from the desired attitude of the aircraft is corrected. This is done by memorizing

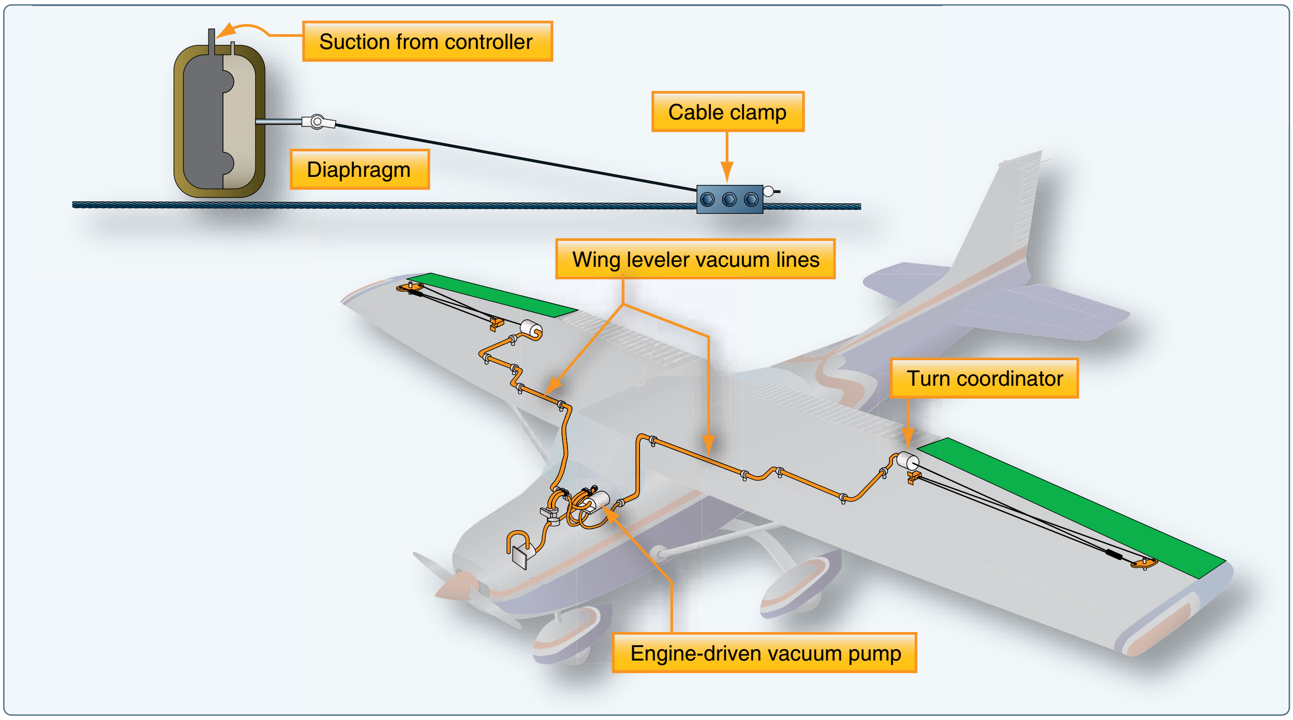


Figure 10-107. *The wing leveler system on a small aircraft is a vacuum-operated single-axis autopilot. Only the ailerons are controlled. The aircraft's turn coordinator is the sensing element. Vacuum from the instrument vacuum system is metered to the diaphragm cable actuators to move the ailerons when the turn coordinator senses roll.*

the desired aircraft attitude and moving the control surfaces so that the aircraft returns to that attitude. Rate based autopilots use information about the rate of movement of the aircraft, and move control surfaces to counter the rate of change that causes the error. Most large aircraft use rate-based autopilot systems. Small aircraft may use either.

Autopilot Components

Most autopilot systems consist of four basic components, plus various switches and auxiliary units. The four basic components are: sensing elements, computing element, output elements, and command elements. Many advanced autopilot systems contain a fifth element: feedback or follow-up. This refers to signals sent as corrections are being made by the output elements to advise the autopilot of the progress being made. *[Figure 10-108]*

Sensing Elements

The attitude and directional gyros, the turn coordinator, and an altitude control are the autopilot sensing elements. These units sense the movements of the aircraft. They generate electric signals that are used by the autopilot to automatically take the required corrective action needed to keep the aircraft flying as intended. The sensing gyros can be located in the cockpit mounted instruments. They can also be remotely mounted. Remote gyro sensors drive the servo displays in the cockpit panel, as well as provide the input signals to the autopilot computer.

Modern digital autopilots may use a variety of different sensors. MEMS gyros may be used or accompanied by the use solid state accelerometers and magnetometers. Rate based systems may not use gyros at all. Various input sensors may be located within the same unit or in separate units that transfer information via digital data bus. Navigation information is also integrated via digital data bus connection to avionics computers.

Computer and Amplifier

The computing element of an autopilot may be analog or digital. Its function is to interpret the sensing element data, integrate commands and navigational input, and send signals to the output elements to move the flight controls as required to control the aircraft. An amplifier is used to strengthen the signal for processing, if needed, and for use by the output devices, such as servo motors. The amplifier and associated circuitry is the computer of an analog autopilot system. Information is handled in channels corresponding to the axis of control for which the signals are intended (i.e., pitch channel, roll channel, or yaw channel). Digital systems use solid state microprocessor computer technology and typically only amplify signals sent to the output elements.

Output Elements

The output elements of an autopilot system are the servos that cause actuation of the flight control surfaces. They are independent devices for each of the control channels that

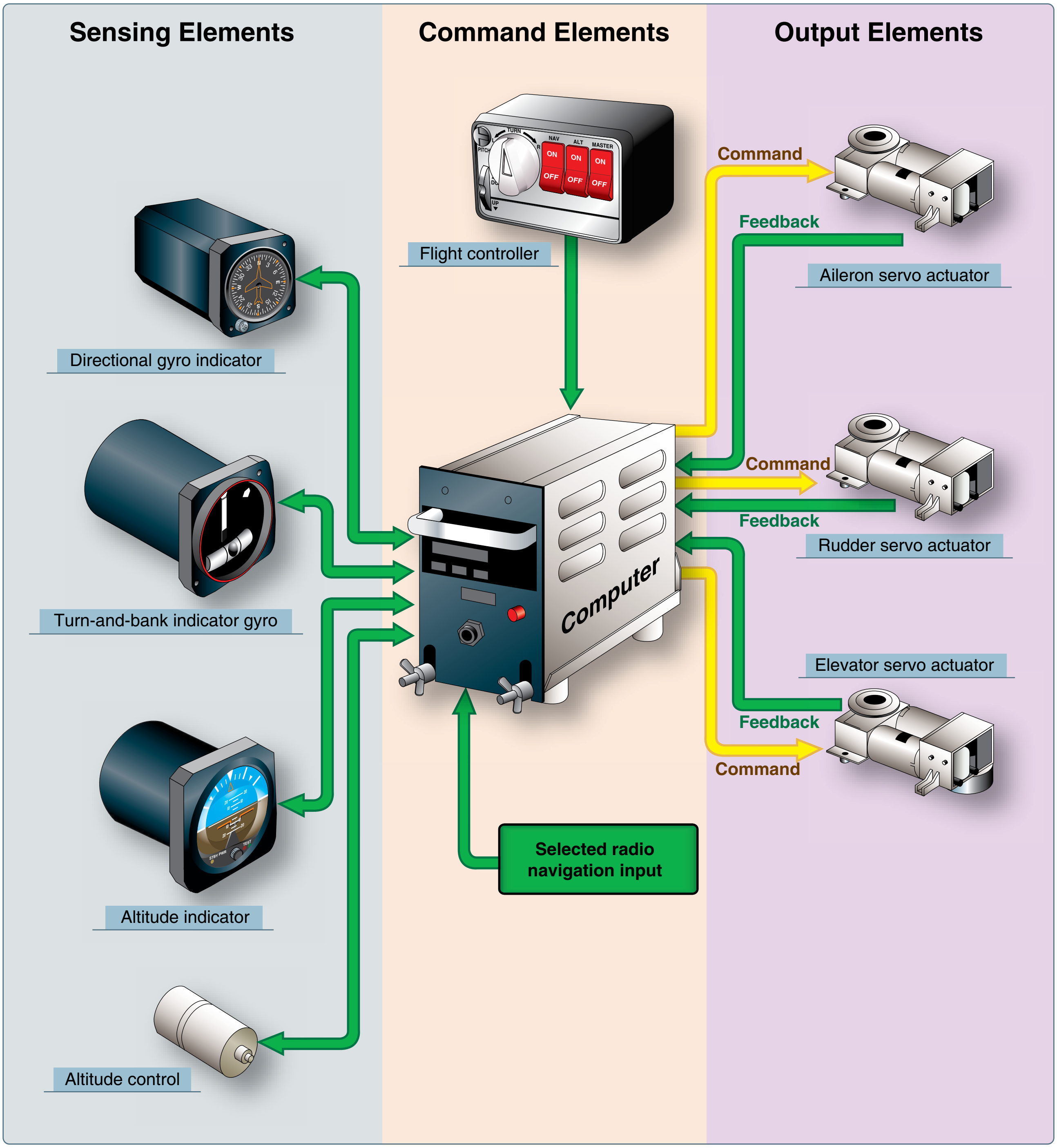


Figure 10-108. *Typical analog autopilot system components.*

integrate into the regular flight control system. Autopilot servo designs vary widely depending on the method of actuation of the flight controls. Cable-actuated systems typically utilize electric servo motors or electro-pneumatic servos. Hydraulic actuated flight control systems use electro-hydraulic autopilot servos. Digital fly-by-wire aircraft utilize the same actuators for carrying out manual and autopilot maneuvers. When the autopilot is engaged, the actuators respond to commands from the autopilot rather than exclusively from the pilot. Regardless, autopilot servos must allow unimpeded control surface movement when the autopilot is not operating.

Aircraft with cable actuated control surfaces use two basic types of electric motor-operated servos. In one, a motor is connected to the servo output shaft through reduction gears. The motor starts, stops, and reverses direction in response to the commands of autopilot computer. The other type of electric servo uses a constantly running motor geared to the output shaft through two magnetic clutches. The clutches are arranged so that energizing one clutch transmits motor torque to turn the output shaft in one direction; energizing the other clutch turns the shaft in the opposite direction. *[Figure 10-109]* Electropneumatic servos can also be used to drive cable flight controls in some autopilot systems. They are controlled by electrical signals from the autopilot amplifier and actuated by an appropriate air pressure source. The source may be a vacuum system pump or turbine engine bleed air. Each servo consists of an electromagnetic valve assembly and an output linkage assembly.

Aircraft with hydraulically actuated flight control systems have autopilot servos that are electro-hydraulic. They are control valves that direct fluid pressure as needed to move the control surfaces via the control surface actuators. They are powered by signals from the autopilot computer. When the autopilot is not engaged, the servos allow hydraulic fluid to flow unrestricted in the flight control system for normal operation. The servo valves can incorporate feedback transducers to update the autopilot of progress during error correction.

Command Elements

The command unit, called a flight controller, is the human interface of the autopilot. It allows the pilot to tell the autopilot what to do. Flight controllers vary with the complexity of the autopilot system. By pressing the desired function buttons, the pilot causes the controller to send instruction signals to the autopilot computer, enabling it to activate the proper servos to carry out the command(s). Level flight, climbs, descents, turning to a heading, or flying a desired heading are some of the choices available on most autopilots. Many aircraft make use of a multitude of radio navigational aids. These can be selected to issue commands directly to the autopilot computer. *[Figure 10-110]*

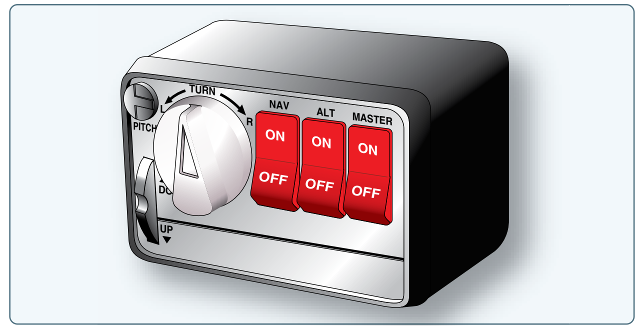


Figure 10-110. *An autopilot controller of a simple autopilot system.*

In addition to an on/off switch on the autopilot controller, most autopilots have a disconnect switch located on the control wheel(s). This switch, operated by thumb pressure, can be used to disengage the autopilot system should a malfunction occur in the system or any time the pilot wishes to take manual control of the aircraft.

Feedback or Follow-up Element

As an autopilot maneuvers the flight controls to attain a desired flight attitude, it must reduce control surface correction as the desired attitude is nearly attained so the controls and aircraft come to rest on course. Without doing so, the system would continuously overcorrect. Surface deflection would occur until the desired attitude is attained. But movement would still occur as the surface(s) returned to pre-error position. The attitude sensor would once again detect an error and begin the correction process all over again.

