NAVAL AIR TRAINING COMMAND

NAS CORPUS CHRISTI, TEXAS **CNATRA P-1231 (Rev. 08-09)**

FLIGHT TRAINING INSTRUCTION

AERODYNAMICS WORKBOOK

T-45

2009

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Subj: FLIGHT TRAINING INSTRUCTION, AERODYNAMICS WORKBOOK, T-45

1. CNATRA P-1231 (Rev. 08-09) PAT, "Flight Training Instruction, Aerodynamics Workbook, T-45" is issued for information, standardization of instruction, and guidance for all flight instructors and student aviators within the Naval Air Training Command.

2. This publication shall be used as an explanatory aid to support the T-45 Strike Flight Training Curriculum. It will be the authority for the execution of all flight procedures and maneuvers herein contained.

3. Recommendations for changes shall be submitted via CNATRA TCR form 1550/19 in accordance with CNATRAINST 1550.6E.

4. CNATRA P-1231 (07-99) PAT is hereby cancelled and superseded.

JAMES A. CRABBE
Chief of Staff

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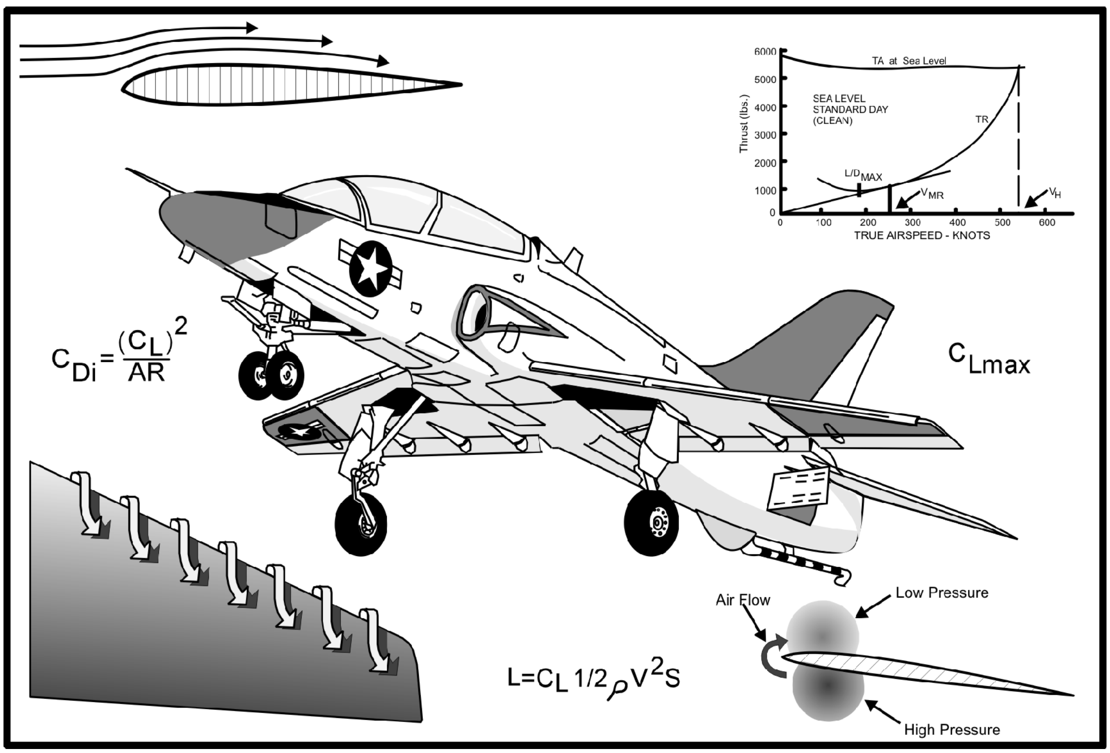
FLIGHT TRAINING INSTRUCTION

FOR

AERODYNAMICS WORKBOOK

T-45

P-1231



PURPOSE OF THIS AERODYNAMICS WORKBOOK

The T-45 Aerodynamics Workbook is intended to help bridge the gap between the aerodynamic theory taught in Pensacola and the practice of T-45 flying. This guide is not the sole source of information for flying or the aerodynamics test.

The NATOPS Flight Manual for the T-45 contains a wealth of aerodynamics information and helpful tips. Study the sections assigned by your instructor and expect to be tested thoroughly on the aerodynamics subjects in NATOPS. The CAI and your instructor will cover some but not all of the subjects in the handout and NATOPS.

The NATOPS manual and pocket checklist will be the only reference material permitted during the exam.

This workbook is a synthesis of the lecture, NATOPS, and CAI material, but the most information will accrue from studying NATOPS thoroughly.

LIST OF EFFECTIVE PAGES

Dates of issue for original and changed pages are:
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COVER	0		
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INTERIM CHANGE SUMMARY

The following Changes have been previously incorporated in this manual:

CHANGE NUMBER	REMARKS/PURPOSE

The following interim Changes have been incorporated in this Change/Revision:

INTERIM CHANGE NUMBER	REMARKS/PURPOSE	ENTERED BY	DATE

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CHAPTER ONE
GENERAL AERODYNAMICS REVIEW

100. INTRODUCTION

This lesson reviews the basic forces acting on an aircraft in flight, the aerodynamic principles involved in producing lift, aircraft stability, and the "envelope." It does not contain T-45 aircraft specific material, as do the remaining aerodynamic lessons.

101. PRESENTATION

Four basic forces act upon an aircraft in flight. They are lift, drag, weight, and thrust (Figure 1-1). Lift acts through the aerodynamic center (AC) of the aircraft. Thrust and drag are sometimes said to act through the center of gravity (CG), but this is a vast simplification of the physics involved. Weight always acts through the center of gravity. In steady flight, it is true that the sum of thrust and drag through the CG is zero. Since Naval Aviators do not require all the underlying physics to fly an aircraft, this course will consider that weight, thrust, and drag act through the center of gravity.

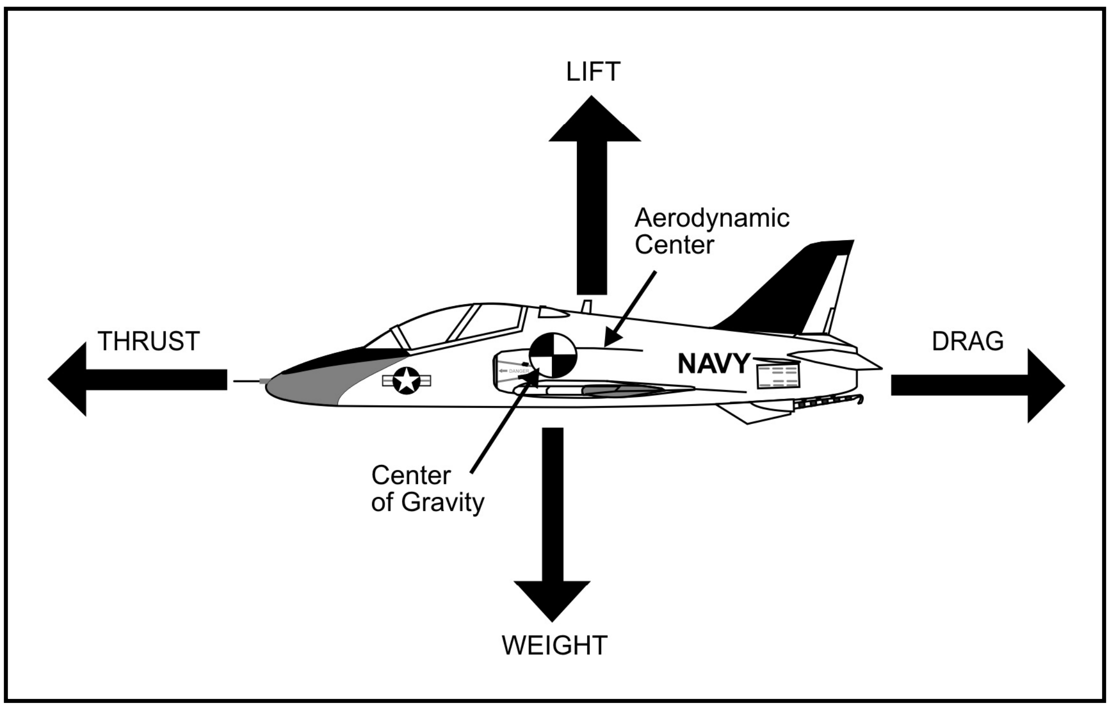

Figure 1-1 Aerodynamic Forces

102. LIFT

Lift, the primary support force of an aircraft, is usually thought of as the force acting in an upward direction. However, lift acts 90 degrees to the relative wind. The aircraft attitude may be such that the lift is acting in varying directions to the other forces that act through the center of gravity.

Lift is the result of air flowing faster over the upper surface of the wing in comparison to the lower surface. According to Bernoulli's principle, this difference in airflow velocity creates an area of low pressure on the upper surface of the wing compared to the lower surface. The pressure differential produces lift.

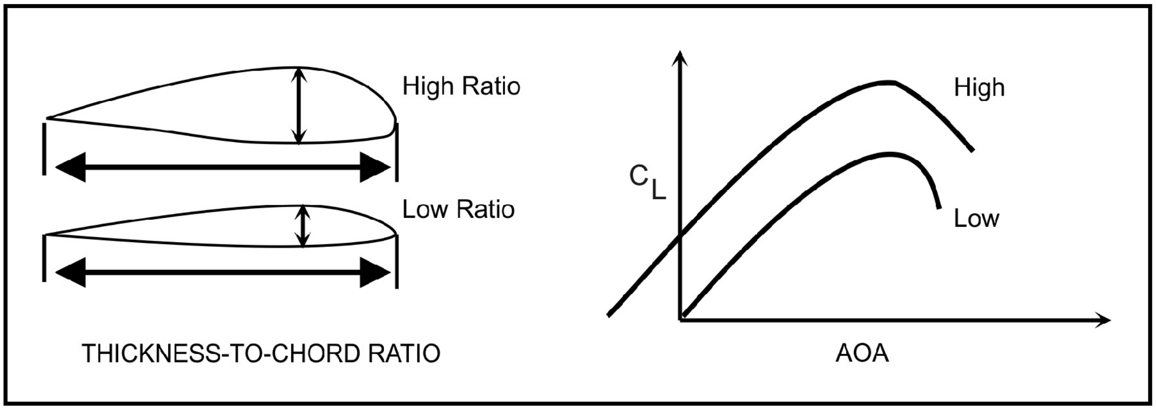

Figure 1-2 C_L Curve of High vs Low Thickness-To-Chord Ratios

The basic lift equation is $L = C_L \, 1/2 \, \rho \, V^2 \, S$

WHERE: L = LIFT
C_L = COEFFICIENT OF LIFT
ρ = AIR DENSITY
V = AIRCRAFT TRUE AIRSPEED
S = WING SURFACE

Coefficient of Lift

The coefficient of lift (C_L) is determined by the shape of the wing, the wing airfoil section/planform, and the angle of attack (AOA). Angle of attack is the angle measured between the chord line of the wing and the relative wind. Shape of the wing includes wing thickness, chord, camber, leading edge radius, and wing sweep. The shape of a wing is dictated by the intended use of the aircraft, whether glider or fighter (Figure 1-2).

If a wing is to have good qualities at both high and low speeds, it must be able to change shape in flight. Flaps and slats are high lift devices used to change the shape of the wing and increase C_L at low airspeeds.

As angle of attack increases, C_L also increases, providing the boundary layer is maintained.

As angle of attack increases beyond the angle where boundary layer can be maintained, a reduction in C_L will occur as separation of the boundary occurs. At this point, stall commences (Figure 1-3).

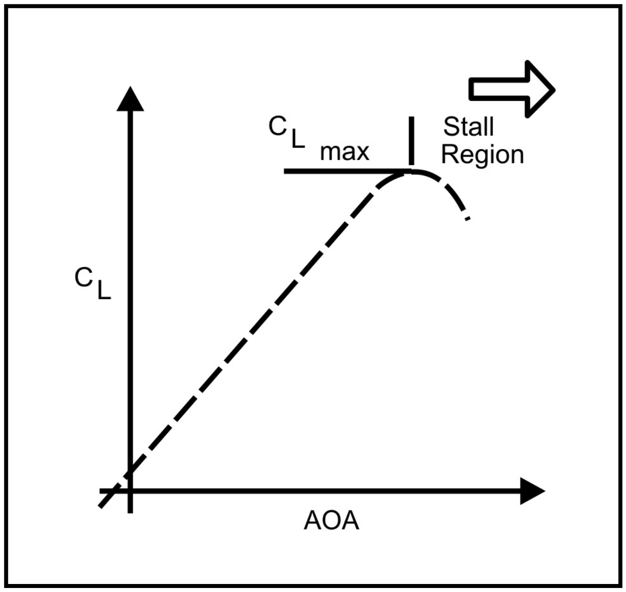

Figure 1-3 AOA vs Coefficient Of Lift (C_L)

Air Density

Air density (ρ) is affected by barometric pressure, temperature, and humidity. Pressure altitude is the altitude in the standard atmosphere corresponding to a particular altitude. On a standard day, pressure altitude and altitude above ground level (AGL) are the same. On a nonstandard day, altitude AGL and pressure altitude will not agree. Simply stated, density will decrease as pressure altitude, temperature, or humidity increase. Remember, pressure decreases as altitude increases. As altitude increases and pressure decreases, density decreases. However, with an altitude increase, temperature decreases. Density decreases at a given rate to the altitude where temperature becomes constant, approximately 36,000 ft. Without the favorable temperature offset, density decreases more rapidly (Figure 1-4) at altitudes above approximately 36,000 ft. Perhaps the more appropriate term for correlating aerodynamic performance in the nonstandard atmosphere is density altitude. Density altitude is the altitude in the standard atmosphere corresponding to a particular value of air density. The computation of density altitude involves pressure (pressure altitude) and temperature. Density altitude is pressure altitude corrected for nonstandard day temperature. At high field elevations on a warm day, the density altitude may be considerably higher than actual field elevation. At a field elevation of 5,000 ft, the standard day temperature is approximately 5°C (41°F). With a temperature of 30°C (86°F), the density altitude is approximately 7,500 ft, 50% more than actual field elevation. The T-45 NATOPS manuals do not provide a density altitude conversion chart. However, density ratio must be computed for use with the Takeoff Charts in the Performance Data section of the T-45 NATOPS.

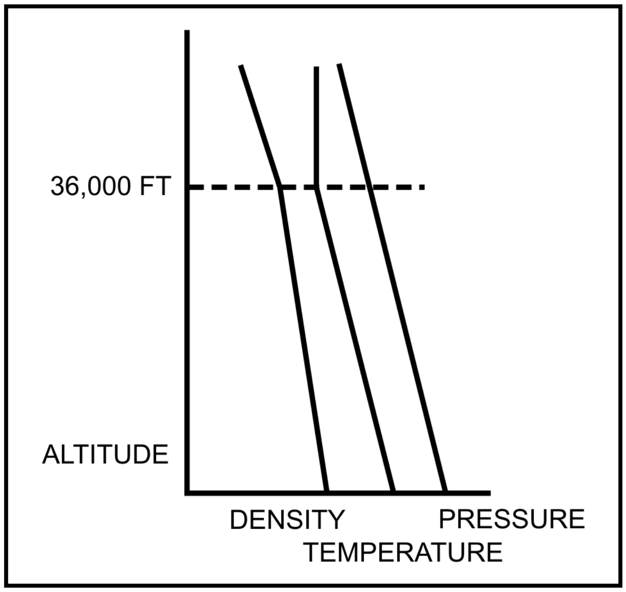

Figure 1-4 Air Density

Velocity

Aircraft velocity (V) is in true airspeed (TAS). The pitot static system measures dynamic pressure (q) and gives the pilot indicated airspeed (IAS). The equation for dynamic pressure is $q = 1/2\ \rho\ V^2$. At sea level, with standard day temperature and pressure conditions, IAS equals TAS. At altitude, air density is less than at sea level and the IAS will be lower than TAS. **BECAUSE THE AIRSPEED INDICATOR IS DIRECTLY AFFECTED BY AIR DENSITY, STALL INDICATED AIRSPEED IS NOT AFFECTED BY ALTITUDE.** Consequently, the same indicated airspeed may be used for takeoffs and landings regardless of field elevation, assuming the same gross weight, configuration, etc.

Wing Surface Area

With most tactical aircraft, wing surface area (S) is not a variable and flap extension will only change the shape of the wing. However, some types of flaps, such as Fowler flaps, do increase surface area of the wing. Lowering the flaps changes the wing's shape and possibly surface area, which increases C_L.

103. DRAG

Drag is the force that acts on the aircraft opposite the direction of flight through the CG. When airspeed is constant during straight and level flight, drag is equal to thrust being produced. For subsonic flight, total drag can be broken down into two types, induced drag and parasite drag.

Induced Drag

Induced drag is created with and results from the production of lift. The major factor affecting the variation of induced drag is the coefficient of lift.

The coefficient of induced drag is illustrated by the equation: $\mathbf{C_{di} = \frac{(C_L)^2}{\pi_{AR}}}$

WHERE: C_{di} = COEFFICIENT OF INDUCED DRAG
CL = COEFFICIENT OF LIFT
AR = ASPECT RATIO (THE RATIO OF WING SPAN TO AVERAGE CHORD)

As airspeed is reduced in level flight, angle of attack is increased to increase coefficient of lift. As C_L is increased, C_{di} increases by the square of the change in C_L (Figure 1-5).

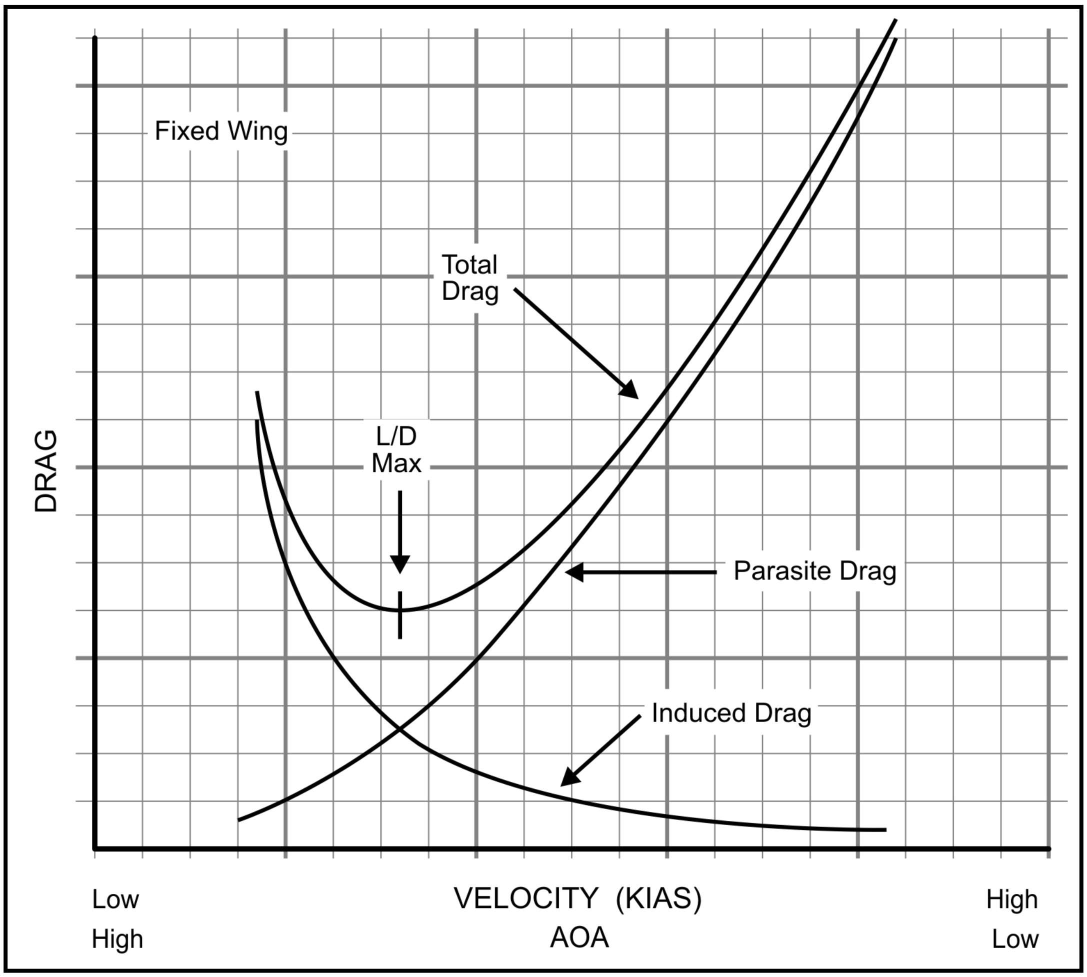

Figure 1-5 Drag Curve (1 G Flight)

Parasite Drag

Parasite drag results from skin friction and the form or frontal area of the aircraft. Parasite drag is greatly influenced by the configuration of the aircraft, external stores, flap or landing gear extension, etc. Parasite drag is also greatly affected by velocity. As airspeed increases, parasite drag will increase by the square of the change in airspeed. As aircraft velocity doubles, parasite drag will increase four times. For example, an aircraft that requires 2,000 pounds of thrust to fly at 200 KTAS will require 8,000 pounds of thrust to fly at 400 KTAS, ignoring induced drag effects (Figure 1-5).

Total Drag

Adding parasite and induced drag forms a "U" shaped total drag curve with total drag at a minimum where induced and parasite drag are equal (Figure 1-5). At the point where the total drag is at a minimum, the lift-to-drag ratio will be maximum L/D or $(L/D)_{max}$. The airspeed/AOA for maximum endurance, maximum climb angle, and maximum power off glide range will be found at $(L/D)_{max}$ in turbojet or turbofan aircraft.

Wave Drag

Wave drag is similar to parasitic drag but only occurs in conditions of supersonic flow. A body generating a shock wave feels this force as a consequence of pressure differences in the shock.

104. WEIGHT

Weight results from the action of gravity on an aircraft and is normally expressed in pounds. Weight varies with fuel, ordnance load, and g-load. The weight vector, by definition, acts through the center of gravity (CG).

105. STABILITY

Stability refers to the tendency of an aircraft to resist displacement from its flight path and, if displaced, to develop moments and forces to return to its original flight path. Stability is commonly represented as movement about one of three axes of flight (Figure 1-6). Stability in roll is stability about the longitudinal axis; stability in pitch is stability about the lateral axis; stability in yaw is stability about the vertical axis.

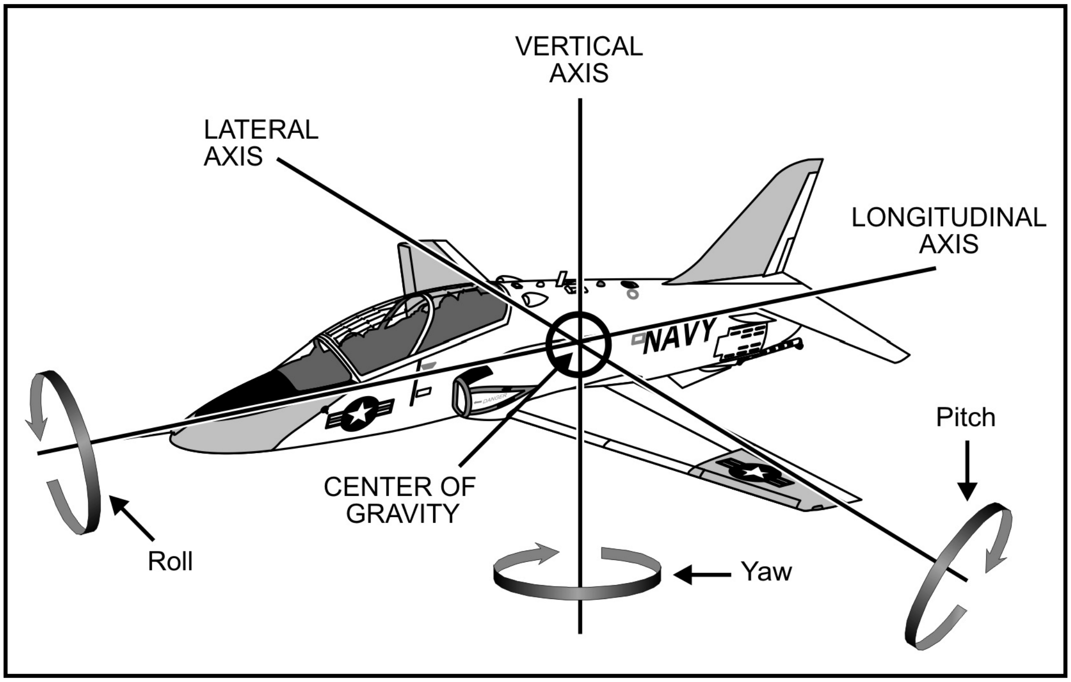

Figure 1-6 Three Axes of Flight

Static Stability

Static stability indicates the initial tendency of the aircraft to return to equilibrium following some disturbance from equilibrium. An aircraft may display positive static stability, a tendency to return to equilibrium; negative static stability, a tendency to continue in the direction of displacement; or neutral static stability, a tendency to neither return to equilibrium nor to continue in the direction of displacement (Figure 1-7).

Dynamic Stability

While static stability is concerned with the initial tendency of an aircraft when disturbed from equilibrium, the resulting motion with time defines dynamic stability (Figure 1-7). In any system, positive static stability is a necessary but not a sufficient condition for the existence of positive dynamic stability. If there is a tendency to return to equilibrium, static stability is positive. However, dynamic stability may be positive (dampening), neutral (same amplitude of oscillations), or negative (increasing amplitude of oscillations with positive static stability). If static stability is neutral, dynamic stability will be neutral, and if static stability is negative, dynamic stability is also negative.

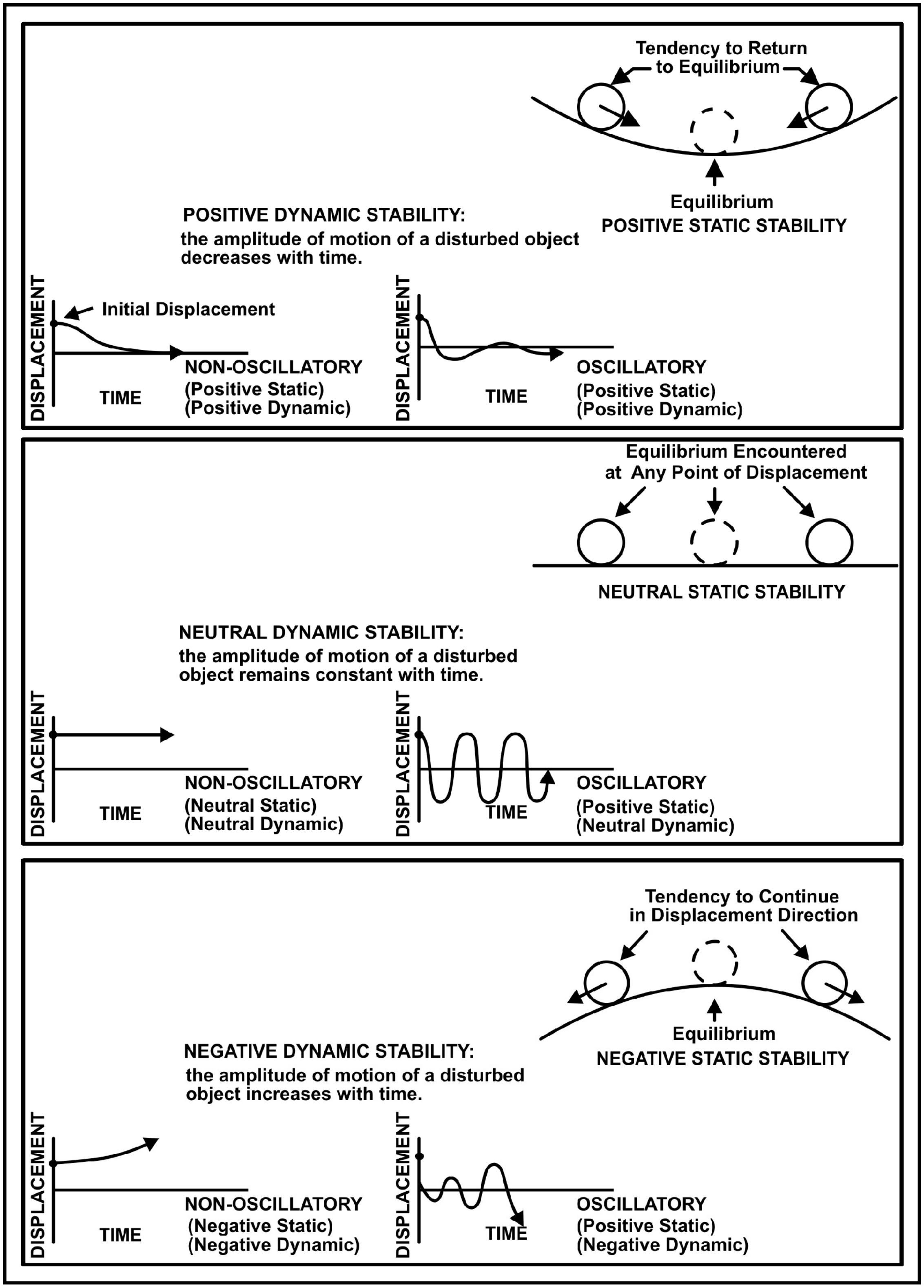

Figure 1-7 Static and Dynamic Stability

Longitudinal Stability

Static longitudinal stability (stability in pitch) is determined by the relationship between the aerodynamic center (AC) and the center of gravity (CG). With the AC aft of the CG, static longitudinal stability is positive. If CG and AC are collocated, static longitudinal stability is neutral, and with the AC forward of CG, static longitudinal stability is negative (Figure 1-8).

Load distribution, external stores, fuel, etc., may affect the location of CG. High AOA (stall or approaching stall) and transonic or supersonic flight will affect the AC.

The closer together the AC and CG are located, the weaker the stability but the greater the controllability. The greater the separation between AC and CG, the greater the stability but controllability is reduced. Maneuverability could be substituted for controllability.

Dynamic longitudinal stability is the time to recover from pitch displacement. Long-period oscillations (Phugoid) are easily controlled. Short-period or deadbeat oscillations may be impossible to control and are both undesirable and dangerous. Pilot-induced oscillations can occur when a pilot attempts to counter an oscillation with control inputs which are of the wrong magnitude or rate to dampen the oscillation.

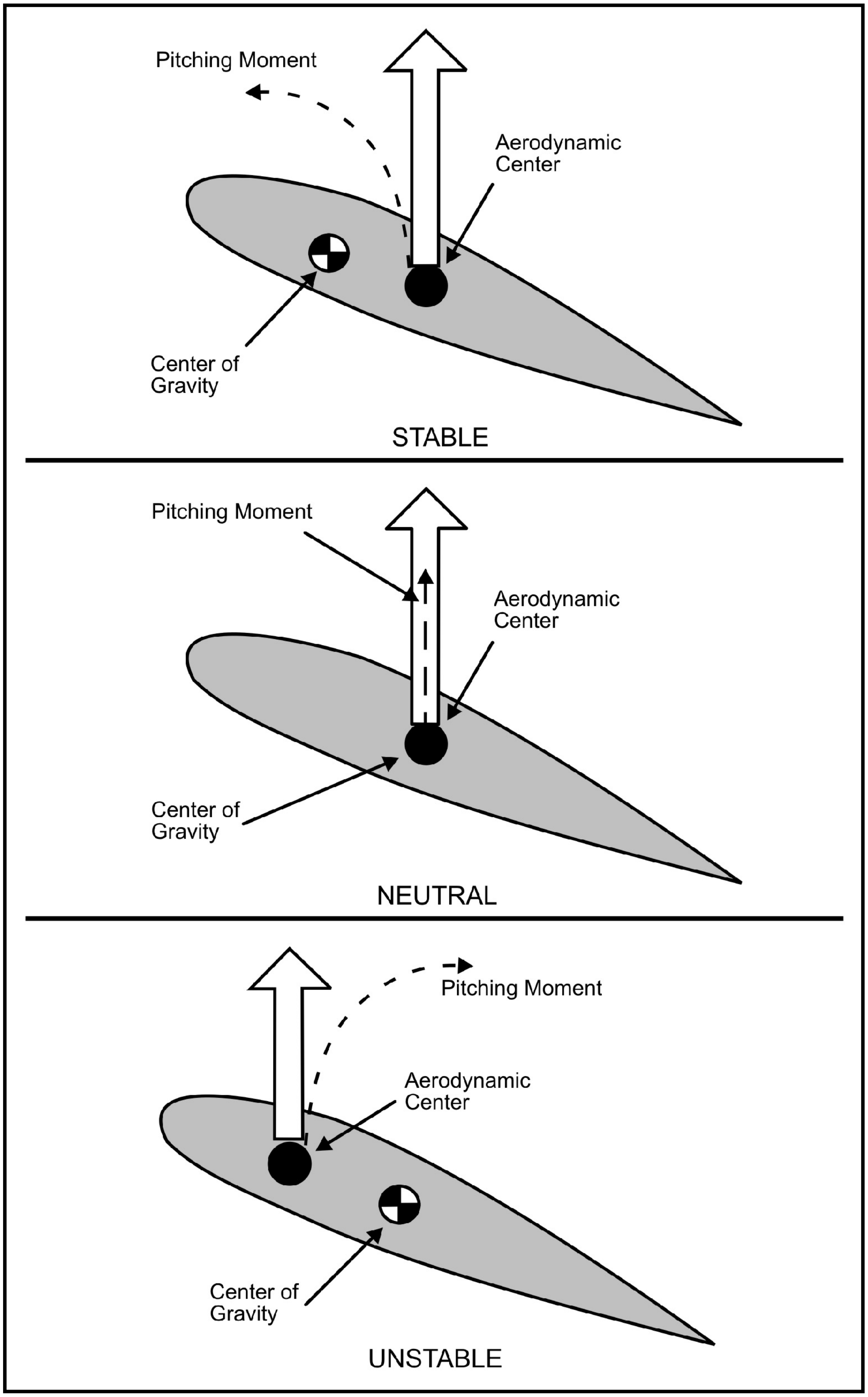

Figure 1-8 Longitudinal Stability (Pitch)

Directional Stability

Static directional stability or stability in yaw indicates an aircraft tendency to return to coordinated flight when displaced by sideslip or skid (Figure 1-9).

Strong directional stability will be present in an aircraft that has a large sail area aft of the CG compared to the area forward of the CG. With a yaw, the wind striking the area aft of CG will restore the nose into the relative wind while the wind affecting the area forward of CG will attempt to continue the aircraft in the yaw. The sideways lift created around the vertical stabilizer will have an additional effect on directional stability. The vertical stabilizer will act as a wing and generate lift that acts horizontally, restoring the aircraft in yaw.

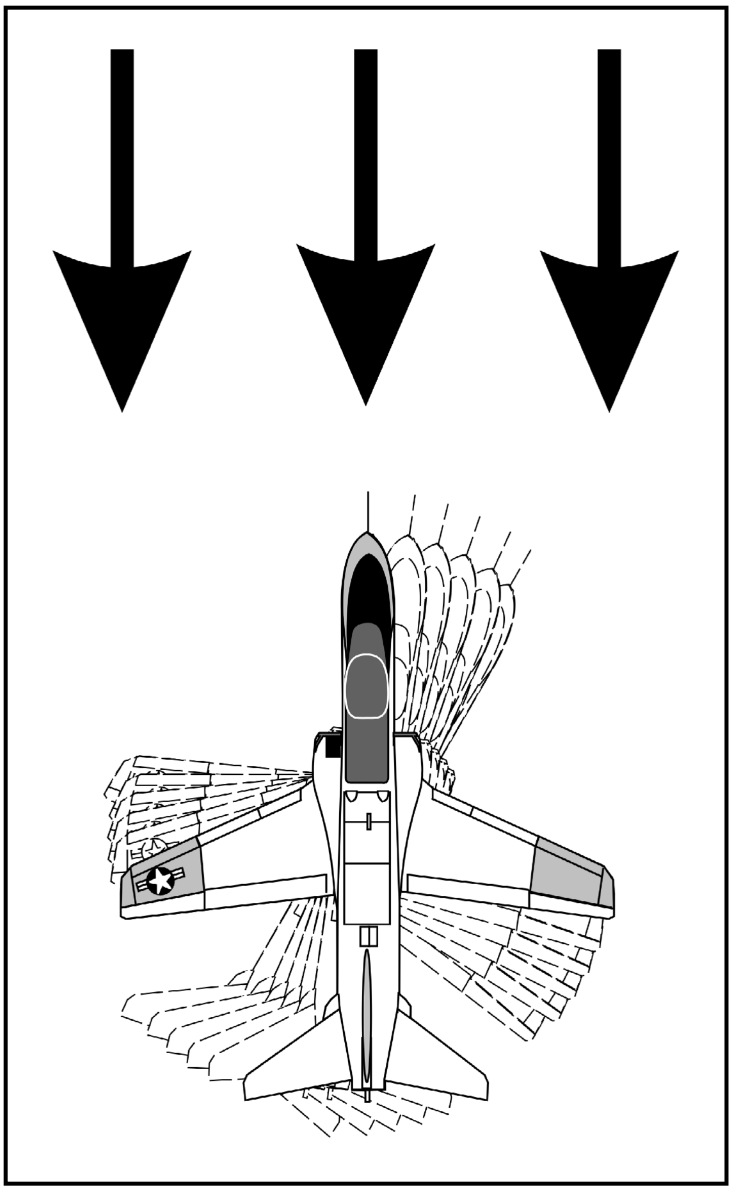

Figure 1-9 Directional Stability

Lateral Stability

Static lateral stability or stability in roll indicates an aircraft's tendency to return to wings-level flight. The effect of the geometric dihedral of a wing is a powerful contribution to lateral stability (Figure 1-10). When a wing with dihedral is in a sideslip, dihedral causes an increase in angle of attack on the downward wing and a decrease in angle of attack on the upward wing. An increase in lift occurs on the down wing and a decrease in lift occurs on the up wing. The result is a rolling moment that restores the aircraft to wings level.

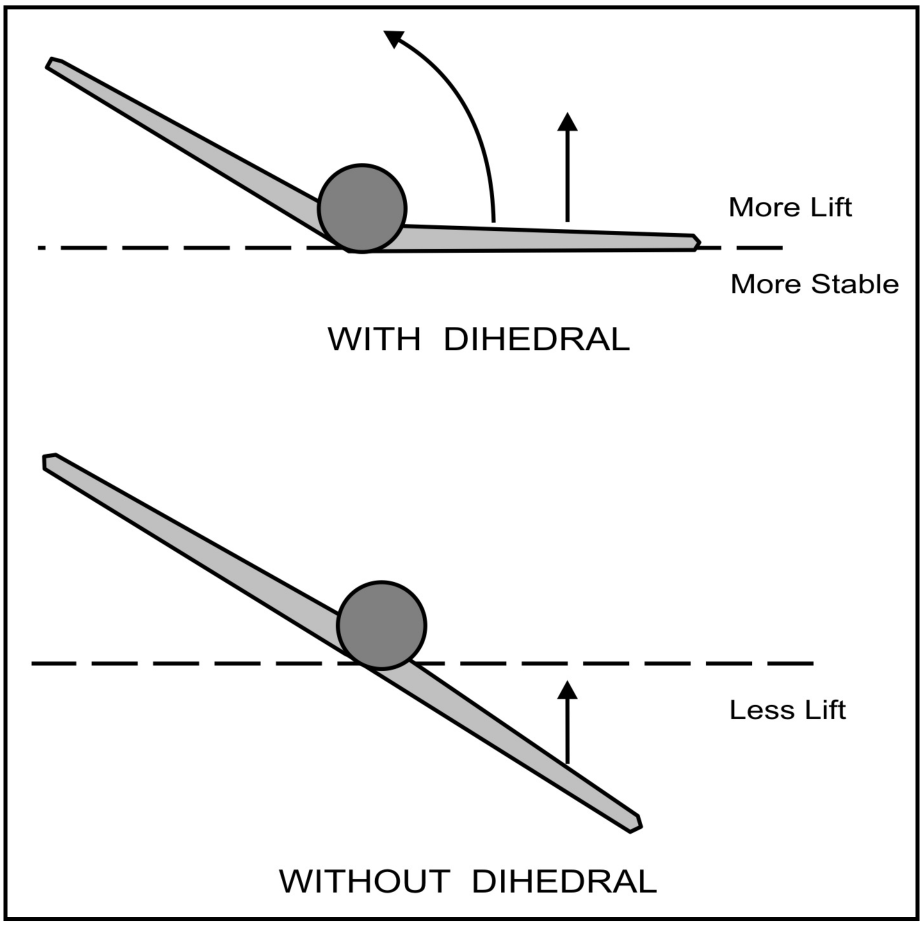

Figure 1-10 Lateral Stability

Wing location in relation to CG will have a pronounced effect on lateral stability due to the offset between lift and weight. A high wing location will create a rolling moment that will aid in restoring the aircraft to wings-level flight. A mid-located wing, where the AC is located on line with the CG, will have a neutral effect on lateral stability. A low wing location will tend to continue an aircraft in a roll (Figure 1-11).

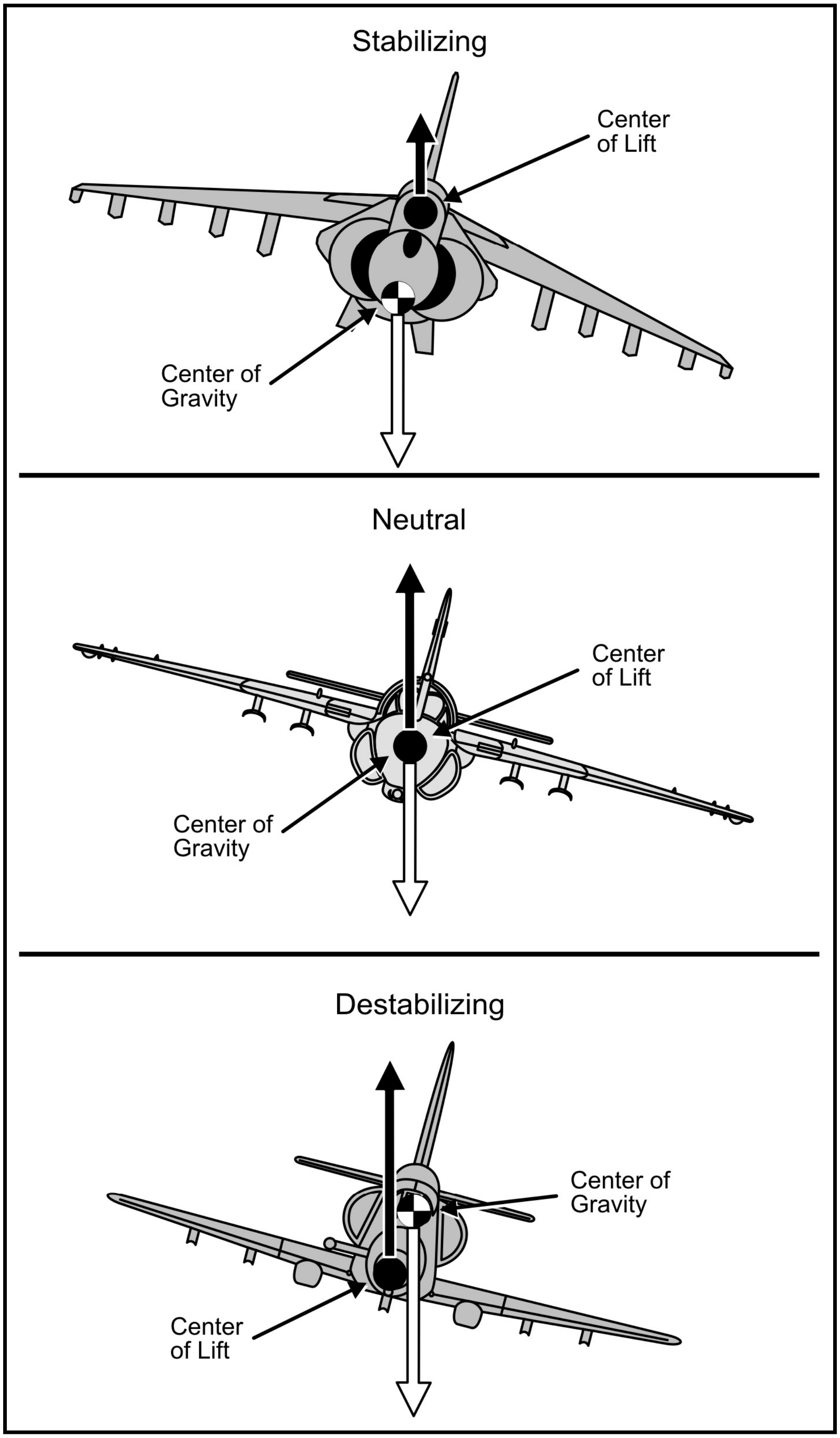

Figure 1-11 Wing Location

Coupling

Coupling is the interaction between roll, yaw, and pitch. Due to coupling between roll and yaw, a swept wing aids both lateral and directional stability. As a swept wing aircraft yaws, one wing becomes more perpendicular to the relative wind while the other becomes less perpendicular. Lift and induced drag are increased on the wing into the wind and are reduced on the wing out of the wind. Roll and adverse yaw (yaw opposite roll) will occur. The nose of the aircraft will be pulled back into the relative wind and lateral and directional stability is restored.

