Appendix

Fighter Performance

> Performance means initiative—the most valuable moral and practical asset in any form of war.
>
> Major Sholto Douglas, RAF

The purpose of this Appendix is to provide a basic understanding of the fundamentals of aircraft performance which allow one fighter to maneuver relative to another and gain a position advantage in air combat. Although the word *performance* encompasses every aspect of aircraft operation, certain capabilities are more germane than others to the subject of air combat maneuvering and fighter tactics. These aircraft maneuvers (i.e., turns, accelerations, climbs, etc.) are covered here in sufficient depth to familiarize the reader with their application to the science of air combat and with the techniques by which their performance is optimized. Other aspects of aircraft performance, such as takeoff, landing, range, and endurance, although possibly critical to the success of any given fighter mission, are more concerned with how the fighter gets to and from the combat arena than with how it performs within that environment, and therefore they are not covered here.

Instantaneous Turn Performance

Turn performance is the ability of an aircraft to change the direction of its motion in flight. This direction is defined by the velocity vector, which may be visualized as an arrow pointing in the direction of aircraft motion and having a length proportional to the speed of that motion. *Maneuverability* is defined in this text as the ability of a fighter to change the direction of its velocity vector. The terms *maneuver ability* and *turn performance,* therefore, may be considered synonymous.

> [The Luftwaffe High Command] were stuck on the idea that maneuverability in banking was primarily the determining factor in air combat. . . . They

> could not or simply would not see that for modern fighter aircraft the tight turn as a form of aerial combat represented the exception.
>
> Lt. General Adolph Galland, Luftwaffe

Maximum-performance turns may be classified as one of two types: instantaneous or sustained. *Instantaneous* refers to the aircraft's maximum turn capabilities at any given moment under the existing flight conditions (e.g., speed and altitude). A particular capability may last for only an instant before flight conditions change, resulting in a change in instantaneous-turn capability. *Sustained* turns are those which the aircraft is able to maintain for an extended length of time under a given set of flight conditions. Sustained turns are discussed later in this Appendix.

Any turn may be measured in three ways. One convenient measure of aircraft turn performance is load factor (n), which is actually a component of the centrifugal acceleration generated by the turn. This acceleration is usually expressed in terms of Gs, with one G unit being the equivalent of the nominal acceleration of gravity, 32.2 ft/sec^2. Therefore, in a "3-G turn" the pilot would feel as though he weighed three times his normal weight. Turn rate (TR) is another important performance measure. This is the angular rate of change of the velocity vector, usually expressed in degrees/second, and in a level turn it would equate to the rate of change in the aircraft's course. Turn radius (R_T), the third important measure of turn performance, is generally expressed in feet or in miles.

> Tight turns were more a defensive than an offensive tactic and did not win air battles.
>
> Air Vice-Marshal J. E. "Johnnie" Johnson, RAF

Instantaneous turn performance is the product of the aerodynamic design of the fighter and its flight conditions. The lift-producing capacity of the aircraft is one of the primary factors in this performance. Lift (L) is the aerodynamic force generated by the aircraft perpendicular to its direction of motion (i.e., perpendicular to the relative wind). This force, most of which is usually produced by the wings, may also be visualized as a vector oriented perpendicular to both the velocity vector and the wings and having a length proportional to the amount of lift. The lift that can be produced by a given wing is dependent on the speed and altitude of the aircraft. Since the wing interacts with air to create lift, the density of the air is crucial. Air density decreases with altitude in the atmosphere, resulting in reduced lift capability. The faster a wing moves through the air, the greater the weight of air influenced during a given length of time will be, resulting in increased lift capability. The amount of lift which may be produced by a wing at a given altitude is roughly proportional to the square of aircraft velocity (V).

One of the most common and useful tools for the study of instantaneous turn performance is known as a "V-n diagram," a graphical plot of load-factor capability versus airspeed. Figure A-1 is an example of such a plot.

The V-n diagram for a fighter contains a great deal of information in a compact, efficient, and visually accessible form. The vertical axis is load factor in G units; when he is operating in the upper (positive) half of the

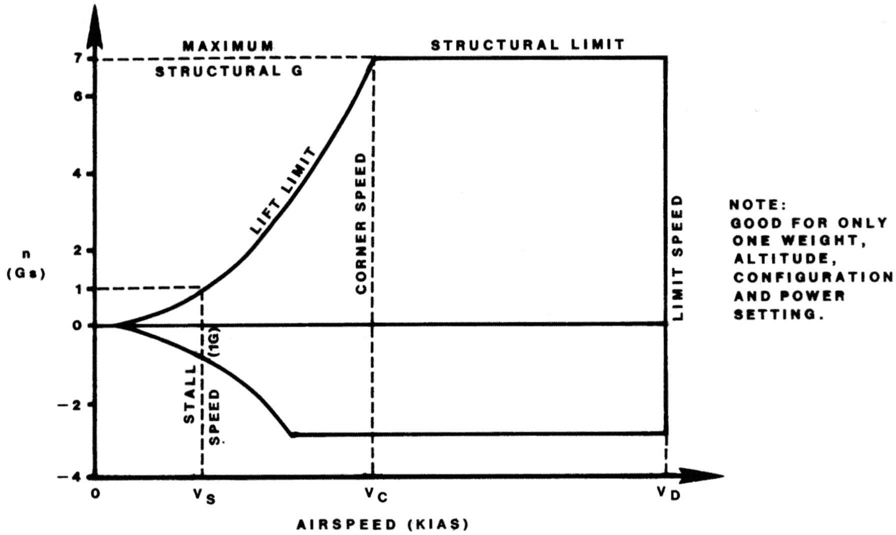

Figure A-1. V-n Diagram

diagram, the pilot is pushed down into his seat, and in the lower (negative) half, he is pulled away from his seat. The horizontal axis is airspeed, specifically in this example knots indicated airspeed (KIAS). This is the speed shown on the pilot's airspeed indicator and is based on the impact pressure of the air hitting the aircraft. This impact pressure, also known as dynamic pressure, is a function of air density as well as aircraft speed and may generally be equated to true airspeed only when the aircraft is operating at sea level. For a given indicated airspeed, true aircraft velocity increases with higher altitude.

The left side of the V-n diagram, labelled "lift limit," indicates the maximum load factor this fighter can generate at a specified airspeed. The curvature of this boundary primarily reflects the variation of lift capability with the square of the airspeed value. Along this line the aircraft is operating at maximum positive lift (pulling upward relative to the aircraft) in the upper half of the diagram and maximum negative lift (pushing downward relative to the aircraft) in the lower half. One important speed which may be identified along this boundary is the minimum 1-G flight speed, known as the unaccelerated stall speed (V_S). If airspeed is reduced below this value in level flight, lift may be lost suddenly (known as a "stall"), resulting in loss of control or at least loss of altitude. Conventional aircraft are physically unable to operate to the left of this aerodynamic boundary.

The upper and lower boundaries of the V-n diagram depict the structural-strength limits of the aircraft in the positive and negative directions, respectively. The more important of these boundaries is the upper (positive) one, which indicates maximum structural-G capability: in this case, +7 Gs. Greater load factor requires the wings to support more weight (in this instance, seven times the actual aircraft weight), so obviously there must be a limit. Usually this limit is independent of airspeed, as indicated by the straight lines. The maximum structural limit is specified by the manufacturer, based on calculations indicating that the aircraft structure will not break or deform permanently during its service life (also calculated by the manufacturer) at that load factor. This does not mean that the aircraft will disintegrate at 7.1 Gs, however, since there is usually a design safety factor of about 50 percent. This safety factor is included because of the likelihood of inadvertent overstresses, and also to increase the service life of the airframe, which is highly dependent on the weakening effects of metal fatigue.

