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Instrument Flying Handbook

U.S. Department
of Transportation
FEDERAL AVIATION ADMINISTRATION

Instrument Flying Handbook

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U.S. Department of Transportation
FEDERAL AVIATION ADMINISTRATION
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Preface

This Instrument Flying Handbook is designed for use by instrument flight instructors and pilots preparing for instrument rating tests. Instructors may find this handbook a valuable training aid as it includes basic reference material for knowledge testing and instrument flight training. Other Federal Aviation Administration (FAA) publications should be consulted for more detailed information on related topics.

This handbook conforms to pilot training and certification concepts established by the FAA. There are different ways of teaching, as well as performing, flight procedures and maneuvers and many variations in the explanations of aerodynamic theories and principles. This handbook adopts selected methods and concepts for instrument flying. The discussion and explanations reflect the most commonly used practices and principles. Occasionally the word "must" or similar language is used where the desired action is deemed critical. The use of such language is not intended to add to, interpret, or relieve a duty imposed by Title 14 of the Code of Federal Regulations (14 CFR).

All of the aeronautical knowledge and skills required to operate in instrument meteorological conditions (IMC) are detailed. Chapters are dedicated to human and aerodynamic factors affecting instrument flight, the flight instruments, attitude instrument flying for airplanes, basic flight maneuvers used in IMC, attitude instrument flying for helicopters, navigation systems, the National Airspace System (NAS), the air traffic control (ATC) system, instrument flight rules (IFR) flight procedures, and IFR emergencies. Clearance shorthand and an integrated instrument lesson guide are also included.

This handbook supersedes FAA-H-8081-15, Instrument Flying Handbook, dated 2001.

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http://bookstore.gpo.gov

This handbook is also available for download, in PDF format, from the Regulatory Support Division's (AFS-600) web site.

http://www.faa.gov/about/office_org/headquarters_offices/avs/offices/afs/afs600

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Introduction

Is an Instrument Rating Necessary?

The answer to this question depends entirely upon individual needs. Pilots may not need an instrument rating if they fly in familiar uncongested areas, stay continually alert to weather developments, and accept an alternative to their original plan. However, some cross-country destinations may take a pilot to unfamiliar airports and/or through high activity areas in marginal visual or instrument meteorological conditions (IMC). Under these conditions, an instrument rating may be an alternative to rerouting, rescheduling, or canceling a flight. Many accidents are the result of pilots who lack the necessary skills or equipment to fly in marginal visual meteorological conditions (VMC) or IMC and attempt flight without outside references.

Pilots originally flew aircraft strictly by sight, sound, and feel while comparing the aircraft's attitude to the natural horizon. As aircraft performance increased, pilots required more inflight information to enhance the safe operation of their aircraft. This information has ranged from a string tied to a wing strut, to development of sophisticated electronic flight information systems (EFIS) and flight management systems (FMS). Interpretation of the instruments and aircraft control have advanced from the "one, two, three" or "needle, ball, and airspeed" system to the use of "attitude instrument flying" techniques.

Navigation began by using ground references with dead reckoning and has led to the development of electronic navigation systems. These include the automatic direction finder (ADF), very-high frequency omnidirectional range (VOR), distance measuring equipment (DME), tactical air navigation (TACAN), long range navigation (LORAN), global positioning system (GPS), instrument landing system (ILS), microwave landing system (MLS), and inertial navigation system (INS).

Perhaps you want an instrument rating for the same basic reason you learned to fly in the first place—because you like flying. Maintaining and extending your proficiency, once you have the rating, means less reliance on chance and more on skill and knowledge. Earn the rating—not because you might need it sometime, but because it represents achievement and provides training you will use continually and build upon as long as you fly. But most importantly it means greater safety in flying.

Instrument Rating Requirements

A private or commercial pilot must have an instrument rating and meet the appropriate currency requirements if that pilot operates an aircraft using an instrument flight rules (IFR) flight plan in conditions less than the minimums prescribed for visual flight rules (VFR), or in any flight in Class A airspace.

You will need to carefully review the aeronautical knowledge and experience requirements for the instrument rating as outlined in Title 14 of the Code of Federal Regulations (14 CFR) part 61. After completing the Federal Aviation Administration (FAA) Knowledge Test issued for the instrument rating, and all the experience requirements have been satisfied, you are eligible to take the practical test. The regulations specify minimum total and pilot-in-command time requirements. This minimum applies to all applicants regardless of ability or previous aviation experience.

Training for the Instrument Rating

A person who wishes to add the instrument rating to his or her pilot certificate must first make commitments of time, money, and quality of training. There are many combinations of training methods available. Independent studies may be adequate preparation to pass the required FAA Knowledge Test for the instrument rating. Occasional periods of ground and flight instruction may provide the skills necessary to pass the required test. Or, individuals may choose a training facility that provides comprehensive aviation education and the training necessary to ensure the pilot will pass all the required tests and operate safely in the National Airspace System (NAS). The aeronautical knowledge may be administered by educational institutions, aviation-oriented schools, correspondence courses, and appropriately rated instructors. Each person must decide for themselves which training program best meets his or her needs and at the same time maintain a high quality of training. Interested persons should make inquiries regarding the available training at nearby airports, training facilities, in aviation publications, and through the FAA Flight Standards District Office (FSDO).

Although the regulations specify minimum requirements, the amount of instructional time needed is determined not by the regulation, but by the individual's ability to achieve a satisfactory level of proficiency. A professional pilot with diversified flying experience may easily attain a satisfactory level of proficiency in the minimum time required by regulation. Your own time requirements will depend upon a variety of factors, including previous flying experience, rate of learning, basic ability, frequency of flight training, type of aircraft flown, quality of ground school training, and quality of flight instruction, to name a few. The total instructional time you will need, the scheduling of such time, is up to the individual most qualified to judge your proficiency—the instructor who supervises your progress and endorses your record of flight training.

You can accelerate and enrich much of your training by informal study. An increasing number of visual aids and programmed instrument courses is available. The best course is one that includes a well-integrated flight and ground school curriculum. The sequential nature of the learning process requires that each element of knowledge and skill be learned and applied in the right manner at the right time.

Part of your instrument training may utilize a flight simulator, flight training device, or a personal computer-based aviation training device (PCATD). This ground-based flight training equipment is a valuable tool for developing your instrument cross-check and learning procedures, such as intercepting and tracking, holding patterns, and instrument approaches. Once these concepts are fully understood, you can then continue with inflight training and refine these techniques for full transference of your new knowledge and skills.

Holding the instrument rating does not necessarily make you a competent all-weather pilot. The rating certifies only that you have complied with the minimum experience requirements, that you can plan and execute a flight under IFR, that you can execute basic instrument maneuvers, and that you have shown acceptable skill and judgment in performing these activities. Your instrument rating permits you to fly into instrument weather conditions with no previous instrument weather experience. Your instrument rating is issued on the assumption that you have the good judgment to avoid situations beyond your capabilities. The instrument training program you undertake should help you to develop not only essential flying skills but also the judgment necessary to use the skills within your own limits.

Regardless of the method of training selected, the curriculum in Appendix B, Instrument Training Lesson Guide, provides guidance as to the minimum training required for the addition of an instrument rating to a private or commercial pilot certificate.

Maintaining the Instrument Rating

Once you hold the instrument rating, you may not act as pilot-in-command under IFR or in weather conditions less than the minimums prescribed for VFR, unless you meet the recent flight experience requirements outlined in 14 CFR part 61. These procedures must be accomplished within the preceding 6 months and include six instrument approaches, holding procedures, and intercepting and tracking courses through the use of navigation systems. If you do not meet the experience requirements during these 6 months, you have another 6 months to meet these minimums. If the requirements are still not met, you must pass an instrument proficiency check, which is an inflight evaluation by a qualified instrument flight instructor using tasks outlined in the instrument rating practical test standards (PTS).

The instrument currency requirements must be accomplished under actual or simulated instrument conditions. You may log instrument flight time during the time for which you control the aircraft solely by reference to the instruments. This can be accomplished by wearing a view-limiting device, such as a hood, flying an approved flight-training device, or flying in actual IMC.

It takes only one harrowing experience to clarify the distinction between minimum practical knowledge and a thorough understanding of how to apply the procedures and techniques used in instrument flight. Your instrument training is never complete; it is adequate when you have absorbed every foreseeable detail of knowledge and skill to ensure a solution will be available if and when you need it.

Table of Contents

Chapter 2

Aerodynamic Factors..2-1

Chapter 3

Flight Instruments..3-1

Chapter 8
The National Airspace System 8-1

Chapter 9
The Air Traffic Control System...........................9-1

Chapter 10

Chapter 11

Chapter 1

Human Factors

Introduction

Human factors is a broad field that examines the interaction between people, machines, and the environment for the purpose of improving performance and reducing errors. As aircraft became more reliable and less prone to mechanical failure, the percentage of accidents related to human factors increased. Some aspect of human factors now accounts for over 80 percent of all accidents. Pilots who have a good understanding of human factors are better equipped to plan and execute a safe and uneventful flight.

Flying in instrument meteorological conditions (IMC) can result in sensations that are misleading to the body's sensory system. A safe pilot needs to understand these sensations and effectively counteract them. Instrument flying requires a pilot to make decisions using all available resources.

The elements of human factors covered in this chapter include sensory systems used for orientation, illusions in flight, physiological and psychological factors, medical factors, aeronautical decision-making, and crew resource management (CRM).

Sensory Systems for Orientation

Orientation is the awareness of the position of the aircraft and of oneself in relation to a specific reference point. Disorientation is the lack of orientation, and spatial disorientation specifically refers to the lack of orientation with regard to position in space and to other objects.

Orientation is maintained through the body's sensory organs in three areas: visual, vestibular, and postural. The eyes maintain visual orientation. The motion sensing system in the inner ear maintains vestibular orientation. The nerves in the skin, joints, and muscles of the body maintain postural orientation. When healthy human beings are in their natural environment, these three systems work well. When the human body is subjected to the forces of flight, these senses can provide misleading information. It is this misleading information that causes pilots to become disoriented.

Eyes

Of all the senses, vision is most important in providing information to maintain safe flight. Even though the human eye is optimized for day vision, it is also capable of vision in very low light environments. During the day, the eye uses receptors called cones, while at night, vision is facilitated by the use of rods. Both of these provide a level of vision optimized for the lighting conditions that they were intended. That is, cones are ineffective at night and rods are ineffective during the day.

Rods, which contain rhodopsin (called visual purple), are especially sensitive to light and increased light washes out the rhodopsin compromising the night vision. Hence, when strong light is momentarily introduced at night, vision may be totally ineffective as the rods take time to become effective again in darkness. Smoking, alcohol, oxygen deprivation, and age affect vision, especially at night. It should be noted that at night, oxygen deprivation such as one caused from a climb to a high altitude causes a significant reduction in vision. A return back to the lower altitude will not restore a pilot's vision in the same transitory period used at the climb altitude.

The eye also has two blind spots. The day blind spot is the location on the light sensitive retina where the optic nerve fiber bundle (which carries messages from the eye to the brain) passes through. This location has no light receptors, and a message cannot be created there to be sent to the brain. The night blind spot is due to a concentration of cones in an area surrounding the fovea on the retina. Because there are no rods in this area, direct vision on an object at night will disappear. As a result, off-center viewing and scanning at night is best for both obstacle avoidance and to maximize situational awareness. [See the Pilot's Handbook of Aeronautical Knowledge and the Aeronautical Information Manual (AIM) for detailed reading.]

The brain also processes visual information based upon color, relationship of colors, and vision from objects around us. *Figure 1-1* demonstrates the visual processing of information. The brain assigns color based on many items to include an object's surroundings. In the figure below, the orange square on the shaded side of the cube is actually the same color as the brown square in the center of the cube's top face.

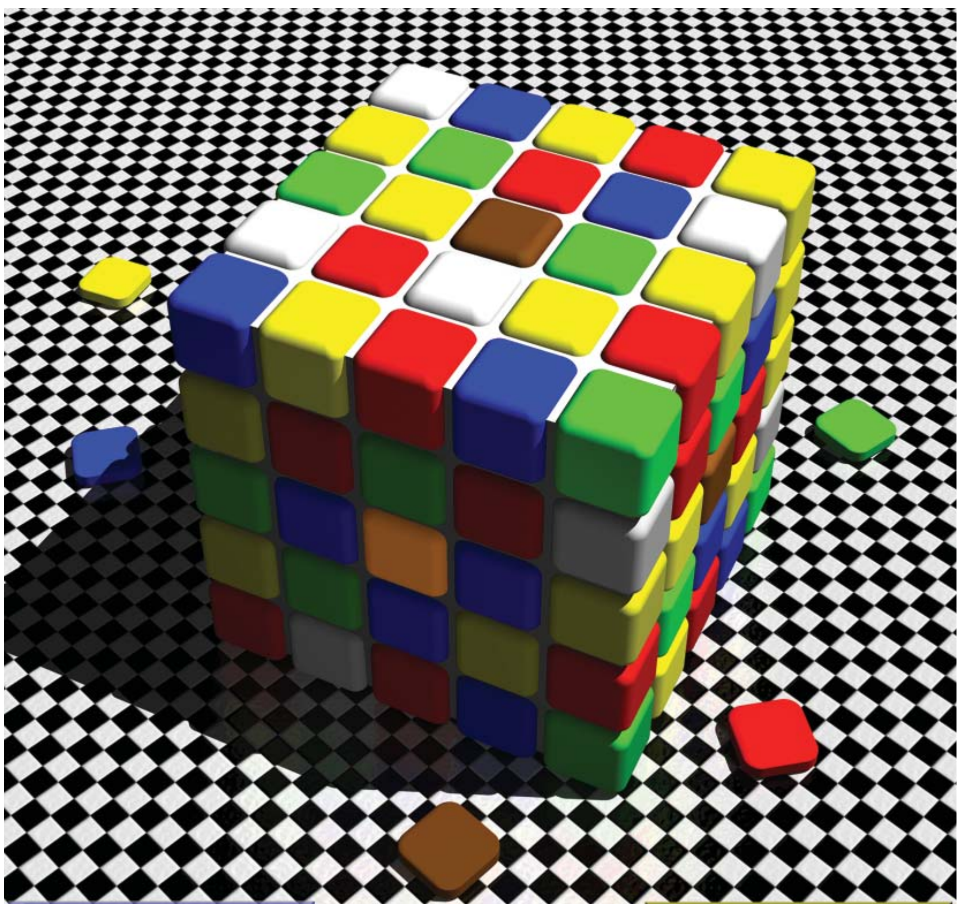


Figure 1-1. *Rubic's Cube Graphic.*

Isolating the orange square from surrounding influences will reveal that it is actually brown. The application to a real environment is evident when processing visual information that is influenced by surroundings. The ability to pick out an airport in varied terrain or another aircraft in a light haze are examples of problems with interpretation that make vigilance all the more necessary.

Figure 1-2 illustrates problems with perception. Both tables are the same lengths. Objects are easily misinterpreted in size to include both length and width. Being accustomed to a 75-foot-wide runway on flat terrain is most likely going to influence a pilot's perception of a wider runway on uneven terrain simply because of the inherent processing experience.

Vision Under Dim and Bright Illumination

Under conditions of dim illumination, aeronautical charts and aircraft instruments can become unreadable unless adequate flight deck lighting is available. In darkness, vision becomes more sensitive to light. This process is called dark adaptation. Although exposure to total darkness for at least 30 minutes is required for complete dark adaptation, a pilot can achieve a moderate degree of dark adaptation within 20 minutes under dim red flight deck lighting.

Red light distorts colors (filters the red spectrum), especially on aeronautical charts, and makes it very difficult for the eyes to focus on objects inside the aircraft. Pilots should use it only where optimum outside night vision capability is necessary. White flight deck lighting (dim lighting) should be available when needed for map and instrument reading, especially under IMC conditions.

Since any degree of dark adaptation is lost within a few seconds of viewing a bright light, pilots should close one eye when using a light to preserve some degree of night vision. During night flights in the vicinity of lightning, flight deck lights should be turned up to help prevent loss of night vision due to the bright flashes. Dark adaptation is also impaired by exposure to cabin pressure altitudes above 5,000 feet, carbon monoxide inhaled through smoking, deficiency of Vitamin A in the diet, and by prolonged exposure to bright sunlight.

During flight in visual meteorological conditions (VMC), the eyes are the major orientation source and usually provide accurate and reliable information. Visual cues usually prevail over false sensations from other sensory systems. When these visual cues are taken away, as they are in IMC, false sensations can cause the pilot to quickly become disoriented.

An effective way to counter these false sensations is to recognize the problem, disregard the false sensations, rely on the flight instruments, and use the eyes to determine the aircraft attitude. The pilot must have an understanding of the problem and the skill to control the aircraft using only instrument indications.

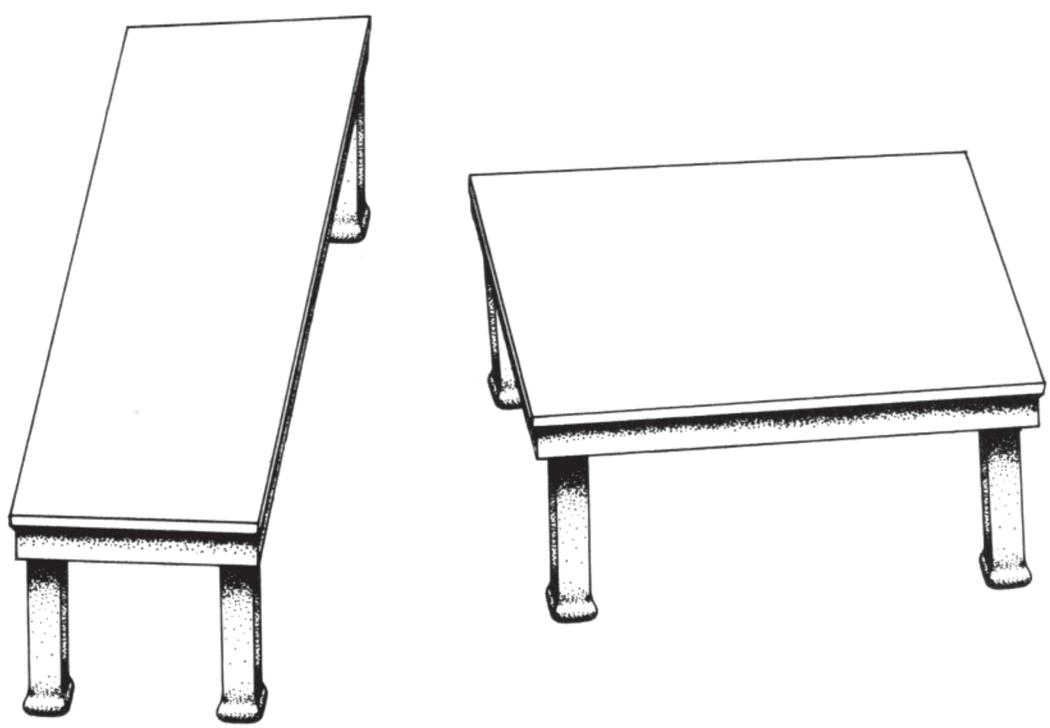


Figure 1-2. *Shepard's Tables.*

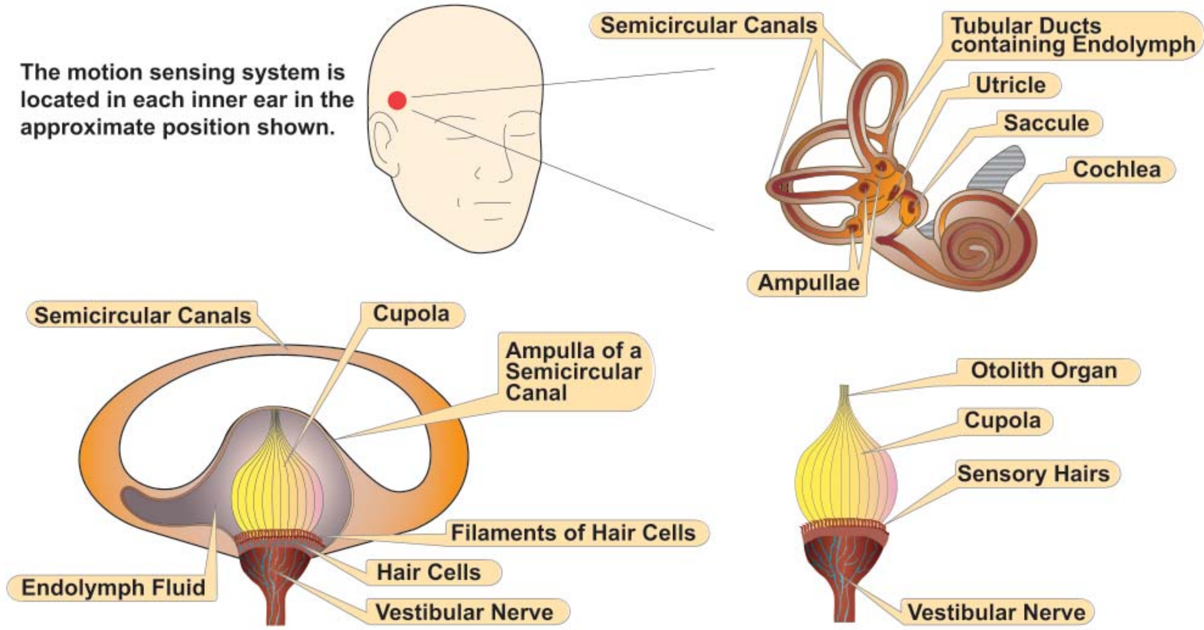


Figure 1-3. *Inner Ear Orientation.*

Ears

The inner ear has two major parts concerned with orientation, the semicircular canals and the otolith organs. *[Figure 1-3]* The semicircular canals detect angular acceleration of the body while the otolith organs detect linear acceleration and gravity. The semicircular canals consist of three tubes at right angles to each other, each located on one of three axes: pitch, roll, or yaw as illustrated in *Figure 1-4*. Each canal is filled with a fluid called endolymph fluid. In the center of the canal is the cupola, a gelatinous structure that rests upon sensory hairs located at the end of the vestibular nerves. It is the movement of these hairs within the fluid which causes sensations of motion.

Because of the friction between the fluid and the canal, it may take about 15–20 seconds for the fluid in the ear canal to reach the same speed as the canal's motion.

To illustrate what happens during a turn, visualize the aircraft in straight and level flight. With no acceleration of the aircraft, the hair cells are upright and the body senses that no turn has occurred. Therefore, the position of the hair cells and the actual sensation correspond.

Placing the aircraft into a turn puts the semicircular canal and its fluid into motion, with the fluid within the semicircular canal lagging behind the accelerated canal walls.*[Figure 1-5]* This lag creates a relative movement of the fluid within the canal. The canal wall and the cupula move in the opposite direction from the motion of the fluid.

The brain interprets the movement of the hairs to be a turn in the same direction as the canal wall. The body correctly senses that a turn is being made. If the turn continues at a constant rate for several seconds or longer, the motion of the fluid in

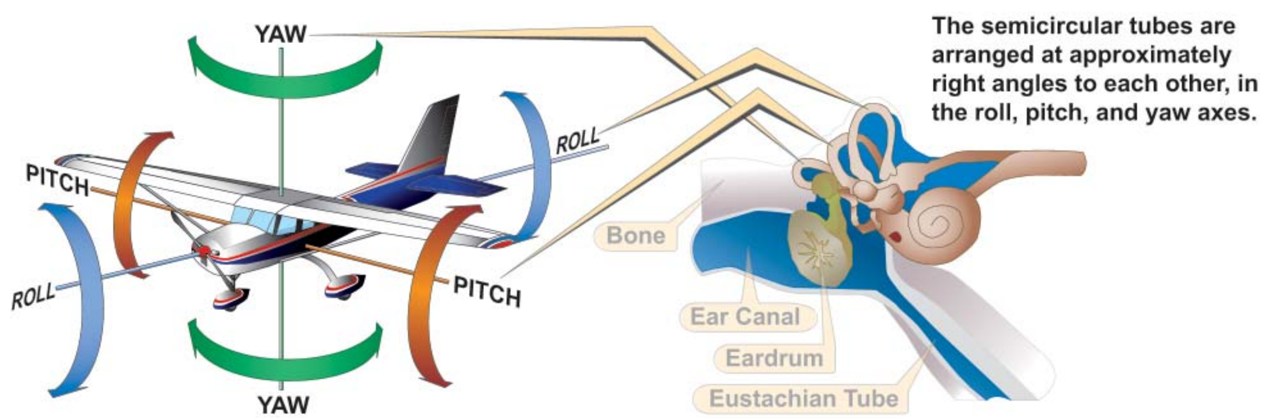


Figure 1-4. *Angular Acceleration and the Semicircular Tubes.*

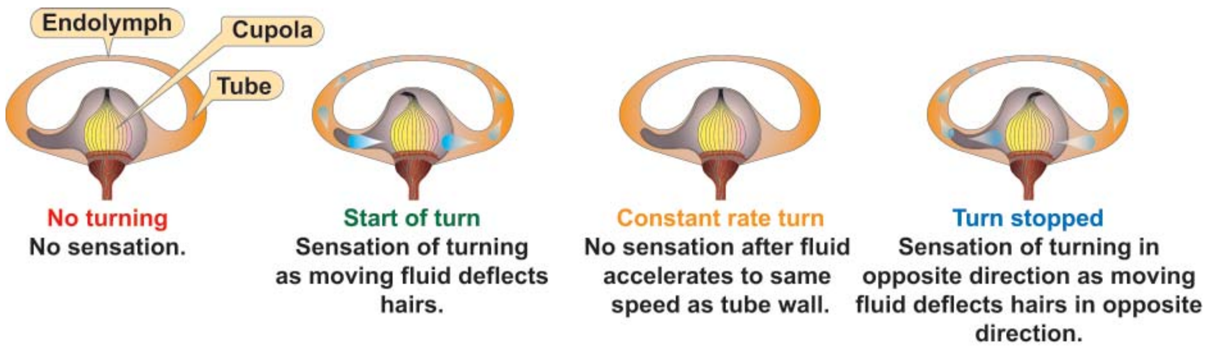


Figure 1-5. *Angular Acceleration.*

the canals catches up with the canal walls. The hairs are no longer bent, and the brain receives the false impression that turning has stopped. Thus, the position of the hair cells and the resulting sensation during a prolonged, constant turn in either direction will result in the false sensation of no turn.

When the aircraft returns to straight-and-level flight, the fluid in the canal moves briefly in the opposite direction. This sends a signal to the brain that is falsely interpreted as movement in the opposite direction. In an attempt to correct the falsely perceived turn, the pilot may reenter the turn placing the aircraft in an out of control situation.

The otolith organs detect linear acceleration and gravity in a similar way. Instead of being filled with a fluid, a gelatinous membrane containing chalk-like crystals covers the sensory hairs. When the pilot tilts his or her head, the weight of these crystals causes this membrane to shift due to gravity and the sensory hairs detect this shift. The brain orients this new position to what it perceives as vertical. Acceleration and deceleration also cause the membrane to shift in a similar manner. Forward acceleration gives the illusion of the head tilting backward. *[Figure 1-6]* As a result, during takeoff and while accelerating, the pilot may sense a steeper than normal climb resulting in a tendency to nose-down.

Nerves

Nerves in the body's skin, muscles, and joints constantly send signals to the brain, which signals the body's relation to gravity. These signals tell the pilot his or her current position. Acceleration will be felt as the pilot is pushed back into the seat. Forces created in turns can lead to false sensations of the true direction of gravity, and may give the pilot a false sense of which way is up.

Uncoordinated turns, especially climbing turns, can cause misleading signals to be sent to the brain. Skids and slips give the sensation of banking or tilting. Turbulence can create motions that confuse the brain as well. Pilots need to be aware that fatigue or illness can exacerbate these sensations and ultimately lead to subtle incapacitation.

Illusions Leading to Spatial Disorientation

The sensory system responsible for most of the illusions leading to spatial disorientation is the vestibular system. Visual illusions can also cause spatial disorientation.

Vestibular Illusions

The Leans

A condition called the leans can result when a banked attitude, to the left for example, may be entered too slowly to set in motion the fluid in the "roll" semicircular tubes. *[Figure 1-5]* An abrupt correction of this attitude sets the fluid in motion, creating the illusion of a banked attitude to the right. The disoriented pilot may make the error of rolling the aircraft into the original left banked attitude, or if level flight is maintained, will feel compelled to lean in the perceived vertical plane until this illusion subsides.

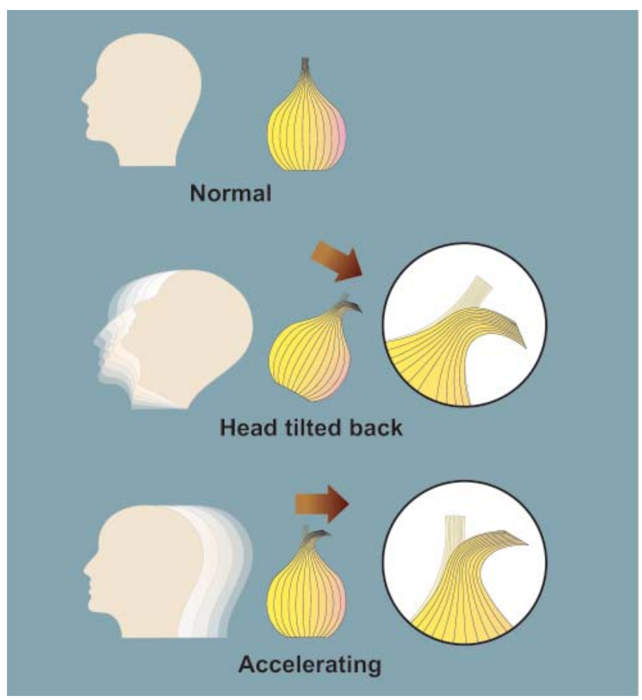


Figure 1-6. *Linear Acceleration.*

Coriolis Illusion

The coriolis illusion occurs when a pilot has been in a turn long enough for the fluid in the ear canal to move at the same speed as the canal. A movement of the head in a different plane, such as looking at something in a different part of the flight deck, may set the fluid moving and create the illusion of turning or accelerating on an entirely different axis. This action causes the pilot to think the aircraft is doing a maneuver that it is not. The disoriented pilot may maneuver the aircraft into a dangerous attitude in an attempt to correct the aircraft's perceived attitude.

For this reason, it is important that pilots develop an instrument cross-check or scan that involves minimal head movement. Take care when retrieving charts and other objects in the flight deck—if something is dropped, retrieve it with minimal head movement and be alert for the coriolis illusion.

Graveyard Spiral

As in other illusions, a pilot in a prolonged coordinated, constant rate turn, will have the illusion of not turning. During the recovery to level flight, the pilot will experience the sensation of turning in the opposite direction. The disoriented pilot may return the aircraft to its original turn. Because an aircraft tends to lose altitude in turns unless the pilot compensates for the loss in lift, the pilot may notice a loss of altitude. The absence of any sensation of turning creates the illusion of being in a level descent. The pilot may pull back on the controls in an attempt to climb or stop the descent. This action tightens the spiral and increases the loss of altitude; hence, this illusion is referred to as a graveyard spiral. *[Figure 1-7]* At some point, this could lead to a loss of control by the pilot.

Somatogravic Illusion

A rapid acceleration, such as experienced during takeoff, stimulates the otolith organs in the same way as tilting the head backwards. This action creates the somatogravic illusion of being in a nose-up attitude, especially in situations without good visual references. The disoriented pilot may push the aircraft into a nose-low or dive attitude. A rapid deceleration by quick reduction of the throttle(s) can have the opposite effect, with the disoriented pilot pulling the aircraft into a nose-up or stall attitude.

Inversion Illusion

An abrupt change from climb to straight-and-level flight can stimulate the otolith organs enough to create the illusion of tumbling backwards, or inversion illusion. The disoriented pilot may push the aircraft abruptly into a nose-low attitude, possibly intensifying this illusion.

Elevator Illusion

An abrupt upward vertical acceleration, as can occur in an updraft, can stimulate the otolith organs to create the illusion of being in a climb. This is called elevator illusion. The disoriented pilot may push the aircraft into a nose-low attitude. An abrupt downward vertical acceleration, usually

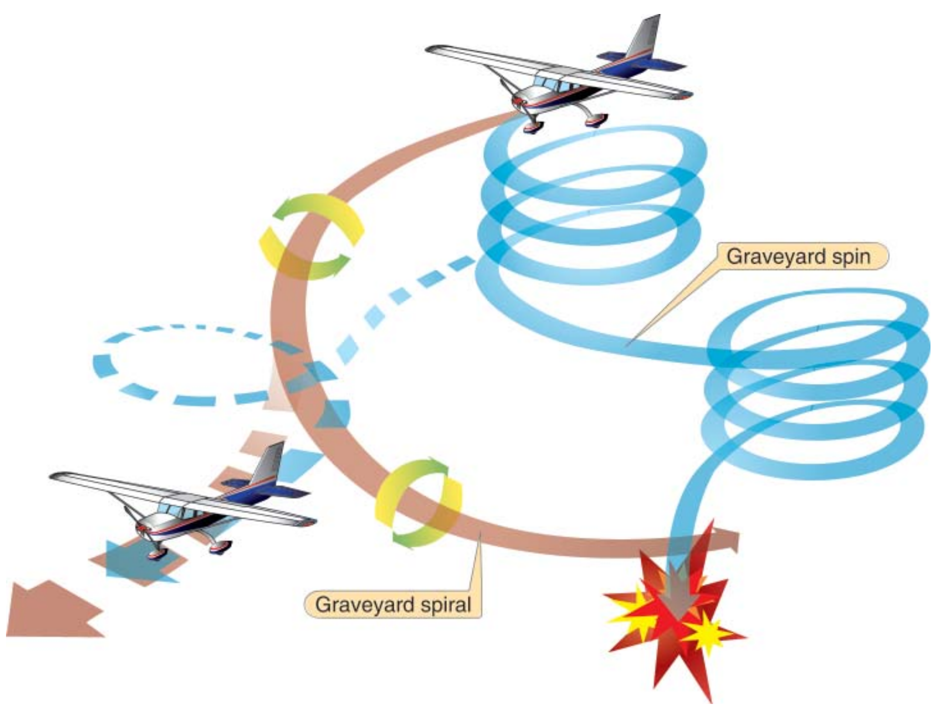


Figure 1-7. *Graveyard Spiral.*

in a downdraft, has the opposite effect, with the disoriented pilot pulling the aircraft into a nose-up attitude.

Visual Illusions

Visual illusions are especially hazardous because pilots rely on their eyes for correct information. Two illusions that lead to spatial disorientation, false horizon and autokinesis, are concerned with only the visual system.

False Horizon

A sloping cloud formation, an obscured horizon, an aurora borealis, a dark scene spread with ground lights and stars, and certain geometric patterns of ground lights can provide inaccurate visual information, or false horizon, for aligning the aircraft correctly with the actual horizon. The disoriented pilot may place the aircraft in a dangerous attitude.

Autokinesis

In the dark, a stationary light will appear to move about when stared at for many seconds. The disoriented pilot could lose control of the aircraft in attempting to align it with the false movements of this light, called autokinesis.

Postural Considerations

The postural system sends signals from the skin, joints, and muscles to the brain that are interpreted in relation to the Earth's gravitational pull. These signals determine posture. Inputs from each movement update the body's position to the brain on a constant basis. "Seat of the pants" flying is largely dependent upon these signals. Used in conjunction with visual and vestibular clues, these sensations can be fairly reliable. However, because of the forces acting upon the body in certain flight situations, many false sensations can occur due to acceleration forces overpowering gravity. *[Figure 1-8]* These situations include uncoordinated turns, climbing turns, and turbulence.

Demonstration of Spatial Disorientation

There are a number of controlled aircraft maneuvers a pilot can perform to experiment with spatial disorientation. While each maneuver will normally create a specific illusion, any false sensation is an effective demonstration of disorientation. Thus, even if there is no sensation during any of these maneuvers, the absence of sensation is still an effective demonstration in that it shows the inability to detect bank or roll. There are several objectives in demonstrating these various maneuvers.

1. They teach pilots to understand the susceptibility of the human system to spatial disorientation.
2. They demonstrate that judgments of aircraft attitude based on bodily sensations are frequently false.
3. They help lessen the occurrence and degree of disorientation through a better understanding of the relationship between aircraft motion, head movements, and resulting disorientation.
4. They help instill a greater confidence in relying on flight instruments for assessing true aircraft attitude.

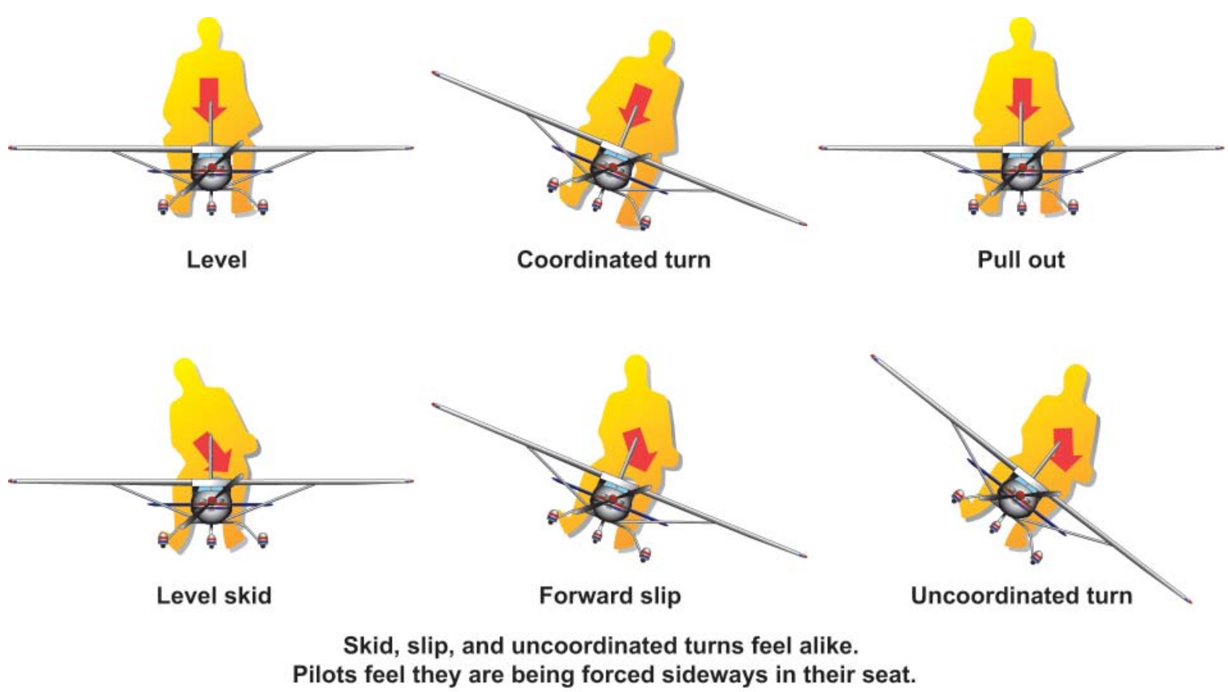


Figure 1-8. *Sensations From Centrifugal Force.*

A pilot should not attempt any of these maneuvers at low altitudes, or in the absence of an instructor pilot or an appropriate safety pilot.

Climbing While Accelerating

With the pilot's eyes closed, the instructor pilot maintains approach airspeed in a straight-and-level attitude for several seconds, and then accelerates while maintaining straight-and-level attitude. The usual illusion during this maneuver, without visual references, will be that the aircraft is climbing.

Climbing While Turning

With the pilot's eyes still closed and the aircraft in a straight-and-level attitude, the instructor pilot now executes, with a relatively slow entry, a well-coordinated turn of about 1.5 positive G (approximately 50° bank) for 90°. While in the turn, without outside visual references and under the effect of the slight positive G, the usual illusion produced is that of a climb. Upon sensing the climb, the pilot should immediately open the eyes and see that a slowly established, coordinated turn produces the same feeling as a climb.

Diving While Turning

Repeating the previous procedure, with the exception that the pilot's eyes should be kept closed until recovery from the turn is approximately one-half completed can create this sensation. With the eyes closed, the usual illusion will be that the aircraft is diving.

Tilting to Right or Left

While in a straight-and-level attitude, with the pilot's eyes closed, the instructor pilot executes a moderate or slight skid to the left with wings level. This creates the illusion of the body being tilted to the right.

Reversal of Motion

This illusion can be demonstrated in any of the three planes of motion. While straight and level, with the pilot's eyes closed, the instructor pilot smoothly and positively rolls the aircraft to approximately a 45° bank attitude while maintaining heading and pitch attitude. This creates the illusion of a strong sense of rotation in the opposite direction. After this illusion is noted, the pilot should open his or her eyes and observe that the aircraft is in a banked attitude.

Diving or Rolling Beyond the Vertical Plane

This maneuver may produce extreme disorientation. While in straight-and-level flight, the pilot should sit normally, either with eyes closed or gaze lowered to the floor. The instructor pilot starts a positive, coordinated roll toward a 30° or 40° angle of bank. As this is in progress, the pilot tilts his or her head forward, looks to the right or left, then immediately returns his or her head to an upright position. The instructor pilot should time the maneuver so the roll is stopped as the pilot returns his or her head upright. An intense disorientation is usually produced by this maneuver, and the pilot experiences the sensation of falling downward into the direction of the roll.

In the descriptions of these maneuvers, the instructor pilot is doing the flying, but having the pilot do the flying can also be a very effective demonstration. The pilot should close his or her eyes and tilt the head to one side. The instructor pilot tells the pilot what control inputs to perform. The pilot then attempts to establish the correct attitude or control input with eyes closed and head tilted. While it is clear the pilot has no idea of the actual attitude, he or she will react to what the senses are saying. After a short time, the pilot will become disoriented and the instructor pilot then tells the pilot to look up and recover. The benefit of this exercise is the pilot experiences the disorientation while flying the aircraft.

Coping with Spatial Disorientation

To prevent illusions and their potentially disastrous consequences, pilots can:

1. Understand the causes of these illusions and remain constantly alert for them. Take the opportunity to understand and then experience spatial disorientation illusions in a device such as a Barany chair, a Vertigon, or a Virtual Reality Spatial Disorientation Demonstrator.
2. Always obtain and understand preflight weather briefings.
3. Before flying in marginal visibility (less than 3 miles) or where a visible horizon is not evident such as flight over open water during the night, obtain training and maintain proficiency in airplane control by reference to instruments.
4. Do not continue flight into adverse weather conditions or into dusk or darkness unless proficient in the use of flight instruments. If intending to fly at night, maintain night-flight currency and proficiency. Include cross-country and local operations at various airfields.
5. Ensure that when outside visual references are used, they are reliable, fixed points on the Earth's surface.
6. Avoid sudden head movement, particularly during takeoffs, turns, and approaches to landing.
7. Be physically tuned for flight into reduced visibility. That is, ensure proper rest, adequate diet, and, if flying at night, allow for night adaptation. Remember that illness, medication, alcohol, fatigue, sleep loss, and mild hypoxia are likely to increase susceptibility to spatial disorientation.

8. Most importantly, become proficient in the use of flight instruments and rely upon them. Trust the instruments and disregard your sensory perceptions.

The sensations that lead to illusions during instrument flight conditions are normal perceptions experienced by pilots. These undesirable sensations cannot be completely prevented, but through training and awareness, pilots can ignore or suppress them by developing absolute reliance on the flight instruments. As pilots gain proficiency in instrument flying, they become less susceptible to these illusions and their effects.

Optical Illusions

Of the senses, vision is the most important for safe flight. However, various terrain features and atmospheric conditions can create optical illusions. These illusions are primarily associated with landing. Since pilots must transition from reliance on instruments to visual cues outside the flight deck for landing at the end of an instrument approach, it is imperative they be aware of the potential problems associated with these illusions, and take appropriate corrective action. The major illusions leading to landing errors are described below.

Runway Width Illusion

A narrower-than-usual runway can create an illusion the aircraft is at a higher altitude than it actually is, especially when runway length-to-width relationships are comparable. *[Figure 1-9A]* The pilot who does not recognize this illusion will fly a lower approach, with the risk of striking objects along the approach path or landing short. A wider-than-usual runway can have the opposite effect, with the risk of leveling out high and landing hard, or overshooting the runway.