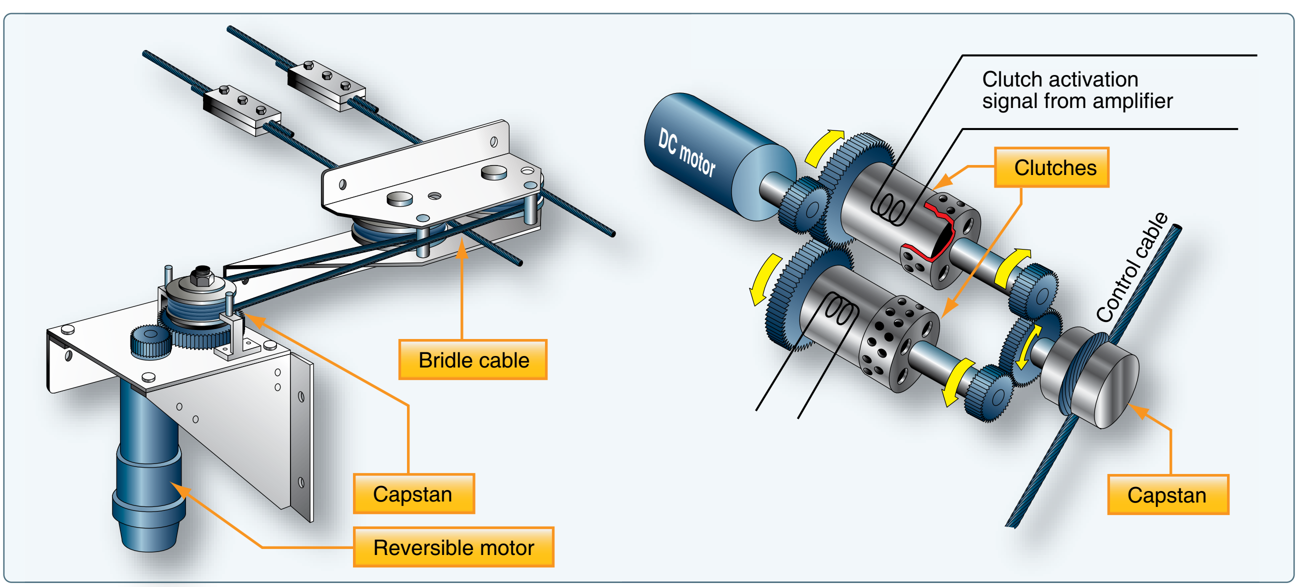


Figure 10-109. *A reversible motor with capstan and bridle cable (left), and a single-direction constant motor with clutches that drive the output shafts and control cable in opposite directions (right).*

Various electric feedback, or follow-up signals, are generated to progressively reduce the error message in the autopilot so that continuous over correction does not take place. This is typically done with transducers on the surface actuators or in the autopilot servo units. Feedback completes a loop as illustrated in *Figure 10-111*.

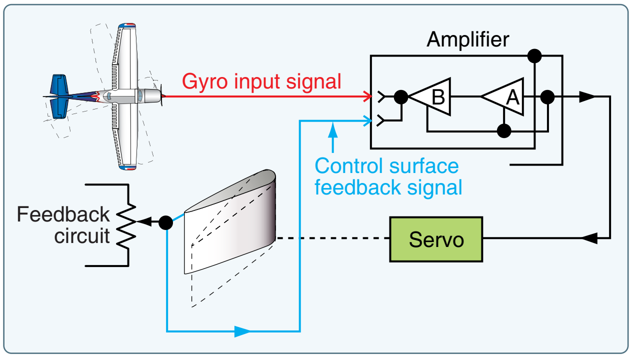


Figure 10-111. *Basic function of an analog autopilot system including follow-up or feedback signal.*

A rate system receives error signals from a rate gyro that are of a certain polarity and magnitude that cause the control surfaces to be moved. As the control surfaces counteract the error and move to correct it, follow-up signals of opposite polarity and increasing magnitude counter the error signal until the aircraft's correct attitude is restored. A displacement follow-up system uses control surface pickups to cancel the error message when the surface has been moved to the correct position.

Autopilot Functions

The following autopilot system description is presented to show the function of a simple analog autopilot. Most autopilots are far more sophisticated; however, many of the operating fundamentals are similar.

The automatic pilot system flies the aircraft by using electrical signals developed in gyro-sensing units. These units are connected to flight instruments that indicate direction, rate of turn, bank, or pitch. If the flight attitude or magnetic heading is changed, electrical signals are developed in the gyros. These signals are sent to the autopilot computer/amplifier and are used to control the operation of servo units.

A servo for each of the three control channels converts electrical signals into mechanical force, which moves the control surface in response to corrective signals or pilot commands. The rudder channel receives two signals that determine when and how much the rudder moves. The first signal is a course signal derived from a compass system. As long as the aircraft remains on the magnetic heading it was on when the autopilot was engaged, no signal develops. But, any deviation causes the compass system to send a signal to the rudder channel that is proportional to the angular displacement of the aircraft from the preset heading.

The second signal received by the rudder channel is the rate signal that provides information anytime the aircraft is turning about the vertical axis. This information is provided by the turn-and-bank indicator gyro. When the aircraft attempts to turn off course, the rate gyro develops a signal proportional to the rate of turn, and the course gyro develops a signal proportional to the amount of displacement. The two signals are sent to the rudder channel of the amplifier, where they are combined and their strength is increased. The amplified signal is then sent to the rudder servo. The servo turns the rudder in the proper direction to return the aircraft to the selected magnetic heading.

As the rudder surface moves, a follow-up signal is developed that opposes the input signal. When the two signals are equal in magnitude, the servo stops moving. As the aircraft arrives on course, the course signal reaches a zero value, and the rudder is returned to the streamline position by the follow-up signal.

The aileron channel receives its input signal from a transmitter located in the gyro horizon indicator. Any movement of the aircraft about its longitudinal axis causes the gyro-sensing unit to develop a signal to correct for the movement. This signal is amplified, phase detected, and sent to the aileron servo, which moves the aileron control surfaces to correct for the error. As the aileron surfaces move, a follow-up signal builds up in opposition to the input signal. When the two signals are equal in magnitude, the servo stops moving. Since the ailerons are displaced from the streamline, the aircraft now starts moving back toward level flight with the input signal becoming smaller and the follow-up signal driving the control surfaces back toward the streamline position. When the aircraft has returned to level flight roll attitude, the input signal is again zero. At the same time, the control surfaces are streamlined, and the follow-up signal is zero.

The elevator channel circuits are similar to those of the aileron channel, with the exception that the elevator channel detects and corrects changes in pitch attitude of the aircraft. For altitude control, a remotely mounted unit containing an altitude pressure diaphragm is used. Similar to the attitude and directional gyros, the altitude unit generates error signals when the aircraft has moved from a preselected altitude. This is known as an altitude hold function. The signals control the pitch servos, which move to correct the error. An altitude select function causes the signals to continuously be sent to the pitch servos until a preselected altitude has been reached. The aircraft then maintains the preselected altitude using altitude hold signals.

Yaw Dampening

Many aircraft have a tendency to oscillate around their vertical axis while flying a fixed heading. Near continuous rudder input is needed to counteract this effect. A yaw damper is used to correct this motion. It can be part of an autopilot system or a completely independent unit. A yaw damper receives error signals from the turn coordinator rate gyro. Oscillating yaw motion is counteracted by rudder movement, which is made automatically by the rudder servo(s) in response to the polarity and magnitude of the error signal.

Automatic Flight Control System (AFCS)

An aircraft autopilot with many features and various autopilot related systems integrated into a single system is called an automatic flight control system (AFCS). These were formerly found only on high-performance aircraft. Currently, due to advances in digital technology for aircraft, modern aircraft of any size may have AFCS.

AFCS capabilities vary from system to system. Some of the advances beyond ordinary autopilot systems are the extent of programmability, the level of integration of navigational aids, the integration of flight director and autothrottle systems, and combining of the command elements of these various systems into a single integrated flight control human interface. *[Figure 10-112]*

It is at the AFCS level of integration that an autothrottle system is integrated into the flight director and autopilot systems with glide scope modes so that auto landings are possible. Small general aviation aircraft being produced with AFCS may lack the throttle-dependent features.

Modern general aviation AFCS are fully integrated with digital attitude heading and reference systems (AHRS) and navigational aids including glideslope. They also contain modern computer architecture for the autopilot (and flight director systems) that is slightly different than described above for analog autopilot systems. Functionality is distributed across a number of interrelated computers and includes the use of intelligent servos that handle some of the error correction calculations. The servos communicate with dedicated avionics computers and display unit computers through a control panel, while no central autopilot computer exists. *[Figure 10-113]*

Flight Director Systems

A flight director system is an instrument system consisting of electronic components that compute and indicate the aircraft attitude required to attain and maintain a preselected flight condition. A command bar on the aircraft's attitude indicator shows the pilot how much and in what direction the attitude of the aircraft must be changed to achieve the desired result. The computed command indications relieve the pilot of many of the mental calculations required for instrument flights, such as interception angles, wind drift correction, and rates of climb and descent.

Essentially, a flight director system is an autopilot system without the servos. All of the same sensing and computations are made, but the pilot controls the airplane and makes maneuvers by following the commands displayed on the instrument panel. Flight director systems can be part of an autopilot system or exist on aircraft that do not possess full autopilot systems. Many autopilot systems allow for the option of engaging or disengaging a flight director display.

Flight director information is displayed on the instrument that displays the aircraft's attitude. The process is accomplished with a visual reference technique. A symbol representing the aircraft is fit into a command bar positioned by the flight director in the proper location for a maneuver to be accomplished. The symbols used to represent the aircraft and the command bar vary by manufacturer. Regardless, the object is always to fly the aircraft symbol into the command bar symbol. *[Figure 10-114]*

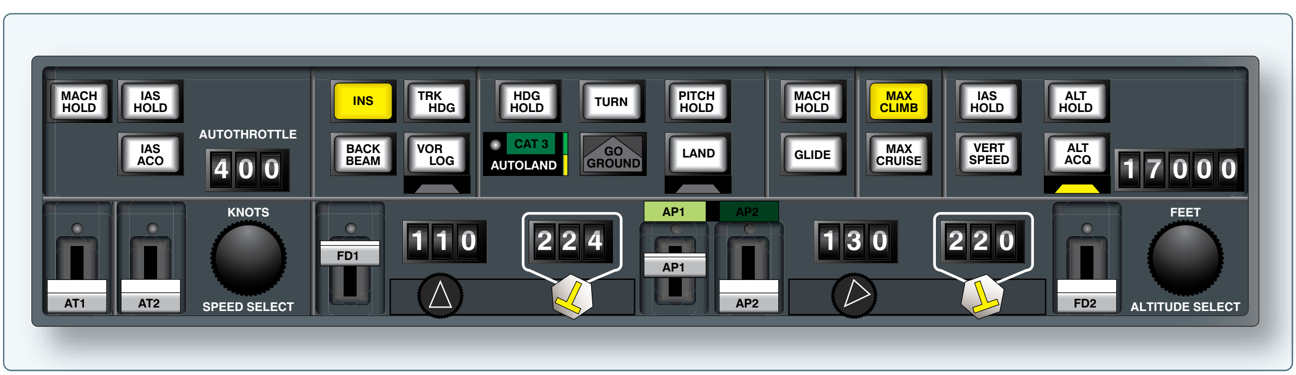


Figure 10-112. *The AFCS control panel commands several integrated systems from a single panel including: flight directors, autopilots, autothrottles, autoland, and navigational aids. Mode selections for many features are made from this single interface.*

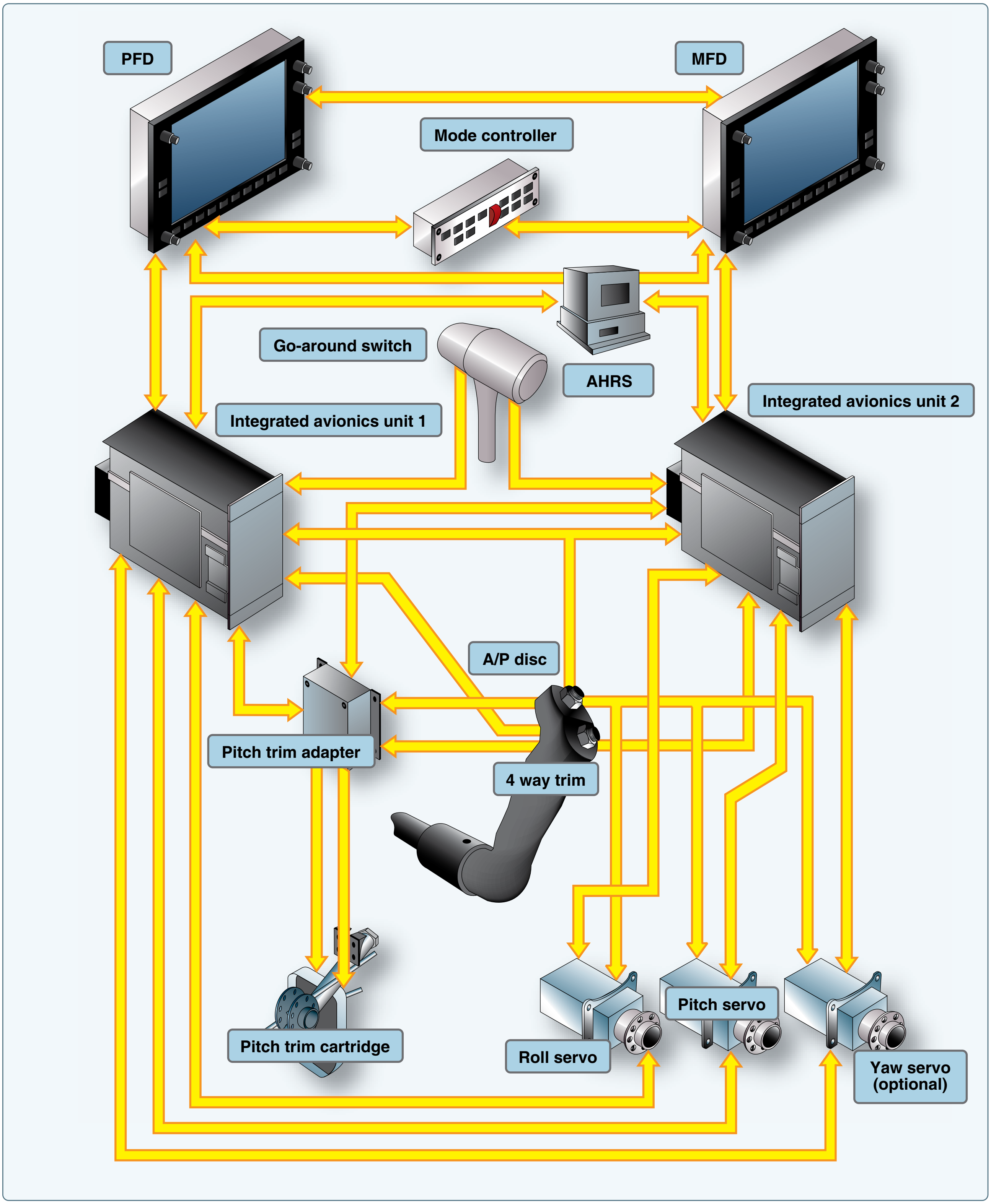


Figure 10-113. *Automatic flight control system (AFCS) of a Garmin G1000 glass cockpit instrument system for a general aviation aircraft.*

