CHAPTER 3 - FLIGHT INSTRUMENTS

INTRODUCTION

The use of instruments as an aid to flight enables the pilot to operate the airplane more precisely, and therefore, obtain maximum performance and enhanced safety. This is particularly true when flying greater distances. Manufacturers have provided the necessary flight instruments; however, it is the pilot's responsibility to gain the essential knowledge about how the instruments operate so that they can be used effectively.

This chapter covers the operational aspects of the pitot-static system and associated instruments: the vacuum system and associated instruments; and the magnetic compass.

THE PITOT-STATIC SYSTEM AND ASSOCIATED INSTRUMENTS

There are two major parts of the pitot-static system: (1) impact pressure chamber and lines; and (2) static pressure chamber and lines, which provides the source of ambient air pressure for the operation of the altimeter, vertical speed indicator (vertical velocity indicator), and the airspeed indicator.

Impact Pressure Chamber and Lines

In this system, the impact air pressure (air striking the airplane because of its forward motion) is taken from a pitot tube, which is mounted either on the leading edge of the wing or on the nose, and aligned to the relative wind. On certain aircraft, the pitot tube is located on the vertical stabilizer. These locations provide minimum disturbance or turbulence caused by the motion of the airplane through the air. The static pressure (pressure of the still air) is usually taken from the static line attached to a vent or vents mounted flush with the side of the fuselage. Airplanes using a flush-type static source, with two vents, have one vent on each side of the fuselage. This compensates for any possible variation in static pressure due to erratic changes in airplane attitude.

The openings of both the pitot tube and the static vent should be checked during the preflight inspection to assure that they are free from obstructions. Clogged or partially clogged openings should be cleaned by a certificated mechanic. Blowing into these openings is not recommended because this could damage any of the three instruments. [Figure 3-1]

As the airplane moves through the air, the impact pressure on the open pitot tube affects the pressure in the pitot chamber. Any change of pressure in the pitot chamber is transmitted through a line connected to the airspeed indicator which utilizes impact pressure for its operation.

Static Pressure Chamber and Lines

The static chamber is vented through small holes to the free undisturbed air, and as the atmospheric pressure increases or decreases, the pressure in the static chamber changes accordingly. Again, this pressure change is transmitted through lines to the instruments which utilize static pressure as illustrated in figure 3-1.

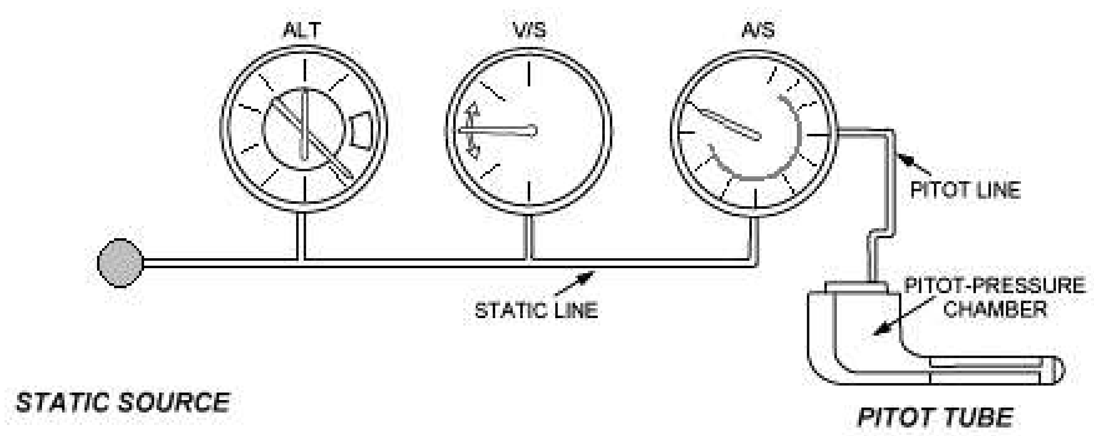

Figure 3-1.—Pitot-static system with instruments.

An alternate source for static pressure is provided in some airplanes in the event the static ports become clogged. This source usually is vented to the pressure inside the cockpit. Because of the venturi effect of the flow of air over the cockpit, this alternate static pressure is usually lower than the pressure provided by the normal static air source. When the alternate static source is used, the following differences in the instrument indications usually occur: the altimeter will indicate higher than the actual altitude, the airspeed will indicate greater than the actual airspeed, and the vertical speed will indicate a climb while in level flight.

Altimeter

The altimeter measures the height of the airplane above a given level. Since it is the only instrument that gives altitude information, the altimeter is one of the most important instruments in the airplane. To use the altimeter effectively, the pilot must thoroughly understand its principle of operation and the effect of atmospheric pressure and temperature on the altimeter. [Figure 3-2]

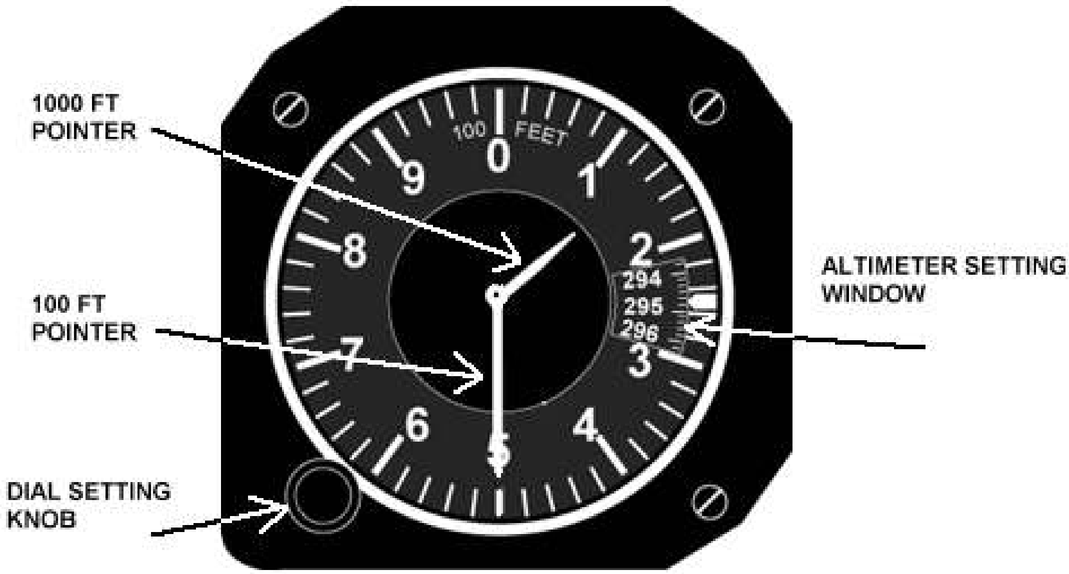

Figure 3-2.—Sensitive altimeter. The instrument is adjusted by the knob (lower left) so the current altimeter setting (29.48) appears in the window to the right.