Runway and Terrain Slopes Illusion

An upsloping runway, upsloping terrain, or both, can create an illusion the aircraft is at a higher altitude than it actually is. *[Figure 1-9B]* The pilot who does not recognize this illusion will fly a lower approach. Downsloping runways and downsloping approach terrain can have the opposite effect.

Featureless Terrain Illusion

An absence of surrounding ground features, as in an overwater approach, over darkened areas, or terrain made featureless by snow, can create an illusion the aircraft is at a higher altitude than it actually is. This illusion, sometimes referred to as the "black hole approach," causes pilots to fly a lower approach than is desired.

Water Refraction

Rain on the windscreen can create an illusion of being at a higher altitude due to the horizon appearing lower than it is. This can result in the pilot flying a lower approach.

Haze

Atmospheric haze can create an illusion of being at a greater distance and height from the runway. As a result, the pilot will have a tendency to be low on the approach. Conversely, extremely clear air (clear bright conditions of a high attitude airport) can give the pilot the illusion of being closer than he or she actually is, resulting in a high approach, which may result in an overshoot or go around. The diffusion of light due to water particles on the windshield can adversely affect depth perception. The lights and terrain features normally used to gauge height during landing become less effective for the pilot.

Fog

Flying into fog can create an illusion of pitching up. Pilots who do not recognize this illusion will often steepen the approach quite abruptly.

Ground Lighting Illusions

Lights along a straight path, such as a road or lights on moving trains, can be mistaken for runway and approach lights. Bright runway and approach lighting systems, especially where few lights illuminate the surrounding terrain, may create the illusion of less distance to the runway. The pilot who does not recognize this illusion will often fly a higher approach.

How To Prevent Landing Errors Due to Optical Illusions

To prevent these illusions and their potentially hazardous consequences, pilots can:

1. Anticipate the possibility of visual illusions during approaches to unfamiliar airports, particularly at night or in adverse weather conditions. Consult airport diagrams and the Airport/Facility Directory (A/FD) for information on runway slope, terrain, and lighting.
2. Make frequent reference to the altimeter, especially during all approaches, day and night.
3. If possible, conduct aerial visual inspection of unfamiliar airports before landing.

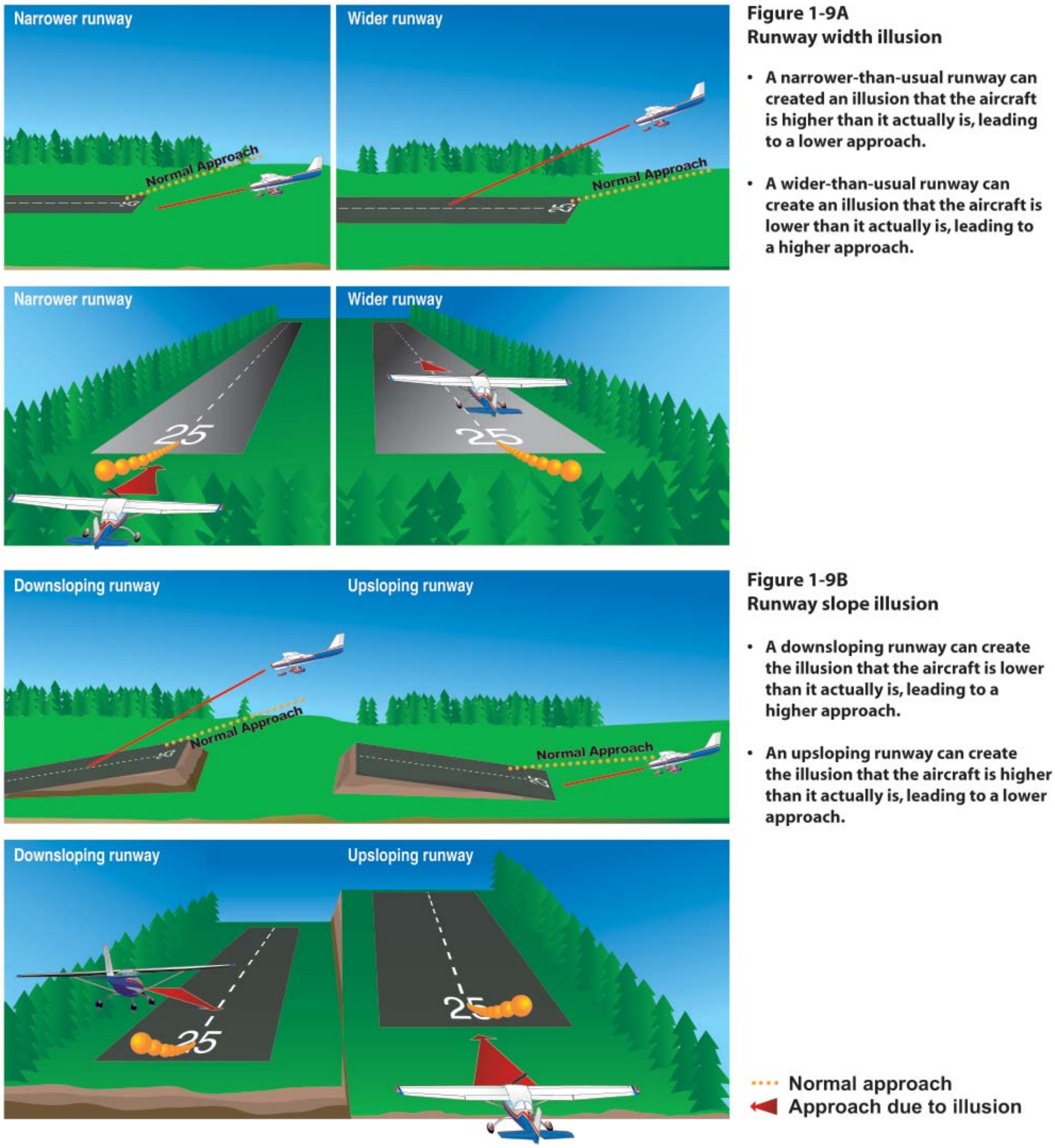


Figure 1-9. *Runway Width and Slope Illusions.*

4. Use Visual Approach Slope Indicator (VASI) or Precision Approach Path Indicator (PAPI) systems for a visual reference, or an electronic glide slope, whenever they are available.
5. Utilize the visual descent point (VDP) found on many nonprecision instrument approach procedure charts.
6. Recognize that the chances of being involved in an approach accident increase when some emergency or other activity distracts from usual procedures.
7. Maintain optimum proficiency in landing procedures.

Physiological and Psychological Factors

Physiological or psychological factors can affect a pilot and compromise the safety of a flight. These factors are stress, medical, alcohol, and fatigue. Any of these factors, individually or in combination, significantly degrade the pilot's decision-making or flying abilities.

Stress

Stress is the body's response to demands placed upon it. These demands can be either pleasant or unpleasant in nature. The causes of stress for a pilot can range from unexpected weather or mechanical problems while in flight, to personal issues unrelated to flying. Stress is an inevitable and necessary part of life; it adds motivation to life and heightens an individual's response to meet any challenge. The effects of stress are cumulative and there is a limit to a person's adaptive nature. This limit, called the stress tolerance level (or channel capacity), is based on the ability to cope with the situation.

At first, some amount of stress can be desirable and can actually improve performance. However, higher stress levels, particularly over long periods of time, can adversely affect performance. Performance will generally increase with the onset of stress, but will peak and then begin to fall off rapidly as stress levels exceed the ability to cope. *[Figure 1-10]*

At this point, a pilot's performance begins to decline and judgment deteriorates. Complex or unfamiliar tasks require higher levels of performance than simple or overlearned tasks. Complex or unfamiliar tasks are also more subject to the adverse effects of increasing stress than simple or familiar tasks. *[Figure 1-10]*

The indicators of excessive stress often show as three types of symptoms: (1) emotional, (2) physical, and (3) behavioral. Emotional symptoms may surface as over-compensation, denial, suspicion, paranoia, agitation, restlessness, or defensiveness. Physical stress can result in acute fatigue while behavioral degradation will be manifested as sensitivity to criticism, tendency to be argumentative, arrogance, and hostility. Pilots need to learn to recognize the symptoms of stress as they begin to occur.

There are many techniques available that can help reduce stress in life or help people cope with it better. Not all of the following ideas may be a solution, but some of them should be effective.

1. Become knowledgeable about stress.
2. Take a realistic self-assessment. (See the Pilot's Handbook of Aeronautical Knowledge).
3. Take a systematic approach to problem solving.
4. Develop a lifestyle that will buffer against the effects of stress.
5. Practice behavior management techniques.
6. Establish and maintain a strong support network.

Good flight deck stress management begins with good life stress management. Many of the stress coping techniques practiced for life stress management are not usually practical in flight. Rather, pilots must condition themselves to relax and think rationally when stress appears. The following checklist outlines some methods of flight deck stress management.

1. Avoid situations that distract from flying the aircraft.
2. Reduce flight deck workload to reduce stress levels. This will create a proper environment in which to make good decisions. Typically, flying involves higher stress levels during takeoff and landing phases. Between the two generally lies a period of low activity resulting in a lower stress level. Transitioning from the cruise phase to the landing phase is generally accompanied by a significant workload that, if not properly accommodated, will increase stress significantly. Proper planning and prioritization of flight deck duties are key to avoiding events that affect the pilot's capacity to maintain situational awareness.

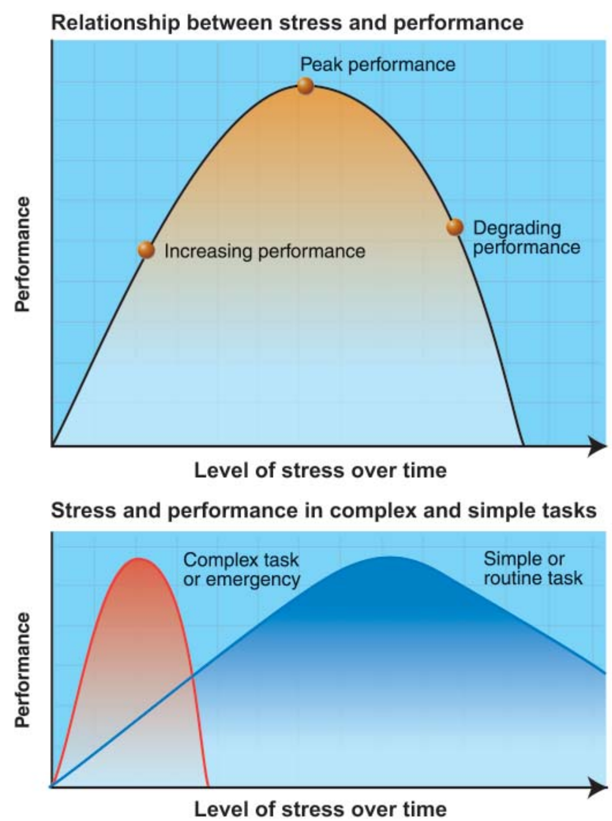


Figure 1-10. *Stress and Performance.*

3. If a problem occurs, remain calm. If time is not a pressing factor, follow the analytical approach to decision-making: think for a moment, weigh the alternatives, select and take an appropriate course of action, and then evaluate its effects.

   If an emergency situation occurs, remain calm and use the aeronautical decision-making (ADM) process to resolve the emergency. This process relies on the pilot's training and experience to accurately and automatically respond to an emergency situation. Constant training in handling emergency procedures will help reduce pilot stress when an emergency occurs.

4. Become thoroughly familiar with the aircraft, its operation, and emergency procedures. Also, maintain flight proficiency to build confidence.

5. Know and respect personal limits. Studies have suggested that highly experienced pilots have taken more chances when flying into potential icing conditions than low time or inexperienced pilots. Very low time pilots without experience may analyze and interpret the likelihood for "potential" flight into icing without the benefit of life experience, thereby making decisions closely aligned with the compilation of their training and recent academic knowledge. Highly experienced pilots may evaluate the current situation based upon the empirical information (sometimes diluted with time) coupled with their vast experience. This may lead to a level of greater acceptability of the situation because their experience has illustrated successful navigation of this problem before. Therefore, the automatic decision may be in error because not all salient facts are evaluated.

6. Do not allow small mistakes to be distractions during flight; rather, review and analyze them after landing.

7. If flying adds stress, either stop flying or seek professional help to manage stress within acceptable limits.

Medical Factors

A "go/no-go" decision based on a pilot's medical factors is made before each flight. The pilot should not only preflight check the aircraft, but also himself or herself before every flight. A pilot should ask, "Can I pass my medical examination right now?" If the answer is not an absolute "yes," *do not fly*. This is especially true for pilots embarking on flights in IMC. Instrument flying is much more demanding than flying in VMC, and peak performance is critical for the safety of flight.

Pilot performance can be seriously degraded by both prescribed and over-the-counter medications, as well as by the medical conditions for which they are taken. Many medications, such as tranquilizers, sedatives, strong pain relievers, and cough suppressants, have primary effects that impair judgment, memory, alertness, coordination, vision, and the ability to make calculations. Others, such as antihistamines, blood pressure drugs, muscle relaxants, and agents to control diarrhea and motion sickness, have side effects that impair the same critical functions. Any medication that depresses the nervous system, such as a sedative, tranquilizer, or antihistamine, makes a pilot much more susceptible to hypoxia.

Title 14 of the Code of Federal Regulations (14 CFR) prohibits pilots from performing crewmember duties while using any medication that affects the faculties in any way contrary to safety. The safest rule is not to fly as a crewmember while taking any medication, unless approved to do so by the Federal Aviation Administration (FAA). If there is any doubt regarding the effects of any medication, consult an Aviation Medical Examiner (AME) before flying.

Alcohol

14 CFR part 91 prohibits pilots from performing crewmember duties within 8 hours after drinking any alcoholic beverage or while under the influence. Extensive research has provided a number of facts about the hazards of alcohol consumption and flying. As little as one ounce of liquor, one bottle of beer, or four ounces of wine can impair flying skills and render a pilot much more susceptible to disorientation and hypoxia. Even after the body completely metabolizes a moderate amount of alcohol, a pilot can still be impaired for many hours. There is simply no way of increasing the metabolism of alcohol or alleviating a hangover.

Fatigue

Fatigue is one of the most treacherous hazards to flight safety, as it may not be apparent to a pilot until serious errors are made. Fatigue can be either acute (short-term) or chronic (long-term).

Acute Fatigue

A normal occurrence of everyday living, acute fatigue is the tiredness felt after long periods of physical and mental strain, including strenuous muscular effort, immobility, heavy mental workload, strong emotional pressure, monotony, and lack of sleep. Adequate rest, regular exercise, and proper nutrition prevent acute fatigue.

Indications of fatigue are generally subtle and hard to recognize because the individual being assessed is generally the person making the assessment, as in single pilot operations. Therefore, the pilot must look at small errors that occur to provide an indication of becoming fatigued. These include:

- Misplacing items during the preflight;
- Leaving material (pencils, charts) in the planning area;
- Missing radio calls;
- Answering calls improperly (read-backs); and
- Improper tuning of frequencies.

Chronic Fatigue

Chronic fatigue occurs when there is not enough time for a full recovery from repeated episodes of acute fatigue. Chronic fatigue's underlying cause is generally not "rest-related" and may have deeper points of origin. Therefore, rest alone may not resolve chronic fatigue.

Chronic fatigue is a combination of both physiological problems and psychological issues. Psychological problems such as financial, home life, or job related stresses cause a lack of qualified rest that is only resolved by mitigating the underpinning problems. Without resolution, performance continues to fall off, judgment becomes impaired, and unwarranted risks are taken. Recovery from chronic fatigue requires a prolonged and deliberate solution. In either case, unless adequate precautions are taken, personal performance could be impaired and adversely affect pilot judgment and decision-making.

IMSAFE Checklist

The following checklist, IMSAFE, is intended for a pilot's personal preflight use. A quick check of the items on this list will help a pilot make a good self-evaluation prior to any flight. If the answer to any of the checklist questions is yes, then the pilot should consider not flying.

Illness
Do I have any symptoms?

Medication
Have I been taking prescription or over-the-counter drugs?

Stress
Am I under psychological pressure from the job? Do I have money, health, or family problems?

Alcohol
Have I been drinking within 8 hours? Within 24 hours?

Fatigue
Am I tired and not adequately rested?

Eating
Have I eaten enough of the proper foods to keep adequately nourished during the entire flight?

Hazard Identification

In order to identify a hazard, it would be useful to define what a hazard is. The FAA System Safety course defines a hazard as: "a present condition, event, object, or circumstance that could lead or contribute to an unplanned or undesired event." Put simply, a hazard is a source of danger. Potential hazards may be identified from a number of internal and external sources. These may be based upon several concurrent factors that provide an indication and ultimate identification of a hazard. Consider the following situations:

Situation 1

The pilot has just taken off and is entering the clouds. Suddenly, there is an explosive sound. The sudden noise is disturbing and occurs as the pilot is given a new heading, a climb restriction, and the frequency for the departure control.

Situation 2

The pilot took off late in a rented aircraft (first time flying this model), and is now in night conditions due to the delay, and flying on an instrument flight rules (IFR) flight plan in IMC conditions. The radios do not seem to work well and develop static. They seem to be getting weaker. As the pilot proceeds, the rotating beacon stops flashing/rotating, and the lights become dimmer. As the situation progresses, the pilot is unaware of the problem because the generator warning light, (on the lower left of the panel) is obscured by the chart on the pilot's lap.

Both situations above represent hazards that must be dealt with differently and a level of risk must be associated with each depending on various factors affecting the flight.

Risk Analysis

Risk is defined as the future impact of a hazard that is not eliminated or controlled. It is the possibility of loss or injury. Risk analysis is the process whereby hazards are characterized by their likelihood and severity. Risk analysis evaluates the hazards to determine the outcomes and how abrupt that outcome will occur. The analysis applied will be qualitative to the degree that time allows resulting in either an analytical or automatic approach in the decision-making process.

In the first situation, the decision may be automatic: fly the airplane to a safe landing. Since automatic decision-making is based upon education and experience, an inexperienced pilot may react improperly to the situation which results in an inadequate action. To mitigate improper decision-making, immediate action items from emergency procedures should be learned. Training, education, and mentorship are all key factors in honing automatic decision-making skills.

In the second situation, if the pilot has a flashlight onboard, it can be used for illumination, although its light may degrade night vision. After changing the appropriate transponder code, and making calls in the blind, awareness of present location becomes imperative, especially if the pilot must execute a controlled descent to VMC conditions. Proper preflight planning conducted before departure and constant awareness of location provide an element of both comfort (reduces stress) and information from which the pilot can draw credible information.

In both cases, the outcomes can be successful through systems understanding, emergency procedures training, and correctly analyzing the risks associated with each course of action.

Crew Resource Management (CRM) and Single-Pilot Resource Management (SRM)

Crew resource management (CRM) and single-pilot resource management (SRM) is the ability for the crew or pilot to manage all resources effectively to ensure the outcome of the flight is successful. In general aviation, SRM will be most often used and its focus is on the single-pilot operation. SRM integrates the following:

- Situational Awareness
- Flight Deck Resource Management
- Task Management
- Aeronautical Decision-making (ADM) and Risk Management

SRM recognizes the need to seek proper information from these sources to make a valid decision. For instance, the pilot may have to request assistance from others and be assertive to resolve situations. Pilots should understand the need to seek information from other sources until they have the proper information to make the best decision. Once a pilot has gathered all pertinent information and made the appropriate decision, the pilot needs to perform an assessment of the action taken.

Situational Awareness

Situational awareness is the accurate perception of operational and environmental factors that affect the flight. It is a logical analysis based upon the machine, external support, environment, and the pilot. It is knowing what is going on.

Flight Deck Resource Management

CRM is the effective use of all available resources: human, equipment, and information. It focuses on communication skills, teamwork, task allocation, and decision-making. While CRM often concentrates on pilots who operate in crew environments, the elements and concepts also apply to single-pilot operations.

Human Resources

Human resources include everyone routinely working with the pilot to ensure flight safety. These people include, but are not limited to: weather briefers, flight line personnel, maintenance personnel, crew members, pilots, and air traffic personnel. Pilots need to effectively communicate with these people. This is accomplished by using the key components of the communication process: inquiry, advocacy, and assertion.

Pilots must recognize the need to seek enough information from these resources to make a valid decision. After the necessary information has been gathered, the pilot's decision must be passed on to those concerned, such as air traffic controllers, crew members, and passengers. The pilot may have to request assistance from others and be assertive to safely resolve some situations.

Equipment

Equipment in many of today's aircraft includes automated flight and navigation systems. These automatic systems, while providing relief from many routine flight deck tasks, present a different set of problems for pilots. The automation intended to reduce pilot workload essentially removes the pilot from the process of managing the aircraft, thereby reducing situational awareness and leading to complacency. Information from these systems needs to be continually monitored to ensure proper situational awareness. Pilots should be thoroughly familiar with the operation of and information provided by all systems used. It is essential that pilots be aware not only of equipment capabilities, but also equipment limitations in order to manage those systems effectively and safely.

Information Workload

Information workloads and automated systems, such as autopilots, need to be properly managed to ensure a safe flight. The pilot flying in IMC is faced with many tasks, each with a different level of importance to the outcome of the flight. For example, a pilot preparing to execute an instrument approach to an airport needs to review the approach chart, prepare the aircraft for the approach and landing, complete checklists, obtain information from Automatic Terminal Information Service (ATIS) or air traffic control (ATC), and set the navigation radios and equipment.

The pilot who effectively manages his or her workload will complete as many of these tasks as early as possible to preclude the possibility of becoming overloaded by last minute changes and communication priorities in the later, more critical stages of the approach. *Figure 1-11* shows the margin of safety is at the minimum level during this stage of the approach. Routine tasks delayed until the last minute can contribute to the pilot becoming overloaded and stressed, resulting in erosion of performance.

By planning ahead, a pilot can effectively reduce workload during critical phases of flight. If a pilot enters the final phases of the instrument approach unprepared, the pilot should recognize the situation, abandon the approach, and try it again after becoming better prepared. Effective resource management includes recognizing hazardous situations and attitudes, decision-making to promote good judgment and headwork, and managing the situation to ensure the safe outcome of the IFR flight.

Task Management

Pilots have a limited capacity for information. Once information flow exceeds the pilot's ability to mentally process the information any additional information will become unattended or displace other tasks and information already being processed. This is termed channel capacity and once reached only two alternatives exist: shed the unimportant tasks or perform all tasks at a less than optimal level. Like an electrical circuit being overloaded, either the consumption must be reduced or a circuit failure is experienced.

The pilot who effectively manages the tasks and properly prioritizes them will have a successful flight. For example, do not become distracted and fixate on an instrument light failure. This unnecessary focus displaces capability and prevents the pilot's ability to appreciate tasks of greater importance. By planning ahead, a pilot can effectively reduce workload during critical phases of a flight.

Aeronautical Decision-Making (ADM)

Flying safely requires the effective integration of three separate sets of skills. Most obvious are the basic stick-and-rudder skills needed to control the airplane. Next, are skills related to proficient operation of aircraft systems, and last, but not least, are ADM skills.

ADM is a systematic approach to the mental process used by pilots to consistently determine the best course of action in response to a given set of circumstances. The importance of learning effective ADM skills cannot be overemphasized. While progress is continually being made in the advancement of pilot training methods, airplane equipment and systems, and services for pilots, accidents still occur. Despite all the changes in technology to improve flight safety, one factor remains the same—the human factor. While the FAA strives to eliminate errors through training and safety programs, one fact remains: humans make errors. It is estimated that approximately 80 percent of all aviation accidents are human factors related.

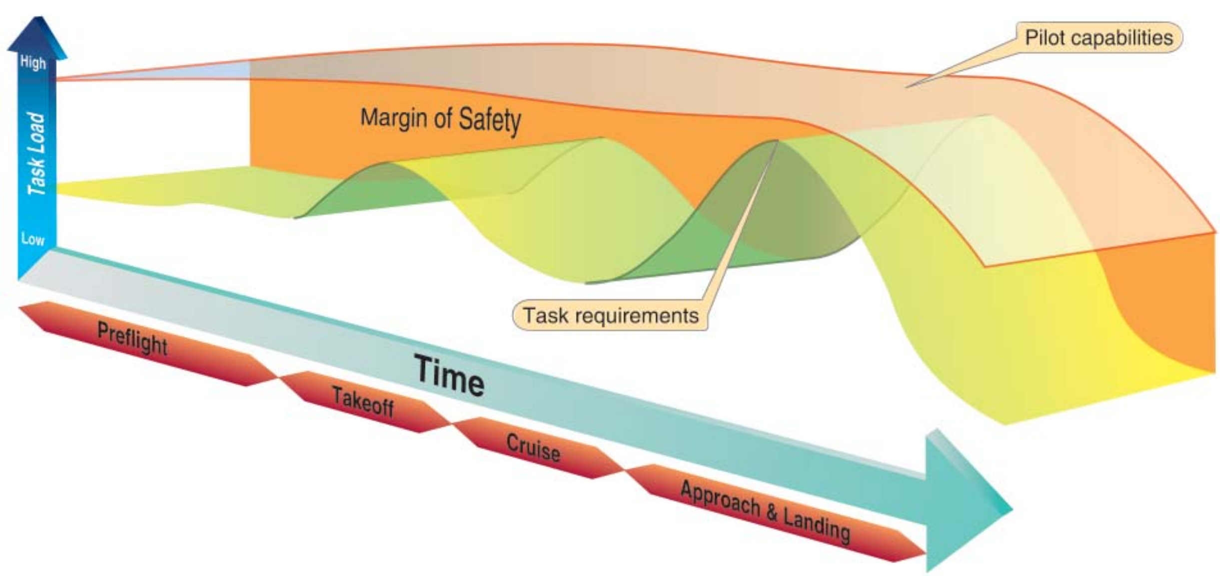


Figure 1-11. *The Margin of Safety.*

The ADM process addresses all aspects of decision making in the flight deck and identifies the steps involved in good decision making. While the ADM process will not eliminate errors, it will help the pilot recognize errors, and in turn enable the pilot to manage the error to minimize its effects. These steps are:

1. Identifying personal attitudes hazardous to safe flight;
2. Learning behavior modification techniques;
3. Learning how to recognize and cope with stress;
4. Developing risk assessment skills;
5. Using all resources; and
6. Evaluating the effectiveness of one's ADM skills.

Historically, the term "pilot error" has been used to describe the causes of these accidents. Pilot error means that an action or decision made by the pilot was the cause, or a contributing factor that led to the accident. This definition also includes the pilot's failure to make a decision or take action. From a broader perspective, the phrase "human factors related" more aptly describes these accidents since it is usually not a single decision that leads to an accident, but a chain of events triggered by a number of factors.

The poor judgment chain, sometimes referred to as the "error chain," is a term used to describe this concept of contributing factors in a human factors related accident. Breaking one link in the chain normally is all that is necessary to change the outcome of the sequence of events.

The Decision-Making Process

An understanding of the decision-making process provides a pilot with a foundation for developing ADM skills. Some situations, such as engine failures, require a pilot to respond immediately using established procedures with a little time for detailed analysis. This is termed automatic decision-making and is based upon training, experience, and recognition. Traditionally, pilots have been well trained to react to emergencies, but are not as well prepared to make decisions requiring a more reflective response where greater analysis is required. Typically during a flight, there is time to examine any changes that occur, gather information, and assess risk before reaching a decision. The steps leading to this conclusion constitute the decision-making process.

Defining the Problem

Problem definition is the first step in the decision-making process. Defining the problem begins with recognizing that a change has occurred or that an expected change did not occur. A problem is perceived first by the senses, then is distinguished through insight and experience. One critical error that can be made during the decision-making process is incorrectly defining the problem. For example, a low oil pressure reading could indicate that the engine is about to fail and an emergency landing should be planned, or it could mean that the oil pressure sensor has failed. The actions to be taken in each of these circumstances would be significantly different. One requires an immediate decision based upon training, experience, and evaluation of the situation; whereas the latter decision is based upon an analysis. It should be noted that the same indication could result in two different actions depending upon other influences.

Choosing a Course of Action

After the problem has been identified, the pilot must evaluate the need to react to it and determine the actions that may be taken to resolve the situation in the time available. The expected outcome of each possible action should be considered and the risks assessed before deciding on a response to the situation.

Implementing the Decision and Evaluating the Outcome

Although a decision may be reached and a course of action implemented, the decision-making process is not complete. It is important to think ahead and determine how the decision could affect other phases of flight. As the flight progresses, the pilot must continue to evaluate the outcome of the decision to ensure that it is producing the desired result.

Improper Decision-Making Outcomes

Pilots sometimes get in trouble not because of deficient basic skills or system knowledge, but rather because of faulty decision-making skills. Although aeronautical decisions may appear to be simple or routine, each individual decision in aviation often defines the options available for the next decision the pilot must make and the options, good or bad, they provide. Therefore, a poor decision early on in a flight can compromise the safety of the flight at a later time necessitating decisions that must be more accurate and decisive. Conversely, good decision-making early on in an emergency provide greater latitude for options later on.

FAA Advisory Circular (AC) 60-22, defines ADM as a systematic approach to the mental process of evaluating a given set of circumstances and determining the best course of action. ADM thus builds upon the foundation of conventional decision-making, but enhances the process to decrease the probability of pilot error. Specifically, ADM provides a structure to help the pilot use all resources to develop comprehensive situational awareness.

Models for Practicing ADM

Two models for practicing ADM are presented below.

Perceive, Process, Perform

The Perceive–Process–Perform (3P) model for ADM offers a simple, practical, and systematic approach that can be used during all phases of flight. *[Figure 1-12]* To use it, the pilot will:

- Perceive the given set of circumstances for a flight;
- Process by evaluating their impact on flight safety; and
- Perform by implementing the best course of action.

Figure 1-12. *The 3P Model for Aeronautical Decision-Making.*

In the first step, the goal is to develop situational awareness by perceiving hazards, which are present events, objects, or circumstances that could contribute to an undesired future event. In this step, the pilot will systematically identify and list hazards associated with all aspects of the flight: pilot, aircraft, environment, and external pressures. It is important to consider how individual hazards might combine. Consider, for example, the hazard that arises when a new instrument pilot with no experience in actual instrument conditions wants to make a cross-country flight to an airport with low ceilings in order to attend an important business meeting.

In the second step, the goal is to process this information to determine whether the identified hazards constitute risk, which is defined as the future impact of a hazard that is not controlled or eliminated. The degree of risk posed by a given hazard can be measured in terms of exposure (number of people or resources affected), severity (extent of possible loss), and probability (the likelihood that a hazard will cause a loss). If the hazard is low ceilings, for example, the level of risk depends on a number of other factors, such as pilot training and experience, aircraft equipment and fuel capacity, and others.

In the third step, the goal is to perform by taking action to eliminate hazards or mitigate risk, and then continuously evaluate the outcome of this action. With the example of low ceilings at destination, for instance, the pilot can perform good ADM by selecting a suitable alternate, knowing where to find good weather, and carrying sufficient fuel to reach it. This course of action would mitigate the risk. The pilot also has the option to eliminate it entirely by waiting for better weather.

Once the pilot has completed the 3P decision process and selected a course of action, the process begins anew because now the set of circumstances brought about by the course of action requires analysis. The decision-making process is a continuous loop of perceiving, processing and performing.

The DECIDE Model

Another structured approach to ADM is the DECIDE model, which is a six-step process intended to provide a logical way of approaching decision-making. As in the 3P model, the elements of the DECIDE model represent a continuous loop process to assist a pilot in the decision-making required when faced with a situational change that requires judgment. *[Figure 1-13C]* The model is primarily focused on the intellectual component, but can have an impact on the motivational component of judgment as well. If a pilot continually uses the DECIDE Model in all decision-making, it becomes natural and results in better decisions being made under all types of situations. The steps in this approach are listed in *Figure 1-13C*.

In conventional decision-making, the need for a decision is triggered by recognition that something has changed or an expected change did not occur. Recognition of the change, or lack of change, is a vital step in any decision making process. Not noticing change in a situation can lead directly to a mishap. *[Figure 1-13A]* The change indicates that an appropriate response or action is necessary in order to modify the situation (or, at least, one of the elements that comprise it) and bring about a desired new situation. Therefore, situational awareness is the key to successful and safe decision making. At this point in the process, the pilot is faced with a need to evaluate the entire range of possible responses to the detected change and to determine the best course of action.

Figure 1-13B illustrates how the ADM process expands conventional decision-making, shows the interactions of the

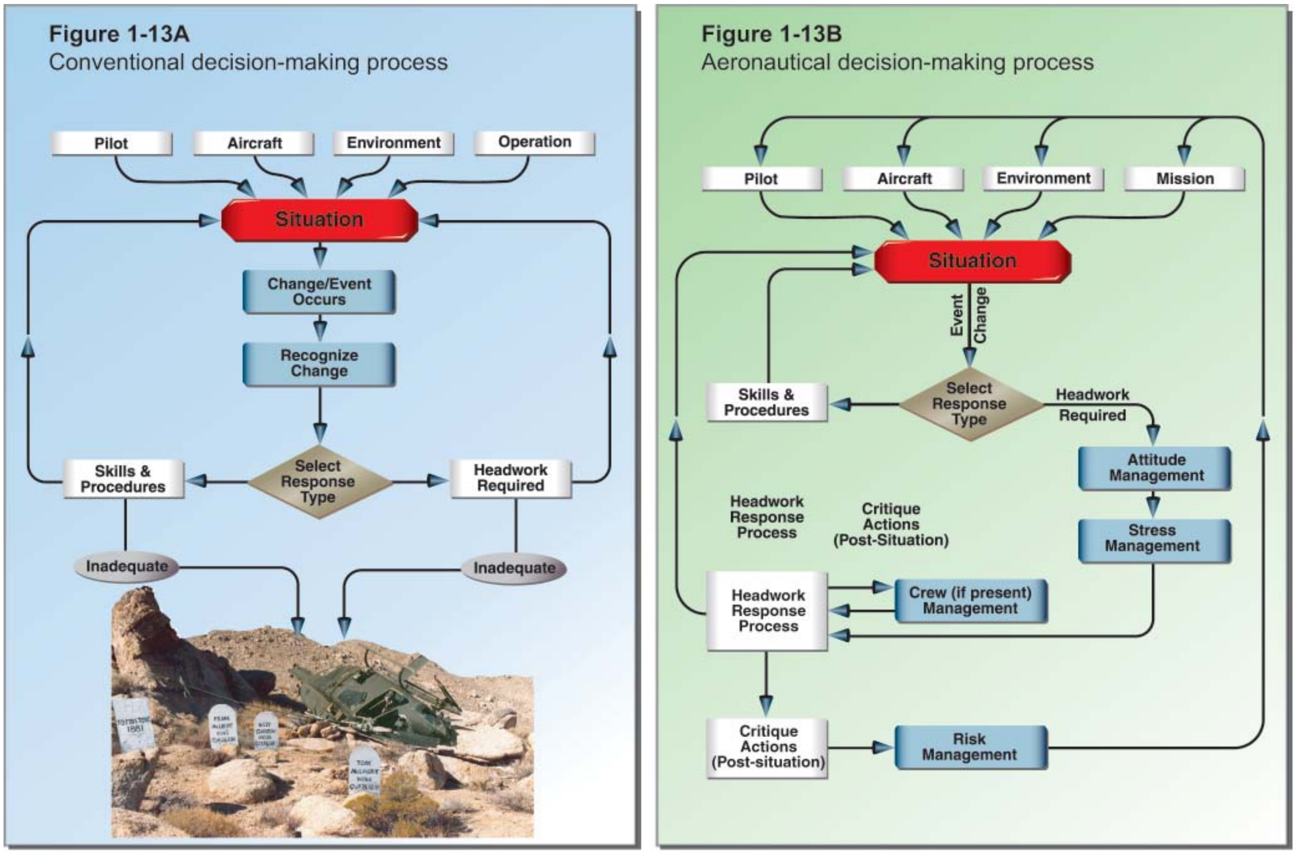


Figure 1-13C
The DECIDE Model

1. **Detect.** The decision maker detects the fact that change has occurred.
2. **Estimate.** The decision maker estimates the need to counter or react to the change.
3. **Choose.** The decision maker chooses a desirable outcome (in terms of success) for the flight.
4. **Identify.** The decision maker identifies actions which could successfully control the change.
5. **Do.** The decision maker takes the necessary action.
6. **Evaluate.** The decision maker evaluates the effect(s) of his/her action countering the change.

Figure 1-13. *Decision-Making.*

ADM steps, and how these steps can produce a safe outcome. Starting with the recognition of change, and following with an assessment of alternatives, a decision to act or not act is made, and the results are monitored. Pilots can use ADM to enhance their conventional decision-making process because it:

1. Increases their awareness of the importance of attitude in decision-making;
2. Teaches the ability to search for and establish relevance of information; and
3. Increases their motivation to choose and execute actions that ensure safety in the situational timeframe.

Hazardous Attitudes and Antidotes

Hazardous attitudes, which contribute to poor pilot judgment, can be effectively counteracted by redirecting that hazardous attitude so that correct action can be taken. Recognition of hazardous thoughts is the first step toward neutralizing them. After recognizing a thought as hazardous, the pilot should label it as hazardous, then state the corresponding antidote. Antidotes should be memorized for each of the hazardous attitudes so they automatically come to mind when needed. Each hazardous attitude along with its appropriate antidote is shown in *Figure 1-14*.

Hazardous Attitude	Antidote
Anti-authority: Don't tell me.	Follow the rules. They are usually right.
Impulsivity: Do something quicky.	Not so fast. Think first.
Invulnerability: It won't happen to me.	It could happen to me.
Macho: I can do it.	Taking chances is foolish.
Resignation: What's the use?	I'm not helpless. I can make a difference.

Figure 1-14. *The Five Antidotes to Hazardous Attitudes.*

Research has identified five hazardous attitudes that can affect a pilot's judgment, as well as antidotes for each of these five attitudes. ADM addresses the following:

1. Anti-authority ("Don't tell me!"). This attitude is found in pilots who do not like anyone telling them what to do. They may be resentful of having someone tell them what to do or may regard rules, regulations, and procedures as silly or unnecessary. However, there is always the prerogative to question authority if it is perceived to be in error.
2. Impulsivity ("Do something quickly!"). This attitude is found in pilots who frequently feel the need to do something—anything—immediately. They do not stop to think about what they are about to do, they do not select the best course of action, and they do the first thing that comes to mind.
3. Invulnerability ("It won't happen to me!"). Many pilots feel that accidents happen to others, but never to them. They know accidents can happen, and they know that anyone can be affected. They never really feel or believe that they will be personally involved. Pilots who think this way are more likely to take chances and increase risk.
4. Macho ("I can do it!"). Pilots who are always trying to prove that they are better than anyone else are thinking, "I can do it—I'll show them." Pilots with this type of attitude will try to prove themselves by taking risks in order to impress others. This pattern is characteristic in both men and women.
5. Resignation ("What's the use?"). These pilots do not see themselves as being able to make a great deal of difference in what happens to them. When things go well, these pilots are apt to think it is due to good luck. When things go badly, they may feel that someone is out to get them, or attribute it to bad luck. The pilot will leave the action to others, for better or worse. Sometimes, they will even go along with unreasonable requests just to be a "nice guy."

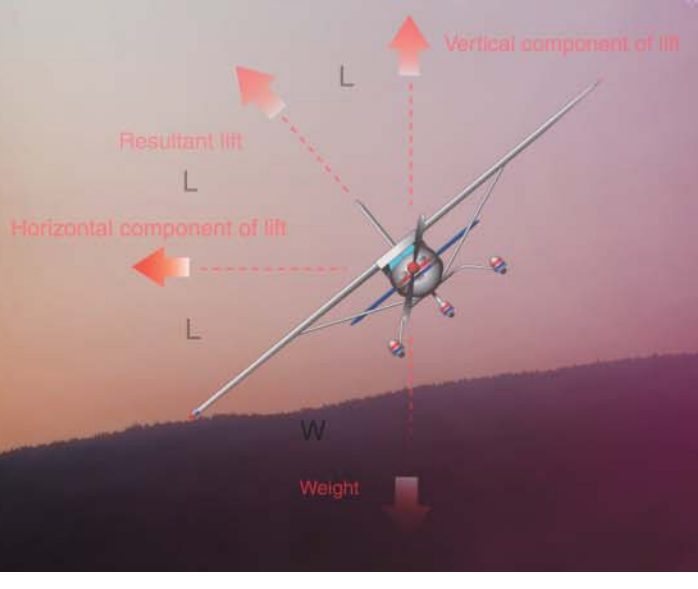
$L = C_L q S$
L=Lift, lbs.
L=Lift, lbs.
CL=Lift coefficient
q=dynamic pressure, psf= $\frac{1}{2}\rho V^2$
S=wing surface area, sq. ft.

Chapter 2

Aerodynamic Factors

Introduction

Several factors affect aircraft performance including the atmosphere, aerodynamics, and aircraft icing. Pilots need an understanding of these factors for a sound basis for prediction of aircraft response to control inputs, especially with regard to instrument approaches, while holding, and when operating at reduced airspeed in instrument meteorological conditions (IMC). Although these factors are important to the pilot flying visual flight rules (VFR), they must be even more thoroughly understood by the pilot operating under instrument flight rules (IFR). Instrument pilots rely strictly on instrument indications to precisely control the aircraft; therefore, they must have a solid understanding of basic aerodynamic principles in order to make accurate judgments regarding aircraft control inputs.



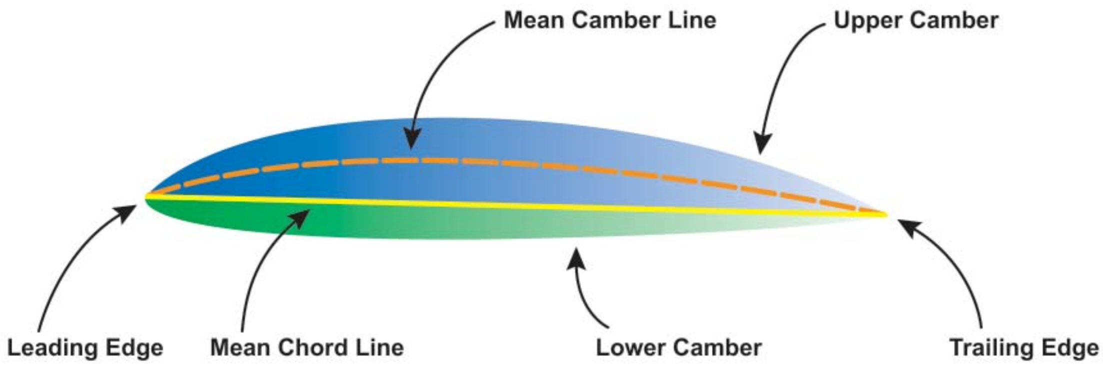


Figure 2-1. *The Airfoil.*

The Wing

To understand aerodynamic forces, a pilot needs to understand basic terminology associated with airfoils. *Figure 2-1* illustrates a typical airfoil.

The chord line is the straight line intersecting the leading and trailing edges of the airfoil, and the term chord refers to the chord line longitudinal length (length as viewed from the side).

The mean camber is a line located halfway between the upper and lower surfaces. Viewing the wing edgewise, the mean camber connects with the chord line at each end. The mean camber is important because it assists in determining aerodynamic qualities of an airfoil. The measurement of the maximum camber; inclusive of both the displacement of the mean camber line and its linear measurement from the end of the chord line, provide properties useful in evaluating airfoils.

Review of Basic Aerodynamics

The instrument pilot must understand the relationship and differences between several factors that affect the performance of an aircraft in flight. Also, it is crucial to understand how the aircraft reacts to various control and power changes, because the environment in which instrument pilots fly has inherent hazards not found in visual flying. The basis for this understanding is found in the four forces acting on an aircraft and Newton's Three Laws of Motion.

Relative Wind is the direction of the airflow with respect to an airfoil.

Angle of Attack is the acute angle measured between the relative wind, or flight path and the chord of the airfoil. *[Figure 2-2]*

Flight path is the course or track along which the aircraft is flying or is intended to be flown.

The Four Forces

The four basic forces *[Figure 2-3]* acting upon an aircraft in flight are lift, weight, thrust, and drag.