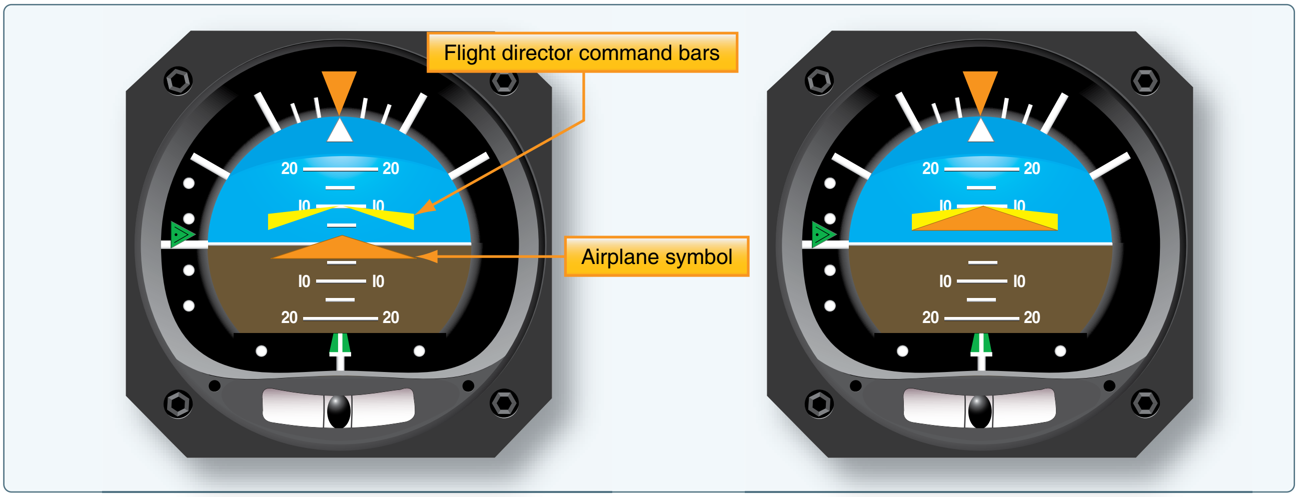


Figure 10-114. *The fight director command bar signals the pilot how to steer the aircraft for a maneuver. By flying the aircraft so the triangular airplane symbol fits into the command bar, the pilot performs the maneuver calculated by the flight director. The instrument shown on the left is commanding a climb while the airplane is flying straight and level. The instrument on the right shows that the pilot has accomplished the maneuver.*

The instrument that displays the flight director commands is known as a flight director indicator (FDI), attitude director indicator (ADI), or electronic attitude director indicator (EADI). It may even be referred to as an artificial horizon with flight director. This display element combines with the other primary components of the flight director system. Like an autopilot, these consist of the sensing elements, a computer, and an interface panel.

Integration of navigation features into the attitude indicator is highly useful. The flight director contributes to this usefulness by indicating to the pilot how to maneuver the airplane to navigate a desired course. Selection of the VOR function on the flight director control panel links the computer to the omnirange receiver. The pilot selects a desired course and the flight director displays the bank attitude necessary to intercept and maintain this course. Allocations for wind drift and calculation of the intercept angle is performed automatically.

Flight director systems vary in complexity and features. Many have altitude hold, altitude select, pitch hold, and other features. But flight director systems are designed to offer the greatest assistance during the instrument approach phase of flight. ILS localizer and glideslope signals are transmitted through the receivers to the computer and are presented as command indications. This allows the pilot to fly the airplane down the optimum approach path to the runway using the flight director system.

With the altitude hold function engaged, level flight can be maintained during the maneuvering and procedure turn phase of an approach. Altitude hold automatically disengages when the glideslope is intercepted. Once inbound on the localizer, the command signals of the flight director are maintained in a centered or zero condition. Interception of the glideslope causes a downward indication of the command pitch indicator. Any deviation from the proper glideslope path causes a fly-up or fly-down command indication. The pilot needs only to keep the airplane symbol fit into the command bar.

Electronic Instruments

Electronic Attitude Director Indicator (EADI)

The EADI is an advanced version of attitude and electric attitude indicators previously discussed. In addition to displaying the aircraft's attitude, numerous other situational flight parameters are displayed. Most notable are those that relate to instrument approaches and the flight director command bars. Annunciation of active systems, such as the AFCS and navigation systems, is typical.

The concept behind an EADI is to put all data related to the flight situation in close proximity for easy observation by the pilot. *[Figure 10-115]* Most EADIs can be switched between different display screens depending on the preference of the pilot and the phase of flight. EADIs vary from manufacturer to manufacturer and aircraft to aircraft. However, most of the same information is displayed.

EADIs can be housed in a single instrument housing or can be part of an electronic instrument display system. One such system, the electronic flight instrument system (EFIS), uses a cathode ray tube EADI display driven by a signal generator. Large-screen glass cockpit displays use LCD technology to display EADI information as part of an entire situational display directly in front of the pilot in the middle of the instrument panel. Regardless, the EADI

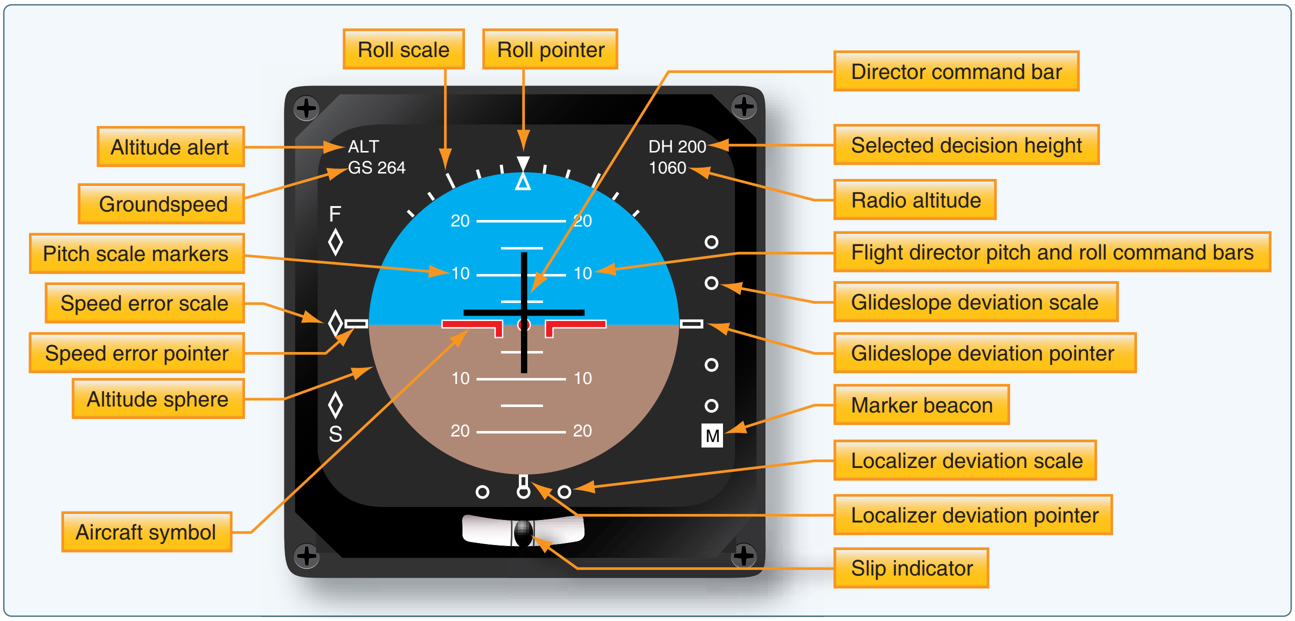


Figure 10-115. *Some of the many parameters and features of an electronic attitude director indicator (EADI).*

is the primary flight instrument used for aircraft attitude information during instrument flying and especially during instrument approaches. It is almost always accompanied by an electronic horizontal situation indicator (EHSI) located just below it in the display panel.

Electronic Horizontal Situation Indicators (EHSI)

The EHSI is an evolved version of the horizontal situation indicator (HSI), which was born from the gyroscopic direction indicator or directional gyro. The HSI incorporates directional information to two different navigational aids, as well as the heading of the aircraft. The EHSI does this and more. Its primary purpose is to display as much useful navigational information as possible.

In conjunction with a flight management computer and a display controller, an EHSI can display information in PLAN, MAP, VOR, and ILS modes. The PLAN mode shows a fixed map of the input flight plan. This usually includes all selected navigational aids for each flight segment and the destination airport. The MAP mode shows the aircraft against a detailed moving map background. Active and inactive navigational aids are shown, as well as other airports and waypoints. Weather radar information may be selected to be shown in scale as a background. Some HSIs can depict other air traffic when integrated with the TCAS system. Unlike a standard HSI, an EHSI may show only the pertinent portion of the compass rose. Annunciation of active mode and selected features appear with other pertinent information, such as distance and arrival time to the next waypoint, airport designators, wind direction and speed, and more. *[Figure 10-116]* There are many different displays that vary by manufacturer.

The VOR view of an EHSI presents a more traditional focus on a selected VOR, or other navigational station being used, during a particular flight segment. The entire compass rose, the traditional lateral deviation pointer, to/from information, heading, and distance information are standard. Other information may also be displayed. *[Figure 10-117]* The ILS mode of an EHSI shows the aircraft in relation to the ILS approach aids and selected runway with varying degrees of details. With this information displayed, the pilot need not consult printed airport approach information, allowing full attention to flying the aircraft.

Electronic Flight Information Systems

In an effort to increase the safety of operating complicated aircraft, computers and computer systems have been incorporated. Flight instrumentation and engine and airframe monitoring are areas particularly well suited to gain advantages from the use of computers. They contribute by helping to reduce instrument panel clutter and focusing the pilot's attention only on matters of imminent importance.

"Glass cockpit" is a term that refers to the use of flat-panel display screens in cockpit instrumentation. In reality, it also refers to the use of computer-produced images that have replaced individual mechanical gauges. Moreover, computers and computer systems monitor the processes and components of an operating aircraft beyond human ability while relieving the pilot of the stress from having to do so.

Computerized electronic flight instrument systems have additional benefits. The solid-state nature of the components increases reliability. Also, microprocessors, data buses, and

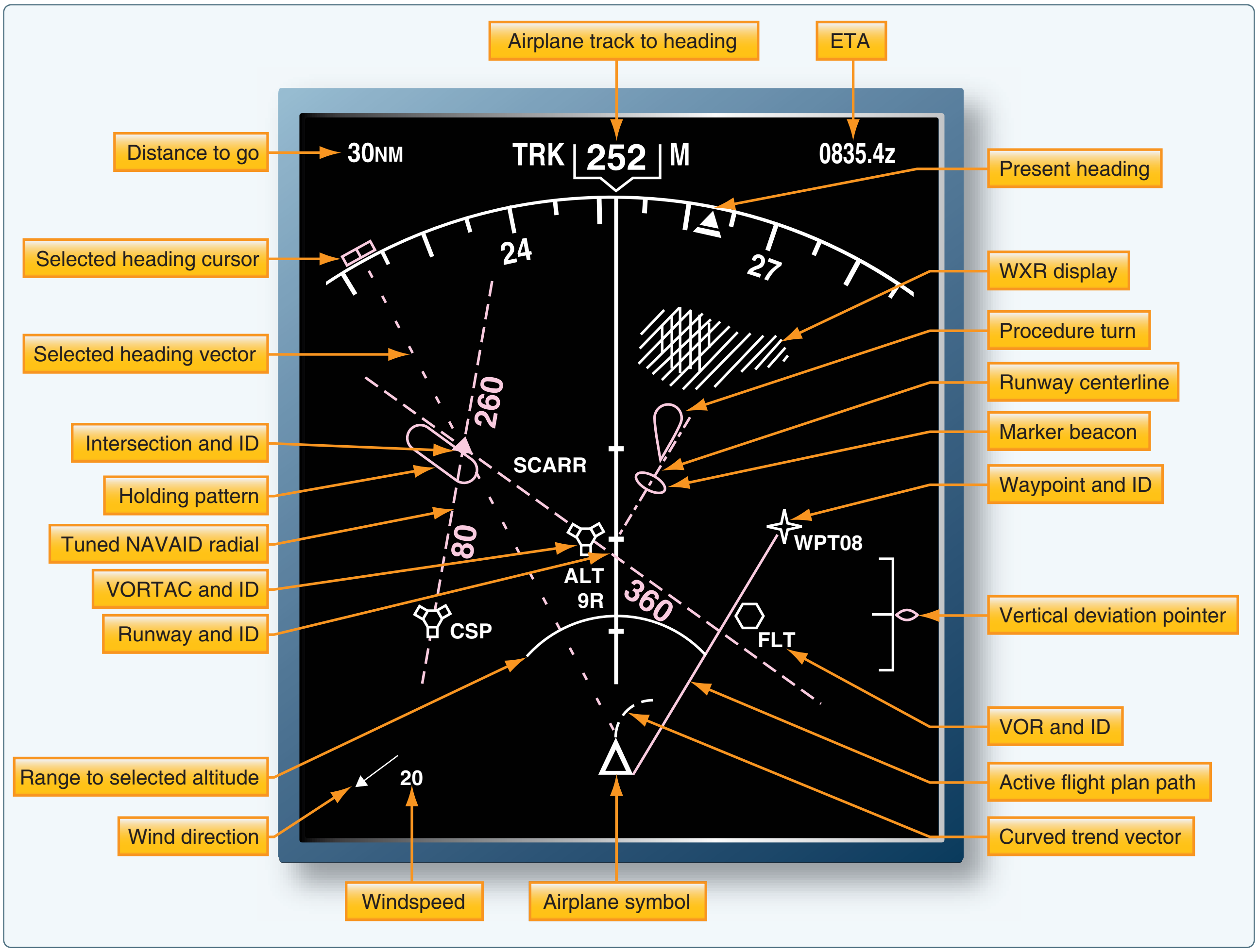


Figure 10-116. *An EHSI presents navigational information for the entire flight. The pilot selects the mode most useful for a particular phase of flight, ranging from navigational planning to instrument approach to landing. The MAP mode is used during most of the flight.*