Principle of Operation

The pressure altimeter is simply an aneroid barometer that measures the pressure of the atmosphere at the level where the altimeter is located, and presents an altitude indication in feet. The altimeter uses static pressure as its source of operation. Air is more dense at the surface of the Earth than aloft, therefore as altitude increases, atmospheric pressure decreases. This difference in pressure at various levels causes the altimeter to indicate changes in altitude.

The presentation of altitude varies considerably between different types of altimeters. Some have one pointer while others have more. Only the multipointer type will be discussed in this handbook.

The dial of a typical altimeter is graduated with numerals arranged clockwise from 0 to 9 inclusive as shown in figure 3-2. Movement of the aneroid element is transmitted through a gear train to the three hands which sweep the calibrated dial to indicate altitude. The shortest hand indicates altitude in tens of thousands of feet; the intermediate hand in thousands of feet; and the longest hand in hundreds of feet, subdivided into 20-foot increments.

This indicated altitude is correct, however, only if the sea level barometric pressure is standard (29.92 in. Hg.), the sea level free air temperature is standard (+15° C or 59° F), and furthermore, the pressure and temperature decrease at a standard rate with an increase in altitude. Since atmospheric pressure continually changes, a means is provided to adjust the altimeter to compensate for nonstandard conditions. This is accomplished through a system by which the altimeter setting (local station barometric pressure reduced to sea level) is set to a barometric scale located on the face of the altimeter. Only after the altimeter is set properly will it indicate the correct altitude.

Effect of Nonstandard Pressure and Temperature

If no means were provided for adjusting altimeters to nonstandard pressure, flight could be hazardous. For example, if a flight is made from a high pressure area to a low pressure area without adjusting the altimeter, the actual altitude of the airplane will be LOWER than the indicated altitude, and when flying from a low pressure area to a high pressure area, the actual altitude of the airplane will be

HIGHER than the indicated altitude. Fortunately, this error can be corrected by setting the altimeter properly.

Variations in air temperature also affect the altimeter. On a warm day, the expanded air is lighter in weight per unit volume than on a cold day, and consequently the pressure levels are raised. For example, the pressure level where the altimeter indicates 10,000 feet will be HIGHER on a warm day than under standard conditions. On a cold day, the reverse is true, and the 10,000-foot level would be LOWER. The adjustment made by the pilot to compensate for nonstandard pressures does not compensate for nonstandard temperatures. Therefore, if terrain or obstacle clearance is a factor in the selection of a cruising altitude, particularly at higher altitudes, remember to anticipate that COLDER-THAN-STANDARD TEMPERATURE will place the aircraft LOWER than the altimeter indicates. Therefore, a higher altitude should be used to provide adequate terrain clearance.

A memory aid in applying the above is "***from high to low (or from hot to cold), look out below***."

Setting the Altimeter

To adjust the altimeter for variation in atmospheric pressure, the pressure scale in the altimeter setting window, calibrated in inches of mercury (in. Hg.), is adjusted to correspond with the given altimeter setting. Altimeter settings can be defined as station pressure reduced to sea level, expressed in inches of mercury.

The station reporting the altimeter setting takes an hourly measurement of the station's atmospheric pressure and corrects this value to sea level pressure. These altimeter settings reflect height above sea level only in the vicinity of the reporting station. Therefore, it is necessary to adjust the altimeter setting as the flight progresses from one station to the next.

Flying the Altimeter in Large Aeroplanes

Large aeroplanes tend to fly at higher altitudes. Above 18,000 feet in Canada is known as the ***Standard Pressure Region.*** According to the Canadian Aviation Regulations (Part 602.36), aircraft flying in this airspace shall set their altimeters to a standard setting or 29.92". This applies also to all aircraft flying within the airspace of the Standard Pressure Region (north of the lower 10 provinces). See Fig 7-1 in Chapter 7 for the location of these two blocks of airspace.

Flying the Altimeter in Small Aeroplanes

The Canadian Aviation Regulations (Part 602.35) provide the following concerning altimeter settings: The cruising altitude of an aircraft *below 18,000 feet* mean sea level (MSL) in the ***Altimeter Setting Region*** shall be maintained by reference to an altimeter that is set to the current reported altimeter setting of the nearest station located along the route of flight. In an aircraft having no radio, the altimeter shall be set to the elevation of the departure airport or an appropriate altimeter setting available before departure.

Many pilots confidently expect that the current altimeter setting will compensate for irregularities in atmospheric pressure at all altitudes. This is not always true because the altimeter setting broadcast by ground stations is the station pressure corrected to mean sea level. The altimeter setting does not account for the irregularities at higher levels, particularly the effect of nonstandard temperature. It should be pointed out, however, that if each pilot in a given area were to use the same altimeter setting, each altimeter will be equally affected by temperature and pressure variation errors, making it possible to maintain the desired separation between aircraft.

When flying over high mountainous terrain, certain atmospheric conditions can cause the altimeter to indicate an altitude of 1,000 feet, or more, HIGHER than the actual altitude. For this reason, a generous margin of altitude should be allowed—not only for possible altimeter error, but also for possible downdrafts which are particularly prevalent if high winds are encountered.