The relative strength of static lateral stability to static directional stability may produce directional divergence, spiral divergence or Dutch roll.

Directional divergence occurs as an aircraft yaws or rolls into a sideslip. Side forces cause increased yaw indicating directional instability. Directional divergence is designed out of most aircraft.

Spiral divergence results from strong directional stability relative to weak lateral stability. Spiral divergence will be discussed in a later lesson.

Dutch roll results from strong lateral stability relative to directional stability. Dutch roll will also be discussed in a later lesson.

106. OPERATING ENVELOPE

The NATOPS OPERATING ENVELOPE is often referred to as the Vg or Vn diagram. It is a graphic representation of the operating envelope of the aircraft. Velocity is plotted on the horizontal in either indicated airspeed (KIAS) or indicated Mach number (IMN). The vertical is plotted in either acceleration (g) or wing load (n), thus the names Vg or Vn diagram. The plot will then depict the operational envelope of the aircraft based on weight, configuration, altitude, and loading (symmetrical or unsymmetrical). The structural limitations will be depicted vertically in either g or maximum wing load. The maximum velocity is depicted on the horizontal in either KIAS or IMN. That plot, combined with the thrust curves, enables the pilot to determine the maximum capability and restrictions of the aircraft.

Construction of the flight envelope graph is depicted in Figure 1-12. Aerodynamic limits define the maximum positive and negative lift an aircraft can develop before stall occurs. The aerodynamic limits are the accelerated stall curve for that aircraft. The aerodynamic limits indicate the available g or maximum acceleration that can be developed.

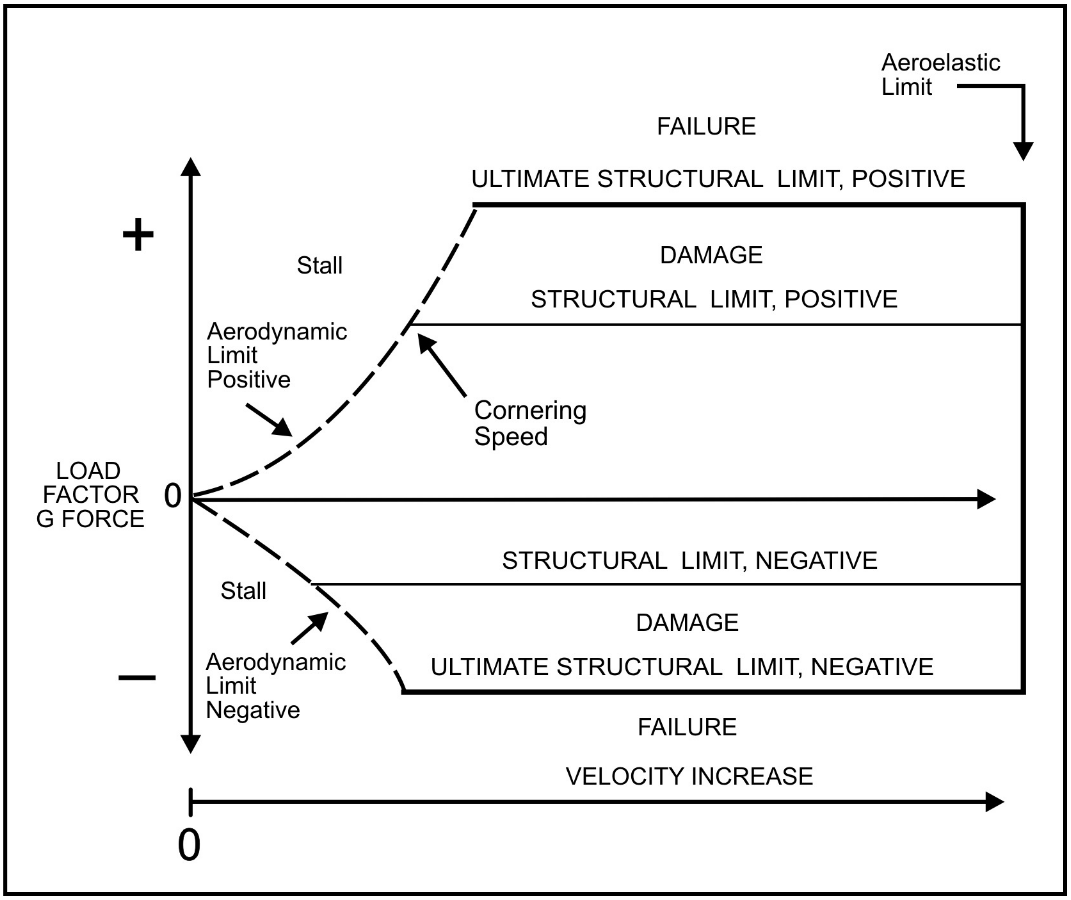

Figure 1-12 Envelope Diagram

Structural Limits

These are the allowed positive and negative g limits of the aircraft. Structural limits are based on the strength of the aircraft structure. Under any loading, even 1 g, the aircraft structure will flex. A large amount of airframe flexure will lead to permanent deformation (a bent airframe) or component failure. A lesser amount of flexure affects the lifetime of the airframe due to metal fatigue, etc. The aircraft structural limits are selected to ensure that g-loading induced flexure will not damage the airframe or shorten its design life. Structural limits are also referred to as acceleration limits or limit load factors. Exceeding the structural limits (overstress of aircraft) may or may not damage the aircraft. Numerous overstresses will shorten the service life of the aircraft.

Aeroelastic Limits

These define the maximum operating speeds in both KIAS and IMN of the aircraft. Above the aeroelastic limits, structural damage or failure may occur as well as a loss of stability and/or control authority. The aeroelastic limit is frequently referred to as the "Redline Airspeed."

Ultimate Structural Limits

These define the ultimate operating strength limits of the aircraft. Flight operations beyond the ultimate structural limits will result in structural failure of some component of the aircraft. It should be noted that the ultimate structural limits are outside the normal operating envelope of the aircraft. The usual aircraft design rule is for the ultimate structural limit to be 150% of the structural limit. However, this may not be strictly true since the structural limits may reflect aircraft lifetime concerns while the ultimate structural limits do not.

Cornering Speed

This point is located at the intersection of the structural limit and the aerodynamic limit. Cornering speed is the minimum speed where the limit load factor can be achieved. Cornering speed defines turning performance of the aircraft at which the aircraft can achieve maximum turn rate and minimum turn radius. At or below cornering speed, the aircraft cannot be overstressed; stall will occur first. Cornering speed may also be referred to as maneuvering speed.

Envelope

The envelope is constructed based on the variables of weight, altitude, configuration, and loading (symmetrical or unsymmetrical).

107. WEIGHT

Weight will generally affect the structural limits and the aerodynamic limits. The aerodynamic limits are based on stall speed of the aircraft. Changing weight changes stall speed and the aerodynamic limits. Likewise, as weight change affects the allowable g's, the structural limits will also be affected. When the structural limits are affected, the ultimate structural limits are also affected. An aircraft is usually structurally limited at low altitudes.

Altitude

Changes in altitude will affect the aerodynamic limits and aeroelastic limits. As altitude changes, the maximum Mach number and maximum IAS change. The ability to generate the necessary speed to achieve maximum g is also affected as density decreases and thrust available is reduced. At higher altitudes, an aircraft is usually aerodynamically limited due to lack of thrust and decreased density.

Configuration (or Loading Change)

This may affect any element of the operational envelope. The elements affected will depend on the change in either configuration or loading. For example, rolling pullouts (an asymmetrical load) always reduce allowable g. Extending landing gear or flaps restricts airspeed, and external stores may reduce maximum airspeed, Mach number, and maximum g.

CHAPTER TWO
HIGH-SPEED FLIGHT

200. INTRODUCTION

1. MOTIVATION. Flight at high Mach numbers affects an aircraft differently than flight at slower speeds. Understanding the effect of compressibility at high Mach numbers is important to you because of the effect on stability, lift, and drag. Knowing the flight characteristics of the T-45 during high-speed flight will help you, as a pilot, to realize the maximum potential of the aircraft.

2. OVERVIEW. Aircraft that are capable of high-speed flight look different from those developed for low-speed flight. Many significant differences exist between high-speed and low-speed aerodynamics. The nature and cause of these differences and their application to the T-45 will be discussed in this lecture. In this lesson, we will be discussing:

a. The effects of high-speed flight on aircraft

b. Methods used to overcome the effects and permit high-speed flight

c. High-speed flight characteristics of the T-45

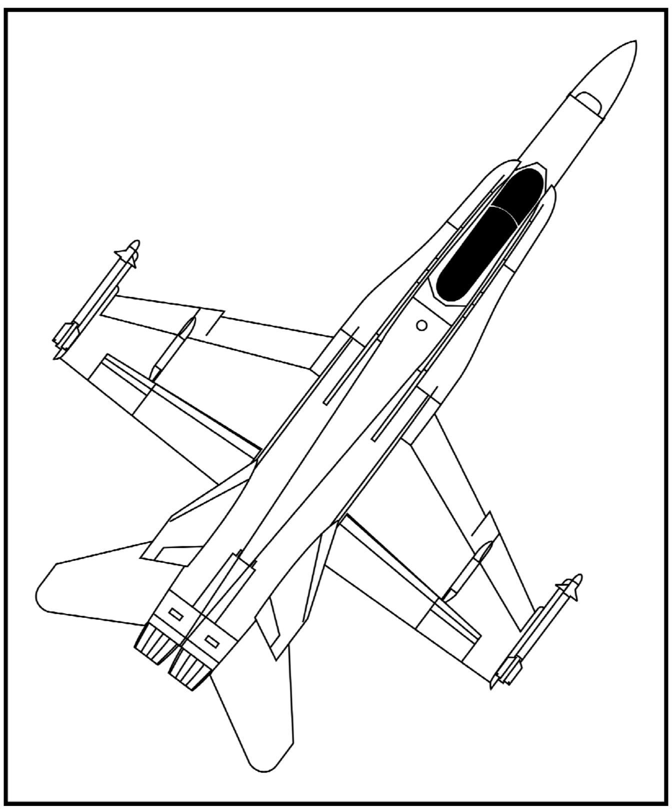

Figure 2-1 Supersonic F-18

Flight Regimes

In the study of subsonic flight, compressibility of airflow is normally ignored. It is important to remember that compressibility effects are not limited to flight greater than the speed of sound. Compressibility is progressive and the effects may be experienced in flight well below the speed of sound. Compressibility effects we will discuss are due to the pressure waves created. On any aircraft, there are local airflow velocities greater than the flight velocity. Both subsonic and supersonic airflow may exist on an aircraft in flight at transonic Mach numbers. These airflow velocities are used to define the flight regimes:

Subsonic Flight: All airflow about the aircraft is subsonic. (Up to 0.8 Mach for the T-45)

Transonic Flight: There is a mixed airflow about the aircraft, that is, part subsonic and part supersonic. (0.8 - 1.2 Mach)

Supersonic Flight: All airflow about the aircraft is supersonic. (1.2 - 5.0 Mach)

Because changes in pressure, density, temperature, and direction of airflow passing through a compression wave occur suddenly, compression waves are frequently referred to as "shock waves." There are three forms of the shock wave: the normal wave, oblique wave, and expansion wave.

Compression Wave Formation

As an object moves through the airmass, pressure disturbances are created in the airflow surrounding the object. These pressure disturbances are propagated through the air at the speed of sound in all directions (Figure 2-2). If the object is traveling at a speed less than the speed of sound, the pressure disturbances move away from the object but are compressed in the direction of motion, as the pressure waves cannot move uniformly away from the object (Figure 2-2). The pressure wave created by the object influences the airflow ahead of the object. The compression wave is not strong enough to obstruct airflow but acts like a wedge to divert the airflow around the object (Figure 2-2). When an object is traveling at speeds close to or greater than the speed of sound, the pressure disturbances are not propagated ahead of the object but "pile up" on each other to form a concentrated compression wave (Figure 2-2). The smooth subsonic flow is shown in Figure 2-3.

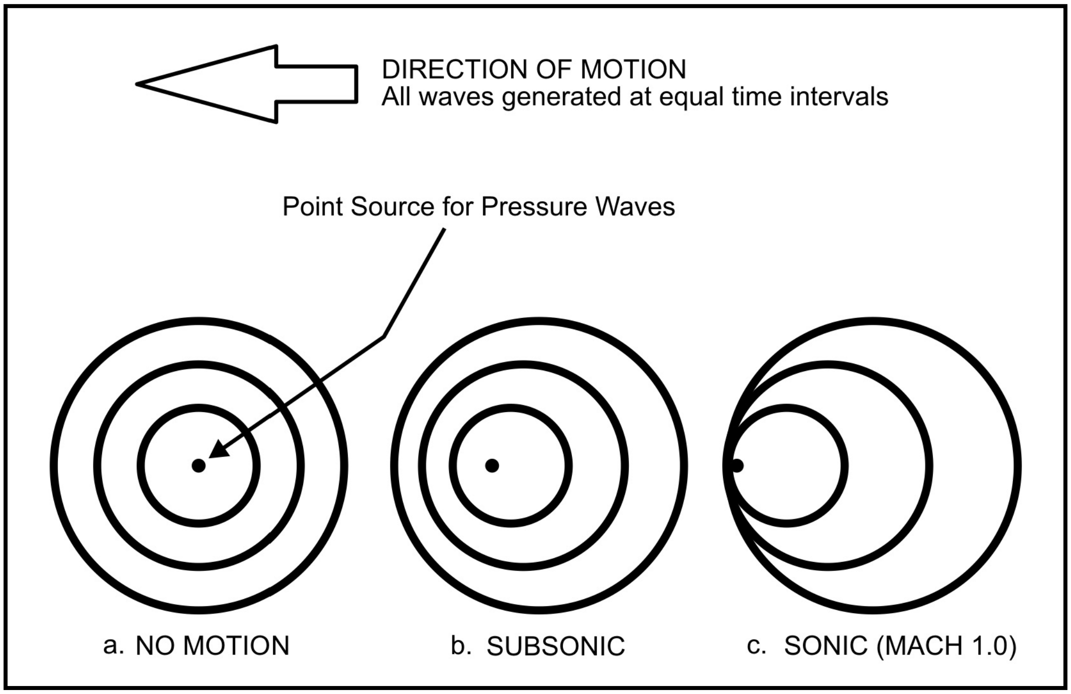

Figure 2-2 Pressure Wave Formation

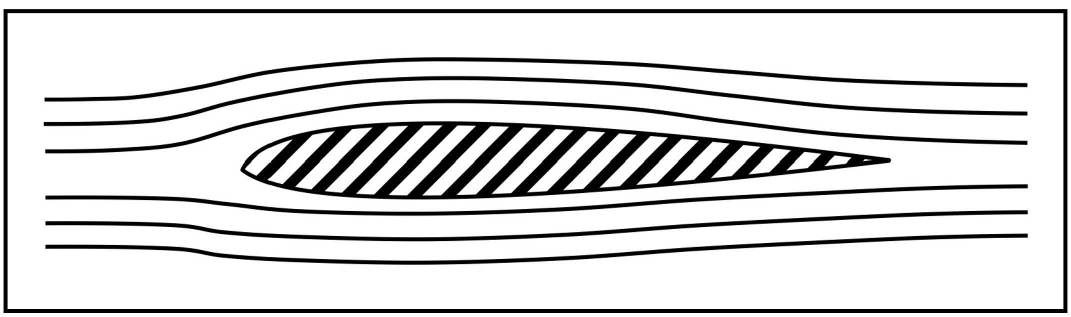

Figure 2-3 Typical Subsonic Flow Pattern

A typical supersonic airflow pattern is shown (Figure 2-4) for a nonsymmetrical wing flying at about Mach 1.05. Note, the bow wave is beginning to curve; at higher speeds (should the plane be capable), the bow wave will become increasingly parabolic. Just behind the bow wave, there is a specific zone of subsonic air. As speed increases, the bow wave comes closer to the leading edge of the airfoil; however, the bow wave will never actually attach to the leading edge of an airfoil. At high speeds, the bow wave will come so close to the leading edge that it will appear to attach, and may be considered attached, for all practical purposes.

As the airstream flows around convex curvatures of the wing, it will accelerate back to a supersonic speed, and in the process form a series of fanlike expansion waves. Those waves are really a series of mild shock waves that allow the airflow to "turn."

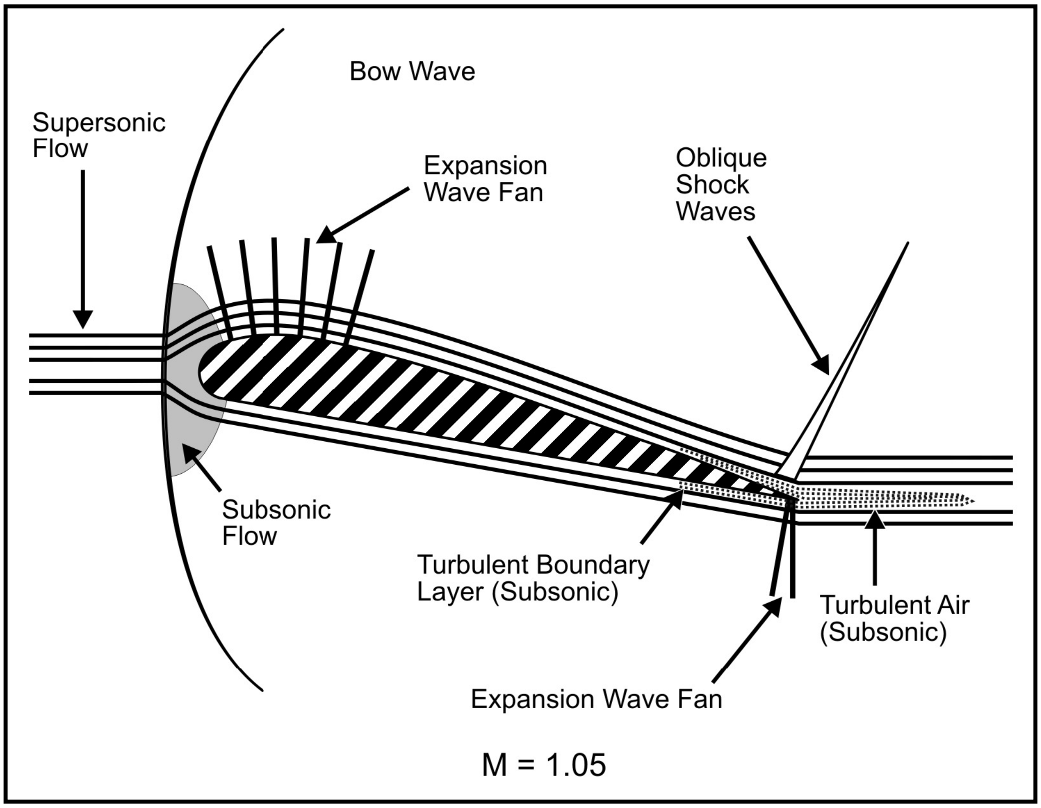

Figure 2-4 Typical Supersonic Flow Pattern

At the trailing edge of the wing, a compression shock wave forms as the airflow is again turned and redirected into the free-flow airstream. Turbulent boundary layer air is shown near the trailing edge. The degree of turbulence will depend upon variable factors such as surface smoothness and speed. This turbulence should be thought of as increased turbulent boundary layer air, rather than a product of boundary layer separation. A thin layer of turbulent boundary layer air exists over the entire skin of an airfoil, because the velocity of air decreases to zero at the skin surface. Finally, all the airflow that circulates around both surfaces of the wing is recombined, creating a turbulence in the trailing airstream.

Like sound waves, pressure waves move at a specific velocity depending upon air temperature. As the temperature decreases, molecular activity decreases and both sound and pressure changes are transmitted at a slower rate. Thus, the speed of sound is much less in the very cold temperatures at high altitudes (Figure 2-5).

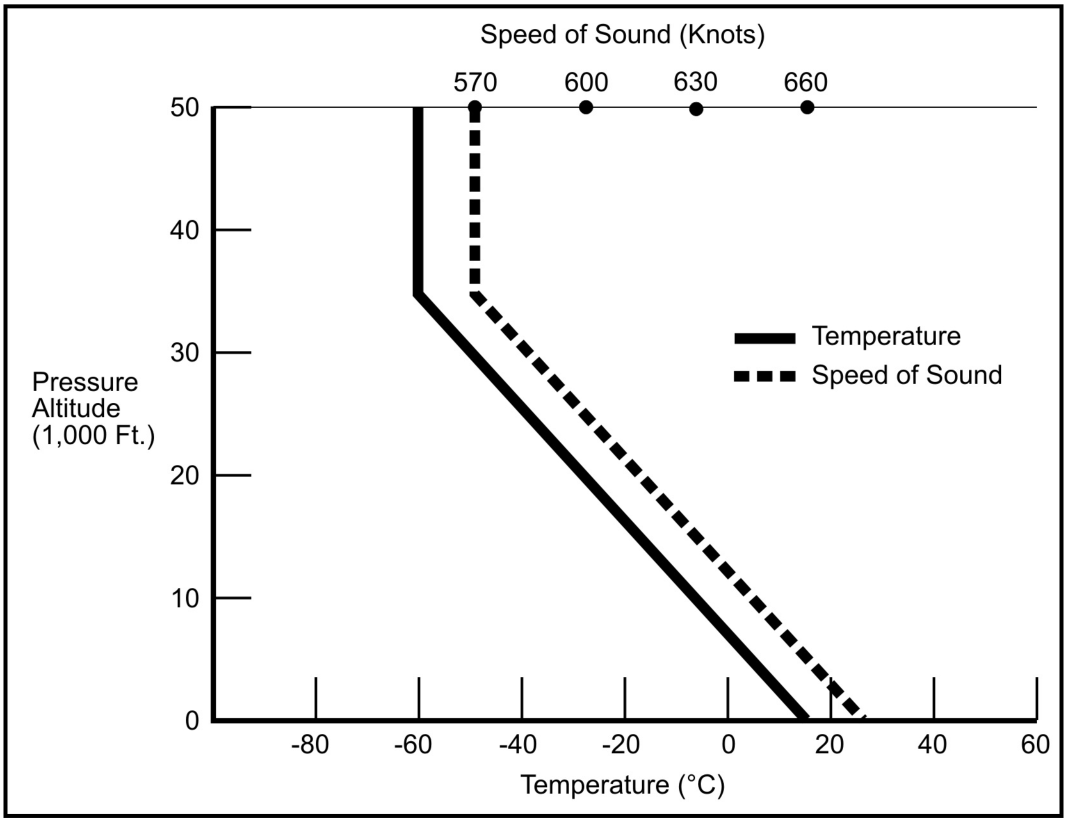

Figure 2-5 Temperature vs Speed of Sound

At sea level with a standard day temperature of 59°F (15°C), the speed of sound is 661.7 kts. At 15,000 ft with a standard day temperature of 5.5°F (-14.7°C), the speed of sound is 626.7 kts, and at 30,000 ft, the speed of sound is 589.6 kts with a standard day temperature of -48°F (-44.4°C). Compressibility effects will be experienced at lower airspeeds as altitude is increased. Mach Number is used to describe the relationship of airspeed to the speed of sound…..

M = TAS/SOS where:

M = Mach Number

TAS = True Airspeed

SOS = Speed of Sound

201. COMPRESSION WAVES

In our discussion we will consider the effect of airflow only on an airfoil section. Keep in mind that airflow about an aircraft is considerably more complicated.

Normal Compression Waves

Initially all airflow about the airfoil is less than the speed of sound (Figure 2-6). The airfoil is in the subsonic flight regime. However, velocity of the airflow about the airfoil is greater than the velocity of the free airstream. At some flight velocity, less than Mach 1, there will be an area of local sonic flow on the airfoil (Figure 2-7). This is the "Critical Mach Number" (M_{crit}) of the airfoil. Critical Mach Number is defined as the flight Mach number where there is first evidence of sonic flow on the aircraft. It is an important reference point because it is the beginning of the transonic flight regime. All compression waves and phenomenon occur at a Mach number greater than M_{crit}. As the airflow accelerates, the area of supersonic airflow increases. Pressure waves created in the area of supersonic airflow begin to pile up against the aft moving airflow. This "piling up" forms a weak normal compression wave. "NORMAL" is a mathematical term meaning perpendicular. Thus, a normal compression wave is perpendicular to the airflow. A supersonic airstream traversing a normal shock wave experiences a rapid reduction in velocity to subsonic speed. If the Mach number ahead of the compression wave is Mach 1.2 or less, the velocity of the airflow after the normal wave is approximately the reciprocal of Mach 0.85 (Figure 2-8). With the great reduction in velocity comes an increase in static pressure, density, and temperature. A great deal of kinetic energy is converted into unusable heat.

The possibility of boundary layer separation from the trailing edge of the airfoil and the degree of that separation relates directly to the aerodynamic design of the airfoil and the existent angle of attack.

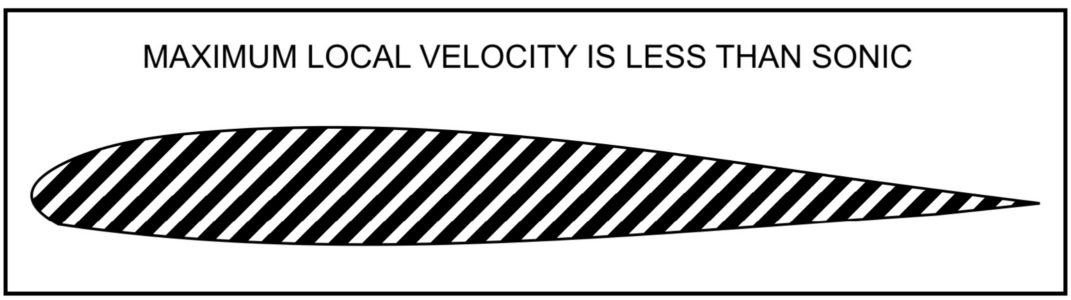

Figure 2-6 Compression Wave at Mach 0.50

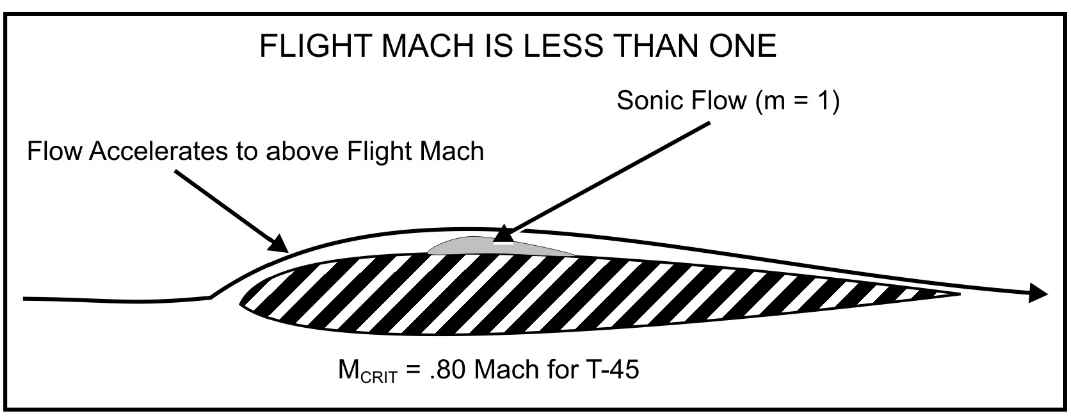

Figure 2-7 Compression Wave at Mach 0.80

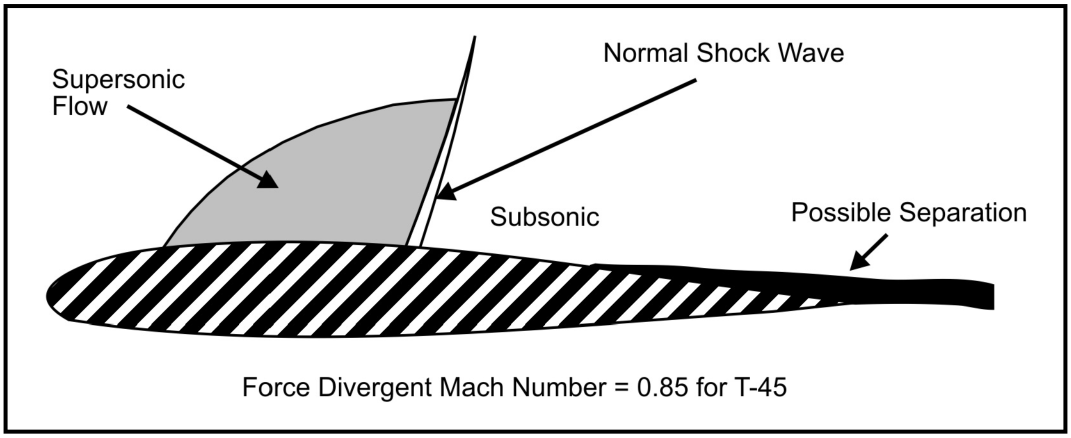

Figure 2-8 Compression Wave at Mach 0.85

As acceleration continues, the normal compression wave will strengthen and move aft. At some speed, approximately 5% above the Critical Mach Number, there is a rapid rise in the drag coefficient due to the formation of the normal compression wave. This speed is the Force Divergent Mach Number (M_{fd}), also known as the Drag Divergence Mach number (Figure 2-9). Additional drag arises from flow separation when it occurs.

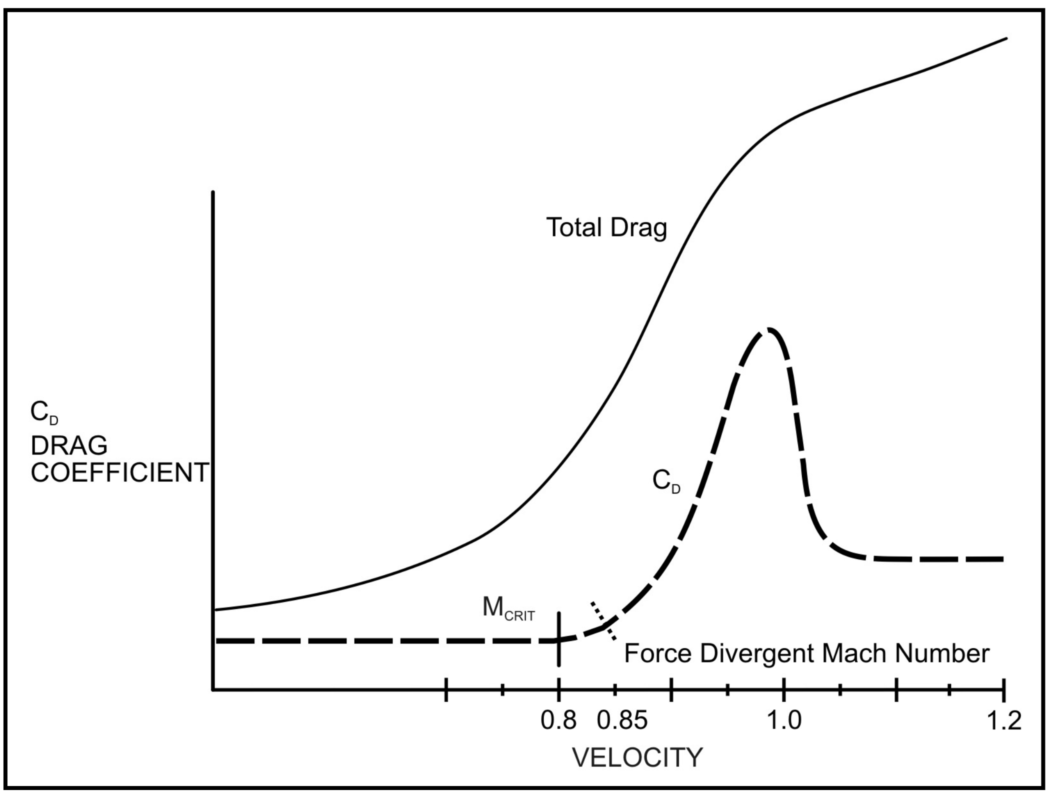

Figure 2-9 Force Divergent Mach Number

As flight speed is increased further, a bottom shock wave will appear (Figure 2-10). The compression wave on the lower surface is usually weaker than the one on the upper surface because acceleration over the lower surface is much less. Wave drag will continue to increase as the compression waves strengthen. Flight controls on the trailing edge of the airfoil begin to lose their effectiveness. In subsonic flight, flight control displacement affects the pressure distribution about the entire airfoil. With a normal wave present, the controls may be operating in a separated or "dead" layer air.

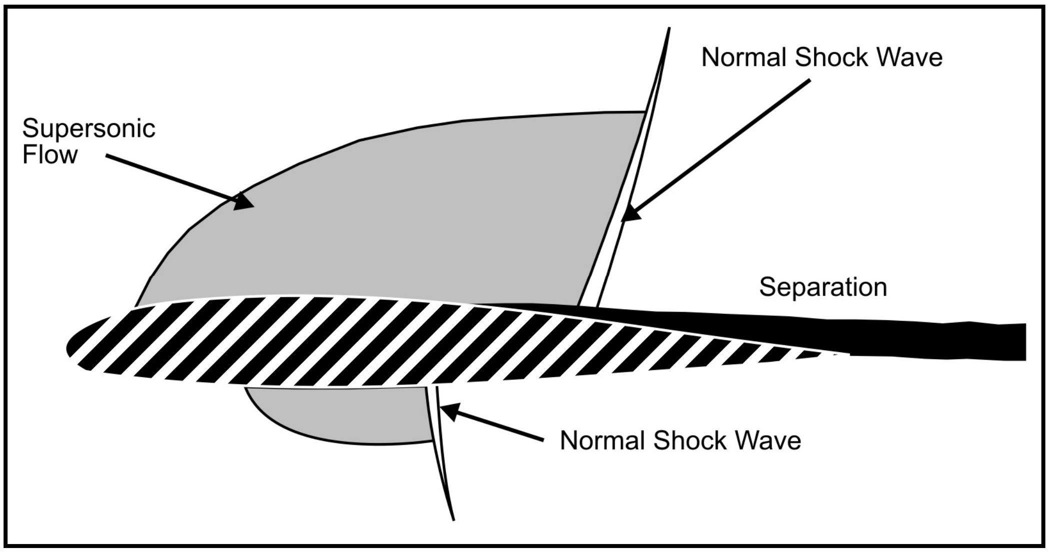

Figure 2-10 Compression Wave at Mach 0.92

Oblique Compression Waves

As airflow velocity continues to increase, the waves continue to move aft and eventually attach to the trailing edge and become "OBLIQUE" waves (Figure 2-11). An oblique angle is an angle greater than 90° which is measured from the airstream and, therefore, describes the oblique wave. A supersonic airstream, as it passes through oblique shock wave, slows down. However, the change in velocity through an oblique wave is not as great as through the normal wave and the velocity will remain supersonic. The airflow will experience an increase in static pressure, density, and temperature. Kinetic energy is converted to heat and lost. The angle of the oblique wave increases with an increase in the airstream Mach Number. Because the airflow is not perpendicular to the pressure wave, the airflow changes direction. Eventually, the airflow decelerates and becomes subsonic passing through a normal shock wave.

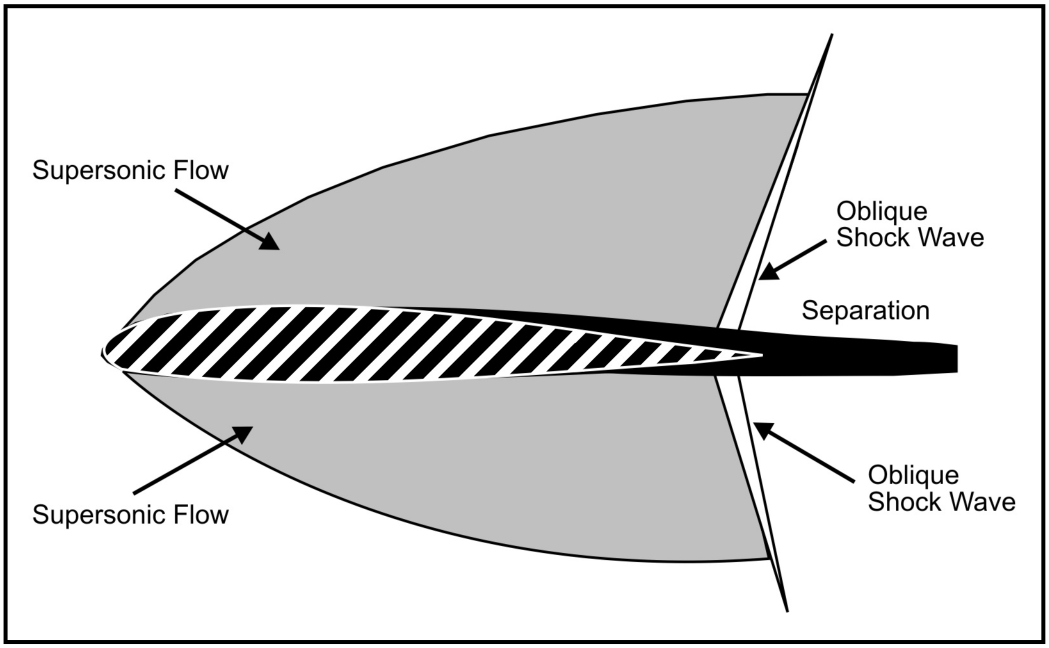

Figure 2-11 Oblique Wave at Mach 0.99

Bow Wave

While the above are occurring, the disturbances in the area forward of the supersonic airflow continue to send out pressure waves. As aircraft speed increases, these waves also pile up and form a bow wave (Figure 2-12). The bow wave is so named because it is similar to a wave in water off the bow of a boat. As the flight velocity approaches the speed of sound, the bow wave will be at or near the leading edge. If the leading edge is large, a large change in direction of the airflow around the object occurs. The large direction change reduces the velocity to subsonic and creates a stagnation region off the leading edge. Until the bow wave attaches, part of the airflow over the airfoil is subsonic and the aircraft remains in the transonic flight regime. The aircraft is not in the supersonic flight regime until all the airflow is supersonic. A detached bow wave possesses both normal and oblique compression wave characteristics. The portion of the detached bow wave perpendicular to the leading edge is normal to the airflow and has the characteristics of a normal compression wave. A stagnation region will be present with the accompanying pressure, density, and temperature increases. Away from the leading edge, the airflow direction change is reduced and, while the velocity is reduced, it remains supersonic. That portion of the bow wave is oblique to the airflow and has characteristics of an oblique pressure wave. If the leading edge radius is small enough or sharp, the bow wave will attach and become an oblique wave (Figure 2-13). An attached bow wave has only the characteristics of an oblique wave.

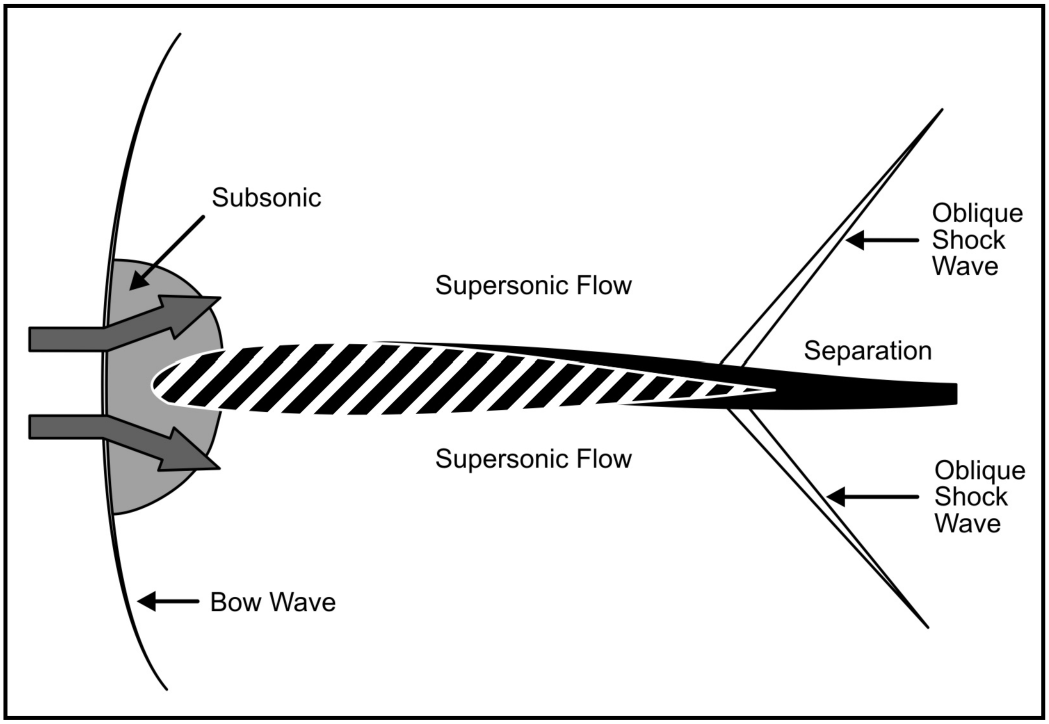

Figure 2-12 Bow Wave

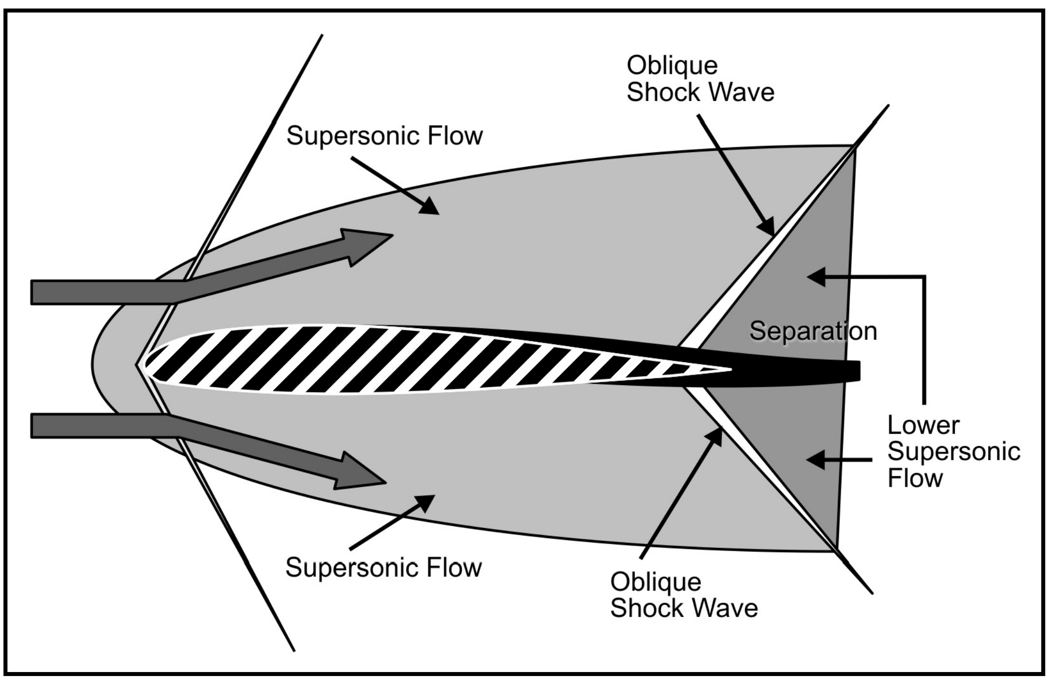

Figure 2-13 Attached Bow Wave

Coefficient of Drag and Total Drag

The formation of compression waves in transonic and supersonic flight brings about large changes in both the drag coefficient and total drag. A rapid increase in coefficient of drag and total drag occurs at the Force Divergent Mach Number and will increase until the normal waves reach the trailing edge. As the normal wave becomes an oblique wave, the coefficient of drag decreases but remains at a level greater than the subsonic coefficient of drag. As the coefficient of drag reduces, the rate of total drag increase is decreased. Figure 2-14 illustrates the behavior of the coefficient of drag and total drag curves.