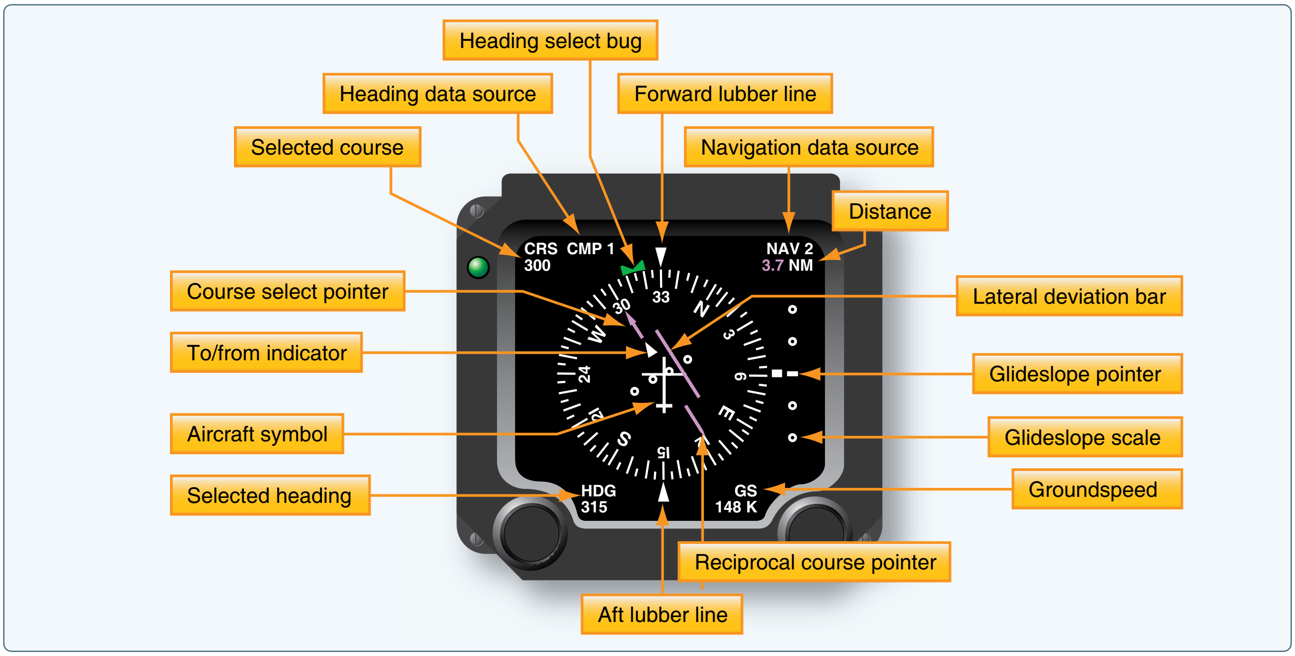


Figure 10-117. *Approach and VOR mode presentation of an electronic horizontal situation indicator.*

LCDs all save space and weight. The following systems have been developed and utilized on aircraft for a number of years. New systems and computer architecture are sure to come in the future.

Electronic Flight Instrument System (EFIS)

The flight instruments were the first to adopt computer technology and utilize flat screen, multifunctional displays (MFD). EFIS uses dedicated signal generators to drive two independent displays in the center of the basic T. The attitude indicator and directional gyro are replaced by cathode ray tubes (CRT) used to display EADI and EHSI presentations. These enhanced instruments operate alongside ordinary mechanic and electric instruments with limited integration. Still, EADI and EHSI technology is very desirable, reducing workload and panel scan with the added safety provided by integration of navigation information as described.

Early EFIS systems have analog technology, while newer models may be digital systems. The signal generators receive information from attitude and navigation equipment. Through a display controller, the pilot can select the various mode or screen features wishing to be displayed. Independent dedicated pilot and copilot systems are normal. A third, backup symbol generator is available to assume operation should one of the two primary units fail. *[Figure 10-118]*

Electronic depiction of ADI and HSI information is the core purpose of an EFIS system. Its expanded size and capabilities over traditional gauges allow for integration of even more flight instrument data. A vertical airspeed scale is typically displayed just left of the attitude field. This is in the same relative position as the airspeed indicator in an analog basic T instrument panel. To the right of the attitude field, many EFIS systems display an altitude and vertical speed scale. Since most EFIS EADI depictions include the inclinometer, normally part of the turn coordinator, all of the basic flight instruments are depicted by the EFIS display. *[Figure 10-119]*

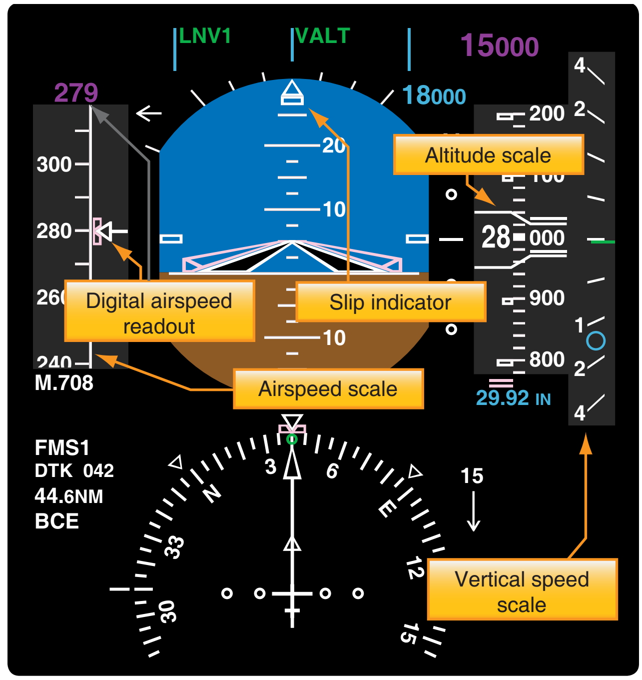


Figure 10-119. *An EFIS EADI displays an airspeed scale to the left of the horizon sphere and an altimeter and vertical speed scale to the right. The slip indicator is the small rectangle under the direction triangles at the top. This EFIS display presents all of the flight information in the conventional cockpit basic T.*

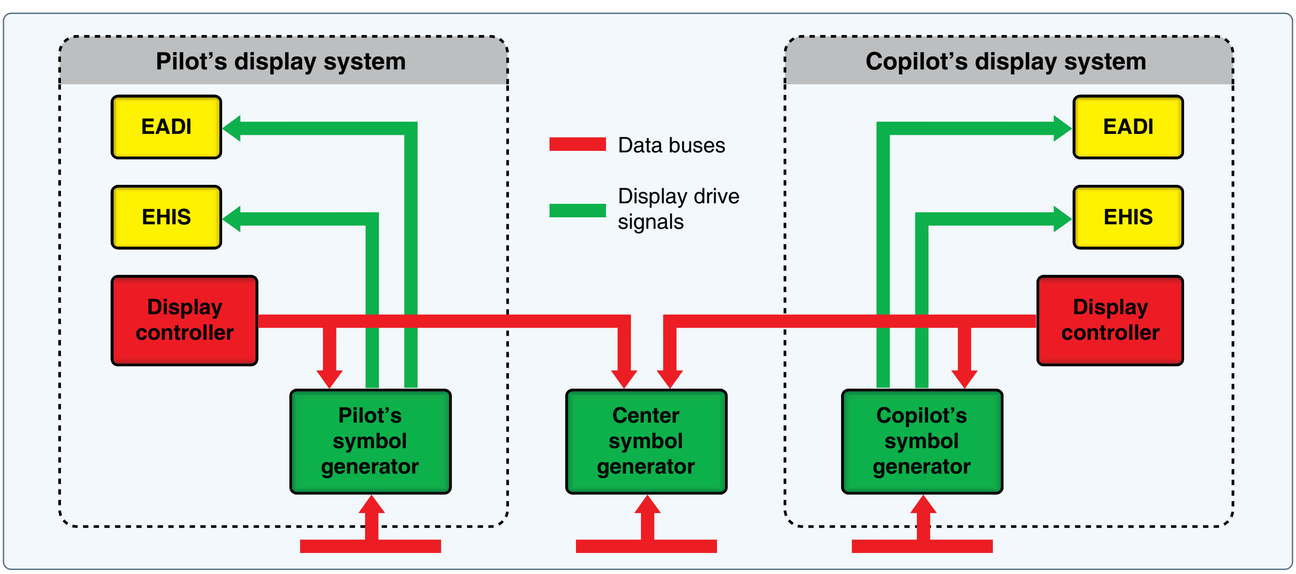


Figure 10-118. *A simplified diagram of an EFIS system. The EADI and EHSI displays are CRT units in earlier systems. Modern systems use digital displays, sometimes with only one multifunctional display unit replacing the two shown. Independent digital processors can also be located in a single unit to replace the three separate symbol generators.*

Electronic Centralized Aircraft Monitor (ECAM)

The pilot's workload on all aircraft includes continuous monitoring of the flight instruments and the sky outside of the aircraft. It also includes vigilant scrutiny for proper operation of the engine and airframe systems. On transport category aircraft, this can mean monitoring numerous gauges in addition to maneuvering the aircraft. The electronic centralized aircraft monitoring (ECAM) system is designed to assist with this duty.

The basic concept behind ECAM (and other monitoring systems) is automatic performance of monitoring duties for the pilot. When a problem is detected or a failure occurs, the primary display, along with an aural and visual cue, alerts the pilot. Corrective action that needs to be taken is displayed, as well as suggested action due to the failure. By performing system monitoring automatically, the pilot is free to fly the aircraft until a problem occurs.

Early ECAM systems only monitor airframe systems. Engine parameters are displayed on traditional full-time cockpit gauges. Later model ECAM systems incorporate engine displays, as well as airframe.

An ECAM system has two CRT monitors. In newer aircraft, these may be LCD. The left or upper monitor, depending on the aircraft panel layout, displays information on system status and any warnings associated corrective actions. This is done in a checklist format. The right or lower monitor displays accompanying system information in a pictorial form, such as a diagram of the system being referred to on the primary monitor.

The ECAM monitors are typically powered by separate signal generators. Aircraft data inputs are fed into two flight warning computers. Analog inputs are first fed through a system data analog converter and then into the warning computers. The warning computers process the information and forward information to the signal generators to illuminate the monitors. *[Figure 10-120]*

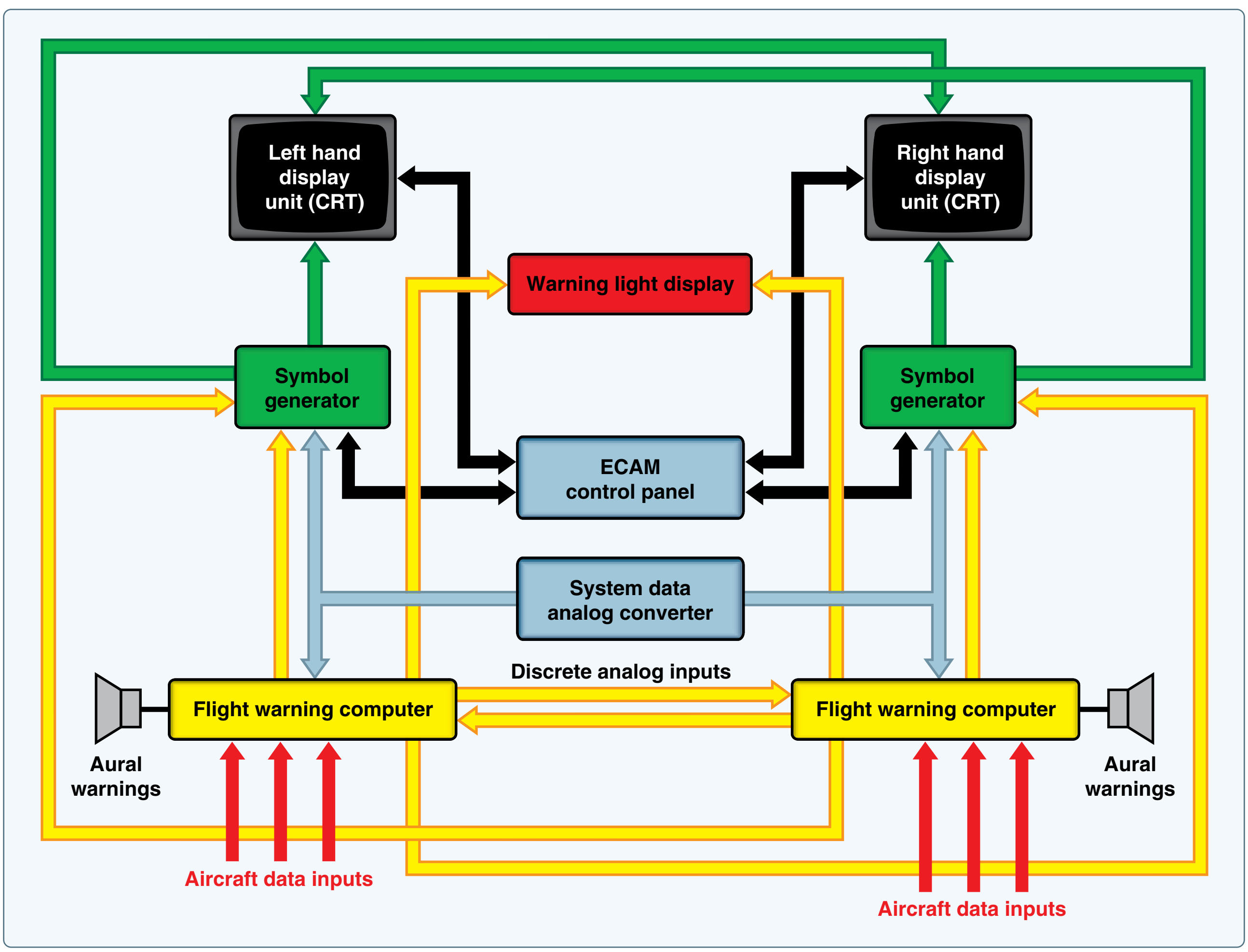


Figure 10-120. *An electronic centralized aircraft monitor (ECAM) system displays aircraft system status, checklists, advisories, and warnings on a pair of controllable monitors.*

There are four basic modes to the ECAM system: flight phase, advisory, failure related, and manual. The flight phase mode is normally used. The phases are: preflight, takeoff, climb, cruise, descent, approach, and post landing. Advisory and failure–related modes will appear automatically as the situation requires. When an advisory is shown on the primary monitor, the secondary monitor will automatically display the system schematic with numerical values. The same is true for the failure-related mode, which takes precedent over all other modes regardless of which mode is selected at the time of the failure. Color coding is used on the displays to draw attention to matters in order of importance. Display modes are selected via a separate ECAM control panel shown in *Figure 10-121*.