The intersection of the positive aerodynamic boundary (lift limit) and structural limit defines a speed that is crucial in fighter performance. This is known appropriately as the corner speed (V_C) or maneuvering speed. At this airspeed a fighter attains maximum instantaneous turn performance (this is discussed more fully later). As the note accompanying this figure states, the boundaries of the V-n diagram are dependent on the fighter's weight, configuration, power, and altitude. As these parameters change, so will the V-n limits and therefore V_C, but the variations in corner speed are usually insignificant in air combat when V_C is expressed in terms of indicated airspeed.

The fourth boundary of the V-n diagram is the right side, which indicates the aircraft's maximum speed limit, or dive speed (V_D). This limit, set by the manufacturer, may be the result of structural, aircraft-control, engine-operation, or some other considerations. Here too there is usually a safety factor, but in this case probably on the order of 15 percent. With the usual exception of weight, those factors mentioned in the figure note can also have considerable influence on V_D. This boundary of the V-n diagram is a limitation, and it says nothing of the fighter's ability to attain such a speed. The aircraft may be able to exceed this speed in level flight, or V_D may not be attainable even in a power dive, depending on the particular design.

There are very well defined physical relationships between the parameters of turn performance: n, TR, R_T, and V. Figure A-2 graphically depicts these relationships for level (constant-altitude) turns. These charts are applicable to any aircraft. Note that for a given turn, if any two of the four variables are known, the other two are fixed. For example, if a fighter pulls 6 Gs at 400 knots, its turn radius will be about 2,400 ft and the corresponding rate of turn will be about 16°/sec. The airspeed scale in these charts is "true airspeed" in knots (KTAS), which may vary considerably from indicated airspeed, depending on altitude.

For fairly high load factors, the level turn relationships depicted in Figure A-2 may be simplified and expressed mathematically as:

$$R_T \sim V^2 / n \tag{1}$$

and

$$TR \sim n / V \tag{2}$$

From these proportionalities and Figure A-2 it can easily be seen that turn radius is minimized by high G at slow speed. Likewise, turn rate is

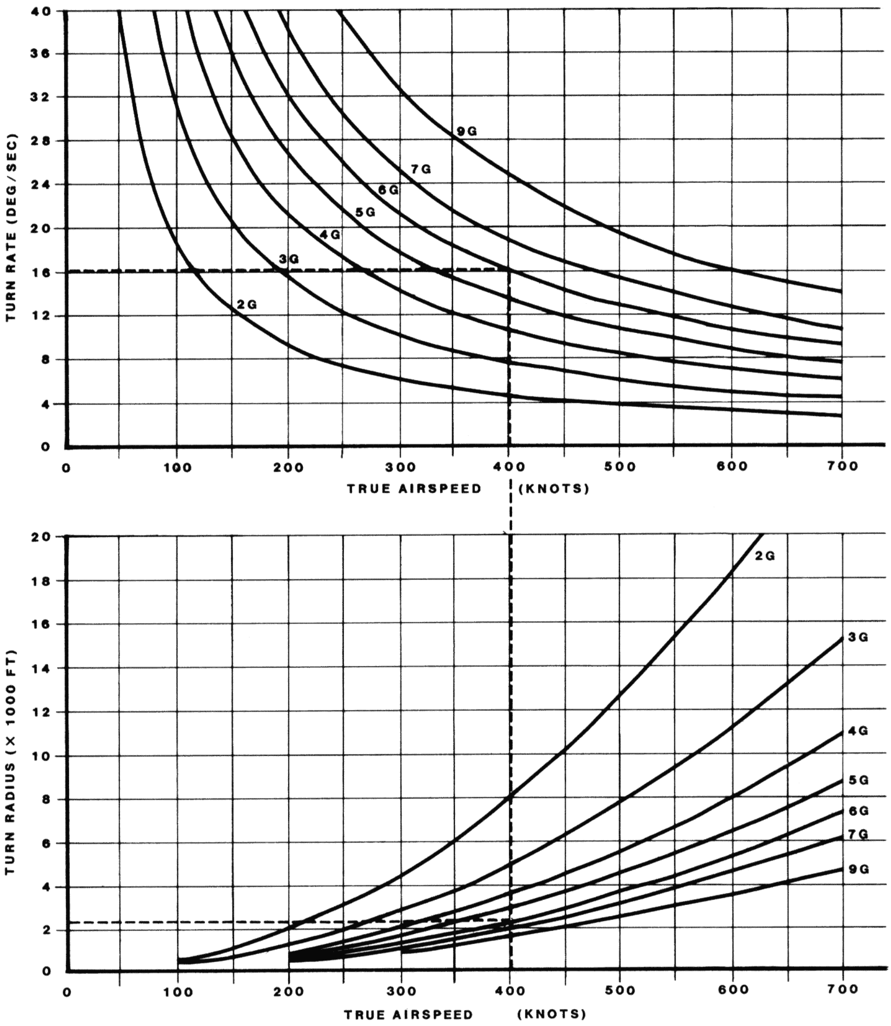

Figure A-2. Aircraft Turn Performance

maximized by high G at slow speed. Since the V-n diagram of a fighter specifies its G capabilities at various speeds, it is possible to determine turn-rate and -radius performance throughout the aircraft's speed range. Figure A-3 is a depiction of the way typical fighter turn-performance varies with airspeed.

In the case of turn rate, the rapid rise in G capability as speed increases above V_S (as shown by the lift boundary in the V-n diagram) leads to improved instantaneous-turn-rate performance, culminating at V_C. Since load factor is limited by structural considerations, however, further increases in airspeed above V_C result in reduced turn rate. Typical fighter turn-radius performance also is degraded (i.e., R_T increases) at speeds above V_C. Although absolute minimum instantaneous turn radius is usually found at speeds considerably below V_C, little change can be expected in R_T

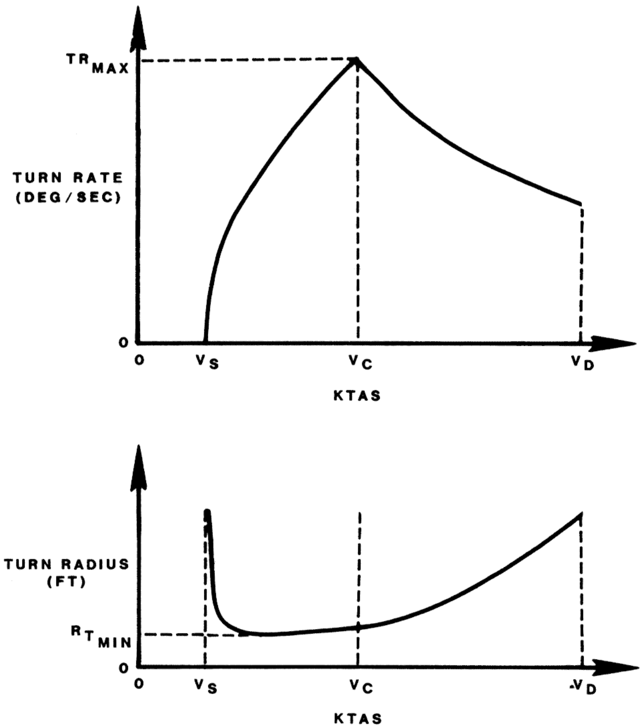

Figure A-3. Level Instantaneous Turn Rate and Radius Performance

at any speed between V_C and slightly greater than V_S. Very slow airspeeds, however, cause dramatic rises in level turn radius. The importance of corner speed in optimizing instantaneous turn performance is highlighted in Figure A-3.