To illustrate the use of the altimeter setting system, follow a flight from Calgary's Springbank, to Edmonton City Centre Airport, via Red Deer. Before takeoff from Springbank, the pilot receives a current altimeter setting of 29.85 from the control tower or automatic terminal information service (ATIS). This value is set in the altimeter setting window of the altimeter. The altimeter indication should then be compared with the known airport elevation of 3937 feet. Since most altimeters are not perfectly calibrated, an error may exist. If an altimeter indication varies from the field elevation more than 75 feet, the accuracy of the instrument is questionable and it should be referred to an instrument technician for recalibration.

When over Red Deer, assume the pilot receives a current altimeter setting of 29.94 and applies this setting to the altimeter. Before entering the traffic pattern at Edmonton City Centre Airport, a new altimeter setting of 29.69 is received from the Edmonton City Centre Airport, and applied to the altimeter. If the pilot desires to fly the traffic pattern at approximately 1000 feet above terrain, and the field elevation of Edmonton City Centre Airport is 2,200 feet, an indicated altitude of 3,200 feet should be maintained (2,200 feet + 1000 feet = 3,200 feet) after resetting the altimeter setting to the Edmonton value.

The importance of properly setting and reading the altimeter cannot be overemphasized. Let's assume that the pilot neglected to adjust the altimeter at Edmonton to the current setting, and uses the Red Deer setting of 29.94. If this occurred, the airplane, when in the

Edmonton traffic pattern, would be approximately 250 feet below the proper traffic pattern altitude of 2,600 feet, and the altimeter would indicate approximately 250 feet more than the field elevation (2,450 feet) upon landing.

Actual altimeter setting	29.94
Proper altimeter setting	29.69
Difference	.25

The difference (.25"/Hg) is equivalent to 250 feet of altitude. The calculation may be confusing, particularly in determining whether to add or subtract the amount of altimeter error. The following additional explanation is offered and can be helpful in finding the solution to this type of problem.

There are two means by which the altimeter pointers can be moved. One utilizes changes in air pressure while the other utilizes the mechanical makeup of the altimeter setting system.

When the aircraft altitude is changed, the changing pressure within the altimeter case expands or contracts the aneroid barometer which through linkage rotates the pointers. A decrease in pressure causes the altimeter to indicate an increase in altitude, and an increase in pressure causes the altimeter to indicate a decrease in altitude. It is obvious then that if the aircraft is flown from a pressure level of 28.75 in. Hg. to a pressure level of 29.75 in. Hg., the altimeter would show a decrease of approximately 1,000 feet in altitude.

The other method of moving the pointers does not rely on changing air pressure, but the mechanical construction of the altimeter. When the knob on the altimeter is rotated, the altimeter setting pressure scale moves simultaneously with the altimeter pointers. This may be confusing because the numerical values of pressure indicated in the window increase while the altimeter indicates an increase in altitude; or decrease while the altimeter indicates a decrease in altitude. This is contrary to the reaction on the pointers when air pressure changes, and is based solely on the mechanical makeup of the altimeter. To further explain this point, assume that the proper altimeter setting is 29.50 and the actual setting is 30.00 or a .50 difference. This would cause a 500-foot error in altitude. In this case if the altimeter setting is adjusted from 30.00 to 29.50, the numerical value decreases and the altimeter indicates a decrease of 500 feet in altitude. Before this correction was made, the aircraft was flying at an altitude of 500 feet lower than was shown on the altimeter.

Types of Altitude

Knowing the aircraft's altitude is vitally important to the pilot for several reasons. The pilot must be sure that the airplane is flying high enough to clear the highest terrain or obstruction along the intended route; this is especially important when visibility is restricted. To keep above mountain peaks, the pilot must note the altitude of the aircraft and elevation of the surrounding terrain at all times. To reduce the possibility of a midair collision, the pilot must maintain altitudes in accordance with air traffic rules. Often certain altitudes are selected to take advantage of favorable winds and weather conditions. Also, a knowledge of the altitude is necessary to calculate true airspeeds.

Altitude is vertical distance above some point or level used as a reference. There may be as many kinds of altitude as there are reference levels from which altitude is measured and each may be used for specific reasons. Pilots are usually concerned, however, with five types of altitudes:

- Absolute Altitude—The vertical distance of an aircraft above the terrain.
- Indicated Altitude—That altitude read directly from the altimeter (uncorrected) after it is set to the current altimeter setting.
- Pressure Altitude—The altitude indicated when the altimeter setting window (barometric scale) is adjusted to 29.92. This is the standard datum plane, a theoretical plane where air pressure (corrected to 15° C) is equal to 29.92 in. Hg. Pressure altitude is used for computer solutions to determine density altitude, true altitude, true airspeed, etc.
- True Altitude—The true vertical distance of the aircraft above sea level—the actual altitude. (Often expressed in this manner; 10,900 feet MSL.) Airport, terrain, and obstacle elevations found on aeronautical charts are true altitudes.
- Density Altitude—This altitude is pressure altitude corrected for nonstandard temperature variations. When conditions are standard, pressure altitude and density altitude are the same. Consequently, if the temperature is above standard, the density altitude will be higher than pressure altitude. If the temperature is below standard, the density altitude will be lower than pressure altitude. This is an important altitude because it is directly related to the aircraft's takeoff and climb performance.

Vertical Speed Indicator

The vertical speed indicator (VSI) or vertical velocity indicator indicates whether the aircraft is climbing, descending, or in level flight. The rate of climb or descent is indicated in feet per minute. If properly calibrated, this indicator will register zero in level flight. [See Figure 3-3]

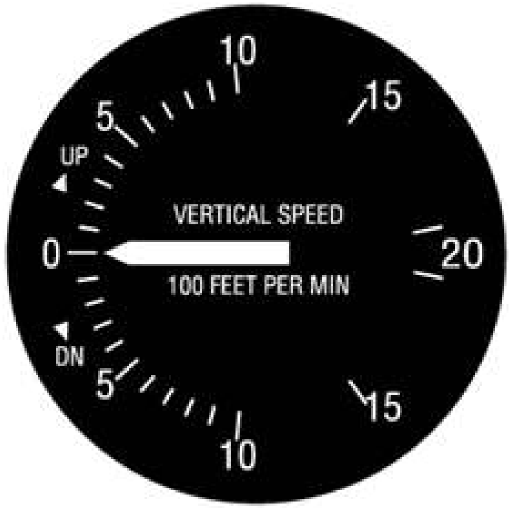

Figure 3-3.—Vertical speed indicator.