The manual mode of an ECAM is set by pressing one of the synoptic display buttons on the control panel. This allows the display of system diagrams. A failure warning or advisory event will cancel this view. *[Figure 10-122]*

ECAM flight warning computers self-test upon startup. The signal generators are also tested. A maintenance panel allows for testing annunciation and further testing upon demand. BITE stands for built-in test equipment. It is standard for monitoring systems to monitor themselves as well as the aircraft systems. All of the system inputs to the flight warning computers can also be tested for continuity from this panel, as well as inputs and outputs of the system data analog converter. Any individual system faults will be listed on the primary display as normal. Faults in the flight warning computers and signal generators will annunciate on the maintenance panel. *[Figure 10-123]* Follow the manufacturer's guidelines when testing ECAM and related systems.

Engine Indicating and Crew Alerting System (EICAS)

An engine indicating and crew alerting system (EICAS) performs many of the same functions as an ECAM system. The objective is still to monitor the aircraft systems for the pilot. All EICAS display engine, as well as airframe, parameters. Traditional gauges are not utilized, other than a standby combination engine gauge in case of total system failure.

EICAS is also a two-monitor, two-computer system with a display select panel. Both monitors receive information from the same computer. The second computer serves as a standby. Digital and analog inputs from the engine and airframe systems are continuously monitored. Caution and warning lights, as well as aural tones, are incorporated. *[Figure 10-124]*

EICAS provides full time primary engine parameters (EPR, N_1, EGT) on the top, primary monitor. Advisories and warning are also shown there. Secondary engine parameters and nonengine system status are displayed on the bottom screen. The lower screen is also used for maintenance diagnosis when the aircraft is on the ground. Color coding is used, as well as message prioritizing.

The display select panel allows the pilot to choose which computer is actively supplying information. It also controls the display of secondary engine information and system status displays on the lower monitor. EICAS has a unique feature that automatically records the parameters of a failure event to be regarded afterwards by maintenance personnel. Pilots that suspect a problem may be occurring during flight can press the event record button on the display select panel. This also records the parameters for that flight period to be studied later by maintenance. Hydraulic, electrical, environmental, performance, and APU data are examples of what may be recorded.

Figure 10-121. *An ECAM display control panel.*

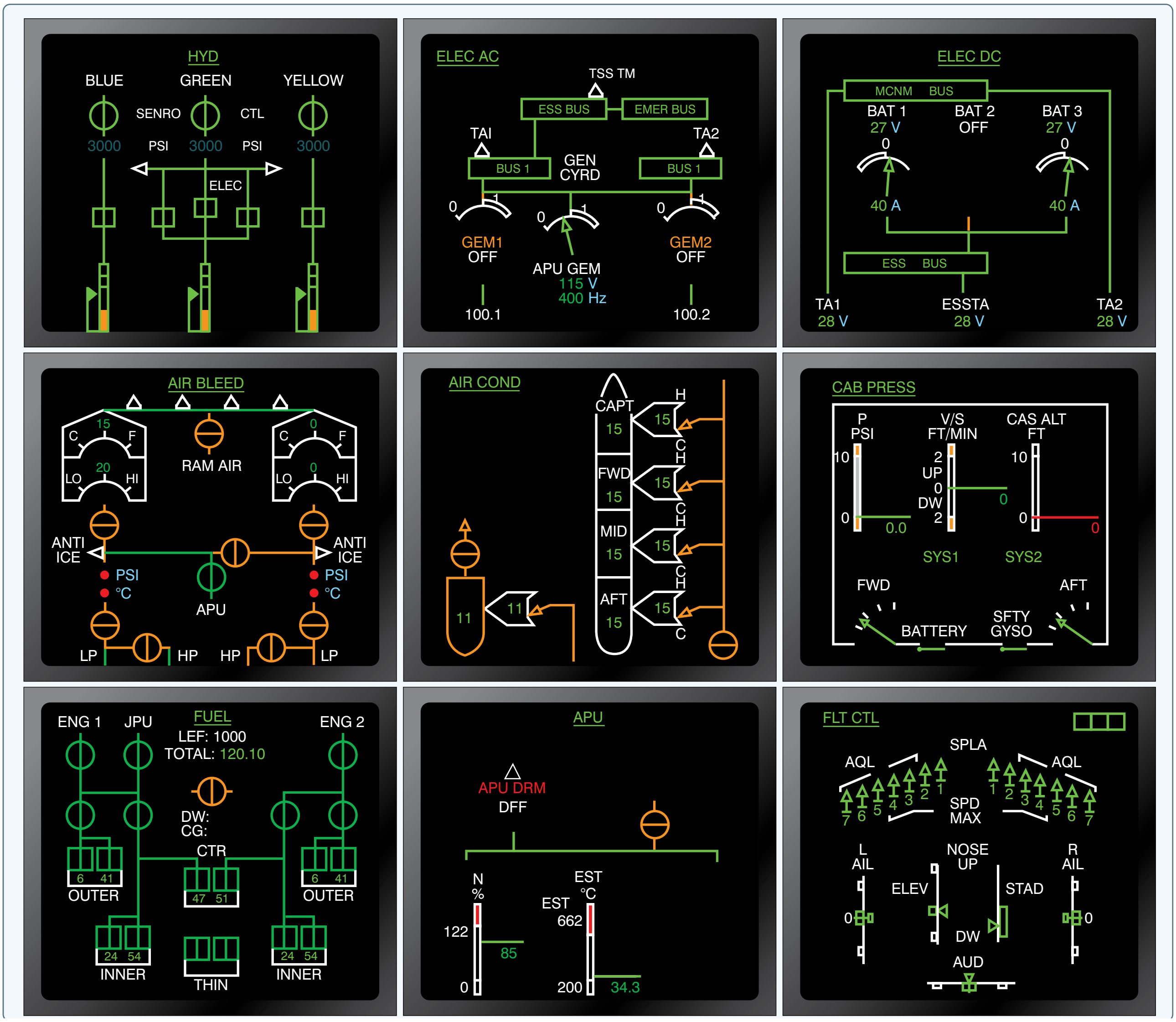


Figure 10-122. *Nine of the 12 available system diagrams from the ECAM manual mode.*

EICAS uses BITE for systems and components. A maintenance panel is included for technicians. From this panel, when the aircraft is on the ground, push-button switches display information pertinent to various systems for analysis. *[Figure 10-125]*

Flight Management System (FMS)

The highest level of automated flight system is the flight FMS. Companies flying aircraft for hire have special results they wish to achieve. On-time performance, fuel conservation, and long engine and component life all contribute to profitability. An FMS helps achieve these results by operating the aircraft with greater precision than possible by a human pilot alone.

A FMS can be thought of as a master computer system that has control over all other systems, computerized and otherwise. As such, it coordinates the adjustment of flight, engine, and airframe parameters either automatically or by instructing the pilot how to do so. Literally, all aspects of the flight are considered, from preflight planning to pulling up to the jet-way upon landing, including in-flight amendments to planned courses of action.

The main component of an FMS is the flight management computer (FMC). It communicates with the EICAS or ECAM, the ADC, the thrust management computer that controls the autothrottle functions, the EIFIS symbol generators, the automatic flight control system, the inertial reference system, collision avoidance systems, and all of the radio navigational aids via data busses. *[Figure 10-126]*

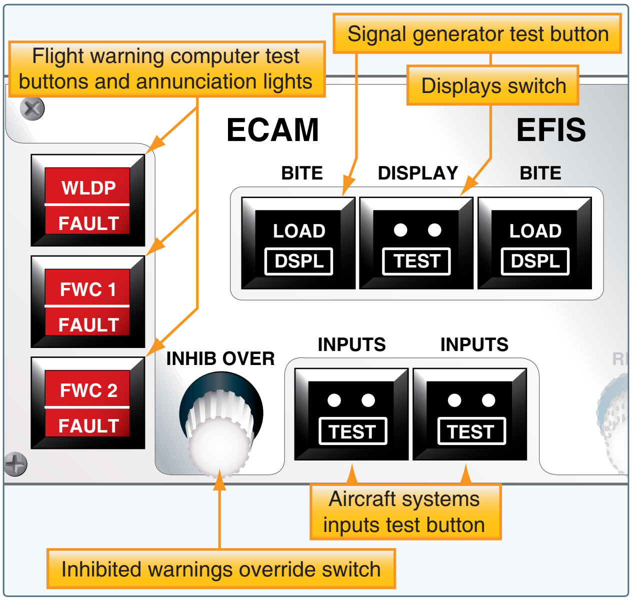


Figure 10-123. *An ECAM maintenance panel used for testing and annunciating faults in the ECAM system.*

The interface to the system is a control display unit (CDU) that is normally located forward on the center pedestal in the cockpit. It contains a full alphanumeric keypad, a CRT or LCD display/work screen, status and condition annunciators, and specialized function keys. *[Figure 10-127]*

The typical FMS uses two FMS FMCs that operate independently as the pilot's unit and the copilot's unit. However, they do crosstalk through the data busses. In normal operation, the pilot and copilot divide the workload, with the pilot's CDU set to supervise and interface with operational parameters and the copilot's CDU handling navigational chores. This is optional at the flightcrew's discretion. If a main component fails (e.g., an FMC or a CDU), the remaining operational units continue to operate with full control and without system compromise.

Each flight of an aircraft has vertical, horizontal, and navigational components, which are maintained by manipulating the engine and airframe controls. While doing so, numerous options are available to the pilot. Rate of climb, thrust settings, EPR levels, airspeed, descent rates, and other terms can be varied. Commercial air carriers use the FMC to establish guidelines by which flights can be flown. Usually, these promote the company's goals for fuel and equipment conservation. The pilot need only enter variables as requested and respond to suggested alternatives as the FMC presents them.

The FMC has stored in its database literally hundreds of flight plans with predetermined operational parameters that can be selected and implemented. Integration with NAV-COM aids allows the FMS to change radio frequencies as the flight plan is enacted. Internal computations using direct input from fuel flow and fuel quantity systems allow the FMC to carry out lean operations or pursue other objectives, such as high performance operations if making up time is paramount on a particular flight. Weather and traffic considerations are also integrated. The FMS can handle all variables automatically, but communicates via the CDU screen to present its planned action, gain consensus, or ask for an input or decision.

As with the monitoring systems, FMS includes BITE. The FMC continuously monitors its entire systems and inputs for faults during operation. Maintenance personal can retrieve system generated and pilot recorded fault messages. They may also access maintenance pages that call out line replaceable units (LRUs) to which faults have been traced by the BITE system. Follow manufacturers' procedures for interfacing with maintenance data information.

Warnings and Cautions

Annunciator Systems

Instruments are installed for two purposes: to display current conditions and to notify of unsatisfactory conditions. Standardized colors are used to differentiate between visual messages. For example, the color green indicates a satisfactory condition. Yellow is used to caution of a serious condition that requires further monitoring. Red is the color for an unsatisfactory condition. Whether part of the instrument face or of a visual warning system, these colors give quick-reference information to the pilot.

Most aircraft include annunciator lights that illuminate when an event demanding attention occurs. These use the aforementioned colors in a variety of presentations. Individual lights near the associated cockpit instrument or a collective display of lights for various systems in a central location are common. Words label each light or are part of the light itself to identify any problem quickly and plainly.

On complex aircraft, the status of numerous systems and components must be known and maintained. Centralized warning systems have been developed to annunciate critical messages concerning a multitude of systems and components in a simplified, organized manner. Often, this will be done by locating a single annunciator panel somewhere on the instrument panel. These analog aircraft warning systems may look different in various aircraft, and depend on manufacturer preference and the systems installed. *[Figure 10-128]* EFIS provide for annunciation of advisory and warning messages as part of its flight control and monitoring capabilities, as previously described. Usually, the primary display unit is designated as the location to display annunciations.