Altitude also has a significant influence on instantaneous turn performance. Figure A-4 depicts the variations for a typical jet fighter. At speeds below V_C, both rate and radius performance are usually degraded (i.e., larger radii and slower turn rates) with increasing altitude, because of reduced lift capability. At speeds above the corner, instantaneous turn performance is generally limited only by structural strength, and so is usually independent of altitude. Since the plots in Figure A-4 use true airspeed for the horizontal scale, V_C is seen to increase with altitude. As explained previously, however, V_C is normally nearly constant with altitude when it is expressed in terms of indicated airspeed.

Energy Maneuverability

> Beware the lessons of a fighter pilot who would rather fly a slide rule than kick your ass!
>
> Commander Ron "Mugs" McKeown, USN
> Commander, U.S. Navy Fighter Weapons School
> 2 Victories, Vietnam Conflict

Energy comes in many forms: heat, light, electromagnetism, etc. In fighter performance the concern is primarily with mechanical energy,

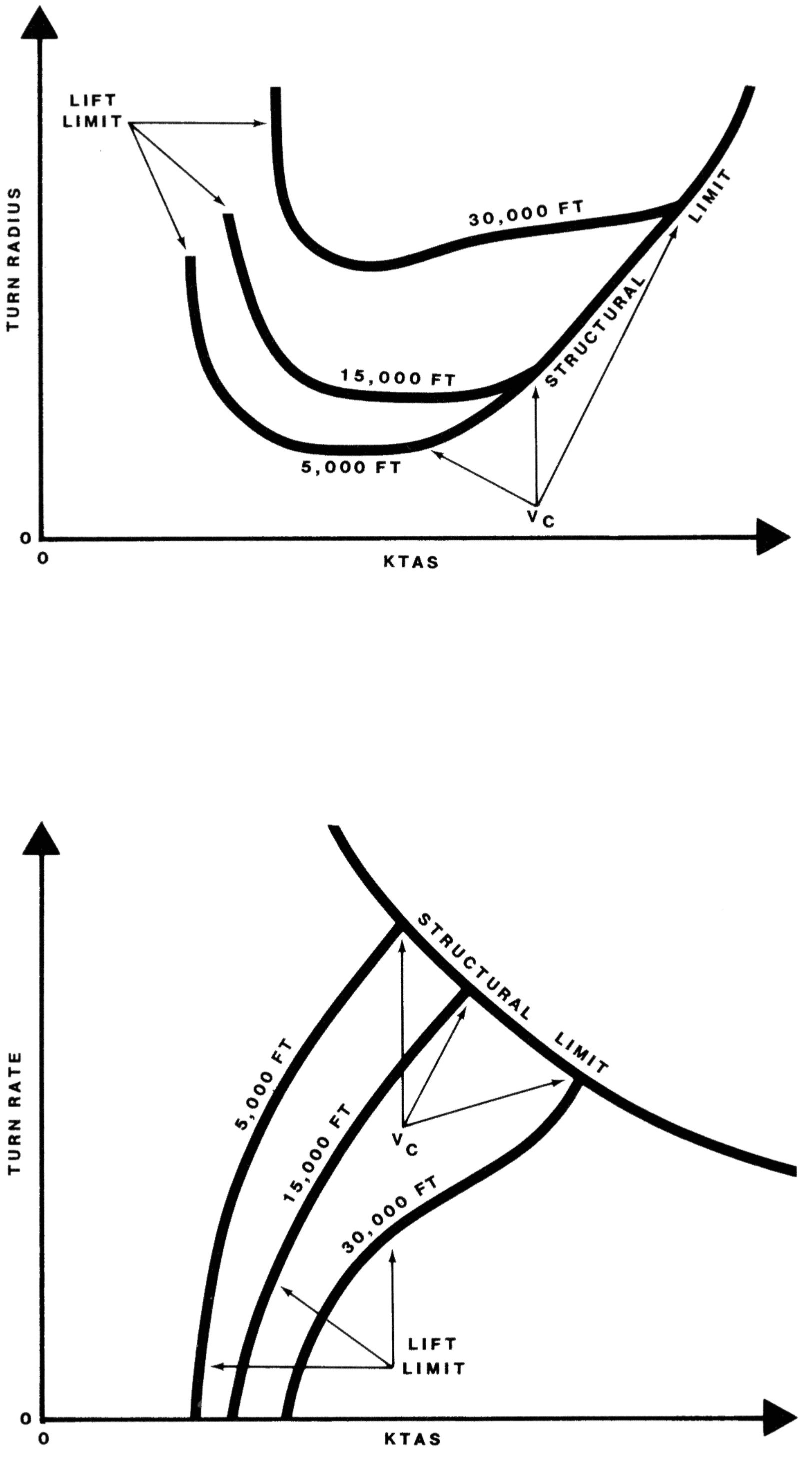

Figure A-4. Instantaneous Turn Performance Variation with Altitude which is classified as either kinetic or potential. "Kinetic energy" is the energy of speed. An aircraft in flight possesses kinetic energy that is proportional to its weight (or, more correctly, its mass) and speed. Under the influence of gravity, it can increase its speed, and its kinetic energy, by falling. Altitude, therefore, may be thought of as "potential energy," since it can be readily transformed into kinetic energy. Potential energy is proportional to the weight of the aircraft and the distance through which it may fall. In the case of airplanes, any combination of speed and altitude may be described by an "energy state." In comparing the energy states of two different fighters it is convenient to eliminate aircraft weight from the energy-state calculations to arrive at a better picture of relative speeds and altitudes. The result is a quantity known as "specific energy" (E_S). E_S is expressed mathematically as:

$$E_S\,(\text{ft}) = H + V^2 / 2g \qquad (3)$$

where H = altitude above some reference, usually sea level (ft); V = true airspeed (ft/sec); and g = acceleration of gravity (32.2 ft/sec^2).

From Equation 3 it is apparent that many combinations of speed and altitude will yield the same specific energy. Figure A-5 plots lines of constant E_S on an altitude-velocity grid. These lines describe speed-altitude combinations that yield the same energy state.

The plot of Figure A-5 is valid for any aircraft—or any rock, for that matter. The "ideal zoom" depicted illustrates how kinetic and potential energy may be traded back and forth while total energy remains constant. Theoretically a powerless aircraft in a vacuum with the speed-altitude combination depicted at the start of this ideal zoom could trade its speed for additional altitude as shown. If the pilot was willing to allow his speed to bleed all the way to zero, this aircraft would top out at about 50,000 ft. Then the aircraft falls, accelerating back to its initial condition. Such ideal zooms seldom occur in practice because of the drag of air resistance and the effects of aircraft thrust, but this example does serve to illustrate the concept of total energy.

Energy state can be changed through the application of power. In the case of aircraft, this power is generally the result of thrust (which tends to increase energy state) and drag (which tends to decrease energy). The rate of change in E_S is known as "specific excess power" (P_S) and is given by the equation

$$P_S\,(\text{ft/sec}) = \frac{(T - D)}{W} V \qquad (4)$$

where T = total engine thrust (lbs.), D = total aircraft drag (lbs.), W = aircraft weight (lbs), and V = true airspeed (ft/sec).

Equation 4 reveals that whenever thrust is greater than drag, P_S will be a positive quantity resulting in increasing energy (i.e., climb or acceleration). Conversely, if drag exceeds thrust at any time, energy will decrease. The P_S of a fighter under given conditions of weight, configuration, engine thrust, speed, altitude, and load factor determines the available performance, or "energy maneuverability," under those conditions. Energy maneuverability may be defined as the ability to change energy state, i.e., to climb and/or to accelerate.