Principle of Operation

Although the vertical speed indicator operates solely from static pressure, it is a differential pressure instrument. The case of the instrument is airtight except for a small connection through a restricted passage to the static line of the pitot-static system.
A diaphragm with connecting linkage and gearing to the indicator pointer is located inside the sealed case. Both the diaphragm and the case receive air from the static line at existing atmospheric pressure. When the aircraft is on the ground or in level flight, the pressures inside the diaphragm and the instrument case remain the same and the pointer is at the zero indication. When the aircraft climbs or descends, the pressure inside the diaphragm changes immediately; but due to the metering action of the restricted passage, the case pressure will remain higher or lower for a short time causing the diaphragm to contract or expand. This causes a differential pressure which is indicated on the instrument needle as a climb or descent.

Integrated Flight Display

The *Integrated Flight Display* (Glass Cockpit) relies on a completely different set of inputs. Although the principal information objectives are the same, the flight data come from a fundamentally different source called an *Attitude-Heading Reference System* (AHRS). This is a digital data system requiring the management of external digital data sources. Vacuum pumps and gyros, for example, may not be required since the required attitude and heading data can be generated from satellite/GPS data or other synthesised data.. Generally speaking, a totally integrated system is available only on new aircraft since the cost of retro-fitting older aircraft is prohibitively expensive. Pilot training for an aircraft with an *Integrated Flight Display,* whether an airliner or a GA aircraft, requires a different specialized curriculum, not usually offered in basic flight schools.

Fig 3-3c The Integrated Flight Display

Airspeed Indicator

The airspeed indicator is a sensitive, differential pressure gauge which measures and shows promptly the difference between (1) pitot, or impact pressure, and (2) static pressure, the undisturbed atmospheric pressure at level flight. These two pressures will be equal when the aircraft is parked on the ground in calm air. When the aircraft moves through the air, the pressure on the pitot line becomes greater than the pressure in the static lines. This difference in pressure is registered by the airspeed pointer on the face of the instrument, which is calibrated in miles per hour (MPH), knots, or both. [Figure 3-4]

Figure 3-4.— Conventional Color-coded Airspeed indicator.

Fig 3-4b Airspeed Display in the Integrated Flight Display

Kinds of Airspeed

There are three kinds of airspeed that the pilot should understand:

- Indicated Airspeed
- Calibrated Airspeed
- True Airspeed

Indicated Airspeed

Indicated airspeed (IAS) is the direct instrument reading obtained from the airspeed indicator, uncorrected for variations in atmospheric density, installation error, or instrument error. This is the airspeed shown on the displays in Fig 3-4 and 3-4b.

Calibrated Airspeed

Calibrated airspeed (CAS) is indicated airspeed corrected for installation error and instrument error. Although manufacturers attempt to keep airspeed errors to a minimum, it is not possible to eliminate all errors throughout the airspeed operating range. At certain airspeeds and with certain flap settings, the installation and instrument error may be several miles per hour. This error is generally greatest at low airspeeds. In the cruising and higher airspeed ranges, indicated airspeed and calibrated airspeed are approximately the same.

It may be important to refer to the airspeed calibration chart to correct for possible airspeed errors because airspeed limitations such as those found on the color-coded face of the airspeed indicator, on placards in the cockpit, or in the Airplane Flight Manual or Owner's Handbook are usually calibrated airspeeds. Some manufacturers use indicated rather than calibrated airspeed to denote the airspeed limitations mentioned.

The airspeed indicator should be calibrated periodically because leaks may develop or moisture may collect in the tubing. Dirt, dust, ice, or snow collecting at the mouth of the tube may obstruct air passage and prevent correct indications, and also vibrations may destroy the sensitivity of the diaphragm.

True Airspeed

The true airspeed indicator (TAS) is calibrated to indicate true airspeed under standard sea level conditions—that is, 29.92 in. Hg. and 15° C. Because air density decreases with an increase in altitude, the airplane has to be flown faster at higher altitudes to cause the same pressure difference between pitot impact pressure and static pressure. Therefore, for a given true airspeed, indicated airspeed decreases as altitude increases or for a given indicated airspeed, true airspeed increases with an increase in altitude.

A pilot can find true airspeed by two methods. The first method, which is more accurate, involves using a computer. In this method, the calibrated airspeed is corrected for temperature and pressure variation by using the airspeed correction scale on the computer.
A second method, which is a "rule of thumb," can be used to compute the approximate true airspeed. This is done by adding to the indicated airspeed 2 percent of the indicated airspeed for each 1,000 feet of altitude.

Airspeed Indicator Markings

Airplanes weighing 12,500 pounds or less, manufactured after 1945 and certificated by the FAA, are required to have airspeed indicators that conform in a standard color-coded marking system. This system of color-coded markings enables the pilot to determine at a glance certain airspeed limitations which are important to the safe operation of the aircraft. For example, if during the execution of a maneuver, the pilot notes that the airspeed needle is in the yellow arc and is rapidly approaching the red line, immediate corrective action to reduce the airspeed should be taken. It is essential at high airspeed that the pilot use smooth control pressures to avoid severe stresses upon the aircraft structure. [Figures 3-4 and 3-4b]

Regardless of the make or model of aeroplane, the colored bands on the airspeed indicator of an FAA/Transport Canada certified aeroplane have the same meaning, although the numbers may vary. Thus, airspeed indicators are not interchangeable from one aeroplane to another. The following is a description of the standard color-code markings on airspeed indicators used on single-engine light aeroplanes:

- **FLAP OPERATING RANGE** (the white arc).
- **POWER-OFF STALLING SPEED WITH THE WING FLAPS AND LANDING GEAR IN THE LANDING POSITION** (the lower limit of the white arc).
- **MAXIMUM FLAPS EXTENDED SPEED** (the upper limit of the white arc). This is the highest airspeed at which the pilot should extend full flaps. If flaps are operated at higher airspeeds, severe strain or structural failure could result.
- **NORMAL OPERATING RANGE** (the green arc).
- **POWER-OFF STALLING SPEED WITH THE WING FLAPS AND LANDING GEAR RETRACTED** (the lower limit of the green arc).
- **MAXIMUM STRUCTURAL CRUISING SPEED** (the upper limit of the green arc). This is the maximum speed for normal operation.
- **CAUTION RANGE** (the yellow arc). The pilot should avoid this area unless in smooth air.
- **NEVER-EXCEED SPEED** (the red line). This is the maximum speed at which the airplane can be operated in smooth air. This speed should never be exceeded intentionally.