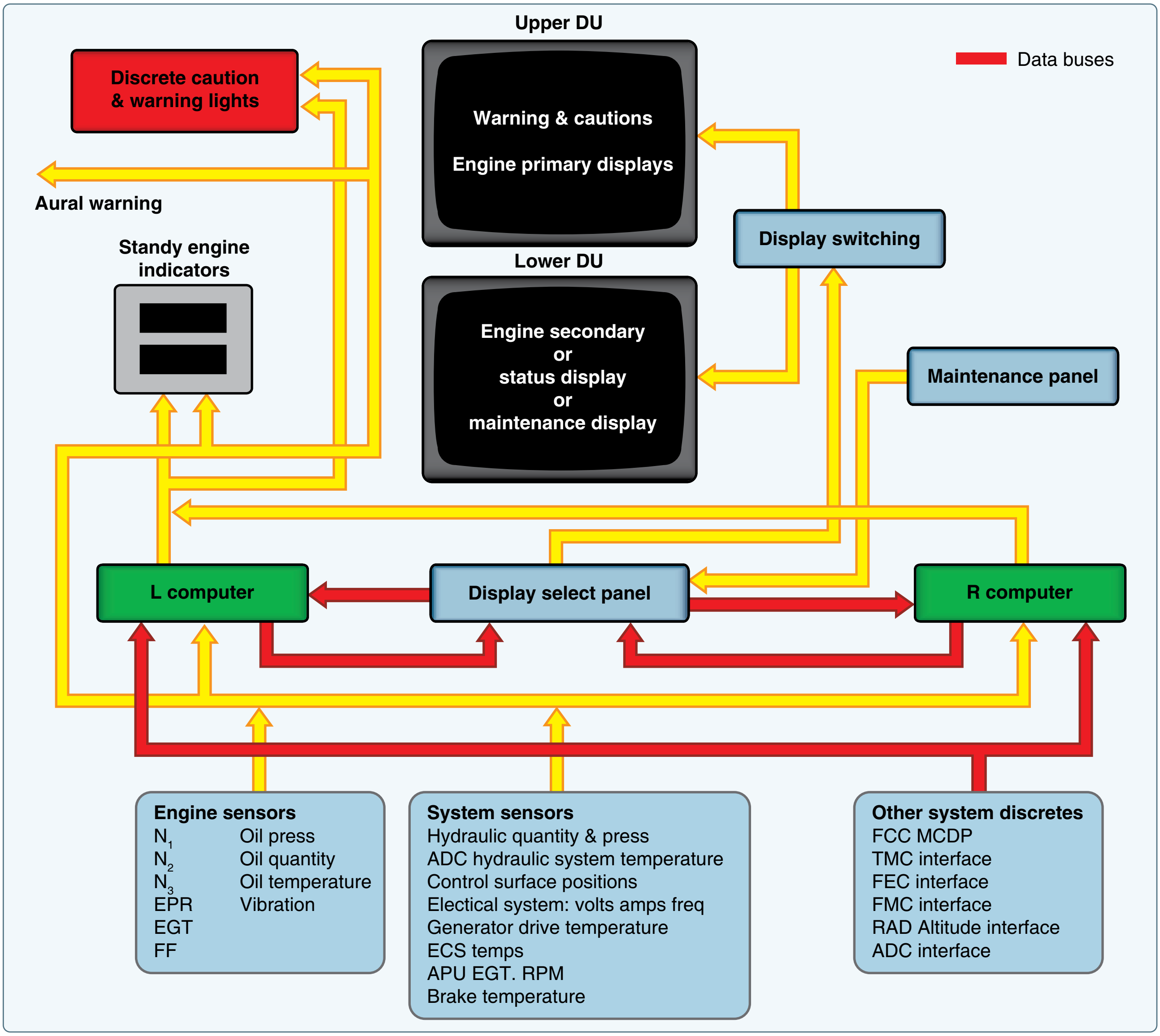


Figure 10-124. *Schematic of an engine indicating and crew alerting system (EICAS).*

Master caution lights are used to draw the attention of the crew to a critical situation in addition to an annunciator that describes the problem. These master caution lights are centrally wired and illuminate whenever any of the participating systems or components require attention. Once notified, the pilot may cancel the master caution, but a dedicated system or component annunciator light stays illuminated until the situation that caused the warning is rectified. Cancelling resets the master caution lights to warn of a subsequent fault event even before the initial fault is corrected. *[Figure 10-129]* Press to test is available for the entire annunciator system, which energizes all warning circuitry and lights to confirm readiness. Often, this test exposes the need to replace the tiny light bulbs that are used in the system.

Aural Warning Systems

Aircraft aural warning systems work in conjunction with illuminated annunciator systems. They audibly inform the pilot of a situation requiring attention. Various tones and phrases sound in the cockpit to alert the crew when certain conditions exist. For example, an aircraft with retractable landing gear uses an aural warning system to alert the crew to an unsafe condition. A bell sounds if the throttle is retarded and the landing gear is not in a down and locked condition.

A typical transport category aircraft has an aural warning system that alerts the pilot with audio signals for the following: abnormal takeoff, landing, pressurization, mach airspeed conditions, an engine or wheel well fire, calls from

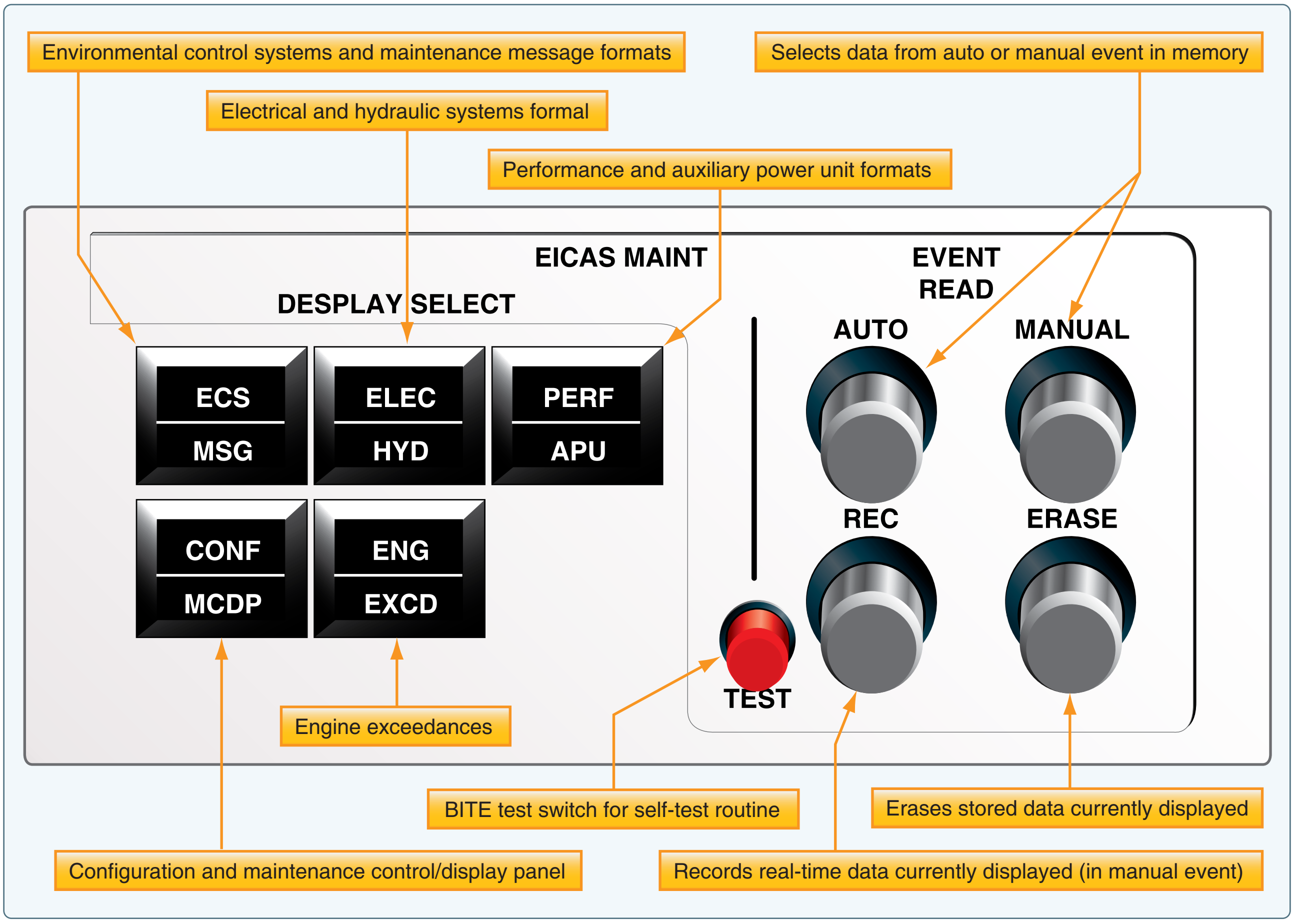


Figure 10-125. *The EICAS maintenance control panel is for the exclusive use of technicians.*

the crew call system, collision avoidance recommendations, and more. *Figure 10-130* shows some of the problems that trigger aural warnings and the action to be taken to correct the situation.

Clocks

Whether called a clock or a chronometer, an FAA-approved time indicator is required in the cockpit of IFR-certified aircraft. Pilots use a clock during flight to time maneuvers and for navigational purposes. The clock is usually mounted near the flight instrument group, often near the turn coordinator. It indicates hours, minutes, and seconds.

For many years, the mechanical 8-day clock was the standard aircraft timekeeping device largely because it continues to run without electrical power as long as it has been hand wound. The mechanical 8-day clock is reliable and accurate enough for its intended use. Some mechanical aircraft clocks feature a push-button elapsed time feature. *[Figure 10-131]*

As electrical systems developed into the reliable, highly redundant systems that exist today, use of an electric clock to replace the mechanical clock began. An electric clock is an analog devise that may also have an elapsed time feature. It can be wired to the battery or battery bus. Thus, it continues to operate in the event of a power failure. Electric aircraft clocks are often used in multiengine aircraft where complete loss of electrical power is unlikely.

Many modern aircraft have a digital electronic clock with LED readout. This device comes with the advantages of low power consumption and high reliability due to the lack of moving parts. It is also very accurate. Solid-state electronics allow for expanded features, such as elapsed time, flight time that starts automatically upon takeoff, a stop watch, and memories for all functions. Some even have temperature and date readouts. Although wired into the aircraft's electrical system, electronic digital clocks may include a small independent battery inside the unit that operates the device should aircraft electrical power fail. *[Figure 10-132]*

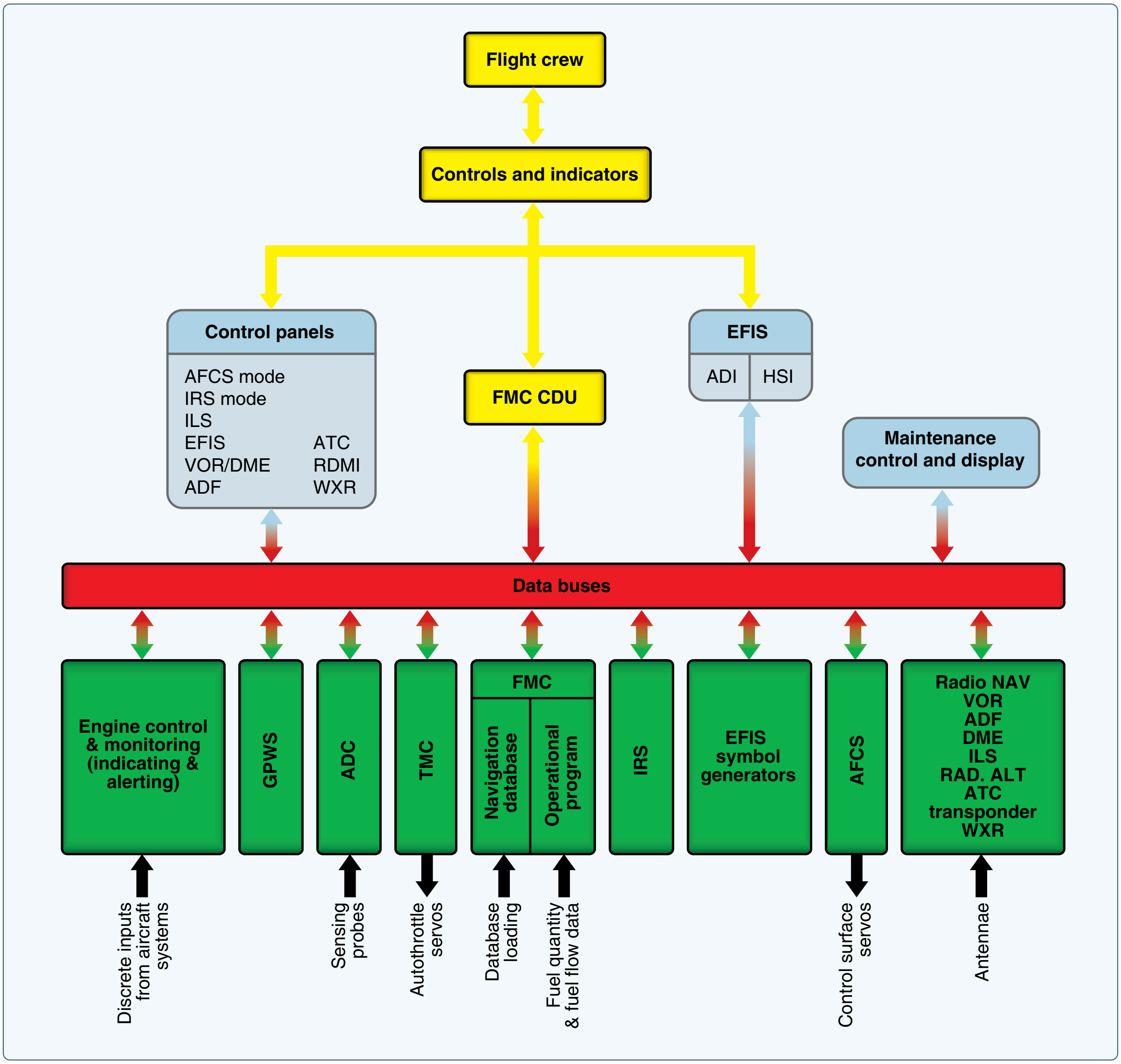


Figure 10-126. *A flight management system (FMS) integrates numerous engine, aircraft, and navigational systems to provide overall management of the flight.*

On aircraft with fully digital computerized instrument systems utilizing flat panel displays, the computer's internal clock, or a GPS clock, can be used with a digital time readout usually located somewhere on the primary flight display.