Lift

Lift is a component of the total aerodynamic force on an airfoil and acts perpendicular to the relative wind. Relative wind is the direction of the airflow with respect to an airfoil. This force acts straight up from the average (called mean) center of pressure (CP), which is called the center of lift. It should be noted that it is a point along the chord line of an airfoil through which all aerodynamic forces are considered to act. The magnitude of lift varies proportionately with speed, air density, shape and size of the airfoil, and angle of attack. During straight-and-level flight, lift and weight are equal.

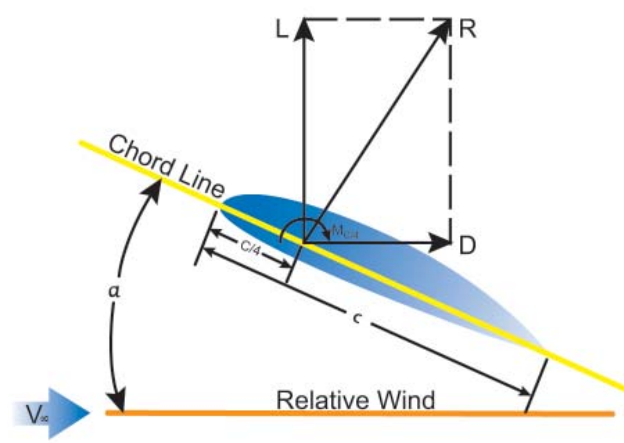


Figure 2-2. *Angle of Attack and Relative Wind.*

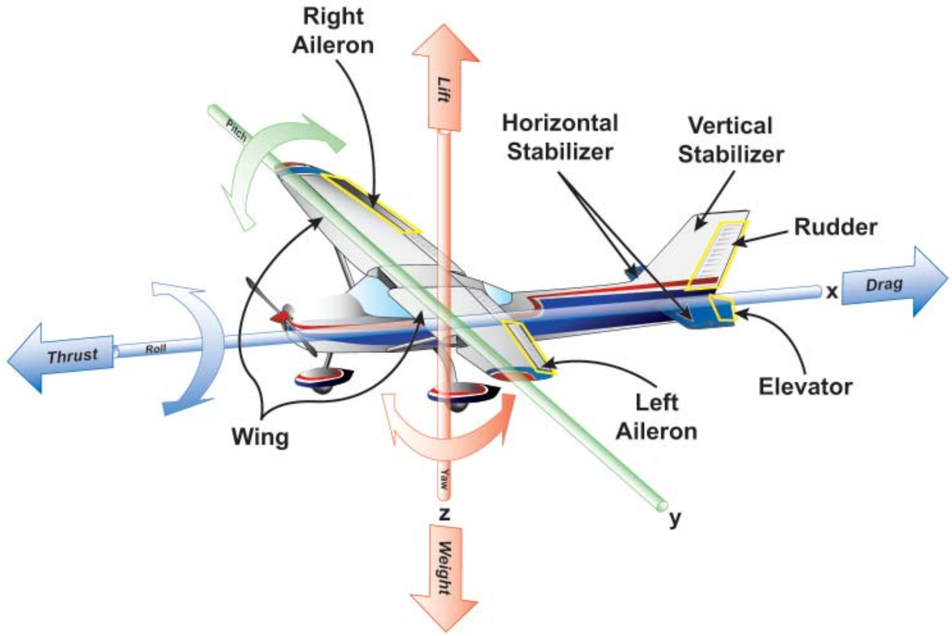


Figure 2-3. *The Four Forces and Three Axes of Rotation.*

Weight

Weight is the force exerted by an aircraft from the pull of gravity. It acts on an aircraft through its center of gravity (CG) and is straight down. This should not be confused with the center of lift, which can be significantly different from the CG. As an aircraft is descending, weight is greater than lift.

Thrust

Thrust is a force that drives an aircraft through the air and can be measured in thrust and/or horsepower. It is a component that is parallel to the center of thrust and overcomes drag providing the aircraft with its forward speed component.

Drag

Drag is the net aerodynamic force parallel to the relative wind and is generally a sum of two components: induced drag and parasite drag.

Induced drag

Induced drag is caused from the creation of lift and increases with airspeed. Therefore, if the wing is not producing lift, induced drag is zero. Conversely, induced drag increases with airspeed.

Parasite drag

Parasite drag is all drag not caused from the production of lift. Parasite drag is created by displacement of air by the aircraft, turbulence generated by the airfoil, and the hindrance of airflow as it passes over the surface of the aircraft or components. All of these forces create drag not from the production of lift but the movement of an object through an air mass. Parasite drag increases with speed and includes skin friction drag, interference drag, and form drag.

• Skin Friction Drag

Covering the entire "wetted" surface of the aircraft is a thin layer of air called a boundary layer. The air molecules on the surface have zero velocity in relation to the surface; however, the layer just above moves over the stagnant molecules below because it is pulled along by a third layer close to the free stream of air. The velocities of the layers increase as the distance from the surface increases until free stream velocity is reached, but all are affected by the free stream. The distance (total) between the skin surface and where free stream velocity is reached is called the boundary layer. At subsonic levels the cumulative layers are about the thickness of a playing card, yet their motion sliding over one another creates a drag force. This force retards motion due to the viscosity of the air and is called skin friction drag. Because skin friction drag is related to a large surface area its affect on smaller aircraft is small versus large transport aircraft where skin friction drag may be considerable.

• Interference Drag

Interference drag is generated by the collision of airstreams creating eddy currents, turbulence, or restrictions to smooth flow. For instance, the airflow around a fuselage and around the wing meet at some point, usually near the wing's root. These airflows interfere with each other causing a greater drag than the individual values. This is often the case when external items are placed on an aircraft. That is, the drag of each item individually, added to that of the aircraft, are less than that of the two items when allowed to interfere with one another.

• Form Drag

Form drag is the drag created because of the shape of a component or the aircraft. If one were to place a circular disk in an air stream, the pressure on both the top and bottom would be equal. However, the airflow starts to break down as the air flows around the back of the disk. This creates turbulence and hence a lower pressure results. Because the total pressure is affected by this reduced pressure, it creates a drag. Newer aircraft are generally made with consideration to this by fairing parts along the fuselage (teardrop) so that turbulence and form drag is reduced.

Total lift must overcome the total weight of the aircraft, which is comprised of the actual weight and the tail-down force used to control the aircraft's pitch attitude. Thrust must overcome total drag in order to provide forward speed with which to produce lift. Understanding how the aircraft's relationship between these elements and the environment provide proper interpretation of the aircraft's instruments.

Newton's First Law, the Law of Inertia

Newton's First Law of Motion is the Law of Inertia. It states that a body at rest will remain at rest, and a body in motion will remain in motion, at the same speed and in the same direction until affected by an outside force. The force with which a body offers resistance to change is called the force of inertia. Two outside forces are always present on an aircraft in flight: gravity and drag. The pilot uses pitch and thrust controls to counter or change these forces to maintain the desired flight path. If a pilot reduces power while in straight-and-level flight, the aircraft will slow due to drag. However, as the aircraft slows there is a reduction of lift, which causes the aircraft to begin a descent due to gravity. *[Figure 2-4]*

Newton's Second Law, the Law of Momentum

Newton's Second Law of Motion is the Law of Momentum, which states that a body will accelerate in the same direction as the force acting upon that body, and the acceleration will be directly proportional to the net force and inversely proportional to the mass of the body. Acceleration refers either to an increase or decrease in velocity, although deceleration is commonly used to indicate a decrease. This law governs the aircraft's ability to change flight path and speed, which are controlled by attitude (both pitch and bank) and thrust inputs. Speeding up, slowing down, entering climbs or descents, and turning are examples of accelerations that the pilot controls in everyday flight. *[Figure 2-5]*

Newton's Third Law, the Law of Reaction

Newton's Third Law of Motion is the Law of Reaction, which states that for every action there is an equal and opposite reaction. As shown in *Figure 2-6*, the action of the jet engine's thrust or the pull of the propeller lead to the reaction of the aircraft's forward motion. This law is also responsible for a portion of the lift that is produced by a wing, from the downward deflection of the airflow around it. This downward force of the relative wind results in an equal but opposite (upward) lifting force created by the airflow over the wing. *[Figure 2-6]*

Atmosphere

The atmosphere is the envelope of air which surrounds the Earth. A given volume of dry air contains about 78 percent nitrogen, 21 percent oxygen, and about 1 percent other gases such as argon, carbon dioxide, and others to a lesser degree. Although seemingly light, air does have weight and a one square inch column of the atmosphere at sea level weighs approximately 14.7 pounds. About one-half of the air by weight is within the first 18,000 feet. The remainder of the air is spread over a vertical distance in excess of 1,000 miles.

Air density is a result of the relationship between temperature and pressure. Air density is inversely related to temperature and directly related to pressure. For a constant pressure to be

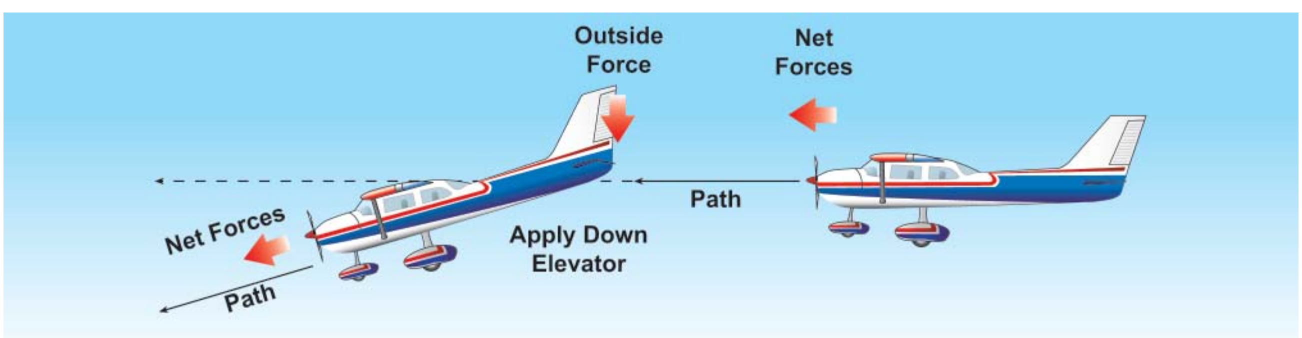


Figure 2-4. *Newton's First Law of Motion: the Law of Inertia.*

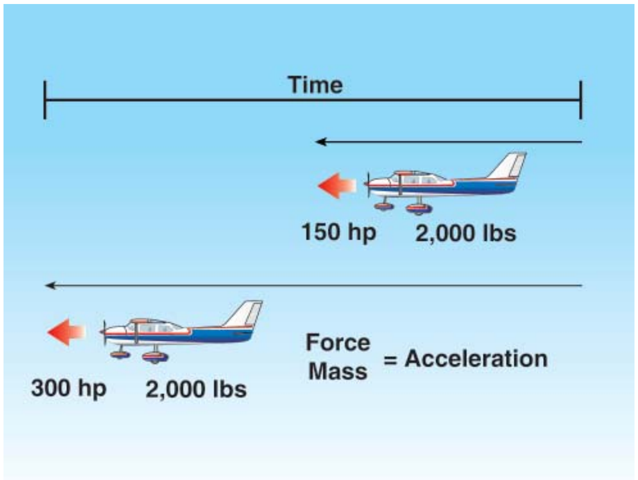


Figure 2-5. *Newton's Second Law of Motion: the Law of Momentum.*

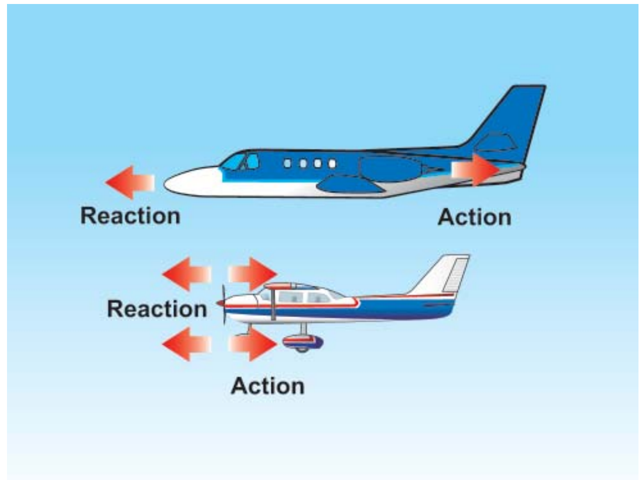


Figure 2-6. *Newton's Third Law of Motion: the Law of Reaction.*

maintained as temperature increases, density must decrease, and vice versa. For a constant temperature to be maintained as pressure increases, density must increase, and vice versa. These relationships provide a basis for understanding instrument indications and aircraft performance.

Layers of the Atmosphere

There are several layers to the atmosphere with the troposphere being closest to the Earth's surface extending to about 60,000 feet. Following is the stratosphere, mesosphere, ionosphere, thermosphere, and finally the exosphere. The tropopause is the thin layer between the troposphere and the stratosphere. It varies in both thickness and altitude but is generally defined where the standard lapse (generally accepted at 2° C per 1,000 feet) decreases significantly (usually down to 1° C or less).

International Standard Atmosphere (ISA)

The International Civil Aviation Organization (ICAO) established the ICAO Standard Atmosphere as a way of creating an international standard for reference and performance computations. Instrument indications and aircraft performance specifications are derived using this standard as a reference. Because the standard atmosphere is a derived set of conditions that rarely exist in reality, pilots need to understand how deviations from the standard affect both instrument indications and aircraft performance.

In the standard atmosphere, sea level pressure is 29.92" inches of mercury (Hg) and the temperature is 15° C (59° F). The standard lapse rate for pressure is approximately a 1" Hg decrease per 1,000 feet increase in altitude. The standard lapse rate for temperature is a 2° C (3.6° F) decrease per 1,000 feet increase, up to the top of the stratosphere. Since all aircraft performance is compared and evaluated in the environment of the standard atmosphere, all aircraft performance instrumentation is calibrated for the standard atmosphere. Because the actual operating conditions rarely, if ever, fit the standard atmosphere, certain corrections must apply to the instrumentation and aircraft performance. For instance, at 10,000 ISA predicts that the air pressure should be 19.92" Hg (29.92" - 10" Hg = 19.92") and the outside temperature at -5°C (15° C - 20° C). If the temperature or the pressure is different than the International Standard Atmosphere (ISA) prediction an adjustment must be made to performance predictions and various instrument indications.

Pressure Altitude

There are two measurements of the atmosphere that affect performance and instrument calibrations: pressure altitude and density altitude. Pressure altitude is the height above the standard datum pressure (SDP) (29.92" Hg, sea level under ISA) and is used for standardizing altitudes for flight levels (FL). Generally, flight levels are at or above 18,000 feet (FL 180), providing the pressure is at or above 29.92"Hg. For calculations involving aircraft performance when the altimeter is set for 29.92" Hg, the altitude indicated is the pressure altitude.

Density Altitude

Density altitude is pressure altitude corrected for nonstandard temperatures, and is used for determining aerodynamic performance in the nonstandard atmosphere. Density altitude increases as the density decreases. Since density varies directly with pressure, and inversely with temperature, a wide range of temperatures may exist with a given pressure altitude, which allows the density to vary. However, a known density occurs for any one temperature and pressure altitude combination. The density of the air has a significant effect on aircraft and engine performance. Regardless of the actual altitude above sea level an aircraft is operating at, its performance will be as though it were operating at an altitude equal to the existing density altitude.

If a chart is not available the density altitude can be estimated by adding 120 feet for every degree Celsius above the ISA. For example, at 3,000 feet pressure altitude (PA), the ISA prediction is 9° C (15° C - [lapse rate of 2° C per 1,000 feet X 3 = 6° C]). However, if the actual temperature is 20° C (11° C more than that predicted by ISA) then the difference of 11° C is multiplied by 120 feet equaling 1,320. Adding this figure to the original 3,000 feet provides a density altitude of 4,320 feet (3,000 feet + 1,320 feet).

Lift

Lift always acts in a direction perpendicular to the relative wind and to the lateral axis of the aircraft. The fact that lift is referenced to the wing, not to the Earth's surface, is the source of many errors in learning flight control. Lift is not always "up." Its direction relative to the Earth's surface changes as the pilot maneuvers the aircraft.

The magnitude of the force of lift is directly proportional to the density of the air, the area of the wings, and the airspeed. It also depends upon the type of wing and the angle of attack. Lift increases with an increase in angle of attack up to the stalling angle, at which point it decreases with any further increase in angle of attack. In conventional aircraft, lift is therefore controlled by varying the angle of attack and speed.

Pitch/Power Relationship

An examination of *Figure 2-7* illustrates the relationship between pitch and power while controlling flight path and airspeed. In order to maintain a constant lift, as airspeed is reduced, pitch must be increased. The pilot controls pitch through the elevators, which control the angle of attack. When back pressure is applied on the elevator control, the tail lowers and the nose rises, thus increasing the wing's angle of attack and lift. Under most conditions the elevator is placing downward pressure on the tail. This pressure requires energy that is taken from aircraft performance (speed). Therefore, when the CG is closer to the aft portion of the aircraft the elevator downward forces are less. This results in less energy used for downward forces, in turn resulting in more energy applied to aircraft performance.

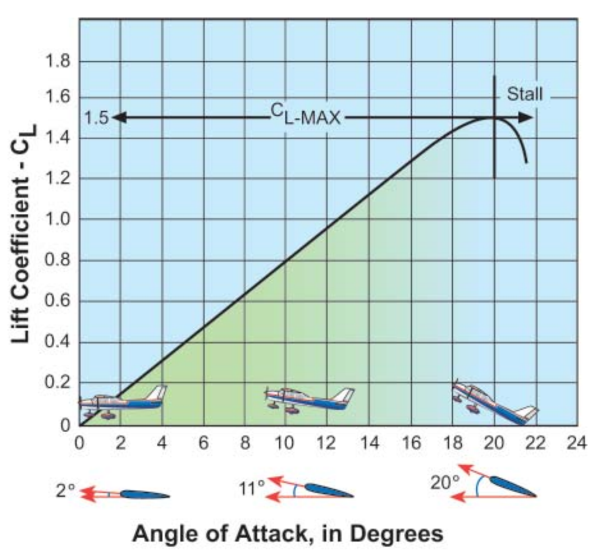


Figure 2-7. *Relationship of Lift to Angle of Attack.*

Thrust is controlled by using the throttle to establish or maintain desired airspeeds. The most precise method of controlling flight path is to use pitch control while simultaneously using power (thrust) to control airspeed. In order to maintain a constant lift, a change in pitch requires a change in power, and vice versa.

If the pilot wants the aircraft to accelerate while maintaining altitude, thrust must be increased to overcome drag. As the aircraft speeds up, lift is increased. To prevent gaining altitude, the pitch angle must be lowered to reduce the angle of attack and maintain altitude. To decelerate while maintaining altitude, thrust must be decreased to less than the value of drag. As the aircraft slows down, lift is reduced. To prevent losing altitude, the pitch angle must be increased in order to increase the angle of attack and maintain altitude.

Drag Curves

When induced drag and parasite drag are plotted on a graph, the total drag on the aircraft appears in the form of a "drag curve." Graph A of *Figure 2-8* shows a curve based on thrust versus drag, which is primarily used for jet aircraft. Graph B of *Figure 2-8* is based on power versus drag, and it is used for propeller-driven aircraft. This chapter focuses on power versus drag charts for propeller-driven aircraft.

Understanding the drag curve can provide valuable insight into the various performance parameters and limitations of the aircraft. Because power must equal drag to maintain a steady airspeed, the curve can be either a drag curve or a power required curve. The power required curve represents the amount of power needed to overcome drag in order to maintain a steady speed in level flight.

The propellers used on most reciprocating engines achieve peak propeller efficiencies in the range of 80 to 88 percent. As airspeed increases, the propeller efficiency increases until it reaches its maximum. Any airspeed above this maximum point causes a reduction in propeller efficiency. An engine that produces 160 horsepower will have only about 80 percent of that power converted into available horsepower,

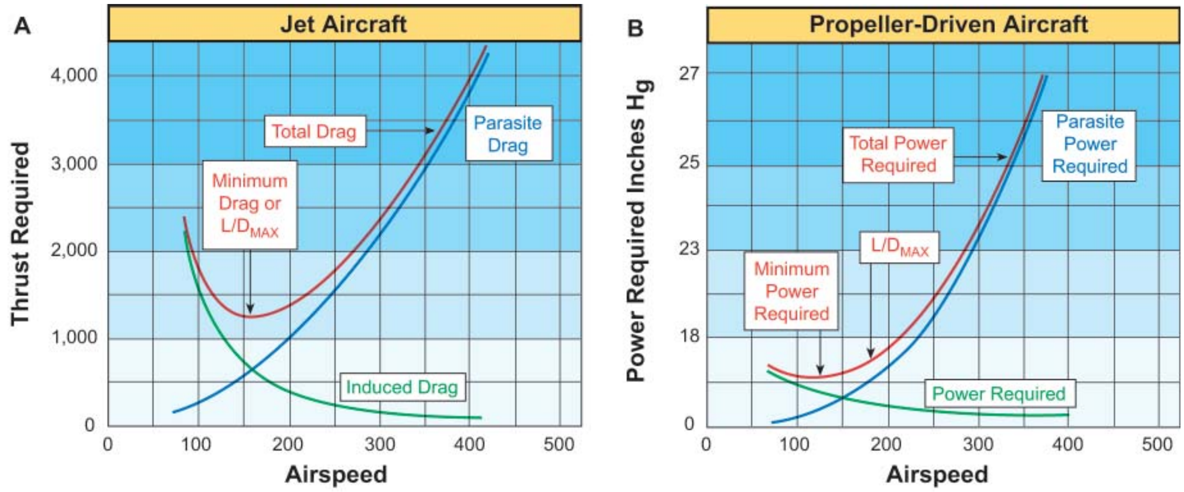


Figure 2-8. *Thrust and Power Required Curves.*

approximately 128 horsepower. The remainder is lost energy. This is the reason the thrust and power available curves change with speed.

Regions of Command

The drag curve also illustrates the two regions of command: the region of normal command, and the region of reversed command. The term "region of command" refers to the relationship between speed and the power required to maintain or change that speed. "Command" refers to the input the pilot must give in terms of power or thrust to maintain a new speed once reached.

The "region of normal command" occurs where power must be added to increase speed. This region exists at speeds higher than the minimum drag point primarily as a result of parasite drag. The "region of reversed command" occurs where additional power is needed to maintain a slower airspeed. This region exists at speeds slower than the minimum drag point (L/D_{MAX} on the thrust required curve, *Figure 2-8*) and is primarily due to induced drag. *Figure 2-9* shows how one

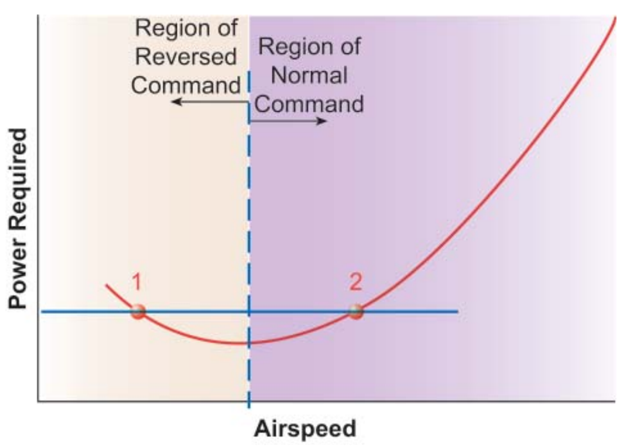


Figure 2-9. *Regions of Command.*

power setting can yield two speeds, points 1 and 2. This is because at point 1 there is high induced drag and low parasite drag, while at point 2 there is high parasite drag and low induced drag.

Control Characteristics

Most flying is conducted in the region of normal command: for example, cruise, climb, and maneuvers. The region of reversed command may be encountered in the slow-speed phases of flight during takeoff and landing; however, for most general aviation aircraft, this region is very small and is below normal approach speeds.

Flight in the region of normal command is characterized by a relatively strong tendency of the aircraft to maintain the trim speed. Flight in the region of reversed command is characterized by a relatively weak tendency of the aircraft to maintain the trim speed. In fact, it is likely the aircraft exhibits no inherent tendency to maintain the trim speed in this area. For this reason, the pilot must give particular attention to precise control of airspeed when operating in the slow-speed phases of the region of reversed command.

Operation in the region of reversed command does not imply that great control difficulty and dangerous conditions exist. However, it does amplify errors of basic flying technique—making proper flying technique and precise control of the aircraft very important.

Speed Stability

Normal Command

The characteristics of flight in the region of normal command are illustrated at point A on the curve in *Figure 2-10*. If the aircraft is established in steady, level flight at point A, lift is equal to weight, and the power available is set equal to the power required. If the airspeed is increased with no changes

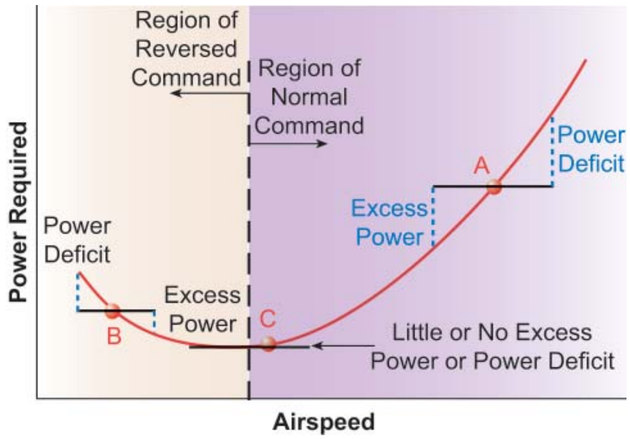


Figure 2-10. *Region of Speed Stability.*

to the power setting, a power deficiency exists. The aircraft has a natural tendency to return to the initial speed to balance power and drag. If the airspeed is reduced with no changes to the power setting, an excess of power exists. The aircraft has a natural tendency to speed up to regain the balance between power and drag. Keeping the aircraft in proper trim enhances this natural tendency. The static longitudinal stability of the aircraft tends to return the aircraft to the original trimmed condition.

An aircraft flying in steady, level flight at point C is in equilibrium. *[Figure 2-10]* If the speed were increased or decreased slightly, the aircraft would tend to remain at that speed. This is because the curve is relatively flat and a slight change in speed does not produce any significant excess or deficiency in power. It has the characteristic of neutral stability, i.e., the aircraft's tendency is to remain at the new speed.

Reversed Command

The characteristics of flight in the region of reversed command are illustrated at point B on the curve in *Figure 2-10*. If the aircraft is established in steady, level flight at point B, lift is equal to weight, and the power available is set equal to the power required. When the airspeed is increased greater than point B, an excess of power exists. This causes the aircraft to accelerate to an even higher speed. When the aircraft is slowed to some airspeed lower than point B, a deficiency of power exists. The natural tendency of the aircraft is to continue to slow to an even lower airspeed.

This tendency toward instability happens because the variation of excess power to either side of point B magnifies the original change in speed. Although the static longitudinal stability of the aircraft tries to maintain the original trimmed condition, this instability is more of an influence because of the increased induced drag due to the higher angles of attack in slow-speed flight.

Trim

The term trim refers to employing adjustable aerodynamic devices on the aircraft to adjust forces so the pilot does not have to manually hold pressure on the controls. One means is to employ trim tabs. A trim tab is a small, adjustable hinged surface, located on the trailing edge of the elevator, aileron, or rudder control surfaces. (Some aircraft use adjustable stabilizers instead of trim tabs for pitch trim.) Trimming is accomplished by deflecting the tab in the direction opposite to that in which the primary control surface must be held. The force of the airflow striking the tab causes the main control surface to be deflected to a position that corrects the unbalanced condition of the aircraft.

Because the trim tabs use airflow to function, trim is a function of speed. Any change in speed results in the need to re-trim the aircraft. An aircraft properly trimmed in pitch seeks to return to the original speed before the change. It is very important for instrument pilots to keep the aircraft in constant trim. This reduces the pilot's workload significantly, allowing attention to other duties without compromising aircraft control.

Slow-Speed Flight

Anytime an aircraft is flying near the stalling speed or the region of reversed command, such as in final approach for a normal landing, the initial part of a go around, or maneuvering in slow flight, it is operating in what is called slow-speed flight. If the aircraft weighs 4,000 pounds, the lift produced by the aircraft must be 4,000 pounds. When lift is less than 4,000 pounds, the aircraft is no longer able to sustain level flight, and consequently descends. During intentional descents, this is an important factor and is used in the total control of the aircraft.

However, because lift is required during low speed flight and is characterized by high angles of attack, flaps or other high lift devices are needed to either change the camber of the airfoil, or delay the boundary level separation. Plain and split flaps *[Figure 2-11]* are most commonly used to change the camber of an airfoil. It should be noted that with the application of flaps, the aircraft will stall at a lower angle of attack. The basic wing stalls at 18° without flaps but with the application of the flaps extended (to $C_{L\text{-}MAX}$ position) the new angle of attack at which point the aircraft will stall is 15°. However, the value of lift (flaps extended to the $C_{L\text{-}MAX}$ position) produces more lift than lift at 18° on the basic wing.

Delaying the boundary layer separation is another way to increase $C_{L\text{-}MAX}$. Several methods are employed (such as suction and use of a blowing boundary layer control), but the most common device used on general aviation light aircraft is the vortex generator. Small strips of metal placed along the wing (usually in front of the control surfaces) create turbulence. The turbulence in turn mixes high energy air from outside the boundary layer with boundary layer air. The effect is similar to other boundary layer devices. *[Figure 2-12]*

Small Airplanes

Most small airplanes maintain a speed well in excess of 1.3 times V_{SO} on an instrument approach. An airplane with a stall speed of 50 knots (V_{SO}) has a normal approach speed of 65 knots. However, this same airplane may maintain 90 knots (1.8 V_{SO}) while on the final segment of an instrument approach. The landing gear will most likely be extended at the beginning of the descent to the minimum descent altitude, or upon intercepting the glide slope of the instrument landing system. The pilot may also select an intermediate flap setting for this phase of the approach. The airplane at this speed has good positive speed stability, as represented by point A on *Figure 2-10*. Flying in this regime permits the pilot to make slight pitch changes without changing power settings, and accept minor speed changes knowing that when the pitch is returned to the initial setting, the speed returns to the original setting. This reduces the pilot's workload.

Aircraft are usually slowed to a normal landing speed when on the final approach just prior to landing. When slowed to 65 knots, (1.3 V_{SO}), the airplane will be close to point C. *[Figure 2-10]* At this point, precise control of the pitch and power becomes more crucial for maintaining the correct speed. Pitch and power coordination is necessary because the speed stability is relatively neutral since the speed tends to remain at the new value and not return to the original setting. In addition to the need for more precise airspeed control, the pilot normally changes the aircraft's configuration by extending landing flaps. This configuration change means the pilot must be alert to unwanted pitch changes at a low altitude.

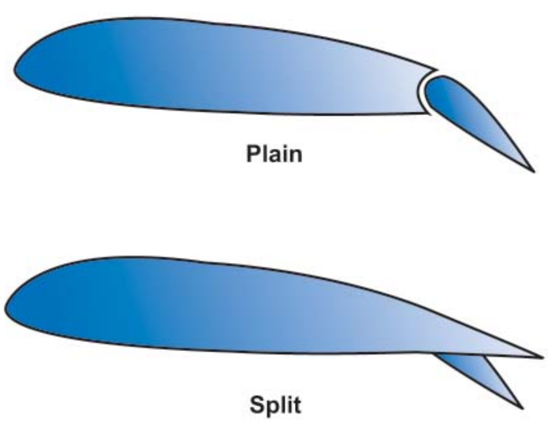


Figure 2-11. *Various Types of Flaps.*

If allowed to slow several knots, the airplane could enter the region of reversed command. At this point, the airplane could develop an unsafe sink rate and continue to lose speed unless the pilot takes a prompt corrective action. Proper pitch and power coordination is critical in this region due to speed instability and the tendency of increased divergence from the desired speed.

Large Airplanes

Pilots of larger airplanes with higher stall speeds may find the speed they maintain on the instrument approach is near 1.3 V_{SO}, putting them near point C *[Figure 2-10]* the entire time the airplane is on the final approach segment. In this case, precise speed control is necessary throughout the approach. It may be necessary to temporarily select excessive, or deficient thrust in relation to the target thrust setting in order to quickly correct for airspeed deviations.

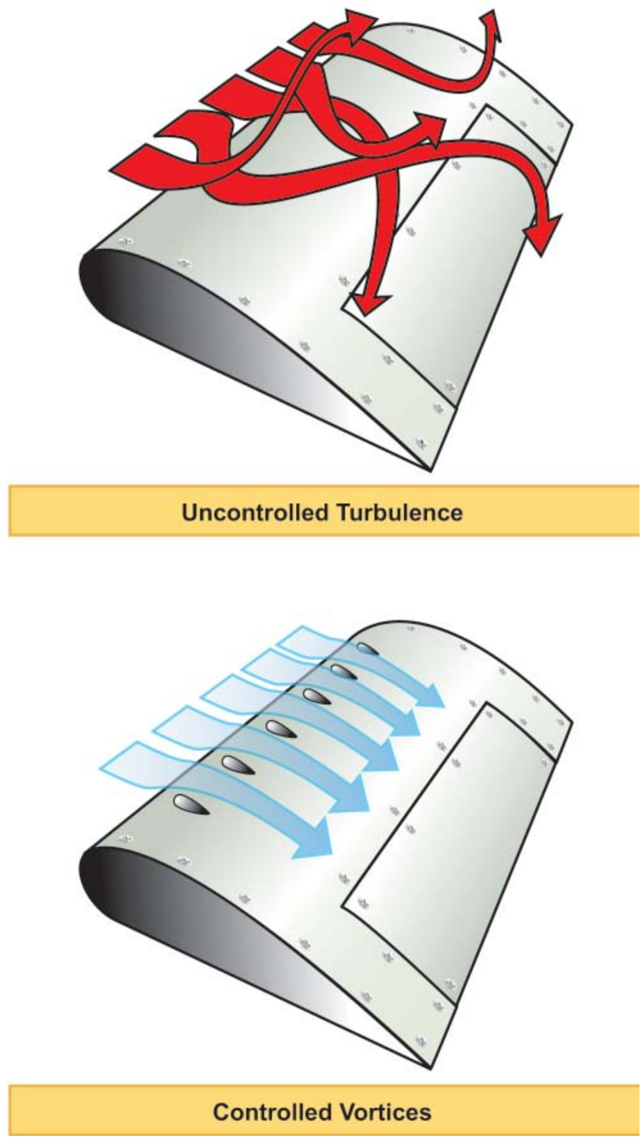


Figure 2-12. *Vortex Generators.*

For example, a pilot is on an instrument approach at 1.3 V_{SO}, a speed near L/D_{MAX}, and knows that a certain power setting maintains that speed. The airplane slows several knots below the desired speed because of a slight reduction in the power setting. The pilot increases the power slightly, and the airplane begins to accelerate, but at a slow rate. Because the airplane is still in the "flat part" of the drag curve, this slight increase in power will not cause a rapid return to the desired speed. The pilot may need to increase the power higher than normally needed to maintain the new speed, allow the airplane to accelerate, then reduce the power to the setting that maintains the desired speed.

Climbs

The ability for an aircraft to climb depends upon an excess power or thrust over what it takes to maintain equilibrium. Excess power is the available power over and above that required to maintain horizontal flight at a given speed. Although the terms power and thrust are sometimes used interchangeably (erroneously implying they are synonymous), distinguishing between the two is important when considering climb performance. Work is the product of a force moving through a distance and is usually independent of time. Power implies work rate or units of work per unit of time, and as such is a function of the speed at which the force is developed. Thrust, also a function of work, means the force which imparts a change in the velocity of a mass.

During take off, the aircraft does not stall even though it may be in a climb near the stall speed. The reason is that excess power (used to produce thrust) is used during this flight regime. Therefore, it is important if an engine fails after take off, to compensate the loss of thrust with pitch and airspeed.

For a given weight of the aircraft, the angle of climb depends on the difference between thrust and drag, or the excess thrust. When the excess thrust is zero, the inclination of the flight path is zero, and the aircraft is in steady, level flight. When thrust is greater than drag, the excess thrust allows a climb angle depending on the amount of excess thrust. When thrust is less than drag, the deficiency of thrust induces an angle of descent.

Acceleration in Cruise Flight

Aircraft accelerate in level flight because of an excess of power over what is required to maintain a steady speed. This is the same excess power used to climb. Upon reaching the desired altitude with pitch being lowered to maintain that altitude, the excess power now accelerates the aircraft to its cruise speed. However, reducing power too soon after level off results in a longer period of time to accelerate.

Turns

Like any moving object, an aircraft requires a sideward force to make it turn. In a normal turn, this force is supplied by banking the aircraft in order to exert lift inward, as well as upward. The force of lift is separated into two components at right angles to each other. *[Figure 2-13]* The upward acting lift together with the opposing weight becomes the vertical lift component. The horizontally acting lift and its opposing centrifugal force are the horizontal lift component, or centripetal force. This horizontal lift component is the sideward force that causes an aircraft to turn. The equal and opposite reaction to this sideward force is centrifugal force, which is merely an apparent force as a result of inertia.

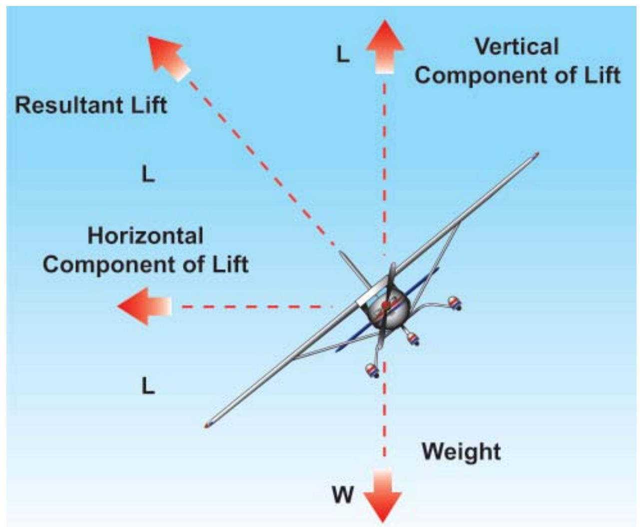


Figure 2-13. *Forces In a Turn.*

The relationship between the aircraft's speed and bank angle to the rate and radius of turns is important for instrument pilots to understand. The pilot can use this knowledge to properly estimate bank angles needed for certain rates of turn, or to determine how much to lead when intercepting a course.

Rate of Turn

The rate of turn, normally measured in degrees per second, is based upon a set bank angle at a set speed. If either one of these elements changes, the rate of turn changes. If the aircraft increases its speed without changing the bank angle, the rate of turn decreases. Likewise, if the speed decreases without changing the bank angle, the rate of turn increases.

Changing the bank angle without changing speed also causes the rate of turn to change. Increasing the bank angle without changing speed increases the rate of turn, while decreasing the bank angle reduces the rate of turn.

The standard rate of turn, 3° per second, is used as the main reference for bank angle. Therefore, the pilot must understand how the angle of bank varies with speed changes, such as slowing down for holding or an instrument approach. *Figure 2-14* shows the turn relationship with reference to a constant bank angle or a constant airspeed, and the effects on rate of turn and radius of turn. A rule of thumb for determining the standard rate turn is to divide the airspeed by ten and add 7. An aircraft with an airspeed of 90 knots takes a bank angle of 16° to maintain a standard rate turn (90 divided by 10 plus 7 equals 16°).

Radius of Turn

The radius of turn varies with changes in either speed or bank. If the speed is increased without changing the bank angle, the radius of turn increases, and vice versa. If the speed is constant, increasing the bank angle reduces the radius of turn, while decreasing the bank angle increases the radius of turn. This means that intercepting a course at a higher speed requires more distance, and therefore, requires a longer lead. If the speed is slowed considerably in preparation for holding or an approach, a shorter lead is needed than that required for cruise flight.

Coordination of Rudder and Aileron Controls

Any time ailerons are used, adverse yaw is produced. Adverse yaw is caused when the ailerons are deflected as a roll motion (as in turn) is initiated. In a right turn, the right aileron is deflected downward while the left is deflected upward. Lift is increased on the left side and reduced on the right, resulting in a bank to the right. However, as a result of producing lift on the left, induced drag is also increased on the left side. The drag causes the left wing to slow down, in turn causing the nose of the aircraft to initially move (left) in the direction opposite of the turn. Correcting for this yaw with rudder, when entering and exiting turns, is necessary for precise control of the airplane when flying on instruments. The pilot can tell if the turn is coordinated by checking the ball in the turn-and-slip indicator or the turn coordinator. *[Figure 2-15]*

As the aircraft banks to enter a turn, a portion of the wing's vertical lift becomes the horizontal component; therefore, without an increase in back pressure, the aircraft loses altitude during the turn. The loss of vertical lift can be offset by increasing the pitch in one-half bar width increments. Trim may be used to relieve the control pressures; however, if used, it has to be removed once the turn is complete.

In a slipping turn, the aircraft is not turning at the rate appropriate to the bank being used, and the aircraft falls to the inside of the turn. The aircraft is banked too much for the rate of turn, so the horizontal lift component is greater than the centrifugal force. A skidding turn results from excess of centrifugal force over the horizontal lift component, pulling the aircraft toward the outside of the turn. The rate of turn is too great for the angle of bank, so the horizontal lift component is less than the centrifugal force.

The ball instrument indicates the quality of the turn, and should be centered when the wings are banked. If the ball is off of center on the side toward the turn, the aircraft is slipping and rudder pressure should be added on that side to increase the rate of turn or the bank angle should be reduced. If the ball is off of center on the side away from the turn, the aircraft is skidding and rudder pressure toward the turn should be relaxed or the bank angle should be increased. If the aircraft is properly rigged, the ball should be in the center when the wings are level; use rudder and/or aileron trim if available.

The increase in induced drag (caused by the increase in angle of attack necessary to maintain altitude) results in a minor loss of airspeed if the power setting is not changed.