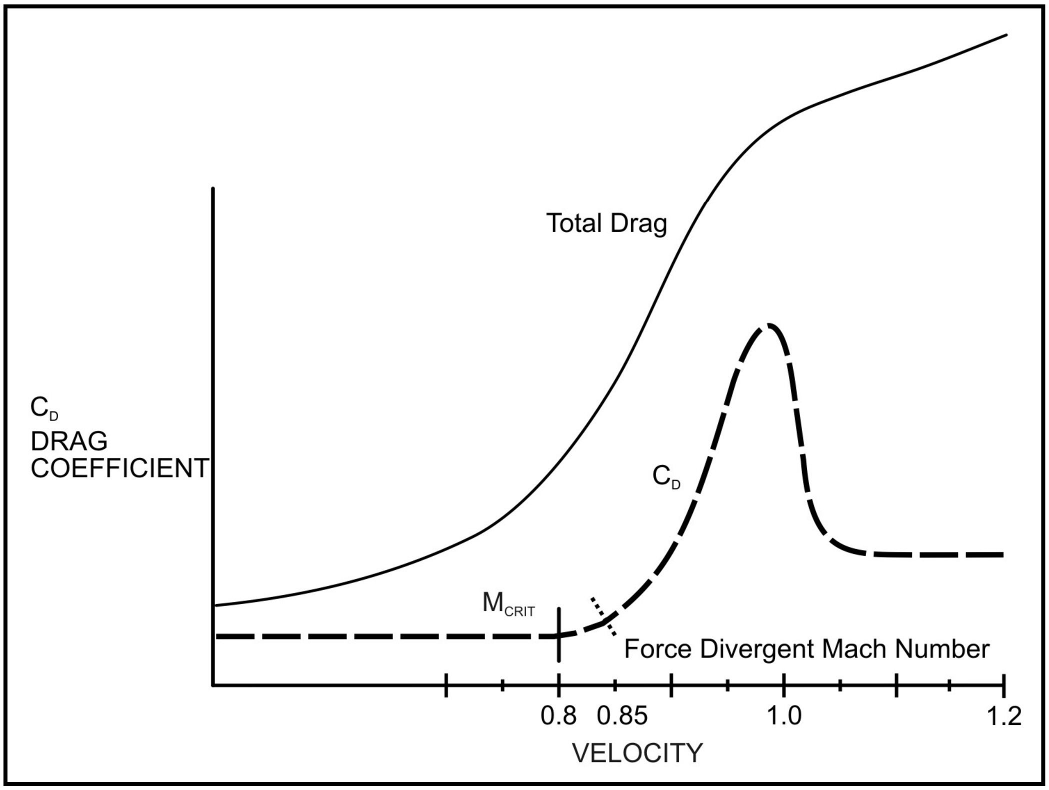

Figure 2-14 Coefficient of Drag at Force Divergent Mach Number

Transonic and Supersonic Effects on Stability

Any of several phenomena may be encountered as an aircraft accelerates into the transonic flight regime. They include buffeting, tuck under or Mach tuck, and wing drop or shock stall.

Buffeting. Buffet of the fuselage is caused by the turbulence associated with separation of the boundary layers as normal compression waves form. Buffeting will occur if the separated boundary layer is close to the fuselage or interferes with the horizontal tail.

Tuck under. As supersonic airflow is achieved over the wing, the aerodynamic center will start to move aft. The effect of the aft movement is to lengthen the lift-to-CG moment arm. As a result, nose down pitch or "tuck under" occurs. Tuck under is also known as Mach tuck. Normally, tuck under is not a sudden or violent action but rather a gradual nose down tendency as the aerodynamic center moves aft.

Wing drop. When compression waves form on the wing unevenly due to either physical differences in the wings or the attitude of the aircraft, separation of the airflow over one wing may occur before the other. That wing will produce less lift and a wing drop will occur. If separation of the airflow occurs over both wings simultaneously, the aircraft will pitch nosedown as in a typical low airspeed stall.

Depending on the aircraft design, any of these phenomenon may or may not occur. However, if any erratic movements should occur, they will be more severe when the Critical Mach Number is exceeded at low altitudes. At lower altitudes, the dynamic pressure for a given Mach Number is greater and results in greater changes in aerodynamic forces.

Other erratic movements associated with transonic flight may include random yaw caused by the greater wave drag on one wing and degradation of flight control effectiveness due to compression wave-induced separation. Lateral stability will degrade if lift distribution over the wing is affected by shock wave formation (Figure 2-15). As an aircraft is accelerated into the supersonic flight regime, longitudinal stability will increase as the aerodynamic center moves aft.

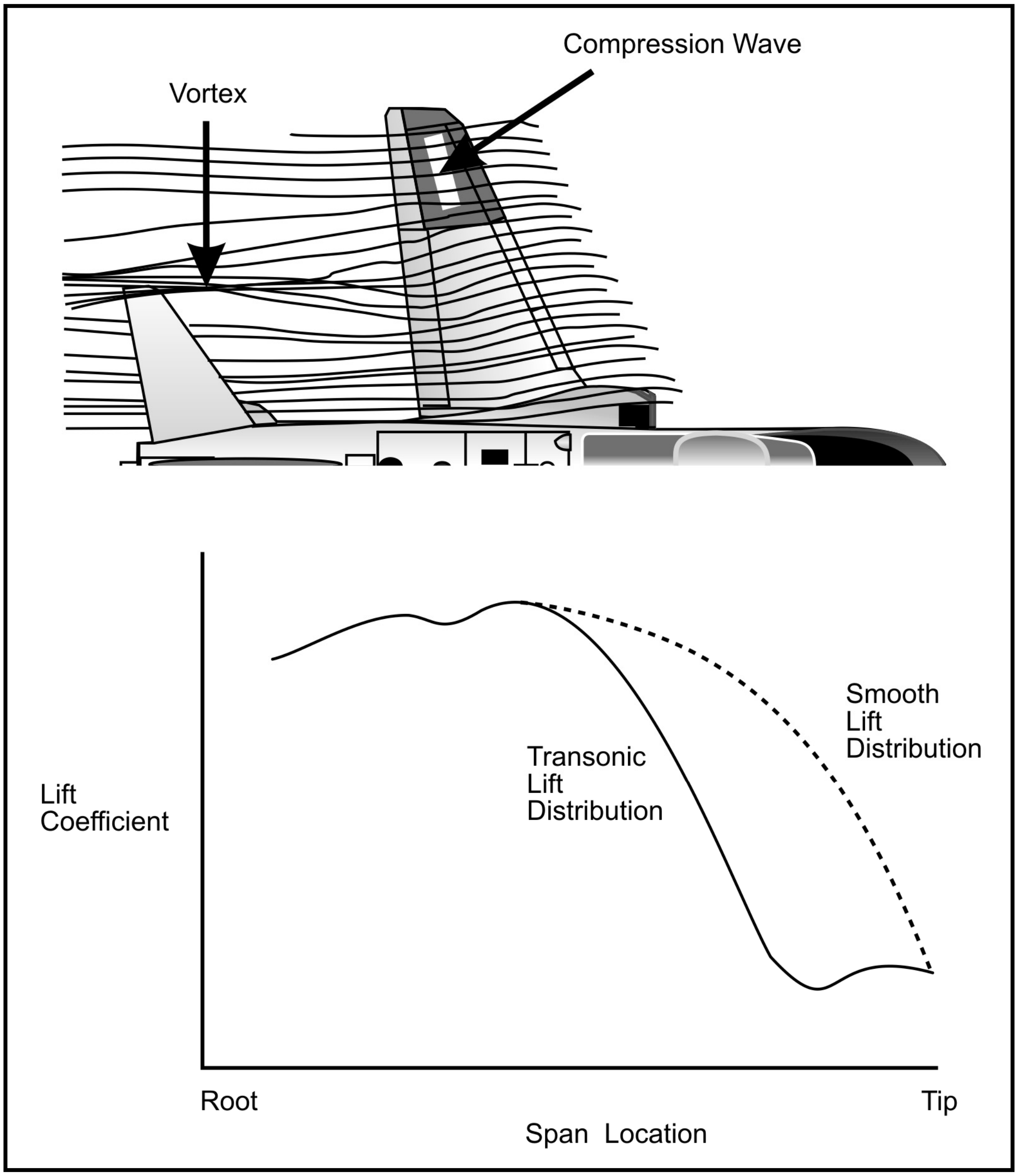

Figure 2-15 Transonic Stability

Transonic Pitchup

Transonic pitchup is a sudden and sometimes violent pitchup that occurs as the aircraft decelerates through a particular Mach number. An increase in downwash angle at the horizontal tail may occur as a result of a strong midspan vortex (Figure 2-16). The increase in downwash angle will contribute to transonic pitchup as positive pressure on the stabilator is reduced. The aft trim or stick position that was used to counter tuck under will cause the aircraft to pitchup suddenly if not relaxed as stabilator effectiveness is regained. Transonic pitchup may be great enough to overstress the aircraft.

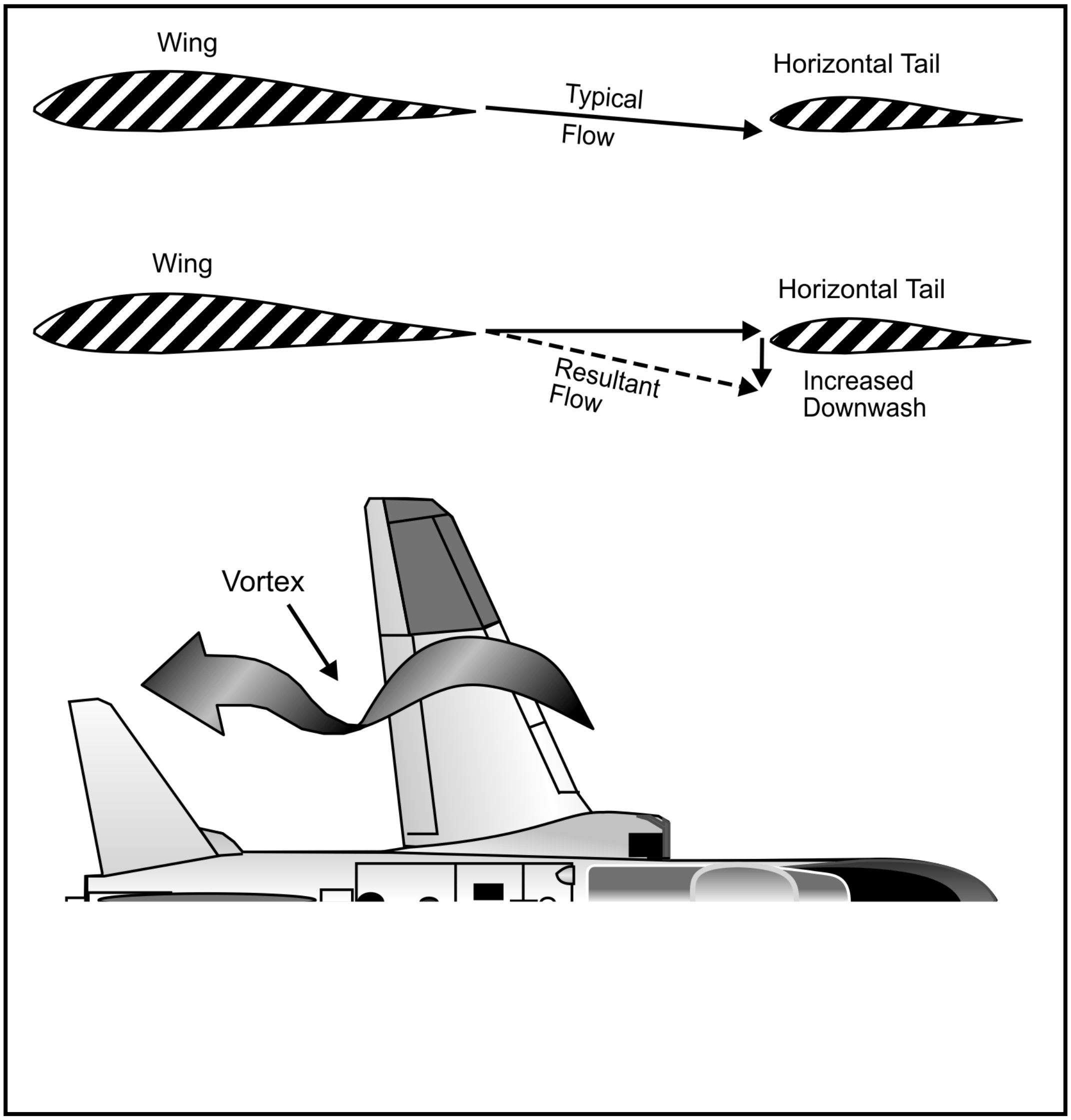

Figure 2-16 Transonic Pitchup

202. HIGH-SPEED AIRCRAFT DESIGN

Thickness-To-Chord Ratio

In order for aircraft to maintain maneuverability at high airspeeds, a means of delaying the Critical Mach Number and compressibility effects on the aircraft is necessary. One means of increasing M_{crit} is by using an airfoil section of low thickness-to-chord ratio (Figure 2-17). A low thickness-to-chord ratio or thin airfoil does not accelerate the air to the same extent as a thick or high thickness-to-chord airfoil. Compression waves will form at a higher Mach number and will not be as strong with the lower thickness-to-chord ratio wing.

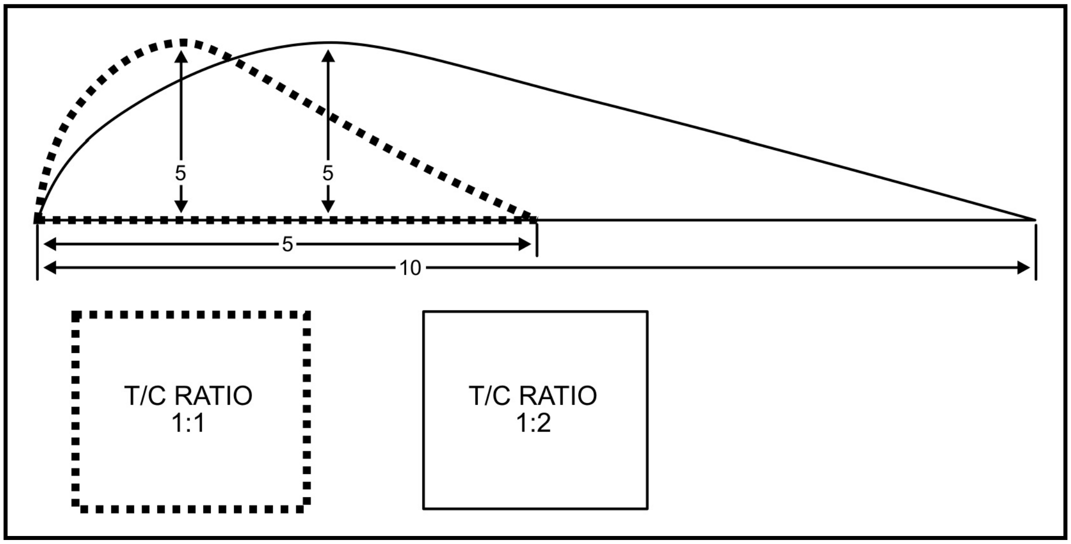

Figure 2-17 Thickness-to-Chord Ratio

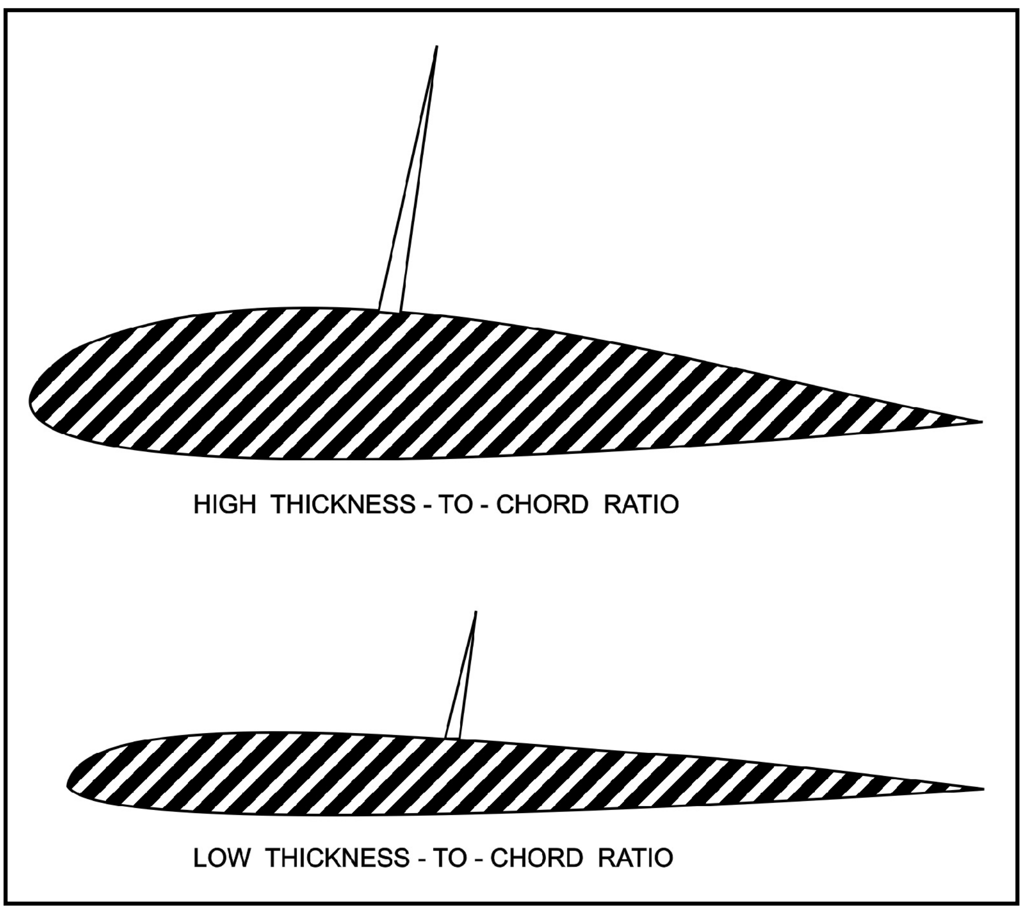

Figure 2-18 Thickness-to-Chord Ratio

In fact, wave drag varies as the square of the thickness-to-chord ratio. At supersonic speed, wave drag in the upper figure (Figure 2-18) is four times greater than the wave drag in the lower figure. However, an excessively low thickness-to-chord ratio would lead to extremely high stall, takeoff, and landing speeds. Additionally, the reduction in thickness-to-chord wings is limited by a lack of structural strength. Another factor that must be considered in aircraft design is an extremely thin wing provides no space for either landing gear or fuel tanks.

Wing Sweep

With greatest advantages in the transonic regime, sweepback will delay the onset of all compressibility effects and delay the onset of M_{crit} and the force divergence Mach number. The peak of drag rise will occur later, and maneuverability in transonic flight is preserved. Swept wings reduce the aspect ratio, frontal area, and parasite drag which allows higher speed flight. The low aspect ratio swept wing increases induced drag.

A means of achieving thin wing characteristics while using a thicker section is with wing sweep. Figure 2-19 illustrates how wing sweep "fools" the air into thinking the wing is of a thin airfoil section. The airflow over the swept wing "sees" a longer chord length than actual chord length or the chord of an equivalent straight wing and would have a reduced thickness-to-chord ratio. Figure 2-19 also illustrates the effect of vectoring airflow. Only the component of the airflow acting perpendicular to the leading edge contributes to compressibility effects. The spanwise component does not. Note that the perpendicular component of the airflow is of a lower velocity than the free airstream component. Figure 2-20 is based on the "wing of infinite length" theory but adequately illustrates the effect of wing sweep on reducing the peak drag rise and delaying the critical Mach number to a higher Mach number. The T-45 has 23.7° of wing sweep at 25% MAC and the stabilator has 30.1° of sweep.

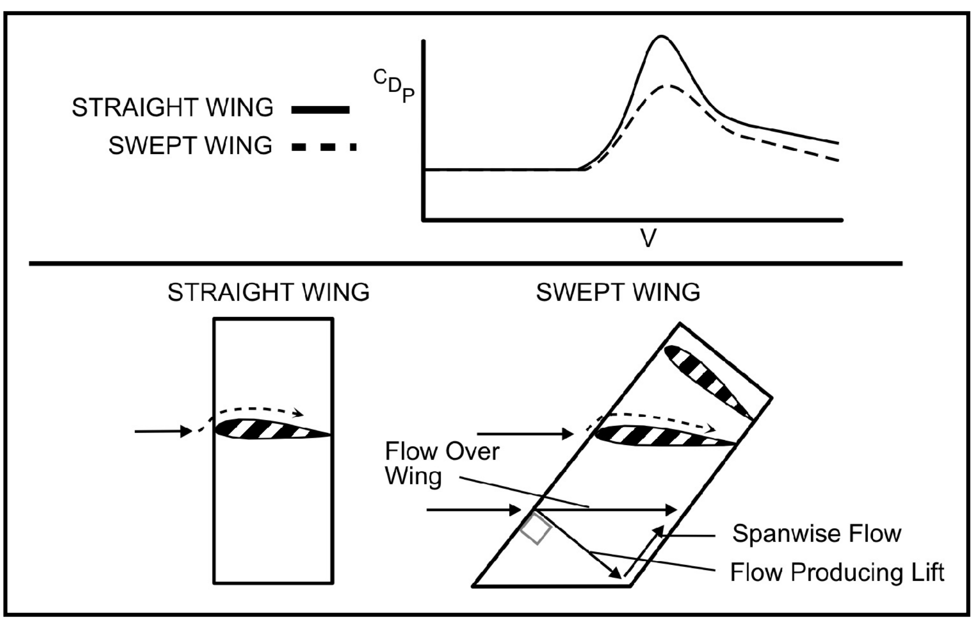

Figure 2-19 Effect of Wing Sweep on High-Speed Airflow

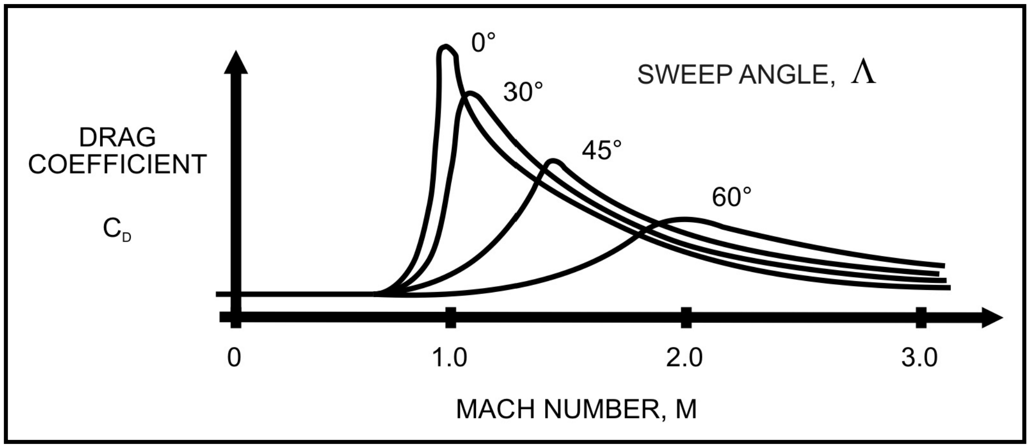

Figure 2-20 Effect of Wing Sweep on Drag

Interference Drag and Area Rule

In addition to wave drag, interference drag (a form of parasite drag) becomes very important at high flight speeds. Interference drag is broadly defined as increased drag due to airflow from one part of the aircraft interfering with airflow over another part. Tests established that the flow about a body at transonic and supersonic speeds is similar to the flow about a body of revolution, such as a bullet, having the same cross-sectional area. A body of revolution which has no "bumps" or abrupt changes in cross-sectional area along its length will produce less drag than one which has abrupt variations. We then have the concept that high-speed drag of an aircraft will be minimized if the distribution of cross-sectional area, including all parts (wings, fuselage, etc.), is made as smooth as possible. To satisfy this, the cross-sectional area of the fuselage must be reduced in the region of the wing and tail to compensate for the additional cross-sectional area of those surfaces (Figure 2-21). The term applied to that concept is Area Rule. Area rule is shaping the planform of an aircraft to cause the cross-sectional area to gradually increase and then decrease. Area rule has not been applied to the T-45.

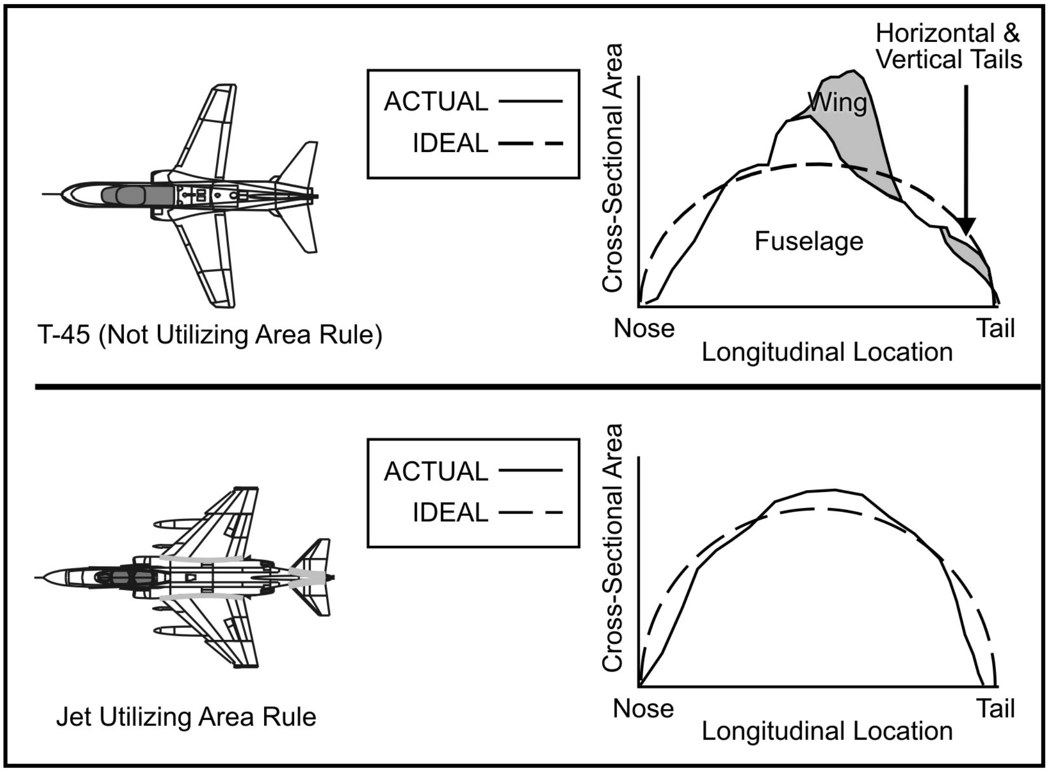

Figure 2-21 Area Rule

Flight Control System

By necessity, flight controls of a transonic or supersonic aircraft are different than those of a subsonic aircraft. Separation of the boundary layer behind a compression wave will occur as the wave strengthens. A control surface operating in the area of separated airflow (Figure 2-22) would be ineffective and not affect the pressure distribution about the rest of the airfoil. However, with a movable leading edge, either stabilator or movable horizontal stabilizer with elevators, the area forward of the shock wave will remain effective and affect pressure distribution about the airfoil (Figure 2-23).

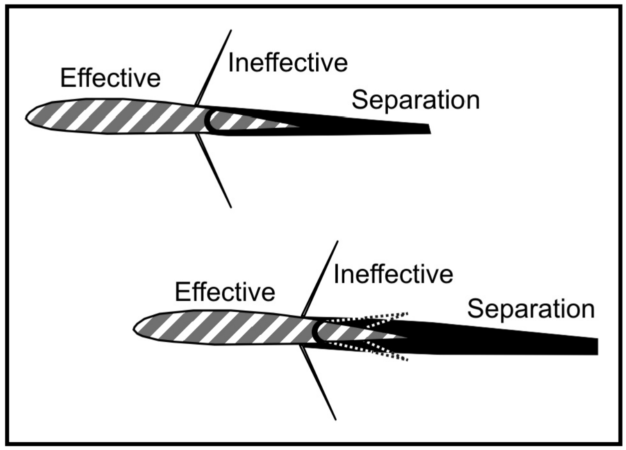

Figure 2-22 Ineffective Transonic Controls

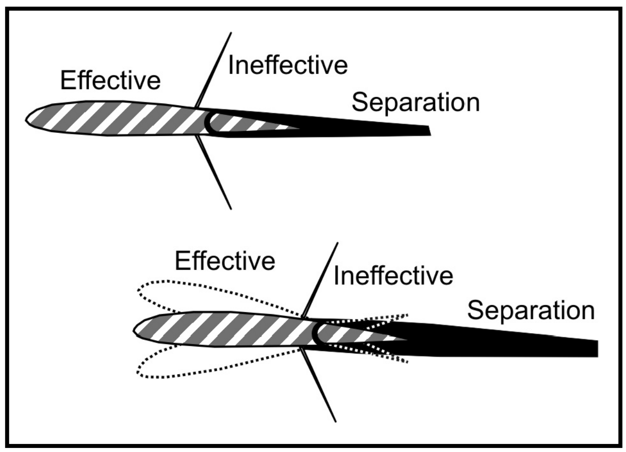

Figure 2-23 Effective Transonic Controls

Differential stabilizers (Figure 2-24), similar to those on the F-14 and F-18, provide not only pitching moments but also rolling moments. The T-45 does not have a differential stabilator system.

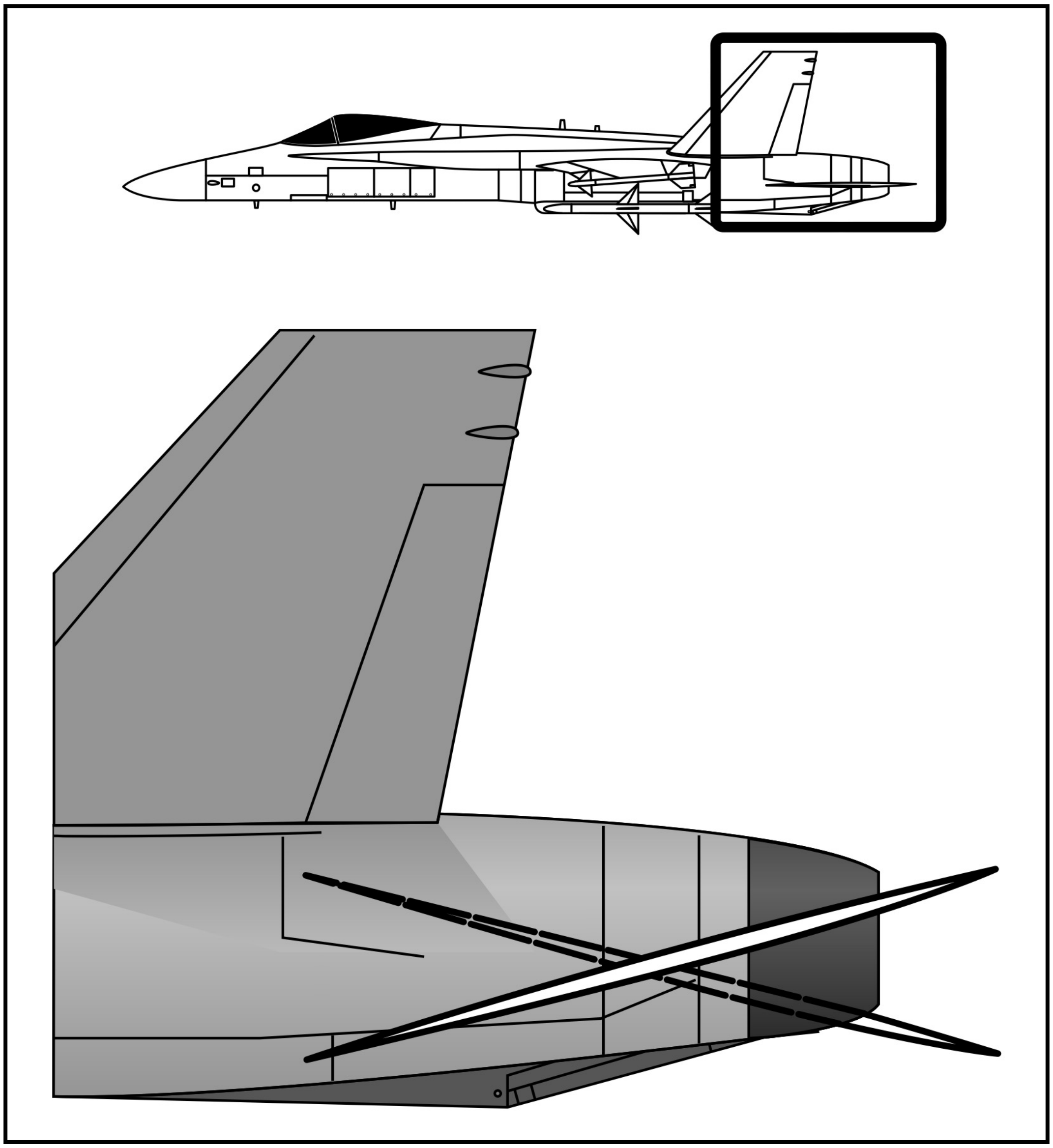

Figure 2-24 Differential Stabilizers

The T-45 has irreversible flight control systems powering ailerons and the stabilator. Aircraft hydraulic systems magnify the pilot's commands and permit aircraft control during high-speed flight. Aerodynamic pressures are not fed back to the pilot from control surfaces as, for example, a shock wave forms on the control surface (Figure 2-25).

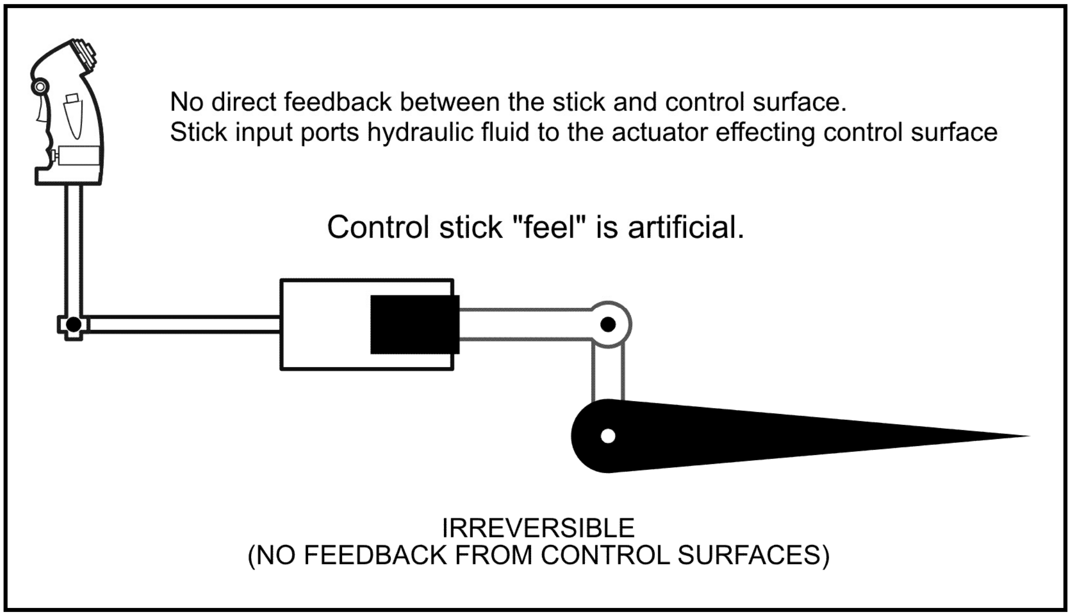

Figure 2-25 Fully Powered Control System

In contrast, the T-45 rudder is a conventional control system having no hydraulic boost or electronic assist (Figure 2-26). Aerodynamic forces may cause rudder vibrations that are fed back to the rudder pedals through the mechanical linkage and are called "rudder buzz." If the rudder "blows out" due to side loads during a post-stall gyration (PSG) or spin, the rudder pedals will be displaced and in excess of 250 pounds of force may be required to center the rudder.

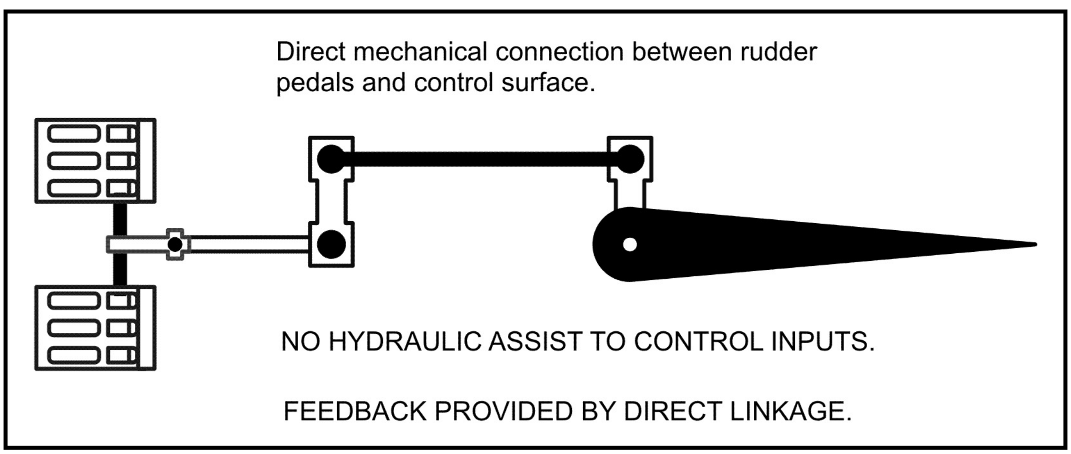

Figure 2-26 Conventional Control System

High-Speed Engine Operation

No operational turbojet or turbofan engine can ingest and operate with supersonic airflow. The shock waves that would form on the fan or turbine blades would cause engine malfunction. Consequentially, in transonic or supersonic flight, all intake airflow must be decelerated to subsonic velocity prior to reaching the engine. Typically, deceleration takes place through a series of compression waves created by the design of the aircraft's intake (Figure 2-27). The airflow velocity will first be reduced to a slower supersonic velocity by one or more oblique waves and then slowed to subsonic velocity through a normal wave. The F-14 uses an adjustable inlet ramp system which reduces the inlet cross section in supersonic flight and creates multiple oblique shock waves to slow the supersonic air.

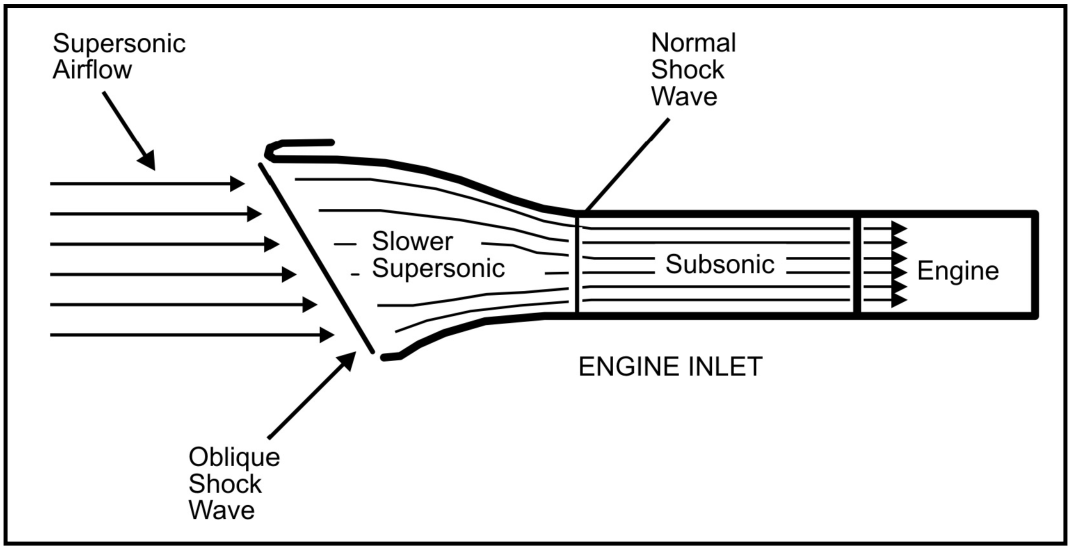

Figure 2-27 Supersonic Flow in an Engine Inlet

Vortex Generators

Regarding efficient high-speed flight, it is undesirable to place vortex generators on any aircraft surface: wing, tail, or fuselage. The obvious reason is that all add-on protuberances increase aircraft parasite drag. Additionally, the need for vortex generators increases aircraft design time and overall cost. Notwithstanding, at times wind tunnel and/or flight tests identify aircraft performance shortcomings in critical flight regimes that must be corrected with vortex generators.

The primary purpose of vortex generators is to improve aerodynamic stability, performance, and/or flight control effectiveness. They come in various sizes and shapes (Figure 2-28). On some aircraft, they are utilized to improve stall performance. On others, they are used to improve flight performance in subsonic and/or transonic flight realms.