Instrument Housings and Handling

Various materials are used to protect the inner workings of aircraft instruments, as well as to enhance the performance of the instrument and other equipment mounted in the immediate vicinity. Instrument cases can be one piece or multipiece. Aluminum alloy, magnesium alloy, steel, iron, and plastic are all common materials for case construction. Electric instruments usually have a steel or iron alloy case to contain electromagnetic flux caused by current flow inside.

Despite their rugged outward appearance, all instruments, especially analog mechanical instruments, should be handled with special care and should never be dropped. A crack in an airtight instrument case renders it unairworthy. Ports should never be blown into and should be plugged until the instrument is installed. Cage all gyro instruments until mounted in the instrument panel. Observe all cautions written on the instrument housing and follow the manufacturer's instruction for proper handling and shipping, as well as installation.

Figure 10-127. *The control display unit (CDU) of an FMS.*

Figure 10-129. *A master caution switch removed from the instrument panel.*

Figure 10-128. *The centralized analog annunciator panel has indicator lights from systems and components throughout the aircraft. It is supported by the master caution system.*

Instrument Installations and Markings

Instrument Panels

Instrument panels are usually made from sheet aluminum alloy and are painted a dark, nonglare color. They sometimes contain subpanels for easier access to the backs of instruments during maintenance. Instrument panels are usually shock-mounted to absorb low-frequency, high-amplitude shocks. The mounts absorb most of the vertical and horizontal vibration, but permit the instruments to operate under conditions of minor vibration. Bonding straps are used to ensure electrical continuity from the panel to the airframe. *[Figure 10-133]*

The type and number of shock mounts to be used for instrument panels are determined by the weight of the unit. Shock-mounted instrument panels should be free to move in all directions and have sufficient clearance to avoid striking the supporting structure. When a panel does not have

Examples of Aircraft Aural Warnings				
Stage of Operation	Warning System	Warning Signal	Cause of Warning Signal Activation	Corrective action
Takeoff	Flight control	Intermittent horn	Throttles are advanced and any of the following conditions exist: 1. Speed brakes are not down 2. Flaps are not in takeoff range 3. Auxiliary power exhaust door is open 4. Stabilizer is not in the takeoff setting	Correct the aircraft to proper takeoff conditions
In flight	Mach warning	Clacker	Equivalent airspeed or mach number exceeds limits	Decrease aircraft speed
In flight	Pressurization	Intermittent horn	If cabin pressure becomes equal to atmospheric pressure at the specific altitude (altitude at time of occurrence)	Correct the condition
Landing	Landing gear	Continuous horn	Landing gear is not down and locked when flaps are less than full up and throttle is retarded to idle	Raise flaps; advance throttle
Any stage	Fire warning	Continuous bell	Any overheat condition or fire in any engine or nacelle, or main wheel or nose wheel well, APU engine, or any compartment having fire warning system installed Whenever the fire warning system is tested	1. Lower the heat in the the area where in the F/W was activated 2. Signal may be silenced pushing the F/W bell cutout switch or the APU cutout switch
Any stage	Communications ATA 2300	High chime	Any time captain's call button is pressed at external power panel forward or rearward cabin attendant's panel	Release button; if button remains locked in, pull button out

Figure 10-130. *Aircraft aural warnings.*

Figure 10-131. *A typical mechanical 8-day aircraft clock.*

Figure 10-132. *A typical aircraft electronic clock.*

adequate clearance, inspect the shock mounts for looseness, cracks, or deterioration.

Instrument panel layout is seemingly random on older aircraft. The advent of instrument flight made the flight instruments of critical importance when flying without outside reference to the horizon or ground. As a result, the basic T arrangement for flight instruments was adopted, as mentioned in the beginning of this chapter. *[Figure 10-4]* Electronic flight instrument systems and digital cockpit displays have kept the same basic T arrangement for flight instrument and data presentations. The flight instruments and basic T are located directly in front of the pilot and copilot's seats. Some light

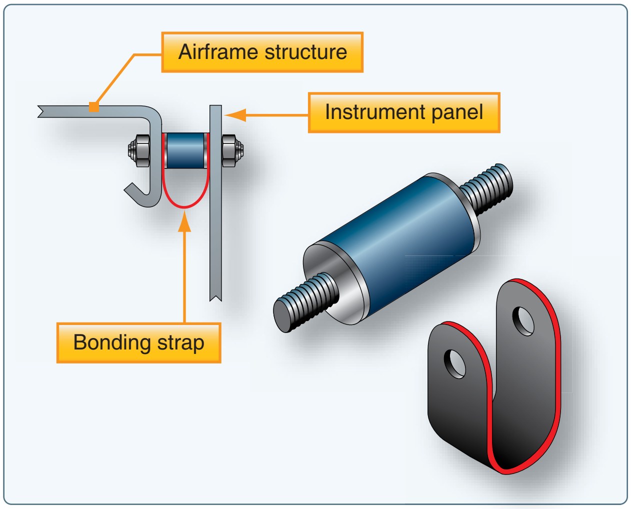


Figure 10-133. *Instrument panel shock mounts.*

aircraft have only one full set of flight instruments that are located in front of the left seat.

The location of engine instruments and navigation instruments varies. Ideally, they should be accessible to both the pilot and copilot. Numerous variations exist to utilize the limited space in the center of the instrument panel and still provide accessibility by the flight crew to all pertinent instruments. On large aircraft, a center pedestal and overhead panels help create more space. On small aircraft, the engine instruments are often moved to allow navigation instruments and radios to occupy the center of the instrument panel. *[Figure 10-134]*

On modern aircraft, EFIS and digital flight information systems reduce panel clutter and allow easier access to all instruments by both crewmembers. Controllable display panels provide the ability to select from pages of information that, when not displayed, are completely gone from view and use no instrument panel space.

Instrument Mounting

The method of mounting instruments in their respective panels depends on the design of the instrument case. In one design, the bezel is flanged in such a manner that the instrument can be flush mounted in its cutout from the rear of the panel. Integral, self-locking nuts are provided at the rear faces of the flange corners to receive mounting screws from the front of the panel. The flanged-type instrument can also be mounted to the front of the panel. In this case, nut-plates are usually installed in the panel itself. Nonferrous screws are usually used to mount the instruments.

There are also instrument mounting systems where the instruments are flangeless. A special clamp, shaped and dimensioned to fit the instrument case, is permanently secured to the rear face of the panel. The instrument is slid into the panel from the front and into the clamp. The clamp's tightening screw is accessible from the front side of the panel. *[Figure 10-135]* Regardless of how an instrument is mounted, it should not be touching or be so close as to touch another instrument during the shock of landing.

Figure 10-134. *Flight instruments directly in front of the pilot, engine instruments to the left and right, and navigation instruments and radios primarily to the right, which is the center of the instrument panel. This arrangement is commonly on light aircraft to be flown by a single pilot.*

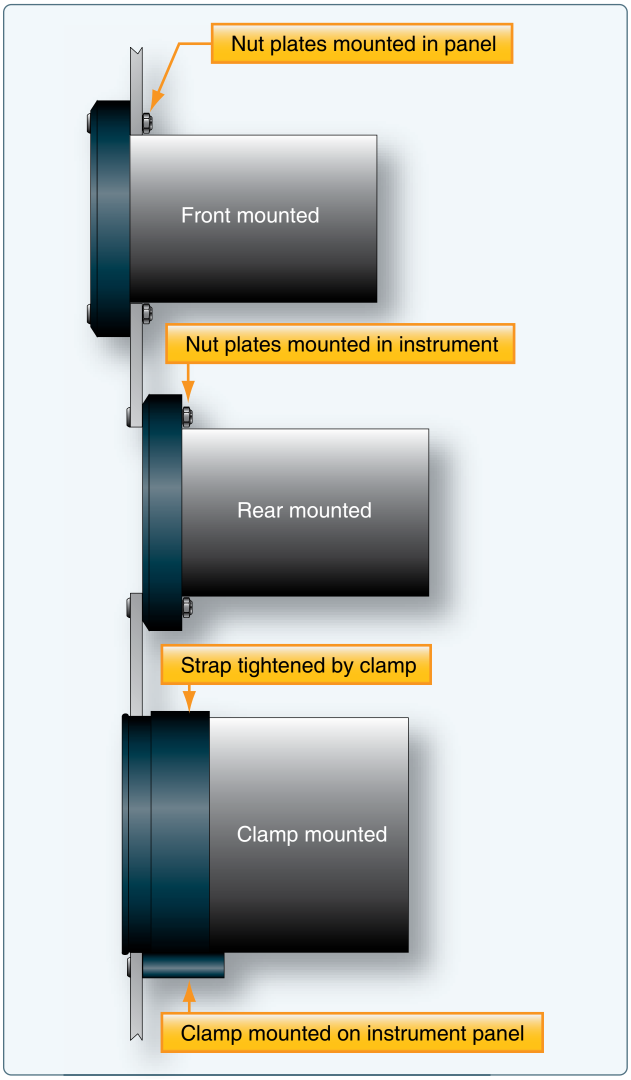


Figure 10-135. *Instrument mounts—flanged (top and middle) and flangeless (bottom).*

Instrument Power Requirements

Many aircraft instruments require electric power for operation. Even nonelectric instruments may include electric lighting. Only a limited amount of electricity is produced by the aircraft's electric generator(s). It is imperative that the electric load of the instruments, radios, and other equipment on board the aircraft does not exceed this amount.

Electric devices, including instruments, have power ratings. These show what voltage is required to correctly operate the unit and the amount of amperage it draws when operating to capacity. The rating must be checked before installing any component. Replacement of a component with one that has the same power rating is recommended to ensure the potential electric load of the installed equipment remains within the limits the aircraft manufacturer intended. Adding a component with a different rating or installing a completely new component may require a load check be performed. This is essentially an on the ground operational check to ensure the electrical system can supply all of the electricity consuming devices installed on the aircraft. Follow the manufacturer's instructions on how to perform this check.

Instrument Range Markings

Many instruments contain colored markings on the dial face to indicate, at a glance, whether a particular system or component is within a range of operation that is safe and desirable or if an undesirable condition exists. These markings are put on the instrument by the original equipment manufacturer in accordance with the Aircraft Specifications in the Type Certificate Data Sheet. Data describing these limitations can also sometimes be found in the aircraft manufacturer's operating and maintenance manuals.

Occasionally, the aircraft technician may find it necessary to apply these marking to an approved replacement instrument on which they do not appear. It is crucial that the instrument be marked correctly and only in accordance with approved data. The marking may be placed on the cover glass of the instrument with paint or decals. A white slippage mark is made to extend from the glass to the instrument case. Should the glass rotate in the bezel, the marking will no longer be aligned properly with the calibrated instrument dial. The broken slippage mark indicates this to the pilot or technician.

The colors used as range markings are red, yellow, green, blue, or white. The markings can be in the form of an arc or a radial line. Red is used to indicate maximum and minimum ranges; operations beyond these markings are dangerous and should be avoided. Green indicates the normal operating range. Yellow is used to indicate caution. Blue and white are used on airspeed indicators to define specific conditions. *[Figures 10-136* and *10-137]*

Maintenance of Instruments and Instrument Systems

An FAA airframe and powerplant (A&P) technician is not qualified to do internal maintenance on instruments and related line replaceable units discussed in this chapter. This must be carried out at facilities equipped with the specialized equipment needed to perform the maintenance properly. Qualified technicians with specialized training and intimate knowledge of instruments perform this type of work, usually under repair station certification.

However, licensed airframe technicians and A&P technicians are charged with a wide variety of maintenance functions related to instruments and instrument systems. Installation, removal, inspection, troubleshooting, and functional checks

Instrument	Range marking
Airspeed indicator	
White arc	Flap operating range
bottom	Flaps-down stall speed
Top	Maximum airspeed for flaps-down flight
Green arc	Normal operating range
bottom	Flaps-up stall speed
Top	Maximum airspeed for rough air
Blue radial line	Best single-engine rate-of-climb airspeed
Yellow arc	Structural warning area
bottom	Maximum airspeed for rough air
top	Never-exceed airspeed
Red radial line	Never-exceed airspeed
Carburetor air temperature	
Green arc	Normal operating range
Yellow arc	Range in which carburetor ice is most likely to form
Red radial line	Maximum allowable inlet air temperature
Cylinder head temperature	
Green arc	Normal operating range
Yellow arc	Operation approved for limited time
Red radial line	Never-exceed temperature
Manifold pressure gauge	
Green arc	Normal operating range
Yellow arc	Precautionary range
Red radial line	Maximum permissible manifold absolute pressure
Fuel pressure gauge	
Green arc	Normal operating range
Yellow arc	Precautionary range
Red radial line	Maximum and/or minimum permissible fuel pressure
Oil pressure gauge	
Green arc	Normal operating range
Yellow arc	Precautionary range
Red radial line	Maximum and/or minimum permissible oil pressure

Instrument	Range marking
Oil temperature gauge	
Green arc	Normal operating range
Yellow arc	Precautionary range
Red radial line	Maximum and/or minimum permissible oil temperature
Tachometer (reciprocating engine)	
Green arc	Normal operating range
Yellow arc	Precautionary range
Red arc	Restricted operating range
Red radial line	Maximum permissible rotational speed
Tachometer (turbine engine)	
Green arc	Normal operating range
Yellow arc	Precautionary range
Red radial line	Maximum permissible rotational speed
Tachometer (helicopter)	
Engine tachometer	
Green arc	Normal operating range
Yellow arc	Precautionary range
Red radial line	Maximum permissible rotational speed
Rotor tachometer	
Green arc	Normal operating range
Red radial line	Maximum and minimum rotor speed for power-off operational conditions
Torque indicator	
Green arc	Normal operating range
Yellow arc	Precautionary range
Red radial line	Maximum permissible torque pressure
Exhaust gas temperature indicator (turbine engine)	
Green arc	Normal operating range
Yellow arc	Precautionary range
Red radial line	Maximum permissible gas temperature
Gas producer N1 tachometer (turboshaft helicopter)	
Green arc	Normal operating range
Yellow arc	Precautionary range
Red radial line	Maximum permissible rotational speed

Figure 10-136. *Instrument range markings.*

are all performed in the field by licensed personnel. It is also a responsibility of the licensed technician holding an airframe rating to know what maintenance is required and to access the approved procedures for meeting those requirements.