Other Airspeed Limitations

The above markings are the minimu standard. There are other important airspeed limitations not marked on the face of the airspeed indicator. These speeds are generally found on placards in view of the pilot and in the *Airplane Flight Manual* or *Pilot's Operating Handbook*.

One example is the **MANEUVERING SPEED**. This is the "rough air" speed and the maximum speed for abrupt maneuvers. If during flight, rough air or severe turbulence is encountered, the airspeed should be reduced to maneuvering speed or less to minimize the stress on the airplane structure.

Other important airspeeds include **LANDING GEAR OPERATING SPEED**, the maximum speed for extending or retracting the landing gear if using aircraft equipped with retractable landing gear; the **BEST ANGLE-OF-CLIMB SPEED**, important when a short-field takeoff to clear an obstacle is required; and the **BEST RATE-OF-CLIMB SPEED**, the airspeed that will give the pilot the most altitude in a given period of time. The pilot who flies the increasingly popular light twin-engine aircraft must know the aircraft's **MINIMUM CONTROL SPEED**, the minimum flight speed at which the aircraft is satisfactorily controllable when an engine is suddenly made inoperative with the remaining engine at takeoff power. The last two airspeeds are now marked either on the face of the airspeed indicator or on the instrument panel of recently manufactured airplanes.

Descriptions of these airspeed limitations areintentionally limited to layman's language to minimize confusion. The following are abbreviations for performance speeds:

Va—design maneuvering speed.
Vc—design cruising speed.
Vf—design flap speed.
Vfe—maximum flap extended speed.
Vle—maximum landing gear extended speed.
Vlo—maximum landing gear operating speed.
Vlof—lift-off speed.
Vne—never-exceed speed.
Vr—rotation speed.
Vs—the stalling speed or the minimum steady flight speed at which the airplane is controllable.
Vso—the stalling speed or the minimum steady flight speed in the landing configuration.
VS1—the stalling speed or the minimum steady flight speed obtained in a specified configuration.
VX—speed for best angle of climb.
VY—speed for best rate of climb.

GYROSCOPIC FLIGHT INSTRUMENTS

Several flight instruments utilize the properties of a gyroscope for their operation. The most common instruments containing gyroscopes are the turn coordinator, heading indicator, and the attitude indicator. To understand how these instruments operate requires a knowledge of the instrument power systems, gyroscopic principles, and the operating principles of each instrument.

Sources of Power for Gyroscopic Operation

In some airplanes, all the gyros are vacuum, pressure, or electrically operated; in others, vacuum, or pressure systems provide the power for the heading and attitude indicators, while the electrical system provides the power for the turn coordinator.

Vacuum or Pressure System

The vacuum or pressure system spins the gyro by drawing a stream of air against the rotor vanes to spin the rotor at high speeds essentially the same as a water wheel or turbine operates. The amount of vacuum or pressure required for instrument operation varies with manufacture and is usually between 4.5 to 5.5 in. Hg.

Engine-Driven Vacuum Pump

One source of vacuum for the gyros installed in light aircraft is the vane-type engine-driven pump which is mounted on the accessory case of the engine. Pump capacity varies in different aircraft, depending on the number of gyros to be operated.
A typical vacuum system consists of an engine-driven vacuum pump, regulator, air filter, gauge, tubing, and manifolds necessary to complete the connections. The gauge is mounted in the airplane instrument panel and indicates the amount of pressure in the system.

The air filter prevents foreign matter from entering the vacuum or pressure system. Airflow is reduced as the master filter becomes dirty; this results in a lower reading on the vacuum or pressure gauge.

Gyroscopic Principles

Any spinning object exhibits gyroscopic properties; however, a wheel designed and mounted to utilize these properties is called a gyroscope. Two important design characteristics of an instrument gyro are great weight or high density for size and rotation at high speeds with low friction bearings. The mountings of the gyro wheels are called "gimbals" which may be circular rings, rectangular frames, or a part of the instrument case itself.

There are two general types of mountings; the type used depends upon which property of the gyro is utilized. A freely or universally mounted gyroscope is free to rotate in any direction about its center of gravity. Such a wheel is said to have three planes of freedom. The wheel or rotor is free to rotate in any plane in relation to the base and is so balanced that with the gyro wheel at rest, it will remain in the position in which it is placed. Restricted or semirigidly mounted gyroscopes are those mounted so that one of the planes of freedom is held fixed in relation to the base.

There are two fundamental properties of gyroscopic action; rigidity in space, and precession.

Rigidity in space can best be explained by applying Newton's First Law of Motion which states, "a body at rest will remain at rest; or if in motion in a straight line, it will continue in a straight line unless acted upon by an outside force." An example of this law is the rotor of a universally mounted gyro. When the wheel is spinning, it exhibits the ability to remain in its original plane of rotation regardless of how the base is moved. However, since it is impossible to design bearings without some friction present, there will be some deflective force upon the wheel.

The flight instruments using the gyroscopic property of rigidity for their operation are the attitude indicator and the heading indicator; therefore, their rotors must be freely or universally mounted.