During development of the T-45, it became necessary to add vortex generators to prevent wing downwash from adversely affecting stabilator performance in the transonic flight regime. They were placed along the 25% chord line on the topside of the wing (Figure 2-29) to force wing downwash further below the stabilator, thus eliminating some undesirable pitchup tendencies. Vortex generators also improve the aircraft's slow-speed flight performance by redirecting wing airflow and reenergizing the boundary layer.

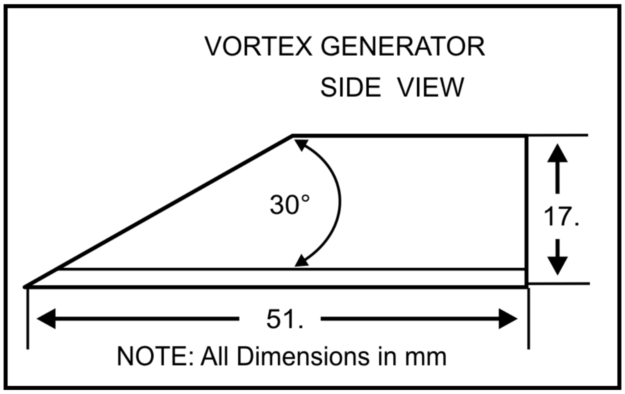

Figure 2-28 Vortex Generators

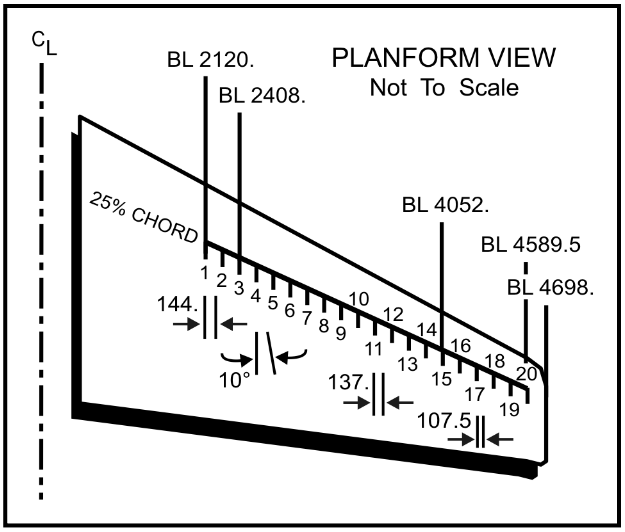

Figure 2-29 Vortex Generators

Rudder Shock Stabilization Strips

The T-45 rudder system is of conventional design. As flight velocity advances into the transonic range, supersonic compression shock waves form on various parts of the aircraft. Some of those shock waves were determined to cause a unique problem with the rudder that was not anticipated during original aircraft design. Transonic regime shock waves were forming on and near the rudder assembly. The main problem was that they were not maintaining a stable position. Consequently, the tail assembly experienced "rudder buzz" problems. To eliminate "rudder buzz," a rudder shock stabilization strip was added to each side of vertical stabilizer, plus another to each side of the rudder. The specific effect of the stabilization strips is to cause the transonic shock waves that form in this area to stop moving back and forth, and to instead stabilize atop these add-on metal strips.

This "fix" has improved the situation, but has not eliminated "rudder buzz." As shown in Figure 2-30, one strip is located at the 50% tail chord position, and the other is on the rudder just aft of the rudder hinge line. A cross-sectional depiction of the strips is also shown. Figure 2-31 is a top view of the fin and rudder.

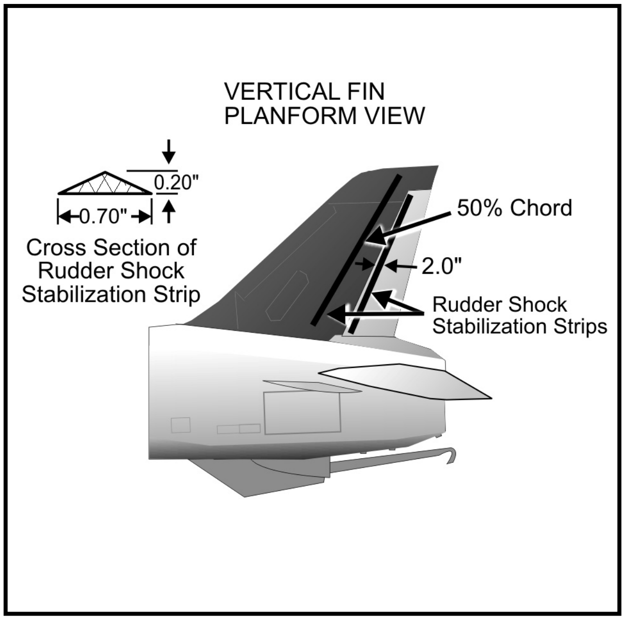

Figure 2-30 Rudder Shock Stabilization Strips (1 of 2)

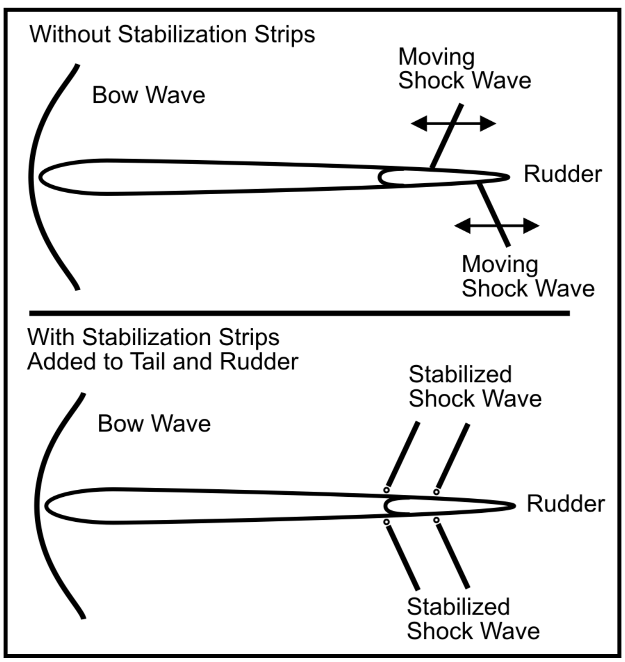

Figure 2-31 Rudder Shock Stabilization Strips (2 of 2)

203. T-45 HIGH-SPEED FLIGHT CHARACTERISTICS

Significant Mach Numbers

The T-45 is a transonic aircraft. The maximum level speed attained is 0.83 Mach with the maximum speed achieved being 1.04 Mach. 1.04 Mach is attainable only in a dive in a clean configuration. The critical Mach number of the T-45 is 0.8 Mach. The force divergent Mach number occurs at 0.85 Mach. As airspeeds increase past 0.9 Mach, slight buffeting is felt that may increase as Mach number increases. Between 0.92 and 0.95 Mach, some wing heaviness may be experienced.

Longitudinal Control

As the aircraft is accelerated above 0.8 Mach, there is a slight nosedown pitch change as the aerodynamic center moves aft. Longitudinal control is predictable to about 0.84 Mach. At a Mach number greater than 0.84 Mach, stick forces become noticeably more sensitive and a band of reduced longitudinal stability exists at approximately 0.87 Mach. Above 0.95 Mach, slight pitch oscillations may be present as the center of pressure moves aft. As airspeed increases above Mach 1.0, stability increases and greater stick forces are required to affect a pitch change because of the aft location of the center of pressure (Figure 2-32).

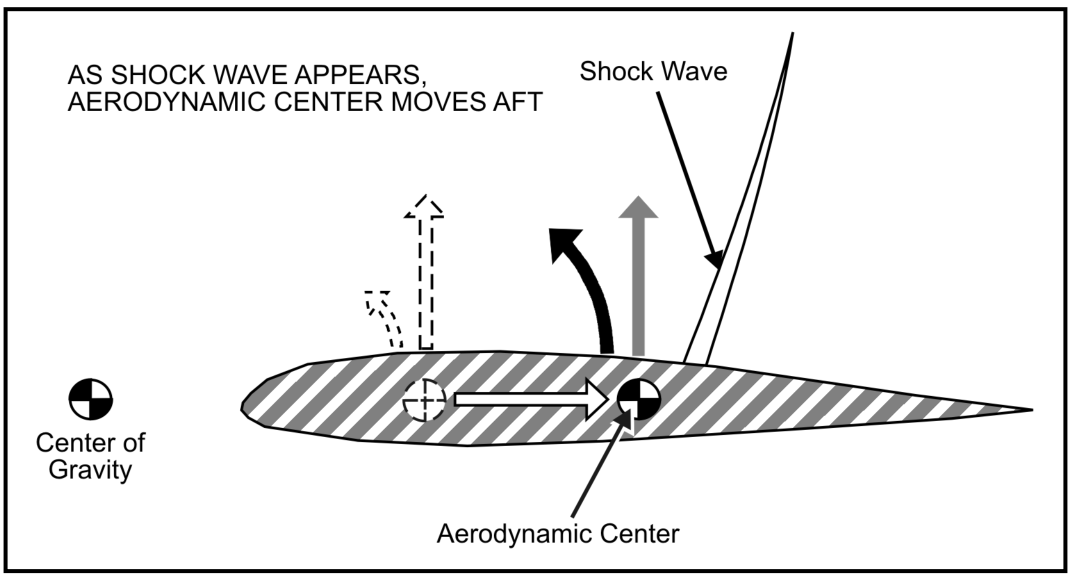

Figure 2-32 Aft Movement of the Center of Pressure

Lateral Control

Lateral control remains crisp to 0.9 Mach. During loaded rolls at Mach numbers greater than 0.8 Mach, roll response can be unpredictable. Roll rates greater than 260° per second may occur due to reduced roll damping at AOA near stall.

At approximately 0.92 Mach, either wing may become heavy due to a normal shock wave in the wing tip area, reducing wing tip effectiveness (Figure 2-33). The aircraft will begin a slow roll. Up to 3/4 lateral stick deflection may be required to maintain wings level flight. Between 0.92 and 0.95 Mach, roll rate degrades rapidly with roll rates as low as 27° per second observed at 0.95 Mach with full stick deflection. As speed increases through 0.95 Mach, wing heaviness disappears and aileron authority returns. Above Mach 1.0, full stick aileron rolls can generate a roll rate of approximately 120° per second.

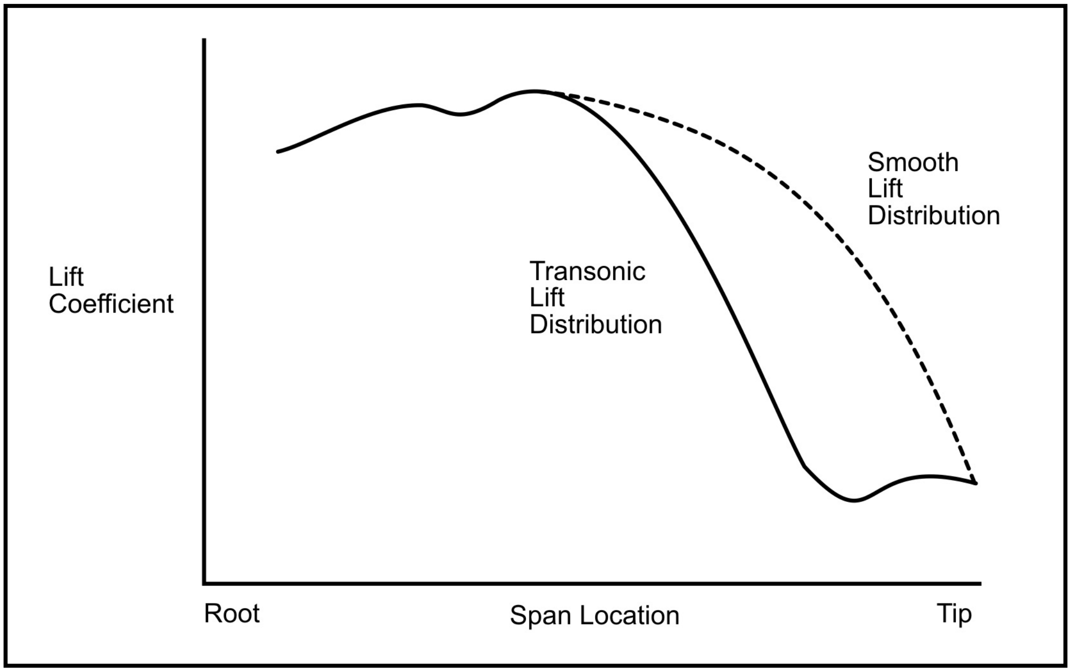

Figure 2-33 Lateral Control

Transonic Pitchup

Shortly into recovery from the dive, at Mach 0.99, a sharp pitchup occurs that must be countered by quickly relaxing back stick to avoid overstress of the aircraft. This pitchup occurs due to the sudden shift in center of pressure as the aircraft slows. No more than 4.0 g's should be maintained following the first pitchup because it is followed shortly by a second pitchup during deceleration between Mach 0.95 and 0.85 as AOA reaches 10 - 11 units. Following the second pitchup, longitudinal characteristics become predictable.

NOTES

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CHAPTER THREE
HIGH AOA/STALL/SPIN

300. INTRODUCTION

High-speed carrier aircraft must be adapted to fly the slow approach speeds necessary to land aboard the carrier. In designing an aircraft, performance trade-offs occur to permit operation at high and low speeds. The capability to land an aircraft on an aircraft carrier is one of the most demanding of requirements and often leads to the addition of high lift devices on the high-speed aircraft.

The Navy's angle of attack system permits the pilot to fly an approach at optimum airspeed in recognition of the aircraft's weight and configuration. The angle of attack is the angle formed between the relative wind and the chord line of the airfoil. The Navy has long used AOA to optimize an aircraft's approach speed to the aircraft carrier. AOA is more sensitive than the pitot static airspeed determinations at low speed. At high speed, the reverse is true. AOA outputs can be used to determine approximate airspeeds for certain functions should the pitot static system ice up or fail. The pocket checklist and NATOPS contain AOA indications for various aircraft functions.

301. LIFT-TO-DRAG RATIO (L/D)

L/D is the ratio of lift to drag obtained by dividing the lift by the drag or coefficient of lift by the coefficient of drag. It is a measure of the wing's efficiency and also is the power off glide ratio at a given AOA.

Lift-to-Drag Ratio Maximum - $(L/D)_{max}$

$(L/D)_{max}$ is the greatest ratio of lift to drag. $(L/D)_{max}$ angle of attack is the most efficient AOA for that airfoil.

302. SWEPT WING

A swept wing has many aerodynamic differences from a straight wing. The overriding differences and the reason that swept wings are incorporated in aircraft designs is to delay the onset of compressibility effects to higher speeds and reduce the forces on the wing caused by compressibility. The effect of this is to reduce drag and improve maneuverability in transonic flight.

The swept wing and straight wing aircraft each have their advantages and disadvantages. A primary distinction between the wing designs is the aerodynamic stall characteristics. Straight wings display abrupt stall characteristics and minimal stall warning; whereas swept wings tend to enter their stall regimes as the stall develops to the maximum. On a graph of C_L versus AOA, the straight wing develops C_L on a more vertical line and stalls quicker. The swept wing increases C_L more gradually and stalls at a higher AOA and lower C_L over a greater AOA range (Figure 3-1).

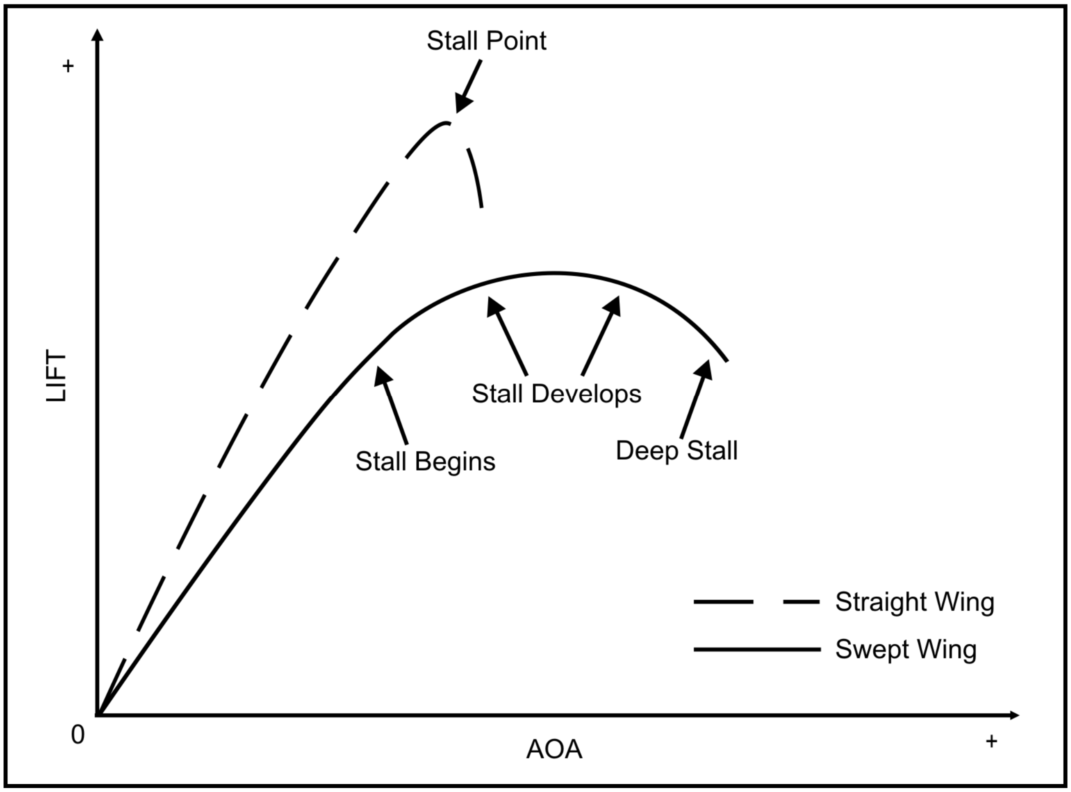

Figure 3-1 Swept Wing vs Straight Wing Characteristics

In a swept wing aircraft, high-speed stall entry tends to be more abrupt in onset and severity than in the low-speed regime stalls. Also, at high airspeeds when rapidly flown into stall, many swept wing aircraft designs will enter a departure, which is loss of aerodynamic stability along one or more axes of flight: lateral, longitudinal, vertical.

A SUMMARY OF SWEPT WING:

ADVANTAGES	DISADVANTAGES
Permits higher speeds	Develops less C_L
Structurally stronger for a given span	Prone to tip stall
	Spanwise flow
	Leading edge vortexing
	Uncontrolled pitchup in some aircraft
	Subject to departures/spins
	High induced drag at low speed

Table 3-1 Summary of Swept Wing

At subsonic speeds, maximum lift is lower and induced drag higher than in straight wings. As a consequence, the aircraft is more "cocked up" in landing approaches. Sweep back reduces effectiveness of trailing edge devices such as ailerons and flaps. Thus, swept wing aircraft tend to have higher approach speeds and need more power during the approach. They, therefore, have less excess power and can enter a stall on the back side of the power curve more easily than straight wing aircraft.

Airflow on the Wing

The swept wing produces less lift at all speeds than the straight wing with similar wing area and chord. Tip stalling is a problem on swept wing aircraft due to spanwise airflow that is exacerbated by leading edge vortexing (Figure 3-2), air that jumps from the high pressure on the bottom of the wing around the leading edge to the top of the wing and moves toward the wing tip. This spanwise flow reduces the wing tip's laminar flow and contributes to tip stall. Increasing angle of attack increases the leading edge vortexing, spanwise flow, and tip stalling tendency. Stall fences were an early solution to spanwise flow and illustrate one method of reducing the problem. The tip stalling causes the center of pressure of the wings to move in and forward as the AOA increases. In turn the AC moves forward and closer to the CG which reduces the longitudinal stability (Figure 3-3). Also, the loss of aileron effectiveness reduces lateral stability.

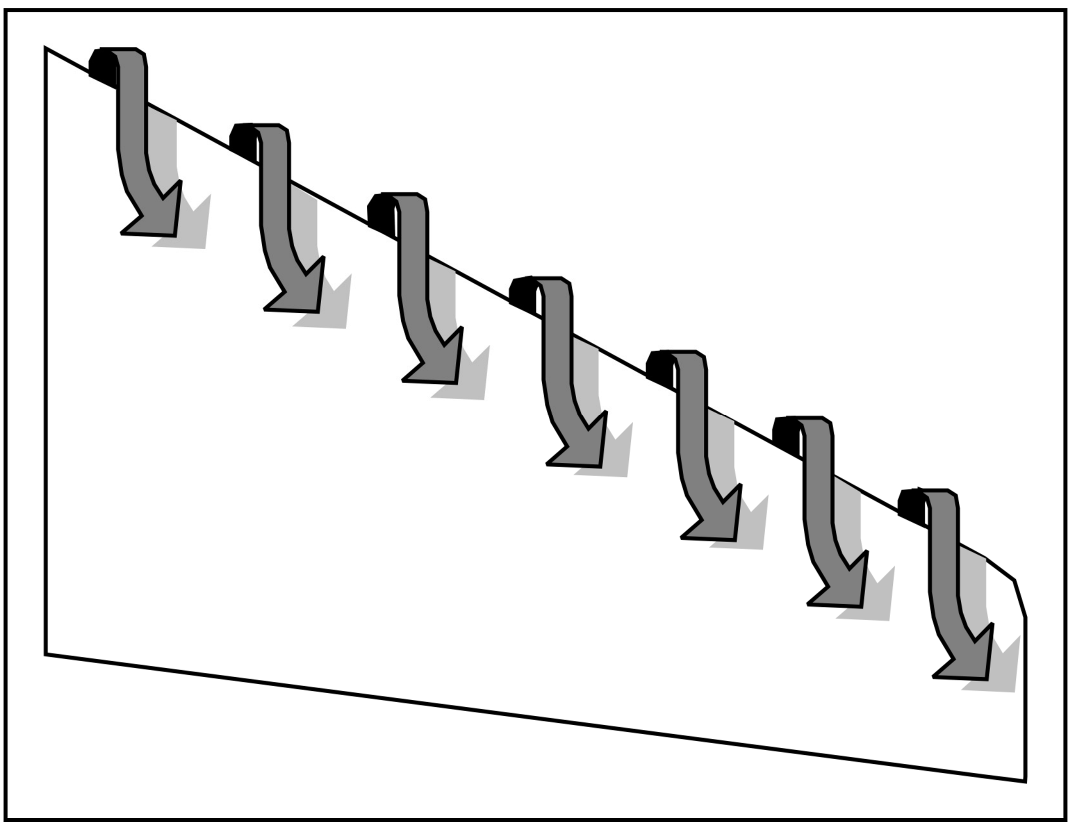

Figure 3-2 Leading Edge Vortexing

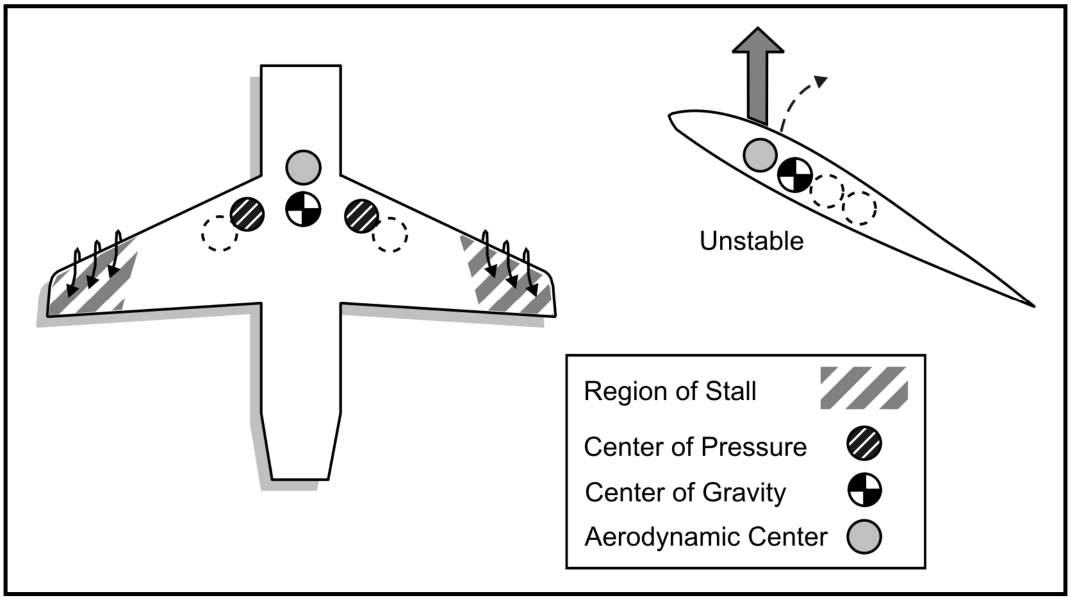

Figure 3-3 Tip Stall

Tip Stall Effects

While tip stall is defined as the stall of the outer portion of the wing (Figure 3-3), a wing does not necessarily stall everywhere along its length at the same AOA. Tip stall may cause a loss of ailerons and reduced control near stall.

Tip stall often comes with swept wing design and is undesirable since there would be little stall warning, a serious reduction in lateral control effectiveness and the forward shift of the center of pressure would contribute to pitchup. Since impending root stall is primarily signaled by turbulence from the root impacting the stabilator, the pilot would receive little natural warning if the tips stalled well before the root.

Tip stall causes the center of pressure (CP) on each wing to move in and forward (Figure 3-3). The aerodynamic center (AC) consequently moves forward relative to the CG. Should the AC move forward of the CG, the aircraft could pitch up uncontrollably if the stabilator cannot counter the pitchup. The T-45 does not have sufficient stabilator effectiveness to raise the nose high enough to achieve a total loss of longitudinal stability at slow speed.

303. ROOT VERSUS TIP STALL

The aeronautical engineer and flight conditions determine the relationship between the onset of root stall and tip stall. Ideally the pilot wants control of the aircraft all the way to stall. The aircraft is consequently more controllable, predictable, and less violent at stall.

The tip is more prone to stall than the root due to the lower camber and shorter chord length at the tip (Figure 3-3). The energy level of the boundary layer is also lower at the tip, aggravated by spanwise flow and leading edge vortexing.

Stall Strips

Stall strips are sharply angled devices installed on the wing and slat leading edges near the fuselage. The strips on the leading edge of the wing cause the root to stall at a lower AOA by inducing premature boundary layer separation at high angles of attack in the landing configuration. The slat leading edge stall strips contribute to root stall at high speed (Figure 3-4).

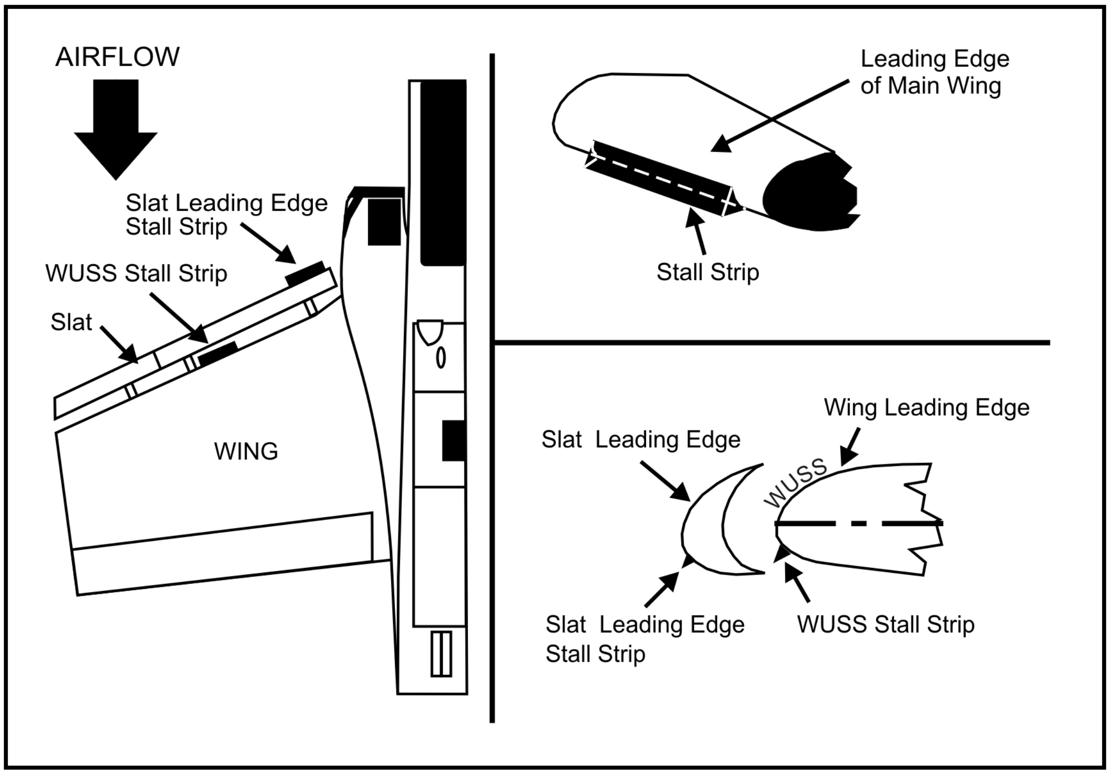

Figure 3-4 Stall Strips

Geometric Twist

Geometric twist is the twist of an airfoil having different geometric angles of attack at different spanwise stations. In the early 1990s, the T-45 stalled dramatically at the tips and rolled off violently. Modifications were made to make the root stall and tip stall occur at approximately the same time. The incidence of the outboard leading edge was modified with 3.5 degrees of geometric twist to make the tip stall at a higher AOA (Figure 3-5).

Combined effect of the geometric twist and the stall strips is that the root and tip stall at approximately the same time (Figure 3-6). The pilot is now able to control the aircraft into the stall, and only a 25-30 degree roll-off occurs at the stall.

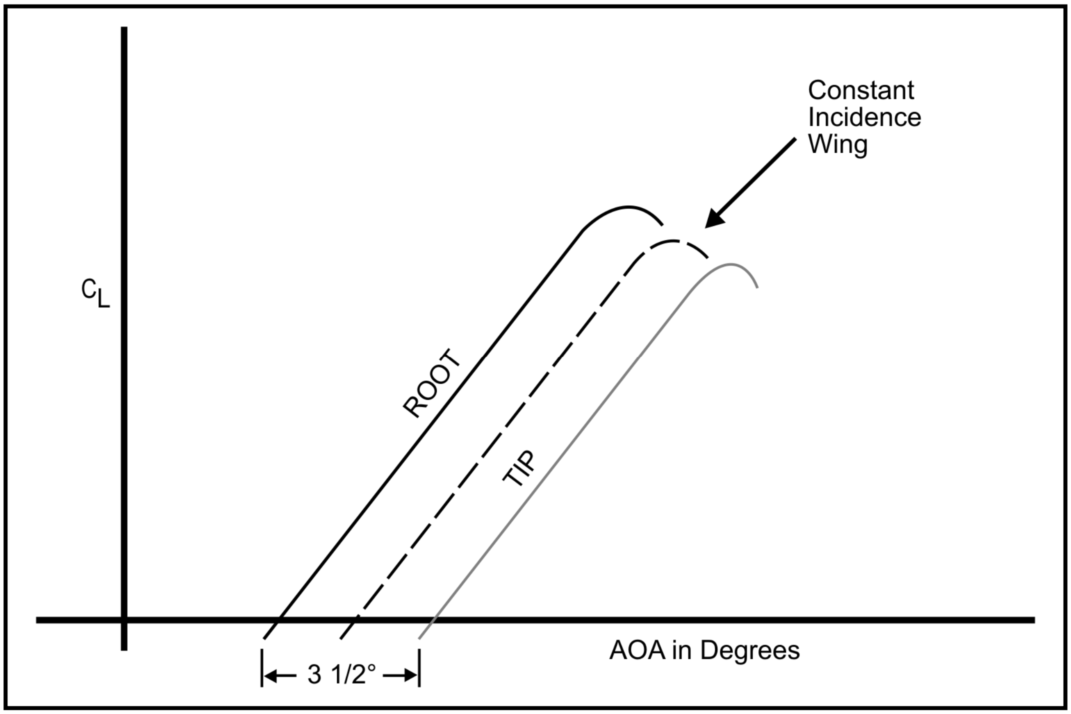

Figure 3-5 Effect of Geometric Twist

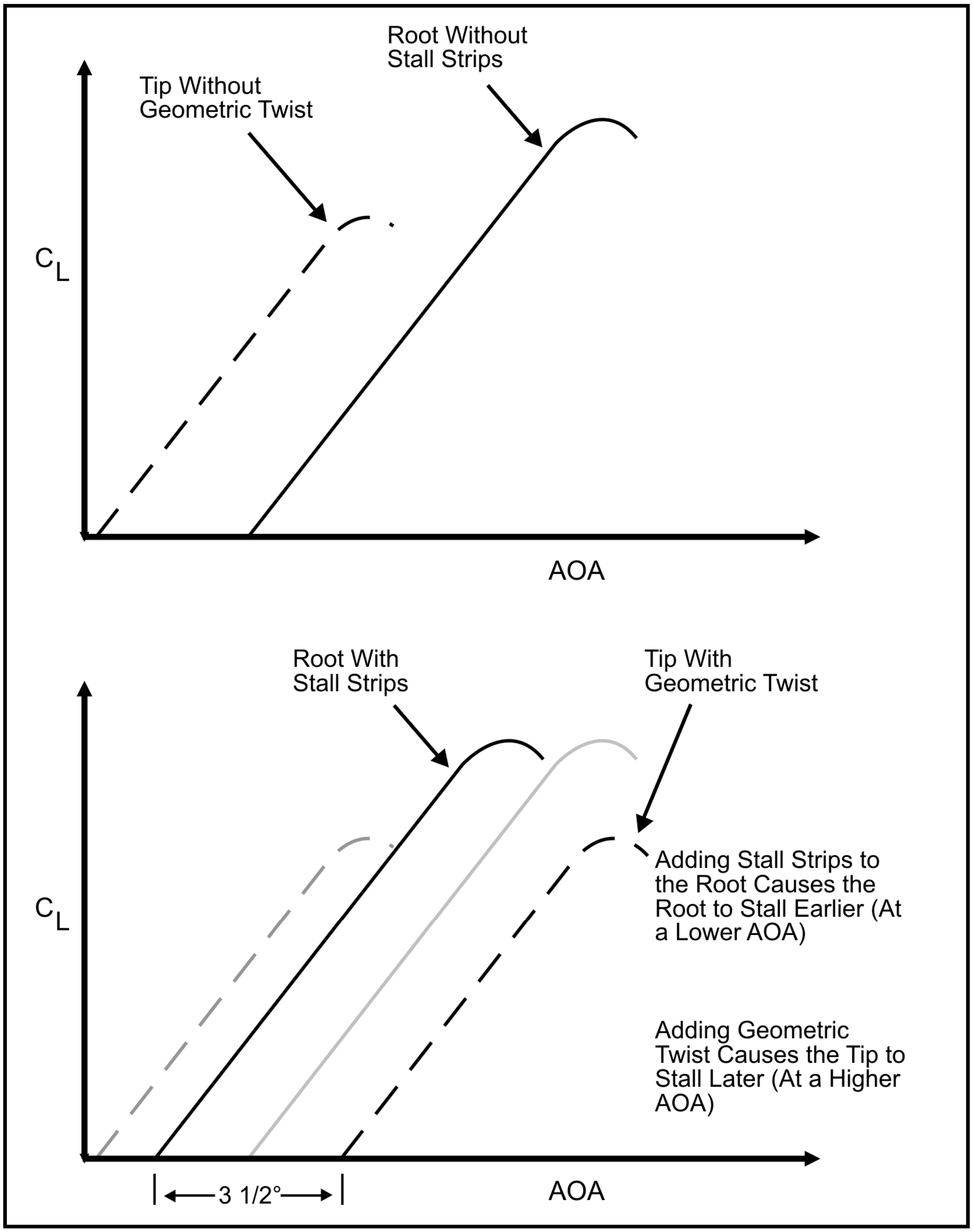

Figure 3-6 Effect of Stall Strips and Geometric Twist

304. HIGH-LIFT DEVICES

Any device that increases the C_L or area of the wing is a high-lift device. The desired result is to reduce the takeoff and landing speeds.

Increases in C_L are achieved by increasing the camber of the airfoil, or by controlling the boundary layer's kinetic energy. The main contributors to increasing C_L generally are flaps (Figure 3-7) and slats (Figure 3-8).

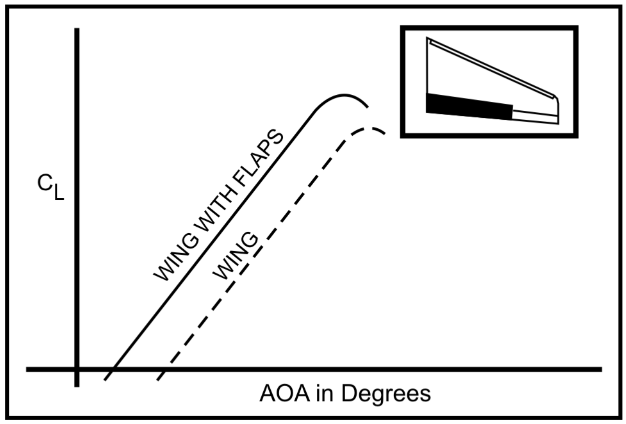

Figure 3-7 Effect of Flaps

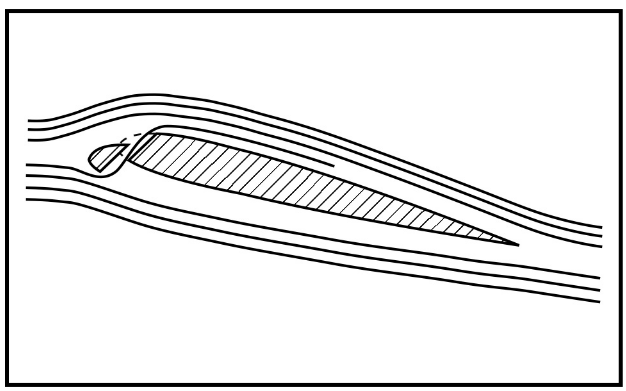

Figure 3-8 Slats

Boundary layer control, whether from the engine's bleed air or from slots in the high-lift devices, adds kinetic energy to the boundary layer, increasing the C_L and permitting the aircraft to fly slower.

The T-45 has double-slotted flaps and slotted slats that increase C_L. The flaps increase the camber of the wing while the double slots add energy to the air over the flaps. When extended, the T-45's slats increase the thickness and radius of the leading edge and open a slot for high-pressure air to energize the lower pressure boundary layer over the top of the wing. The flaps' downward transit opens the double slots allowing high-pressure air from the underside of the wing to pass through the slots and energize the boundary layer of the flap.

Stabilator

The stabilator is a moveable control surface that replaces the horizontal stabilizer and elevators. The T-45's stabilator has 10 degrees of anhedral (negative dihedral) which makes it more effective over the aircraft's speed range.

Vortex Generators

The T-45 wing has vortex generators on the upper surface. They were added, primarily, to correct performance problems in the transonic flight regime. At some airspeeds, wing downwash was found to be interfering with the stabilator. The addition of vortex generators greatly reduced the problem. A beneficial by-product, due to reenergizing the wing boundary layer, is that slow speed performance was also improved. Boundary layer separation was retarded. The result is a reduction in the aircraft's slow speed stall onset and a lowering of the minimum slow-flight airspeed. The vortex generators are shown in Figure 3-9.

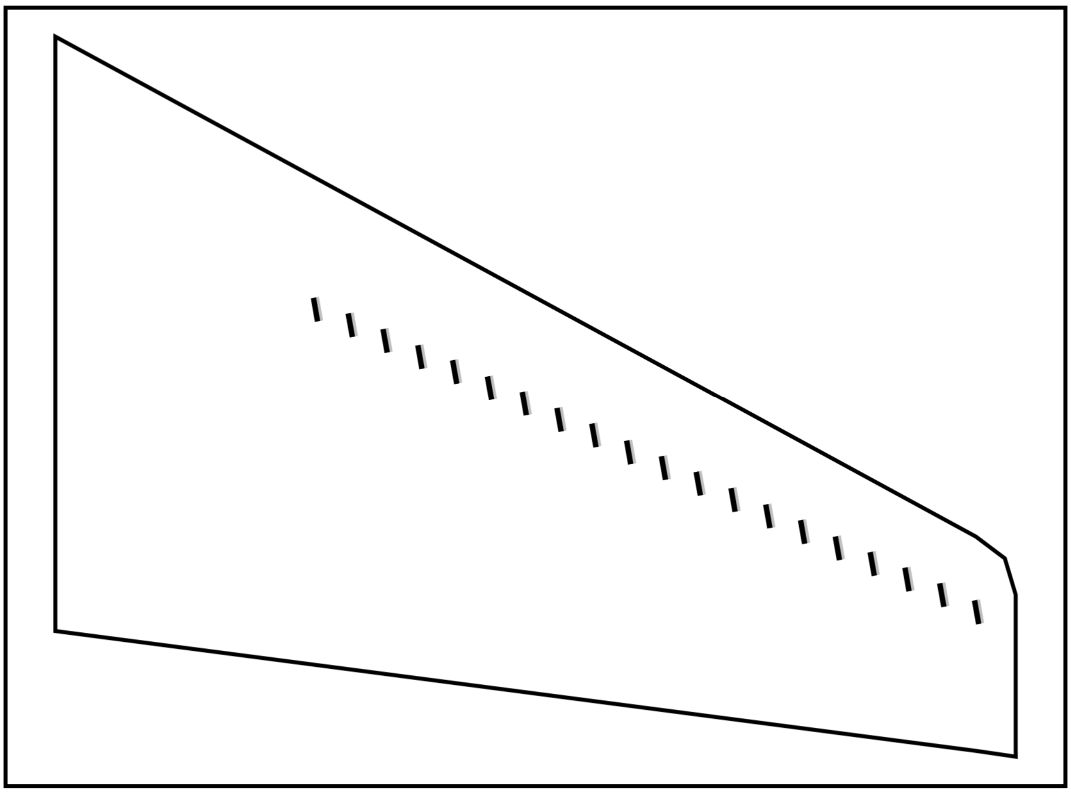

Figure 3-9 Vortex Generators

Stabilator Vanes

A stabilator vane (strake) is located on both sides of the fuselage above the speed brakes (Figure 3-10). The vanes generate a vortex, which passes below the stabilator and keeps the stabilator effective by energizing the airflow, especially at maximum leading edge down stabilator deflection. The stabilator vane also helps maintain the flow pattern over the stabilator when the speed brakes are extended.

305. STALL

Stall is defined as a condition of flight in which any increase in angle of attack (AOA) will result in a decrease in coefficient of lift (C_L). Stalling angle of attack is the AOA on an airfoil at which stall commences. This point occurs at the maximum coefficient of lift or C_L max. Beyond this angle of attack, the boundary layer is increasingly unable to remain attached to the wing, resulting in a continuing decrease in C_L.

The swept wing aircraft generates less C_L and stalls at a higher AOA than a straight wing aircraft. The stall is also less dramatic as shown by the flatter curve (Figure 3-11).