In the following paragraphs, various maintenance and servicing procedures and suggestions are given. The discussion follows the order in which the various instruments and instrument systems were presented throughout this chapter. This is not meant to represent all of the maintenance required by any of the instruments or instruments systems. The aircraft manufacturer's and instrument manufacturer's approved maintenance documents should always be consulted for required maintenance and servicing instructions. FAA regulations must also be observed.

Altimeter Tests

When an aircraft is to be operated under IFR, an altimeter test must have been performed within the previous 24 months. Title 14 of the Code of Federal Regulations (14 CFR) part 91, section 91.411, requires this test, as well as tests on the pitot static system and on the automatic pressure altitude reporting system. The licensed airframe or A&P mechanic is not qualified to perform the altimeter inspections. They must be conducted by either the manufacturer or a certified repair station. 14 CFR part 43, Appendixes E and F detail the requirements for these tests.

Figure 10-137. *An airspeed indicator makes extensive use of range markings.*

Pitot-Static System Maintenance and Tests

Water trapped in a pitot static system may cause inaccurate or intermittent indications on the pitot-static flight instruments. This is especially a problem if the water freezes in flight. Many systems are fitted with drains at the low points in the system to remove any moisture during maintenance. Lacking this, dry compressed air or nitrogen may be blown through the lines of the system. Always disconnect all pitot-static instruments before doing so and always blow from the instrument end of the system towards the pitot and static ports. This procedure must be followed by a leak check described below. Systems with drains can be drained without requiring a leak check. Upon completion, the technician must ensure that the drains are closed and made secure in accordance with approved maintenance procedures.

Aircraft pitot-static systems must be tested for leaks after the installation of any component parts or when system malfunction is suspected. It must also be tested every 24 months if on an IFR certified aircraft intended to be flown as such as called out in 14 CFR section 91.411. Licensed airframe and A&P technicians may perform this test.

The method of leak testing depends on the type of aircraft, its pitot-static system, and the testing equipment available. *[Figure 10-138]* Essentially, a testing device is connected into the static system at the static vent end, and pressure is reduced in the system by the amount required to indicate 1,000 feet on the altimeter. Then, the system is sealed and observed for 1 minute. A loss of altitude of more than 100 feet is not permissible. If a leak exists, a systematic check of portions of the system is conducted until the leak is isolated. Most leaks occur at fittings. The pitot portion of the pitot-static system is checked in a similar fashion. Follow the manufacturer's instructions when performing all pitot-static system checks.

In all cases, pressure and suction must be applied and released slowly to avoid damage to the aircraft instruments. Pitot-static system leak check units usually have their own built-in altimeters. This allows a functional cross-check of the aircraft's altimeter with the calibrated test unit's altimeter while performing the static system check. However, this does not meet the requirements of 14 CFR section 91.411 for altimeter tests.

Upon completion of the leak test, be sure that the system is returned to the normal flight configuration. If it is necessary to block off various portions of a system, check to be sure that all blanking plugs, adaptors, or pieces of adhesive tape have been removed.

Figure 10-138. *An analog pitot-static system test unit (left) and a digital pitot static test unit (right).*

Tachometer Maintenance

Tachometer indicators should be checked for loose glass, chipped scale markings, or loose pointers. The difference in indications between readings taken before and after lightly tapping the instrument should not exceed approximately 15 rpm. This value may vary, depending on the tolerance established by the indicator manufacturer. Both tachometer generator and indicator should be inspected for tightness of mechanical and electrical connections, security of mounting, and general condition. For detailed maintenance procedures, the manufacturer's instructions should always be consulted.

When an engine equipped with an electrical tachometer is running at idle rpm, the tachometer indicator pointers may fluctuate and read low. This is an indication that the synchronous motor is not synchronized with the generator output. As the engine speed is increased, the motor should synchronize and register the rpm correctly. The rpm at which synchronization occurs varies with the design of the tachometer system. If the instrument pointer(s) oscillate(s) at speeds above the synchronizing value, determine that the total oscillation does not exceed the allowable tolerance.

Pointer oscillation can also occur with a mechanical indication system if the flexible drive is permitted to whip. The drive shaft should be secured at frequent intervals to prevent it from whipping. When installing mechanical type indicators, be sure that the flexible drive has adequate clearance behind the panel. Any bends necessary to route the drive should not cause strain on the instrument when it is secured to the panel. Avoid sharp bends in the drive. An improperly installed drive can cause the indicator to fail to read or to read incorrectly.

Magnetic Compass Maintenance and Compensation

The magnetic compass is a simple instrument that does not require setting or a source of power. A minimum of maintenance is necessary, but the instrument is delicate and should be handled carefully during inspection. The following items are usually included in an inspection:

1. The compass indicator should be checked for correct readings on various cardinal headings and re-compensated if necessary.
2. Moving parts of the compass should work easily.
3. The compass bowl should be correctly suspended on an antivibration device and should not touch any part of the metal container.
4. The compass bowl should be filled with liquid. The liquid should not contain any bubbles or have any discoloration.
5. The scale should be readable and be well lit.

Compass magnetic deviation is caused by electromagnetic interference from ferrous materials and operating electrical components in the cockpit. Deviation can be reduced by swinging the compass and adjusting its compensating magnets. An example of how to perform this calibration process is given below. The results are recorded on a compass correction card which is placed near the compass in the cockpit. *[Figure 10-139]*

Figure 10-139. *A magnetic compass with a deviation correction card attached, on which the results of swinging the compass should be recorded.*

There are various ways to swing a compass. The following is meant as a representative method. Follow the aircraft manufacturer's instructions for method and frequency of swinging the magnetic compass. This is usually accomplished at flight hour or calendar intervals. Compass calibration is also performed when a new electric component is added to the cockpit, such as a new radio. A complete list of conditions requiring a compass swing and procedure can be found in FAA Advisory Circular (AC) 43.13-1 (as revised), Chapter 12-37.

To swing a compass, a compass rose is required. Most airports have one painted on the tarmac in a low-traffic area where maintenance personnel can work. One can also be made with chalk and a good compass. The area where the compass rose is laid out should be far from any possible electromagnetic disturbances, including those underground, and should remain clear of any ferrous vehicles or large equipment while the procedure takes place. *[Figure 10-140]*

Figure 10-140. *The compass rose on this airport ramp can be used to swing an aircraft magnetic compass.*

The aircraft should be in level flight attitude for the compass swing procedure. Tail draggers need to have the aft end of the fuselage propped up, preferably with wood, aluminum, or some other nonferrous material. The aircraft interior and baggage compartments should be free from miscellaneous items that might interfere with the compass. All normal equipment should be on board and turned on to simulate a flight condition. The engine(s) should be running.

The basic idea when swinging a compass is to note the deviation along the north-south radial and the east-west radial. Then, adjust the compensating magnets of the compass to eliminate as much deviation as possible. Begin by centering or zeroing the compass' compensating magnets with a non-ferrous screw driver. Align the longitudinal axis of the aircraft on the N-S radial facing north. Adjust the N-S compensating screw so the indication is 0°. Next, align the longitudinal axis of the aircraft on the E-W radial facing east. Adjust the E-W compensating screw so that the compass indicates 90°. Now, move the aircraft to be aligned with the N-S radial facing south. If the compass indicates 180°, there is no deviation while the aircraft is heading due north or due south. However, this is unlikely. Whatever the south-facing indication is, adjust the N-S compensating screw to eliminate half of the deviation from 180°. Continue around to face the aircraft west on the E-W radial, and use the E-W compensating screw to eliminate half of the west-facing deviation from 270°.

Once this is done, return the aircraft to alignment with the N-S radial facing north and record the indication. Up to 10° deviation is allowed. Align the aircraft with the radials every 30° around the compass rose and record each indication on the compass compensation card. Date and sign the card and place it in full view of the pilot near the compass in the cockpit.

Vacuum System Maintenance

Errors in the indication presented on a vacuum gyroscopic instrument could be the result of any factor that prevents the vacuum system from operating within the design suction limits. Errors can also be caused by problems within the instrument, such as friction, worn parts, or broken parts. Any source that disturbs the free rotation of the gyro at design speed is undesirable resulting in excessive precession and failure of the instruments to maintain accurate indication.

The aircraft technician is responsible for the prevention or correction of vacuum system malfunctions. Usually this consists of cleaning or replacing filters, checking and correcting insufficient vacuum, or removing and replacing the vacuum pump or instruments. A list of the most common malfunctions, together with their correction, is included in *Figure 10-141*.

Autopilot System Maintenance

The information in this section does not apply to any particular autopilot system, but gives general information that relates to all autopilot systems. Maintenance of an autopilot system consists of visual inspection, replacement of components, cleaning, lubrication, and an operational checkout of the system. Consult the manufacturer's maintenance manual for all of these procedures.

With the autopilot disengaged, the flight controls should function smoothly. The resistance offered by the autopilot servos should not affect the control of the aircraft. The interconnecting mechanisms between the autopilot system and the flight control system should be correctly aligned and smooth in operation. When applicable, the operating cables should be checked for tension.

An operational check is important to assure that every circuit is functioning properly. An autopilot operational check should be performed on new installations, after replacement of an autopilot component, or whenever a malfunction in the autopilot is suspected.

After the aircraft's main power switch has been turned on, allow the gyros to come up to speed and the amplifier to warm up before engaging the autopilot. Some systems are designed with safeguards that prevent premature autopilot engagement. While holding the control column in the normal flight position, engage the autopilot system using the switch on the autopilot controller.

Problem and Potential Causes	Isolation Procedure	Correction
1. No vacuum pressure or insufficient pressure		
Defective vacuum gauge	Check opposite engine system on the gauge	Replace faulty vacuum gauge
Vacuum relief valve incorrectly adjusted	Change valve adjustment	Make final adjustment to correct setting
Vacuum relief valve installed backward	Visually inspect	Install lines properly
Broken lines	Visually inspect	Replace line
Lines crossed	Visually inspect	Install lines properly
Obstruction in vacuum line	Check for collapsed line	Clean & test line; replace defective part(s)
Vacuum pump failure	Remove and inspect	Replace faulty pump
Vacuum regulator valve incorrectly adjusted	Make valve adjustment and note pressure	Adjust to proper pressure
Vacuum relief valve dirty	Clean and adjust relief valve	Replace valve if adjustment fails
2. Excessive vacuum		
Relief valve improperly adjusted		Adjust relief valve to proper setting
Inaccurate vacuum gauge	Check calibration of gauge	Replace faulty gauge
3. Gyro horizon bar fails to respond		
Instrument caged	Visually inspect	Uncage instrument
Instrument filter dirty	Check filter	Replace or clean as necessary
Insufficient vacuum	Check vacuum setting	Adjust relief valve to proper setting
Instrument assembly worn or dirty		Replace instrument
4. Turn-and-bank indicator fails to respond		
No vacuum supplied to instrument	Check lines and vacuum system	Clean and replace lines and components
Instrument filter clogged	Visually inspect	Replace filter
Defective instrument	Test with properly functioning instrument	Replace faulty instrument
5. Turn-and-bank pointer vibrates		
Defective instrument	Test with properly functioning instrument	Replace defective instrument

Figure 10-141. *Vacuum system troubleshooting guide.*

After the system is engaged, perform the operational checks specified for the particular aircraft. In general, the checks are as follows:

1. Rotate the turn knob to the left; the left rudder pedal should move forward, and the control column wheel should move to the left and slightly aft.
2. Rotate the turn knob to the right; the right rudder pedal should move forward, and the control column wheel should move to the right and slightly aft. Return the turn knob to the center position; the flight controls should return to the level-flight position.
3. Rotate the pitch-trim knob forward; the control column should move forward.
4. Rotate the pitch-trim knob aft; the control column should move aft.

If the aircraft has a pitch-trim system installed, it should function to add down-trim as the control column moves forward and add up-trim as the column moves aft. Many pitch-trim systems have an automatic and a manual mode of operation. The above action occurs only in the automatic mode.

Check to see if it is possible to manually override or overpower the autopilot system in all control positions. Center all the controls when the operational checks have been completed.

Disengage the autopilot system and check for freedom of the control surfaces by moving the control columns and rudder pedals. Then, reengage the system and check the emergency disconnect release circuit. The autopilot should disengage each time the release button on the control yoke is actuated.

When performing maintenance and operational checks on a specific autopilot system, always follow the procedure recommended by the aircraft or equipment manufacturer.

LCD Display Screens

Electronic and digital instrument systems utilizing LCD technology may have special considerations for the care of the display screens. Antireflective coatings are sometimes used to reduce glare and make the displays more visible. These treatments can be degraded by human skin oils and certain cleaning agents, such as those containing ammonia. It is very important to clean the display lens using a clean, lint-free cloth and a cleaner that is specified as safe for antireflective coatings, preferable one recommended by the aircraft manufacturer.