Load Factor

Any force applied to an aircraft to deflect its flight from a straight line produces a stress on its structure; the amount of this force is termed load factor. A load factor is the ratio of

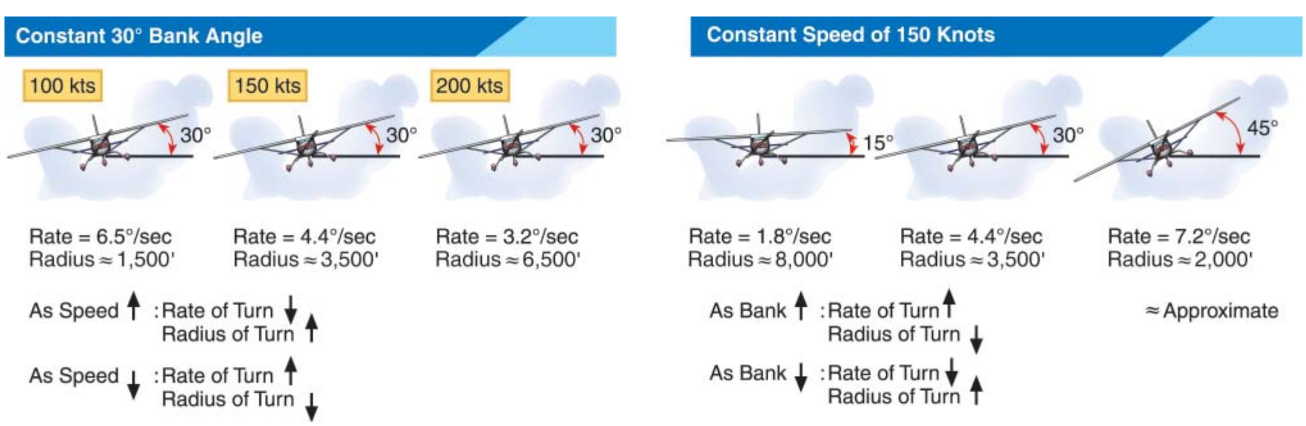


Figure 2-14. *Turns.*

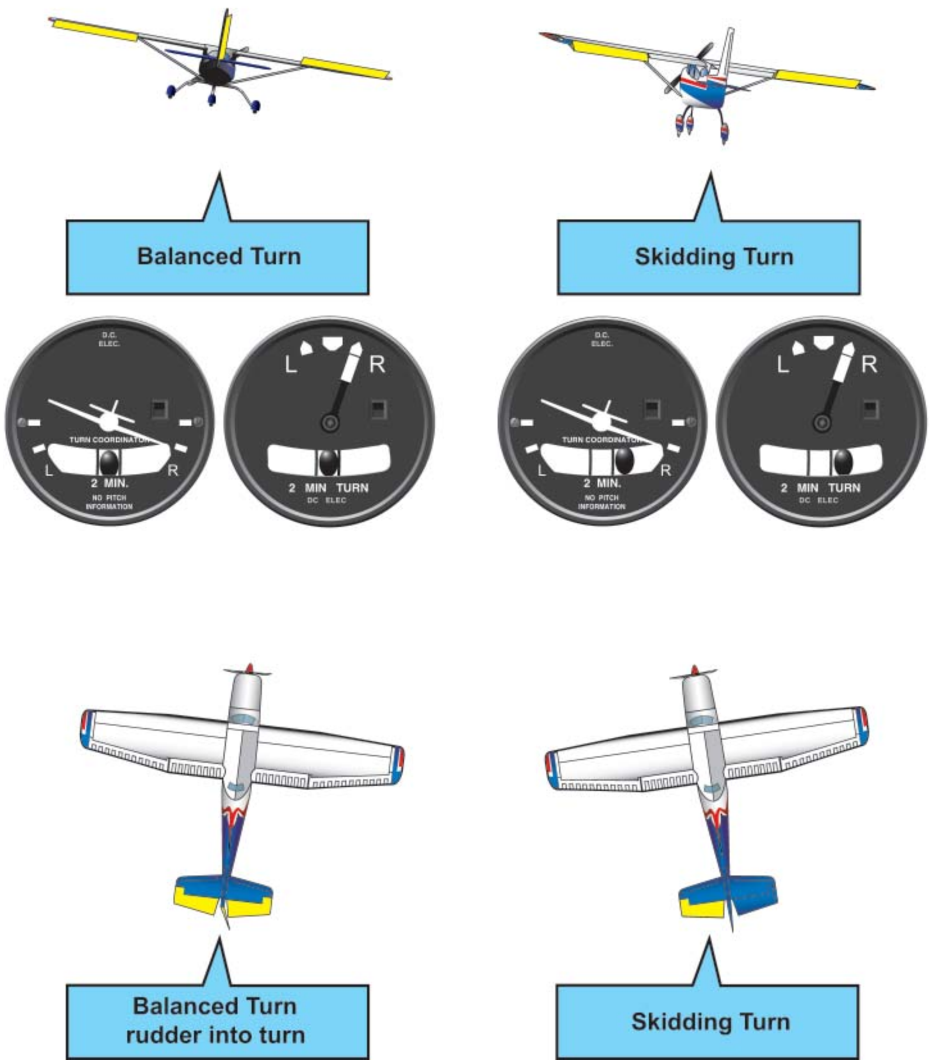


Figure 2-15. *Adverse Yaw.*

the aerodynamic force on the aircraft to the gross weight of the aircraft (e.g., lift/weight). For example, a load factor of 3 means the total load on an aircraft's structure is three times its gross weight. When designing an aircraft, it is necessary to determine the highest load factors that can be expected in normal operation under various operational situations. These "highest" load factors are called "limit load factors."

Aircraft are placed in various categories, i.e., normal, utility, and acrobatic, depending upon the load factors they are designed to take. For reasons of safety, the aircraft must be designed to withstand certain maximum load factors without any structural damage.

The specified load may be expected in terms of aerodynamic forces, as in turns. In level flight in undisturbed air, the wings are supporting not only the weight of the aircraft, but centrifugal force as well. As the bank steepens, the horizontal lift component increases, centrifugal force increases, and the load factor increases. If the load factor becomes so great that an increase in angle of attack cannot provide enough lift to support the load, the wing stalls. Since the stalling speed increases directly with the square root of the load factor, the pilot should be aware of the flight conditions during which the load factor can become critical. Steep turns at slow airspeed, structural ice accumulation, and vertical gusts in turbulent air can increase the load factor to a critical level.

Icing

One of the greatest hazards to flight is aircraft icing. The instrument pilot must be aware of the conditions conducive to aircraft icing. These conditions include the types of icing, the effects of icing on aircraft control and performance, effects of icing on aircraft systems, and the use and limitations of aircraft deice and anti-ice equipment. Coping with the hazards of icing begins with preflight planning to determine where icing may occur during a flight and ensuring the aircraft is free of ice and frost prior to takeoff. This attention to detail extends to managing deice and anti-ice systems properly during the flight, because weather conditions may change rapidly, and the pilot must be able to recognize when a change of flight plan is required.

Types of Icing

Structural Icing

Structural icing refers to the accumulation of ice on the exterior of the aircraft. Ice forms on aircraft structures and surfaces when super-cooled droplets impinge on them and freeze. Small and/or narrow objects are the best collectors of droplets and ice up most rapidly. This is why a small protuberance within sight of the pilot can be used as an "ice evidence probe." It is generally one of the first parts of the airplane on which an appreciable amount of ice forms. An aircraft's tailplane is a better collector than its wings, because the tailplane presents a thinner surface to the airstream.

Induction Icing

Ice in the induction system can reduce the amount of air available for combustion. The most common example of reciprocating engine induction icing is carburetor ice. Most pilots are familiar with this phenomenon, which occurs when moist air passes through a carburetor venturi and is cooled. As a result of this process, ice may form on the venturi walls and throttle plate, restricting airflow to the engine. This may occur at temperatures between 20° F (-7° C) and 70° F (21° C). The problem is remedied by applying carburetor heat, which uses the engine's own exhaust as a heat source to melt the ice or prevent its formation. On the other hand, fuel-injected aircraft engines usually are less vulnerable to icing but still can be affected if the engine's air source becomes blocked with ice. Manufacturers provide an alternate air source that may be selected in case the normal system malfunctions.

In turbojet aircraft, air that is drawn into the engines creates an area of reduced pressure at the inlet, which lowers the temperature below that of the surrounding air. In marginal icing conditions (i.e., conditions where icing is possible), this reduction in temperature may be sufficient to cause ice to form on the engine inlet, disrupting the airflow into the engine. Another hazard occurs when ice breaks off and is ingested into a running engine, which can cause damage to fan blades, engine compressor stall, or combustor flameout. When anti-icing systems are used, runback water also can refreeze on unprotected surfaces of the inlet and, if excessive, reduce airflow into the engine or distort the airflow pattern in such a manner as to cause compressor or fan blades to vibrate, possibly damaging the engine. Another problem in turbine engines is the icing of engine probes used to set power levels (for example, engine inlet temperature or engine pressure ratio (EPR) probes), which can lead to erroneous readings of engine instrumentation operational difficulties or total power loss.

The type of ice that forms can be classified as clear, rime, or mixed, based on the structure and appearance of the ice. The type of ice that forms varies depending on the atmospheric and flight conditions in which it forms. Significant structural icing on an aircraft can cause serious aircraft control and performance problems.

Clear Ice

A glossy, transparent ice formed by the relatively slow freezing of super cooled water is referred to as clear ice. *[Figure 2-16]* The terms "clear" and "glaze" have been used for essentially the same type of ice accretion. This type of ice is denser, harder, and sometimes more transparent than rime ice. With larger accretions, clear ice may form "horns." *[Figure 2-17]* Temperatures close to the freezing point, large amounts of liquid water, high aircraft velocities, and large droplets are conducive to the formation of clear ice.

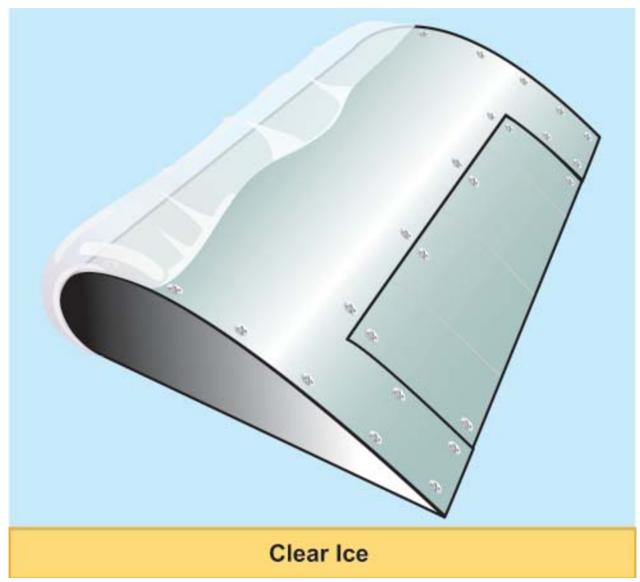


Figure 2-16. *Clear Ice.*

Rime Ice

A rough, milky, opaque ice formed by the instantaneous or very rapid freezing of super cooled droplets as they strike the aircraft is known as rime ice. *[Figure 2-18]* The rapid freezing results in the formation of air pockets in the ice, giving it an opaque appearance and making it porous and brittle. For larger accretions, rime ice may form a streamlined extension of the wing. Low temperatures, lesser amounts of liquid water, low velocities, and small droplets are conducive to the formation of rime ice.

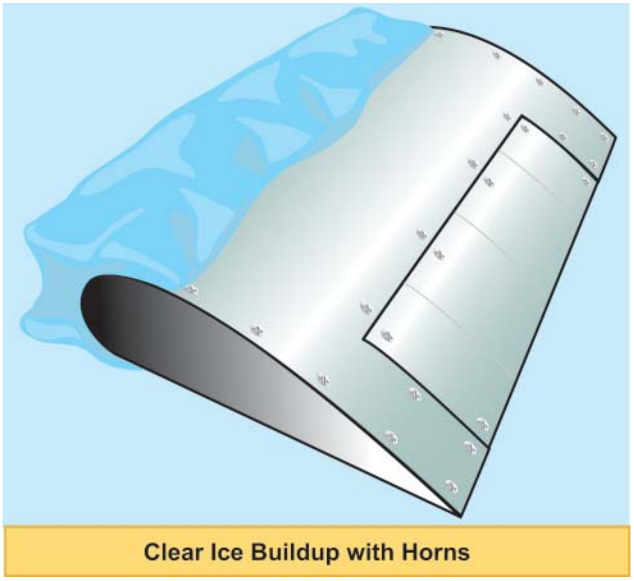


Figure 2-17. *Clear Ice Buildup.*

Figure 2-18. *Rime Ice.*

Mixed Ice

Mixed ice is a combination of clear and rime ice formed on the same surface. It is the shape and roughness of the ice that is most important from an aerodynamic point of view.

General Effects of Icing on Airfoils

The most hazardous aspect of structural icing is its aerodynamic effects. *[Figure 2-19]* Ice alters the shape of an airfoil, reducing the maximum coefficient of lift and angle of attack at which the aircraft stalls. Note that at very low angles of attack, there may be little or no effect of the ice on the coefficient of lift. Therefore, when cruising at a low angle of attack, ice on the wing may have little effect on the lift. However, note that the ice significantly reduces the $C_{L\text{-}MAX}$, and the angle of attack at which it occurs (the stall angle) is much lower. Thus, when slowing down and increasing the angle of attack for approach, the pilot may find that ice on the wing, which had little effect on lift in cruise now, causes stall to occur at a lower angle of attack and higher speed. Even a thin layer of ice at the leading edge of a wing, especially if it is rough, can have a significant effect in increasing stall speed. For large ice shapes, especially those with horns, the lift may also be reduced at a lower angle of attack. The accumulation of ice affects the coefficient of drag of the airfoil. *[Figure 2-19]* Note that the effect is significant even at very small angles of attack.

A significant reduction in $C_{L\text{-}MAX}$ and a reduction in the angle of attack where stall occurs can result from a relatively small ice accretion. A reduction of $C_{L\text{-}MAX}$ by 30 percent is not unusual, and a large horn ice accretion can result in reductions of 40 percent to 50 percent. Drag tends to increase steadily as ice accretes. An airfoil drag increase of 100 percent is not unusual, and for large horn ice accretions, the increase can be 200 percent or even higher.

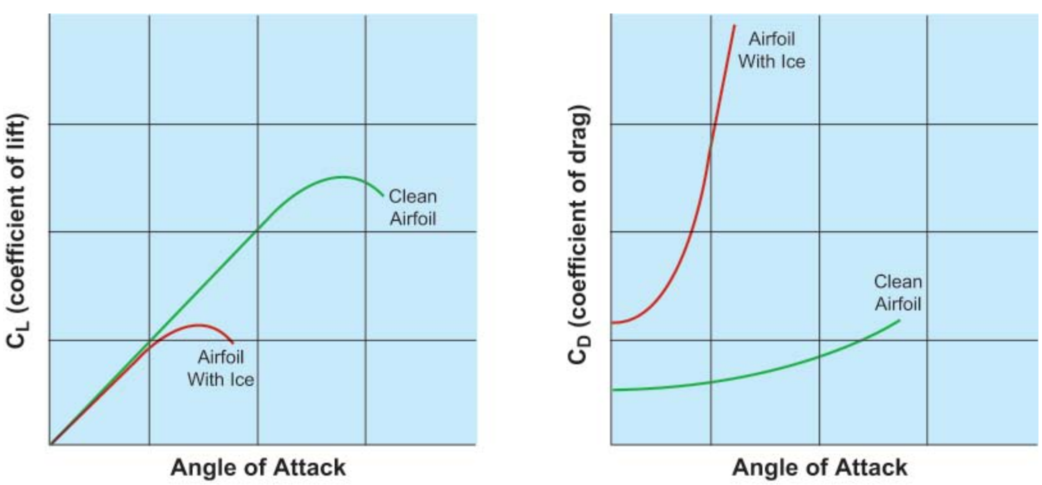


Figure 2-19. *Aerodynamic Effects of Icing.*

Ice on an airfoil can have other effects not depicted in these curves. Even before airfoil stall, there can be changes in the pressure over the airfoil that may affect a control surface at the trailing edge. Furthermore, on takeoff, approach, and landing, the wings of many aircraft are multi-element airfoils with three or more elements. Ice may affect the different elements in different ways. Ice may also affect the way in which the air streams interact over the elements.

Ice can partially block or limit control surfaces, which limits or makes control movements ineffective. Also, if the extra weight caused by ice accumulation is too great, the aircraft may not be able to become airborne and, if in flight, the aircraft may not be able to maintain altitude. Therefore any accumulation of ice or frost should be removed before attempting flight.

Another hazard of structural icing is the possible uncommanded and uncontrolled roll phenomenon, referred to as roll upset, associated with severe in-flight icing. Pilots flying aircraft certificated for flight in known icing conditions should be aware that severe icing is a condition outside of the aircraft's certification icing envelope. Roll upset may be caused by airflow separation (aerodynamic stall), which induces self-deflection of the ailerons and loss of or degraded roll handling characteristics *[Figure 2-20]*. These phenomena can result from severe icing conditions without the usual symptoms of ice accumulation or a perceived aerodynamic stall.

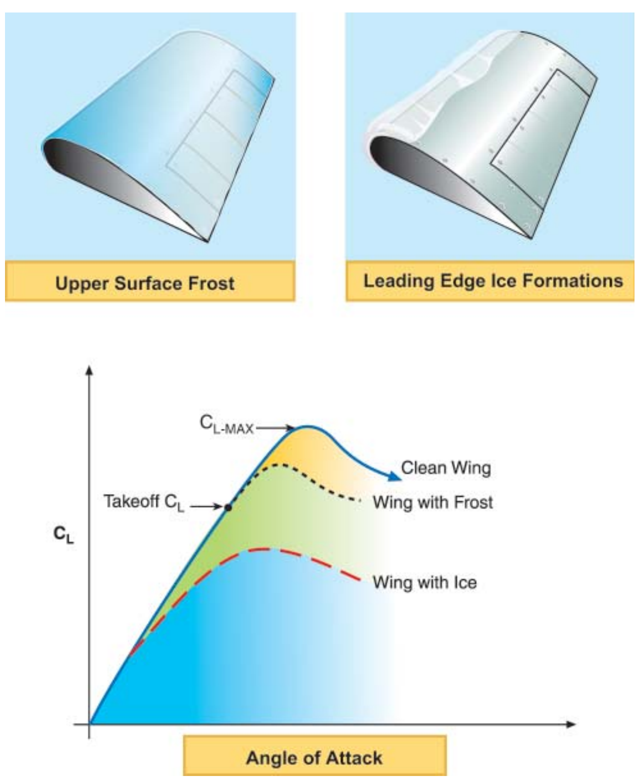


Figure 2-20. *Effect of Ice and Frost on Lift.*

Most aircraft have a nose-down pitching moment from the wings because the CG is ahead of the CP. It is the role of the tailplane to counteract this moment by providing a downward force. *[Figure 2-21]* The result of this configuration is that actions which move the wing away from stall, such as deployment of flaps or increasing speed, may increase the negative angle of attack of the tail. With ice on the tailplane, it may stall after full or partial deployment of flaps. *[Figure 2-22]*

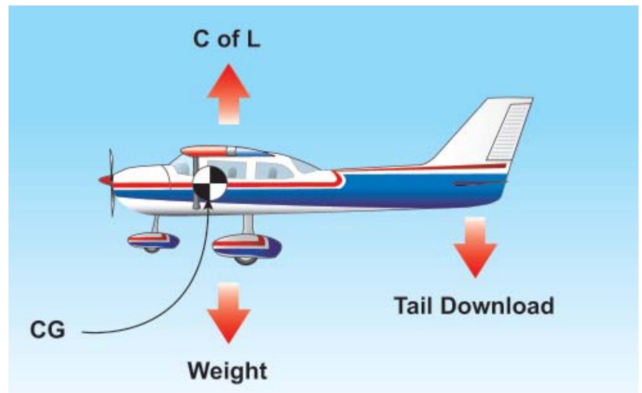


Figure 2-21. *Downward Force on the Tailplane.*

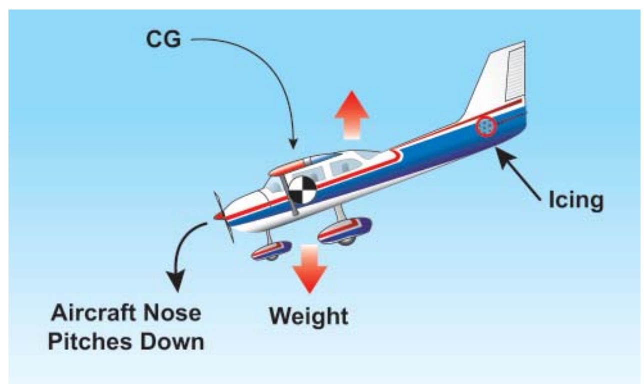


Figure 2-22. *Ice on the Tailplane.*

Since the tailplane is ordinarily thinner than the wing, it is a more efficient collector of ice. On most aircraft the tailplane is not visible to the pilot, who therefore cannot observe how well it has been cleared of ice by any deicing system. Thus, it is important that the pilot be alert to the possibility of tailplane stall, particularly on approach and landing.

Piper PA-34-200T (Des Moines, Iowa)

The pilot of this flight, which took place on January 9, 1996, said that upon crossing the runway threshold and lowering the flaps 25°, "the airplane pitched down." The pilot "immediately released the flaps and added power, but the airplane was basically uncontrollable at this point." The pilot reduced power and lowered the flaps before striking the runway on its centerline and sliding 1,000 feet before coming to a stop. The accident resulted in serious injury to the pilot, the sole occupant.

Examination of the wreckage revealed heavy impact damage to the airplane's forward fuselage, engines, and wings. Approximately one-half inch of rime ice was observed adhering to the leading edges of the left and right horizontal stabilizers and along the leading edge of the vertical stabilizer.

The National Transportation Safety Board (NTSB) determined the probable cause of the accident was the pilot's failure to use the airplane's deicing system, which resulted in an accumulation of empennage ice and a tailplane stall. Factors relating to this accident were the icing conditions and the pilot's intentional flight into those known conditions.

Tailplane Stall Symptoms

Any of the following symptoms, occurring singly or in combination, may be a warning of tailplane icing:

- Elevator control pulsing, oscillations, or vibrations;
- Abnormal nose-down trim change;
- Any other unusual or abnormal pitch anomalies (possibly resulting in pilot induced oscillations);
- Reduction or loss of elevator effectiveness;
- Sudden change in elevator force (control would move nose-down if unrestrained); and
- Sudden uncommanded nose-down pitch.

If any of the above symptoms occur, the pilot should:

- Immediately retract the flaps to the previous setting and apply appropriate nose-up elevator pressure;
- Increase airspeed appropriately for the reduced flap extension setting;
- Apply sufficient power for aircraft configuration and conditions. (High engine power settings may adversely impact response to tailplane stall conditions at high airspeed in some aircraft designs. Observe the manufacturer's recommendations regarding power settings.);
- Make nose-down pitch changes slowly, even in gusting conditions, if circumstances allow; and
- If a pneumatic deicing system is used, operate the system several times in an attempt to clear the tailplane of ice.

Once a tailplane stall is encountered, the stall condition tends to worsen with increased airspeed and possibly may worsen with increased power settings at the same flap setting. Airspeed, at any flap setting, in excess of the airplane manufacturer's recommendations, accompanied by uncleared ice contaminating the tailplane, may result in a tailplane stall and uncommanded pitch down from which recovery may not be possible. A tailplane stall may occur at speeds less than the maximum flap extended speed (VFE).

Propeller Icing

Ice buildup on propeller blades reduces thrust for the same aerodynamic reasons that wings tend to lose lift and increase drag when ice accumulates on them. The greatest quantity of ice normally collects on the spinner and inner radius of the propeller. Propeller areas on which ice may accumulate and be ingested into the engine normally are anti-iced rather than deiced to reduce the probability of ice being shed into the engine.

Effects of Icing on Critical Aircraft Systems

In addition to the hazards of structural and induction icing, the pilot must be aware of other aircraft systems susceptible to icing. The effects of icing do not produce the performance loss of structural icing or the power loss of induction icing but can present serious problems to the instrument pilot. Examples of such systems are flight instruments, stall warning systems, and windshields.

Flight Instruments

Various aircraft instruments including the airspeed indicator, altimeter, and rate-of-climb indicator utilize pressures sensed by pitot tubes and static ports for normal operation. When covered by ice these instruments display incorrect information thereby presenting serious hazard to instrument flight. Detailed information on the operation of these instruments and the specific effects of icing is presented in Chapter 3, Flight Instruments.

Stall Warning Systems

Stall warning systems provide essential information to pilots. These systems range from a sophisticated stall warning vane to a simple stall warning switch. Icing affects these systems in several ways resulting in possible loss of stall warning to the pilot. The loss of these systems can exacerbate an already hazardous situation. Even when an aircraft's stall warning system remains operational during icing conditions, it may be ineffective because the wing stalls at a lower angle of attack due to ice on the airfoil.

Windshields

Accumulation of ice on flight deck windows can severely restrict the pilot's visibility outside of the aircraft. Aircraft equipped for flight into known icing conditions typically have some form of windshield anti-icing to enable the pilot to see outside the aircraft in case icing is encountered in flight. One system consists of an electrically heated plate installed onto the airplane's windshield to give the pilot a narrow band of clear visibility. Another system uses a bar at the lower end of the windshield to spray deicing fluid onto it and prevent ice from forming. On high performance aircraft that require complex windshields to protect against bird strikes and withstand pressurization loads, the heating element often is a layer of conductive film or thin wire strands through which electric current is run to heat the windshield and prevent ice from forming.

Antenna Icing

Because of their small size and shape, antennas that do not lay flush with the aircraft's skin tend to accumulate ice rapidly. Furthermore, they often are devoid of internal anti-icing or deicing capability for protection. During flight in icing conditions, ice accumulations on an antenna may cause it to begin to vibrate or cause radio signals to become distorted and it may cause damage to the antenna. If a frozen antenna breaks off, it can damage other areas of the aircraft in addition to causing a communication or navigation system failure.

Summary

Ice-contaminated aircraft have been involved in many accidents. Takeoff accidents have usually been due to failure to deice or anti-ice critical surfaces properly on the ground. Proper deicing and anti-icing procedures are addressed in two other pilot guides, Advisory Circular (AC) 120-58, Pilot Guide: Large Aircraft Ground Deicing and AC 135-17, Pilot Guide: Small Aircraft Ground Deicing.

The pilot of an aircraft, which is not certificated or equipped for flight in icing conditions, should avoid all icing conditions. The aforementioned guides provide direction on how to do this, and on how to exit icing conditions promptly and safely should they be inadvertently encountered.

The pilot of an aircraft, which is certificated for flight in icing conditions can safely operate in the conditions for which the aircraft was evaluated during the certification process but should never become complacent about icing. Even short encounters with small amounts of rough icing can be very hazardous. The pilot should be familiar with all information in the Aircraft Flight Manual (AFM) or Pilot's Operating Handbook (POH) concerning flight in icing conditions and follow it carefully. Of particular importance are proper operation of ice protection systems and any airspeed minimums to be observed during or after flight in icing conditions. There are some icing conditions for which no aircraft is evaluated in the certification process, such as super-cooled large drops (SLD). These subfreezing water droplets, with diameters greater than 50 microns, occur within or below clouds and sustained flight in these conditions can be very hazardous. The pilot should be familiar with any information in the AFM or POH relating to these conditions, including aircraft-specific cues for recognizing these hazardous conditions within clouds.

The information in this chapter is an overview of the hazards of aircraft icing. For more detailed information refer to AC 91-74, Pilot Guide: Flight in Icing Conditions, AC 91-51A, Effect of Icing on Aircraft Control and Airplane Deice and Anti-Ice Systems, AC 20-73A, Aircraft Ice Protection and AC 23.143-1, Ice Contaminated Tailplane Stall (ICTS).

Chapter 3

Flight Instruments

Introduction

Aircraft became a practical means of transportation when accurate flight instruments freed the pilot from the necessity of maintaining visual contact with the ground. Flight instruments are crucial to conducting safe flight operations and it is important that the pilot have a basic understanding of their operation. The basic flight instruments required for operation under visual flight rules (VFR) are airspeed indicator (ASI), altimeter, and magnetic direction indicator. In addition to these, operation under instrument flight rules (IFR) requires a gyroscopic rate-of-turn indicator, slip-skid indicator, sensitive altimeter adjustable for barometric pressure, clock displaying hours, minutes, and seconds with a sweep-second pointer or digital presentation, gyroscopic pitch-and-bank indicator (artificial horizon), and gyroscopic direction indicator (directional gyro or equivalent).

Aircraft that are flown in instrument meteorological conditions (IMC) are equipped with instruments that provide attitude and direction reference, as well as navigation instruments that allow precision flight from takeoff to landing with limited or no outside visual reference.

The instruments discussed in this chapter are those required by Title 14 of the Code of Federal Regulations (14 CFR) part 91, and are organized into three groups: pitot-static instruments, compass systems, and gyroscopic instruments. The chapter concludes with a discussion of how to preflight these systems for IFR flight. This chapter addresses additional avionics systems such as Electronic Flight Information Systems (EFIS), Ground Proximity Warning System (GPWS), Terrain Awareness and Warning System (TAWS), Traffic Alert and Collision Avoidance System (TCAS), Head Up Display (HUD), etc., that are increasingly being incorporated into general aviation aircraft.

Pitot/Static Systems

Pitot pressure, or impact air pressure, is sensed through an open-end tube pointed directly into the relative wind flowing around the aircraft. The pitot tube connects to pressure operated flight instruments such as the ASI.

Static Pressure

Other instruments depend upon accurate sampling of the ambient still air atmospheric pressure to determine the height and speed of movement of the aircraft through the air, both horizontally and vertically. This pressure, called static pressure, is sampled at one or more locations outside the aircraft. The pressure of the static air is sensed at a flush port where the air is not disturbed. On some aircraft, air is sampled by static ports on the side of the electrically heated pitot-static head. *[Figure 3-1]* Other aircraft pick up the static pressure through flush ports on the side of the fuselage or the vertical fin. These ports are in locations proven by flight tests to be in undisturbed air, and they are normally paired, one on either side of the aircraft. This dual location prevents lateral movement of the aircraft from giving erroneous static pressure indications. The areas around the static ports may be heated with electric heater elements to prevent ice forming over the port and blocking the entry of the static air.

Three basic pressure-operated instruments are found in most aircraft instrument panels. These are the sensitive altimeter, ASI, and vertical speed indicator (VSI). All three receive pressures sensed by the aircraft pitot-static system. The static ports supply pressure to the ASI, altimeter, and VSI.

Blockage Considerations

The pitot tube is particularly sensitive to blockage especially by icing. Even light icing can block the entry hole of the pitot tube where ram air enters the system. This affects the ASI and is the reason most airplanes are equipped with a pitot heating system.

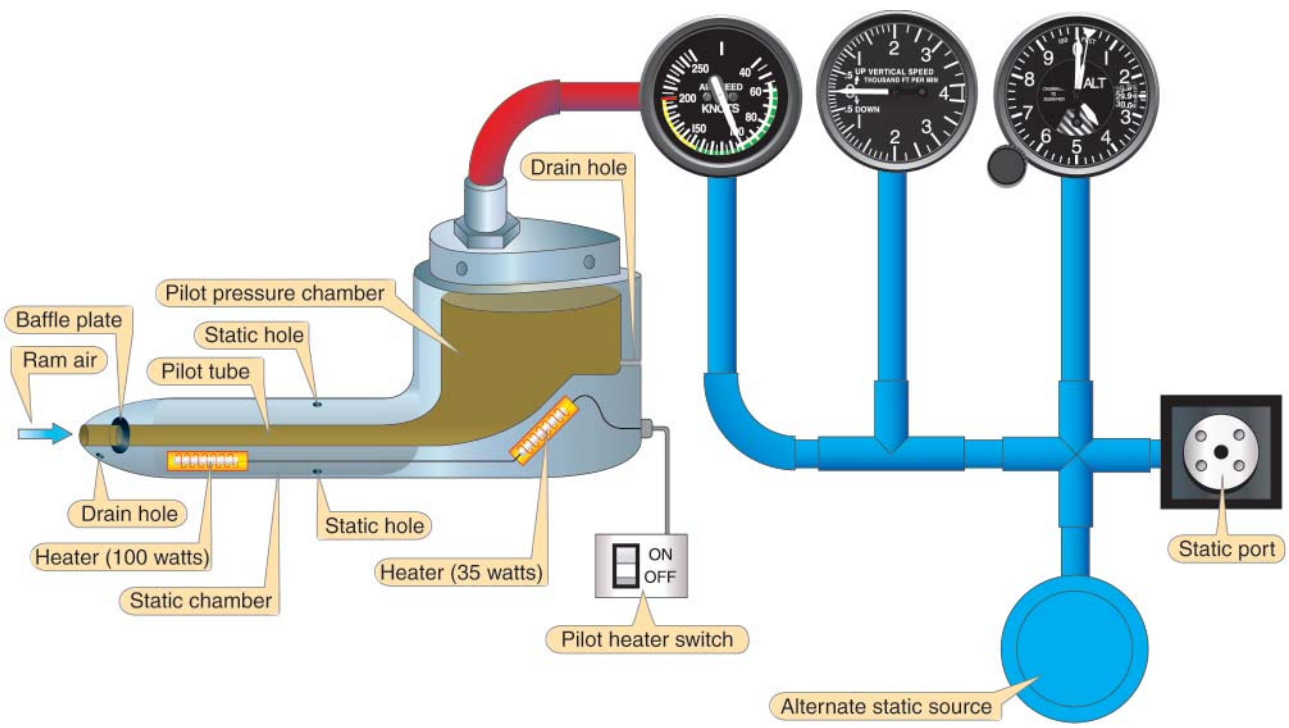


Figure 3-1. *A Typical Electrically Heated Pitot-Static Head.*

Indications of Pitot Tube Blockage

If the pitot tube becomes blocked, the ASI displays inaccurate speeds. At the altitude where the pitot tube becomes blocked, the ASI remains at the existing airspeed and doesn't reflect actual changes in speed.

- At altitudes above where the pitot tube became blocked, the ASI displays a higher-than-actual airspeed increasing steadily as altitude increases.
- At lower altitudes, the ASI displays a lower-than-actual airspeed decreasing steadily as altitude decreases.

Indications from Static Port Blockage

Many aircraft also have a heating system to protect the static ports to ensure the entire pitot-static system is clear of ice. If the static ports become blocked, the ASI would still function but could produce inaccurate indications. At the altitude where the blockage occurs, airspeed indications would be normal.

- At altitudes above which the static ports became blocked, the ASI displays a lower-than-actual airspeed continually decreasing as altitude is increased.
- At lower altitudes, the ASI displays a higher-than-actual airspeed increasing steadily as altitude decreases.

The trapped pressure in the static system causes the altimeter to remain at the altitude where the blockage occurred. The VSI remains at zero. On some aircraft, an alternate static air source valve is used for emergencies. *[Figure 3-2]* If the alternate source is vented inside the airplane, where static pressure is usually lower than outside static pressure, selection of the alternate source may result in the following erroneous instrument indications:

1. Altimeter reads higher than normal,
2. Indicated airspeed (IAS) reads greater than normal, and
3. VSI momentarily shows a climb. Consult the Pilot's Operating Handbook/Airplane Flight Manual (POH/AFM) to determine the amount of error.

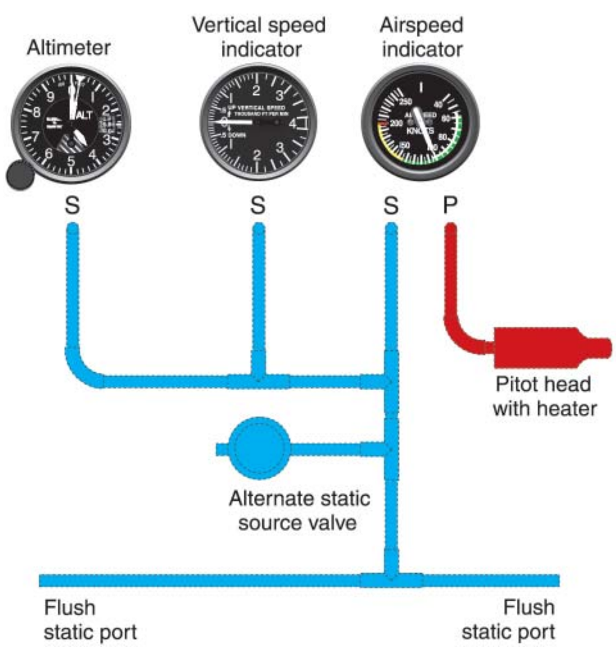


Figure 3-2. *A Typical Pitot-Static System.*

Effects of Flight Conditions

The static ports are located in a position where the air at their surface is as undisturbed as possible. But under some flight conditions, particularly at a high angle of attack with the landing gear and flaps down, the air around the static port may be disturbed to the extent that it can cause an error in the indication of the altimeter and ASI. Because of the importance of accuracy in these instruments, part of the certification tests for an aircraft is a check of position error in the static system.

The POH/AFM contains any corrections that must be applied to the airspeed for the various configurations of flaps and landing gear.

Pitot/Static Instruments

Sensitive Altimeter

A sensitive altimeter is an aneroid barometer that measures the absolute pressure of the ambient air and displays it in terms of feet or meters above a selected pressure level.

Principle of Operation

The sensitive element in a sensitive altimeter is a stack of evacuated, corrugated bronze aneroid capsules. *[Figure 3-3]* The air pressure acting on these aneroids tries to compress them against their natural springiness, which tries to expand them. The result is that their thickness changes as the air pressure changes. Stacking several aneroids increases the dimension change as the pressure varies over the usable range of the instrument.

Below 10,000 feet, a striped segment is visible. Above this altitude, a mask begins to cover it, and above 15,000 feet, all of the stripes are covered. *[Figure 3-4]*

Another configuration of the altimeter is the drum-type. *[Figure 3-5]* These instruments have only one pointer that makes one revolution for every 1,000 feet. Each number represents 100 feet and each mark represents 20 feet. A drum, marked in thousands of feet, is geared to the mechanism that drives the pointer. To read this type of altimeter, first look at

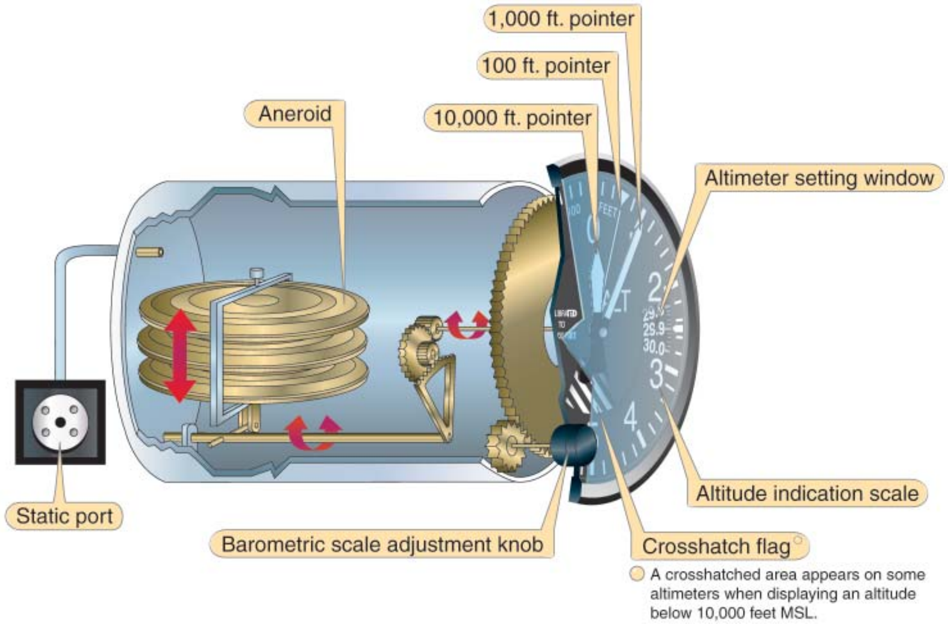


Figure 3-3. *Sensitive Altimeter Components.*

the drum to get the thousands of feet, and then at the pointer to get the feet and hundreds of feet.

A sensitive altimeter is one with an adjustable barometric scale allowing the pilot to set the reference pressure from which the altitude is measured. This scale is visible in a small window called the Kollsman window. A knob on the instrument adjusts the scale. The range of the scale is from 28.00" to 31.00" inches of mercury (Hg), or 948 to 1,050 millibars.

Rotating the knob changes both the barometric scale and the altimeter pointers in such a way that a change in the barometric scale of 1" Hg changes the pointer indication by 1,000 feet. This is the standard pressure lapse rate below 5,000 feet. When the barometric scale is adjusted to 29.92" Hg or 1,013.2 millibars, the pointers indicate the pressure altitude. The pilot displays indicate altitude by adjusting the barometric scale to the local altimeter setting. The altimeter then indicates the height above the existing sea level pressure.

Altimeter Errors

A sensitive altimeter is designed to indicate standard changes from standard conditions, but most flying involves errors caused by nonstandard conditions and the pilot must be able to modify the indications to correct for these errors. There are two types of errors: mechanical and inherent.

Mechanical

A preflight check to determine the condition of an altimeter consists of setting the barometric scale to the local altimeter setting. The altimeter should indicate the surveyed elevation

Figure 3-4. *Three-Pointer Altimeter.*

Figure 3-5. *Drum-Type Altimeter.*

of the airport. If the indication is off by more than 75 feet from the surveyed elevation, the instrument should be referred to a certificated instrument repair station for recalibration. Differences between ambient temperature and/or pressure causes an erroneous indication on the altimeter.

Inherent Altimeter Error

Figure 3-6 shows how nonstandard temperature affects an altimeter. When the aircraft is flying in air that is warmer than standard, the air is less dense and the pressure levels are farther apart. When the aircraft is flying at an indicated altitude of 5,000 feet, the pressure level for that altitude is higher than it would be in air at standard temperature, and the aircraft is higher than it would be if the air were cooler. If the air is colder than standard, it is denser and the pressure levels are closer together. When the aircraft is flying at an indicated altitude of 5,000 feet, its true altitude is lower than it would be if the air were warmer.

Cold Weather Altimeter Errors

A correctly calibrated pressure altimeter indicates true altitude above mean sea level (MSL) when operating within the International Standard Atmosphere (ISA) parameters of pressure and temperature. Nonstandard pressure conditions are corrected by applying the correct local area altimeter setting.

Temperature errors from ISA result in true altitude being higher than indicated altitude whenever the temperature is warmer than ISA and true altitude being lower than indicated altitude whenever the temperature is colder than ISA. True altitude variance under conditions of colder than ISA temperatures poses the risk of inadequate obstacle clearance.

Under extremely cold conditions, pilots may need to add an appropriate temperature correction determined from the chart in *Figure 3-7* to charted IFR altitudes to ensure terrain and obstacle clearance with the following restrictions:

- Altitudes specifically assigned by Air Traffic Control (ATC), such as "maintain 5,000 feet" shall not be corrected. Assigned altitudes may be rejected if the pilot decides that low temperatures pose a risk of inadequate terrain or obstacle clearance.
- If temperature corrections are applied to charted IFR altitudes (such as procedure turn altitudes, final approach fix crossing altitudes, etc.), the pilot must advise ATC of the applied correction.

ICAO Cold Temperature Error Table

The cold temperature induced altimeter error may be significant when considering obstacle clearances when temperatures are well below standard. Pilots may wish to increase their minimum terrain clearance altitudes with a corresponding increase in ceiling from the normal minimum when flying in extreme cold temperature conditions. Higher altitudes may need to be selected when flying at low terrain clearances. Most flight management systems (FMS) with air data computers implement a capability to compensate for cold temperature errors. Pilots flying with these systems should ensure they are aware of the conditions under which the system will automatically compensate. If compensation is applied by the FMS or manually, ATC must be informed that the aircraft is not flying the assigned altitude. Otherwise, vertical separation from other aircraft may be reduced creating a potentially hazardous situation. The table in *Figure 3-7*, derived from International Civil Aviation

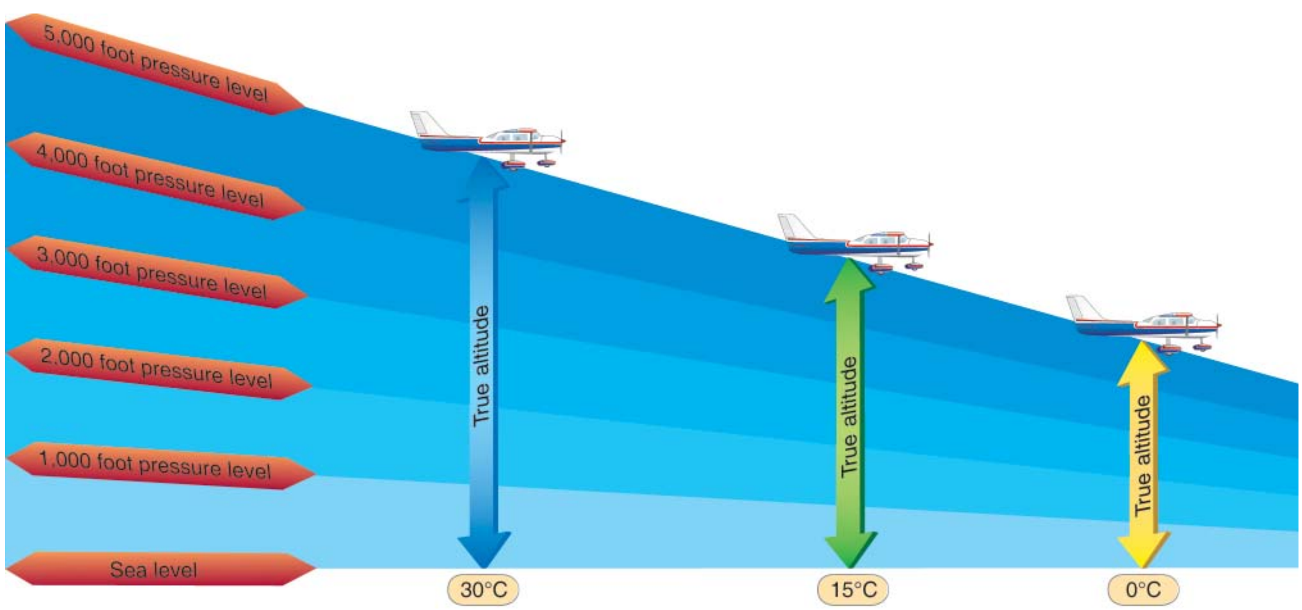


Figure 3-6. *The loss of altitude experienced when flying into an area where the air is warmer (less dense) than standard.*

Reported Temp C°	Height Above Airport in Feet													
	200	300	400	500	600	700	800	900	1,000	1,500	2,000	3,000	4,000	5,000
+10	10	10	10	10	20	20	20	20	20	30	40	60	80	90
0	20	20	30	30	40	40	50	50	60	90	120	170	230	280
-10	20	30	40	50	60	70	80	90	100	150	200	290	390	490
-20	30	50	60	70	90	100	120	130	140	210	280	420	570	710
-30	40	60	80	100	120	130	150	170	190	280	380	570	760	950
-40	50	80	100	120	150	170	190	220	240	360	480	720	970	1,210
-50	60	90	120	150	180	210	240	270	300	450	590	890	1,190	1,500

Figure 3-7. *ICAO Cold Temperature Error Table.*

Organization (ICAO) standard formulas, shows how much error can exist when the temperature is extremely cold. To use the table, find the reported temperature in the left column, and then read across the top row to the height above the airport/reporting station. Subtract the airport elevation from the altitude of the final approach fix (FAF). The intersection of the column and row is the amount of possible error.