Returning to Equation 3 for a moment, note that aircraft weight has been eliminated and does not enter into ideal-zoom calculations, as shown in Figure A-5. In reality, however, this is not quite the case. Since a zoom takes a finite length of time to complete, the fighter is subject to the effects of weight, thrust, and drag (i.e., P_S) during the maneuver. The amount of energy gained or lost in the zoom depends on the average value of P_S during this period. To illustrate this concept, assume two fighters are identical in all respects, except one is heavier (maybe it is carrying more internal fuel). If they begin zooms at the same speed and altitude (i.e., same E_S), Equation 4 shows that the lighter fighter will have greater P_S, will therefore add more energy during the zoom, and will ultimately zoom higher than the heavy fighter. P_S as well as energy state must, therefore, be taken into account when calculating the zoom capability, or "true energy height," of a fighter.

Thrust Variations

The effect of altitude on both piston and jet engines is usually to reduce their performance. "Normally aspirated" piston engines tend to lose power with increasing altitude approximately in proportion to the reduction in atmospheric air pressure. This results in such an engine producing

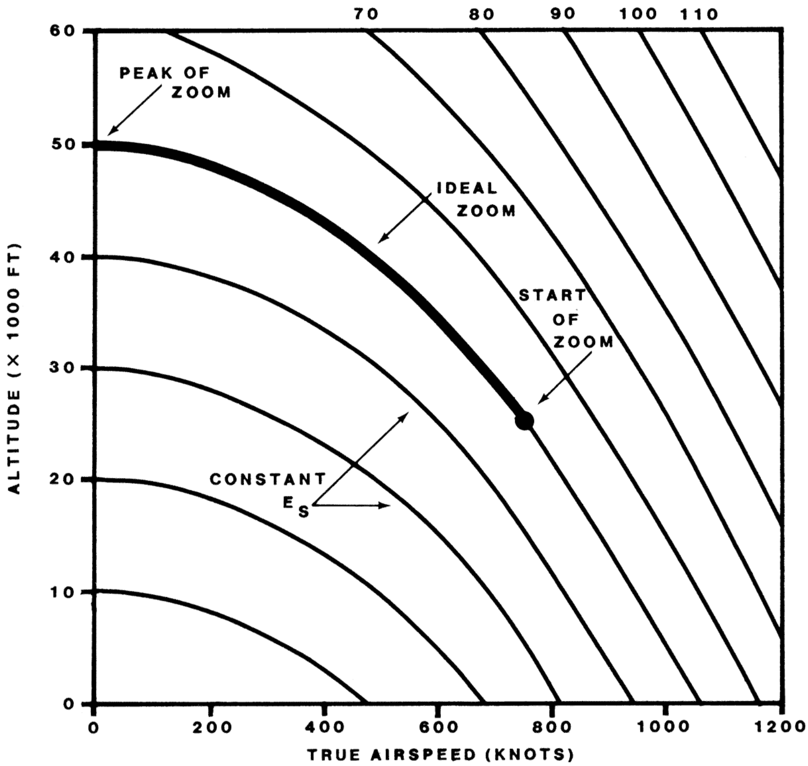

Figure A-5. Specific Energy and the Zoom Climb only about half its sea-level power at 18,000 ft above mean sea level (MSL). Since the 1930s, however, most first-line fighters have been equipped with superchargers or turbochargers which can allow the engine to maintain its rated power to near 30,000 ft MSL. Jet engines, on the other hand, suffer a loss in thrust which is slightly less than the rate of air density reduction with altitude, and significantly less than that for normally aspirated piston engines. Jets typically lose about half their thrust by 25,000 ft. However, there is no common device similar to the turbocharger for maintaining jet-engine performance at altitude. Figure A-6 shows the typical thrust variations.

The altitude labelled "tropopause" in this plot denotes the level at which atmospheric air temperature ceases to fall. Above this height, typically about 36,000 ft MSL, air temperature is constant. Jet engines in particular benefit from lower air temperatures as altitude increases. Above the tropopause this benefit no longer exists, resulting in a faster rate of jet-thrust decay. Consequently the tropopause is an important altitude in jet-fighter performance. "Critical altitude" is of great significance for turbocharged fighters. This is the highest level at which the turbocharger can maintain full-rated engine power.

The effect of speed on engine thrust is illustrated in Figure A-7. Propeller thrust is usually greatest in the static condition (i.e., zero airspeed) and falls rather rapidly with increasing airspeed. Jet thrust also may be expected to diminish slightly as speed increases above the static condition. As airspeed rises farther, however, ram compression in the engine inlet generally results in significant increases in thrust until engine and inlet design limits are approached. It is quite obvious from this plot why jet fighters exhibit superior high-speed performance.

Drag

As shown by Equation 4, engine thrust is only part of the energy-maneuverability story; aircraft drag characteristics are equally important. Many phenomena contribute to total aircraft drag, some of which can be

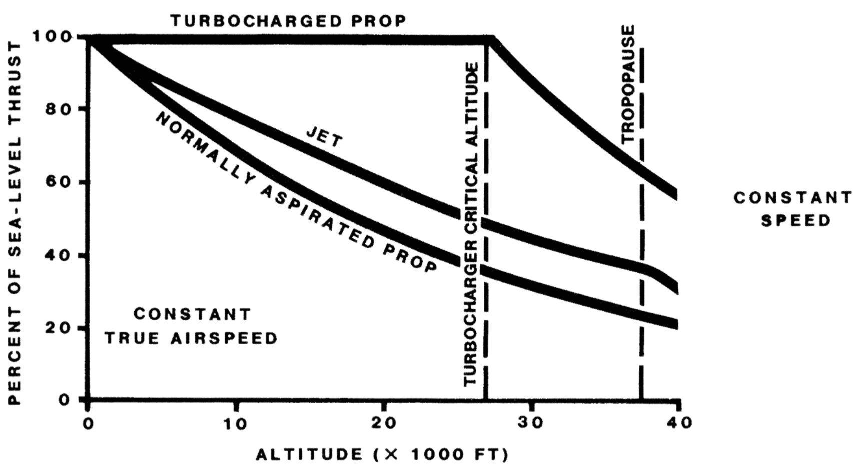

Figure A-6. Engine Thrust Variation with Altitude

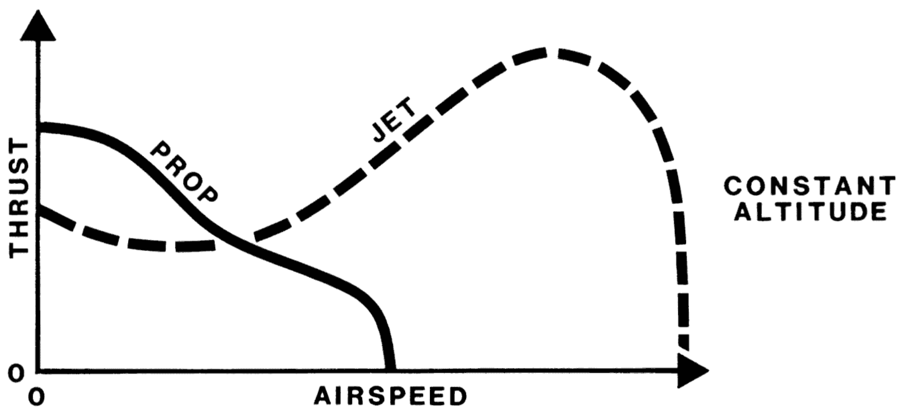

Figure A-7. Engine Thrust Variation with Airspeed

very complex. The most important types of drag are discussed briefly here, but no attempt will be made to qualify the reader as an aeronautical engineer.

"Parasite drag" has many causes, but the most significant forms are skin friction and pressure drag. Skin friction results from air molecules moving across the surfaces of the aircraft. These molecules tend to stick to the aircraft, and much air must be pulled along, adding resistance to the aircraft's motion. Skin-friction drag is reduced by minimizing aircraft surface area and maintaining the smoothest possible surfaces, and by other, more esoteric, methods. Pressure drag results when high-impact air pressure on the leading edges of the aircraft combine with reduced pressure on trailing edges to produce a net rearward force. This form of drag is reduced primarily by minimizing aircraft frontal area, and also by streamlining, which tends to reduce air turbulence and decrease the size of the low-pressure region that forms behind the moving aircraft.