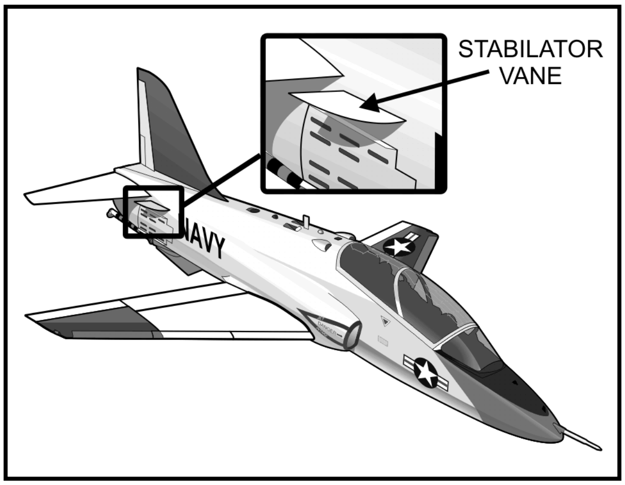

Figure 3-10 Stabilator Vanes

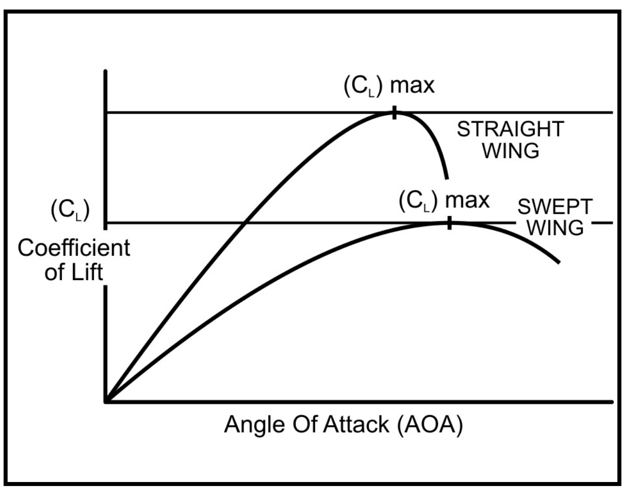

Figure 3-11 Coefficient of Lift Curve, Straight Wing vs Swept Wing

Stall Warning

Stall occurs when an increase in AOA produces a reduction in C_L (Figure 3-12). The maximum lift coefficient of a particular wing configuration is obtained at one angle of attack. Weight, bank angle, load factor, density altitude, and airspeed have no direct effect on the stall angle of attack of the wing. Note that some indirect effects may show up with large changes in the cited measures.

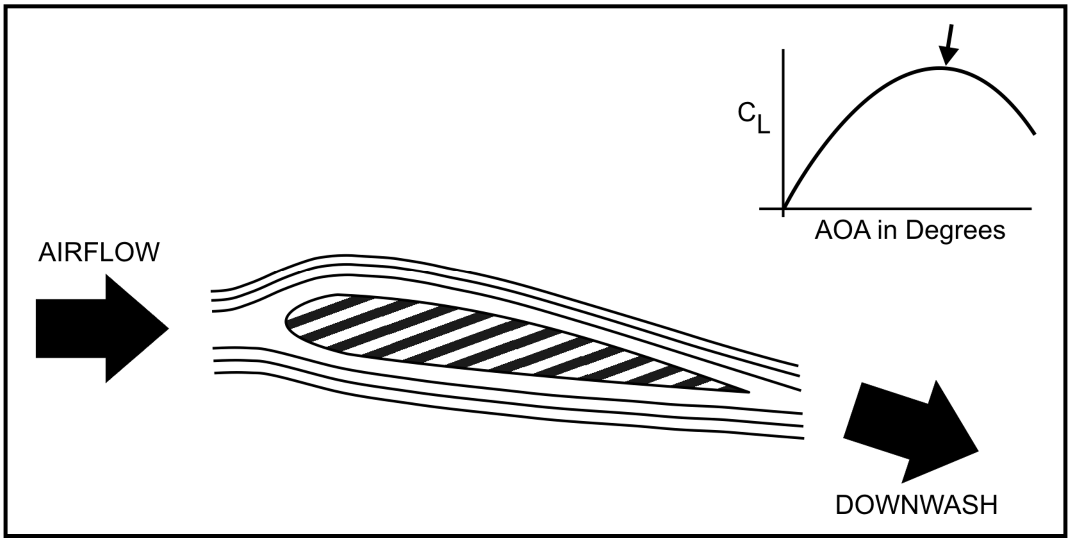

Figure 3-12 Aerodynamics of a Stall

Because the T-45 provides minimal stall warning by natural airframe buffet, an artificial stall warning is installed. At 21.5 units angle of attack, about 10 kts above stall, the left rudder pedal vibrates and a tone is heard in the headset to alert the pilot of an impending stall. The natural airframe buffet commences only **one to two** KIAS above stall, clean, and only **one** KIAS above stall in the approach configuration (Figure 3-13).

Clean Stall

In the clean configuration, there is little or no aerodynamic stall warning such as buffet or wing rock until immediately prior (1-2 kts) to stall (Figure 3-13). In power-on stalls with cruise power set, an approximate 20 degrees noseup attitude is a secondary indication of impending stall. With idle power, the pitch attitude is significantly less and might not be noticeable. Artificial stall warning comes on at 21.5 units AOA, about 4.5 units and 10 kts prior to stall. At less than one unit AOA prior to stall, expect a slight wing rock and buffet. If the back stick is eased at this point, the T-45 will not stall. If the aft stick force is increased, an uncommanded wing drop of 25-30 degrees occurs, accompanied by a mild pitch break which defines the stall at about 26 units AOA clean. Due to the longitudinal stick gearing at near full aft stick travel, a small amount of aft stick commands a large stabilator deflection, so the rate of stall onset occurs more rapidly.

Approach Stall

With the gear down and flaps/slats HALF or FULL, there is no noticeable increase in buffet during the approach to stall until immediately prior to the stall. The first indication of stall is a slight longitudinal instability at about 28 units AOA. At 29-30 units AOA, buffet increases noticeably, followed closely by an uncommanded wing drop of 15-20 degrees and a pitch break that defines the stall. The indicated airspeed may decrease only one knot from 28 units AOA to the stall (Figure 3-13). Release of aft stick pressure at this point produces an immediate reduction in AOA and stall recovery. If aft stick is maintained, the nose pitches down about 6 degrees. Speed brake position has no effect on stall characteristics. Stall recovery is immediate upon the release of aft stick. Altitude loss is minimized by applying MRT power and recovering at 24 units AOA.

Stalls with External Stores

Stall occurs about one unit AOA lower with external stores loaded. With wing store asymmetry, the T-45 rolls into the heavy wing and may require up to one-third lateral stick to maintain wings level on approach to stall. Otherwise the characteristics with stores loaded are similar to the clean stall.

	ARTIFICIAL STALL WARNING	STALL BUFFET	STALL
CLEAN	21.5 Units / 10 KIAS	25 Units / 1-2 KIAS	26 Units / 0 KIAS
APPROACH	21.5 Units / 10 KIAS	28 Units / 1 KIAS	29-30 Units / 0 KIAS

NOTE: All Speeds Are KIAS Above Stall Speed

Figure 3-13 Stall Characteristics

Accelerated Stalls

An accelerated stall is one in which the aircraft stalls while under g loading. Accelerated stall warning depends upon the airspeed and altitude. At higher altitude, the buffet begins mild and increases to heavy at the stall. As altitude decreases and airspeed increases, the magnitude of the initial buffet increases and the buffet band compresses, and at low altitude and high speed, there is very little buffet and warning at the stall. Stall AOA decreases as Mach increases. The stall itself is indicated as a pitch oscillation (bucking motion) that is noticeable at AOA anywhere between buffet offset, which is essentially where maximum lift occurs, and full aft stick. Bucking, which is caused by the T-45's stabilator stalling, is accompanied by wing rock at all airspeeds. Easing aft stick is all that is required to recover.

It is difficult to obtain an accelerated stall in the approach configuration because nearly full aft stick with high stick forces is necessary. The T-45 may wallow laterally near stall and the pilot may induce wing rock. Recovery is immediate with relaxation of back stick. Rudder is effective in controlling the roll/yaw oscillations following the stall.

Stall Recovery

In all configurations, stall recovery is immediate upon the release of aft stick (Figure 3-14).

306. OUT OF CONTROLLED FLIGHT (OCF)

Departure

In a departure, the aircraft produces an asymmetric amount of lift and drag, causing an abrupt pitch, roll, and yaw. The departure may lead to a post-stall gyration if controls are not neutralized. The proper recovery technique from a departure is to neutralize the controls (Figure 3-14).

Post-Stall Gyration (PSG)

Control inputs during a departure may aggravate the situation, producing post-stall gyrations. During PSG, pilots will probably encounter extremely high sideslip angles. These high sideslip angles will likely force the unpowered rudder to full deflection. The pilot may need to apply considerable force on one rudder pedal to center the rudder. The proper recovery technique from a PSG is to neutralize the controls (Figure 3-14).

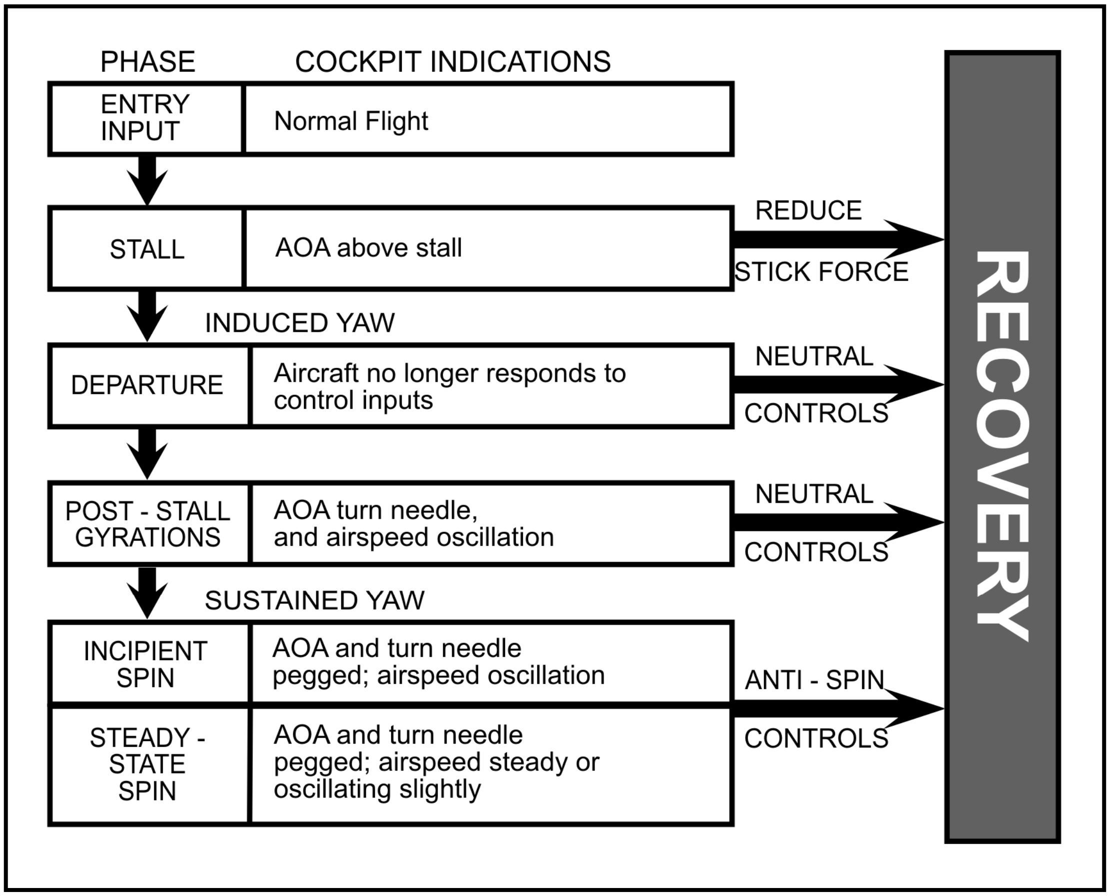

Figure 3-14 Stall Progression Diagram

Rudder Blowout

Rudder blowouts occur because the rudder control system is reversible and sideslip angles as little as 15 degrees in a post-stall gyration or spin may produce airloads that fully deflect the rudder. The pilot may need to apply considerable force on the rudder pedals, in excess of 250 pounds, to center the rudder (Figure 3-15).

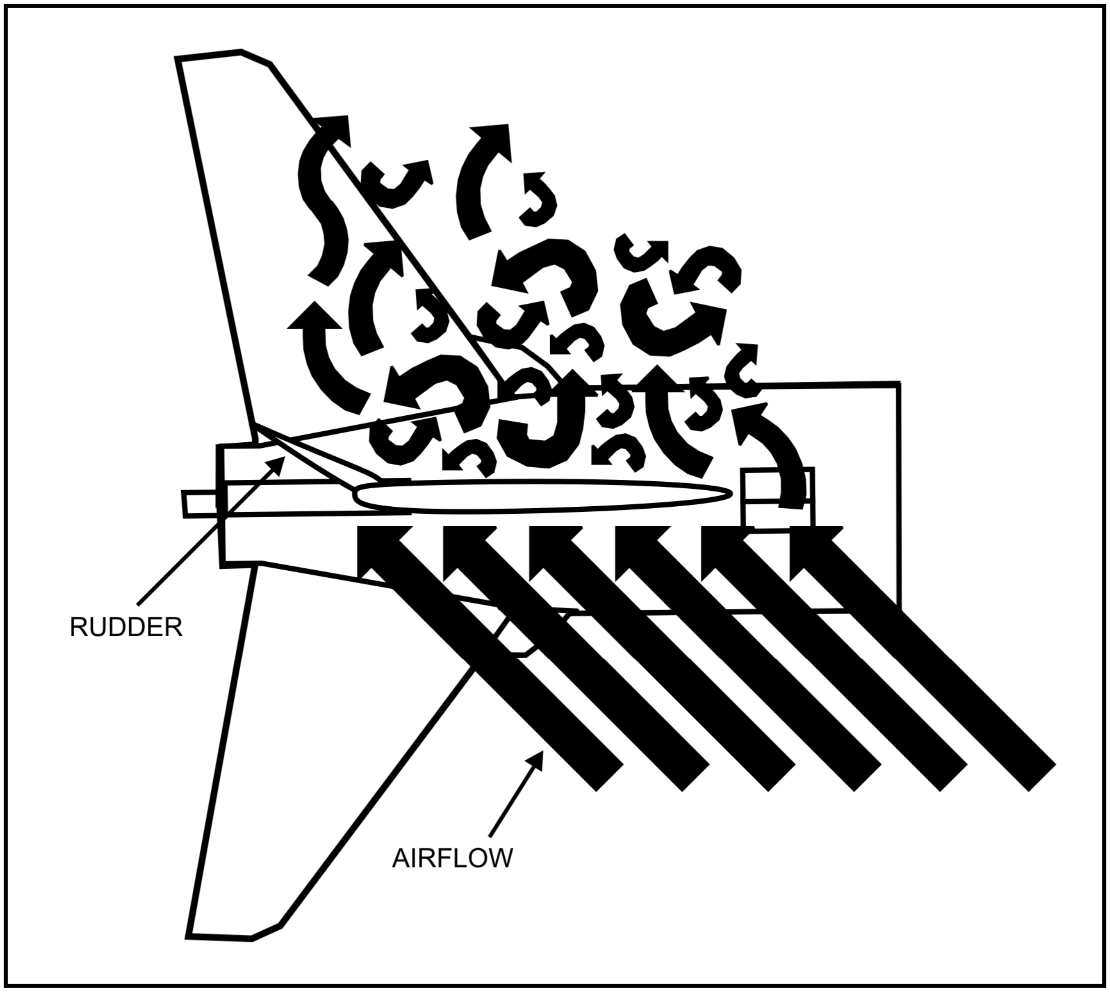

Figure 3-15 Rudder Blowout

Spins

A spin is an aggravated stall condition with autorotation describing a helical path. Autorotation is a steady state, self-sustained mode that is a combination of roll and yaw caused by an asymmetric stalled condition on the up-going and down-going wings. If the aircraft were nosedown, the motion would be pure roll. If the aircraft were flat, the motion would be pure yaw. In most cases, anticipate a confusing combination of both.

An aircraft will not normally enter a spin from a wings-level stall. A spin is initiated by holding pro-spin controls after the stall which introduces a yawing moment that produces a roll. The two things necessary to enter a spin are:

1. Stalled AOA

2. Yaw

T-45 Spins

The T-45 is highly resistant to upright and inverted spins. The pilot should determine whether he is in a PSG or a spin before applying anti-spin controls. Inadvertent entry into any spin mode is possible during recovery from a spin, nose-high vertical maneuvering, maneuvering near full forward stick, a sustained cross-controlled roll, or a sustained high AOA roll.

The proper recovery from a spin is described and detailed in NATOPS. The departure/spin procedure must be memorized and understood.

T-45 Engine in a PSG/Spin

An engine anomaly will usually occur during PSGs and spins. An inverted spin will likely result in either a flameout or surge, regardless of power setting. Although less likely in an upright spin, an engine anomaly may occur if the upright spin was entered above 25,000 ft or at a power setting above idle. Engine EGT and rpm should be monitored after departure/spin recovery to determine engine status.

Spin Indications

Visual cues may deceive the pilot during the spin. The best spin information is obtained from the cockpit instruments. The pilot must systematically check altitude, airspeed, AOA, and turn needle to determine the proper spin recovery procedures.

The altimeter should be the pilot's first reference in a spin to determine if sufficient altitude remains to affect recovery. The airspeed would be less than 200 kts in a spin, but an airspeed less than 200 kts does not necessarily mean you are in a spin. The angle of attack indicator will indicate whether the aircraft is in a post-stall gyration in an upright or inverted spin, or if recovery is indicated. The turn needle always indicates the direction of the spin. If the turn needle and/or AOA is fluctuating, the aircraft most likely is in a post-stall gyration.

A lot is happening very fast, and forces on the pilot may be disorienting. The above instrument scan is a repetitive process. Once applied, give the controls time to take effect. Time is not passing as fast as it seems.

SPIN INDICATOR\TYPE	SPIN TYPE	
	UPRIGHT	INVERTED
AOA	28-30	0
Airspeed	100-180	60-200
Altimeter	Decreasing rapidly	Decreasing rapidly
VSI	> 6,000 fpm descent	> 6,000 fpm descent
Turn Needle	Full in direction of spin	Full in direction of spin
g's	positive	negative 1-1.4
Recovery AOA	decreasing past 20 units	increasing past 5 units

Table 3-2 Spin Indications

True Angle of Attack

True angle of attack is the angle between the relative wind passing the aircraft and the chord line of the wing. In an upright spin, the true angle of attack will be at or above 30 units and is considered positive. In an inverted spin, the relative wind will impact the other side of the chord line, and the angle of attack is considered negative.

Two Upright Spin Modes

The two upright modes are 30 degrees true angle of attack and 45 degrees true angle of attack (Figure 3-16). Both are above 28 units indicated angle of attack indicating the aircraft is stalled. Airspeed best differentiates between the spin modes. The differences as described in NATOPS are:

UPRIGHT SPIN MODES (true AOA)		
TRUE AOA	+30 degrees	+45 degrees
Indicated AOA	Above 28	30
Airspeed	Increasing through 180	Steady 100-110
Altimeter	Decreasing rapidly	Decreasing rapidly
VSI	> 6,000 fpm descent	> 6,000 fpm descent
Turn needle	In direction of the spin	In direction of the spin
Descent rate	12,000 fpm	15,000 fpm
g's	Positive	Positive

Table 3-3 Upright Spin Modes

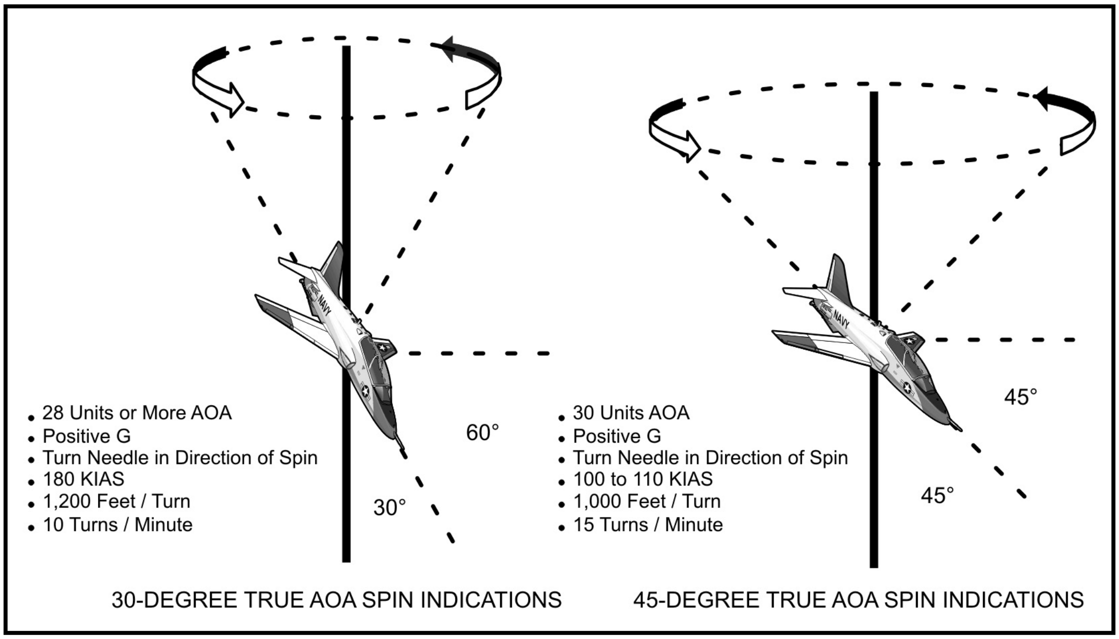

Figure 3-16 Upright Spin Modes

Three Inverted Spin Modes

Airspeed is the best means of differentiating between the spin modes. Inverted spins have relatively high lateral accelerations (0.5 to 1.5 g's) which may add to pilot disorientation (Figure 3-17).

INVERTED SPIN MODES (true AOA)			
TRUE AOA	**-60 degrees**	**-40 degrees**	**-25 degrees**
Indicated AOA	0	0	0
Airspeed	50-120	100-160	140-200
Altimeter	Decreasing rapidly	Decreasing rapidly	Decreasing rapidly
VSI	6,000 fpm descent	6,000 fpm descent	6,000 fpm descent
Turn needle	In direction of spin	In direction of spin	In direction of spin
Descent rate	15,000-20,000 fpm	15,000-20,000 fpm	11,000 fpm
Nose attitude	30 degrees down	50 degrees down	65 degrees down
g's	-1 to -1.4 g's	-1 to -1.4 g's	-1 to -1.4 g's

Table 3-4 Inverted Spin Modes

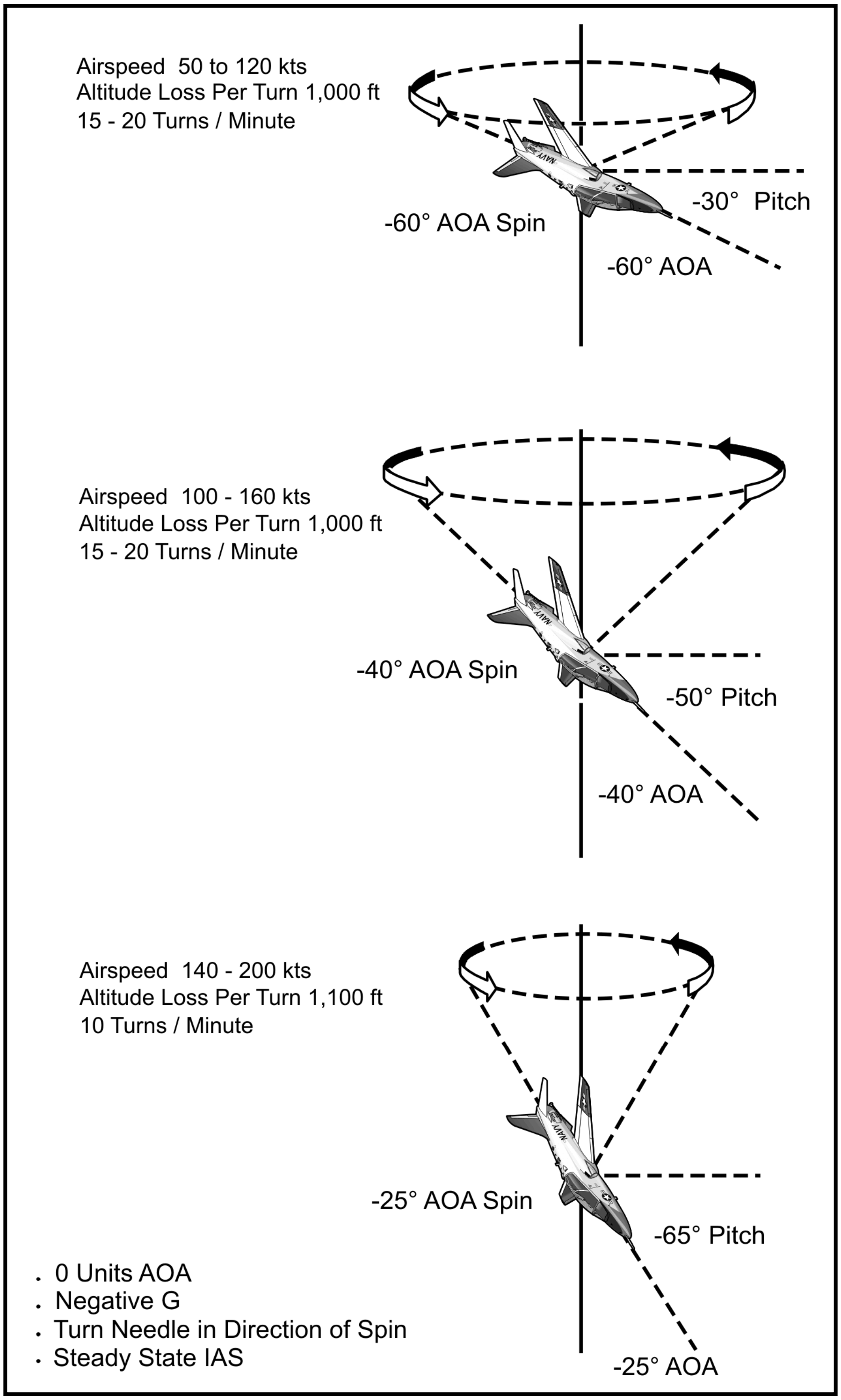

Figure 3-17 Inverted Spin Modes

Spin Recovery

While spins are disorienting, forces on the pilot are tolerable and anti-spin controls, as specified in NATOPS, can be maintained. Recovery is indicated in an upright spin by the AOA decreasing past 20 units. Inverted spin recovery is indicated by the AOA increasing past 5 units. The T-45 NATOPS Flight Manuals specify the pilot's procedures to recover from a departure, post-stall gyration, and spin. The NATOPS departure/spin procedures must be memorized. There is not enough time in a departure or spin to try to think through them.

Before OCF occurs, locate and remember the position of neutral stick and rudder pedals so you can accurately and positively position the controls to neutral during OCF. A small control deflection can make a big difference at high AOA. The pilot should neutralize lateral stick and forcefully center the rudder pedals until it can be determined whether the out-of-control motion is a PSG or a spin, then either maintain neutral controls in a PSG or apply anti-spin controls if spinning (Figure 3-18). Realize that your internal sense of time may not be accurate in a spin. Be patient, you may have to give the aircraft time to respond to the control inputs. Always remember, EJECT if out of control passing 10,000 ft AGL.

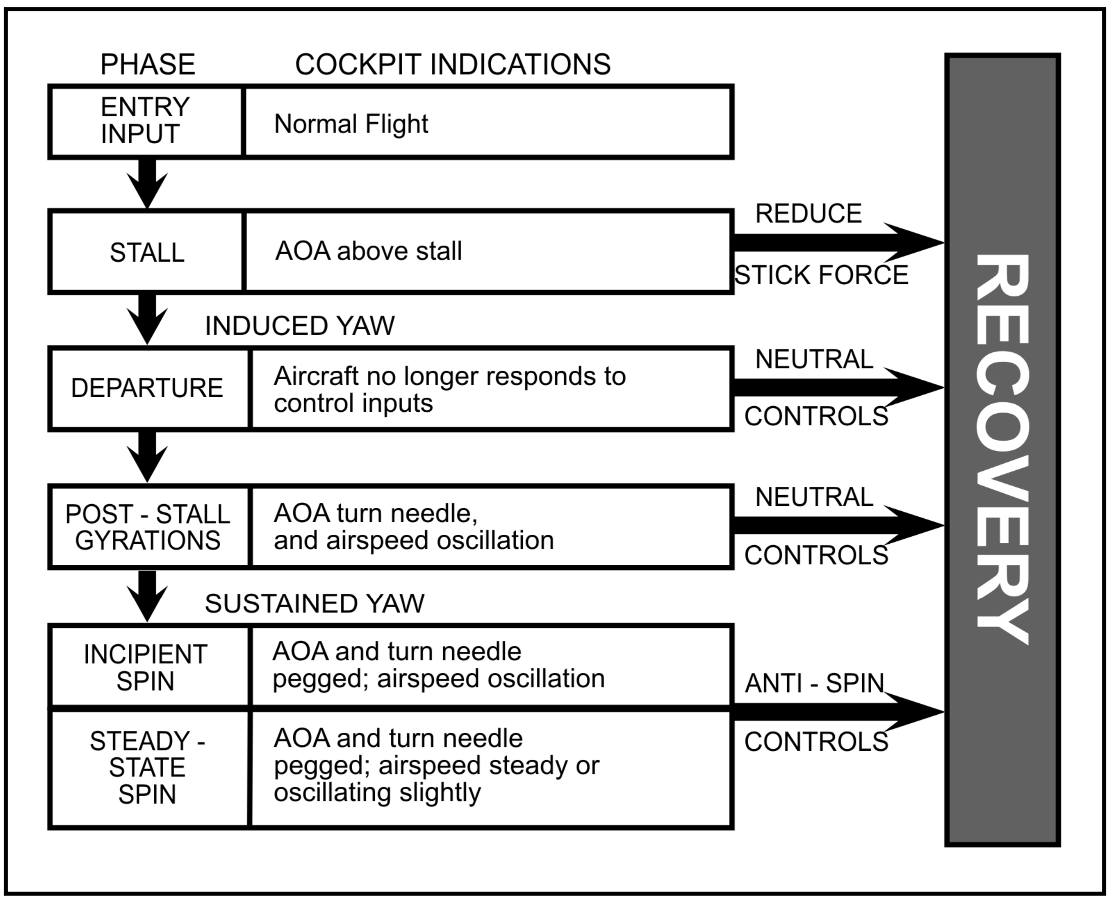

Figure 3-18 Stall Progression Diagram

NATOPS Departure/Spin Procedure and Explanation

1. Controls - NEUTRALIZE (forcibly center rudder pedals). It may be crucial that the controls are truly neutral. An inadvertent control input could lead to a spin or delay recovery. Transients may require that the rudder pedals be forcibly centered. If the rudder blows out, an inverted spin is likely.

2. Speed brakes – RETRACT. Extended speed brakes are destabilizing and may aggravate the departure and delay recovery.

3. Throttle – IDLE. Retarding the engine to idle minimizes engine problems but does not eliminate the potential for a flameout or locked surge. The pilot should expect anomalies following any departure.

4. Check altitude, airspeed, AOA and turn needle. These are the only instruments that need to be scanned.

If spin confirmed:

5. Rudder pedal - FULL OPPOSITE TURN NEEDLE (opposite spin direction)

6. Lateral Stick - INVERTED SPIN: FULL OPPOSITE TURN NEEDLE (opposite spin direction)

UPRIGHT SPIN: FULL WITH TURN NEEDLE (with spin direction)

7. Longitudinal stick - NEUTRALIZE

If recovery indicated or Airspeed increasing through 160 kts:

8. Lateral stick - NEUTRALIZE

When recovery indicated:

Rudder - SLOWLY RELEASE PEDAL FORCE

Releasing the pedal force prior to recovery may allow the rudder to blow out in the prospin direction and delay recovery to below 10,000 feet.

AOA increasing past 5 units indicates inverted spin recovery and AOA decreasing through 20 units indicates recovery from an upright spin.

If the aircraft reenters a spin, reapply the departure/spin recovery procedure beginning with neutral controls.

If out of control passing through 10,000 feet AGL:

9. EJECT

Altitude Loss

A Dive Recovery Chart in NATOPS Performance Data permits one to compute the altitude loss given the dive angle, airspeed, and recovery initiation altitude. The altimeter after recovery will read the recovery initiation altitude less the computed altitude loss.

Operating Limitations

In chapter 4 of NATOPS, the T-45 Operating Limitations are defined. The basis for prohibited maneuvers and limitations are not specified, but one may assume that some undesirable outcome will be the result of exceeding these limits, i.e., a departure or structural damage. Realize there is good reason for these restrictions, and NATOPS is trying to protect you and the aircraft.

307. ANGLE OF ATTACK SYSTEM

Angle of Attack (AOA)

The angle of attack is the angle formed between the relative wind and the chord line of the airfoil. The Navy has long used AOA to optimize an aircraft's approach speed to the aircraft carrier. AOA is more sensitive than the pitot static airspeed determinations at low speed. At high speed, the reverse is true. AOA outputs can be used to determine approximate airspeeds for certain functions should the pitot static system ice up or fail. The pocket checklist contains AOA indications for various aircraft functions.

AOA Check

The AOA system calculates the optimum AOA for approach considering the gross weight and configuration of the aircraft. At the optimum approach AOA, the IAS will be greater for a greater gross weight. The aircraft gross weight calculation begins with the zero fuel weight, which is approximately 10,400 pounds and includes trapped fuel, oil, and two aircrew. (See NATOPS chapter 1 and the Pocket Checklist.) To ensure the AOA is indicating properly during deceleration, the pilot should compare the indicated AOA to the IAS computed from the gross weight. Using the NATOPS pocket checklist, at 17 units AOA, the T-45 airspeed should be 116 +/- 2 KIAS at 11,400 lb gross weight (1,000# of fuel remaining). Add or subtract 2.5 kts for every 500# above or below a gross weight of 11,400#. Add 5 KIAS for every 1,000# of additional gross weight above 11,400# or subtract 5 kts if the gross weight is 1,000# less than 11,400#.

AOA Components

The AOA probe rotates to balance the pressure in its slots (Figure 3-19). The probe senses the relative wind and sends the probe angle to both cockpit AOA indicators and the airborne data recorder for the ADI display and head-up display (HUD). The AOA indicator, ADI, and HUD display the AOA to the pilot in units from 0 to 30.

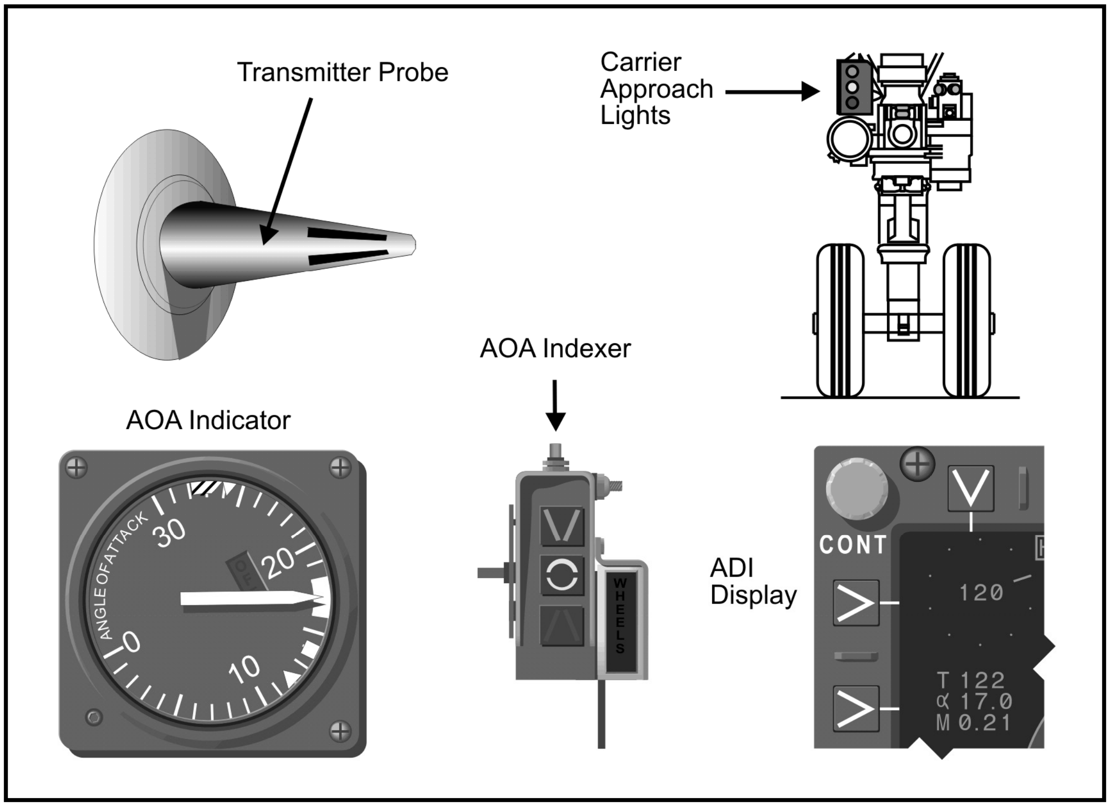

Figure 3-19 AOA Components (T-45C)

AOA Indicator

The AOA indicator (Figure 3-19) provides optimum approach and other airspeed information. On all Navy aircraft, the optimum approach speed is with the needle at precisely three o'clock on the AOA indicator.

Indicators or bugs on the face of the AOA indicator highlight the maximum endurance (14 units) and maximum range (12-13 units depending on gross weight). Max range airspeed decreases with decreasing gross weight. The off flag indicates the AOA indicator is out of service.

Above 21.5 units, the front cockpit AOA indicator triggers the artificial stall warning tone and left pedal shaker. The front indicator inputs to both cockpit indexers and the approach lights on the nose gear. Due to the different circuitry for the rear cockpit AOA indicator and indexer, an error in the system could cause a different reading between the rear seat indexer and indicator.

The AOA indicator is useful in all phases of flight, while the AOA indexer is only illuminated when the landing gear is down.

Indexers

The indexers function similarly in both cockpits (Figure 3-19). The upper "V" indicates slow (18 units or greater), the donut is optimum (17 units), and the" Λ "indicates fast (16 units or less). The upper "V" and a donut lighted simultaneously indicate a little slow (17.5 units). The" Λ "and a donut indicate a little fast (16.5 units).

AOA on ADI Display (T-45C)

A digital AOA indication in tenths of units is displayed in the upper left portion on the T-45C ADI display just below the barometric altitude (Figure 3-19). The AOA prefix is the " ∝ " symbol.

AOA on HUD Display

The head-up display (HUD) also provides a digital indication of AOA on the left side of the HUD just below the indicated airspeed. The AOA prefix is the " ∝ " symbol. The digital AOA is displayed all the time when the landing gear is up. When the landing gear is down, the digital AOA is displayed only when AOA is more than 18 units or less than 16 units (Figure 3-20).

An AOA bracket "E" (Figure 3-20) is displayed to the left of the water line symbol on the T-45A and the velocity vector on the T-45C. The "E" moves up and down with AOA to indicate slow (high on "E") or fast (low on "E"). On speed is when the HUD indicator is on the middle arm of the "E."

On the T-45A, the AOA bracket does not go past the water line symbol for AOA more than 18 units or less than 16 units. On the T-45C, the AOA bracket moves beyond the velocity vector when the AOA is more than 18 units or less than 16 units.

When the AOA bracket reaches the edge of the HUD display, the digital AOA numbers will flash.

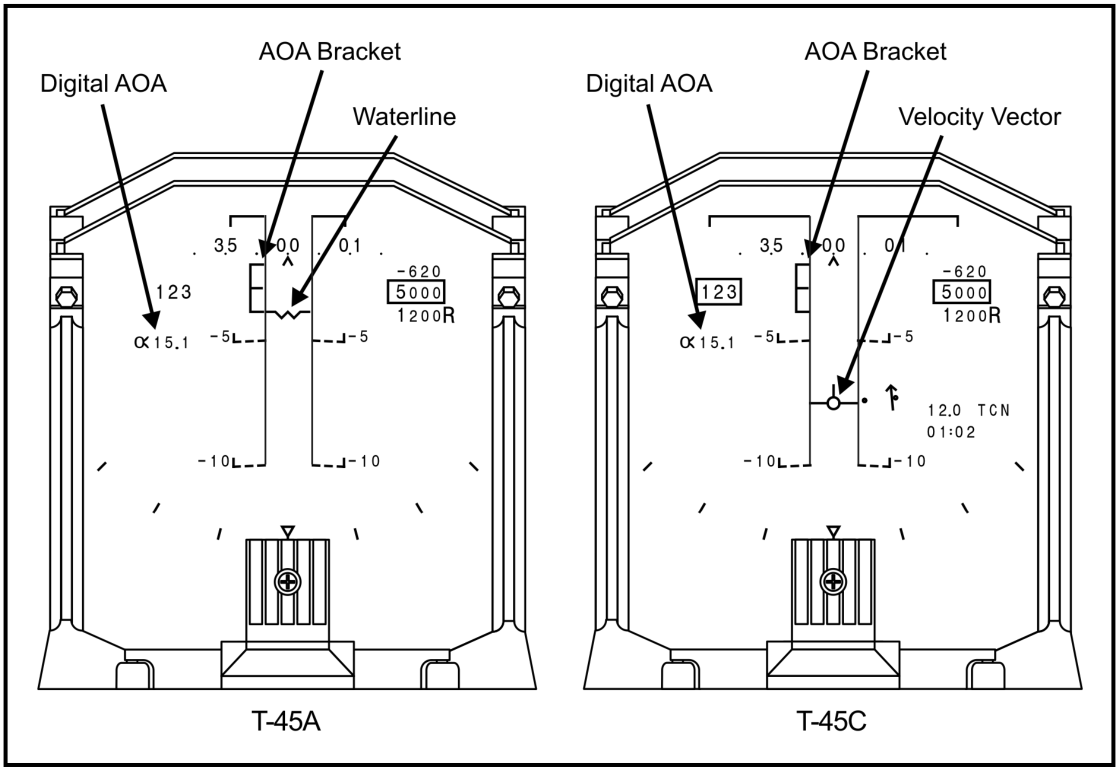

Figure 3-20 HUD AOA Display

Approach Lights

The approach lights are located on the nose landing gear strut (Figure 3-19) and provide the Landing Signal Officer (LSO) an indication of the aircraft's speed. The green light indicates slow, the yellow light on-speed, and the red light fast.

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CHAPTER FOUR
STABILITY

400. INTRODUCTION

The T-45 is a very stable aircraft yet is fully maneuverable. Its flight characteristics vary throughout the flight envelope. Knowledge of these variables is beneficial to the pilot in anticipating and controlling the transitions encountered during flight. Experienced pilots use accurate anticipation based on experience while they fly. The student pilot may also use anticipation following a thorough study of the T-45.

401. STABILITY VERSUS MANEUVERABILITY

Aircraft design is a trade-off between many variables including stability and maneuverability (Figure 4-1). The balance is determined by the aeronautical engineer, based on many factors but primarily by the mission of the aircraft. Maneuverability implies the pilot's capability to make the aircraft respond.

Transports are very stable but not as responsive because their mission requires minimal maneuverability. The fighter mission demands maximum maneuverability, and therefore stability is less important than maneuverability.

Mission considered, the T-45 is between the fighter and transport extremes. Additionally, student training dictates a stable platform, but as a preparation for fleet missions, the aircraft must simulate fleet maneuvers.