Example: The reported temperature is -10° Celsius and the FAF is 500 feet above the airport elevation. The reported current altimeter setting may place the aircraft as much as 50 feet below the altitude indicated by the altimeter.

When using the cold temperature error table, the altitude error is proportional to both the height above the reporting station elevation and the temperature at the reporting station. For IFR approach procedures, the reporting station elevation is assumed to be airport elevation. It is important to understand that corrections are based upon the temperature at the reporting station, not the temperature observed at the aircraft's current altitude and height above the reporting station and not the charted IFR altitude.

To see how corrections are applied, note the following example:

Airport Elevation	496 feet
Airport Temperature	- 50° C

A charted IFR approach to the airport provides the following data:

Minimum Procedure Turn Altitude	1,800 feet
Minimum FAF Crossing Altitude	1,200 feet
Straight-in Minimum Descent Altitude	800 feet
Circling MDA	1,000 feet

The Minimum Procedure Turn Altitude of 1,800 feet will be used as an example to demonstrate determination of the appropriate temperature correction. Typically, altitude values are rounded up to the nearest 100-foot level. The charted procedure turn altitude of 1,800 feet minus the airport elevation of 500 feet equals 1,300 feet. The altitude difference of 1,300 feet falls between the correction chart elevations of 1,000 feet and 1,500 feet. At the station temperature of -50°C, the correction falls between 300 feet and 450 feet. Dividing the difference in compensation values by the difference in altitude above the airport gives the error value per foot.

In this case, 150 feet divided by 500 feet = 0.33 feet for each additional foot of altitude above 1,000 feet. This provides a correction of 300 feet for the first 1,000 feet and an additional value of 0.33 times 300 feet, or 99 feet, which is rounded to 100 feet. 300 feet + 100 feet = total temperature correction of 400 feet. For the given conditions, correcting the charted value of 1,800 feet above MSL (equal to a height above the reporting station of 1,300 feet) requires the addition of 400 feet. Thus, when flying at an indicated altitude of 2,200 feet, the aircraft is actually flying a true altitude of 1,800 feet.

Minimum Procedure Turn Altitude
1,800 feet charted = 2,200 feet corrected
Minimum FAF Crossing Altitude
1,200 feet charted = 1,500 feet corrected
Straight-in MDA
800 feet charted = 900 feet corrected
Circling MDA
1,000 feet charted = 1,200 feet corrected

Nonstandard Pressure on an Altimeter

Maintaining a current altimeter setting is critical because the atmosphere pressure is not constant. That is, in one location the pressure might be higher than the pressure just a short distance away. Take an aircraft whose altimeter setting is set to 29.92" of local pressure. As the aircraft moves to an area of lower pressure (Point A to B in *Figure 3-8*) and the pilot fails to readjust the altimeter setting (essentially calibrating it to local pressure), then as the pressure decreases, the indicated altitude will be lower. Adjusting the altimeter settings compensates for this. When the altimeter shows an indicated altitude of 5,000 feet, the true altitude at Point A (the height above mean sea level) is only 3,500 feet at Point B. The fact that the altitude indication is not always true lends itself to the memory aid, "When flying from hot to cold or from a high to a low, look out below." *[Figure 3-8]*

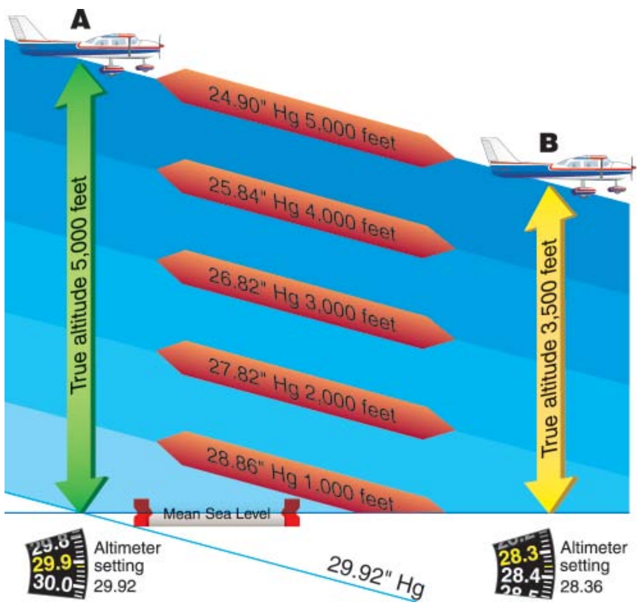


Figure 3-8. *Effects of Nonstandard Pressure on an Altimeter of an Aircraft Flown into Air of Lower Than Standard Pressure (Air is Less Dense).*

Altimeter Enhancements (Encoding)

It is not sufficient in the airspace system for only the pilot to have an indication of the aircraft's altitude; the air traffic controller on the ground must also know the altitude of the aircraft. To provide this information, the aircraft is typically equipped with an encoding altimeter.

When the ATC transponder is set to Mode C, the encoding altimeter supplies the transponder with a series of pulses identifying the flight level (in increments of 100 feet) at which the aircraft is flying. This series of pulses is transmitted to the ground radar where they appear on the controller's scope as an alphanumeric display around the return for the aircraft. The transponder allows the ground controller to identify the aircraft and determine the pressure altitude at which it is flying.

A computer inside the encoding altimeter measures the pressure referenced from 29.92" Hg and delivers this data to the transponder. When the pilot adjusts the barometric scale to the local altimeter setting, the data sent to the transponder is not affected. This is to ensure that all Mode C aircraft are transmitting data referenced to a common pressure level. ATC equipment adjusts the displayed altitudes to compensate for local pressure differences allowing display of targets at correct altitudes. 14 CFR part 91 requires the altitude transmitted by the transponder to be within 125 feet of the altitude indicated on the instrument used to maintain flight altitude.

Reduced Vertical Separation Minimum (RVSM)

Below 31,000 feet, a 1,000 foot separation is the minimum required between usable flight levels. Flight levels (FLs) generally start at 18,000 feet where the local pressure is 29.92" Hg or greater. All aircraft 18,000 feet and above use a standard altimeter setting of 29.92" Hg, and the altitudes are in reference to a standard hence termed FL. Between FL 180 and FL 290, the minimum altitude separation is 1,000 feet between aircraft. However, for flight above FL 290 (primarily due to aircraft equipage and reporting capability; potential error) ATC applied the requirement of 2,000 feet of separation. FL 290, an altitude appropriate for an eastbound aircraft, would be followed by FL 310 for a westbound aircraft, and so on to FL 410, or seven FLs available for flight. With 1,000-foot separation, or a reduction of the vertical separation between FL 290 and FL 410, an additional six FLs become available. This results in normal flight level and direction management being maintained from FL 180 through FL 410. Hence the name is Reduced Vertical Separation Minimum (RVSM). Because it is applied domestically, it is called United States Domestic Reduced Vertical Separation Minimum, or DRVSM.

However, there is a cost to participate in the DRVSM program which relates to both aircraft equipage and pilot training. For example, altimetry error must be reduced significantly and operators using RVSM must receive authorization from the appropriate civil aviation authority. RVSM aircraft must meet required altitude-keeping performance standards. Additionally, operators must operate in accordance with RVSM policies/procedures applicable to the airspace where they are flying.

The aircraft must be equipped with at least one automatic altitude control—

- Within a tolerance band of ±65 feet about an acquired altitude when the aircraft is operated in straight-and-level flight.
- Within a tolerance band of ±130 feet under no turbulent, conditions for aircraft for which application for type certification occurred on or before April 9, 1997 that are equipped with an automatic altitude control system with flight management/performance system inputs.

That aircraft must be equipped with an altitude alert system that signals an alert when the altitude displayed to the flight crew deviates from the selected altitude by more than (in most cases) 200 feet. For each condition in the full RVSM flight envelope, the largest combined absolute value for residual static source error plus the avionics error may not exceed 200 feet. Aircraft with TCAS must have compatibility with RVSM Operations. *Figure 3-9* illustrates the increase in aircraft permitted between FL 180 and FL 410. Most noteworthy, however, is the economization that aircraft can take advantage of by the higher FLs being available to more aircraft.

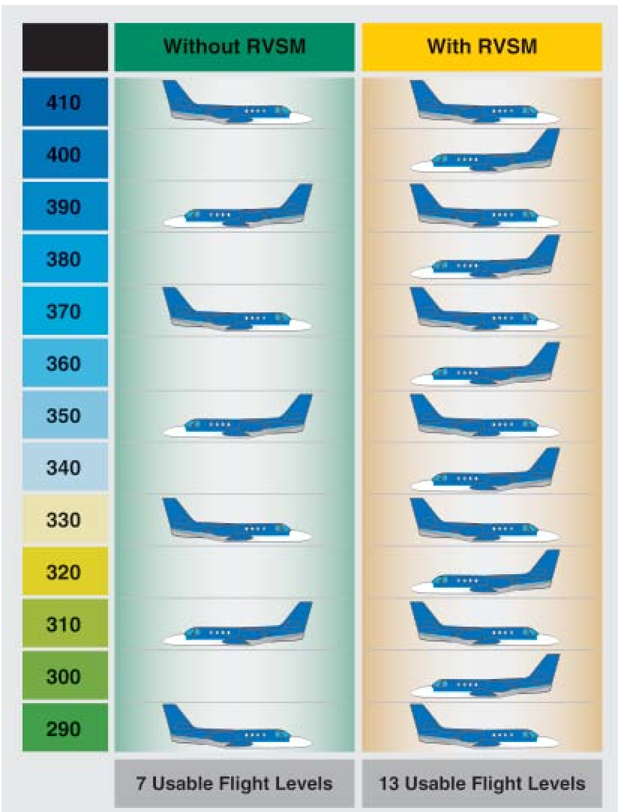


Figure 3-9. *Increase in Aircraft Permitted Between FL 180 and FL 410.*

Vertical Speed Indicator (VSI)

The VSI in *Figure 3-10* is also called a vertical velocity indicator (VVI), and was formerly known as a rate-of-climb indicator. It is a rate-of-pressure change instrument that gives an indication of any deviation from a constant pressure level.

Inside the instrument case is an aneroid very much like the one in an ASI. Both the inside of this aneroid and the inside of the instrument case are vented to the static system, but the case is vented through a calibrated orifice that causes the pressure inside the case to change more slowly than the pressure inside the aneroid. As the aircraft ascends, the static pressure becomes lower. The pressure inside the case compresses the aneroid, moving the pointer upward, showing a climb and indicating the rate of ascent in number of feet per minute (fpm).

When the aircraft levels off, the pressure no longer changes. The pressure inside the case becomes equal to that inside the aneroid, and the pointer returns to its horizontal, or zero, position. When the aircraft descends, the static pressure increases. The aneroid expands, moving the pointer downward, indicating a descent.

The pointer indication in a VSI lags a few seconds behind the actual change in pressure. However, it is more sensitive than an altimeter and is useful in alerting the pilot of an upward or downward trend, thereby helping maintain a constant altitude.

Some of the more complex VSIs, called instantaneous vertical speed indicators (IVSI), have two accelerometer-actuated air pumps that sense an upward or downward pitch of the aircraft and instantaneously create a pressure differential. By the time the pressure caused by the pitch acceleration dissipates, the altitude pressure change is effective.

Dynamic Pressure Type Instruments

Airspeed Indicator (ASI)

An ASI is a differential pressure gauge that measures the dynamic pressure of the air through which the aircraft is flying. Dynamic pressure is the difference in the ambient static air pressure and the total, or ram, pressure caused by the motion of the aircraft through the air. These two pressures are taken from the pitot-static system.

Figure 3-10. *Rate of Climb or Descent in Thousands of Feet Per Minute.*

The mechanism of the ASI in *Figure 3-11* consists of a thin, corrugated phosphor bronze aneroid, or diaphragm, that receives its pressure from the pitot tube. The instrument case is sealed and connected to the static ports. As the pitot pressure increases or the static pressure decreases, the diaphragm expands. This dimensional change is measured by a rocking shaft and a set of gears that drives a pointer across the instrument dial. Most ASIs are calibrated in knots, or nautical miles per hour; some instruments show statute miles per hour, and some instruments show both.

Types of Airspeed

Just as there are several types of altitude, there are multiple types of airspeed: Indicated Airspeed (IAS), Calibrated Airspeed (CAS), Equivalent Airspeed (EAS), and True Airspeed (TAS).

Indicated Airspeed (IAS)

IAS is shown on the dial of the instrument, uncorrected for instrument or system errors.

Calibrated Airspeed (CAS)

CAS is the speed at which the aircraft is moving through the air, which is found by correcting IAS for instrument and position errors. The POH/AFM has a chart or graph to correct IAS for these errors and provide the correct CAS for the various flap and landing gear configurations.

Equivalent Airspeed (EAS)

EAS is CAS corrected for compression of the air inside the pitot tube. EAS is the same as CAS in standard atmosphere at sea level. As the airspeed and pressure altitude increase, the CAS becomes higher than it should be, and a correction for compression must be subtracted from the CAS.

True Airspeed (TAS)

TAS is CAS corrected for nonstandard pressure and temperature. TAS and CAS are the same in standard atmosphere at sea level. Under nonstandard conditions, TAS is found by applying a correction for pressure altitude and temperature to the CAS.

Some aircraft are equipped with true ASIs that have a temperature-compensated aneroid bellows inside the instrument case. This bellows modifies the movement of the rocking shaft inside the instrument case so the pointer shows the actual TAS.

The TAS indicator provides both true and IAS. These instruments have the conventional airspeed mechanism, with an added subdial visible through cutouts in the regular dial. A knob on the instrument allows the pilot to rotate the subdial and align an indication of the outside air temperature with the pressure altitude being flown. This alignment causes the instrument pointer to indicate the TAS on the subdial. *[Figure 3-12]*

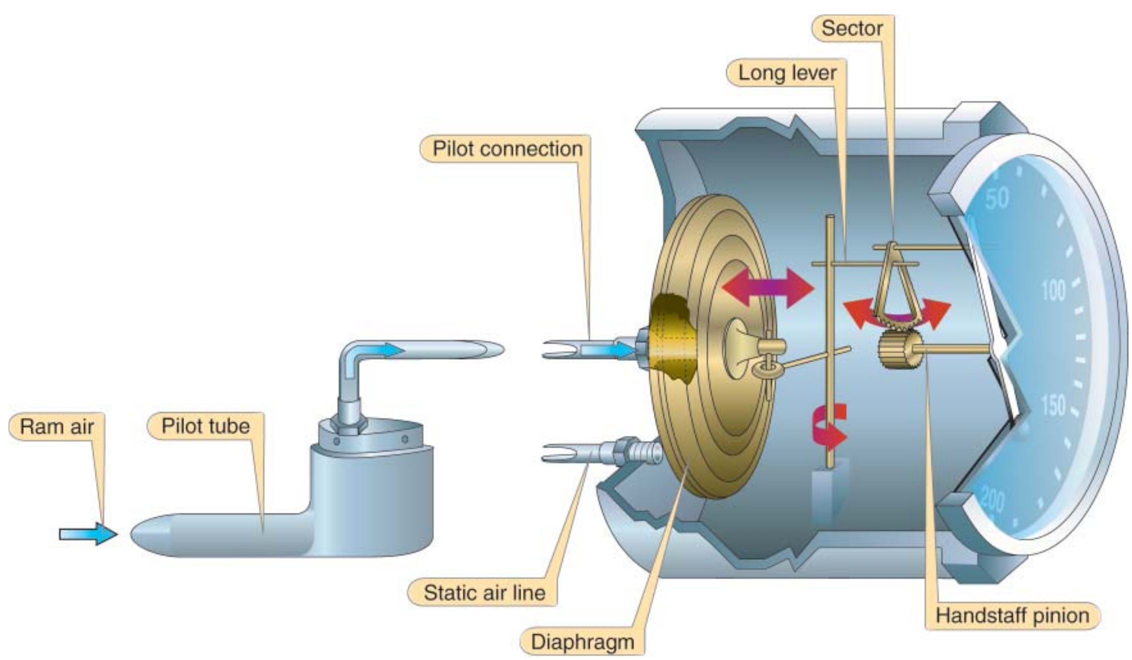


Figure 3-11. *Mechanism of an Airspeed Indicator.*

Figure 3-12. *A true airspeed indicator allows the pilot to correct IAS for nonstandard temperature and pressure.*

Mach Number

As an aircraft approaches the speed of sound, the air flowing over certain areas of its surface speeds up until it reaches the speed of sound, and shock waves form. The IAS at which these conditions occur changes with temperature. Therefore, in this case, airspeed is not entirely adequate to warn the pilot of the impending problems. Mach number is more useful. Mach number is the ratio of the TAS of the aircraft to the speed of sound in the same atmospheric conditions. An aircraft flying at the speed of sound is flying at Mach 1.0. Some older mechanical Machmeters not driven from an air data computer use an altitude aneroid inside the instrument that converts pitot-static pressure into Mach number. These systems assume that the temperature at any altitude is standard; therefore, the indicated Mach number is inaccurate whenever the temperature deviates from standard. These systems are called indicated Machmeters. Modern electronic Machmeters use information from an air data computer system to correct for temperature errors. These systems display true Mach number.

Figure 3-13. *A Machmeter shows the ratio of the speed of sound to the TAS the aircraft is flying.*

Most high-speed aircraft are limited to a maximum Mach number at which they can fly. This is shown on a Machmeter as a decimal fraction. *[Figure 3-13]* For example, if the Machmeter indicates .83 and the aircraft is flying at 30,000 feet where the speed of sound under standard conditions is 589.5 knots, the airspeed is 489.3 knots. The speed of sound varies with the air temperature. If the aircraft were flying at Mach .83 at 10,000 feet where the air is much warmer, its airspeed would be 530 knots.

Maximum Allowable Airspeed

Some aircraft that fly at high subsonic speeds are equipped with maximum allowable ASIs like the one in *Figure 3-14*. This instrument looks much like a standard air-speed indicator, calibrated in knots, but has an additional pointer colored red, checkered, or striped. The maximum airspeed pointer is actuated by an aneroid, or altimeter mechanism, that moves it to a lower value as air density decreases. By keeping the airspeed pointer at a lower value than the maximum pointer, the pilot avoids the onset of transonic shock waves.

Figure 3-14. *A maximum allowable airspeed indicator has a movable pointer that indicates the never-exceed speed, which changes with altitude to avoid the onset of transonic shock waves.*

Airspeed Color Codes

The dial of an ASI is color coded to alert the pilot, at a glance, of the significance of the speed at which the aircraft is flying. These colors and their associated airspeeds are shown in *Figure 3-15*.

Magnetism

The Earth is a huge magnet, spinning in space, surrounded by a magnetic field made up of invisible lines of flux. These lines leave the surface at the magnetic north pole and reenter at the magnetic South Pole.

Lines of magnetic flux have two important characteristics: any magnet that is free to rotate will align with them, and

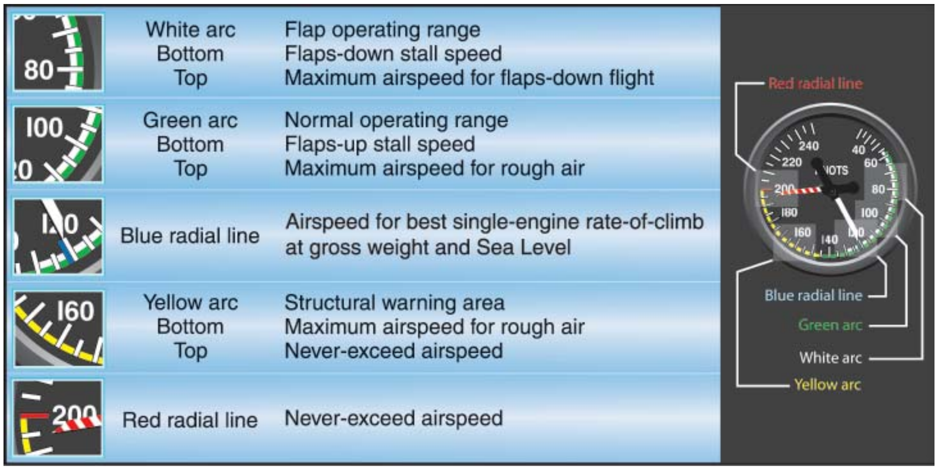


Figure 3-15. *Color Codes for an Airspeed Indicator.*

an electrical current is induced into any conductor that cuts across them. Most direction indicators installed in aircraft make use of one of these two characteristics.

The Basic Aviation Magnetic Compass

One of the oldest and simplest instruments for indicating direction is the magnetic compass. It is also one of the basic instruments required by 14 CFR part 91 for both VFR and IFR flight.

Magnetic Compass Overview

A magnet is a piece of material, usually a metal containing iron, which attracts and holds lines of magnetic flux. Regardless of size, every magnet has two poles: a north pole and a south pole. When one magnet is placed in the field of another, the unlike poles attract each other and like poles repel.

An aircraft magnetic compass, such as the one in *Figure 3-16*, has two small magnets attached to a metal float sealed inside a bowl of clear compass fluid similar to kerosene. A graduated scale, called a card, is wrapped around the float and viewed through a glass window with a lubber line across it. The card is marked with letters representing the cardinal directions, north, east, south, and west, and a number for each 30° between these letters. The final "0" is omitted from these directions; for example, 3 = 30°, 6 = 60°, and 33 = 330°. There are long and short graduation marks between the letters and numbers, with each long mark representing 10° and each short mark representing 5°.

Figure 3-16. *A Magnetic Compass. The vertical line is called the lubber line.*

Magnetic Compass Construction

The float and card assembly has a hardened steel pivot in its center that rides inside a special, spring-loaded, hard-glass jewel cup. The buoyancy of the float takes most of the weight off the pivot, and the fluid damps the oscillation of the float and card. This jewel-and-pivot type mounting allows the float freedom to rotate and tilt up to approximately 18° angle of bank. At steeper bank angles, the compass indications are erratic and unpredictable.

The compass housing is entirely full of compass fluid. To prevent damage or leakage when the fluid expands and contracts with temperature changes, the rear of the compass case is sealed with a flexible diaphragm, or with a metal bellows in some compasses.

Magnetic Compass Theory of Operations

The magnets align with the Earth's magnetic field and the pilot reads the direction on the scale opposite the lubber line. Note that in *Figure 3-16*, the pilot sees the compass card from its backside. When the pilot is flying north as the compass shows, east is to the pilot's right, but on the card "33", which represents 330° (west of north), is to the right of north. The reason for this apparent backward graduation is that the card remains stationary, and the compass housing and the pilot turn around it, always viewing the card from its backside.

A compensator assembly mounted on the top or bottom of the compass allows an aviation maintenance technician (AMT) to create a magnetic field inside the compass housing that cancels the influence of local outside magnetic fields. This is done to correct for deviation error. The compensator assembly has two shafts whose ends have screwdriver slots accessible from the front of the compass. Each shaft rotates one or two small compensating magnets. The end of one shaft is marked E-W, and its magnets affect the compass when the aircraft is pointed east or west. The other shaft is marked N-S and its magnets affect the compass when the aircraft is pointed north or south.

Magnetic Compass Induced Errors

The magnetic compass is the simplest instrument in the panel, but it is subject to a number of errors that must be considered.

Variation

The Earth rotates about its geographic axis; maps and charts are drawn using meridians of longitude that pass through the geographic poles. Directions measured from the geographic poles are called true directions. The north magnetic pole to which the magnetic compass points is not collocated with the geographic north pole, but is some 1,300 miles away; directions measured from the magnetic poles are called magnetic directions. In aerial navigation, the difference between true and magnetic directions is called variation. This same angular difference in surveying and land navigation is called declination.

Figure 3-17 shows the isogonic lines that identify the number of degrees of variation in their area. The line that passes near Chicago is called the agonic line. Anywhere along this line the two poles are aligned, and there is no variation. East of this line, the magnetic pole is to the west of the geographic pole and a correction must be applied to a compass indication to get a true direction.

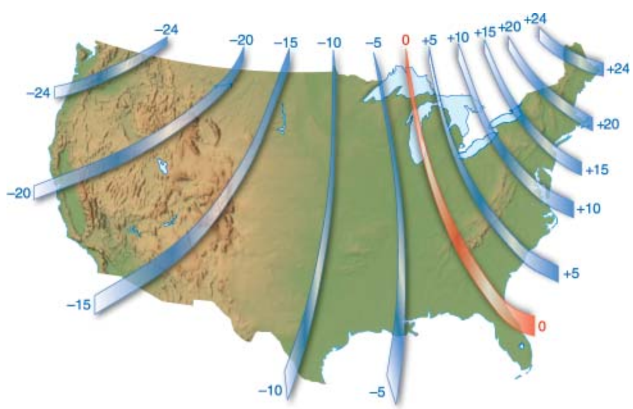


Figure 3-17. *Isogonic lines are lines of equal variation.*

Flying in the Washington, D.C. area, for example, the variation is 10° west. If the pilot wants to fly a true course of south (180°), the variation must be added to this resulting in a magnetic course to fly of 190°. Flying in the Los Angeles, CA area, the variation is 14° east. To fly a true course of 180° there, the pilot would have to subtract the variation and fly a magnetic course of 166°. The variation error does not change with the heading of the aircraft; it is the same anywhere along the isogonic line.

Deviation

The magnets in a compass align with any magnetic field. Local magnetic fields in an aircraft caused by electrical current flowing in the structure, in nearby wiring or any magnetized part of the structure, conflict with the Earth's magnetic field and cause a compass error called deviation.

Deviation, unlike variation, is different on each heading, but it is not affected by the geographic location. Variation error cannot be reduced or changed, but deviation error can be minimized when a pilot or AMT performs the maintenance task known as "swinging the compass."

Most airports have a compass rose, which is a series of lines marked out on a taxiway or ramp at some location where there is no magnetic interference. Lines, oriented to magnetic north, are painted every 30°, as shown in *Figure 3-18*.

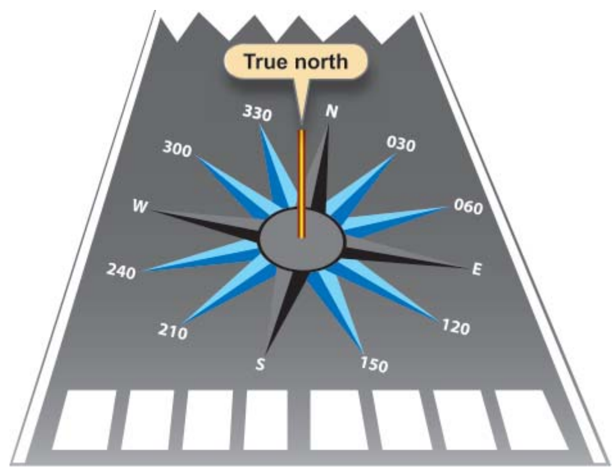


Figure 3-18. *Utilization of a Compass Rose Aids Compensation for Deviation Errors.*

The pilot or AMT aligns the aircraft on each magnetic heading and adjusts the compensating magnets to minimize the difference between the compass indication and the actual magnetic heading of the aircraft. Any error that cannot be removed is recorded on a compass correction card, like the one in *Figure 3-19*, and placed in a cardholder near the compass. If the pilot wants to fly a magnetic heading of 120° and the

FOR	000	030	060	090	120	150
STEER						
RDO. ON	001	032	062	095	123	155
RDO. OFF	002	031	064	094	125	157

FOR	180	210	240	270	300	330
STEER						
RDO. ON	176	210	243	271	296	325
RDO. OFF	174	210	240	273	298	327

Figure 3-19. *A compass correction card shows the deviation correction for any heading.*

aircraft is operating with the radios on, the pilot should fly a compass heading of 123°.

The corrections for variation and deviation must be applied in the correct sequence and is shown below starting from the true course desired.

Step 1: Determine the Magnetic Course
True Course (180°) ± Variation (+10°) = Magnetic Course (190°)

The Magnetic Course (190°) is steered if there is no deviation error to be applied. The compass card must now be considered for the compass course of 190°.

Step 2: Determine the Compass Course
Magnetic Course (190°, from step 1) ± Deviation (-2°, from correction card) = Compass Course (188°)

NOTE: Intermediate magnetic courses between those listed on the compass card need to be interpreted. Therefore, to steer a true course of 180°, the pilot would follow a compass course of 188°.

To find the true course that is being flown when the compass course is known:
Compass Course ± Deviation = Magnetic Course ± Variation = True Course

Dip Errors

The lines of magnetic flux are considered to leave the Earth at the magnetic north pole and enter at the magnetic South Pole. At both locations the lines are perpendicular to the Earth's surface. At the magnetic equator, which is halfway between the poles, the lines are parallel with the surface. The magnets in a compass align with this field, and near the poles they dip, or tilt, the float and card. The float is balanced with a small dip-compensating weight, so it stays relatively level when operating in the middle latitudes of the northern hemisphere. This dip along with this weight causes two very noticeable errors: northerly turning error and acceleration error.

The pull of the vertical component of the Earth's magnetic field causes northerly turning error, which is apparent on a heading of north or south. When an aircraft flying on a heading of north makes a turn toward east, the aircraft banks to the right, and the compass card tilts to the right. The vertical component of the Earth's magnetic field pulls the north-seeking end of the magnet to the right, and the float rotates, causing the card to rotate toward west, the direction opposite the direction the turn is being made. *[Figure 3-20]*

If the turn is made from north to west, the aircraft banks to the left and the compass card tilts down on the left side. The magnetic field pulls on the end of the magnet that causes the card to rotate toward east. This indication is again opposite to the direction the turn is being made. The rule for this error is: when starting

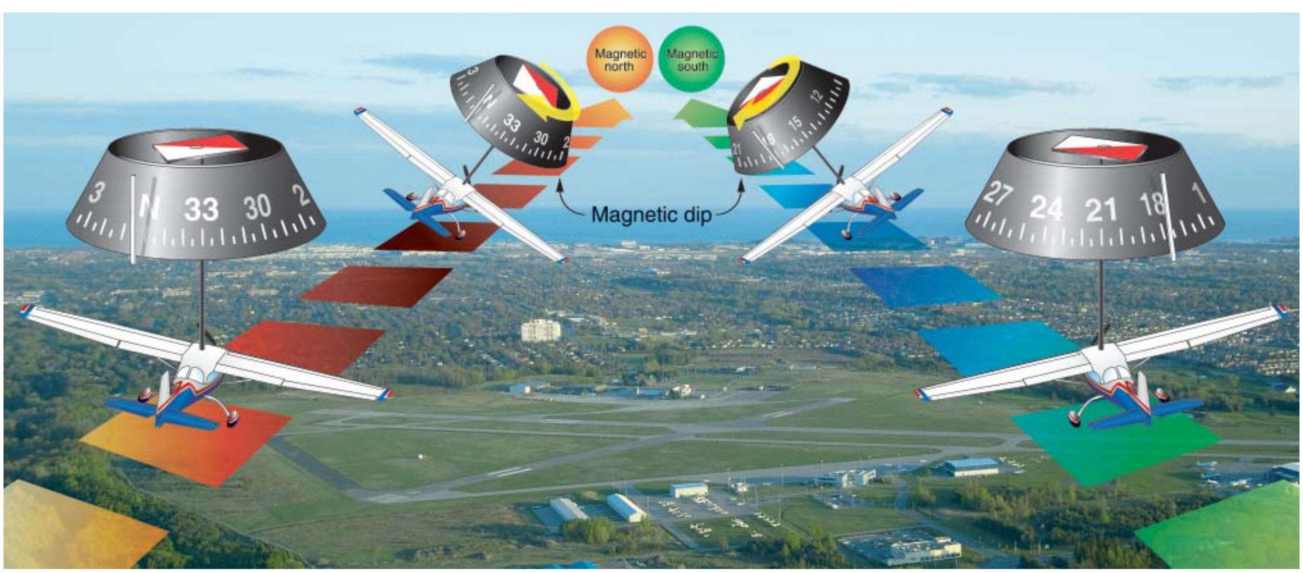


Figure 3-20. *Northerly Turning Error.*

Figure 3-21. *The Effects of Acceleration Error.*

a turn from a northerly heading, the compass indication lags behind the turn.

When an aircraft is flying on a heading of south and begins a turn toward east, the Earth's magnetic field pulls on the end of the magnet that rotates the card toward east, the same direction the turn is being made. If the turn is made from south toward west, the magnetic pull starts the card rotating toward west—again, in the same direction the turn is being made. The rule for this error is: When starting a turn from a southerly heading, the compass indication leads the turn.

In acceleration error, the dip-correction weight causes the end of the float and card marked N (the south-seeking end) to be heavier than the opposite end. When the aircraft is flying at a constant speed on a heading of east or west, the float and card is level. The effects of magnetic dip and the weight are approximately equal. If the aircraft accelerates on a heading of east *[Figure 3-21]*, the inertia of the weight holds its end of the float back and the card rotates toward north. As soon as the speed of the aircraft stabilizes, the card swings back to its east indication. If, while flying on this easterly heading, the aircraft decelerates, the inertia causes the weight to move ahead and the card rotates toward south until the speed again stabilizes.

When flying on a heading of west, the same things happen. Inertia from acceleration causes the weight to lag, and the card rotates toward north. When the aircraft decelerates on a heading of west, inertia causes the weight to move ahead and the card rotates toward south.

Oscillation Error

Oscillation is a combination of all of the other errors, and it results in the compass card swinging back and forth around the heading being flown. When setting the gyroscopic heading indicator to agree with the magnetic compass, use the average indication between the swings.

The Vertical Card Magnetic Compass

The floating magnet type of compass not only has all the errors just described, but also lends itself to confused reading. It is easy to begin a turn in the wrong direction because its card appears backward. East is on what the pilot would expect to be the west side. The vertical card magnetic compass eliminates some of the errors and confusion. The dial of this compass is graduated with letters representing the cardinal directions, numbers every 30°, and marks every 5°. The dial is rotated by a set of gears from the shaft-mounted magnet, and the nose of the symbolic airplane on the instrument glass represents the lubber line for reading the heading of the aircraft from the dial. Eddy currents induced into an aluminum-damping cup damp oscillation of the magnet. *[Figure 3-22]*

The Flux Gate Compass System

As mentioned earlier, the lines of flux in the Earth's magnetic field have two basic characteristics: a magnet aligns with these lines, and an electrical current is induced, or generated, in any wire crossed by them.

Figure 3-22. *Vertical Card Magnetic Compass.*

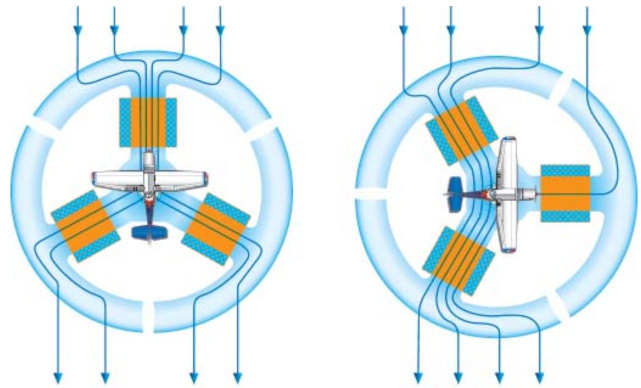


Figure 3-24. *The current in each of the three pickup coils changes with the heading of the aircraft.*

The flux gate compass that drives slaved gyros uses the characteristic of current induction. The flux valve is a small, segmented ring, like the one in *Figure 3-23*, made of soft iron that readily accepts lines of magnetic flux. An electrical coil is wound around each of the three legs to accept the current induced in this ring by the Earth's magnetic field. A coil wound around the iron spacer in the center of the frame has 400-Hz alternating current (A.C.) flowing through it. During the times when this current reaches its peak, twice during each cycle, there is so much magnetism produced by this coil that the frame cannot accept the lines of flux from the Earth's field.

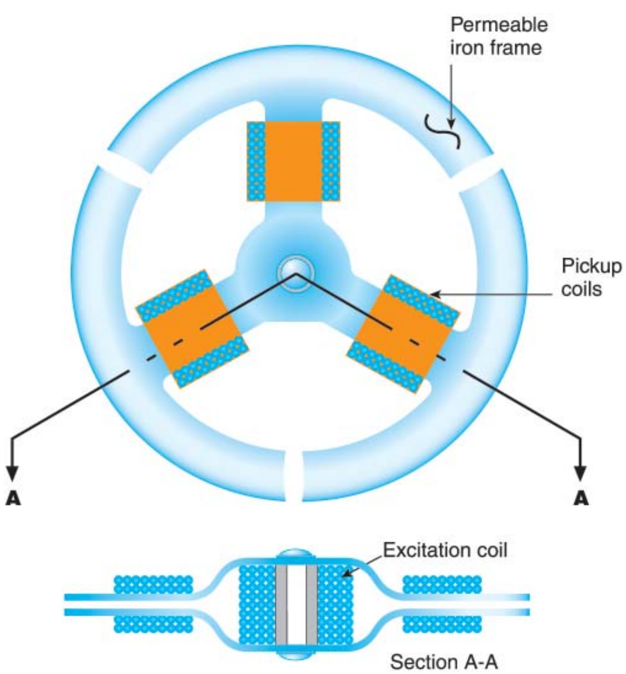


Figure 3-23. *The soft iron frame of the flux valve accepts the flux from the Earth's magnetic field each time the current in the center coil reverses. This flux causes current to flow in the three pickup coils.*

But as the current reverses between the peaks, it demagnetizes the frame so it can accept the flux from the Earth's field. As this flux cuts across the windings in the three coils, it causes current to flow in them. These three coils are connected in such a way that the current flowing in them changes as the heading of the aircraft changes. *[Figure 3-24]*

The three coils are connected to three similar but smaller coils in a synchro inside the instrument case. The synchro rotates the dial of a radio magnetic indicator (RMI) or a horizontal situation indicator (HSI).

Remote Indicating Compass

Remote indicating compasses were developed to compensate for the errors and limitations of the older type of heading indicators. The two panel-mounted components of a typical system are the pictorial navigation indicator and the slaving control and compensator unit. *[Figure 3-25]* The pictorial navigation indicator is commonly referred to as a HSI.

Figure 3-25. *Pictorial Navigation Indicator (HSI Top), Slaving Control and Compensator Unit.*

The slaving control and compensator unit has a pushbutton that provides a means of selecting either the "slaved gyro" or "free gyro" mode. This unit also has a slaving meter and two manual heading-drive buttons. The slaving meter indicates the difference between the displayed heading and the magnetic heading. A right deflection indicates a clockwise error of the compass card; a left deflection indicates a counterclockwise error. Whenever the aircraft is in a turn and the card rotates, the slaving meter shows a full deflection to one side or the other. When the system is in "free gyro" mode, the compass card may be adjusted by depressing the appropriate heading-drive button.

A separate unit, the magnetic slaving transmitter is mounted remotely; usually in a wingtip to eliminate the possibility of magnetic interference. It contains the flux valve, which is the direction-sensing device of the system. A concentration of lines of magnetic force, after being amplified, becomes a signal relayed to the heading indicator unit, which is also remotely mounted. This signal operates a torque motor in the heading indicator unit that processes the gyro unit until it is aligned with the transmitter signal. The magnetic slaving transmitter is connected electrically to the HSI.

There are a number of designs of the remote indicating compass; therefore, only the basic features of the system are covered here. Instrument pilots must become familiar with the characteristics of the equipment in their aircraft.

As instrument panels become more crowded and the pilot's available scan time is reduced by a heavier flight deck workload, instrument manufacturers have worked toward combining instruments. One good example of this is the RMI in *Figure 3-26*. The compass card is driven by signals from the flux valve, and the two pointers are driven by an automatic direction finder (ADF) and a very high frequency omnidirectional range (VOR).

Figure 3-26. *Driven by signals from a flux valve, the compass card in this RMI indicates the heading of the aircraft opposite the upper center index mark. The green pointer is driven by the ADF.*

Gyroscopic Systems

Flight without reference to a visible horizon can be safely accomplished by the use of gyroscopic instrument systems and the two characteristics of gyroscopes, which are rigidity and precession. These systems include attitude, heading, and rate instruments, along with their power sources. These instruments include a gyroscope (or gyro) that is a small wheel with its weight concentrated around its periphery. When this wheel is spun at high speed, it becomes rigid and resists tilting or turning in any direction other than around its spin axis.

Attitude and heading instruments operate on the principle of rigidity. For these instruments, the gyro remains rigid in its case and the aircraft rotates about it. Rate indicators, such as turn indicators and turn coordinators, operate on the principle of precession. In this case, the gyro processes (or rolls over) proportionate to the rate the aircraft rotates about one or more of its axes.

Power Sources

Aircraft and instrument manufacturers have designed redundancy in the flight instruments so that any single failure will not deprive the pilot of the ability to safely conclude the flight. Gyroscopic instruments are crucial for instrument flight; therefore, they are powered by separate electrical or pneumatic sources.

Pneumatic Systems

Pneumatic gyros are driven by a jet of air impinging on buckets cut into the periphery of the wheel. On many aircraft this stream of air is obtained by evacuating the instrument case with a vacuum source and allowing filtered air to flow into the case through a nozzle to spin the wheel.

Venturi Tube Systems

Aircraft that do not have a pneumatic pump to evacuate the instrument case can use venturi tubes mounted on the outside of the aircraft, similar to the system shown in *Figure 3-27*. Air flowing through the venturi tube speeds up in the narrowest part and, according to Bernoulli's principle, the pressure drops. This location is connected to the instrument case by a piece of tubing. The two attitude instruments operate on approximately 4" Hg of suction; the turn-and-slip indicator needs only 2" Hg, so a pressure-reducing needle valve is used to decrease the suction. Air flows into the instruments through filters built into the instrument cases. In this system, ice can clog the venturi tube and stop the instruments when they are most needed.

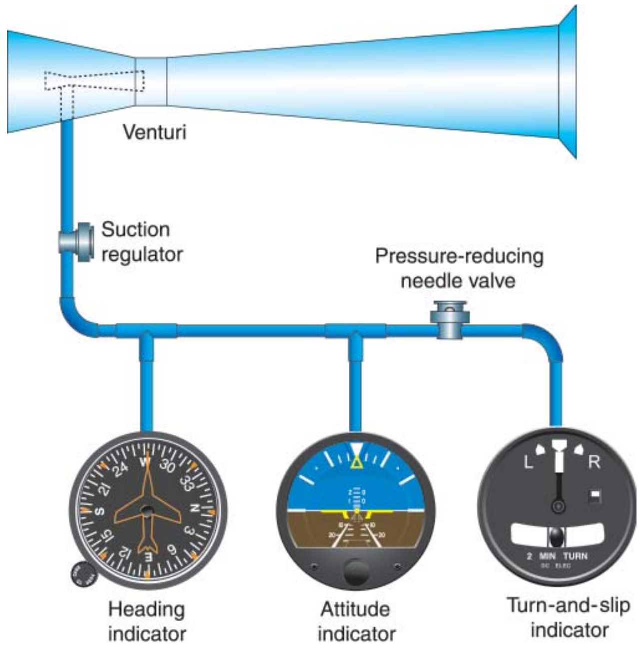


Figure 3-27. *A venturi tube system that provides necessary vacuum to operate key instruments.*

Vacuum Pump Systems

Wet-Type Vacuum Pump

Steel-vane air pumps have been used for many years to evacuate the instrument cases. The vanes in these pumps are lubricated by a small amount of engine oil metered into the pump and discharged with the air. In some aircraft the discharge air is used to inflate rubber deicer boots on the wing and empennage leading edges. To keep the oil from deteriorating the rubber boots, it must be removed with an oil separator like the one in *Figure 3-28*.