Another type of drag, known as "induced drag," is actually a result of lift. When a wing begins to produce lift, the actual resultant force is not perfectly perpendicular to the relative wind, as lift is defined, but tends to tilt backward somewhat. As illustrated in Figure A-8, this resultant force (FRJ has components both perpendicular to (lift) and parallel with (drag) the relative wind.

In general, for a wing of a given size and shape, the greater the lift produced under given conditions, the greater the induced drag will be. Although this relationship is important for any aircraft, it is especially critical for fighters, since their mission often involves high-load factors requiring a great amount of lift. Induced drag is minimized by designing wings of large area with long, thin planforms. The actual shape of the wing is also very important. For subsonic flight an elliptical planform, made famous by the Spitfire fighter of World War II, is theoretically optimum. Other shapes, however, may be nearly as efficient from an induced-drag standpoint and have other overriding advantages.

Reducing aircraft weight is another critical factor in minimizing induced drag. Less weight requires less lift for a given turn performance, resulting in less induced drag. The aircraft's center of gravity (CG) also has

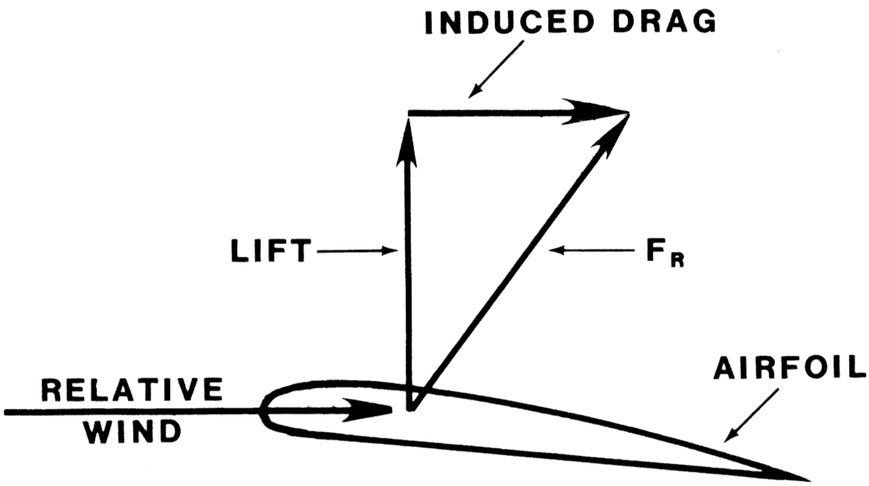

Figure A-8. Origin of Induced Drag

an effect by altering the fighter's apparent weight. Figure A-9 shows how this occurs.

This figure depicts a fighter of a given weight (W) in steady-state flight supported by its lift (L). In this condition the vertical forces must balance each other as well as the pitching moments (torques), which tend to cause the aircraft to rotate ("pitch") nose-up or nose-down. Since weight acts through the CG and lift through the "aerodynamic center" (AC), these two forces cause a nose-down pitching moment with the CG forward as shown. In order to maintain a level flight attitude under these conditions, the tail must produce a downward lift (L_t large enough to offset the nose-down moment of the wings (i.e., $X_W L = X_t L_t$). This download on the tail, however, must also be supported by the wings, just like dead weight, so induced drag will increase for a given load factor. This additional induced drag is known as "trim drag."

If the CG was moved rearward (by fuel distribution, ordnance loading, etc.) until it coincided with the AC, the tail lift requirement and resulting trim drag would be eliminated. Further rearward movement in the CG would require an upward lift from the tail, which essentially adds additional wing area to the aircraft, thereby reducing induced drag. In practice, however, there is a limit to rearward CG location because of aircraft controllability considerations.

Conventional fighters (i.e., those with rear-mounted pitch-control surfaces) benefit from aft CGs. Canard-configured fighters (i.e., those with pitch controls located forward of the wings), however, normally benefit from forward CG location.

As the speeds of fighters increased through the years, the phenomenon of "compressibility" was encountered. As aircraft move through the air, pressure disturbances are created which propagate outward in all directions at the speed of sound. Those pressure waves that move ahead of the aircraft tend to provide an "advance warning" to the air that the aircraft is approaching, thus giving the air molecules time to begin moving out of the way. The air then begins to part even before the aircraft arrives, which tends to reduce pressure drag. But once a fighter reaches the speed of sound, it begins to outrun its pressure waves and collides with the air molecules with no warning. The air then must be pushed aside almost instantaneously in a process that creates a "shock wave." Shock waves are a relatively inefficient method of changing the flow direction of air, and they create added drag, known as "wave drag," "compressibility drag," or "Mach drag."

Air tends to speed up when flowing over convex curved surfaces, so there may be supersonic flow and shock waves which form at various places on a fighter, even though the aircraft itself is still subsonic. The speed at which the first shock wave appears on a fighter is called its "critical Mach," where Mach number is the ratio of aircraft speed to the speed of sound through the air. Critical Mach (M_{CR}) for modern fighters is usually in the range of 80 to 90 percent of the speed of sound, or .8 to .9 M. At high subsonic and low supersonic speeds it is possible to have a mixture of subsonic and supersonic flow on the aircraft surfaces in a condition termed "transonic."

In addition to increasing pressure drag, shock waves tend to create turbulence and increase skin-friction drag as well. Fundamental changes in the way wings produce lift in supersonic flight also tend to increase trim drag by causing the AC of the wing to move rearward. Because of these combined effects, wave drag is often the most significant form of drag at speeds above MCR.

Fighters began to encounter compressibility problems in the 1930s, usually in the form of large drops in propeller efficiency as the combined aircraft and propeller rotational speeds caused the prop tips to reach their MCR. By the 1940s the aircraft themselves were reaching compressibility limits, usually in prolonged dives from high altitude, which in addition to wave drag also often caused severe control problems. Techniques de-

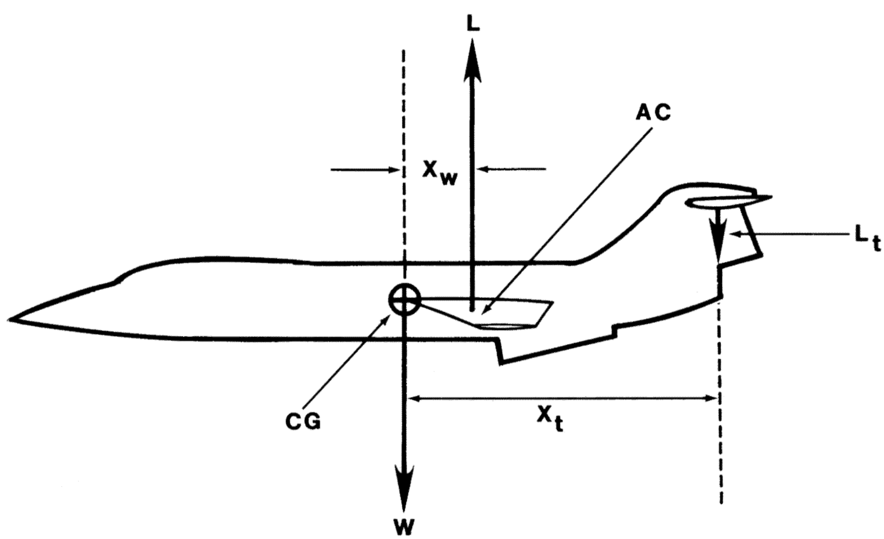

Figure A-9. Origin of Trim Drag

veloped to lessen the effects of wave drag and increase M_{CR} include reducing aircraft cross-sectional area, sharpening leading edges, and sweeping wings. The familiar "Coke-bottle" shape of many jet-fighter fuselages also helps by smoothing out the changes in total aircraft cross-sectional area from nose to tail.