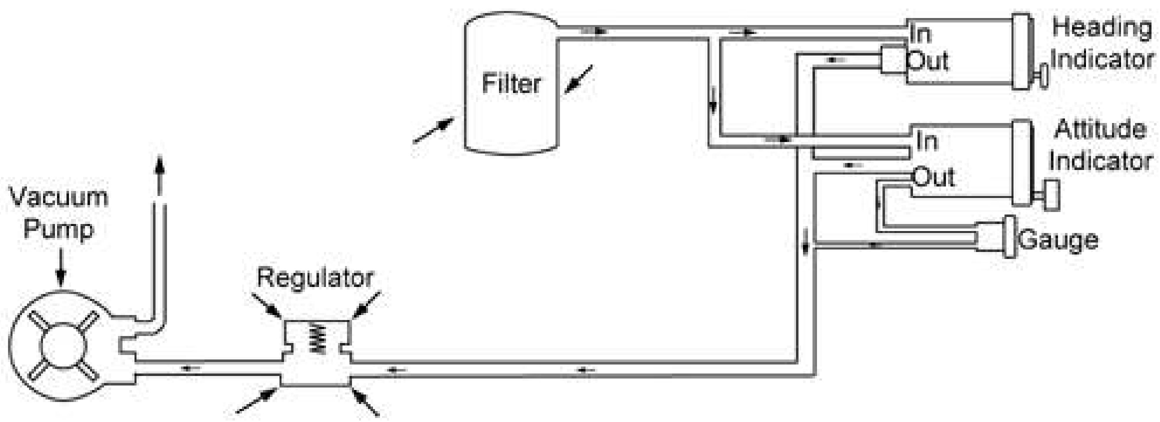

Figure 3-5.—Typical pump-driven vacuum system.

With the Integrated Flight Display (available only on new certified aircraft and some high-performance homebuilts), the "indicators" in the above diagram are replaced with a display computer which processes the pressures at each connection and generates the inputs for the cockpit display screen. All other aerodynamic phenomena are identical for both types of display system. The only thing that is different is the integration of the individual display units. Both systems are equally subject to physical phenomena such as precession, and both have to be

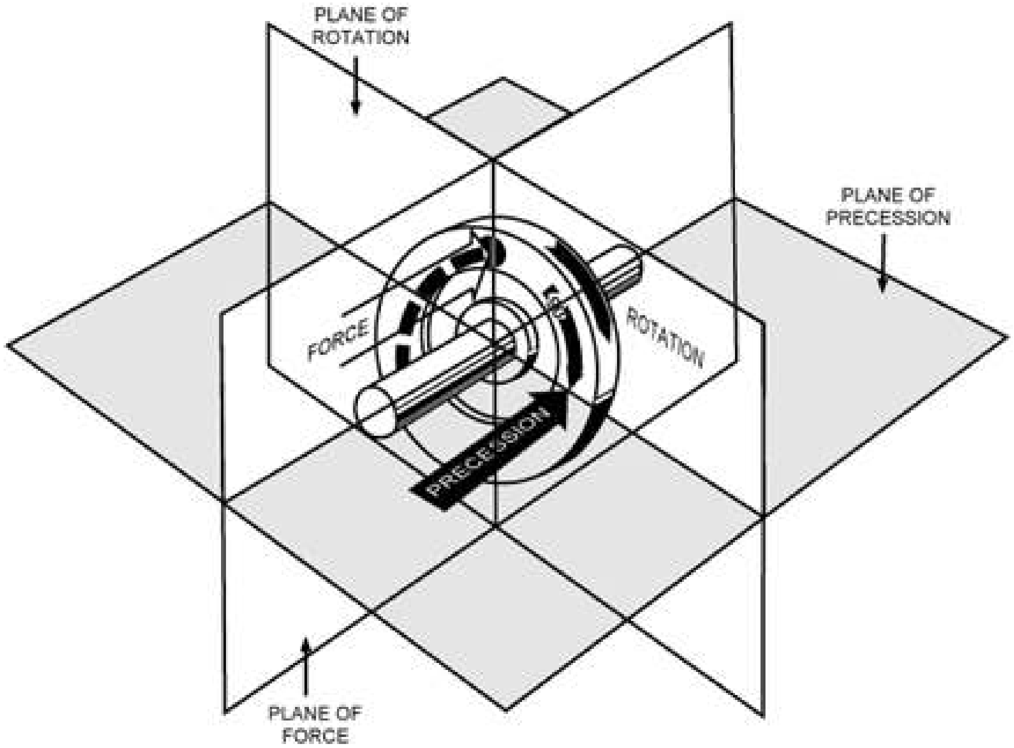

Figure 3-6.—Precession of a gyroscope resulting from an applied deflective force.

The second property of a gyroscope - *precession* - is the resultant action or deflection of a spinning wheel when a deflective force is applied to its rim. When a deflective force is applied to the rim of a rotating wheel, the resultant force is 90° ahead in the direction of rotation and in the direction of the applied force. The rate at which the wheel precesses is inversely proportional to the speed of the rotor and proportional to the deflective force. The force with which the wheel precesses is the same as the deflective force applied (minus the friction in the bearings). If too great a deflective force is applied for the amount of rigidity in the wheel, the wheel precesses and topples over at the same time. [Figure 3-6]

Turn Coordinator

The turn coordinator shows the yaw and roll of the aircraft around the vertical and longitudinal axes.

When rolling in or rolling out of a turn, the miniature airplane banks in the direction of the turn. The miniature airplane does not indicate the angle of bank, but indicates the rate of turn. When aligned with the turn index, it represents a standard rate of turn of 3° per second. [Figure 3-7]

Figure 3-7.—Turn coordinator.

The inclinometer of the turn coordinator indicates the coordination of aileron and rudder. The ball indicates whether the airplane is in coordinated flight or is in a slip or skid. [Figure 3-8]

Figure 3-8.—Turn coordinator indications.

The Heading Indicator

The heading indicator (or directional gyro) is fundamentally a mechanical instrument designed to facilitate the use of the magnetic compass. Errors in the magnetic compass are numerous, making straight flight and precision turns to headings difficult to accomplish, particularly in turbulent air. A heading indicator, however, is not affected by the forces that make the magnetic compass difficult to interpret. [Figure 3-9]

The Integrated Flight Display does not have a Turn Coordinator.

Figure 3-9.—Heading indicator.

The operation of the heading indicator depends upon the principle of *rigidity in space*. The rotor turns in a vertical plane, and fixed to the rotor is a compass card. Since the rotor remains rigid in space, the points on the card hold the same position in space relative to the vertical plane. As the instrument case and the airplane revolve around the vertical axis, the card provides clear and accurate heading information.