The vacuum pump moves a greater volume of air than is needed to supply the instruments with the suction needed, so a suction-relief valve is installed in the inlet side of the pump. This spring-loaded valve draws in just enough air to maintain the required low pressure inside the instruments, as is shown on the suction gauge in the instrument panel. Filtered air enters the instrument cases from a central air filter. As long as aircraft fly at relatively low altitudes, enough air is drawn into the instrument cases to spin the gyros at a sufficiently high speed.

Dry Air Vacuum Pump

As flight altitudes increase, the air is less dense and more air must be forced through the instruments. Air pumps that do not mix oil with the discharge air are used in high flying aircraft.

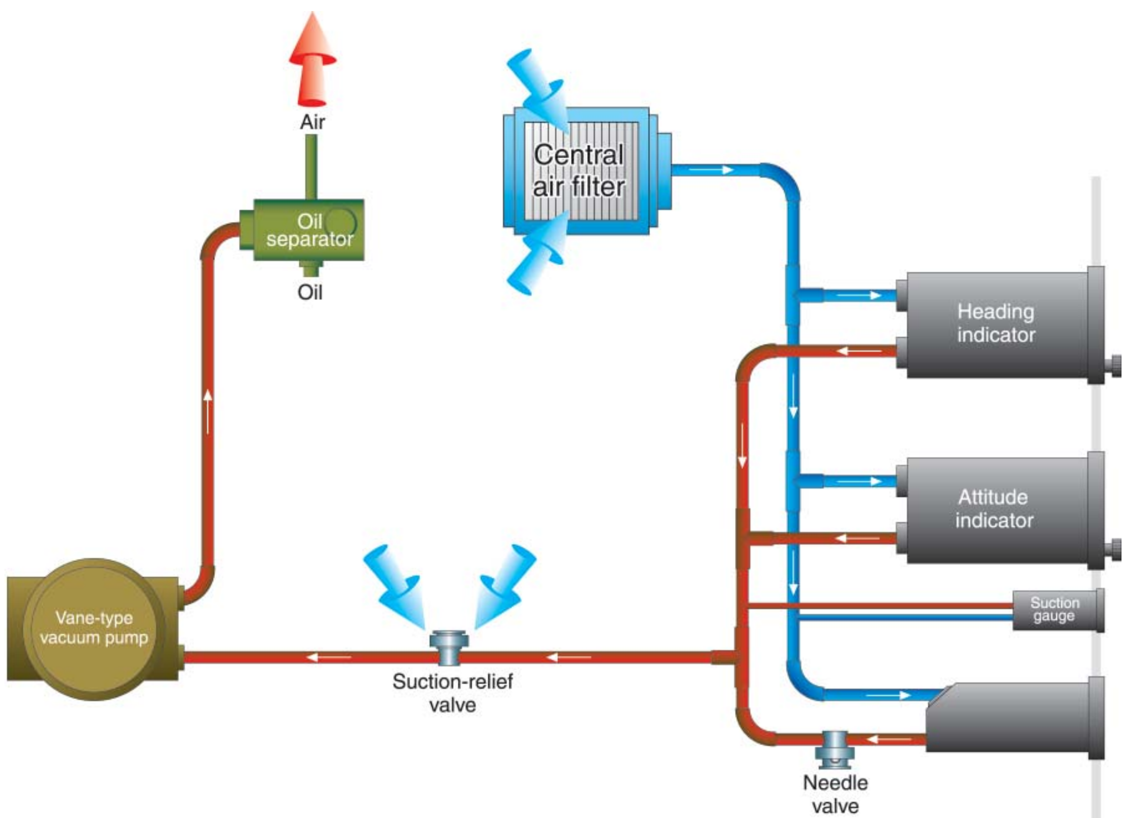


Figure 3-28. *Single-engine instrument vacuum system using a steel-vane wet-type vacuum pump.*

Steel vanes sliding in a steel housing need to be lubricated, but vanes made of a special formulation of carbon sliding inside carbon housing provide their own lubrication in a microscopic amount as they wear.

Pressure Indicating Systems

Figure 3-29 is a diagram of the instrument pneumatic system of a twin-engine general aviation airplane. Two dry air pumps are used with filters in their inlet to filter out any contaminants that could damage the fragile carbon vanes in the pump. The discharge air from the pump flows through a regulator, where excess air is bled off to maintain the pressure in the system at the desired level. The regulated air then flows through inline filters to remove any contamination that could have been picked up from the pump, and from there into a manifold check valve. If either engine should become inoperative or either pump should fail, the check valve isolates the inoperative system and the instruments are driven by air from the operating system. After the air passes through the instruments and drives the gyros, it is exhausted from the case. The gyro pressure gauge measures the pressure drop across the instruments.

Electrical Systems

Many general aviation aircraft that use pneumatic attitude indicators use electric rate indicators and/or the reverse. Some instruments identify their power source on their dial, but it is extremely important that pilots consult the POH/AFM to determine the power source of all instruments to know what action to take in the event of an instrument failure. Direct current (D.C.) electrical instruments are available in 14- or 28-volt models, depending upon the electrical system in the aircraft. A.C. is used to operate some attitude gyros and autopilots. Aircraft with only D.C. electrical systems can use A.C. instruments via installation of a solid-state D.C. to A.C. inverter, which changes 14 or 28 volts D.C. into three-phase 115-volt, 400-Hz A.C.

Gyroscopic Instruments

Attitude Indicators

The first attitude instrument (AI) was originally referred to as an artificial horizon, later as a gyro horizon; now it is more properly called an attitude indicator. Its operating mechanism is a small brass wheel with a vertical spin axis, spun at a high speed by either a stream of air impinging on buckets cut into its periphery, or by an electric motor. The gyro is mounted in a double gimbal, which allows the aircraft to pitch and roll about the gyro as it remains fixed in space.

A horizon disk is attached to the gimbals so it remains in the same plane as the gyro, and the aircraft pitches and rolls about it. On early instruments, this was just a bar that

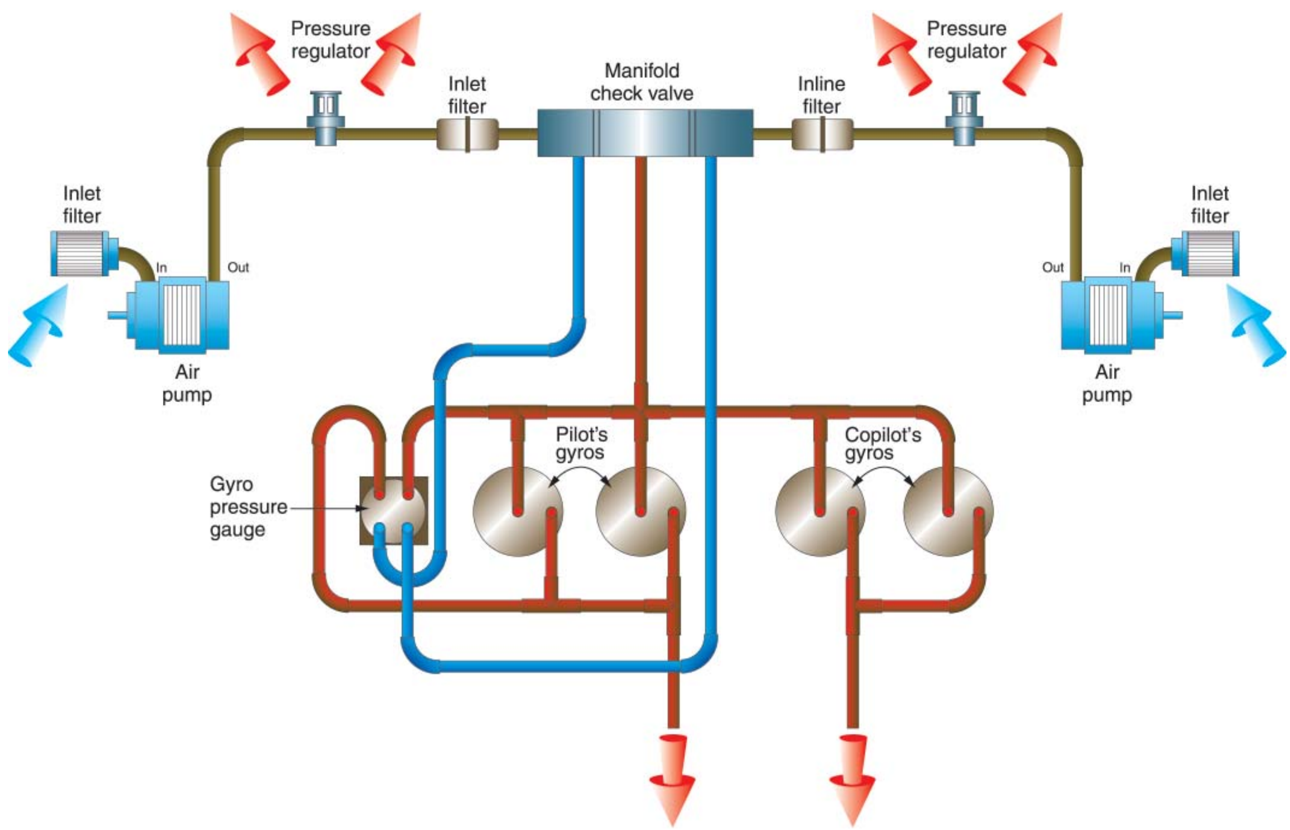


Figure 3-29. *Twin-Engine Instrument Pressure System Using a Carbon-Vane Dry-Type Air Pump.*

represented the horizon, but now it is a disc with a line representing the horizon and both pitch marks and bank-angle lines. The top half of the instrument dial and horizon disc is blue, representing the sky; and the bottom half is brown, representing the ground. A bank index at the top of the instrument shows the angle of bank marked on the banking scale with lines that represent 10°, 20°, 30°, 45°, and 60°. *[Figure 3-30]*

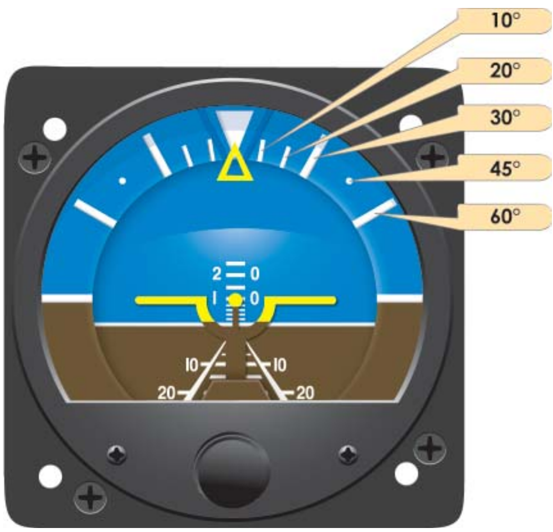


Figure 3-30. *The dial of this attitude indicator has reference lines to show pitch and roll.*

A small symbolic aircraft is mounted in the instrument case so it appears to be flying relative to the horizon. A knob at the bottom center of the instrument case raises or lowers the aircraft to compensate for pitch trim changes as the airspeed changes. The width of the wings of the symbolic aircraft and the dot in the center of the wings represent a pitch change of approximately 2°.

For an AI to function properly, the gyro must remain vertically upright while the aircraft rolls and pitches around it. The bearings in these instruments have a minimum of friction; however, even this small amount places a restraint on the gyro producing precession and causing the gyro to tilt. To minimize this tilting, an erection mechanism inside the instrument case applies a force any time the gyro tilts from its vertical position. This force acts in such a way to return the spinning wheel to its upright position.

The older artificial horizons were limited in the amount of pitch or roll they could tolerate, normally about 60° in pitch and 100° in roll. After either of these limits was exceeded, the gyro housing contacted the gimbals, applying such a precessing force that the gyro tumbled. Because of this limitation, these instruments had a caging mechanism that locked the gyro in its vertical position during any maneuvers that exceeded the instrument limits. Newer instruments do not have these restrictive tumble limits; therefore, they do not have a caging mechanism.

When an aircraft engine is first started and pneumatic or electric power is supplied to the instruments, the gyro is not erect. A self-erecting mechanism inside the instrument actuated by the force of gravity applies a precessing force, causing the gyro to rise to its vertical position. This erection can take as long as 5 minutes, but is normally done within 2 to 3 minutes.

Attitude indicators are free from most errors, but depending upon the speed with which the erection system functions, there may be a slight nose-up indication during a rapid acceleration and a nose-down indication during a rapid deceleration. There is also a possibility of a small bank angle and pitch error after a 180° turn. These inherent errors are small and correct themselves within a minute or so after returning to straight-and-level flight.

Heading Indicators

A magnetic compass is a dependable instrument used as a backup instrument. Although very reliable, it has so many inherent errors that it has been supplemented with gyroscopic heading indicators.

The gyro in a heading indicator is mounted in a double gimbal, as in an attitude indicator, but its spin axis is horizontal permitting sensing of rotation about the vertical axis of the aircraft. Gyro heading indicators, with the exception of slaved gyro indicators, are not north seeking, therefore they must be manually set to the appropriate heading by referring to a magnetic compass. Rigidity causes them to maintain this heading indication, without the oscillation and other errors inherent in a magnetic compass.

Older directional gyros use a drum-like card marked in the same way as the magnetic compass card. The gyro and the card remain rigid inside the case with the pilot viewing the card from the back. This creates the possibility the pilot might start a turn in the wrong direction similar to using a magnetic compass. A knob on the front of the instrument, below the dial, can be pushed in to engage the gimbals. This locks the gimbals allowing the pilot to rotate the gyro and card until the number opposite the lubber line agrees with the magnetic compass. When the knob is pulled out, the gyro remains rigid and the aircraft is free to turn around the card.

Directional gyros are almost all air-driven by evacuating the case and allowing filtered air to flow into the case and out through a nozzle, blowing against buckets cut in the periphery of the wheel. The Earth constantly rotates at 15° per hour while the gyro is maintaining a position relative to space, thus causing an apparent drift in the displayed heading of 15° per hour. When using these instruments, it is standard practice to compare the heading indicated on the directional gyro with the magnetic compass at least every 15 minutes and to reset the heading as necessary to agree with the magnetic compass.

Heading indicators like the one in *Figure 3-31* work on the same principle as the older horizontal card indicators, except that the gyro drives a vertical dial that looks much like the dial of a vertical card magnetic compass. The heading of the aircraft is shown against the nose of the symbolic aircraft on the instrument glass, which serves as the lubber line. A knob in the front of the instrument may be pushed in and turned to rotate the gyro and dial. The knob is spring loaded so it disengages from the gimbals as soon as it is released. This instrument should be checked about every 15 minutes to see if it agrees with the magnetic compass.

Figure 3-31. *The heading indicator is not north seeking, but must be set periodically (about every 15 minutes) to agree with the magnetic compass.*

Turn Indicators

Attitude and heading indicators function on the principle of rigidity, but rate instruments such as the turn-and-slip indicator operate on precession. Precession is the characteristic of a gyroscope that causes an applied force to produce a movement, not at the point of application, but at a point 90° from the point of application in the direction of rotation. *[Figure 3-32]*

Turn-and-Slip Indicator

The first gyroscopic aircraft instrument was the turn indicator in the needle and ball, or turn-and-bank indicator, which has more recently been called a turn-and-slip indicator. *[Figure 3-33]*

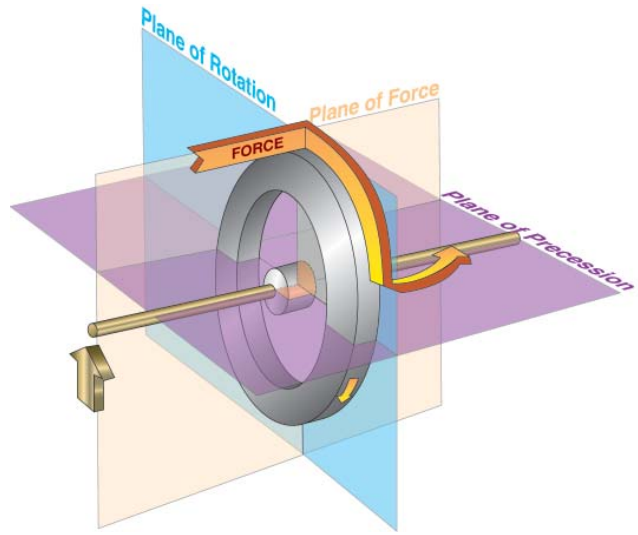


Figure 3-32. *Precession causes a force applied to a spinning wheel to be felt 90° from the point of application in the direction of rotation.*

The inclinometer in the instrument is a black glass ball sealed inside a curved glass tube that is partially filled with a liquid for damping. This ball measures the relative strength of the force of gravity and the force of inertia caused by a turn. When the aircraft is flying straight-and-level, there is no inertia acting on the ball, and it remains in the center of the tube between two wires. In a turn made with a bank angle that is too steep, the force of gravity is greater than the inertia and the ball rolls down to the inside of the turn. If the turn is made with too shallow a bank angle, the inertia is greater than gravity and the ball rolls upward to the outside of the turn.

The inclinometer does not indicate the amount of bank, nor does it indicate slip; it only indicates the relationship between the angle of bank and the rate of yaw.

Figure 3-33. *Turn-and-Slip Indicator.*

The turn indicator is a small gyro spun either by air or by an electric motor. The gyro is mounted in a single gimbal with its spin axis parallel to the lateral axis of the aircraft and the axis of the gimbal parallel with the longitudinal axis. *[Figure 3-34]*

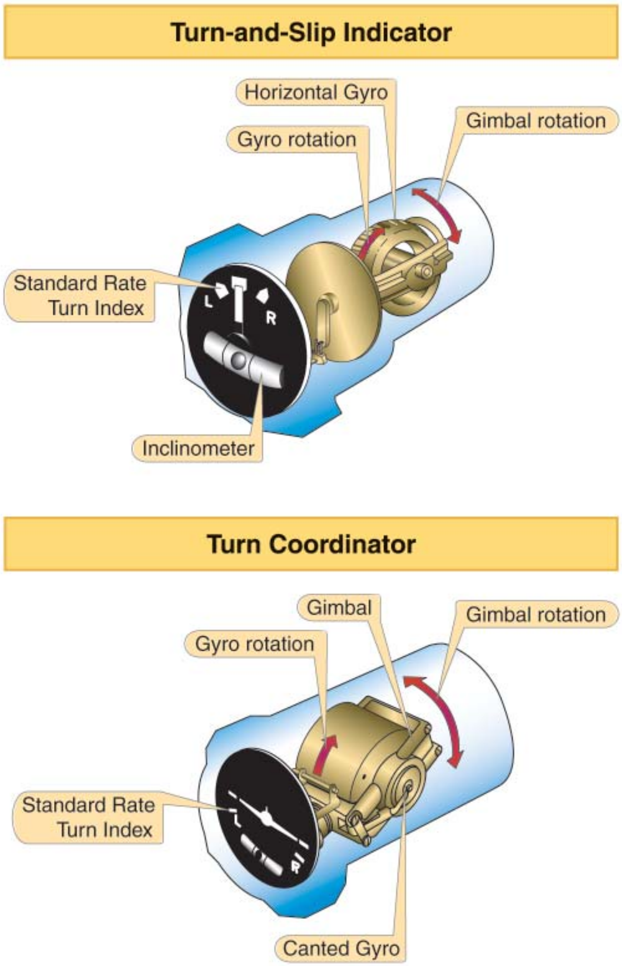


Figure 3-34. *The rate gyro in both turn-and-slip indicator and turn coordinator.*

When the aircraft yaws, or rotates about its vertical axis, it produces a force in the horizontal plane that, due to precession, causes the gyro and its gimbal to rotate about the gimbal's axis. It is restrained in this rotation plane by a calibration spring; it rolls over just enough to cause the pointer to deflect until it aligns with one of the doghouse-shaped marks on the dial, when the aircraft is making a standard rate turn.

The dial of these instruments is marked "2 MIN TURN." Some turn-and-slip indicators used in faster aircraft are marked "4 MIN TURN." In either instrument, a standard rate turn is being made whenever the needle aligns with a doghouse.

Turn Coordinator

The major limitation of the older turn-and-slip indicator is that it senses rotation only about the vertical axis of the aircraft. It tells nothing of the rotation around the longitudinal axis, which in normal flight occurs before the aircraft begins to turn.

A turn coordinator operates on precession, the same as the turn indicator, but its gimbals frame is angled upward about 30° from the longitudinal axis of the aircraft. *[Figure 3-34]* This allows it to sense both roll and yaw. Therefore during a turn, the indicator first shows the rate of banking and once stabilized, the turn rate. Some turn coordinator gyros are dual-powered and can be driven by either air or electricity.

Rather than using a needle as an indicator, the gimbal moves a dial that is the rear view of a symbolic aircraft. The bezel of the instrument is marked to show wings-level flight and bank angles for a standard rate turn. *[Figure 3-35]*

Figure 3-35. *A turn coordinator senses rotation about both roll and yaw axes.*

The inclinometer, similar to the one in a turn-and-slip indicator, is called a coordination ball, which shows the relationship between the bank angle and the rate of yaw. The turn is coordinated when the ball is in the center, between the marks. The aircraft is skidding when the ball rolls toward the outside of the turn and is slipping when it moves toward the inside of the turn. A turn coordinator does not sense pitch. This is indicated on some instruments by placing the words "NO PITCH INFORMATION" on the dial.

Flight Support Systems

Attitude and Heading Reference System (AHRS)

As aircraft displays have transitioned to new technology, the sensors that feed them have also undergone significant change. Traditional gyroscopic flight instruments have been replaced by Attitude and Heading Reference Systems (AHRS) improving reliability and thereby reducing cost and maintenance.

The function of an AHRS is the same as gyroscopic systems; that is, to determine which way is level and which way is north. By knowing the initial heading the AHRS can determine both the attitude and magnetic heading of the aircraft.

The genesis of this system was initiated by the development of the ring-LASAR gyroscope developed by Kearfott located in Little Falls, New Jersey. *[Figure 3-36]* Their development of the Ring-LASAR gyroscope in the 1960s/1970s was in support of Department of Defense (DOD) programs to include cruise missile technology. With the precision of these gyroscopes, it became readily apparent that they could be leveraged for multiple tasks and functions. Gyroscopic miniaturization has become so common that solid-state gyroscopes are found in products from robotics to toys.

Because the AHRS system replaces separate gyroscopes, such as those associated with an attitude indicator, magnetic heading indicator and turn indicator these individual systems are no longer needed. As with many systems today, AHRS itself had matured with time. Early AHRS systems used expensive inertial sensors and flux valves. However, today the AHRS for aviation and general aviation in particular are small solid-state systems integrating a variety of technology such as low cost inertial sensors, rate gyros, and magnetometers, and have capability for satellite signal reception.

Air Data Computer (ADC)

An Air Data Computer (ADC) *[Figure 3-37]* is an aircraft computer that receives and processes pitot pressure, static pressure, and temperature to calculate very precise altitude, IAS, TAS, and air temperature. The ADC outputs this information in a digital format that can be used by a variety of aircraft systems including an EFIS. Modern ADCs are small solid-state units. Increasingly, aircraft systems such as autopilots, pressurization, and FMS utilize ADC information for normal operations. NOTE: In most modern general aviation systems, both the AHRS and ADC are integrated within the electronic displays themselves thereby reducing the number of units, reducing weight, and providing simplification for installation resulting in reduced costs.

Analog Pictorial Displays

Horizontal Situation Indicator (HSI)

The HSI is a direction indicator that uses the output from a flux valve to drive the dial, which acts as the compass card. This instrument, shown in *Figure 3-37*, combines the magnetic compass with navigation signals and a glide slope. This gives the pilot an indication of the location of the aircraft with relationship to the chosen course.

Figure 3-36. *The Kearfott Attitude Heading Reference System (AHRS) on the left incorporates a Monolithic Ring Laser Gyro (MRLG) (center), which is housed in an Inertial Sensor Assembly (ISA) on the right.*

Figure 3-37. *Air Data Computer (Collins).*

In *Figure 3-38*, the aircraft heading displayed on the rotating azimuth card under the upper lubber line is North or 360°. The course-indicating arrowhead shown is set to 020; the tail indicates the reciprocal, 200°. The course deviation bar operates with a VOR/Localizer (VOR/LOC) navigation receiver to indicate left or right deviations from the course selected with the course-indicating arrow, operating in the same manner that the angular movement of a conventional VOR/LOC needle indicates deviation from course.

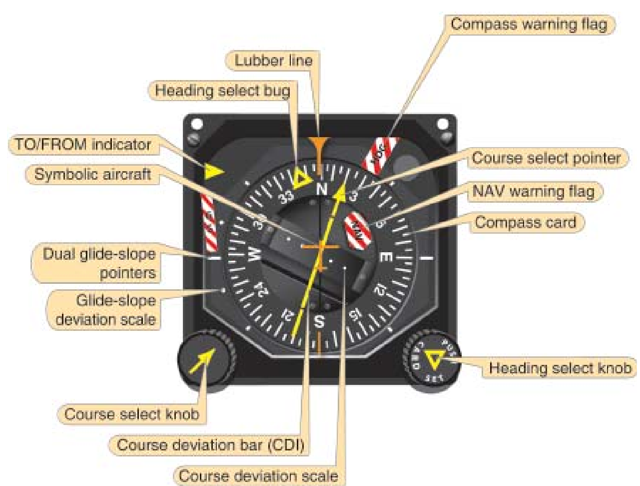


Figure 3-38. *Horizontal Situation Indicator (HSI).*

The desired course is selected by rotating the course-indicating arrow in relation to the azimuth card by means of the course select knob. This gives the pilot a pictorial presentation: the fixed aircraft symbol and course deviation bar display the aircraft relative to the selected course, as though the pilot were above the aircraft looking down. The TO/FROM indicator is a triangular pointer. When the indicator points to the head of the course arrow, it shows that the course selected, if properly intercepted and flown, takes the aircraft to the selected facility. When the indicator points to the tail of the course arrow, it shows that the course selected, if properly intercepted and flown, takes the aircraft directly away from the selected facility.

The glide slope deviation pointer indicates the relation of the aircraft to the glide slope. When the pointer is below the center position, the aircraft is above the glide slope, and an increased rate of descent is required. In most installations, the azimuth card is a remote indicating compass driven by a fluxgate; however, in few installations where a fluxgate is not installed, or in emergency operation, the heading must be checked against the magnetic compass occasionally and reset with the course select knob.

Attitude Direction Indicator (ADI)

Advances in attitude instrumentation combine the gyro horizon with other instruments such as the HSI, thereby reducing the number of separate instruments to which the pilot must devote attention. The attitude direction indicator (ADI) is an example of such technological advancement. A flight director incorporates the ADI within its system, which is further explained below (Flight Director System). However, an ADI need not have command cues; however, it is normally equipped with this feature.

Flight Director System (FDS)

A Flight Director System (FDS) combines many instruments into one display that provides an easily interpreted understanding of the aircraft's flight path. The computed solution furnishes the steering commands necessary to obtain and hold a desired path.

Major components of an FDS include an ADI, also called a Flight Director Indicator (FDI), an HSI, a mode selector, and a flight director computer. It should be noted that a flight director in use does not infer the aircraft is being manipulated by the autopilot (coupled), but is providing steering commands that the pilot (or the autopilot, if coupled) follows.

Typical flight directors use one of two display systems for steerage. The first is a set of command bars, one horizontal and one vertical. The command bars in this configuration are maintained in a centered position (much like a centered glide slope). The second uses a miniature aircraft aligned to a command cue.

A flight director displays steerage commands to the pilot on the ADI. As previously mentioned, the flight director receives its signals from one of various sources and provides that to the ADI for steerage commands. The mode controller provides signals through the ADI to drive the steering bars, e.g., the pilot flies the aircraft to place the delta symbol in the V of the steering bars. "Command" indicators tell the pilot in which direction and how much to change aircraft attitude to achieve the desired result.

The computed command indications relieve the pilot of many of the mental calculations required for instrument flight. The yellow cue in the ADI *[Figure 3-39]* provides all steering commands to the pilot. It is driven by a computer that receives information from the navigation systems, the ADC, AHRS, and other sources of data. The computer processes this information, providing the pilot with a single cue to follow. Following the cue provides the pilot with the necessary three-dimensional flight trajectory to maintain the desired path.

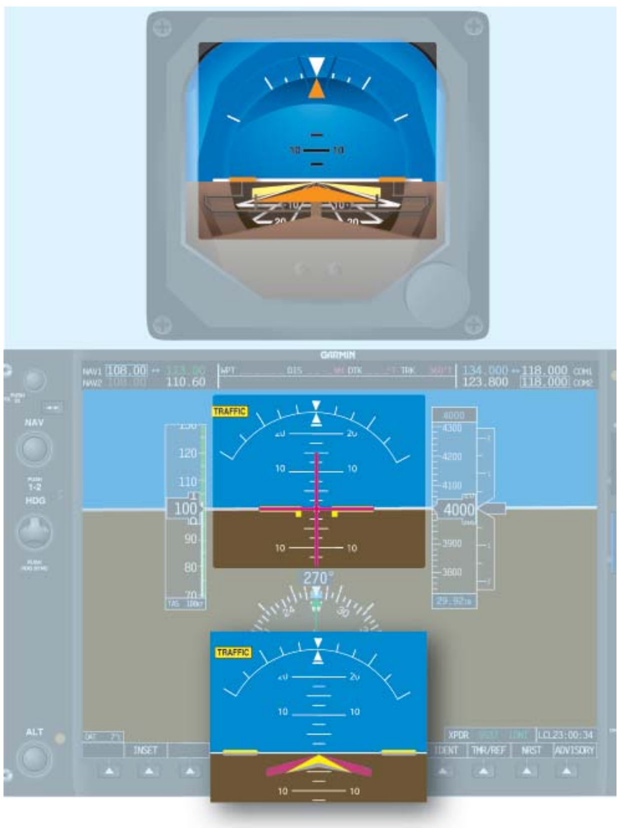


Figure 3-39. *A Typical Cue That a Pilot Would Follow.*

One of the first widely used flight directors was developed by Sperry and was called the Sperry Three Axis Attitude Reference System (STARS). Developed in the 1960s, it was commonly found on both commercial and business aircraft alike. STARS (with a modification) and successive flight directors were integrated with the autopilots and aircraft providing a fully integrated flight system.

The flight director/autopilot system described below is typical of installations in many general aviation aircraft. The components of a typical flight director include the mode controller, ADI, HSI, and annunciator panel. These units are illustrated in *Figure 3-40*.

Figure 3-40. *Components of a Typical Flight Director System.*

The pilot may choose from among many modes including the HDG (heading) mode, the VOR/LOC (localizer tracking) mode, or the AUTO Approach (APP) or G/S (automatic capture and tracking of instrument landing system (ILS) localizers and glide path) mode. The auto mode has a fully automatic pitch selection computer that takes into account aircraft performance and wind conditions, and operates once the pilot has reached the ILS glide slope. More sophisticated systems allow more flight director modes.

Integrated Flight Control System

The integrated flight control system integrates and merges various systems into a system operated and controlled by one principal component. *Figure 3-41* illustrates key components of the flight control system that was developed from the onset as a fully integrated system comprised of the airframe, autopilot, and flight director system. This trend of complete integration, once seen only in large commercial aircraft, are now becoming common in the general aviation field.

Autopilot Systems

An autopilot is a mechanical means to control an aircraft using electrical, hydraulic, or digital systems. Autopilots can control three axes of the aircraft: roll, pitch, and yaw. Most autopilots in general aviation control roll and pitch.

Autopilots also function using different methods. The first is position based. That is, the attitude gyro senses the degree of difference from a position such as wings level, a change in pitch, or a heading change.

Figure 3-41. *The S-TEC/Meggit Corporation Integrated Autopilot Installed in the Cirrus.*

Determining whether a design is position based and/or rate based lies primarily within the type of sensors used. In order for an autopilot to possess the capability of controlling an aircraft's attitude (i.e., roll and pitch), that system must be provided with constant information on the actual attitude of that aircraft. This is accomplished by the use of several different types of gyroscopic sensors. Some sensors are designed to indicate the aircraft's attitude in the form of position in relation to the horizon, while others indicate rate (position change over time).

Rate-based systems use the turn-and-bank sensor for the autopilot system. The autopilot uses rate information on two of the aircraft's three axes: movement about the vertical axis (heading change or yaw) and about the longitudinal axis (roll). This combined information from a single sensor is made possible by the 30° offset in the gyro's axis to the longitudinal axis.

Other systems use a combination of both position and rate-based information to benefit from the attributes of both systems while newer autopilots are digital. *Figure 3-42* illustrates an autopilot by Century.

Figure 3-43 is a diagram layout of a rate-based autopilot by S-Tec, which permits the purchaser to add modular capability form basic wing leveling to increased capability.

Flight Management Systems (FMS)

In the mid-1970s, visionaries in the avionics industry such as Hubert Naimer of Universal, and followed by others such as Ed King, Jr., were looking to advance the technology of aircraft navigation. As early as 1976, Naimer had a vision of a "Master Navigation System" that would accept inputs from a variety of different types of sensors on an aircraft and automatically provide guidance throughout all phases of flight.

Figure 3-42. *An Autopilot by Century.*

At that time aircraft navigated over relatively short distances with radio systems, principally VOR or ADF. For long-range flight inertial navigation systems (INS), Omega, Doppler, and Loran were in common use. Short-range radio systems usually did not provide area navigation capability. Long-range systems were only capable of en route point-to-point navigation between manually entered waypoints described as longitude and latitude coordinates, with typical systems containing a limited number of waypoints.

Figure 3-43. *A Diagram Layout of an Autopilot by S-Tec.*

The laborious process of manually entering cryptic latitude and longitude data for each flight waypoint created high crew workloads and frequently resulted in incorrect data entry. The requirement of a separate control panel for each long-range system consumed precious flight deck space and increased the complexity of interfacing the systems with display instruments, flight directors, and autopilots.

The concept employed a master computer interfaced with all of the navigation sensors on the aircraft. A common control display unit (CDU) interfaced with the master computer would provide the pilot with a single control point for all navigation systems, thereby reducing the number of required flight deck panels. Management of the various individual sensors would be transferred from the pilot to the new computer.

Since navigation sensors rarely agree exactly about position, Naimer believed that blending all available sensor position data through a highly sophisticated, mathematical filtering system would produce a more accurate aircraft position. He called the process output the "Best Computed Position." By using all available sensors to keep track of position, the system could readily provide area navigation capability. The master computer, not the individual sensors, would be integrated into the airplane, greatly reducing wiring complexity.

To solve the problems of manual waypoint entry, a pre-loaded database of global navigation information would be readily accessible by the pilot through the CDU. Using such a system a pilot could quickly and accurately construct a flight plan consisting of dozens of waypoints, avoiding the tedious typing of data and the error potential of latitude/longitude coordinates. Rather than simply navigating point-to-point, the master system would be able to maneuver the aircraft, permitting use of the system for terminal procedures including departures, arrivals, and approaches. The system would be able to automate any aspect of manual pilot navigation of the aircraft. When the first system, called the UNS-1, was released by Universal in 1982, it was called a flight management system (FMS). *[Figure 3-44]*

Figure 3-44. *A Control Display Unit (CDU) Used to Control the Flight Management System.*

An FMS uses an electronic database of worldwide navigational data including navigation aids, airways and intersections, Standard Instrument Departures (SIDs), Standard Terminal Arrival Routes (STARs), and Instrument Approach Procedures (IAPs) together with pilot input through a CDU to create a flight plan. The FMS provides outputs to several aircraft systems including desired track, bearing and distance to the active waypoint, lateral course deviation and related data to the flight guidance system for the HSI displays, and roll steering command for the autopilot/flight director system. This allows outputs from the FMS to command the airplane where to go and when and how to turn. To support adaptation to numerous aircraft types, an FMS is usually capable of receiving and outputting both analog and digital data and discrete information. Currently, electronic navigation databases are updated every 28 days.

The introduction of the Global Positioning System (GPS) has provided extremely precise position at low cost, making GPS the dominant FMS navigation sensor today. Currently, typical FMS installations require that air data and heading information be available electronically from the aircraft. This limits FMS usage in smaller aircraft, but emerging technologies allow this data from increasingly smaller and less costly systems.

Some systems interface with a dedicated Distance Measuring Equipment (DME) receiver channel under the control of the FMS to provide an additional sensor. In these systems, the FMS determines which DME sites should be interrogated for distance information using aircraft position and the navigation database to locate appropriate DME sites. The FMS then compensates aircraft altitude and station altitude with the aid of the database to determine the precise distance to the station. With the distances from a number of sites the FMS can compute a position nearly as accurately as GPS.

Aimer visualized three-dimensional aircraft control with an FMS. Modern systems provide Vertical Navigation (VNAV) as well as Lateral Navigation (LNAV) allowing the pilot to create a vertical flight profile synchronous with the lateral flight plan. Unlike early systems, such as Inertial Reference Systems (IRS) that were only suitable for en route navigation, the modern FMS can guide an aircraft during instrument approaches.

Today, an FMS provides not only real-time navigation capability but typically interfaces with other aircraft systems providing fuel management, control of cabin briefing and display systems, display of uplinked text and graphic weather data and air/ground data link communications.

Electronic Flight Instrument Systems

Modern technology has introduced into aviation a new method of displaying flight instruments, such as electronic flight instrument systems, integrated flight deck displays, and others. For the purpose of the practical test standards, any flight instrument display that utilizes LCD or picture tube like displays is referred to as "electronic flight instrument display" and/or a glass flight deck. In general aviation there is typically a primary flight display (PFD) and a multi-function display (MFD). Although both displays are in many cases identical, the PFD provides the pilot instrumentation necessary for flight to include altitude, airspeed, vertical velocity, attitude, heading and trim and trend information.

Glass flight decks (a term coined to describe electronic flight instrument systems) are becoming more widespread as cost falls and dependability continually increases. These systems provide many advantages such as being lighter, more reliable, no moving parts to wear out, consuming less power, and replacing numerous mechanical indicators with a single glass display. Because the versatility offered by glass displays is much greater than that offered by analog displays, the use of such systems will only increase with time until analog systems are eclipsed.

Primary Flight Display (PFD)

PFDs provide increased situational awareness to the pilot by replacing the traditional six instruments used for instrument flight with an easy-to-scan display that provides the horizon, airspeed, altitude, vertical speed, trend, trim, rate of turn among other key relevant indications. Examples of PFDs are illustrated in *Figure 3-45*.

Synthetic Vision

Synthetic vision provides a realistic depiction of the aircraft in relation to terrain and flight path. Systems such as those produced by Chelton Flight Systems, Universal Flight Systems, and others provide for depictions of terrain and course. *Figure 3-46* is an example of the Chelton Flight System providing both 3-dimensional situational awareness and a synthetic highway in the sky, representing the desired flight path. Synthetic vision is used as a PFD, but provides guidance in a more normal, outside reference format.

Figure 3-45. *Two Primary Flight Displays (Avidyne on the Left and Garmin on the Right).*

Figure 3-46. *The benefits of realistic visualization imagery, as illustrated by Synthetic Vision manufactured by Chelton Flight Systems. The system provides the pilot a realistic, real-time, three-dimensional depiction of the aircraft and its relation to terrain around it.*

Multi-Function Display (MFD)

In addition to a PFD directly in front of the pilot, an MFD that provides the display of information in addition to primary flight information is used within the flight deck. *[Figure 3-47]* Information such as a moving map, approach charts, Terrain Awareness Warning System, and weather depiction can all be illustrated on the MFD. For additional redundancy both the PFD and MFD can display all critical information that the other normally presents thereby providing redundancy (using a reversionary mode) not normally found in general aviation flight decks.

Advanced Technology Systems

Automatic Dependent Surveillance—Broadcast (ADS-B)

Although standards for Automatic Dependent Surveillance (Broadcast) (ADS-B) are still under continuing development, the concept is simple: aircraft broadcast a message on a regular basis, which includes their position (such as latitude, longitude and altitude), velocity, and possibly other information. Other aircraft or systems can receive this information for use in a wide variety of applications. The key to ADS-B is GPS, which provides three-dimensional position of the aircraft.

As an simplified example, consider air-traffic radar. The radar measures the range and bearing of an aircraft. The bearing is measured by the position of the rotating radar antenna when it receives a reply to its interrogation from the aircraft, and the range by the time it takes for the radar to receive the reply.

An ADS-B based system, on the other hand, would listen for position reports broadcast by the aircraft. *[Figure 3-48]* These position reports are based on satellite navigation systems. These transmissions include the transmitting aircraft's position, which the receiving aircraft processes into usable pilot information. The accuracy of the system is now determined by the accuracy of the navigation system, not measurement errors. Furthermore the accuracy is unaffected by the range to the aircraft as in the case of radar. With radar, detecting aircraft speed changes require tracking the data and changes can only be detected over a period of several position updates. With ADS-B, speed changes are broadcast almost instantaneously and received by properly equipped aircraft.

Figure 3-47. *Example of a Multi-Function Display (MFD).*

Figure 3-48. *Aircraft equipped with Automatic Dependent Surveillance—Broadcast (ADS-B) continuously broadcast their identification, altitude, direction, and vertical trend. The transmitted signal carries significant information for other aircraft and ground stations alike. Other ADS-equipped aircraft receive this information and process it in a variety of ways. It is possible that in a saturated environment (assuming all aircraft are ADS equipped), the systems can project tracks for their respective aircraft and retransmit to other aircraft their projected tracks, thereby enhancing collision avoidance. At one time, there was an Automatic Dependent Surveillance—Addressed (ADS-A) and that is explained in the Pilot's Handbook of Aeronautical Knowledge.*

Additionally, other information can be obtained by properly equipped aircraft to include notices to airmen (NOTAM), weather, etc. *[Figures 3-49* and *3-50]* At the present time, ADS-B is predominantly available along the east coast of the United States where it is matured.

Safety Systems

Radio Altimeters

A radio altimeter, commonly referred to as a radar altimeter, is a system used for accurately measuring and displaying the height above the terrain directly beneath the aircraft. It sends a signal to the ground and processes the timed information.