Figure A-10 shows how the various types of drag vary with airspeed and combine to produce total aircraft drag (D). Note that parasite drag (D_P) is insignificant at slow speeds but rises very rapidly as airspeed increases. Conversely, induced drag (D_i) is greatest at very slow speeds and diminishes quickly as the aircraft becomes faster. It should be understood, however, that this plot is representative of an aircraft in straight and level flight (i.e., load factor = 1). Since D_i is proportional to the square of the load factor, this drag component could still predominate in the total drag picture of a high-G fighter even at high airspeeds. Trim drag is not shown explicitly in this figure, but it can be considered as part of the induced-drag component. Wave drag (D_M) can be seen to begin at about M_{CR}; it rises very rapidly in the transonic regime and increases at a slower rate thereafter.

The effects of altitude on drag can be quite complex. Both parasite drag and wave drag usually decrease with higher altitude, but induced drag normally increases. Whether this results in more total drag or less generally depends on aircraft speed and load factor. At low speeds or high G, total drag tends to increase with altitude, but under high-speed, low-G conditions, drag often decreases with increasing altitude.

H-M Diagrams

It should be obvious, considering all the variations in thrust and drag with speed, altitude, etc., that the Ps capabilities of a fighter can be complex. These capabilities are usually determined by flight tests and displayed in graphical formats for pilot study. One such common format is called the H-M (altitude-Mach) diagram. Figure A-11 is an example of this plot for a typical supersonic jet fighter.

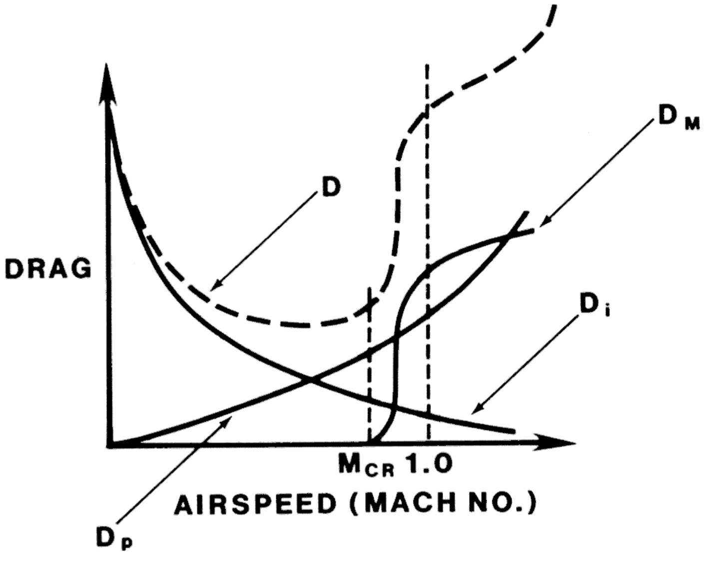

Figure A-10. Drag Variation with Airspeed

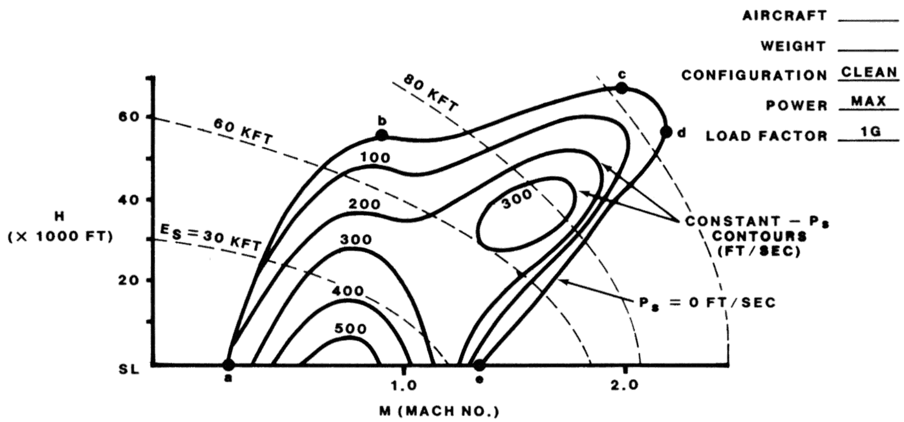

Figure A-11. Typical H-M Diagram

The H-M diagram shows a fighter's Ps capability on a grid of altitude (H) versus Mach number (M). Often lines of constant Es are also provided for additional reference. Specific excess power is depicted by lines of constant PS, in this case using ft/sec as the unit of measurement. For the given conditions (weight, configuration, power, load factor), P_S can be related directly with climb rate. For instance, at about 35,000 ft MSL and 1.0 M, this aircraft shows a P_S of about 200 ft/sec. Therefore, under these conditions its climb rate would be 200 ft/sec.

The P_S = 0 line on this diagram (the outermost contour) shows the fighter's maximum 1-G steady-state performance. When operating at a speed-altitude combination (energy state) which places it on this line, the fighter cannot climb without losing airspeed and cannot accelerate without losing altitude. Inside this "operating envelope" (region of positive P_S values) the aircraft is free to climb and/or accelerate at will, subject to the rate limitations specified by the P_S contours. Outside this steady-state envelope is a region of negative P_S, where the fighter may operate for short periods of time by giving up energy (i.e., decelerating and/or diving).

Many important operating capabilities of a fighter may be found along the P_S = 0 line. Assuming this plot is representative of a 1-G condition, some of these capabilities are:

point *a:* minimum sustained Mach number at any altitude (.3 M at sea level)
point *b:* maximum sustained subsonic altitude (56,000 ft at .9 M)
point *c:* maximum sustained altitude at any speed (67,000 ft at 1.95 M)
point *d:* maximum sustained Mach at any altitude (2.2 M at 55,000 ft)
point *e:* maximum sustained Mach at sea level (1.35 M)

Although this fighter may be capable of the performance depicted from a strictly thrust-versus-drag standpoint, other factors, such as those illustrated by the V-n diagram, may limit performance capabilities. Figure A-12 illustrates the possible impact of such limitations.

The H-M plots presented in Figures A-11 and A-12 have been representative of H-M plots for supersonic fighters. Subsonic jets and prop-driven