Because of precession, caused chiefly by friction, the heading indicator will creep or drift from a heading to which it is set. Among other factors, the amount of drift depends largely upon the condition of the instrument. If the bearings are worn, dirty, or improperly lubricated, the drift may be excessive.
Bear in mind that the heading indicator is not direction-seeking, as is the magnetic compass. It is important to check the indications frequently and reset the heading indicator to align it with the magnetic compass when required. Adjusting the heading indicator to the magnetic compass heading should be done only when the airplane is in wings-level unaccelerated flight; otherwise erroneous magnetic compass readings may be obtained.

The bank and pitch limits of the heading indicator vary with the particular design and make of instrument. On some heading indicators found in light airplanes, the limits are approximately 55° of pitch and 55° of bank. When either of these attitude limits is exceeded, the instrument “tumbles” or “spills” and no longer gives the correct indication until reset. After spilling, it may be reset with the caging knob. Many of the modern instruments used are designed in such a manner that they will not tumble.

Fig 3-9b The Heading Indicator in the Integrated Flight Display

The Attitude Indicator
The attitude indicator, with its miniature aircraft and horizon bar, displays a picture of the attitude of the airplane. The relationship of the miniature aircraft to the horizon bar is the same as the relationship of the real aircraft to the actual horizon. The instrument gives an instantaneous indication of even the smallest changes in attitude. [Figure 3-10]

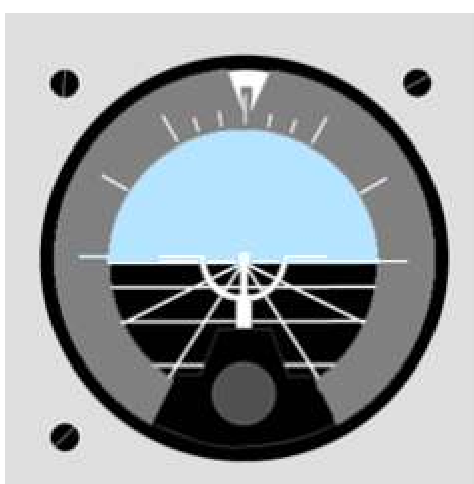

Figure 3-10.—Attitude indicator.

Figure 3-11.—Various indications on the attitude indicator.

The gyro in the attitude indicator is mounted on a horizontal plane and depends upon rigidity in space for its operation. The horizon bar represents the true horizon. This bar is fixed to the gyro and remains in a horizontal plane as the airplane is pitched or banked about its lateral or longitudinal axis, indicating the attitude of the airplane relative to the true horizon.

An adjustment knob is provided with which the pilot may move the miniature airplane up or down to align the miniature airplane with the horizon bar to suit the pilot's line of vision. Normally, the miniature airplane is adjusted so that the wings overlap the horizon bar when the airplane is in straight-and-level cruising flight.

The pitch and bank limits depend upon the make and model of the instrument. Limits in the banking plane are usually from 100° to 110°, and the pitch limits are usually from 60° to 70°. If either limit is exceeded, the instrument will tumble or spill and will give incorrect indications until restabilized. A number of modern attitude indicators will not tumble.

Every pilot should be able to interpret the banking scale. Most banking scale indicators on the top of the instrument move in the same direction from that in which the airplane is actually banked. Some other models move in the opposite direction from that in which the airplane is actually banked. This may confuse the pilot if the indicator is used to determine the direction of bank. This scale should be used only to control the degree of desired bank. The relationship of the miniature airplane to the horizon bar should be used for an indication of the direction of bank. [Figure 3-11]

The attitude indicator is reliable and the most realistic flight instrument on the instrument panel. Its indications are very close approximations of the actual attitude of the airplane.

MAGNETIC COMPASS

Since the magnetic compass works on the principle of magnetism, it is well for the pilot to have at least a basic understanding of magnetism. A simple bar magnet has two centers of magnetism which are called poles. Lines of magnetic force flow out from each pole in all directions, eventually bending around and returning to the other pole. The area through which these lines of force flow is called the field of the magnet. For the purpose of this discussion, the poles are designated "north" and "south." If two bar magnets are placed near each other, the north pole of one will attract the south pole of the other. There is evidence that there is a magnetic field surrounding the Earth, and this theory is applied in the design of the magnetic compass. It acts very much as though there were a huge bar magnet running along the axis of the Earth which ends several hundred miles below the surface. [Figure 3-12]

The lines of force have a vertical component (or pull) which is zero at the Equator but builds to 100 percent of the total force at the poles. If magnetic needles, such as the airplane magnetic compass bars, are held along these lines of force, the vertical component causes one end of the needle to dip or deflect downward. The amount of dip increases as the needles are moved closer and closer to the poles. It is this deflection or dip which causes some of the larger compass errors.

The magnetic compass, which is the only direction-seeking instrument in the airplane, is simple in construction. It contains two steel magnetized needles fastened to a float around which is mounted a compass card. The needles are parallel, with their north-seeking ends pointed in the same direction. The compass card has letters for cardinal headings, and each 30° interval is represented by a number, the last zero of which is omitted. For example, 30° would appear as a 3 and 300° would appear as 30. Between these numbers, the card is graduated for each 5°. [Figure 3-13]