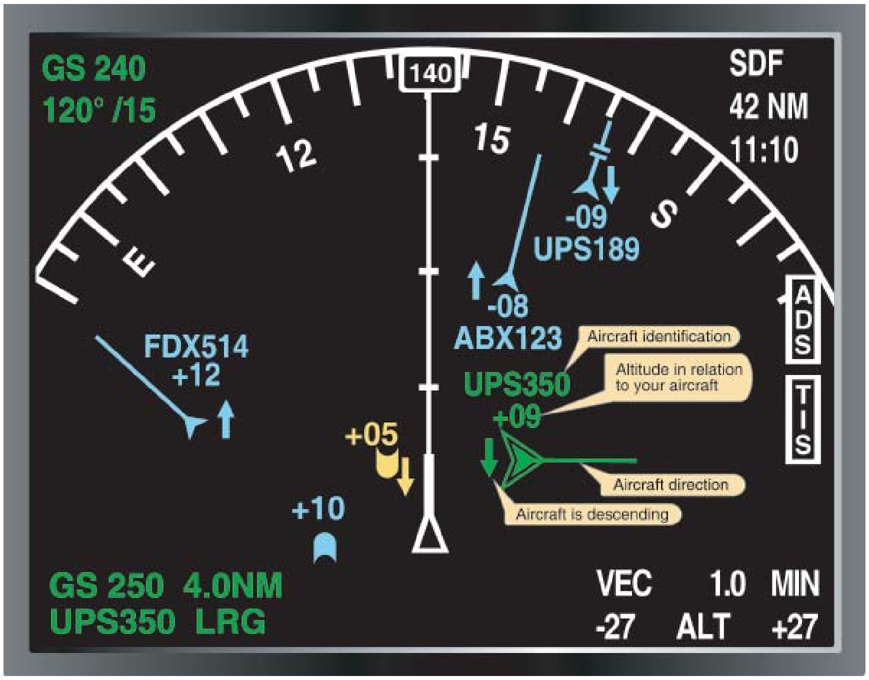


Figure 3-49. *An aircraft equipped with ADS will receive identification, altitude in hundreds of feet (above or below using + or -), direction of the traffic, and aircraft descent or climb using an up or down arrow. The yellow target is an illustration of how a non-ADS equipped aircraft would appear on an ADS-equipped aircraft's display.*

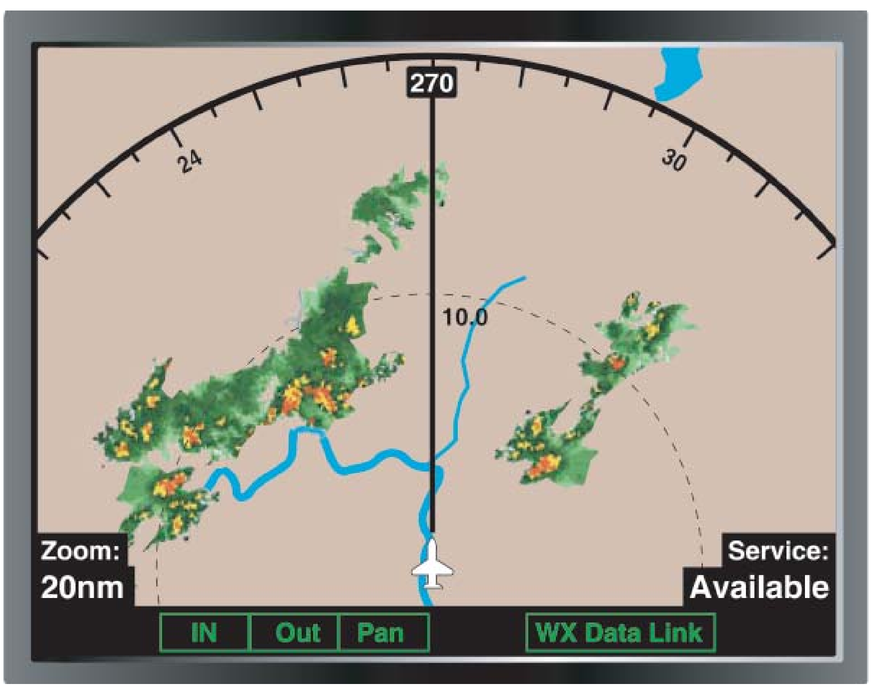


Figure 3-50. *An aircraft equipped with ADS has the ability to upload and display weather.*

Its primary application is to provide accurate absolute altitude information to the pilot during approach and landing. In advanced aircraft today, the radar altimeter also provides its information to other onboard systems such as the autopilot and flight directors while they are in the glide slope capture mode below 200-300 feet above ground level (AGL).

A typical system consists of a receiver-transmitter (RT) unit, antenna(s) for receiving and transmitting the signal, and an indicator. *[Figure 3-51]* Category II and III precision approach procedures require the use of a radar altimeter and specify the exact minimum height above the terrain as a decision height (DH) or radio altitude (RA).

Figure 3-51. *Components of a Radar Altimeter.*

Traffic Advisory Systems

Traffic Information System

The Traffic Information Service (TIS) is a ground-based service providing information to the flight deck via data link using the S-mode transponder and altitude encoder. TIS improves the safety and efficiency of "see and avoid" flight through an automatic display that informs the pilot of nearby traffic. The display can show location, direction, altitude and the climb/descent trend of other transponder-equipped aircraft. TIS provides estimated position, altitude, altitude trend, and ground track information for up to several aircraft simultaneously within about 7 NM horizontally, 3,500 feet above and 3,500 feet below the aircraft. *[Figure 3-52]* This data can be displayed on a variety of MFDs. *[Figure 3-53]*

Figure 3-54 displays the pictorial concept of the traffic information system. Noteworthy is the requirement to have Mode S and that the ground air traffic station processes the Mode S signal.

Traffic Alert Systems

Traffic alert systems receive transponder information from nearby aircraft to help determine their relative position to the equipped aircraft. They provide three-dimensional location

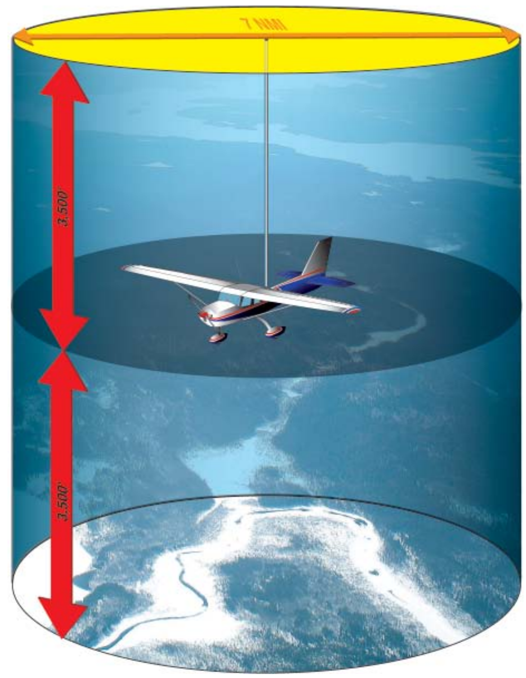


Figure 3-52. *Coverage Provided by a Traffic Information System.*

of other aircraft *[Figures 3-55, 3-56,* and *3-57]* and are cost effective alternatives to TCAS equipage for smaller aircraft.

Traffic Avoidance Systems

Traffic Alert and Collision Avoidance System (TCAS)

The TCAS is an airborne system developed by the FAA that operates independently from the ground-based ATC system. TCAS was designed to increase flight deck awareness of proximate aircraft and to serve as a "last line of defense" for the prevention of mid-air collisions.

There are two levels of TCAS systems. TCAS I was developed to accommodate the general aviation (GA) community and the regional airlines. This system issues traffic advisories (TAs) to assist pilots in visual acquisition of intruder aircraft. TCAS I provides approximate bearing and relative altitude of aircraft with a selectable range. It provides the pilot with traffic advisory (TA) alerting him or her to potentially conflicting traffic. The pilot then visually acquires the traffic and takes appropriate action for collision avoidance.

TCAS II is a more sophisticated system which provides the same information of TCAS I. It also analyzes the projected flight path of approaching aircraft and issues resolution advisories (RAs) to the pilot to resolve potential mid-air collisions. Additionally, if communicating with another TCAS II equipped aircraft, the two systems coordinate the resolution alerts provided to their respective flight crews. *[Figure 3-58]*

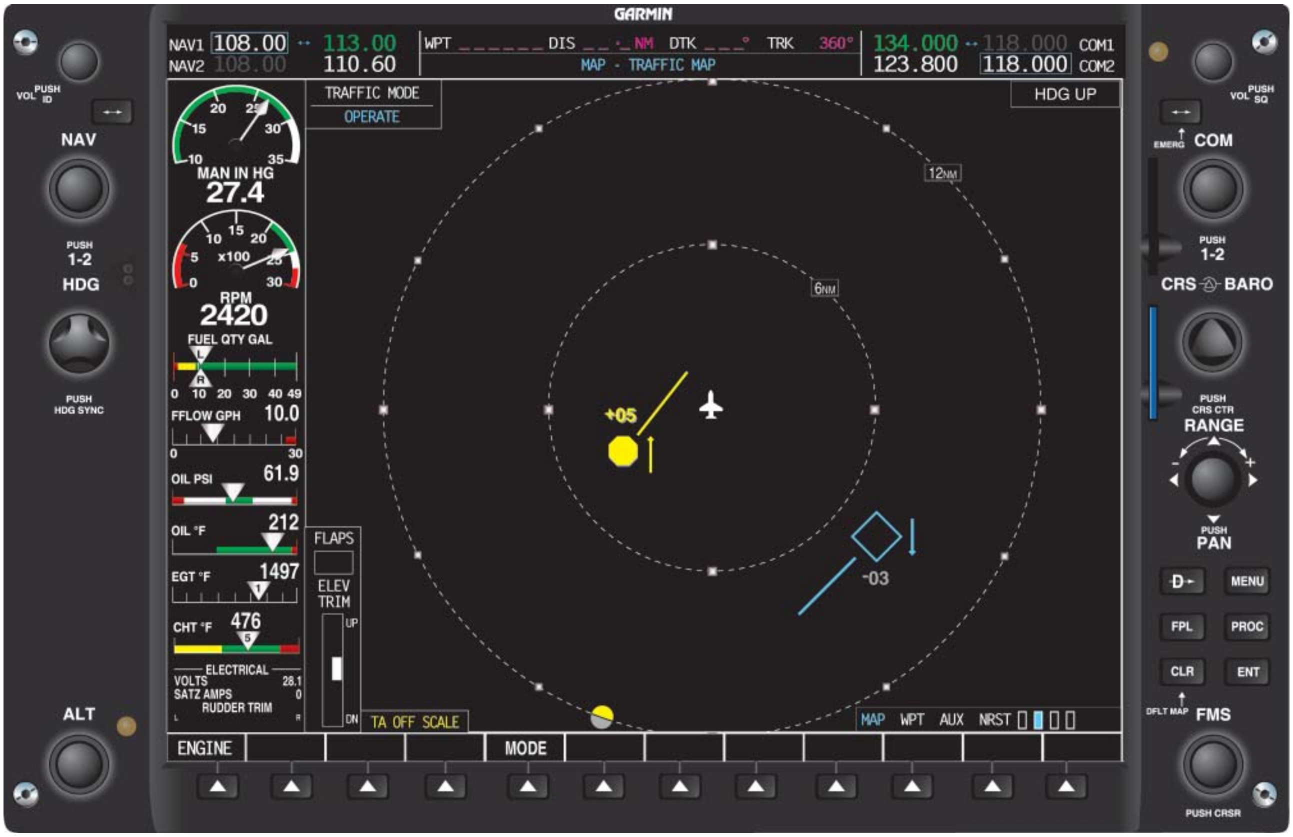


Figure 3-53. *Multi-Function Display (MFD).*

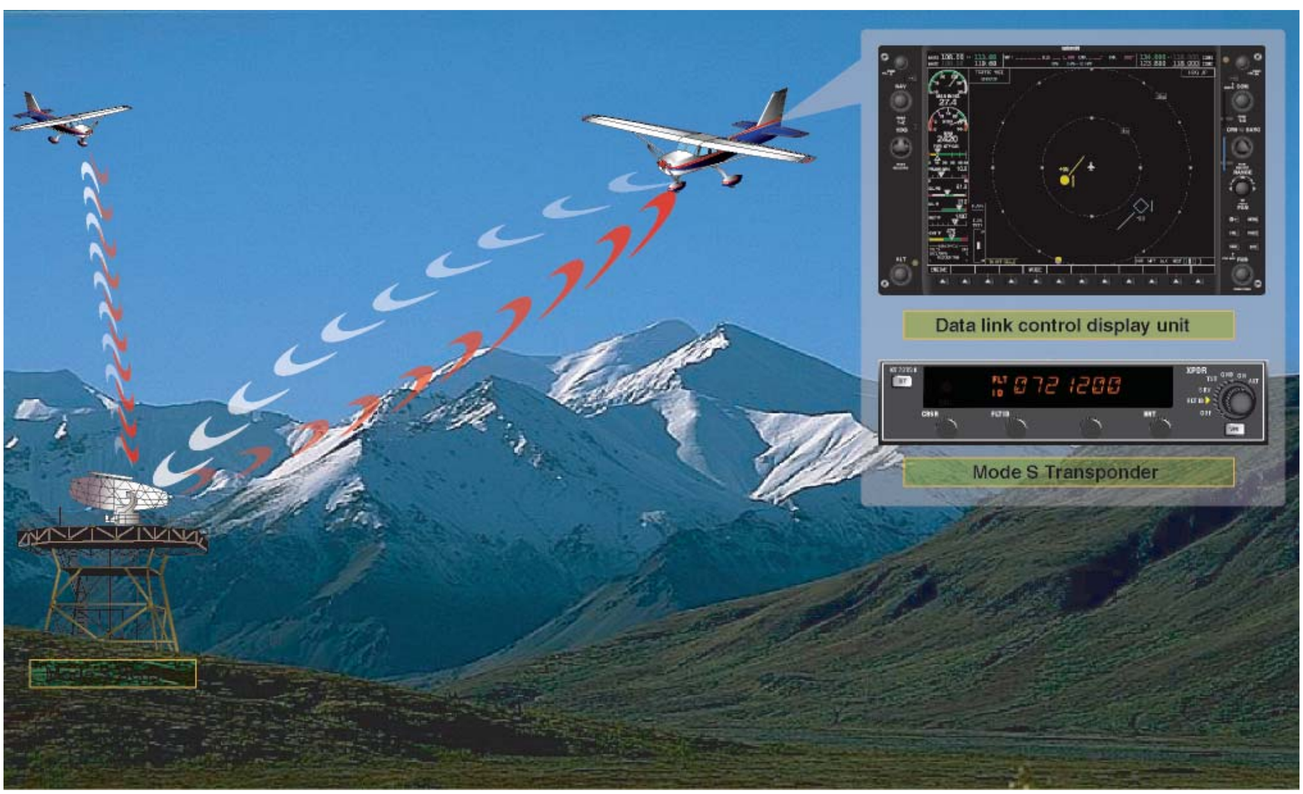


Figure 3-54. *Concept of the Traffic Information System.*

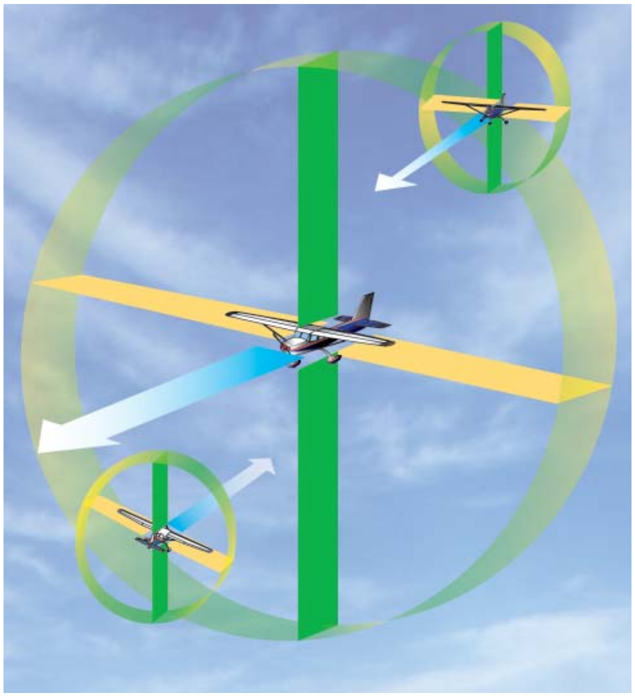


Figure 3-55. *Theory of a Typical Alert System.*

Figure 3-56. *A Skywatch System.*

Figure 3-57. *Alert System by Avidyne (Ryan).*

Figure 3-58. *An example of a resolution advisory being provided the pilot. In this case, the pilot is requested to climb, with 1,200 feet being the appropriate rate of ascent to avoid traffic conflict. This visual indication plus the aural warning provide the pilot with excellent traffic awareness that augments see and avoid practices.*

Terrain Alerting Systems

Ground Proximity Warning System (GPWS)

An early application of technology to reduce CFIT was the GPWS. In airline use since the early 1970s, GPWS uses the radio altimeter, speed, and barometric altitude to determine the aircraft's position relative to the ground. The system uses this information in determining aircraft clearance above the Earth and provides limited predictability about aircraft position relative to rising terrain. It does this based upon algorithms within the system and developed by the manufacturer for different airplanes or helicopters. However, in mountainous areas the system is unable to provide predictive information due to the unusual slope encountered.

This inability to provide predictive information was evidenced in 1999 when a DH-7 crashed in South America. The crew had a GPWS onboard, but the sudden rise of the terrain rendered it ineffective; the crew continued unintentionally into a mountain with steep terrain. Another incident involved Secretary of Commerce Brown who, along with all on board, was lost when the crew flew over rapidly rising terrain where the GPWS capability is offset by terrain gradient. However, the GPWS is tied into and considers landing gear status, flap position, and ILS glide slope deviation to detect unsafe aircraft operation with respect to terrain, excessive descent rate, excessive closure rate to terrain, unsafe terrain clearance while not in a landing configuration, excessive deviation below an ILS glide slope. It also provides advisory callouts.

Generally, the GPWS is tied into the hot bus bar of the electrical system to prevent inadvertent switch off. This was demonstrated in an accident involving a large four-engine turboprop airplane. While on final for landing with the landing gear inadvertently up, the crew failed to heed the GPWS warning as the aircraft crossed a large berm close to the threshold. In fact, the crew attempted without success to shut the system down and attributed the signal to a malfunction. Only after the mishap did the crew realize the importance of the GPWS warning.

Terrain Awareness and Warning System (TAWS)

A TAWS uses GPS positioning and a database of terrain and obstructions to provide true predictability of the upcoming terrain and obstacles. The warnings it provides pilots are both aural and visual, instructing the pilot to take specific action. Because TAWS relies on GPS and a database of terrain/obstacle information, predictability is based upon aircraft location and projected location. The system is time based and therefore compensates for the performance of the aircraft and its speed. *[Figure 3-59]*

Head-Up Display (HUD)

The HUD is a display system that provides a projection of navigation and air data (airspeed in relation to approach reference speed, altitude, left/right and up/down glide slope) on a transparent screen between the pilot and the windshield. The concept of a HUD is to diminish the shift between looking at the instrument panel and outside. Virtually any information desired can be displayed on the HUD if it is available in the aircraft's flight computer. The display for the HUD can be projected on a separate panel near the windscreen or as shown in *Figure 3-60* on an eye piece. Other information may be displayed, including a runway target in relation to the nose of the aircraft, which allows the pilot to see the information necessary to make the approach while also being able to see out the windshield.

Required Navigation Instrument System Inspection

Systems Preflight Procedures

Inspecting the instrument system requires a relatively small part of the total time required for preflight activities, but its importance cannot be overemphasized. Before any flight involving aircraft control by instrument reference, the pilot should check all instruments and their sources of power for proper operation. NOTE: The following procedures are appropriate for conventional aircraft instrument systems. Aircraft equipped with electronic instrument systems utilize different procedures.

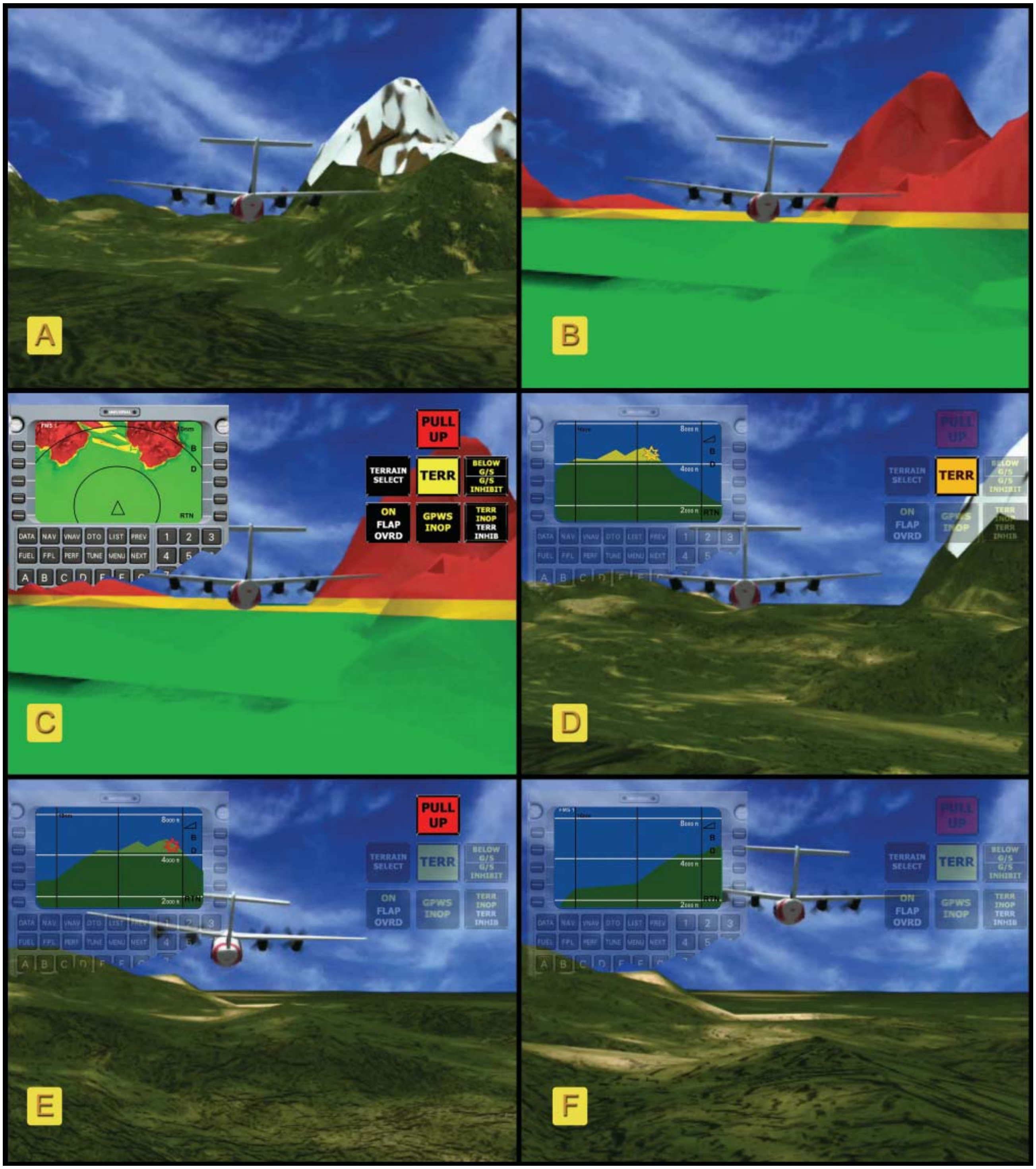


Figure 3-59. *A six-frame sequence illustrating the manner in which TAWS operates. A TAWS installation is aircraft specific and provides warnings and cautions based upon time to potential impact with terrain rather than distance. The TAWS is illustrated in an upper left window while aircrew view is provided out of the windscreen.* A *illustrates the aircraft in relation to the outside terrain while* B *and* C *illustrate the manner in which the TAWS system displays the terrain.* D *is providing a caution of terrain to be traversed, while* E *provides an illustration of a warning with an aural and textural advisory (red) to pull up.* E *also illustrates a pilot taking appropriate action (climb in this case) while* F *illustrates that a hazard is no longer a factor.*

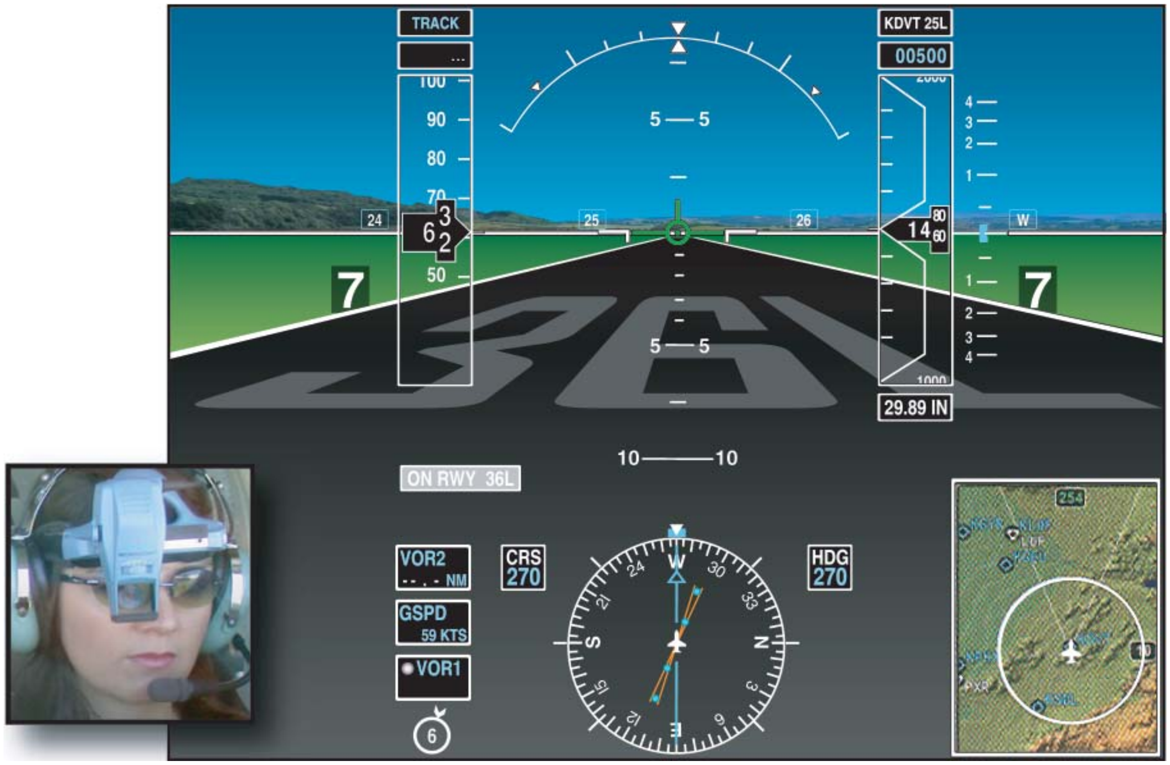


Figure 3-60. *A Head-Up Display.*

Before Engine Start

1. Walk-around inspection: Check the condition of all antennas and check the pitot tube for the presence of any obstructions and remove the cover. Check the static ports to be sure they are free from dirt and obstructions, and ensure there is nothing on the structure near the ports that would disturb the air flowing over them.
2. Aircraft records: Confirm that the altimeter and static system have been checked and found within approved limits within the past 24 calendar months. Check the replacement date for the emergency locator transmitter (ELT) batteries noted in the maintenance record, and be sure they have been replaced within this time interval.
3. Preflight paperwork: Check the Airport/Facility Directory (A/FD) and all Notices to Airmen (NOTAMs) for the condition and frequencies of all the navigation aid (NAVAIDs) that are used on the flight. Handbooks, en route charts, approach charts, computer and flight log should be appropriate for the departure, en route, destination, and alternate airports.
4. Radio equipment: Switches off.
5. Suction gauge: Proper markings as applicable if electronic flight instrumentation is installed.
6. ASI: Proper reading, as applicable. If electronic flight instrumentation is installed, check emergency instrument.
7. Attitude indicator: Uncaged, if applicable. If electronic flight instrumentation is installed, check emergency system to include its battery as appropriate.
8. Altimeter: Set the current altimeter setting and ensure that the pointers indicate the elevation of the airport.
9. VSI: Zero indication, as applicable (if electronic flight instrumentation is installed).
10. Heading indicator: Uncaged, if applicable.
11. Turn coordinator: If applicable, miniature aircraft level, ball approximately centered (level terrain).
12. Magnetic compass: Full of fluid and the correction card is in place and current.
13. Clock: Set to the correct time and running.
14. Engine instruments: Proper markings and readings, as applicable if electronic flight instrumentation is installed.
15. Deicing and anti-icing equipment: Check availability and fluid quantity.
16. Alternate static-source valve: Be sure it can be opened if needed, and that it is fully closed.

17. Pitot tube heater: Check by watching the ammeter when it is turned on, or by using the method specified in the POH/AFM.

After Engine Start

1. When the master switch is turned on, listen to the gyros as they spin up. Any hesitation or unusual noises should be investigated before flight.
2. Suction gauge or electrical indicators: Check the source of power for the gyro instruments. The suction developed should be appropriate for the instruments in that particular aircraft. If the gyros are electrically driven, check the generators and inverters for proper operation.
3. Magnetic compass: Check the card for freedom of movement and confirm the bowl is full of fluid. Determine compass accuracy by comparing the indicated heading against a known heading (runway heading) while the airplane is stopped or taxiing straight. Remote indicating compasses should also be checked against known headings. Note the compass card correction for the takeoff runway heading.
4. Heading indicator: Allow 5 minutes after starting engines for the gyro to spin up. Before taxiing, or while taxiing straight, set the heading indicator to correspond with the magnetic compass heading. A slaved gyrocompass should be checked for slaving action and its indications compared with those of the magnetic compass. If an electronic flight instrument system is installed, consult the flight manual for proper procedures.
5. Attitude indicator: Allow the same time as noted above for gyros to spin up. If the horizon bar erects to the horizontal position and remains at the correct position for the attitude of the airplane, or if it begins to vibrate after this attitude is reached and then slowly stops vibrating altogether, the instrument is operating properly. If an electronic flight instrument system is installed, consult the flight manual for proper procedures.
6. Altimeter: With the altimeter set to the current reported altimeter setting, note any variation between the known field elevation and the altimeter indication. If the indication is not within 75 feet of field elevation, the accuracy of the altimeter is questionable and the problem should be referred to a repair station for evaluation and possible correction. Because the elevation of the ramp or hangar area might differ significantly from field elevation, recheck when in the run-up area if the error exceeds 75 feet. When no altimeter setting is available, set the altimeter to the published field elevation during the preflight instrument check.
7. VSI: The instrument should read zero. If it does not, tap the panel gently. If an electronic flight instrument system is installed, consult the flight manual for proper procedures.
8. Engine instruments: Check for proper readings.
9. Radio equipment: Check for proper operation and set as desired.
10. Deicing and anti-icing equipment: Check operation.

Taxiing and Takeoff

1. Turn coordinator: During taxi turns, check the miniature aircraft for proper turn indications. The ball or slip/skid should move freely. The ball or slip/skid indicator should move opposite to the direction of turns. The turn instrument should indicate the direction of the turn. While taxiing straight, the miniature aircraft (as appropriate) should be level.
2. Heading indicator: Before takeoff, recheck the heading indicator. If the magnetic compass and deviation card are accurate, the heading indicator should show the known taxiway or runway direction when the airplane is aligned with them (within 5°).
3. Attitude indicator: If the horizon bar fails to remain in the horizontal position during straight taxiing, or tips in excess of 5° during taxi turns, the instrument is unreliable. Adjust the miniature aircraft with reference to the horizon bar for the particular airplane while on the ground. For some tricycle-gear airplanes, a slightly nose-low attitude on the ground gives a level flight attitude at normal cruising speed.

Engine Shut Down

When shutting down the engine, note any abnormal instrument indications.

Chapter 4, Section I

Airplane Attitude Instrument Flying

Using Analog Instrumentation

Introduction

Attitude instrument flying is defined as the control of an aircraft's spatial position by using instruments rather than outside visual references. Today's aircraft come equipped with analog and/or digital instruments. Analog instrument systems are mechanical and operate with numbers representing directly measurable quantities, such as a watch with a sweep second hand. In contrast, digital instrument systems are electronic and operate with numbers expressed in digits. Although more manufacturers are providing aircraft with digital instrumentation, analog instruments remain more prevalent. This section acquaints the pilot with the use of analog flight instruments.

Any flight, regardless of the aircraft used or route flown, consists of basic maneuvers. In visual flight, aircraft attitude is controlled by using certain reference points on the aircraft with relation to the natural horizon. In instrument flight, the aircraft attitude is controlled by reference to the flight instruments. Proper interpretation of the flight instruments provides essentially the same information that outside references do in visual flight. Once the role of each instrument in establishing and maintaining a desired aircraft attitude is learned, a pilot is better equipped to control the aircraft in emergency situations involving failure of one or more key instruments.

Learning Methods

The two basic methods used for learning attitude instrument flying are "control and performance" and "primary and supporting." Both methods utilize the same instruments and responses for attitude control. They differ in their reliance on the attitude indicator and interpretation of other instruments.

Attitude Instrument Flying Using the Control and Performance Method

Aircraft performance is achieved by controlling the aircraft attitude and power. Aircraft attitude is the relationship of both the aircraft's pitch and roll axes in relation to the Earth's horizon. An aircraft is flown in instrument flight by controlling the attitude and power, as necessary, to produce both controlled and stabilized flight without reference to a visible horizon. This overall process is known as the control and performance method of attitude instrument flying. Starting with basic instrument maneuvers, this process can be applied through the use of control, performance, and navigation instruments, resulting in a smooth flight, from takeoff to landing.

Control Instruments

The control instruments display immediate attitude and power indications and are calibrated to permit those respective adjustments in precise increments. In this discussion, the term "power" is used in place of the more technically correct term "thrust or drag relationship." Control is determined by reference to the attitude and power indicators. Power indicators vary with aircraft and may include manifold pressure, tachometers, fuel flow, etc. *[Figure 4-1]*

Performance Instruments

The performance instruments indicate the aircraft's actual performance. Performance is determined by reference to the altimeter, airspeed or vertical speed indicator (VSI), heading indicator, and turn-and-slip indicator. *[Figure 4-2]*

Navigation Instruments

The navigation instruments indicate the position of the aircraft in relation to a selected navigation facility or fix. This group of instruments includes various types of course indicators, range indicators, glide-slope indicators, and bearing pointers. *[Figure 4-3]* Newer aircraft with more technologically advanced instrumentation provide blended information, giving the pilot more accurate positional information.

Procedural Steps in Using Control and Performance

1. Establish an attitude and power setting on the control instruments that results in the desired performance. Known or computed attitude changes and approximated power settings helps to reduce the pilot's workload.
2. Trim (fine tune the control forces) until control pressures are neutralized. Trimming for hands-off flight is essential for smooth, precise aircraft control.

Figure 4-1. *Control Instruments.*

It allows a pilot to attend to other flight deck duties with minimum deviation from the desired attitude.

3. Cross-check the performance instruments to determine if the established attitude or power setting is providing the desired performance. The cross-check involves both seeing and interpreting. If a deviation is noted, determine the magnitude and direction of adjustment required to achieve the desired performance.

4. Adjust the attitude and/or power setting on the control instruments as necessary.

Aircraft Control During Instrument Flight

Attitude Control

Proper control of aircraft attitude is the result of proper use of the attitude indicator, knowledge of when to change the

Figure 4-2. *Performance Instruments.*

Figure 4-3. *Flight Panel Instrumentation.*

attitude, and then smoothly changing the attitude a precise amount. The attitude reference provides an immediate, direct, and corresponding indication of any change in aircraft pitch or bank attitude.

Pitch Control

Changing the "pitch attitude" of the miniature aircraft or fuselage dot by precise amounts in relation to the horizon makes pitch changes. These changes are measured in degrees or fractions thereof, or bar widths depending upon the type of attitude reference. The amount of deviation from the desired performance determines the magnitude of the correction.

Bank Control

Bank changes are made by changing the "bank attitude" or bank pointers by precise amounts in relation to the bank scale. The bank scale is normally graduated at 0°, 10°, 20°, 30°, 60°, and 90° and is located at the top or bottom of the attitude reference. Normally, use a bank angle that approximates the degrees to turn, not to exceed 30°.

Power Control

Proper power control results from the ability to smoothly establish or maintain desired airspeeds in coordination with attitude changes. Power changes are made by throttle adjustments and reference to the power indicators. Power indicators are not affected by such factors as turbulence, improper trim, or inadvertent control pressures. Therefore, in most aircraft little attention is required to ensure the power setting remains constant.

Experience in an aircraft teaches a pilot approximately how far to move the throttle to change the power a given amount. Power changes are made primarily by throttle movement, followed by an indicator cross-check to establish a more precise setting. The key is to avoid fixating on the indicators while setting the power. Knowledge of approximate power settings for various flight configurations helps the pilot avoid overcontrolling power.

Attitude Instrument Flying Using the Primary and Supporting Method

Another basic method for teaching attitude instrument flying classifies the instruments as they relate to control function as well as aircraft performance. All maneuvers involve some degree of motion about the lateral (pitch), longitudinal (bank/roll), and vertical (yaw) axes. Attitude control is stressed in this handbook in terms of pitch control, bank control, power control, and trim control. Instruments are grouped as they relate to control function and aircraft performance as pitch control, bank control, power control, and trim.

Pitch Control

Pitch control is controlling the rotation of the aircraft about the lateral axis by movement of the elevators. After interpreting the pitch attitude from the proper flight instruments, exert control pressures to effect the desired pitch attitude with reference to the horizon. These instruments include the attitude indicator, altimeter, VSI, and airspeed indicator. *[Figure 4-4]* The attitude indicator displays a direct indication of the aircraft's pitch attitude while the other pitch attitude control instruments indirectly indicate the pitch attitude of the aircraft.

Attitude Indicator

The pitch attitude control of an aircraft controls the angular relationship between the longitudinal axis of the aircraft and the actual horizon. The attitude indicator gives a direct and immediate indication of the pitch attitude of the aircraft. The aircraft controls are used to position the miniature aircraft in relation to the horizon bar or horizon line for any pitch attitude required. *[Figure 4-5]*

Figure 4-4. *Pitch Instruments.*

Figure 4-5. *Attitude Indicator.*

The miniature aircraft should be placed in the proper position in relation to the horizon bar or horizon line before takeoff. The aircraft operator's manual explains this position. As soon as practicable in level flight and at desired cruise airspeed, the miniature aircraft should be moved to a position that aligns its wings in front of the horizon bar or horizon line. This adjustment can be made anytime varying loads or other conditions indicate a need. Otherwise, the position of the miniature aircraft should not be changed for flight at other than cruise speed. This is to make sure that the attitude indicator displays a true picture of pitch attitude in all maneuvers.

When using the attitude indicator in applying pitch attitude corrections, control pressure should be extremely light. Movement of the horizon bar above or below the miniature aircraft of the attitude indicator in an airplane should not exceed one-half the bar width. *[Figure 4-6]* If further change is required, an additional correction of not more than one-half horizon bar wide normally counteracts any deviation from normal flight.

Figure 4-6. *Pitch Correction Using the Attitude Indicator.*

Altimeter

If the aircraft is maintaining level flight, the altimeter needles maintain a constant indication of altitude. If the altimeter indicates a loss of altitude, the pitch attitude must be adjusted upward to stop the descent. If the altimeter indicates a gain in altitude, the pitch attitude must be adjusted downward to stop the climb. *[Figure 4-7]* The altimeter can also indicate the pitch attitude in a climb or descent by how rapidly the needles move. A minor adjustment in pitch attitude may be made to control the rate at which altitude is gained or lost. Pitch attitude is used only to correct small altitude changes caused by external forces, such as turbulence or up and down drafts.

Figure 4-7. *Pitch Correction Using the Altimeter.*

Vertical Speed Indicator (VSI)

In flight at a constant altitude, the VSI (sometimes referred to as vertical velocity indicator or rate-of-climb indicator) remains at zero. If the needle moves above zero, the pitch attitude must be adjusted downward to stop the climb and return to level flight. Prompt adjustments to the changes in the indications of the VSI can prevent any significant change in altitude. *[Figure 4-8]* Turbulent air causes the needle to fluctuate near zero. In such conditions, the average of the fluctuations should be considered as the correct reading. Reference to the altimeter helps in turbulent air because it is not as sensitive as the VSI.

Vertical speed is represented in feet per minute (fpm). *[Figure 4-8]* The face of the instrument is graduated with numbers such as 1, 2, 3, etc. These represent thousands of feet up or down in a minute. For instance, if the pointer is aligned with .5 (1/2 of a thousand, or 500 fpm) the aircraft will climb 500 feet in one minute. The instrument is divided into two regions, one for climbing (up) and one for descending (down).

Figure 4-8. *Vertical Speed Indicator.*

During turbulence, it is not uncommon to see large fluctuations on the VSI. It is important to remember that small corrections should be employed to avoid further exacerbating a potentially divergent situation.

Overcorrecting causes the aircraft to overshoot the desired altitude; however, corrections should not be so small that the return to altitude is unnecessarily prolonged. As a guide, the pitch attitude should produce a rate of change on the VSI about twice the size of the altitude deviation. For example, if the aircraft is 100 feet off the desired altitude, a 200 fpm rate of correction would be used.

During climbs or descents, the VSI is used to change the altitude at a desired rate. Pitch attitude and power adjustments are made to maintain the desired rate of climb or descent on the VSI.

When pressure is applied to the controls and the VSI shows an excess of 200 fpm from that desired, overcontrolling is indicated. For example, if attempting to regain lost altitude at the rate of 500 fpm, a reading of more than 700 fpm would indicate overcontrolling. Initial movement of the needle indicates the trend of vertical movement. The time for the VSI to reach its maximum point of deflection after a correction is called lag. The lag is proportional to speed and magnitude of pitch change. In an airplane, overcontrolling may be reduced by relaxing pressure on the controls, allowing the pitch attitude to neutralize. In some helicopters with servo-assisted controls, no control pressures are apparent. In this case, overcontrolling can be reduced by reference to the attitude indicator.

Some aircraft are equipped with an instantaneous vertical speed indicator (IVSI). The letters "IVSI" appear on the face of the indicator. This instrument assists in interpretation by instantaneously indicating the rate of climb or descent at a given moment with little or no lag as displayed in a VSI.

Occasionally, the VSI is slightly out of calibration and indicates a gradual climb or descent when the aircraft is in level flight. If readjustments cannot be accomplished, the error in the indicator should be considered when the instrument is used for pitch control. For example, an improperly set VSI may indicate a descent of 100 fpm when the aircraft is in level flight. Any deviation from this reading would indicate a change in pitch attitude.

Airspeed Indicator

The airspeed indicator gives an indirect reading of the pitch attitude. With a constant power setting and a constant altitude, the aircraft is in level flight and airspeed remains constant. If the airspeed increases, the pitch attitude has lowered and should be raised. *[Figure 4-9]* If the airspeed decreases, the pitch attitude has moved higher and should be lowered. *[Figure 4-10]* A rapid change in airspeed indicates a large change in pitch; a slow change in airspeed indicates a small change in pitch. Although the airspeed indicator is used as a pitch instrument, it may be used in level fight for power control. Changes in pitch are reflected immediately by a change in airspeed. There is very little lag in the airspeed indicator.

Pitch Attitude Instrument Cross-Check

The altimeter is an important instrument for indicating pitch attitude in level flight except when used in conditions of exceptionally strong vertical currents, such as thunderstorms. With proper power settings, any of the pitch attitude instruments can be used to hold reasonably level flight attitude. However, only the altimeter gives the exact altitude information. Regardless of which pitch attitude control instrument indicates a need for a pitch attitude adjustment, the attitude indicator, if available, should be used to make the

Figure 4-9. *Pitch attitude has lowered.*

Figure 4-10. *Pitch attitude has moved higher.*

adjustment. Common errors in pitch attitude control are:

- Overcontrolling,
- Improperly using power, and
- Failing to adequately cross-check the pitch attitude instruments and take corrective action when pitch attitude change is needed

Bank Control

Bank control is controlling the angle made by the wing and the horizon. After interpreting the bank attitude from the appropriate instruments, exert the necessary pressures to move the ailerons and roll the aircraft about the longitudinal axis. As illustrated in *Figure 4-11*, these instruments include:

Attitude Indicator

As previously discussed, the attitude indicator is the only instrument that portrays both instantly and directly the actual flight attitude and is the basic attitude reference.

Heading Indicator

The heading indicator supplies the pertinent bank and heading information and is considered a primary instrument for bank.

Magnetic Compass

The magnetic compass provides heading information and is considered a bank instrument when used with the heading indicator. Care should be exercised when using the magnetic compass as it is affected by acceleration, deceleration in flight caused by turbulence, climbing, descending, power changes, and airspeed adjustments. Additionally, the magnetic compass indication will lead and lag in its reading depending upon the direction of turn. As a result, acceptance of its indication should be considered with other instruments that indicate turn information. These include the already mentioned attitude and heading indicators as well as the turn-and-slip indicator and turn coordinator.

Figure 4-11. *Bank Instruments.*

Turn Coordinator/Turn-and-Slip Indicator

Both of these instruments provide turn information. *[Figure 4-12]* The turn coordinator provides both bank rate and then turn rate once stabilized. The turn-and-slip indicator provides only turn rate.