In a word, the relationship of longitudinal stability to maneuverability is inverse. As one increases, the other decreases and vice versa. Primarily the relative location of the CG and AC determine the degree of longitudinal stability to maneuverability that exists. Since the location of both CG and AC can affect the aircraft's stability and movement, the result is truly dynamic.

Displacement of the AC from the CG creates a moment arm with the CG as the fulcrum. The longer the moment arm, assuming the force remains constant, the more stable and less maneuverable the aircraft will be. A shorter moment arm will result in a more controllable but less stable aircraft. The moment arm times the force applied at the end of the moment arm creates an aerodynamic pitching moment that produces aircraft movement about the CG.

Since the pilot cannot know precisely, nor select directly, the location of either the CG or AC, it suffices that the pilot anticipate certain changes will increase the moment arm and others will decrease it (Figure 4-2). An active trim button is the best counter to movements acting about the CG.

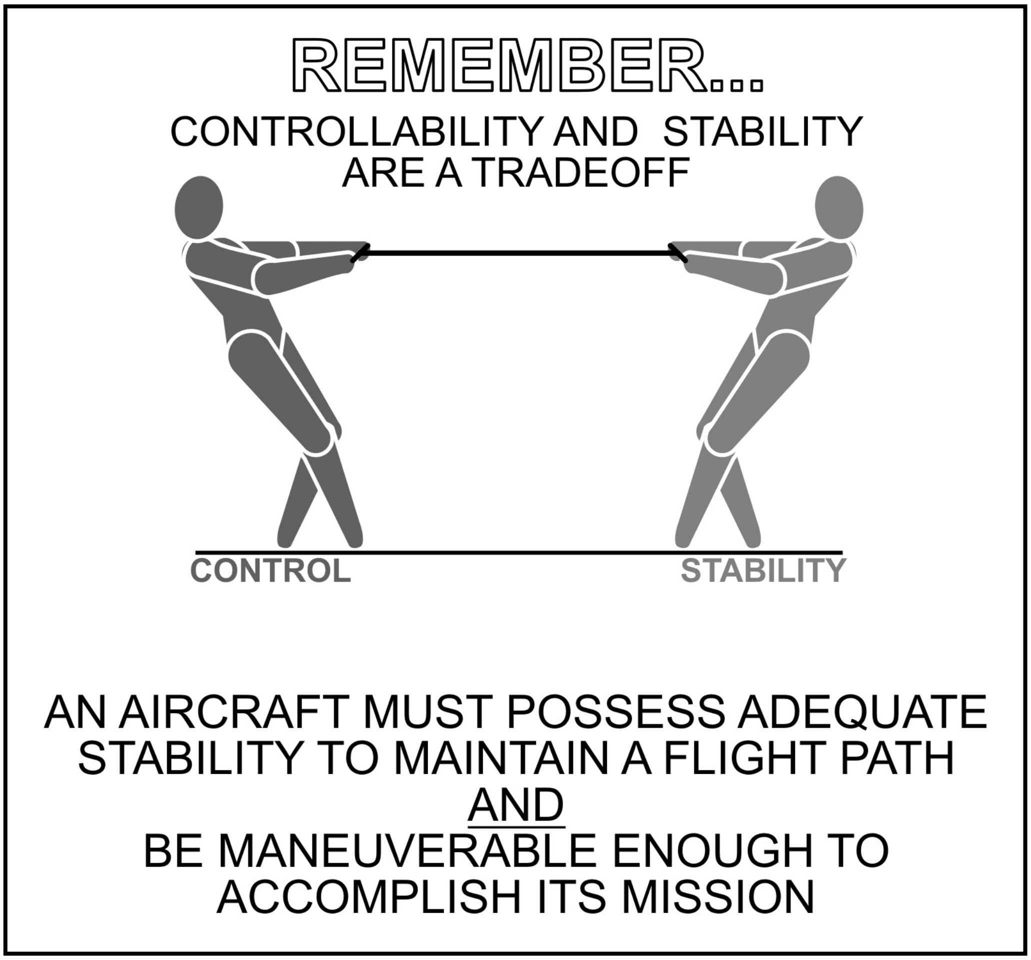

Figure 4-1 Stability vs Maneuverability

402. MEAN AERODYNAMIC CHORD (MAC)

The mean aerodynamic chord is located on the reference axis of the aircraft and is used by the aeronautical engineer as a primary reference for longitudinal stability considerations. The limitations of the allowable location aircraft's center of gravity are customarily referenced to the MAC (Figure 4-2).

The T-45's leading edge of the mean aerodynamic chord (LEMAC) is located 240.9" aft of datum (which is the tip of the nose boom). The MAC extends aft of the LEMAC 74.03" and the CG location will be measured as a percentage of the entire MAC that the CG is aft of LEMAC.

403. T-45 CENTER OF GRAVITY (CG) LIMITATIONS

The CG is the point at which the weight of an object can be considered to be concentrated. The aircraft is viewed as rotating about the CG in response to the forces of lift, weight, thrust, and drag. The aeronautical engineers design each aircraft for a certain range of CG movement.

Factors such as landing gear repositioning, the ejection of one pilot, fuel burn, wing sweep, and ordnance release can affect the CG location while in flight.

The T-45 was designed to have the CG move between 14% and 25% of the mean aerodynamic chord (MAC). The only significant CG variables the T-45 pilot has are gear positioning, speed, fuel burn, and dual or solo manning (Figure 4-3). Some of the larger factors that affect the CG movement follow:

- Extending the T-45's landing gear moves the CG aft 2% of MAC or 1.4 inches. Raising the gear causes a forward shift of equal magnitude.

- Fuel burn causes the CG to move slightly forward from full fuel to minimum fuel. CG shifts aft 1% of MAC or 0.7" during lower fuselage tank burn and 3% or 2.1" forward during outer wing fuel burn.

NOTE

Weapons release has little effect on the T-45's CG due to the suspension points' relationship to the CG.

The pilot does not control these CG shifts directly but does respond to them with trim.

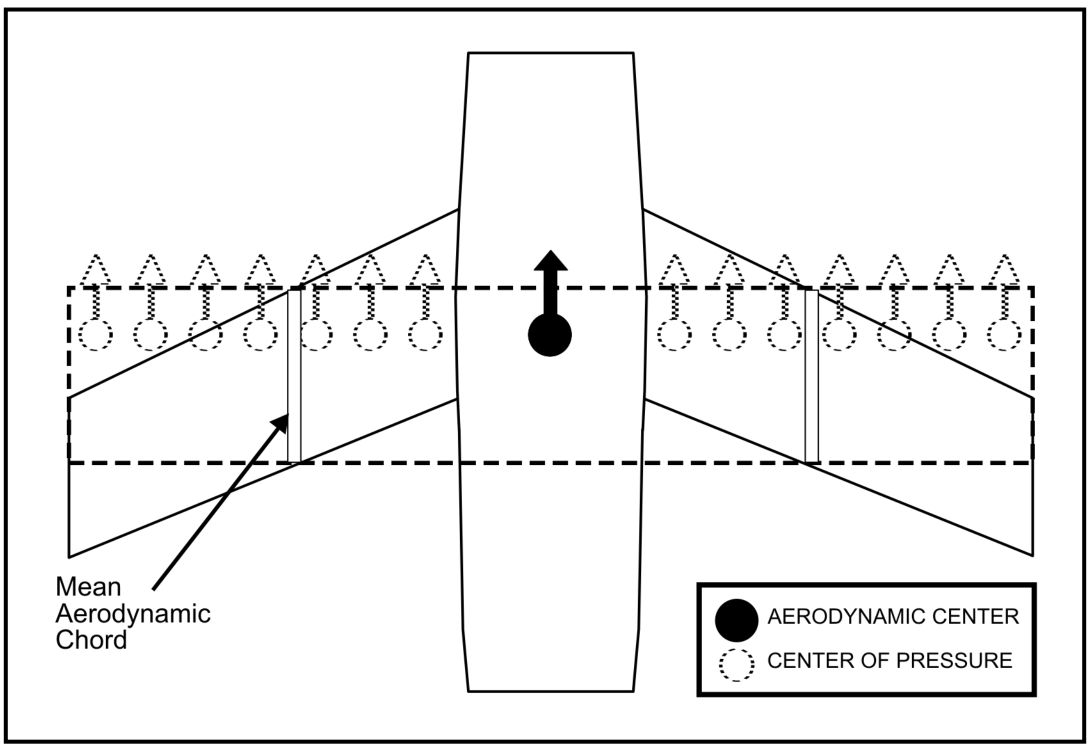

Figure 4-2 Mean Aerodynamic Chord

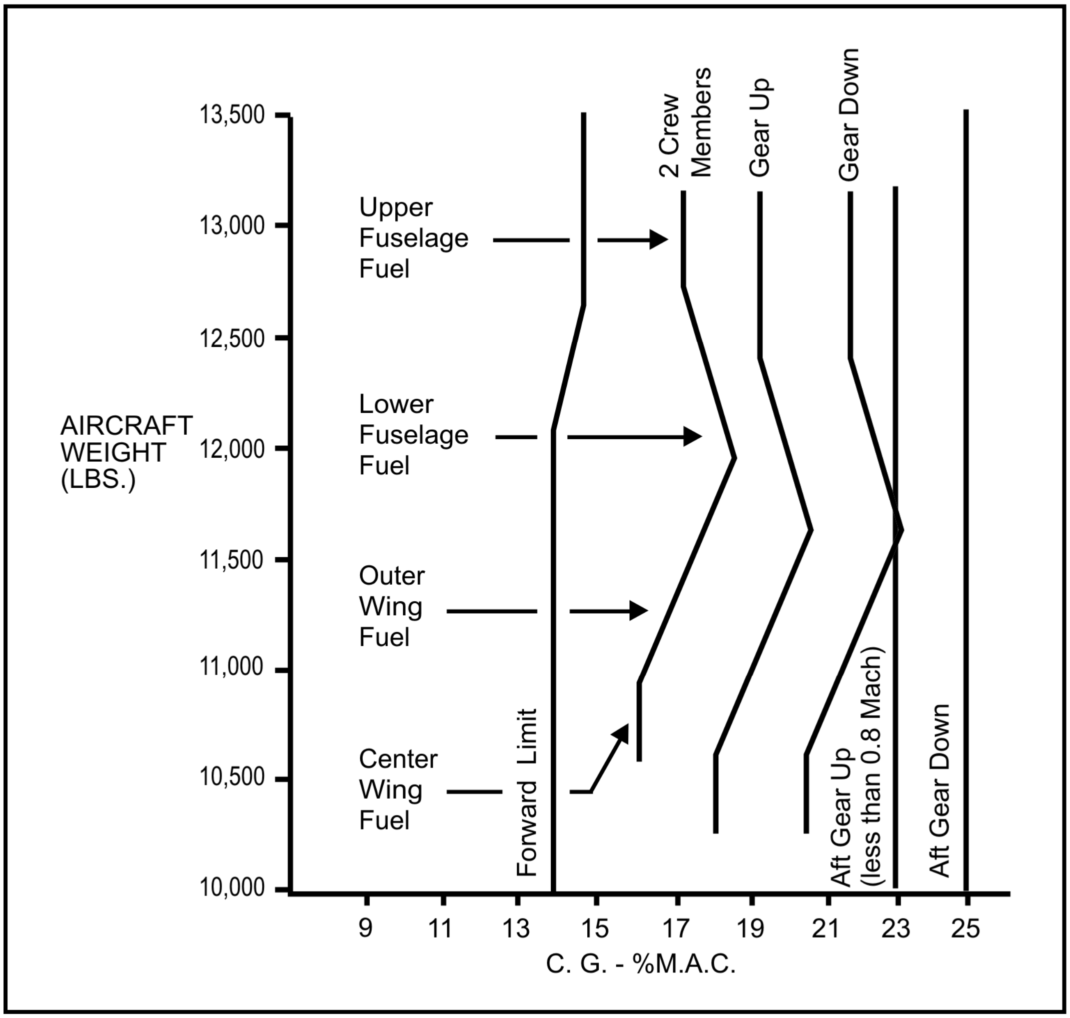

Figure 4-3 Center of Gravity Travel

404. T-45 AERODYNAMIC CENTER (AC)

The aerodynamic center is the point along the chord where all changes in lift effectively take place. The wings and fuselage are the main contributors to lift. The aerodynamic center forms a moment arm with the CG and creates a twisting moment about the CG (Figure 4-4). The length of the moment arm between the CG and AC affects stability. If the aerodynamic center and/or CG move, reducing the moment arm length, the aircraft becomes less stable and more maneuverable. The direction of this twisting moment is crucial to the aircraft's performance.

When the AC is far aft of the CG, the aircraft is very stable but less maneuverable. When the AC moves forward to the CG, the aircraft is neutrally stable, less stable than before but very maneuverable. (Figure 4-4).

The stabilator is capable of controlling the aircraft longitudinally in the designed range when the AC is at or behind the CG. When the aircraft is very slow and the AC moves in front of the CG, the aircraft is unstable, may pitch up, and may lack the stabilator effectiveness to stop the pitchup (Figure 4-4).

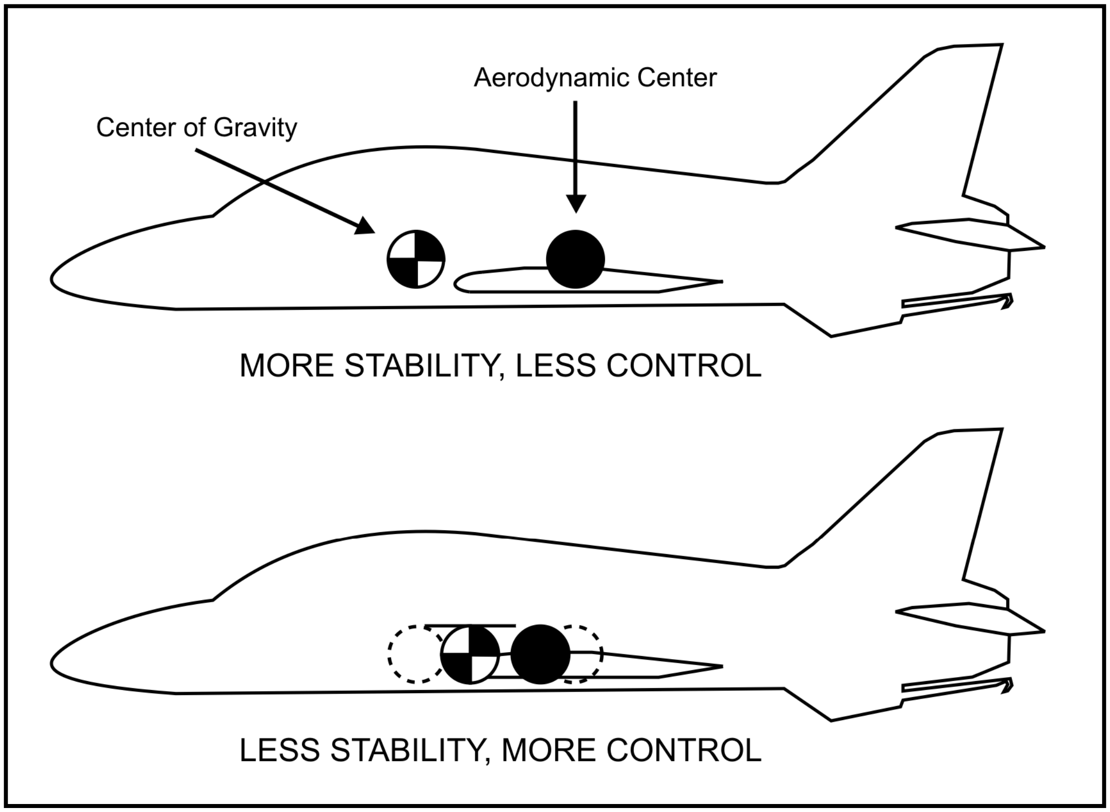

Figure 4-4 Center of Gravity and Aero Center vs Stability

Flaps and Slats

Flap and slat extension on final approach increases the camber of the T-45's wing and produces more lift. Flap extension moves the AC forward 3.49" which is a large change and makes the aircraft less stable but more maneuverable (Figure 4-5). The aircraft will balloon unless the pilot counters the increased lift with 3-4 pounds of forward stick. As the T-45 slows, it will then settle unless the pilot applies up to 1/3 aft stick. This balloon/settle sequence is more pronounced at 200 KIAS than at lower airspeeds. Anticipating this sequence when selecting "flaps down" will keep the aircraft on altitude. Retraction of these high-lift devices will have the opposite result of extension.

When the flaps and slats move from up to down, slots open up behind the slats and double slots open up in front of the flaps. These slots permit high pressure air under the wing to energize the boundary layer on the top of the wing and flap. The slots opening increases the lift produced by the wing and contributes to the ballooning and resulting slower approach speed.

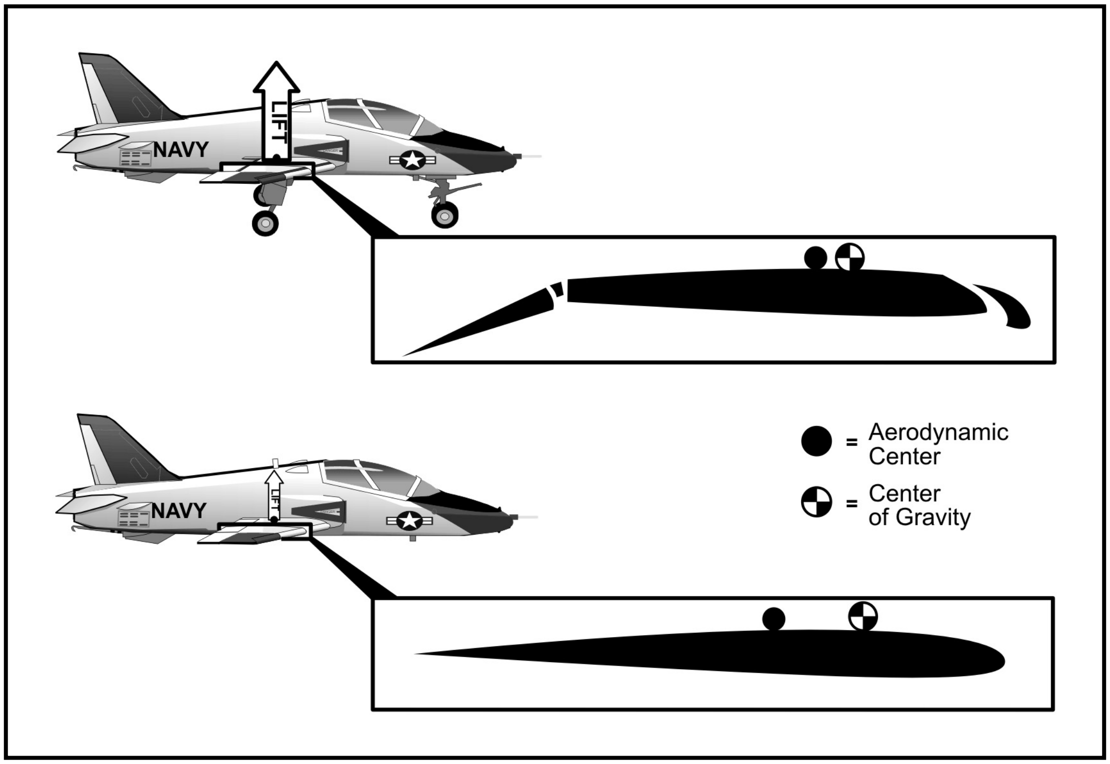

Figure 4-5 Longitudinal Stability – Gear, Flap/Slat Extension

405. SPEED BRAKES

Extending the speed brakes causes the aircraft to pitch up, more so at high speed than at low speed (Figure 4-6). The pitchup is caused by the extended speed brakes changing the flow pattern over the horizontal stabilizer and increasing downward force of the stabilator.

The speed brakes on the Goshawk were moved to the sides of the empennage so a tail hook could be added. The speed brake on the predecessor to the Goshawk, the Hawk, was on the bottom of the empennage. The Hawk did not land with the speed brake out, but the Goshawk needed speed brakes extended during carrier approach to increase the engine rpm, making the engine more responsive on approach and waveoff.

A speed brake-to-stabilator interconnect (SBI) function is added to the T-45 control augmentation system to reduce pitch transients when the speed brakes are extended or retracted. When the speed brakes are extended, the SBI reduces positive pitch transients from 0.2 to 0.7 Mach and negative pitch above 0.7 Mach. When the speed brakes are retracted, the opposite occurs. As the speed brakes extend, the control augmentation system mechanically moves the stabilator to counter the pitchup. The control stick does not move during SBI operation. Even with SBI, the pilot still must counter some pitch transients during speed brake extension or retraction.

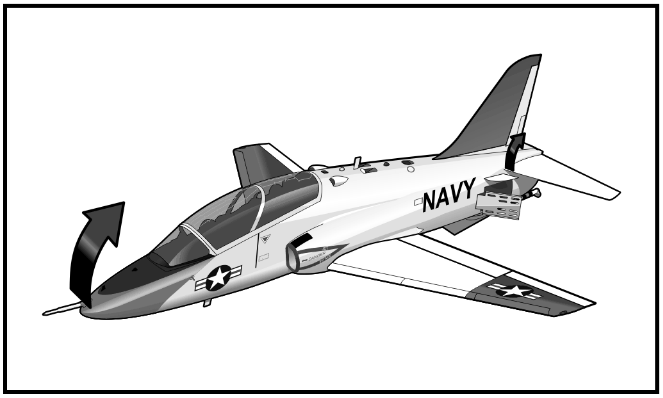

Figure 4-6 Longitudinal Stability – Speed Brake Effect

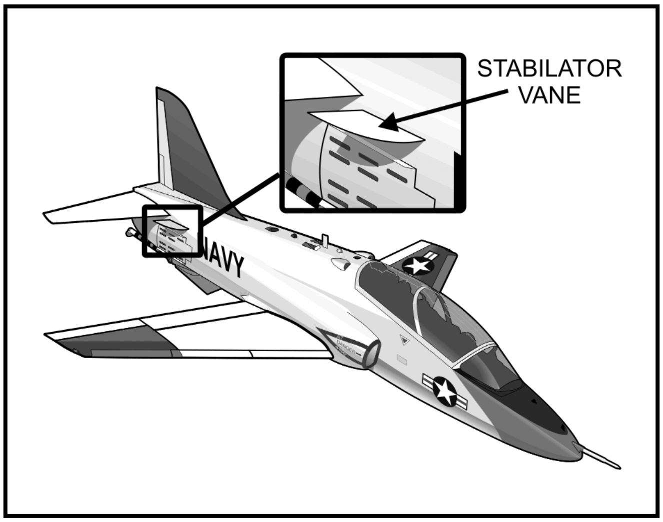

Figure 4-7 Stabilator Vanes (Strakes)

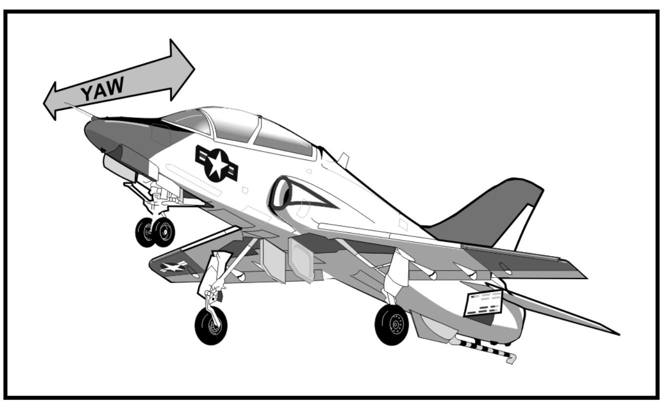

Figure 4-8 Landing Gear Doors Effect on Directional Stability

406. STABILATOR VANES

A stabilator vane, strake, is installed on both sides of the fuselage forward of the stabilator and above the speed brake (Figure 4-7). The purpose is to generate a vortex, which passes below the stabilator, energizes the flow over the lower surface of the stabilator, and keeps it effective particularly at maximum leading edge down stabilator deflection.

407. T-45 LANDING GEAR DOORS EFFECT ON DIRECTIONAL STABILITY

As the landing gear transit, the T-45 directional stability is reduced due to the inner main landing gear (MLG) doors and forward nose landing gear (NLG) doors opening (Figure 4-8). The yawing tendency is caused by the increased sail area of the opened MLG doors and the forward NLG doors. The MLG and forward NLG doors close when the landing gear is fully extended. During emergency gear extension, the inner MLG doors remain open and the forward nose landing gear doors are partially closed by an electric motor. In this configuration, the aircraft is less stable directionally and coordinated stick and rudder are required to control the slight yaw excursions that may occur.

408. DIHEDRAL

The wings of the T-45 exhibit two degrees of dihedral, measured between the spanwise inclination of the wing and the lateral axis, which increases the aircraft's lateral stability. When an aircraft is sideslipping laterally, dihedral wings cause an increase in angle of attack and lift on the downgoing wing. The reverse is true of the upgoing wing. The difference in lift creates a rolling moment that rights the aircraft and stops the sideslip. Dihedral wings are the greatest positive contributor to lateral static stability.

The T-45's stabilator has ten degrees of negative dihedral (or anhedral). This anhedral makes the stabilator effective under a greater range of airspeeds and conditions.

409. ASPECT RATIO (AR)

Aspect ratio is the span of the wing (b) divided by the average chord [c] (AR = b/c). Where curvature makes determining the average chord difficult, an alternate expression is $AR = b^2/S$ where b is the wing span and S is the wing area. The aspect ratio is a fineness ratio of the wing, which affects the aerodynamic characteristics and structural weight. Sailplanes may have an AR of 35 and a jet fighter only 3.5.

410. COUPLING

Coupling is the interaction of simultaneous roll and yaw movements (Figure 4-9). Depending upon the strength of directional stability to lateral stability, the T-45 may exhibit the following tendencies:

Dutch Roll

Dutch roll results from a compromise between directional divergence and spiral divergence. The lateral stability is stronger than the directional stability (Figure 4-10).

Induced drag increases on the wing into the wind when the aircraft yaws. Weak directional stability allows adverse yaw to pull the nose through the relative wind and causes roll and yaw in the other direction. Neutral dynamic directional and lateral stability are the causes of Dutch roll. A swept-wing aircraft will increase its lateral stability by increasing the angle of attack.

An aircraft might not exhibit Dutch roll at high speed and low angles of attack. But when coming in to land at low airspeed and high angle of attack, the increase in lateral stability at the higher angle of attack could produce a Dutch roll tendency.

Dutch roll is normally countered by the T-45's yaw damper system. With the yaw damper inoperative, the oscillations will be quite noticeable, and the pilot will experience an increased workload.

COUPLING

DEFINITION - THE INTERACTION OF SIMULTANEOUS ROLL AND YAW MOMENTS

COUPLING IN THE T-45
DUTCH ROLL AND SPIRAL DIVERGENCE

Figure 4-9 Coupling Definition

COUPLING
(DUTCH ROLL)

STRONG LATERAL WITH WEAK DIRECTIONAL STABILITY

WITH A ROLL OR YAW, LIFT AND INDUCED DRAG INCREASE ON WING INTO THE WIND - WEAK DIRECTIONAL STABILITY ALLOWS ADVERSE YAW TO PULL THE NOSE THROUGH THE RELATIVE WIND CAUSING ROLL AND IN THE OTHER DIRECTION. IN THE T-45, DUTCH ROLL BUILDS TO A LEVEL AND THEN STABILIZES AT THAT LEVEL - NEUTRAL DYNAMIC STABILITY

DIRECTIONAL STABILITY - POSITIVE STATIC/NEGATIVE DYNAMIC
LATERAL STABILITY - POSITIVE STATIC/NEUTRAL DYNAMIC

Figure 4-10 Coupling (Dutch Roll)

Spiral Divergence

Bank angle and small sideslip is induced at stall. Strong directional stability attempts to align the nose with the relative wind, but weak lateral stability lags in righting the aircraft. The bank angle keeps the relative wind moving off the nose. The aircraft continues to chase the relative wind and will develop a tight descending spiral. This is an example of negative dynamic directional stability (Figure 4-11).

The T-45 has demonstrated a slowly divergent spiral mode with asymmetric store loadings. To correct this condition, the pilot need only raise the wing with aileron and the spiral will stop immediately. Because this spiral is slow, and there is no oscillation, the directional stability is usually designed stronger than the lateral stability in most aircraft.

COUPLING
(SPIRAL DIVERGENCE)

STRONG DIRECTIONAL CONTROL WITH WEAK LATERAL STABILITY

BANK ANGLE AND SMALL SIDESLIP INDUCED AT STALL. STRONG DIRECTIONAL STABILITY ATTEMPTS TO ALIGN THE NOSE WITH THE RELATIVE WIND, BUT WEAK LATERAL STABILITY LAGS IN RIGHTING THE AIRCRAFT. THE RESULT IS THAT THE BANK ANGLE KEEPS THE RELATIVE WIND MOVING OFF THE NOSE

EXAMPLE OF NEGATIVE DYNAMIC DIRECTIONAL STABILITY AS RATE OF TURN IS INCREASING

DIRECTIONAL STABILITY - POSITIVE STATIC/NEGATIVE DYNAMIC
LATERAL STABILITY - POSITIVE STATIC/NEUTRAL DYNAMIC

Figure 4-11 Coupling (Spiral Divergence)

411. T-45 LANDING IN A CROSSWIND

Pilots must be alert while landing the T-45 in a crosswind. After landing, the T-45 does not fare into the wind as most aircraft do but turns away from the crosswind. The upwind wing will generate more lift and rise which places more weight and wheel drag on the downwind landing gear. This additional drag produces more friction at the downwind wheel and the T-45 TURNS AWAY from the crosswind (Figure 4-12).

The NATOPS crosswind procedure should be studied but is summarized as follows: The aircraft is flown in a crab on final and straightened out so as to land straight down the runway with the rudder pedals centered. The nose wheel steering will engage when one main gear and the nose strut compress, so it is important to have the rudder pedals centered to avoid a swerve. On touchdown the stick is moved into the wind.

The crab method is better during the approach because the yaw damper fights the rudder pedal inputs of the cross-controlled method. Full flaps are recommended for crosswind landings, but the approach and roll-out characteristics with half flaps are the same as full flaps except for the speed increase of 18 kts.

The maximum T-45 NATOPS crosswind limit for takeoff and landing is 20 kts, 15 kts if the runway is wet. Ten knots is the maximum for a section takeoff. Training Air Wing SOP limits the student crosswind component to 10 kts. Carefully read the crosswind landing section in NATOPS.

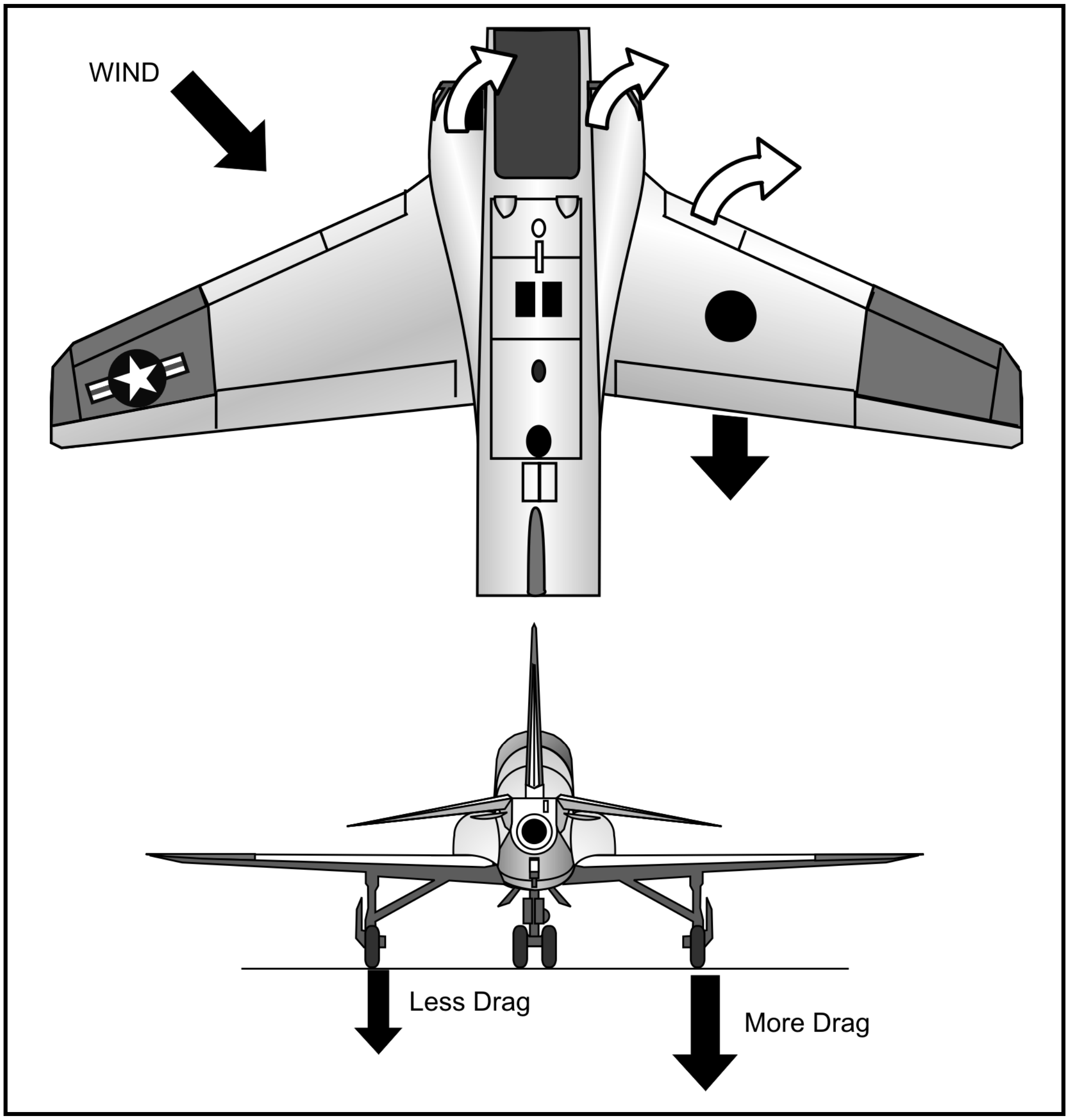

Figure 4-12 Landing in a Crosswind

CHAPTER FIVE
THRUST AND THRUST CURVE REVIEW

500. INTRODUCTION

This lesson discusses the factors that affect the thrust output of a turbofan engine and how changes in weight, altitude, and configuration affect the thrust-required curve and aircraft performance, relevant to the T-45.

Jet Propulsion Theory

The thrust of a turbojet or turbofan engine comes from taking a large mass of air in and pushing it out the exhaust nozzle at a much higher velocity. This is a direct application of Sir Isaac Newton's Third Law that states "for every action, there is an equal and opposite reaction." Jet engine thrust is the result of reaction to the acceleration of an airmass created by the engine and not, as is sometimes supposed, the effect of exhaust gases pushing against the outside air.

Understanding the HOW of thrust production requires familiarity initially with the construction of the turbojet engine (Figure 5-1). The forward or input part of the turbojet engine is the compressor section. Through a series of stationary vanes and rotating blades, the incoming air is compressed and passed to the combustion section where nozzles spray fuel and mix it with the highly compressed air. The burning fuel/air mixture adds energy to the airflow through the engine. From the combustion section, the gases enter the turbine section. Power is produced in the turbine section to drive the compressors, accessories, etc. In the exhaust section, following the turbine section, the pressure forces the gases at very high velocities through the jet nozzle at the rear of the engine.

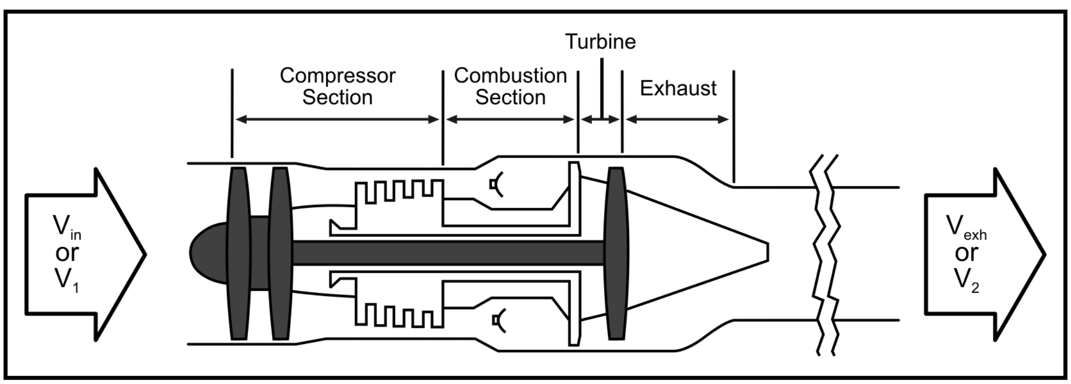

Figure 5-1 Jet Propulsion Theory

In the turbofan (Figure 5-2), power is also provided from the turbine to drive the fan at the front of the engine. Where a turbojet engine derives its thrust by the large acceleration of a relatively small airmass, a turbofan derives its thrust by imparting less acceleration to a relatively larger airmass. A turbofan version of a similar turbojet engine will have more static takeoff thrust, more climb thrust, more cruise thrust, lower specific fuel consumption, and a lower specific weight.

The turbojet came first because it was simpler technology. The turbofan engine is preferred in most modern applications.

The afterburner is a section added to some jet engines, which can provide a large thrust increase with little weight. The afterburner section consists of another set of fuel spray nozzles, flame holders behind the turbines, and variable exhaust nozzles. Since there are no highly stressed engine components (turbine blades) behind the afterburner, a large amount of fuel can be burned there. Afterburners are a very inefficient use of the fuel; however, as fuel flow will typically triple or quadruple in afterburner operation for a 50% increase in thrust.

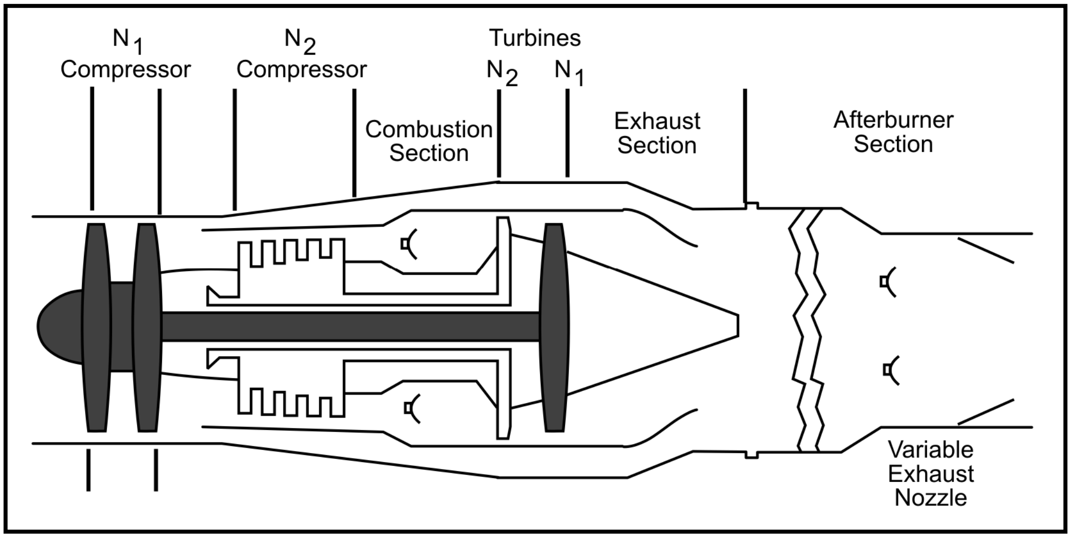

Figure 5-2 Turbofan Engine with Afterburner

T-45 Thrust

A single Rolls-Royce F405-RR-401 turbofan engine that develops an installed static sea level thrust of 5,527 pounds provides thrust in the T-45. Referring to Figure 5-3, air enters the engine directly at the first stage of N_1. Between N_1 components and N_2 components (which is typical of turbofan engine design), airflow is divided into two paths, one of which enters the N_2 compressor stage and the other enters the annular bypass duct. The airflow from the N_2 section then enters the combustion section where eighteen fuel spray nozzles provide fuel for combustion. From the combustion section, the heated and accelerated airflow enters and flows through the turbine section.

The N_2 turbine turns the shaft, which drives the N_2 compressor and engine accessory gearbox. The N_1 turbine drives the N_1 compressor (the engine fan) via the N_1 shaft. There is no direct mechanical connection between the N_1 and N_2 sections.

Airflow from the turbine section then moves into the exhaust section. The heated and accelerated airflow is mixed with the airflow from the annular bypass duct. The mixed airflow then is discharged through a fixed geometry, converging exhaust nozzle, the shape of which increases the thrust.

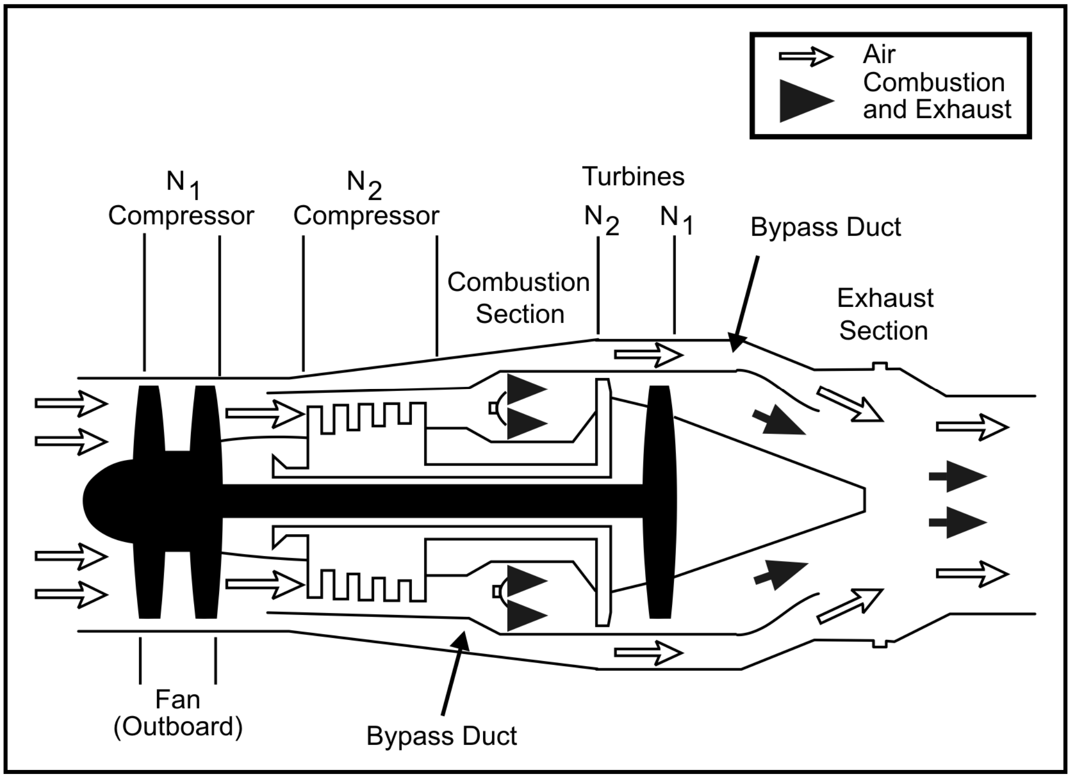

Figure 5-3 Turbofan Engine

Thrust Available

The thrust available from a turbofan engine is illustrated by the equation:

$$\mathbf{T_a = Q\ (V_2 - V_1)}$$

Where:
- $\mathbf{T_a}$ = Thrust available
- **Q** = Airmass flow in slugs per second (kilograms/sec in metric units)
- $\mathbf{V_1}$ = Inlet air velocity in feet per second
- $\mathbf{V_2}$ = Exhaust air velocity in feet per second

NOTE

The terms $\mathbf{V_1}$ and $\mathbf{V_2}$ are used interchangeably with $\mathbf{V_{in}}$ and $\mathbf{V_{exh}}$ respectively.