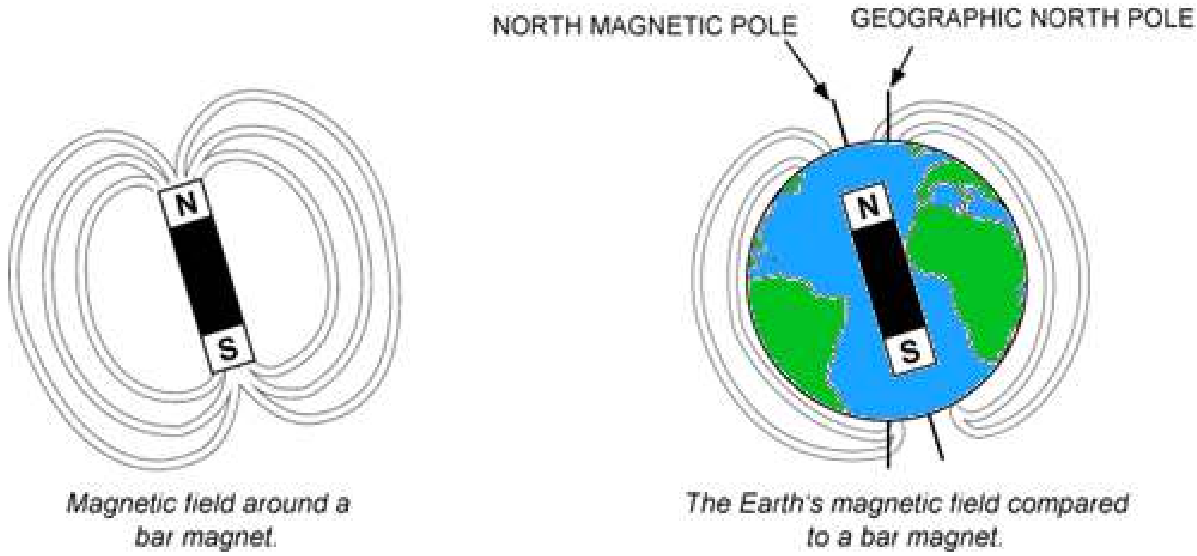

Figure 3-12.—Earth's magnetic field.

The float assembly is housed in a bowl filled with acid-free white kerosene. The purposes of the liquid are to dampen out excessive oscillations of the compass card and relieve by buoyancy part of the weight of the float from the bearings. Jewel bearings are used to mount the float assembly on top of a pedestal. A line (called the lubber line) is mounted behind the glass of the instrument that can be used for a reference line when aligning the headings on the compass card.

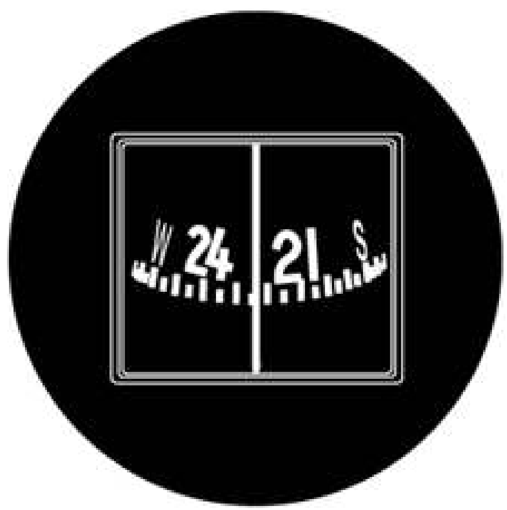

Figure 3-13.—Magnetic compass.

COMPASS ERRORS

Variation

Although the magnetic field of the Earth lies roughly north and south, the Earth's magnetic poles do not coincide with its geographic poles, which are used in the construction of aeronautical charts. Consequently, at most places on the Earth's surface, the direction-sensitive steel needles which seek the Earth's magnetic field will not point to True North but to Magnetic North. Furthermore, local magnetic fields from mineral deposits and other conditions may distort the Earth's magnetic field and cause an additional error in the position of the compass' north-seeking magnetized needles with reference to True North. The angular difference between True North and the direction indicated by the magnetic compass—excluding deviation error—is variation. Variation is different for different points on the Earth's surface and is shown on the aeronautical charts as broken lines connecting points of equal variation. These lines are isogonic lines. The line where the magnetic variation is zero is an agonic line. Variation will be discussed further in Chapter 8 (Navigation).

Deviation

Actually, a compass is very rarely influenced solely by the Earth's magnetic lines of force. Magnetic disturbances from magnetic fields produced by metals and electrical accessories in an aircraft disturb the compass needles and produce an additional error. The difference between the direction indicated by a magnetic compass not installed in an airplane, and one installed in an airplane, is deviation.
If an aircraft changes heading, the compass' direction-sensitive magnetized needles will continue to point in about the same direction while the aircraft turns with relation to it. As the aircraft turns, metallic and electrical equipment in the aircraft change their position relative to the steel needles; hence, their influence on the compass needle changes and deviation changes. Thus, deviation depends, in part, on the heading of the aircraft. Although compensating magnets on the compass are adjusted to reduce this deviation on most headings, it is impossible to eliminate this error entirely on all headings. Therefore, a deviation card, installed in the cockpit in view of the pilot, enables the pilot to maintain the desired magnetic headings. Deviation will be discussed further in Chapter 8 (Navigation).

Using the Magnetic Compass

Since the magnetic compass is the only direction-seeking instrument in most airplanes, the pilot must be able to turn the airplane to a magnetic compass heading and maintain this heading. It's helpful to remember the following characteristics of the magnetic compass which are caused by magnetic dip. These characteristics are only applicable in the Northern Hemisphere. In the Southern Hemisphere the opposite is true.

Compass Turning Error

- If on a northerly heading and a turn is made toward east or west, the initial indication of the compass lags or indicates a turn in the opposite direction. This lag diminishes as the turn progresses toward east or west (where there is no turn error).
- If on a southerly heading and a turn is made toward the east or west, the initial indication of the compass needle will indicate a greater amount of turn than is actually made. This lead also diminishes as the turn progresses toward east or west where there is no turn error.
- If a turn is made to a northerly heading from any direction, the compass indication when approaching north lags behind the turn. Therefore, the rollout of the turn is made before the desired heading is reached.
- If a turn is made to a southerly heading from any direction, the compass indication when approaching southerly headings leads behind the turn. Therefore, the rollout is made after the desired heading is passed. The amount of lead or lag is maximum on the north-south headings and depends upon the angle of bank used and geographic position of the airplane with regard to latitude.

Compass Acceleration Error:

- When on an east or west heading, no error is apparent while entering a turn to north or south; however, an increase in airspeed or acceleration will cause the compass to indicate a turn toward north; a decrease in airspeed or acceleration will cause the compass to indicate a turn toward south.
- If on a north or south heading, no error will be apparent because of acceleration or deceleration.

Reading the Compass

The magnetic compass should be read only when the aircraft is flying straight and level at a constant speed. The compass is extremely erratic in any other flight condition! Following this simple rule will help reduce navigation errors to a minimum.

If the pilot thoroughly understands the errors and characteristics of the magnetic compass, this instrument can become the most reliable means of determining headings.