Figure 4-12. *Turn Coordinator and Turn-and-Slip Indicator.*

Power Control

A power change to adjust airspeed may cause movement around some or all of the aircraft axes. The amount and direction of movement depends on how much or how rapidly the power is changed, whether single-engine or multiengine airplane or helicopter. The effect on pitch attitude and airspeed caused by power changes during level flight is illustrated in *Figures 4-13* and *4-14*. During or immediately after adjusting the power control(s), the power instruments should be cross-checked to see if the power adjustment is as desired. Whether or not the need for a power adjustment is indicated by another instrument(s), adjustment is made by cross-checking the power instruments. Aircraft are powered by a variety of power plants, each power plant having certain instruments that indicate the amount of power being applied to operate the aircraft. During instrument flight, these instruments must be used to make the required power adjustments.

As illustrated in *Figure 4-15,* power indicator instruments include:

Airspeed Indicator

The airspeed indicator provides an indication of power best observed initially in level flight where the aircraft is in balance and trim. If in level flight the airspeed is increasing, it can generally be assumed that the power has increased, necessitating the need to adjust power or re-trim the aircraft.

Engine Instruments

Engine instruments, such as the manifold pressure (MP) indicator, provide an indication of aircraft performance for a given setting under stable conditions. If the power conditions are changed, as reflected in the respective engine instrument readings, there is an affect upon the aircraft performance, either an increase or decrease of airspeed. When the propeller rotational speed (revolutions per minute (RPM) as viewed on a tachometer) is increased or decreased on fixed-pitch propellers, the performance of the aircraft reflects a gain or loss of airspeed as well.

Trim Control

Proper trim technique is essential for smooth and accurate instrument flying and utilizes instrumentation illustrated in *Figure 4-16.* The aircraft should be properly trimmed while executing a maneuver. The degree of flying skill, which ultimately develops, depends largely upon how well the aviator learns to keep the aircraft trimmed.

Airplane Trim

An airplane is correctly trimmed when it is maintaining a desired attitude with all control pressures neutralized. By relieving all control pressures, it is much easier to maintain the aircraft at a certain attitude. This allows more time to devote to the navigation instruments and additional flight deck duties.

Figure 4-13. *An Increase in Power Inscreasing Airpseed Accordingly in Level Flight.*

Figure 4-14. *Pitch Control and Power Adjustment Required To Bring Aircraft to Level Flight.*

Figure 4-15. *Power Instruments.*

Figure 4-16. *Trim Instruments.*

An aircraft is placed in trim by:

- Applying control pressure(s) to establish a desired attitude. Then, the trim is adjusted so that the aircraft maintains that attitude when flight controls are released. The aircraft is trimmed for coordinated flight by centering the ball of the turn-and-slip indicator.
- Moving the rudder trim in the direction where the ball is displaced from center. Aileron trim may then be adjusted to maintain a wings-level attitude.
- Using balanced power or thrust when possible to aid in maintaining coordinated flight. Changes in attitude, power, or configuration may require trim adjustments. Use of trim alone to establish a change in aircraft attitude usually results in erratic aircraft control. Smooth and precise attitude changes are best attained by a combination of control pressures and subsequent trim adjustments. The trim controls are aids to smooth aircraft control.

Helicopter Trim

A helicopter is placed in trim by continually cross-checking the instruments and performing the following:

- Using the cyclic centering button. If the helicopter is so equipped, this relieves all possible cyclic pressures.
- Using the pedal adjustment to center the ball of the turn indicator. Pedal trim is required during all power changes and is used to relieve all control pressures held after a desired attitude has been attained.

An improperly trimmed helicopter requires constant control pressures, produces tension, distracts attention from cross-checking, and contributes to abrupt and erratic attitude control. The pressures felt on the controls should be only those applied while controlling the helicopter.

Adjust the pitch attitude, as airspeed changes, to maintain desired attitude for the maneuver being executed. The bank must be adjusted to maintain a desired rate of turn, and the pedals must be used to maintain coordinated flight. Trim must be adjusted as control pressures indicate a change is needed.

Example of Primary and Support Instruments

Straight-and-level flight at a constant airspeed means that an exact altitude is to be maintained with zero bank (constant heading). The primary pitch, bank, and power instruments used to maintain this flight condition are:

- Altimeter—supplies the most pertinent altitude information and is primary for pitch.
- Heading Indicator—supplies the most pertinent bank or heading information and is primary for bank.
- Airspeed Indicator—supplies the most pertinent information concerning performance in level flight in terms of power output and is primary for power.

Although the attitude indicator is the basic attitude reference, the concept of primary and supporting instruments does not devalue any particular flight instrument, when available, in establishing and maintaining pitch-and-bank attitudes. It is the only instrument that instantly and directly portrays the actual flight attitude. It should always be used, when available, in establishing and maintaining pitch-and-bank attitudes. The specific use of primary and supporting instruments during basic instrument maneuvers is presented in more detail in Chapter 5, Airplane Basic Flight Maneuvers.

Fundamental Skills

During attitude instrument training, two fundamental flight skills must be developed. They are instrument cross-check and instrument interpretation, both resulting in positive aircraft control. Although these skills are learned separately and in deliberate sequence, a measure of proficiency in precision flying is the ability to integrate these skills into unified, smooth, positive control responses to maintain any prescribed flight path.

Instrument Cross-Check

The first fundamental skill is cross-checking (also called "scanning" or "instrument coverage"). Cross-checking is the continuous and logical observation of instruments for attitude and performance information. In attitude instrument flying, the pilot maintains an attitude by reference to instruments, producing the desired result in performance. Observing and interpreting two or more instruments to determine attitude and performance of an aircraft is called cross-checking. Although no specific method of cross-checking is recommended, those instruments that give the best information for controlling the aircraft in any given maneuver should be used. The important instruments are the ones that give the most pertinent information for any particular phase of the maneuver. These are usually the instruments that should be held at a constant indication. The remaining instruments should help maintain the important instruments at the desired indications, which is also true in using the emergency panel.

Cross-checking is mandatory in instrument flying. In visual flight, a level attitude can be maintained by outside references. However, even then the altimeter must be checked to determine if altitude is being maintained. Due to human error, instrument error, and airplane performance differences in various atmospheric and loading conditions, it is impossible to establish an attitude and have performance remain constant for a long period of time. These variables make it necessary for the pilot to constantly check the instruments and make appropriate changes in airplane attitude using cross-checking of instruments. Examples of cross-checking are explained in the following paragraphs.

Selected Radial Cross-Check

When the selected radial cross-check is used, a pilot spends 80 to 90 percent of flight time looking at the attitude indicator, taking only quick glances at the other flight instruments (for this discussion, the five instruments surrounding the attitude indicator are called the flight instruments). With this method, the pilot's eyes never travel directly between the flight instruments but move by way of the attitude indicator. The maneuver being performed determines which instruments to look at in the pattern. *[Figure 4-17]*

Inverted-V Cross-Check

In the inverted-V cross-check, the pilot scans from the attitude indicator down to the turn coordinator, up to the attitude indicator, down to the VSI, and back up to the attitude indicator. *[Figure 4-18]*

Rectangular Cross-Check

In the rectangular cross-check, the pilot scans across the top three instruments (airspeed indicator, attitude indicator, and altimeter) and then drops down to scan the bottom three instruments (VSI, heading indicator, and turn instrument). This scan follows a rectangular path (clockwise or counterclockwise rotation is a personal choice). *[Figure 4-19]*

This cross-checking method gives equal weight to the information from each instrument, regardless of its importance to the maneuver being performed. However, this method lengthens the time it takes to return to an instrument critical to the successful completion of the maneuver.

Common Cross-Check Errors

A beginner might cross-check rapidly, looking at the instruments without knowing exactly what to look for. With increasing experience in basic instrument maneuvers and familiarity with the instrument indications associated with them, a pilot learns what to look for, when to look for it, and what response to make. As proficiency increases, a pilot cross-checks primarily from habit, suiting scanning rate and sequence to the demands of the flight situation. Failure to maintain basic instrument proficiency through practice can result in many of the following common scanning errors, both during training and at any subsequent time.

Fixation, or staring at a single instrument, usually occurs for a reason, but has poor results. For example, a pilot may stare at the altimeter reading 200 feet below the assigned altitude, and wonder how the needle got there. While fixated on the

Figure 4-17. *Radial Cross-Check.*

Figure 4-18. *Inverted-V Cross-Check.*

Figure 4-19. *Rectangular Cross-Check.*

instrument, increasing tension may be unconsciously exerted on the controls, which leads to an unnoticed heading change that leads to more errors. Another common fixation is likely when initiating an attitude change. For example, a shallow bank is established for a 90° turn and, instead of maintaining a cross-check of other pertinent instruments, the pilot stares at the heading indicator throughout the turn. Since the aircraft is turning, there is no need to recheck the heading indicator for approximately 25 seconds after turn entry. The problem here may not be entirely due to cross-check error. It may be related to difficulties with instrument interpretation. Uncertainty about reading the heading indicator (interpretation) or uncertainty because of inconsistency in rolling out of turns (control) may cause the fixation.

Omission of an instrument from a cross-check is another likely fault. It may be caused by failure to anticipate significant instrument indications following attitude changes. For example, in a roll-out from a 180° steep turn, straight-and-level flight is established with reference only to the attitude indicator, and the pilot neglects to check the heading indicator for constant heading information. Because of precession error, the attitude indicator temporarily shows a slight error, correctable by quick reference to the other flight instruments.

Emphasis on a single instrument, instead of on the combination of instruments necessary for attitude information, is an understandable fault during the initial stages of training. It is a natural tendency to rely on the instrument that is most readily understood, even when it provides erroneous or inadequate information. Reliance on a single instrument is poor technique. For example, a pilot can maintain reasonably close altitude control with the attitude indicator, but cannot hold altitude with precision without including the altimeter in the cross-check.

Instrument Interpretation

The second fundamental skill, instrument interpretation, requires more thorough study and analysis. It begins by understanding each instrument's construction and operating principles. Then, this knowledge must be applied to the performance of the aircraft being flown, the particular maneuvers to be executed, the cross-check and control techniques applicable to that aircraft, and the flight conditions.

For example, a pilot uses full power in a small airplane for a 5-minute climb from near sea level, and the attitude indicator shows the miniature aircraft two bar widths (twice the thickness of the miniature aircraft wings) above the artificial horizon. *[Figure 4-20]* The airplane is climbing at 500 fpm as shown on the VSI, and at airspeed of 90 knots, as shown on the airspeed indicator. With the power available in this particular airplane and the attitude selected by the pilot, the performance is shown on the instruments. Now, set up the identical picture on the attitude indicator in a jet airplane. With the same airplane attitude as shown in the first example, the VSI in the jet reads 2,000 fpm and the airspeed indicator reads 300 knots.

As the performance capabilities of the aircraft are learned, a pilot interprets the instrument indications appropriately

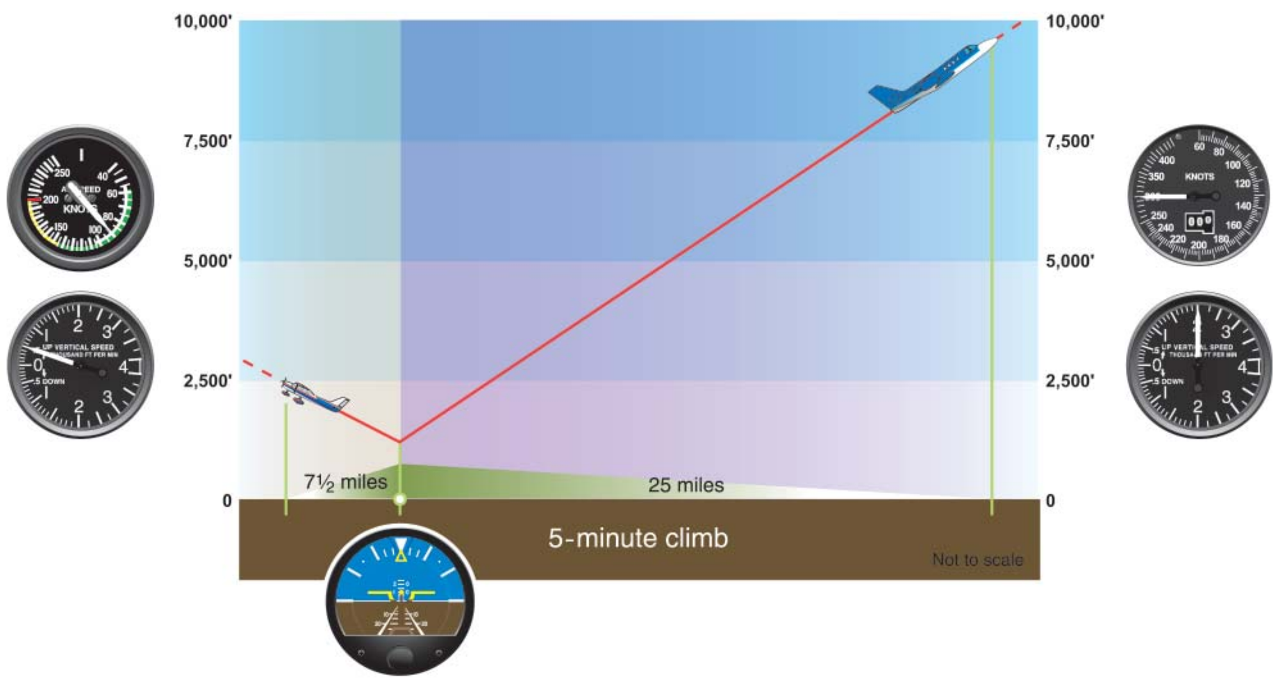


Figure 4-20. *Power and Attitude Equal Performance.*

in terms of the attitude of the aircraft. If the pitch attitude is to be determined, the airspeed indicator, altimeter, VSI, and attitude indicator provide the necessary information. If the bank attitude is to be determined, the heading indicator, turn coordinator, and attitude indicator must be interpreted. For each maneuver, learn what performance to expect and the combination of instruments to be interpreted in order to control aircraft attitude during the maneuver. It is the two fundamental flight skills, instrument cross-check and instrument interpretation, that provide the smooth and seamless control necessary for basic instrument flight as discussed at the beginning of the chapter.

Chapter 4, Section II

Airplane Attitude Instrument Flying

Using an Electronic Flight Display

Introduction

Attitude instrument flying is defined as the control of an aircraft's spatial position by using instruments rather than outside visual references. As noted in Section I, today's aircraft come equipped with analog and/or digital instruments. Section II acquaints the pilot with the use of digital instruments known as an electronic flight display (EFD).

The improvements in avionics coupled with the introduction of EFDs to general aviation aircraft offer today's pilot an unprecedented array of accurate instrumentation to use in the support of instrument flying.

Until recently, most general aviation aircraft were equipped with individual instruments utilized collectively to safely maneuver the aircraft by instrument reference alone. With the release of the electronic flight display system, the conventional instruments have been replaced by multiple liquid crystal display (LCD) screens. The first screen is installed in front of the left seat pilot position and is referred to as the primary flight display (PFD). *[Figure 4-21]* The second screen is positioned in approximately the center of the instrument panel and is referred to as the multi-function display (MFD). *[Figure 4-22]* The pilot can use the MFD to display navigation information (moving maps), aircraft systems information (engine monitoring), or should the need arise, a PFD. *[Figure 4-23]* With just these two screens, aircraft designers have been able to de-clutter instrument panels while increasing safety. This has been accomplished through the utilization of solid-state instruments which have a failure rate far lower than those of conventional analog instrumentation.

However, in the event of electrical failure, the pilot still has emergency instruments as a backup. These instruments either do not require electrical power, or as in the case of many attitude indicators, they are battery equipped. *[Figure 4-24]*

Pilots flying under visual flight rules (VFR) maneuver their aircraft by reference to the natural horizon, utilizing specific reference points on the aircraft. In order to operate the aircraft in other than VFR weather, with no visual reference to the natural horizon, pilots need to develop additional skills. These skills come from the ability to maneuver the aircraft by reference to flight instruments alone. These flight instruments replicate all the same key elements that a VFR pilot utilizes during a normal flight. The natural horizon is replicated on the attitude indicator by the artificial horizon.

Understanding how each flight instrument operates and what role it plays in controlling the attitude of the aircraft is fundamental in learning attitude instrument flying. When the pilot understands how all the instruments are used in establishing and maintaining a desired aircraft attitude, the pilot is better prepared to control the aircraft should one or more key instruments fail or if the pilot should enter instrument flight conditions.

Learning Methods

There are two basic methods utilized for learning attitude instrument flying. They are "control and performance" and "primary and supporting." These methods rely on the same flight instruments and require the pilot to make the same adjustments to the flight and power controls to control aircraft attitude. The main difference between the two methods is the importance that is placed on the attitude indicator and the interpretation of the other flight instruments.

Figure 4-21. *Primary Flight Display (PFD) and Analog Counterparts.*

Figure 4-22. *Multifunction Display (MFD).*

Figure 4-23. *Reversionary Displays.*

Figure 4-24. *Emergency Back-up of the Airspeed Indicator, Attitude Indicator, and Altitude Indicator.*

Control and Performance Method

Aircraft performance is accomplished by controlling the aircraft attitude and power output. Aircraft attitude is the relationship of its longitudinal and lateral axes to the Earth's horizon. When flying in instrument flight conditions, the pilot controls the attitude of the aircraft by referencing the flight instruments and manipulating the power output of the engine to achieve the performance desired. This method can be used to achieve a specific performance level enabling a pilot to perform any basic instrument maneuver.

The instrumentation can be broken up into three different categories: control, performance, and navigation.

Control Instruments

The control instruments depict immediate attitude and power changes. The instrument for attitude display is the attitude indicator. Power changes are directly reflected on the manifold pressure gauge and the tachometer. *[Figure 4-25]* All three of these instruments can reflect small adjustments, allowing for precise control of aircraft attitude.

Figure 4-25. *Control Instruments.*

Figure 4-26. *Performance Instruments.*

In addition, the configuration of the power indicators installed in each aircraft may vary to include the following types of power indicators: tachometers, manifold pressure indicator, engine pressure ratio indicator, fuel flow gauges, etc.

The control instruments do not indicate how fast the aircraft is flying or at what altitude it is flying. In order to determine these variables and others, a pilot needs to refer to the performance instruments.

Performance Instruments

The performance instruments directly reflect the performance the aircraft is achieving. The speed of the aircraft can be referenced on the airspeed indicator. The altitude can be referenced on the altimeter. The aircraft's climb performance can be determined by referencing the vertical speed indicator (VSI). *[Figure 4-26]* Other performance instruments available are the heading indicator, angle of attack indicator, and the slip/skid indicator.

The performance instruments will most directly reflect a change in acceleration, which is defined as change in velocity or direction. Therefore, these instruments indicate if the aircraft is changing airspeed, altitude, or heading, which are horizontal, vertical, or lateral vectors.

Navigation Instruments

The navigation instruments are comprised of global positioning system (GPS) displays and indicators, very high frequency omnidirectional range/nondirectional radio beacon (VOR/NDB) indicators, moving map displays, localizer, and glide slope (GS) indicators. *[Figure 4-27]* The instruments indicate the position of the aircraft relative to a selected navigation facility or fix. Navigation instruments allow the pilot to maneuver the aircraft along a predetermined path of ground-based or spaced-based navigation signals without reference to any external visual cues. The navigation instruments can support both lateral and visual inputs.

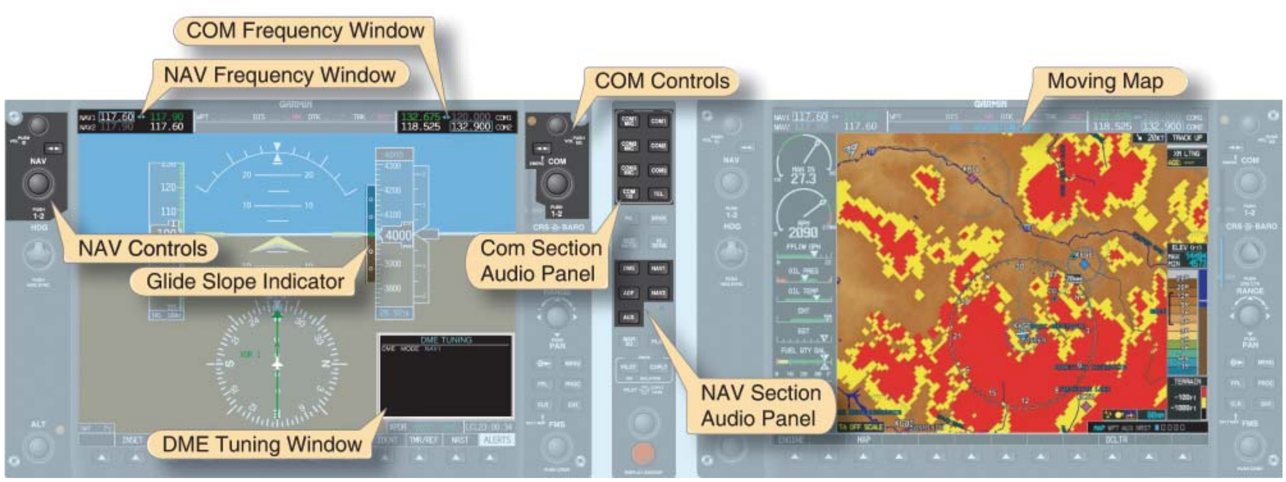


Figure 4-27. *Navigation Instruments.*

The Four-Step Process Used to Change Attitude

In order to change the attitude of the aircraft, the pilot must make the proper changes to the pitch, bank, or power settings of the aircraft. Four steps (establish, trim, cross-check, and adjust) have been developed in order to aid in the process.

Establish

Any time the attitude of the aircraft requires changing, the pilot must adjust the pitch and/or bank in conjunction with power to establish the desired performance. The changes in pitch and bank require the pilot to reference the attitude indicator in order to make precise changes. Power changes should be verified on the tachometer, manifold pressure gauge, etc. To ease the workload, the pilot should become familiar with the approximate pitch and power changes necessary to establish a specified attitude.

Trim

Another important step in attitude instrument flying is trimming the aircraft. Trim is utilized to eliminate the need to apply force to the control yoke in order to maintain the desired attitude. When the aircraft is trimmed appropriately, the pilot is able to relax pressure on the control yoke and momentarily divert attention to another task at hand without deviating from the desired attitude. Trimming the aircraft is very important, and poor trim is one of the most common errors instructors note in instrument students.

Cross-Check

Once the initial attitude changes have been made, the pilot should verify the performance of the aircraft. Cross-checking the control and performance instruments requires the pilot to visually scan the instruments as well as interpret the indications. All the instruments must be utilized collectively in order to develop a full understanding of the aircraft attitude. During the cross-check, the pilot needs to determine the magnitude of any deviations and determine how much of a change is required. All changes are then made based on the control instrument indications.

Adjust

The final step in the process is adjusting for any deviations that have been noted during the cross-check. Adjustments should be made in small increments. The attitude indicator and the power instruments are graduated in small increments to allow for precise changes to be made. The pitch should be made in reference to bar widths on the miniature airplane. The bank angle can be changed in reference to the roll scale and the power can be adjusted in reference to the tachometer, manifold pressure gauge, etc.

By utilizing these four steps, pilots can better manage the attitude of their aircraft. One common error associated with this process is making a larger than necessary change when a deviation is noted. Pilots need to become familiar with the aircraft and learn how great a change in attitude is needed to produce the desired performance.

Applying the Four-Step Process

In attitude instrument flight, the four-step process is used to control pitch attitude, bank attitude, and power application of the aircraft. The EFD displays indications precisely enough that a pilot can apply control more accurately.

Pitch Control

The pitch control is indicated on the attitude indicator which spans the full width of the PFD. Due to the increased size of the display, minute changes in pitch can be made and corrected for. The pitch scale on the attitude indicator is graduated in 5-degree increments which allow the pilot to make correction with precision to approximately 1/2 degree. The miniature airplane utilized to represent the aircraft in conventional attitude indicators is replaced in glass panel displays by a yellow chevron. *[Figure 4-28]* Representing the nose of the aircraft, the point of the chevron affords the pilot a much more precise indication of the degree of pitch and allows the pilot to make small, precise changes should the desired aircraft performance change. When the desired performance is not being achieved, precise pitch changes should be made by referencing the point of the yellow chevron.

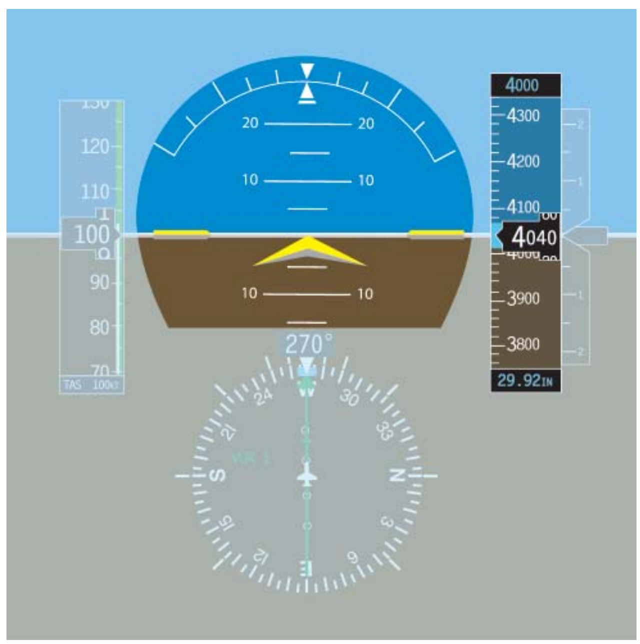


Figure 4-28. *The chevron's relationship to the horizon line indicates the pitch of the aircraft.*

Bank Control

Precise bank control can be developed utilizing the roll pointer in conjunction with the roll index displayed on the attitude indicator. The roll index is sectioned by hash marks at 0°, 10°, 20°, 30°, 45°, 60° and the horizon line which depicts 90° of bank. *[Figure 4-29]* The addition of the 45° hash mark is an improvement over conventional attitude indicators. In addition to the roll index, the instrument pilot utilizes the turn rate indicator to maintain the aircraft in a standard rate turn (3° per second). Most instrument maneuvers can be done comfortably, safely, and efficiently by utilizing a standard rate turn.

Figure 4-29. *Bank Control Index Lines.*

Power Control

The power instruments indicate how much power is being generated by the engine. They are not affected by turbulence, improper trim, or control pressures. All changes in power should be made with reference to power instruments and cross-checked on performance instruments.

Power control needs to be learned from the beginning of flight training. Attitude instrument flying demands increased precision when it comes to power control. As experience increases, pilots begin to know approximately how much change in throttle position is required to produce the desired change in airspeed. Different aircraft demand differing amounts of throttle change to produce specific performance. It is imperative that the pilot make the specific changes on the power instruments and allow the performance to stabilize. Avoid the tendency to overcontrol.

One common error encountered with glass panel displays is associated with the precision of the digital readouts. This precision causes pilots to focus too much attention on establishing the exact power setting.

Control and power instruments are the foundation for precise attitude instrument flying. The keys to attitude instrument flying are establishing the desired aircraft attitude on the attitude indicator and selecting the desired engine output on the power instruments. Cross-checking is the vital ingredient in maintaining precise attitude instrument flight.

Attitude Instrument Flying—Primary and Supporting Method

The second method for performing attitude instrument flight is a direct extension of the control/power method. By utilizing the primary and supporting flight instruments in conjunction with the control and power instruments, the pilot can precisely maintain aircraft attitude. This method utilizes the same instruments as the control/power method; however, it focuses more on the instruments that depict the most accurate indication for the aspect of the aircraft attitude being controlled. The four key elements (pitch, bank, roll, and trim) are discussed in detail.

Similar to the control/power method, all changes to aircraft attitude need to be made using the attitude indicator and the power instruments (tachometer, manifold pressure gauge, etc.). The following explains how each component of the aircraft attitude is monitored for performance.

Pitch Control

The pitch of the aircraft refers to the angle between the longitudinal axis of the aircraft and the natural horizon. When flying in instrument meteorological conditions, the natural horizon is unavailable for reference, and an artificial horizon is utilized in its place. *[Figure 4-30]* The only instrument capable of depicting the aircraft attitude is the attitude indicator displayed on the PFD. The attitude and heading reference system (AHRS) is the engine that drives the attitude display. The AHRS unit is capable of precisely tracking minute changes in the pitch, bank, and yaw axes, thereby making the PFD very accurate and reliable. The AHRS unit determines the angle between the aircraft's longitudinal axis and the horizon line on initialization. There is no need

Figure 4-30. *Pitch of the Aircraft.*

or means for the pilot to adjust the position of the yellow chevron which represents the nose of the aircraft.

Straight-and-Level Flight

In straight-and-level flight, the pilot maintains a constant altitude, airspeed and, for the most part, heading for extended periods of time. To achieve this, three primary instruments need to be referenced in order to maintain these three variables.

Primary Pitch

When the pilot is maintaining a constant altitude, the primary instrument for pitch is the altimeter. As long as the aircraft maintains a constant airspeed and pitch attitude, the altitude should remain constant.

Two factors that cause the altitude to deviate are turbulence and momentary distractions. When a deviation occurs, a change in the pitch needs to be made on the attitude indicator. Small deviations require small corrections while large deviations require larger corrections. Pilots should avoid making large corrections that result in rapid attitude changes, for this may lead to spatial disorientation. Smooth, timely corrections should be made to bring the aircraft back to the desired attitude.

Pay close attention to indications on the PFD. An increase in pitch of 2.5° produces a climb rate of 450 feet per minute (fpm). Small deviations do not require large attitude changes.

A rule of thumb for correcting altitude deviations is to establish a change rate of twice the altitude deviation, not to exceed 500 fpm. For example, if the aircraft is off altitude by 40 feet, 2 x 40 = 80 feet, so a descent of approximately 100 fpm allows the aircraft to return to the desired altitude in a controlled, timely fashion.

In addition to the primary instrument, there are also supporting instruments that assist the pilot in cross-checking the pitch attitude. The supporting instruments indicate trend, but they do not indicate precise attitude indications. Three instruments (vertical speed, airspeed, and altitude trend tape) indicate when the pitch attitude has changed and that the altitude is changing. *[Figure 4-31]* When the altitude is constant, the VSI and altitude trend tape are not shown on the PFD. When these two trend indicators are displayed, the pilot is made aware that the pitch attitude of the aircraft has changed and may need adjustment.

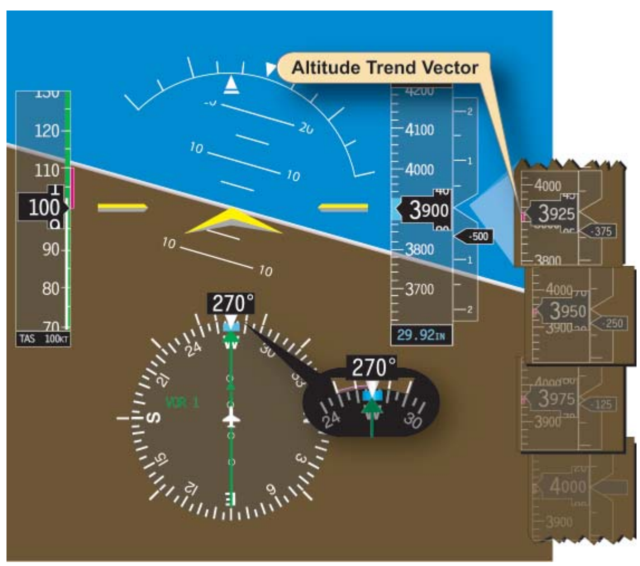


Figure 4-31. *Supporting Instruments.*

The instrument cross-check necessitates utilizing these supporting instruments to better manage altitude control. The VSI and trend tape provide the pilot with information regarding the direction and rate of altitude deviations. The pilot is thus able to make correction to the pitch attitude before a large deviation in altitude occurs. The airspeed indicator depicts an increase if the pitch attitude is lowered. Conversely, when the pitch attitude increases, the pilot should note a decrease in the airspeed.

Primary Bank

When flying in instrument meteorological conditions, pilots maintain preplanned or assigned headings. With this in mind, the primary instrument for bank angle is the heading indicator. Heading changes are displayed instantaneously. The heading indicator is the only instrument that displays the current magnetic heading, provided that it is matched to the magnetic compass with all deviation adjustments accounted for. *[Figure 4-32]*

There are supporting instruments associated with bank as well. The turn rate trend indicator shows the pilot when the aircraft is changing heading. The magnetic compass is also useful for maintaining a heading; however, it is influenced by several errors in various phases of flight.

Primary Yaw

The slip/skid indicator is the primary instrument for yaw. It is the only instrument that can indicate if the aircraft is moving through the air with the longitudinal axis of the aircraft aligned with the relative wind.

Primary Power

The primary power instrument for straight-and-level flight is the airspeed indicator. The main focus of power is to maintain a desired airspeed during level flight. No other instrument delivers instantaneous indication.

Learning the primary and supporting instruments for each variable is the key to successfully mastering attitude instrument flying. At no point does the primary and supporting method devalue the importance of the attitude indicator or the power instruments. All instruments (control, performance, primary, and supporting) must be utilized collectively.

Fundamental Skills of Attitude Instrument Flying

When first learning attitude instrument flying, it is very important that two major skills be mastered. Instrument cross-check and instrument interpretation comprise the foundation for safely maneuvering the aircraft by reference to instruments alone. Without mastering both skills, the pilot will not be able to maintain precise control of aircraft attitude.

Figure 4-32. *Primary Bank.*

Instrument Cross-Check

The first fundamental skill is cross-checking (also call "scanning"). Cross-checking is the continuous observation of the indications on the control and performance instruments. It is imperative that the new instrument pilot learn to observe and interpret the various indications in order to control the attitude and performance of the aircraft. Due to the configuration of some glass panel displays such as the Garmin G1000, one or more of the performance instruments may be located on an MFD installed to the right of the pilot's direct forward line of sight. *[Figure 4-33]*

How a pilot gathers the necessary information to control the aircraft varies by individual pilot. No specific method of cross-checking (scanning) is recommended; the pilot must learn to determine which instruments give the most pertinent information for any particular phase of a maneuver. With practice, the pilot is able to observe the primary instruments quickly and cross-check with the supporting instruments in order to maintain the desired attitude. At no time during instrument flying should the pilot stop cross-checking the instrumentation.

Scanning Techniques

Since most of the primary and supporting aircraft attitude information is displayed on the PFD, standard scanning techniques can be utilized. It is important to remember to include the stand-by flight instruments as well as the engine indications in the scan. Due to the size of the attitude instrument display, scanning techniques have been simplified because the attitude indicator is never out of peripheral view.

Selected Radial Cross-Check

The radial scan is designed so that your eyes remain on the attitude indicator 80–90 percent of the time. The remainder of the time is spent transitioning from the attitude indicator to the various other flight instruments. *[Figure 4-34]*

The radial scan pattern works well for scanning the PFD. The close proximity of the instrument tape displays necessitates very little eye movement in order to focus in on the desired instrument. While the eyes move in any direction, the extended artificial horizon line allows the pilot to keep the pitch attitude in his or her peripheral vision. This extended horizon line greatly reduces the tendency to fixate on one instrument and completely ignore all others. Because of the size of the attitude display, some portion of the attitude indicator is always visible while viewing another instrument display on the PFD.

Starting the Scan

Start the scan in the center of the PFD on the yellow chevron. Note the pitch attitude and then transition the eyes upward to the slip/skid indicator. Ensure that the aircraft is coordinated

Figure 4-33. *Note that the altitude and vertical speed tapes are slightly to the right of the pilot's direct forward line of sight.*

Figure 4-34. *Selected Radial Cross-Check.*

by aligning the split triangle symbol. The top of the split triangle is referred to as the roll pointer. The lower portion of the split triangle is the slip/skid indicator. If the lower portion of the triangle is off to one side, step on the rudder pedal on the same side to offset it. *[Figure 4-35 NOTE: The aircraft is not changing heading. There is no trend vector on the turn rate indicator.]*

While scanning that region, check the roll pointer and assure that the desired degree of roll is being indicated on the bank scale. The roll index and the bank scale remain stationary at the top of the attitude indicator. The index is marked with angles of 10°, 20°, 30°, 45° and 60° in both directions. If the desired bank angle is not indicated, make the appropriate

Figure 4-35. *Roll Pointer and Slip/Skid Indicator.*

aileron corrections. Verify the bank angle is correct and continue scanning back to the yellow chevron.

Scan left to the airspeed tape and verify that the airspeed is as desired, then return back to the center of the display. Scan right to the altimeter tape. Verify that the desired altitude is being maintained. If it is not, make the appropriate pitch change and verify the result. Once the desired altitude has been verified, return to the center of the display. Transition down to the heading indicator to verify the desired heading. When the heading has been confirmed, scan to the center of the display.

It is also important to include the engine indications in the scan. Individualized scan methods may require adjustment if engine indications are presented on a separate MFD. A modified radial scan can be performed to incorporate these instruments into the scan pattern. Another critical component to include in the scan is the moving map display located on the MFD. To aid in situational awareness and facilitate a more centralized scan, a smaller inset map can be displayed in the lower left corner of the PFD screen.

Trend Indicators

One improvement the glass panel displays brought to the general aviation industry is the trend vector. Trend vectors are magenta lines that appear on the airspeed and altitude tapes as well as on the turn rate indicator. These magenta lines indicate what the associated airspeed, altitude, or heading will be in 6 seconds *[Figure 4-36]* if the current rate is maintained. The trend vector is not displayed if there is no change to the associated tape and the value remains constant *[Figure 4-37]* or if there is a failure in some portion of the system that would preclude the vector from being determined.

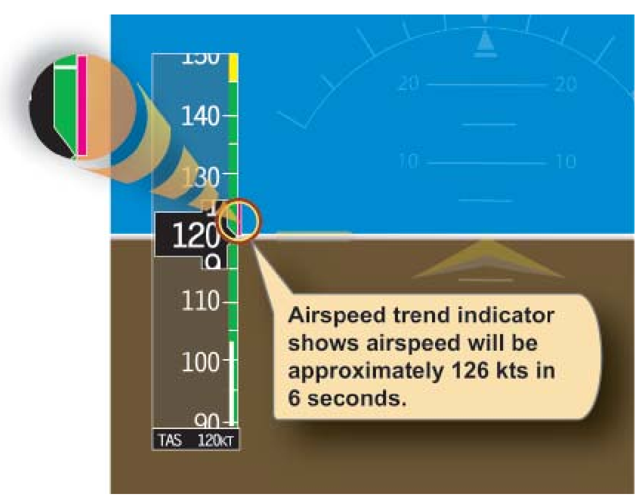


Figure 4-36. *Airspeed Trend Indicators.*

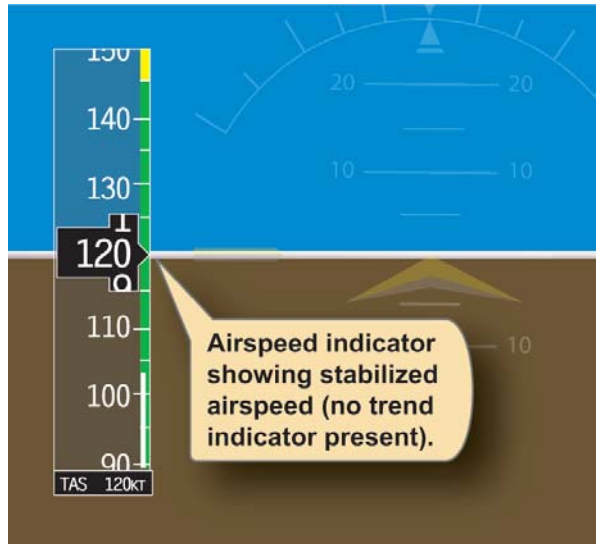


Figure 4-37. *Airspeed Indicators With No Trend Present.*

Trend vectors are a very good source of information for the new instrument flight rules (IFR) pilot. Pilots who utilize good scanning techniques can pick up subtle deviations from desired parameters and make small correction to the desired attitude. As soon as a trend is indicated on the PFD, a conscientious pilot can adjust to regain the desired attitude. *[Figure 4-38]*

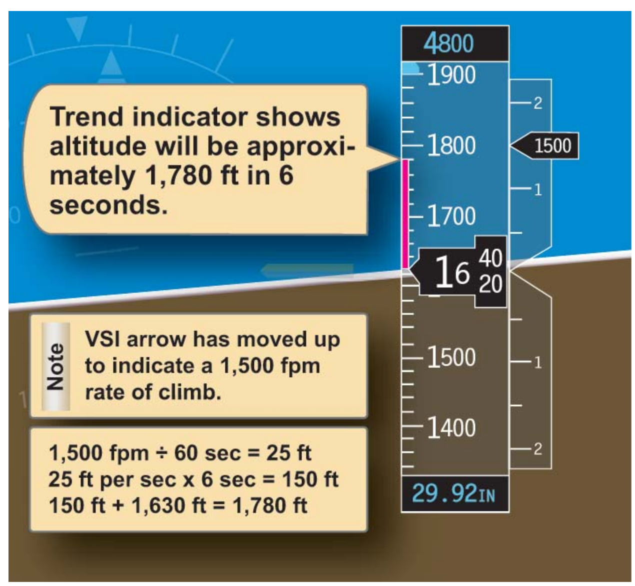


Figure 4-38. *Altimeter Trend Indicators.*

Another advancement in attitude instrument flying is the turn rate trend indicator. As in the cases of airspeed, altitude, and vertical speed trend indicators, the turn rate trend indicator depicts what the aircraft's heading will be in 6 seconds. While examining the top of the heading indicator, notice two white lines on the exterior of the compass rose. *[Figure 4-39]* These

Figure 4-39. *Horizontal Situation Indicator (HSI) Trend Indicator Elongates Proportionally With the Rate of Turn.*

two tick marks located on both sides of the top of the heading indicator show half-standard rate turns as well as standard rate turns.

In *Figure 4-40*, when the aircraft begins its turn to the left, the magenta trend indicator elongates proportionally with the rate of turn. To initiate a half-standard rate turn, position the indicator on the first tick mark. A standard rate turn would be indicated by the trend indicator extending to the second tick mark. A turn rate in excess of standard rate would be indicated by the trend indicator extending past the second tick mark. This trend indicator shows what the aircraft's heading will be in 6 seconds, but is limited to indicate no more than 24° in front of the aircraft, or 4° per second. When the aircraft exceeds a turning rate of 25° in 6 seconds, the trend indicator has an arrowhead attached to it.

Trend indicators are very useful when leveling off at a specific altitude, when rolling out on a heading, or when stabilizing airspeed. One method of determining when to start to level off from a climb or descent is to start leveling at 10 percent of the vertical speed rate prior to the desired altitude.

As the aircraft approaches the desired altitude, adjust the pitch attitude to keep the trend indicator aligned with the target altitude. As the target approaches, the trend indicator gradually shrinks until altitude stabilizes. Trend indicators should be used as a supplement, not as a primary means of determining pitch change.

Figure 4-40. *HSI Indicator (enlargement).*

Common Errors

Fixation

Fixation, or staring at one instrument, is a common error observed in pilots first learning to utilize trend indicators. The pilot may initially fixate on the trend indicator and make adjustments with reference to that alone. Trend indicators are not the only tools to aid the pilot in maintaining the desired power or attitude; they should be used in conjunction with the primary and supporting instruments in order to better manage the flight. With the introduction of airspeed tapes, the pilot can monitor airspeed to within one knot. Fixation can lead to attempting to keep the airspeed to an unnecessarily tight tolerance. There is no need to hold airspeed to within one knot; the Instrument Rating Practical Test Standards (PTS) allows greater latitude.

Omission

Another common error associated with attitude instrument flying is omission of an instrument from the cross-check. Due to the high reliability of the PFD and associated components, pilots tend to omit the stand-by instruments as well as the magnetic compass from their scans. An additional reason for the omission is the position of the stand-by instruments. Pilots should continue to monitor the stand-by instruments in order to detect failures within those systems. One of the most commonly omitted instruments from the scan is the slip/skid indicator.

Emphasis

In initial training, placing emphasis on a single instrument is very common and can become a habit if not corrected. When the importance of a single instrument is elevated above another, the pilot begins to rely solely on that instrument for guidance. When rolling out of a 180° turn, the attitude indicator, heading indicator, slip/skid indicator, and altimeter need to be referenced. If a pilot omits the slip/skid indicator, coordination is sacrificed.