RPM Effect

One of the most obvious factors affecting thrust output is the speed of the rotor assembly, generally referred to as revolutions per minute (rpm) of the engine. Because turbofan engines operate at very high rpm, it is more convenient to refer to engine revolutions as a percent of maximum allowable rpm or indicated rpm.

The indicated rpm is NOT an indication of thrust or power. It is only an indication of the rpm the engine is turning in relation to the maximum allowable rpm. Rather, some other engine variable indicators such as engine pressure ratio or turbine discharge pressure must be employed as an indication of thrust being produced. As rpm increases, both airmass flow (Q) and acceleration through the engine (V_2-V_1) will increase.

Thrust production does not relate linearly to engine rpm (Figure 5-4). At low rpm, there is very little change in thrust with a large rpm change. Between 80 and 90% rpm, 25% of the total thrust is produced. Between 90 and 100% rpm, 30% of the total thrust is produced. At high rpm, a small change in rpm will produce a large change in thrust.

The T-45 rpm-to-thrust output is tabularized in (Figure 5-5). An indicated 100% rpm produces an actual N_2 rpm of 15,512.

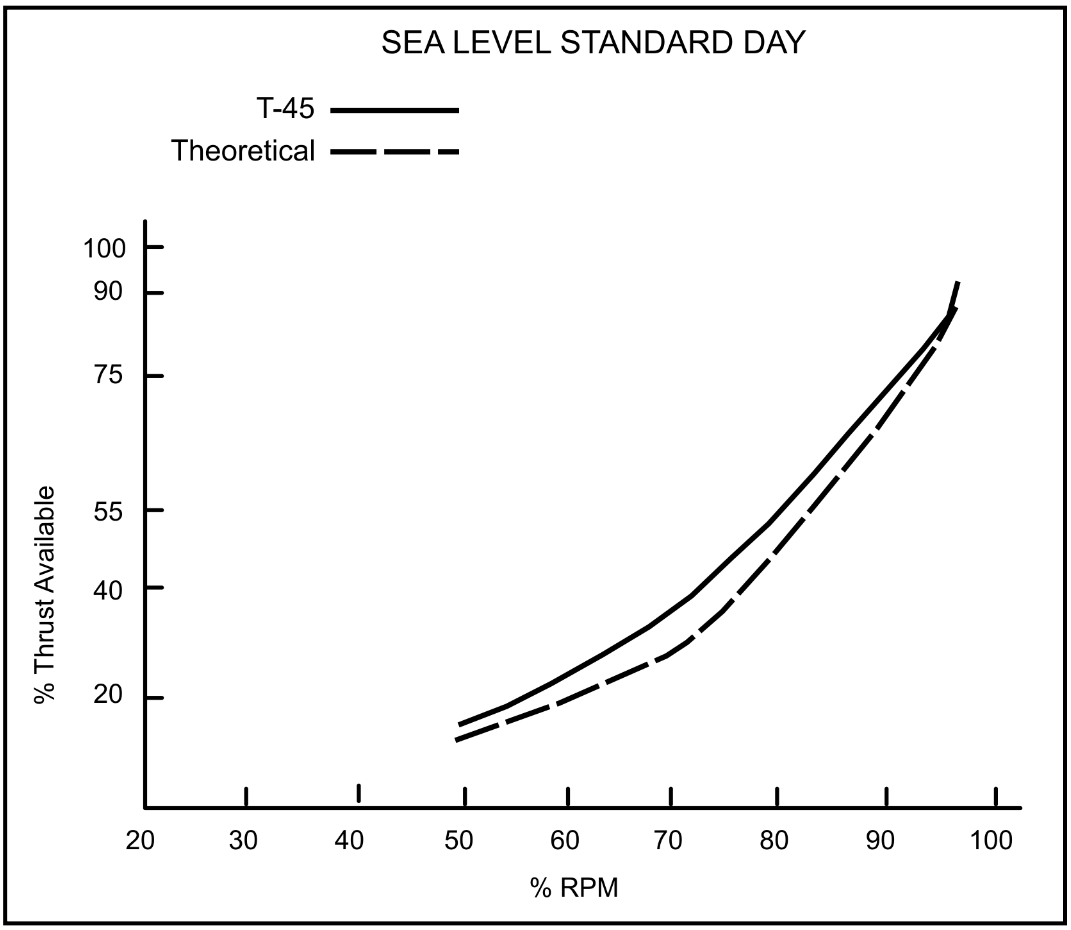

Figure 5-4 T-45 RPM vs Thrust Graph

JET ENGINE RPM VS. THRUST						
% of MAX RPM	100	99	95	90	80	70
% of MAX THRUST	100	97	84	69	46	29

Figure 5-5 T-45 RPM vs Thrust Matrix

Airspeed

The thrust available from turbojet and turbofan engines is approximately unaffected by changes in airspeed. From the thrust available equation, acceleration through the engine (V_2-V_1) will decrease as inlet velocity increases. Thrust available would decrease with the increase in inlet velocity. However, as inlet velocity increases, airmass flow (Q) through the engine also increases due to ram effect (Figure 5-6).

Ram effect, as the name implies, refers to the effect of additional air forced into the engine intake as the aircraft moves at high speed through the airmass. Inlet velocity increase and ram effect approximately cancel each other's effect on thrust available. In practice, there is a slight decrease of thrust with increasing airspeed at low airspeeds.

(Figure 5-7) indicates the theoretical and actual effect of increasing airspeed on thrust available in the T-45. For practical purposes, the T-45's thrust is the same over the aircraft's speed range.

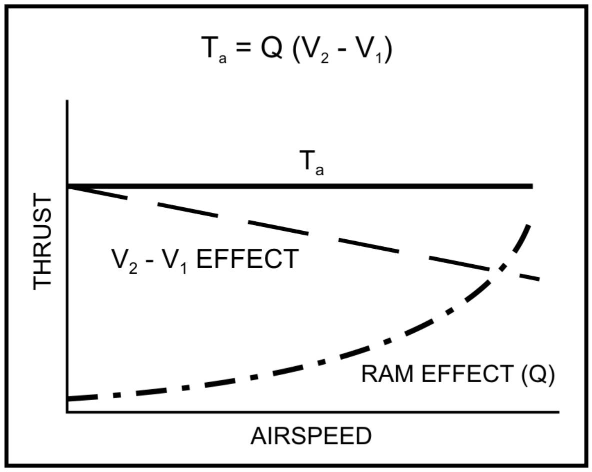

Figure 5-6 T-45 Airspeed vs Thrust

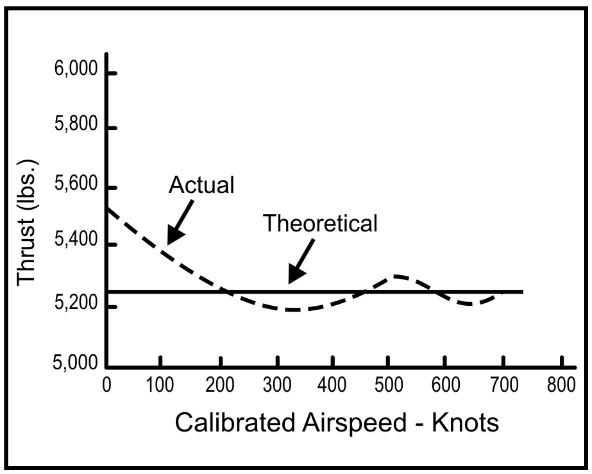

Figure 5-7 T-45 Airspeed vs Thrust Curve

501. ATMOSPHERIC CONDITIONS

Altitude and Temperature

When a turbofan is operated at a constant airspeed, the airmass flow through the engine will depend on the density of the air. Thrust output, which is directly proportional to the airmass flow, will decrease with a decrease in air density (Figure 5-8). There is an appreciable thrust loss with an increase in altitude. At 30,000 ft, there is a thrust loss of approximately 40% due to the decrease in density.

Actually, the decrease in thrust due to an altitude increase is not as severe as the altitude increase alone would indicate. The decrease in inlet air temperature as altitude increases provides for the addition of more combustion energy and, therefore, an increase in nozzle velocity. Up to the tropopause, approximately 36,000 ft, an increase in altitude will provide a decrease in temperature and partially offset the decrease in airmass flow. Above the tropopause, temperature becomes constant and the reduction in density and thrust is more rapid (Figure 5-8).

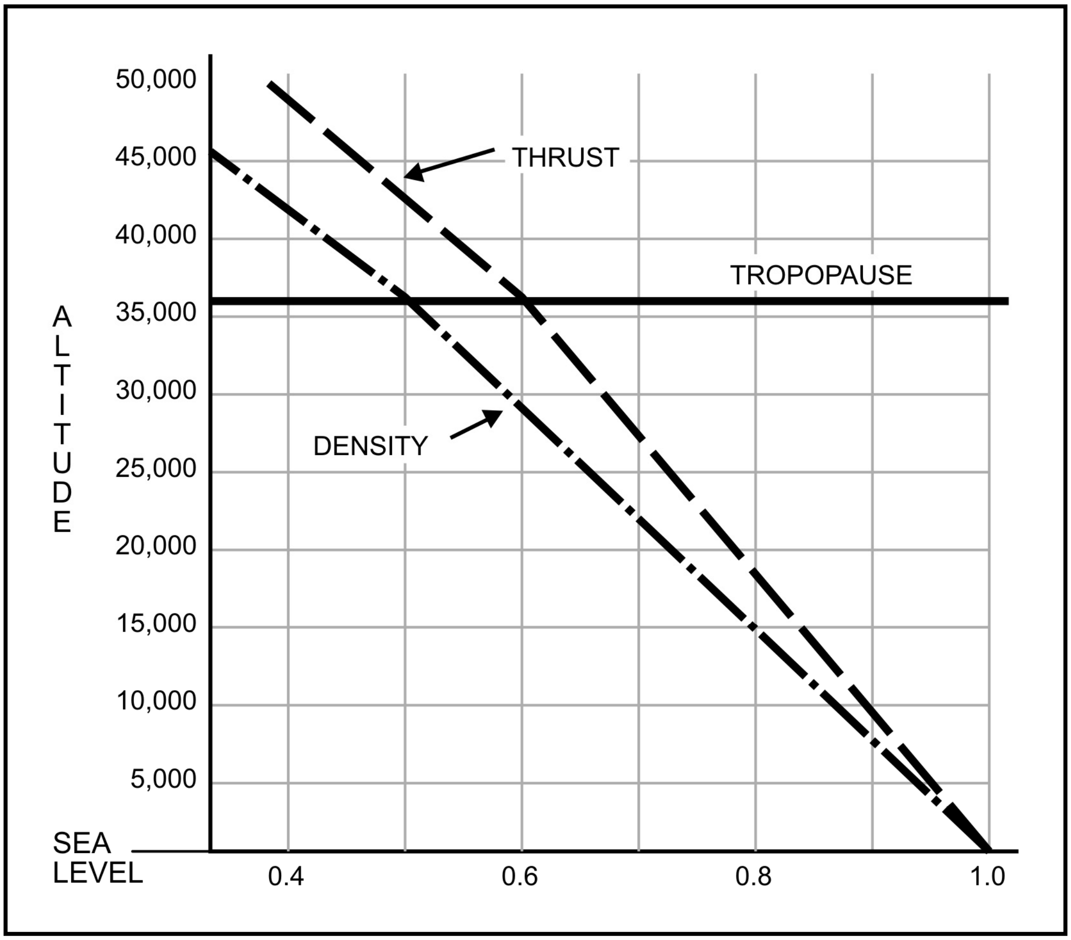

Figure 5-8 T-45 Altitude vs Density and Thrust

While thrust is reduced at altitude, drag at altitude is also reduced due to reduced air density. In addition to increased engine efficiency, an aircraft realizes increased true airspeed in the less dense air at higher altitudes (Figure 5-9).

Summarizing the effect of temperature alone on the thrust output of a turbofan engine, as temperature increases, density, mass flow, and thrust available will decrease. As density decreases, mass flow (Q) and thrust available will decrease. According to the thrust available equation, T_a= $Q(V_2-V_1,)$, as Q goes, so goes T_a. Density will increase with a temperature decrease and T_a will increase.

(Figure 5-10) illustrates the difference in thrust that can be expected at sea level with -42°F, 59°F (standard day), and 105°F temperatures.

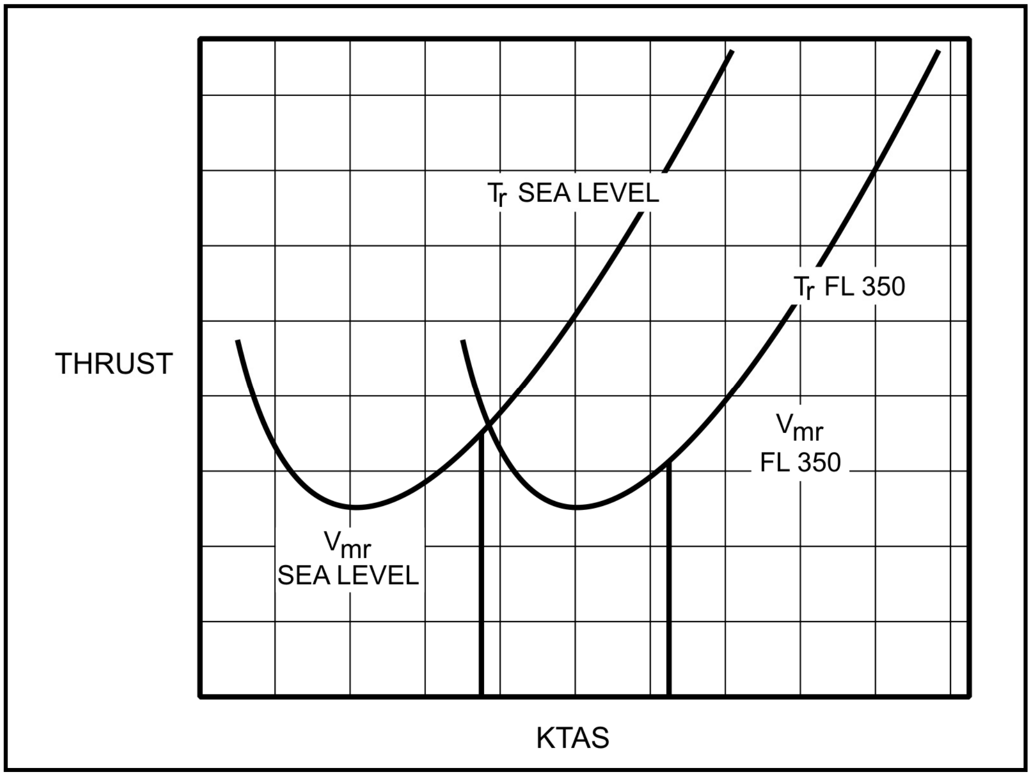

Figure 5-9 T-45 True Airspeed vs Thrust

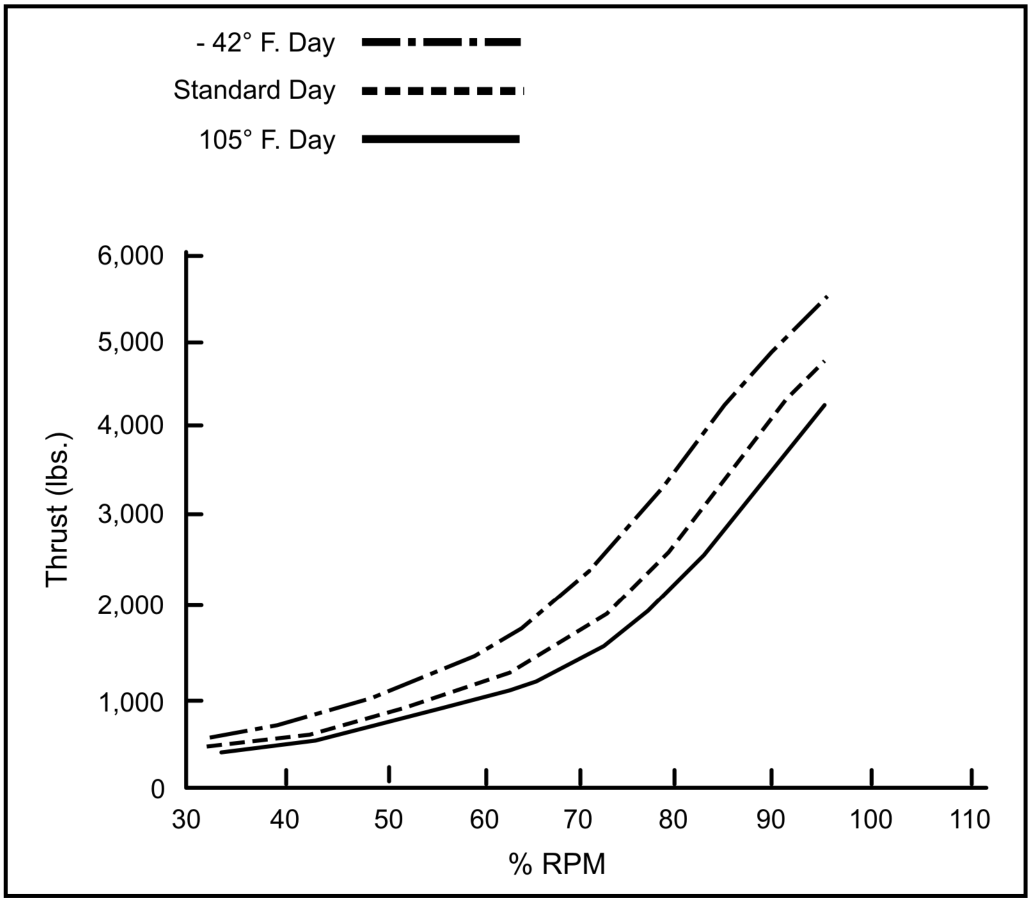

Figure 5-10 T-45 Temperature vs Thrust

Humidity

High humidity will cause a reduction in thrust because the density of moist air is less than that of dry air. Water vapor molecules have less mass than air molecules and replace the air molecules resulting in less mass flow through the engine.

Relative humidity, which affects reciprocating engine power appreciably, has much less effect on turbojet and turbofan engine thrust, fuel flow, and rpm. Therefore, humidity is not normally taken into consideration when determining fuel flow and rpm for normal jet operations.

502. SUMMARY OF ATMOSPHERE TO TURBOFAN PERFORMANCE

The following chart (Figure 5-11) summarizes the relationship between atmospheric changes and turbofan engine performance. Assume the change of <u>one or more</u> atmospheric conditions listed in the left column. The engine performance will be affected as stated in the right column. Sequential changes are connected by the symbol "->". The first situation below translates "an increase of temperature produces a decrease of density, mass flow, and thrust available."

INCREASE OF BELOW CONDITION(S) Temperature Humidity Altitude	CAUSES BELOW TO DECREASE Density -> Mass flow -> Thrust Avail
DECREASE OF BELOW CONDITION(S) Temperature Humidity Altitude	CAUSES BELOW TO INCREASE Density -> Mass flow -> Thrust Avail
WHEN ALTITUDE INCREASES (Up to 36,000')	CAUSES FOLLOWING DECREASES Density Temperature (partially compensates for decrease in density) Mass flow Thrust available Drag
Summary: WHEN ONE OF DENSITY OR MASS FLOW OR (V_{exh}-V_{in}) CHANGES>	THRUST AVAILABLE ALSO CHANGES DIRECTLY

Figure 5-11 Summary of Atmosphere to Turbofan Performance

503. JET ENGINE ANOMALIES

Compressor Stalls

The rotating blades of the engine compressor have airfoil profiles and act like little wings. Just like a wing, they can stall if the airflow over them is disrupted or exceeds the stall angle of attack. When this happens, the smooth flow of compressed air to the combustion section is interrupted and a compressor stall occurs. Effects and indications of a compressor stall can be a loss of thrust; rising EGT; stagnant or falling rpm; or audible bangs, pops, and vibrations. Compressor stalls can lead to engine damage if not cleared quickly (mostly through excessive internal temperatures). For specific T-45 compressor stall characteristics, read T-45A or T-45C NATOPS.

Flameout

Flameout refers to the inadvertent shutdown of burning in the combustion chamber. Usually an interruption of fuel flow or misadjustment of the fuel control is the cause of a flameout induced by mechanical failure. Pilot-induced flameouts caused by inadvertently pulling the throttle lever past idle while airborne are common enough to be a real hazard. Indications of flameout are low and falling EGT and low and falling rpm. Flameouts are not usually damaging to the engine, but obviously are undesirable. Pilot-induced flameouts caused when the engine is quickly reduced to idle from a high power setting may not be immediately recognized by the pilot since the engine and aircraft "feel" the same until the engine rpm drops below idle. The NATOPS airstart procedure is the pilot's action following a flameout.

Thrust-Required Curve (T_r)

Recall induced drag results from the production of lift. Induced drag dominates at low airspeeds and is nearly negligible at high airspeeds and low angles-of-attack.

Parasite drag is drag resulting from skin friction and form (or frontal area of the aircraft). Parasite drag is very low at low airspeeds and dominates at high airspeeds.

Total drag is the sum of parasite and induced drag (Figure 5-12). The total drag curve is frequently referred to as the thrust required (T_r) curve because thrust is the force acting opposite drag. Thrust required for any airspeed may be determined from a thrust-required curve. At the point where total drag and thrust required are at a minimum, the lift-to-drag ratio will be maximum and is referred to as $(L/D)_{max}$.

$(L/D)_{max}$

At $(L/D)_{max}$ the wing (actually the entire airframe including the wings) is at its most efficient operating point, producing the most lift for the least drag. The airspeed/AOA for maximum endurance, maximum climb angle, and maximum power-off glide range occur at $(L/D)_{max}$ in turbojet or turbofan aircraft.

Maximum endurance is found at $(L/D)_{max}$ because thrust required and thus fuel flow (fuel required) are at a minimum, giving maximum time airborne. Maximum climb angle is also found at $(L/D)_{max}$. At $(L/D)_{max}$, thrust required is at a minimum and all excess thrust available can be converted to climb angle which is obstacle avoidance climb angle and not rate-of-climb. Maximum glide range is also found at $(L/D)_{max}$ because the airframe is at its most efficient operating point and drag is at a minimum. Note it is power-off glide range, which is at $(L/D)_{max}$ and not maximum powered range. The lift-to-drag ratio is also the glide ratio of the aircraft. Maximum range is found on the thrust-required curve at the point where the ratio of airspeed to T_r is greatest (Figure 5-13). Maximum range may also be found by drawing a line from the point of origin tangent to the thrust-required curve. This point defines maximum range airspeed (no-wind).

Maximum range airspeed and AOA will vary with the aircraft's gross weight. As the weight decreases due to the fuel burn in the T-45, the AOA for max range increases from 12 to 13 units and the airspeed decreases accordingly. Maximum range airspeed and AOA are drastically affected by extension of landing gear and flaps as the T-45 bingo charts indicate.

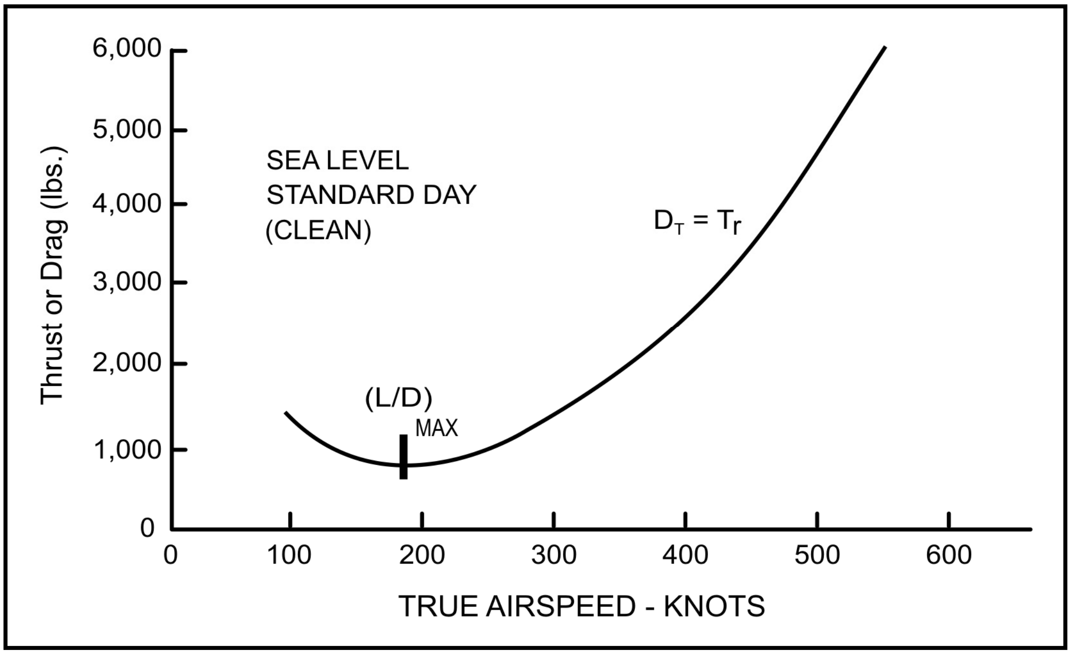

Figure 5-12 Total Drag = Thrust Required

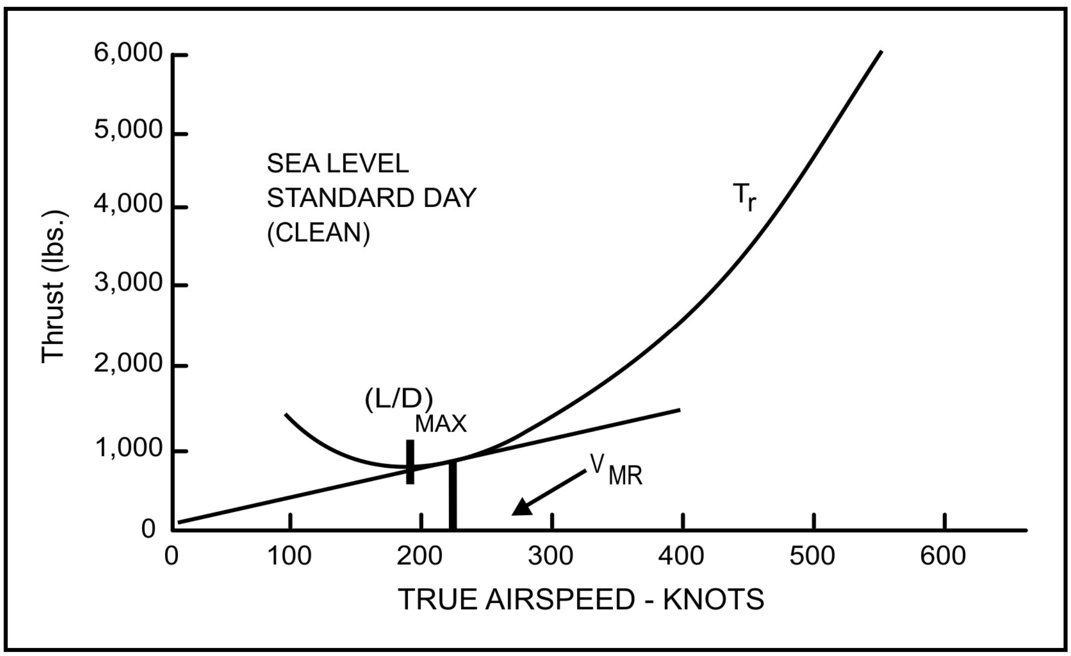

Figure 5-13 Total Drag (Max Range)

Maximum horizontal airspeed for an aircraft is where the thrust available (T_a) line intersects the thrust required (T_r) curve (Figure 5-14).

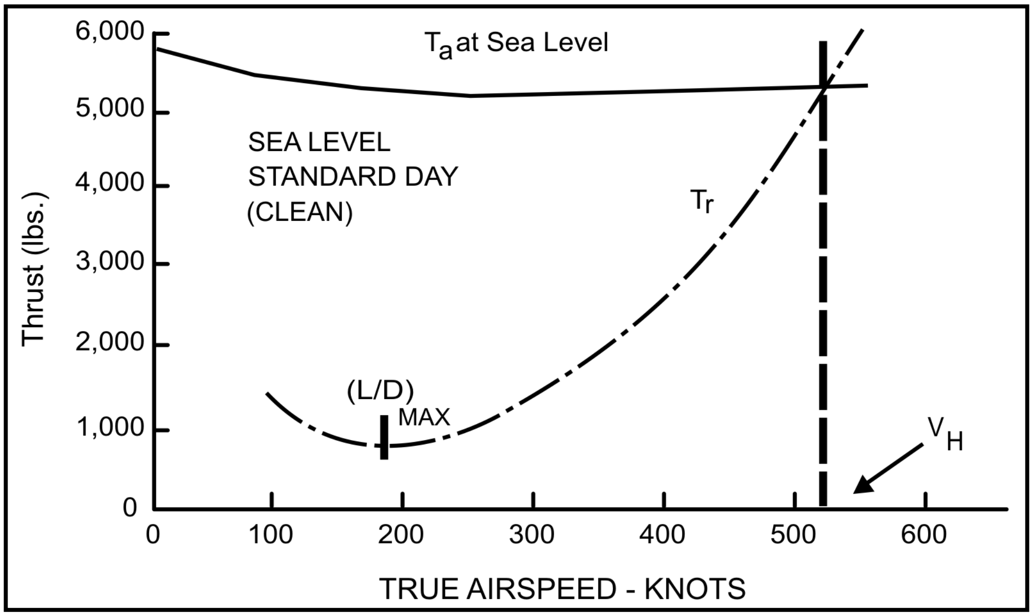

Figure 5-14 T-45 Maximum Horizontal Speed

Region of Normal Command/ Region of Reverse Command

$(L/D)_{max}$ divides the "Region of Normal Command" and the "Region of Reverse Command" (Figure 5-15). Flight in the region of normal command involves velocities greater than maximum endurance airspeed, in which an aircraft is in stable equilibrium. That is, if disturbed (slowed down), it tends to return to equilibrium. At speeds greater than $(L/D)_{max}$, more power is required to fly faster.

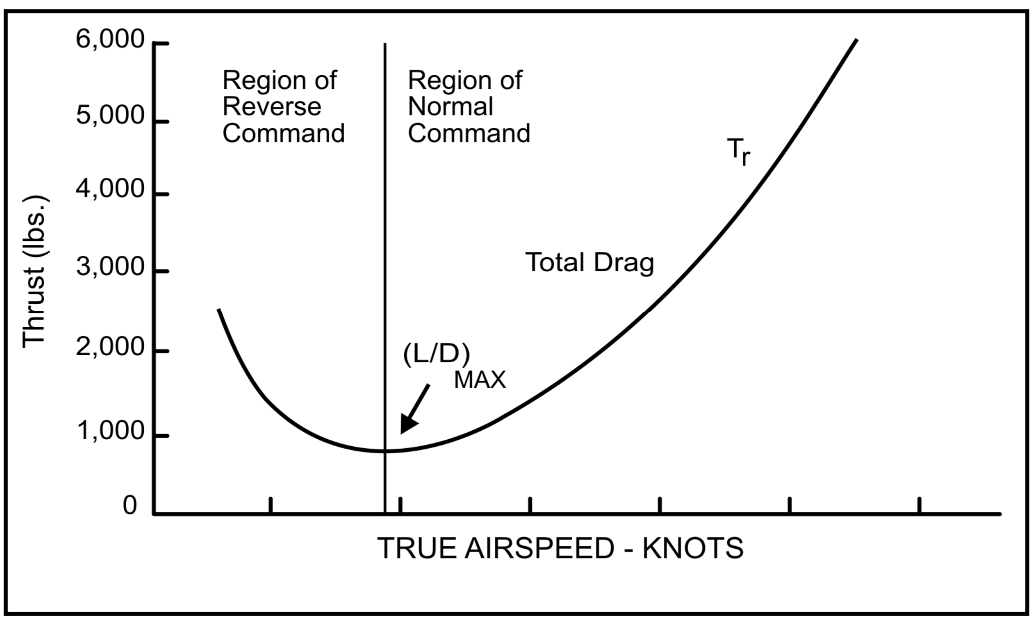

Figure 5-15 Regions of Normal Command and Reverse Command

A pilot cruising in the region of normal command at 88% rpm increases the throttle to 95% rpm; the aircraft would accelerate as thrust exceeds drag. The aircraft would accelerate and parasite drag would increase until total drag equaled thrust. Throttle reduction would cause the aircraft to decelerate until parasite and total drag decreased sufficiently that total drag equaled thrust.

In the region of reverse command, speeds less than maximum endurance airspeeds, more power is required to fly slower due to the increased induced drag. To fly at a slower speed, a pilot would be required to add thrust to overcome the additional drag. Takeoff and landing may venture into this region, also called the "back side of the power curve." In the region of reverse command, a pilot on an approach might raise the nose of the aircraft in an attempt to reduce the rate of descent.

The large increase in induced drag and rapid reduction in airspeed could cause an increase in the rate of descent and a stalled condition. In the region of reverse command, airspeed must be controlled with angle-of-attack or nose position and rate of descent must be controlled with thrust. During a normal on- speed approach, the T-45 is approximately 13 kts above the region of reverse command.

Thrust Curve Variables

A thrust-required curve is based on the variables of weight, altitude, and aircraft configuration. If any of these variables change, the thrust-required curve would also change.

Altitude

The effect of altitude on the thrust-required curve is illustrated in (Figure 5-16). A pilot desiring to fly at $(L/D)_{max}$, as altitude increases must fly at the same indicated airspeed for that weight and aircraft configuration. However, the true airspeed of the aircraft is much higher. It can then be said, as altitude increases, the thrust curve will shift to the right. As altitude increases, the same thrust will produce a higher TAS due to less drag from the less dense air.

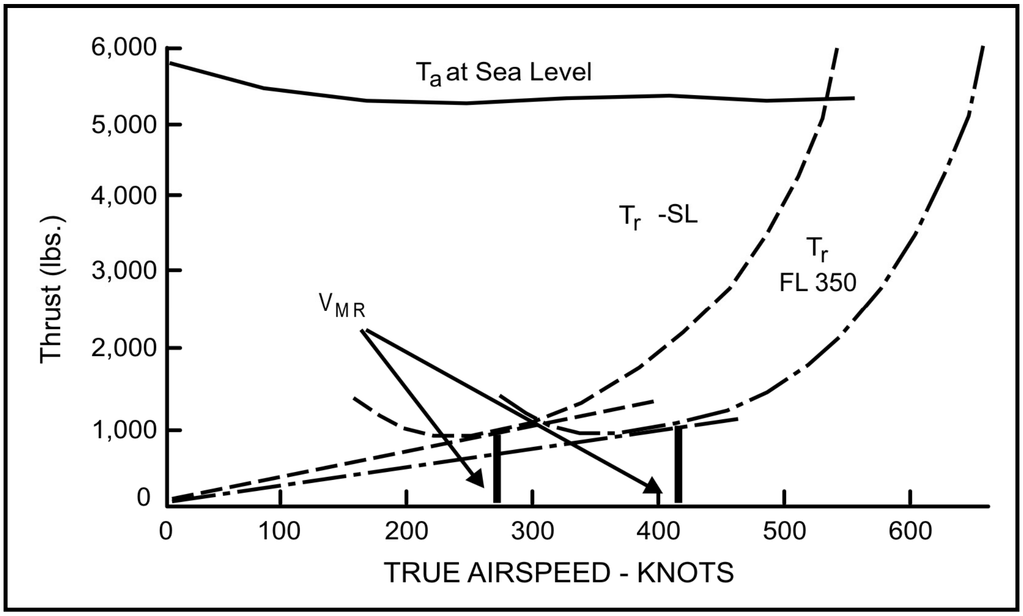

Figure 5-16 Altitude vs Thrust

Weight

The effect of weight on the thrust-required curve is illustrated by (Figure 5-17). As weight increases, more lift resulting from increased airspeed is required to support the weight of the aircraft. $(L/D)_{max}$ would occur at a higher airspeed, and more thrust is required to produce the higher airspeed.

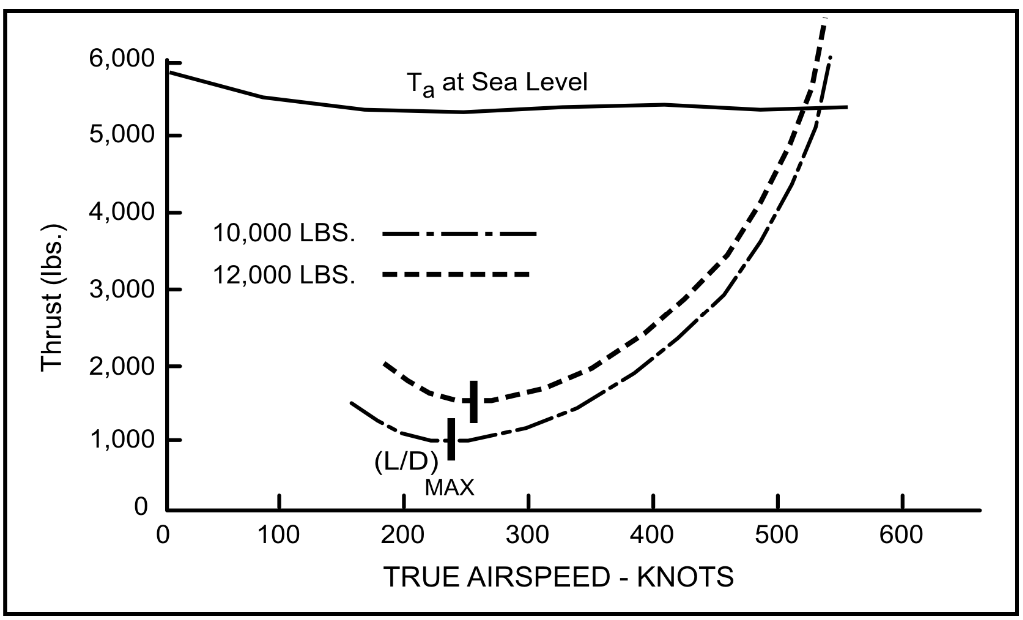

Figure 5-17 Weight vs Thrust

Configuration

A configuration change will have a different effect on the thrust-required curve depending on the change. If, for example, the configuration change is external stores that only add drag, the thrust-required curve would shift upward indicating the requirement to overcome the additional drag (Figure 5-18).

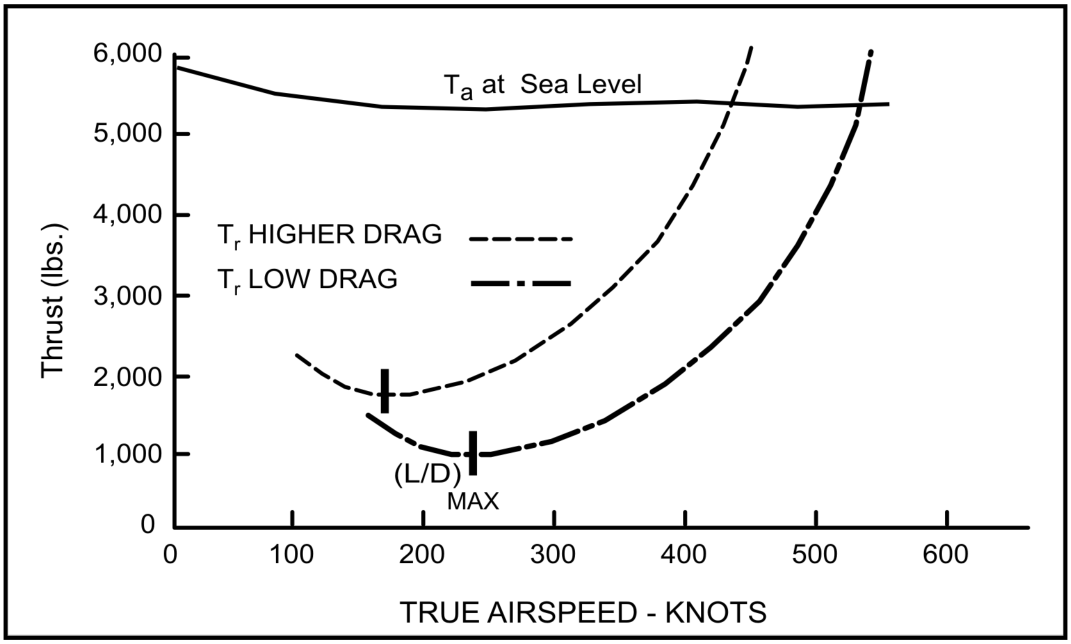

Figure 5-18 Configuration Change (Drag) vs Thrust

With a change to approach configuration, the thrust-required curve would shift left and up (Figure 5-19). The aircraft would fly at a much lower airspeed with the increase in C_L provided by the flaps producing a shift left in the T_r curve. However, the flaps and landing gear will increase drag significantly, requiring additional thrust, causing a shift up. The net result is a shift up and left when transitioning to the approach configuration.

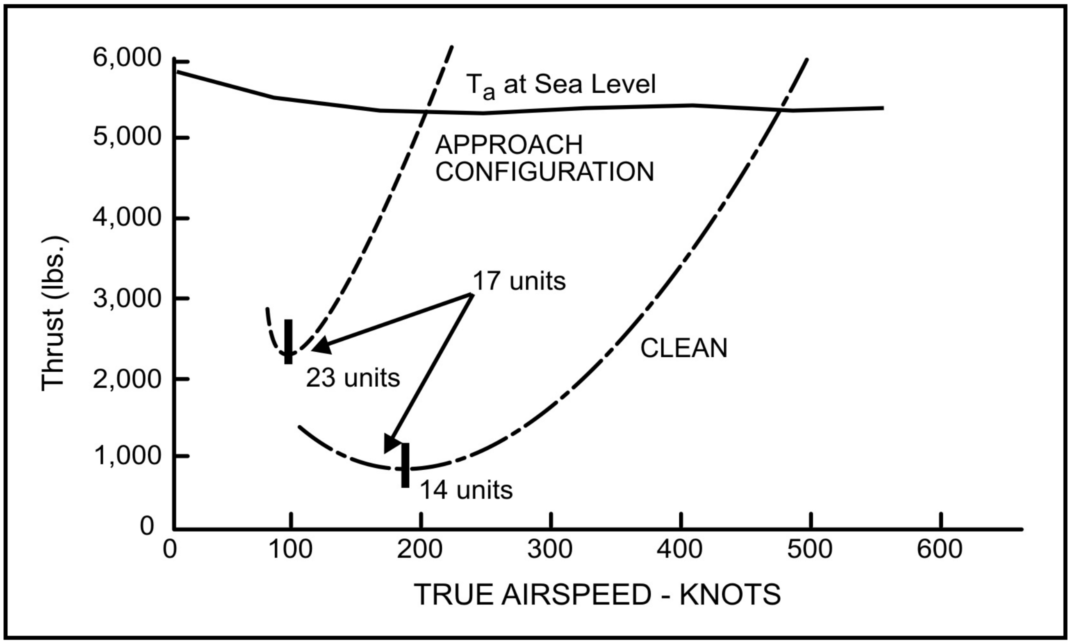

Figure 5-19 Configuration Change (Approach) vs Thrust

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CHAPTER SIX
AERO PERFORMANCE

600. INTRODUCTION

Introduction to T-45 Performance Charts

The NATOPS Flight Manuals for the T-45 contain a wealth of performance information and helpful tips. Study the sections assigned by your instructor and expect to be tested thoroughly on the charts.