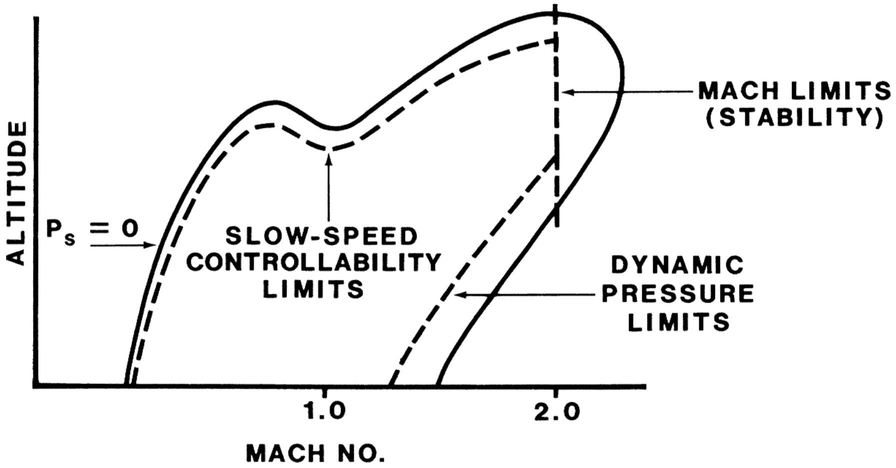

Figure A-12. Possible Limitations to Fighter Performance

fighters can be expected to exhibit fundamentally different operating envelopes. Figure A-13 shows some typical comparisons. Piston-powered fighters suffer from rapid loss of engine performance above critical altitude, thrust decay with increasing airspeed, and possibly prop-compressibility losses at moderate subsonic Mach. These effects can be seen to limit severely the operating envelopes of such aircraft. By contrast, the better high-altitude performance of the jet engine, the typically cleaner aerodynamics of the airframe, and the usually increasing thrust with speed provide the jet fighter with a greater range of operating speed and altitude. The subsonic fighter, however, typically lacks sufficient thrust to overcome the dramatic rise in wave drag above critical Mach, so its performance degenerates badly above that speed. Since the rise in wave drag is usually greater than the corresponding increase in jet thrust with speed, even the supersonic fighter generally exhibits a loss of performance in the transonic region. This aircraft, however, has sufficient excess thrust to carry it through the transonic range so that it may take advantage of the slower rate of drag rise at higher Mach, particularly at high altitude.

As stated in the note to Figure A-11, the performance capabilities depicted in the H-M plot are good for only one condition of weight, configuration, power setting, and load factor. A change in any of these parameters affects the P_S contours and the sustained operating envelope (P_S = 0 line), as shown in Figure A-14. To illustrate this effect, assume a fighter is operating at the energy state represented by point *f*. In the first plot (assume 1 G) the fighter is in an area of positive P_S (inside the steady-state envelope) and can therefore climb or accelerate under these conditions. But if load factor (for example) is increased substantially, as depicted in the second plot, the P_S = 0 contour shrinks, placing the fighter outside the steady-state envelope and into a region of negative P_S. This negative P_S, which is probably the result of increased induced drag and wave drag at the higher load factor, will cause the aircraft to lose speed and/or altitude. Obviously there must be some load factor that would cause the $P_S = 0$ line to run exactly through point *f*. This load factor is defined as the "sustained-G" capability of the fighter at the speed/altitude conditions represented by point *f*. Sustained G at a given speed defines sustained turn performance in terms of radius and rate. Although H-M diagrams for various load factors may be used to display fighter turn-performance capabilities, other display formats are much better suited to this purpose, as they directly show turn rate and radius values. H-M plots are more convenient for the study of fighter climb performance.

Climb Performance

> Throughout the story of air fighting runs the quest for height, for the fighter on top had control of the air battle.
>
> Air Vice-Marshal J. E. "Johnnie" Johnson, RAF

As explained previously, the climb-rate capability of a fighter under any given flight conditions can be equated to its P_S. The H-M diagram therefore provides an excellent vehicle for the determination of climb rates and optimum climb techniques. At any altitude there is usually one speed that offers the maximum climb rate for a given fighter. The H-M diagram plainly shows this speed as the peak of the P_S contours at that altitude, since any other speed at that altitude would yield a lower P_S value and therefore a lower climb rate. Connecting the P_S peaks with a continuous line generates a "climb profile," which defines the speeds required to maximize climb rate at any point in the climb.

Aircraft, however, can trade altitude for airspeed, and vice versa, almost at will (by zoom climbs and diving accelerations), so an increase in airspeed is essentially the same as an increase in altitude. This fact complicates climb optimization somewhat, since it becomes necessary to maximize

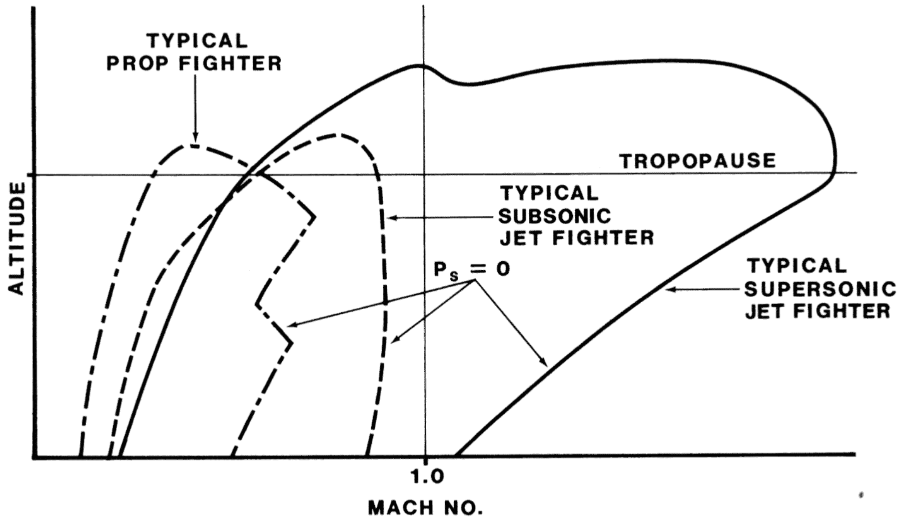

Figure A-13. Typical Fighter Flight Envelopes

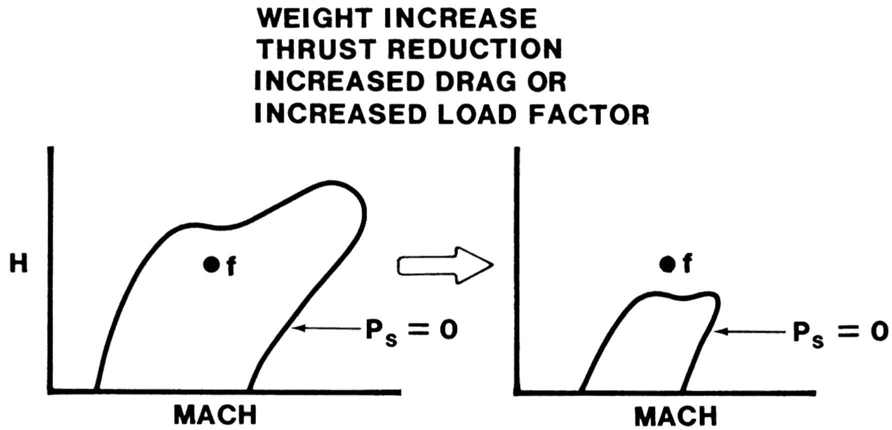

Figure A-14. Effect of Weight, Thrust, Drag, and Load Factor on P_S Contours

the rate of total energy gain rather than just the rate of climb. Such a "maximum energy-rate" climb profile can also be constructed with an H-M diagram, as demonstrated by the example of a supersonic fighter in Figure A-15.

The maximum energy-rate profile is constructed by connecting the points of tangency between the P_S contours and the lines of constant E_S. For the sample fighter at low altitudes this profile, labelled the "subsonic path," differs little from that generated by the P_S peaks. Only slightly faster speeds result, yielding a climb profile of nearly constant Mach between .92 M at sea level and 1.0 M at the climb ceiling of 51,000 ft. Above about 25,000 ft, however, this chart exhibits the characteristic double peaks of the supersonic fighter. As the climb progresses to about 30,000 ft along the subsonic climb path (E_S = 44,000 ft), equal or greater climb rates are available in the supersonic regime at the same energy level. Above this level the faster "supersonic path" becomes the optimum energy-rate profile. This situation becomes quite apparent at higher levels. If, for example, the climb is continued along the subsonic path until it intersects the E_S = 60 KFT (i.e., 60,000 ft) line, climb rate will have dropped to about 50 ft/sec. At the same energy level along the supersonic path the corresponding climb rate still exceeds 200 ft/sec.