While the T-45's NATOPS Flight Manual is the best source of information for your study prior to flight, you can't take it with you. Know what is in the pocket checklist and how to find it quickly. The order to divert from the carrier to a shore base should not trigger a panic because the bingo charts are included in three separate locations of the pocket checklist, but are not identified on a tab by name.

Chart Usage

The performance charts in the NATOPS manual are difficult to use, but must be understood before using them. The charts are arranged in the same order for most of the Navy's tactical aircraft. Most of the charts are in the logical sequence in which one would fly a cross-country. The mission-related charts are at the end of the manual. Grouped in sections, the introduction gives the background, definitions, explanations, conditions, assumptions, and sample problems to enhance your understanding of that section's charts. One should establish an understanding of the problem and the use of the chart before wasting a lot of time making mistakes in the chart.

The guide, in the upper right corner of many charts, shows the path to use when traversing that particular chart. A better explanation of the route through each chart is in the introduction to that chapter. When one moves from one grid to another grid with channels, normally one parallels the channel until reaching a value on the left side of the grid. Proceed straight down to the bottom of the grid. Check the sense of your answer and redo the problem if necessary.

601. TECHNIQUES THAT WORK BEST IN USING THE CHARTS:

1. Study the chapter introduction and sample problem.

2. Select the correct chart. This is the most frequent mistake.

3. Verify you selected the right configuration and conditions.

4. Study the guide and chapter introduction to determine the proper route.

5. Do you need a value from another chart or elsewhere?

6. Lay the chart flat under good light.

7. Count lines from the heavy black lines to navigate from location to location and avoid straight edging long distances across the chart.

8. Compute the grid value throughout the problem to ensure a correct answer.

9. Realize you may solve a problem in the middle of a chart, at the end of the guide's course, or on another chart.

10. Ask yourself if the answer makes sense. If not, do it again.

Density Ratio Chart

The use of density ratio combines the effect of temperature and pressure altitude on engine performance. Jet engines perform better at higher density ratios, that is, with lower temperatures or lower pressure altitudes. Density ratio must be computed before using the takeoff and landing charts.

Takeoff Distance Chart

The takeoff distance chart contains a table that shows main wheel lift-off speed for various gross weights. Lift-off occurs when the lift generated by air moving over the wings exceeds the weight of the aircraft.

To obtain the takeoff distance under three circumstances, one will first obtain a no-wind solution and, if appropriate, a wind solution, and finally the distance required from the commencement of takeoff roll to clear a 50-ft obstacle. One might find a 50-ft obstacle at the end of a short runway while showing a static display at a small New England airport. Note the wind correction can be for head or tail wind. Most likely you will find your solution in the middle of this chart and not use the 50-ft calculation.

Line Check Speed

Line check speed is the speed to which the aircraft should accelerate in a given distance during takeoff. The pilot uses the known distance to an object such as the arresting gear or a runway distance remaining marker to compute the speed. On takeoff, if the aircraft does not achieve the calculated speed by the selected obstacle, the pilot should abort and have the aircraft checked.

Use the Velocity During Takeoff Ground Run chart to calculate the line check speed. Enter the chart with the distance from the commencement of takeoff roll to the selected object.

Velocity During Takeoff Ground Run

This chart is used to determine the ground velocity during the takeoff at any distance down the runway. The line check speed is determined for the distance from commencement of takeoff roll to the object. Dry runway charts are the only charts included as T-45 acceleration is essentially the same under dry and wet conditions.

Maximum Abort Speed

This chart calculates the maximum speed to which an aircraft can accelerate on takeoff roll and commence an abort that will permit the aircraft to stop on the remaining runway without using the overrun or the arresting gear. Wet and dry charts are presented because the aircraft's stopping distance is much greater on a wet runway.

Compressibility Correction to Calibrated Airspeed

This chart indicates that subsonic air is compressible at higher speeds. One can gain airspeed over that computed in the charts by using this table to increase CAS and TAS. At the extreme limits of the T-45's envelope, 550 KCAS and 40,000 ft, the compressibility correction would be 75 KCAS. Under most circumstances, it will be less than half of that.

Climb Speed Schedule

This matrix is used to determine climb speed for various drag indexes and altitudes. This schedule is a simplified normal climb speed schedule. It is independent of weight and is expressed in indicated airspeed or Mach number.

Time, Fuel, and Distance to Climb

These three charts are used to determine the time, fuel, or distance to climb to a selected altitude. Climb is at maximum-rated thrust at the climb speed schedule in NATOPS (see previous paragraph). These charts account for kinetic energy corrections due to rate of climb.

Bingo

Bingo charts are in your NATOPS manual and pocket checklist. Learn to use the pocket checklist, as it will be with you when your signal is "bingo." Bingo is a fuel state that will permit you to fly to a divert field and land with a fuel reserve, 300 pounds in the case of the T-45. Bingo is sometimes used to mean, "Go to your divert field," which could occur for many reasons, i.e., the carrier deck will not be ready within your fuel remaining, the ship needs to move to another operating area, etc.

The divert/bingo concept could apply to operations at any shore-based airport, especially the vulnerable ones with a single runway. A crosswind out of limits, arrestment, or accident could dictate a divert. To conserve fuel for an unknown eventuality, use the bingo chart and fly the recommended profile. What if you should have to hold at your divert field while a plane is removed from the runway? Is there a second divert field nearby? The chart shows the fuel, time, and speed to proceed at sea level.

To use the bingo chart, enter with the distance to divert field and appropriate drag index. In succeeding columns, read fuel required, climb speeds, optimum range cruise, and maximum range descent.

The "FUEL REQD" and "DESCEND DISTANCE" columns have figures for NO HEADWIND and 100-KT HEADWIND. Compute the headwind component in the WIND COMPONENT chart of NATOPS or the PCL. Using the calculated headwind component, interpolate between the zero and 100-knot wind values and between the entry mileage and the chart values, if necessary. Compute the descent point by interpolation, realizing that the descent point will be closer to the bingo field if the headwind is stronger.

The bingo charts consider the 300 pounds required as a fuel reserve. Remember that reserve fuel is yours to burn if circumstances warrant. It will be on your fuel gauge but only should be used in an emergency. Anticipate that a runway might be closed suddenly and for a long period.

Landing Approach Speed

This chart calculates the approach speed that a given gross weight will produce when flying a steady 17 units angle of attack. You must calculate the gross weight by knowing the zero fuel weight of the particular bureau number aircraft that you are flying. Add the weight of external stores and the fuel on the gauge. Enter the table with this total weight and go up to the appropriate flap configuration line and left to the airspeed that will result at 17 units AOA.

The weight-to-speed ratio is a constant. Each additional 200 pounds of fuel increases approach speed by 1 knot. Conversely, 200 pounds less fuel reduces the speed by 1 knot.

Each increment of flaps less than full flaps adds 19 kts to the approach speed. Calculations like these will be used to verify that the angle of attack at 17 units is providing the correct airspeed. If uncertain, fly the higher of the AOA or airspeed.

Landing Distance

These charts provide landing ground roll distance for various flap configurations, gross weights, and runway conditions - dry, wet or icy. Variables of temperature and pressure altitude are also taken into consideration. The data is for a normal 17-unit AOA approach and landing using moderate braking coefficients.

Dive Recovery

Using altitude commencing pullout, dive angle, and CAS or Mach, compute the altitude lost in a pullout from a dive. Subtract the altitude lost during pullout from the altitude the pullout is initiated to find the altitude remaining after pullout.

Operating Envelope

The T-45 operating envelope is a graphic representation of the airspeed and altitude limits. In addition, portions of the envelope impose additional restrictions on throttle movement and position.

Acceleration Limits

The symmetrical and unsymmetrical maneuvering limits are shown on this graph. The graph depicts the T-45 load limits under various gross weight, altitude, and airspeed conditions. Unsymmetrical maneuvers are rolling maneuvers at other than 1-g flight.

External Stores Limitations

The external stores limitation matrix shows the station loading, airspeed, acceleration, dive angle, AOA, and center of gravity limits for various external stores. Also shown are the stores weight and applicable notes. Some limitations are listed as "LBA” or Limit Basic Aircraft. This means that limitations are the same as the basic aircraft limitations.

602. AERODYNAMICS PERFORMANCE PROBLEMS

The problems that follow will demonstrate principles governing T-45 performance, improve your proficiency with NATOPS performance charts, and help you prepare for the exam. **Before using any chart, read the introduction to that chapter to learn how to use the charts in that chapter.**

Aero Problem 1 7/18
1.1.5.1

While approaching the ship at 800 ft for break, the ship directs that you divert to NAS Oceana, 358 degrees, 200 miles. Your T-45 has no pylons and a weight of 10,500 pounds without usable fuel. Average wind is 020 degrees at 60 kts. Your fuel remaining is 1,000 pounds.

Enter the appropriate figures for the best bingo profile to Oceana:

Climb speed ____________________ KNOTS _______________________MACH

Cruise altitude ____________________ FEET
Cruise speed ____________________ KCAS ____________________ IMN

En route descent speed ____________________ KCAS
En route descent distance ____________________ MI.

Fuel used ____________________ LB.

WHAT SHOULD YOU TRANSMIT TO THE SHIP?

ANSWER:

REF: NATOPS 1/15/97, Chapter 29

Aero Problem 2 12/15
1.1.5.1

The T-45 acceleration limits between 260 kts and <0.8 Mach are:

	Below 5,000 ft		Above 5,000 ft	
	Positive	Negative	Positive	Negative
Symmetric				
Unsymmetric				

REF: NATOPS 1/15/97, Chapter 4

Aero Problem 3 7/18
1.1.5.1

Maximum abort speed is the speed at which the takeoff can be rejected and the aircraft safely stopped on the runway. Line check speed is the speed an aircraft should achieve in a specified takeoff roll. Given the following situation at Buckley ANGB, calculate the line check speed after 1,000 ft of takeoff roll, the lift-off speed, the takeoff distance, and the maximum abort speed:

Takeoff gross wt.	13,000 pounds
Temperature	100 degrees
Pressure altitude	5,663 ft
Runway length	11,000 ft
Flap	1/2
Weather	Overcast clouds, 8 miles visibility Light rain No wind
NOTAM	RWY 13-32 northwest 3,000 ft closed

ANSWERS:

Line Check Speed KCAS	Lift-off Speed KCAS	Takeoff Distance feet	Max Abort Speed KCAS

REF: NATOPS 1/15/97, Chapter 11

Aero Problem 4 7/18
1.1.5.1

For both dry and wet conditions, calculate the line check speed after 1,000 ft of takeoff roll, the lift-off speed, the takeoff distance, and the maximum abort speed given the following situation:

Start takeoff	200 ft down runway
Takeoff gross wt.	13,000 pounds
Temperature	100 degrees F
Pressure altitude	50 ft
Runway length	8,000 ft
Flaps	1/2
Weather	Overcast clouds
	8 miles visibility
	Dry then light rain
	No wind

ANSWERS:

	Line Check Speed KCAS	Lift-off Speed KCAS	Takeoff Distance feet	Max Abort Speed KCAS
Dry Runway				
Wet Runway				

Additional questions related to problems 3 and 4:

IF YOU ABORT ABOVE THE MAX ABORT SPEED, WHAT MAY SAVE YOU?
Answer:

WHY IS TAKEOFF DISTANCE GREATER AT BUCKLEY ANGB THAN AT KINGSVILLE?
Answer:

WHAT CAUSES THE CHANGE IN RELATIONSHIP BETWEEN LIFT-OFF SPEED/TAKEOFF DISTANCE AND MAX ABORT SPEED IN PROBLEMS 3 AND 4 ABOVE?
Answer:

WHAT IS YOUR PREPLANNED ACTION WHEN THE ENGINE SHOWS SIGNS OF FAILING AFTER PASSING THE MAX ABORT SPEED, BUT JUST BEFORE LIFT-OFF AT BUCKLEY ANGB (USE ANSWERS TO QUESTION 3)?
Answer:

WHAT IS THE MOST IMPORTANT DETERMINANT OF LIFT-OFF SPEED?
Answer:

REF: NATOPS 1/15/97, Chapter 11

SOLUTION TO PROBLEM 4:

<u>Aero Problem 4 Dry runway:</u>

Entering the Density Ratio chart with the ambient 100-degree F temperature and going up to Kingsville's 50-ft elevation yields a Density Ratio of 0.925. Entering the 1/2 Flap Takeoff Distance chart with the Density Ratio, 13,000# aircraft gross weight yields a takeoff roll of 2,750 ft for "ground roll without wind." Entering the Velocity During Takeoff Ground Run chart with 1,000 ft, and going right to the 13,000# gross weight, then descending and following the middle grid's channel to the density ratio and descending to the line in the bottom grid yields a line check speed of 93 KCAS on the left border. To determine lift-off velocity, enter the box chart on the Takeoff Distance chart with the 13,000 pound gross weight (GW) and read the lift-off speed of 124 KCAS in the column to the right.

For additional sample problems with solutions, see the introductions in the NATOPS chapters that deal with performance.

NOTES

CHAPTER SEVEN
AERO EXAM

700. INTRODUCTION

The T-45 NATOPS Flight Manuals, A1-T45AB-NFM-000 or A1-T45AC-NFM-000 and A1-T45AB-NFM-300, and pocket checklist, A1-T45AB-NFM-500 or A1-T45AC-NFM-500, will be the only reference materials permitted during the CAI exam.

NOTES

APPENDIX A
GLOSSARY

A100. GLOSSARY

A

Absolute Angle of Attack: An angle of attack measured between a reference line in an airfoil and the position the reference line would be if the airfoil were producing zero lift, i.e., the sum of the geometric angle of attack and the zero-lift angle of attack. Also called an aerodynamic angle of attack. See angle of attack.

Accelerated Stall: A stall with an airplane under acceleration, as in a pullout. Such a stall usually produces more violent motions of the airplane than does a stall occurring in unaccelerated flight.

Acceleration: In mechanics, a change in the acceleration of a body, or the rate of such a change, with respect to speed or direction or both. The state or condition of a body undergoing such change.

Adjustable Stabilizer: A stabilizer, especially a horizontal stabilizer, whose angle of incidence may be varied, usually both on the ground and in flight.

Adverse Pressure Gradient: In a fluid flow system or field, a pressure gradient of increasing static pressure in the direction of the flow.

Adverse Yaw: Yaw in the opposite sense to that of the roll of an aircraft, i.e., a yaw to the left with the aircraft rolling to the right.

Aerodynamic Axis: The axis is a line containing the aerodynamic centers of a body, such as the line joining the aerodynamic centers along a wingspan.

Aerodynamic Balanced Surface: A control surface so designed or fitted out with auxiliary devices that the magnitude of the aerodynamic moment about the hinge axis is reduced.

Aerodynamic Center (AC): A point in a cross section of an airfoil or other aerodynamic body or combination of bodies, about which the pitching moment coefficient remains practically constant with nearly all changes in angle of attack.

Aerodynamic Coefficient: Any nondimensional coefficient relating to aerodynamic forces or moments, such as a coefficient of drag or a coefficient of lift.

Aerodynamic Efficiency: The efficiency with which a body overcomes or makes use of aerodynamic forces or actions; specifically, the efficiency with which an airfoil or other lifting body produces lift in proportion to drag, determined numerically from the lift-drag ratio (L/D).

Aerodynamic Heating: The rise in the skin temperature of an aircraft due to friction of the air at high speed.

Aerodynamic Overbalance: A condition existing when aerodynamic forces cause an aircraft or aircraft component to rotate or turn excessively about a point or line; specifically, the condition of an aircraft control surface existing when its deflection results in a hinge moment tending to increase the deflection.

Aerodynamic Twist: The twist of an airfoil having different absolute angles of attack at different spanwise stations.

Aeroelasticity: *1.* The quality or state of an elastic structure acted on by aerodynamic forces. *2.* The study of the effect of aerodynamic forces on elastic bodies.

Aileron Buzz: A rapid vibration of an aileron, considered a type of flutter, as occurs especially at transonic speeds; the noise resulting from this vibration.

Aileron Droop: The simultaneous downward or positive deflection or hang of the ailerons on both sides of an airplane so as to create additional camber.

Aileron Reversal: A reversal of the control effect usually produced by the deflection of an aileron in a given direction, e.g., the lowering, rather than the rising, of a wing when the attached aileron is deflected downward, caused by the aileron action twisting the wing and changing its angle of attack so that it overcomes the lifting effect of the downward aileron deflection. This condition arises at certain flight speeds with wings insufficiently stiff in torsion.

Airflow: A flow or stream of air. An airflow may take place in a wind tunnel, in the induction system of an engine, etc., or a relative airflow can occur, as past the wing or other parts of a moving airplane; a rate of flow, measured by mass or volume per unit of time.

Airfoil: A structure, piece, or body, originally likened to a foil or leaf in being wide and thin, designed to obtain a useful reaction on itself in its motion through the air. An airfoil may be no more than a flat place, but usually it has a cross section carefully contoured in accordance with its intended application or function. Airfoils are applied to aircraft, missiles, or other aerial vehicles or projectiles for sustentation (as a wing), for stability (as a fin), or for control (as a propeller blade). Certain airfoils combine some of these functions.

Airfoil Section: *1.* A section of an airfoil, especially a cross section taken at right angles to the span axis or some other specified axis of the airfoil. *2.* In most usages, the form or shape of an airfoil section; an airfoil profile, or the area defined by the profile.

Airstream: A stream of air, as in a wind tunnel or past a moving airplane; an airflow.

All-Movab1e Tai1: A horizontal or vertical tail surface that pivots as a whole, as distinct from the usual combination of fixed and movable surfaces. Also called a slab tail.

Ambient: Surrounding; specifically, of or pertaining to the air or air conditions about a flying aircraft or other body but undisturbed or unaffected by it, as in ambient air or ambient temperature.

Angle of Attack: The angle at which a body, such as an airfoil or fuselage meets a flow. More commonly, the angle between the relative wind and the chord line. It is a reference for achieving desired aircraft performance, regardless of weight, configuration, or g load.

Angle of Incidence: The acute angle between a chord of an airfoil (usually the geometric chord) and the longitudinal axis of an aircraft.

Angle of Sideslip: The angle, as seen from above, between the longitudinal body axis of an aircraft or similar body and the direction of the undisturbed airflow past the body. This angle is positive when the forward part of the longitudinal axis is directed to port.

Angle of Sweep: The acute angle between a reference line in a swept or tapered airfoil and some other chosen reference line or place. For fixed airfoils, the angle is measured from a plane perpendicular to the longitudinal axis of the aircraft to the reference line of the airfoil. The angle is positive if the outboard end of the airfoil reference line is after the inboard end.

Anhedral: A negative dihedral; anhedral angle.

Area Rule: A prescribed method of design for obtaining minimum zero-lift drag for a given aerodynamic configuration, at a given speed. For transonic body, the area rule is applied by subtracting from, or adding to, its cross-sectional area distribution normal to the airstream at various stations so as to make its cross-sectional area distribution approach that of an ideal body of minimum drag; for a supersonic body, the sectional areas are frontal projections of areas intercepted by planes inclined at Mach angle.

Artificial Feel: A control feel simulated by mechanisms incorporated in the control system of an aircraft where the forces acting on the control surfaces are not transmitted to the cockpit controls, as in the case of an irreversible control system.

Aspect Ratio: The ratio of wing span to average chord (AR = span/chord) or $span^2$/wing area.

Attached Shock Wave or Attached Shock: An oblique or conical shock wave that is in contact with the leading edge or the nose of a body in a supersonic flow field.

Attitude: The position of a body as determined by the inclination of the axes to some frame of reference. If not otherwise specified, this frame of reference is fixed to the Earth.

Axis: *1. a.* A line passing through a body, about which the body rotates or may be assumed to rotate. *b.* Any arbitrary line of reference, such as a line about which the parts of a body or system are symmetrically distributed. *c.* A line along which a force is directed, as an axis of thrust. *2.* Specifically, any one of a set or system of mutually perpendicular reference axes, usually intersecting at the center of gravity of an aircraft, about which the motions, moments, and forces of roll, pitch, and yaw are measured.

B

Bernoulli's law: In aeronautics, a law or theory stating that a flow of incompressible fluid, the sum of the static and the dynamic pressure along a streamline, is constant if gravity and frictional effects are disregarded.

Biconvex Airfoil: An airfoil profile whose sides are convex (circular-arc lines); applied to such profiles that are symmetric about the chord.

Body of Revolution: A symmetrical body, such as a bullet, having the form described by an element rotated about an axis.

Boost: Additional power, pressure, or force supplied by a booster, as hydraulic boost.

Boundary-Layer Control: The control of the flow in the boundary layer about a body or of the region of flow near the surface of the body to reduce or eliminate undesirable aerodynamic effects and hence to improve performance.

Bound Vortex: In aerodynamic theory, a hypothetical vortex assumed to lie in an airfoil and traveling with it and corresponding to the lifting forces acting on the airfoil.

Bow Wave: A shock wave in front of a body, such as a wing's leading edge, or attached to the forward part of the body.

C

Calibrated Airspeed: Indicated airspeed corrected for instrument installation error.

Camber: The curvature of the mean line of an airfoil or airfoil section from leading edge to trailing edge; the amount of this curvature, expressed as the ratio of the maximum departure of the curve from the chord to the chord length.

Center of Pressure: The point along the chord of an airfoil section where all changes in lift effectively take place.

Center-of-Pressure Travel: The movement of the center of pressure of an airfoil along the chord with changing angle of attack; expressed in percentage of the chord.

Chord: In aeronautics, a straight line intersecting or touching an airfoil profile at two points; specifically that part of such a line between two points of intersection. This line is usually a datum line joining the leading and trailing edges of an airfoil, joining the ends of the mean line of an airfoil profile, or running along the lower surface or line of an airfoil profile, from which the ordinates and angles of the airfoil are measured. As such a datum line, it is sometimes called the geometric chord, to distinguish it from a chord established on the basis of any other considerations.

Chord Length: The length of the chord of an airfoil section between the extremities of the section.

Chordwise: Moving, located, or directed along the chord.

Compressibility: The property of a substance, as air, by virtue of which its density increases with increase in pressure.

Compressible Flow: In aerodynamics, flow at speeds sufficiently high that density changes in the fluid can no longer be neglected.

Compression Wave: A shock wave, when the emphasis is upon the compression of the fluid passing through it.

Control Force: *1*. An aerodynamic force acting on a control surface. *2.* A deflecting force exerted on a control surface by the pilot or by power devices in the aircraft control system.

Controllability: The capability of an aircraft to respond to control, especially in direction or attitude.

Cornering Speed (Maneuvering Speed): The intersection of the positive aerodynamic boundary (lift limit) and structural limit defines a speed that is crucial in fighter performances. Here a fighter obtains maximum instantaneous turn performance. Referred to as "maneuver speed" by aerodynamics texts.

Coupling: The interaction between roll, yaw and pitch in swept wing aircraft which leads to Dutch Roll, spiral divergence, and spiral dive.

Critical Mach Number: The free-stream Mach number at which a local Mach number of 1.0 is attained at any point on the body under consideration.

D

Delta Wing: A wing shaped in planform substantially like the Greek capital letter delta or like an isosceles triangle, the base forming the trailing edge.

Detached Shock Wave or Detached Shock: A shock wave not in contact with the body which originates it.

Differential Ailerons: Ailerons geared so that, when they are deflected, the up aileron moves through a greater angle than the down aileron; used to reduce adverse yaw or to lessen the control force necessary for deflection.

Dihedral: The spanwise inclination of a wing or other surface, such as a stabilizer, or of a part of a wing or other surface to the horizontal or to a line or place equivalent to the horizontal; specifically, a positive or upward inclination.

Dihedral Effect: An effect due to dihedral. The rolling movement of an aircraft due to sideslip, resulting from whatever causes, but resulting principally from the actual dihedral of the wing or wings. The dihedral effect is said to be positive if it is such that it tends to raise the forward wing in the sideslip.

Double-Slotted Flap: A flap consisting of two sections jointed together, providing two slots for the passage of air.

Double-Wedge Airfoil: An airfoil profile usually having the shape of a slim rhombus with maximum thickness at midchord point; however, maximum thickness can also occur at other locations.

Downwash: A flow deflected or forced downward, as by the passage of a wing.

Downwash Angle: The angle, measured in a plane parallel to the plane of symmetry of an aircraft, between the direction of the undisturbed airstream. This angle is positive when the deflected stream is downward.

Drag: The retarding force acting on an aircraft in motion, parallel and opposite to its direction. There are two types of drag: induced and parasitic.

Drag Coefficient: A coefficient representing the drag on a given airfoil or other body, or a coefficient representing a particular kind of drag.

Dynamic Pressure: In aerodynamics, the pressure of a fluid resulting from its motion, equal to one-half the fluid density times the fluid velocity, squared ($1/2\ p\ V^2$). In compressible flow, dynamic pressure is the difference between total pressure and the static pressure.

Dynamic Stability: The property of an aircraft that causes it, when disturbed from an original state of steady flight or motion, to damp any oscillations set up by restoring moments and gradually to return to its original state.

E

Elevator: A control surface, usually hinged to a horizontal stabilizer, deflected to impress a pitching moment, i.e., to make the aircraft rotate about its lateral axis.

Elevon: (elevator + aileron) A control surface that functions both as an elevator and as an aileron. Also called an **ailavator or ailevator.**

Empennage: The assembly of stabilizing and control surfaces at the tail of an aircraft.

Equivalent Airspeed: Calibrated airspeed corrected for compressibility error.

F

Feedback: In aeronautics, the transmittal of forces initiated by aerodynamic action on control surfaces to the cockpit controls; the forces so transmitted.

Fence: A stationary plate or vane projecting from the upper surface of a wing (sometimes continued around the leading edge), substantially parallel to the airstream; used to prevent spanwise flow. Sometimes called a **stall fence.**

Fixed Slot: A slot that remains open at all times.

Flap: Specifically, a hinged, pivoted, or sliding airfoil or plate, or a combination of such objects regarded as a single surface, normally located at the rear of a wing, extended or deflected for increasing camber, especially at takeoff or during landing.

Flat Spin: A spin in which the airplane remains in a more level attitude than that of a normal spin; usually more difficult to recover from.

Flight Path: The line or way connecting the continuous positions occupied, or to be occupied, by an aircraft as it moves through the air with reference to the vertical or horizontal planes. The direction and velocity of the center of gravity of an aircraft.

Force Divergence Mach Number: The Mach number where the coefficient-of-drag and total drag increase rapidly due to wave drag.

Flow Separation: The breakaway of flow from a surface, the condition of a flow separated from the surface of a body and no longer following its contours.

Flutter: A vibration or oscillation of definite period set up in an aileron, wing, or the like by aerodynamic forces and maintained by the aerodynamic forces and by the elastic and inertial forces of the object itself.

Fowler Flap: A type of extensible trailing-edge flap that increases both the camber and wing area.

Frontal Area: The projection of a body on a plane perpendicular to the fore-and-aft axis of the body.

Full-Cantilever: Supported at one end only, as in full-cantilever wing; a wing attached to the fuselage at one end and not supported otherwise.

G

Geometric Twist: The twist of an airfoil having different geometric angles of attack at different spanwise stations.

Glide Ratio: The ratio of the horizontal distance traveled to the vertical distance descended in a glide. Also called **gliding ratio.**

Ground Effect: *1.* The effect of the ground or surface in turning the downwash or induced flow from the wings of an aircraft flying near it, thus reducing induced drag and increasing lift within one wingspan of the ground. *2.* The zone close to the ground in which the ground effect is operative.

H

High-Lift Device: Any device, such as a flap, slat, or boundary-layer-control device, used to increase the coefficient of lift of the wing.

Horizontal Tail: The entire horizontal part of an aircraft's empennage extending on both sides of the plane of symmetry and in most forms comprising both fixed and movable surfaces.

I

Induced Angle: Also induced angle of attack. The difference between the actual angle of attack of an airfoil and the angle of attack of an airfoil with infinite aspect ratio and the same lift coefficient, i.e., the angle between the direction of movement of the airfoil and the resultant wind past it.

Induced Drag: All drag associated with production of lift-inversely related to velocity and directly related to AOA.

Infinite-Span Wing: In aerodynamic theory, a wing of endless span, thus having no tip vortices nor induced drag, assumed for purposes of simplification.

Interference Drag: Increased drag at high speeds due to airflow from one part of the aircraft interfering with airflow over another part. For example, the total drag of a wing-fuselage combination will usually be greater than the sum of the wing area and fuselage drag independently of each other.

L

Laminar Flow: A smooth flow in which no cross flow of fluid particles occurs, hence a flow conceived as made up of layers.

Laminar-Flow Airfoil: An airfoil specially designed to maintain an extensive laminar-flow boundary layer about a body.

Laminar Separation: The separation of a laminar-flow boundary layer from a body.

Lateral Axis: An axis going from side-to-side of an aircraft, usually the side-to-side body axis passing through the center of gravity.

Lateral Control: Control over the rolling movement of an aircraft. With a fixed-wing airplane, this control is usually accomplished by the use of ailerons.

Lateral Oscillation: A rolling or sideslipping oscillation, or a combination of these oscillations.

Lateral Stability: The tendency of an aircraft to resist rolling or sometimes, also, to resist lateral displacement; the tendency of an aircraft to remain at wings-level, either in flight or at rest.

Leading Edge: The forward edge of a wing or airfoil; the edge which normally meets the air or fluid first.

Leading-Edge Flap: A flap installed at the leading edge of a wing to change the camber of the wing. It may be a plain or slotted flap.

Lift: That component of the total aerodynamic force acting on a body perpendicular to the direction of the relative wind. This lift, sometimes called **aerodynamic lift**, acts on any body or system of bodies such as an airfoil, a fuselage, or an airplane at a suitable angle of attack in the airflow.

Lift Coefficient: The coefficient representing the lift of a given airfoil.

Lift-Drag Ratio: The ratio of lift to drag, obtained by dividing the lift by the drag or the lift coefficient by the drag coefficient.

Limit Load: The calculated maximum load that an aircraft member or part will experience in service.

Longitudinal Axis: An axis going from nose-to-tail of an aircraft, usually a fore-and-aft body axis passing through the center of gravity.

Longitudinal Control: Control over the pitching movement of an aircraft.

Longitudinal Oscillation: The oscillation of an aircraft in its plane of symmetry, consisting of pitching, climbing, and diving motions.

Longitudinal Stability: The stability of an aircraft with respect to pitching motions or, sometimes also, with respect to vertical displacement and fore-and-aft motion.

M

Mach Angle: The cone-shaped shock wave theoretically emanating from an infinitesimally small particle moving at supersonic speed through a fluid medium. It is the locus of the Mach lines.

Mach Number: (Pronounced "mock." Named after Ernst Mach (1838-1916), Austrian scientist.) The ratio of the true airspeed (TAS) of a body to that of sound in the surrounding medium.

Mach Wave: *1.* A shock wave theoretically occurring along a common line of intersection of all pressure disturbances emanating from an infinitesimally small particle moving at supersonic speed through a fluid medium, such a wave considered to exert no changes in the condition of the fluid passing through it. The concept of the Mach wave is used in defining and studying the realm of certain disturbances in a supersonic field of flow. *2.* A very weak shock wave appearing, e.g., at the nose of a very sharp body, where the fluid undergoes no substantial change in direction.

Maneuverability: The property of an aircraft that permits it to be maneuvered easily and to withstand the stresses imposed by maneuvers; the capability of an aircraft readily to alter its flight path.

Maneuver Speed: See cornering speed.

P

Pitching Moment: A moment about a lateral "Y" axis of an aircraft. This moment is positive when it tends to increase the angle of attack or to nose the body upward.

Plain Flap: The elemental flap - nonextensible, nonslotted, and nonsplit hinge to a wing and forming part of the trailing edge. Also called a **simple flap**.

Plenum Chamber: Specifically, a chamber in certain ducting systems, as in a gas-turbine engine, that receives ram air for the compressor.

Position Error: An error in the reading of an airspeed indicator owing to the difference between the pressure (especially the static pressure) at the pressure measuring location and the free-stream pressure.

Positive G: In a gravitational field or during an acceleration, when the human body is so positioned that the force of inertia acts on it in a head-to-foot direction, i.e., the footward inertial force produced by a headward acceleration.

Pressure Drag: The drag on a body moving in a fluid medium due to the aerodynamic pressure distribution on the body, the net effect of which is to retard the body in its movement.

Pressure Gradient: A change in the pressure of a gas or fluid per unit of distance.

R

Rate of Climb: The rate at which an aircraft gains altitude, i.e., the vertical component of its airspeed in climbing.

Rate of Descent: The rate at which an aircraft descends, i.e., the vertical component of its airspeed in descending.

Relative Wind: Air in motion with respect to a body in the airmass. It is equal and opposite to the flight path of an aircraft.

Rolling Moment: The moment about the longitudinal "X" axis of an aircraft. A positive rolling moment about the longitudinal axis is to the right.

Rudder: An upright control surface that is deflected to impress a yawing moment, i.e., to make the aircraft rotate about its vertical axis.

S

Separated Flow: Flow over or about a body that has broken away from the surface of the body and no longer follows its contours.

Shock Wave: In aerodynamics, a surface or sheet of discontinuity, i.e., of abrupt changes in conditions, set up in a supersonic field of flow, through which the fluid undergoes a definite decrease in velocity accompanied by a marked increase in pressure, density, and temperature.

Sideslip: A movement of an aircraft such that the relative wind has a velocity component along the lateral axis.

Skin Friction: The friction of a fluid against the skin of an aircraft or other body; friction drag, a form of parasitic drag.

Slab Tail: See all-movable tail.

Slat: Any of certain long, narrow vanes or auxiliary airfoils; specifically, the vane used in an automatic slot.

Slot: A long and narrow opening, as between a wing and a deflected Fowler flap; specifically, a long and narrow spanwise passage in a wing, usually near the leading edge, for improving flow conditions at high angles of attack.

Slotted Aileron: An aileron having a specifically contoured leading edge which, in conjunction with the wing, forms a slot for the smooth passage of air over the aileron upper surfaces when the aileron trailing edge is deflected downward.

Slotted Flap: A flap that exposes a slot between itself and the wing when deflected, or a flap consisting of a number of slim surfaces or slats fastened together with slots between them.

Sonic Speed: Pertaining to sound or the speed of sound.

Span: The dimension of a wing from end to end.

Speed of Sound: The speed at which sound travels in a given medium under specified conditions.

Spin: A maneuver in which the aircraft descends in a helical path while flying at an angle of attack greater than the angle of maximum lift.

Spiral: A maneuver in which the aircraft ascends or descends in a helical (corkscrew) path distinguished from a spin in that the angle of attack is within the normal range of flight angles.

Split Flap: A plate or surface hinged to the bottom of a wing, usually near the trailing edge, deflected downward for increased camber and drag.

Spoiler: A device that projects into the airstream about a body to break up or spoil the smoothness of the flow, especially such a device that projects from the upper surface of a wing, giving an increased drag and decreased lift.

Stability: The property of an aircraft to maintain its attitude or to resist displacement and, if displaced, to develop forces and moments tending to restore the original condition.

Stabilizer: A fixed or adjustable airfoil or vane that provides stability for an aircraft, i.e., a fin - specifically, the horizontal stabilizer on an airplane.

Stall: *1. a.* A condition in which a wing or other dynamically lifting body flies at an angle of attack greater than the angle of maximum lift, resulting in the loss of lift and an increase of drag. *b.* A loss of lift and an increase of drag brought on by a shock wave, i.e., a shock-stall. *c.* A condition of the flow about the blade or blades of a compressor, analogous to the stall described above. *2.* The flight condition or behavior of an aircraft flying at an angle greater than the angle of maximum lift; any of various airplane performances involving a stall.

Stalling Angle of Attack: *1.* The minimum angle of attack of an airfoil or airfoil section or other dynamically lifting body at which a stall occurs, i.e., a critical angle of attack. *2.* The angle of maximum lift.

Stalling Speed: The airspeed at which, under a given set of conditions, an aircraft will stall.

Static Pressure: The atmospheric pressure of the air through which an aircraft is flying.

Steady State: The condition of a substance or system whose local physical and chemical properties do not vary with time.

Streamline: The path of a particle or small portion of a nondrying fluid, commonly taken with respect to a body in it; more technically, such a path whose tangent at any point is in the direction of the velocity vector at that point.

Subsonic Flow: Flow at a velocity less than the speed of sound in the medium under the prevailing conditions.

Supersonic Flow: Flow at the speed greater than the speed of sound in the medium under the prevailing conditions.

Sweepback: *1.* The backward slant from root to tip of a wing or to the leading edge or other reference line of a wing. Sweepback usually refers to a design in which both the leading and trailing edges of the wing have a backward slant. *2.* The amount of this slant.

T

Tab: A small auxiliary airfoil set into the trailing edge of an aircraft control surface and used for trim or to move or assist in moving the larger surface.

Thrust: The resultant force in the direction of motion due to the components of the pressure forces in excess of ambient atmospheric pressure acting on all inner surfaces of the vehicle propulsion system parallel to the direction of motion.

Thrust Available: The maximum thrust an engine can produce under specific conditions of temperature, atmospheric pressure, altitude, humidity, and rpm.

Thrust Required: The thrust needed to offset drag and thus maintain equilibrium in flight.

Thrust Axis: A line or axis through an aircraft, along which the thrust acts; an axis through the longitudinal center of a jet engine, along which the thrust of the engine acts; a center of thrust.

Thrust Horsepower: The thrust of a jet engine expressed in terms of horsepower. In this sense, thrust horsepower is equal to the product of the thrust and the velocity of the free stream.

Tip Vortex: A vortex springing from the tip of a wing, owing to the flow of air around the tip from the high-pressure region below the surface to the flow pressure region above it.

Trailing-Edge Flap: A flap, especially a plain flap, installed at the rear of a wing.

Trailing Vortex: A vortex that is shed from a wing or other lifting body and trailing behind it, especially such a vortex trailing from a wingtip (or from the end of a bound vortex).

Transonic Speed: The speed of a body relative to the surrounding fluid at which the flow is in some places subsonic and in other places supersonic.

Trim: The condition of an aircraft in which it maintains a fixed attitude with respect to the wind axes, the moments about the aircraft's axes being in equilibrium. The word trim is often used with special reference to the balance of control forces.

Trim Tab: A tab that is deflected to a position where it remains to keep the aircraft in the desired trim. Also called a **trimming tab**.

Tropopause: The upper boundary of the troposphere.

Troposphere: The lowest layer of the Earth's atmosphere, characterized especially by a relatively steady temperature lapse rate, varying humidity, and turbulence.

True Airspeed: Speed of the center of gravity of the aircraft. Equivalent airspeed corrected for error due to air density (altitude and temperature).

Turbulence: An agitated condition of the air or other fluids; a disordered, irregular, mixing motion of a fluid flow, as about a body in motion through the air, as in an air compressor, in combustion gases, etc.; technically, a condition of fluid flow characterized by fluctuations of velocity random in magnitude and direction.

Turbulent Boundary Layer: A boundary layer characterized by random fluctuations of velocity and by pronounced lateral mixing of the fluid.

Turbulent Flow: A flow characterized by turbulence, i.e., an irregular, eddying fluctuating flow; technically, a flow in which the velocity at a given point varies erratically in magnitude and direction with time.

U

Unsymmetrical Maneuvers: Rolling maneuvers at other than 1 g flight.

Ultimate Load: A load that causes or is calculated to cause destructive failure of a structural member or part of an aircraft.

Upwash: A flow deflected upward by a wing.

Upwash Angle: A negative downwash angle, i.e., the acute angle, measured in a plane parallel to the plane of symmetry of an aircraft, between the direction of upwash and the direction of the undisturbed airstream.

V

Velocity: *1.* Speed. *2.* A vector quantity that includes both magnitude (speed) and direction relative to a given frame of reference. *3.* Time rate of motion in a given direction.

Venturi: A converging-diverging for fluid, which increases the fluid velocity and lowers its static pressure: a venturi tube.

Vertical Axis: A "Z" axis passing through an aircraft from top to bottom and usually passing through the center of gravity. Also called a **normal axis**.

Vertical Stabilizer: A fin mounted approximately parallel to the plane of symmetry of an airplane, airship, or other aircraft to which the rudder, when present, is attached. Also called a **vertical fin.**

Vertical Tail: A vertical or substantially vertical component of an aircraft's stabilizing and controlling surfaces, in most forms comprising both a fixed surface (vertical stabilizer) and a movable surface (rudder).

W

Wave Drag: Drag due to the variation of pressure and velocity through a shock wave, with consequent variation of momentum in the mass flow of air; begins at force divergence Mach number. Also called **shock drag.**

Wing: An airfoil that provides or that is designed to provide sustentation for an airplane, extending on either side of the airplane, separated from its mate by the fuselage.

Wing Area: The area within the outline of the projection of a wing on the plane of its chords (the wing in this case considered as a unit, extending on both sides of the airplane), including that area lying within the fuselage, hull, or nacelles.

Wingtip Vortex: A tip vortex of a wing.

Y

Yaw: Rotation about the vertical "Z" axis of the aircraft.

Yawing Moment: The moment about the vertical "Z" axis of an aircraft. A positive yawing moment about the vertical axis is to the right.

Z

Zero Angle of Attack: The position of an airfoil, fuselage, or other body when no angle of attack exists between two specified or understood reference lines.

Zero-Lift Angle of Attack: The geometric angle of attack at which no lift is created. Often called the **angle of zero lift** or the **zero-lift angle.**

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APPENDIX B
T-45 AERONAUTICAL DATA

B100. T-45 AERONAUTICAL DATA

ASPECT RATIO: [wing span^2/wing area]	*5.0*
GEOMETRIC TWIST: [wingtip compared to root]	*2.67 degrees less at wingtip*
MAC:	*74.03 inches*
STABILATOR SWEEP ANGLES:	*30.14 degrees @ 114 stab chord* *34.41 degrees @ leading edge*
STABILATOR ANHEDRAL:	*10 degrees*
TAPER: [tip chord/root chord]	*0.31*
THICKNESS-TO-CHORD RATIO: [(thickness/chord) x 100]	*10.2 % @ root* *6.0 % @ tip*
WING AREA: [all exposed and covered wing surfaces]	*179.64 sq ft*
WING DIHEDRAL:	*2 degrees*
WING LOADING: [weight/wing area]	*75.4 lbs/sq ft, 2,904 lbs fuel, clean* *59.2 lbs/sq ft, empty, clean*
WING SWEEP:	*23.67 degrees @ 1/4 wing chord* *28.67 degrees @ leading edge*
WING SPAN	**30 FT 10 IN*
LENGTH	**39 FT 4 IN*
HEIGHT	**13 FT 5 IN*
PITOT BOOM TO LEMAC	*240.98 IN*

CG LOCATION (2 CREW)		GEAR ⇧	GEAR ⇩
AT GROSS WEIGHT:	*13,000#*	*18.1*	*20.5*
	12,000#	*19.1*	*20.7*
	11,000#	*17.3*	*20.1*
	10,500#	*16.1*	*19.1*

OVERALL CG LIMITS* ***4-25% GEAR UP OR DOWN***

ZERO FUEL WEIGHT		
	163600-163609	**10,332*
	163619 AND UP	**10,400*

***NATOPS FIGURES**