Optimum climb techniques for this fighter are best demonstrated through an example. Assume the aircraft is at point *A* (10 KFT, .6 M) and a climb is to be made to point *F* (45 KFT, 1.75 M). Theoretically the optimum climb profile would begin with a diving acceleration at constant energy (i.e., parallel to the lines of constant Es) to intersect the subsonic path at point *B* (1 KFT, .92 M). The climb would then be continued along the subsonic path until the aircraft reached point *C* (about 30 KFT), at which time another diving acceleration would be performed to reach the supersonic path at point *D* (21 KFT, 1.17 M). The supersonic path would be followed to point *E* (38 KFT, 1.88 M), which represents the final desired energy state (E_S = 90 KFT), and finally a constant-energy zoom climb would be used to reach the goal at point *F*.

In theory the energy transfers beginning at points *A*, *C*, and *E* in this example are instantaneous. In practice, however, the aircraft attitude changes necessary to make the transition from climbs to dives, and vice versa, are made slowly and result in a rounding-off of the corners in the climb profile, as shown by the broken lines in these areas. AL'o because of the finite times involved in such energy transfers, climbs of fairly short duration can sometimes be made more quickly by following "non-optimum" paths, which avoid these time-consuming techniques.

Because of the difficulty of following optimum climb profiles precisely, approximations are usually made. A typical rule of thumb for the fighter in this example might be: climb at .92 M to 25 KFT, then accelerate to and climb at 600 KIAS. Optimum climb profiles for subsonic jet fighters usually begin with a slowly decreasing indicated airspeed until the jet reaches approximately critical Mach, and thereafter a constant Mach number is maintained.

The advantage of using this best energy-rate climb profile as opposed to opting for the nominal best climb-rate path (approximated by the "subsonic path") is quite apparent in the ultimate energy levels attainable. Along the subsonic path this fighter can reach about 51 KFT, and from there it could zoom to about 66 KFT (E_S = 66 KFT), while the supersonic path provides energy levels (and therefore zoom capabilities) in excess of 100 KFT.

Acceleration Performance

The important thing in aeroplanes is that they shall be speedy.

Baron Manfred von Richthofen

Aircraft accelerate most quickly by maximizing thrust while minimizing drag. Equation 4 shows that this condition also tends to maximize P_S, so an H-M diagram can give a good indication of the relative acceleration capabilities of a fighter throughout its flight envelope. At any given altitude a fighter tends to accelerate fastest at a speed just slightly below that at which P_S peaks (subsonic peak for supersonic fighters).

Techniques to optimize acceleration include using the highest possible forward thrust and reducing weight and drag as much as practicable. Jettisoning external fuel tanks and nonessential ordnance is useful, since this action reduces both weight and drag.

One of the most effective methods for improving the acceleration performance of fighters is known as "unloading." This involves pushing forward on the pitch controls to reduce load factor, lift, and induced drag. For most fighters induced drag is minimized at a zero-G condition, which may be recognized either by cockpit G-meter readings or by "seat-of-the-pants" indications such as the pilot's feet floating off the rudder pedals, loss by the pilot of any sensation of pressure against the seat, or loose articles and dirt floating around in the cockpit. This last indicator can be hazardous, resulting in jammed controls or dirt in the pilot's eyes, and should be avoided by securing loose articles and maintaining a clean cockpit.

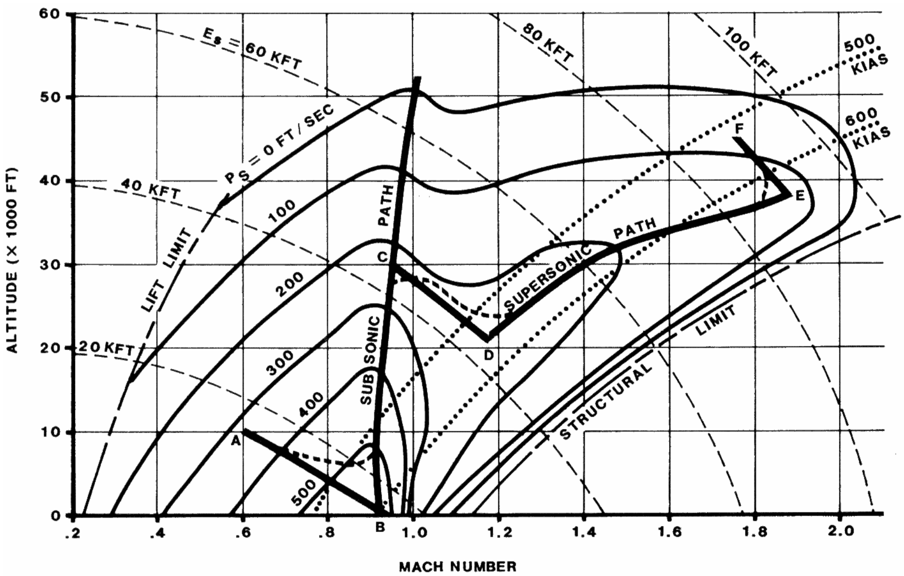

Figure A-15. Sample Climb Profile

Unloading to a full zero-G condition may be limited in some fighters because of engine design. Piston engines with float-type carburetors are notorious for "cutting out" under zero G, which, although usually a temporary condition, obviously would not help acceleration. During World War II fuel-injected German aircraft often used steep unloaded climbs and dives to escape from carbureted Allied fighters. The fuel and oil systems of many other power plants, including quite a few jets, are also restricted or time limited in this maneuver. In such cases unloading may have to be performed at a slightly positive G or be limited in its duration. It is also possible that minimum induced drag will be achieved with some fighters at other than zero G. The fighter pilot should be aware of the characteristics of his particular aircraft and operate accordingly. Figure A-16 illustrates the effects of unloading from 1 G to zero G on the acceleration performance of a typical jet fighter.

This figure is a plot of percentage improvement in acceleration (Δ Acceleration) versus Mach number at various altitudes from sea level to 30 KFT. Note the very large improvement in acceleration at slower speeds, particularly at high altitudes, which can be attributed to the fact that induced drag is the major contributor to total aircraft drag under these conditions. At medium speeds, where induced drag is not as great, its elimination by unloading is seen to have less effect.

Acceleration is of key importance and often overlooked.

Lt. General Adolph Galland, Luftwaffe

Aside from induced-drag reduction, unloading may have other benefits. Parasite drag also may be lowered because of the reduction in frontal area presented to the airstream and a lessening of airflow turbulence over the aircraft surfaces. In the high-subsonic speed range, critical Mach number is usually increased substantially by unloading, which delays the sharp rise in wave drag until the fighter reaches higher speeds. Unloading also tends to reduce the severity of this wave drag once the aircraft accelerates past M_{CR}. These high-speed effects are quite evident in the example of Figure A-16. The impact of unloading on the acceleration performance of a fighter is, however, highly dependent on the fighter's aerodynamic design.

One further method of increasing fighter acceleration is by the use of gravity; a steep dive will often multiply acceleration many times. Such a dive may follow unloading, which causes the aircraft to fly a ballistic trajectory resulting in gradually steepening dive angles. If altitude is available, however, a sharp pull-down to a steep dive attitude, followed by unloading, produces the most rapid long-term acceleration. Discounting the effects of thrust, the acceleration of an aircraft in a dive is a function of its "density," that is, its ratio of weight (actually its mass) to drag. When two fighters are similar in all respects except that one is heavier, the heavier aircraft will accelerate faster in a dive and, assuming structural considerations allow, will have a faster terminal velocity. Likewise, with two fighters of the same weight, the cleaner one (i.e., the one with less drag) will dive better. (This is why a brick falls faster than a feather in air.)

Sustained Turn Performance

In order for a fighter to make a level (constant-altitude) turn, load factor must be increased above 1 G. As load factor is increased at a given airspeed,

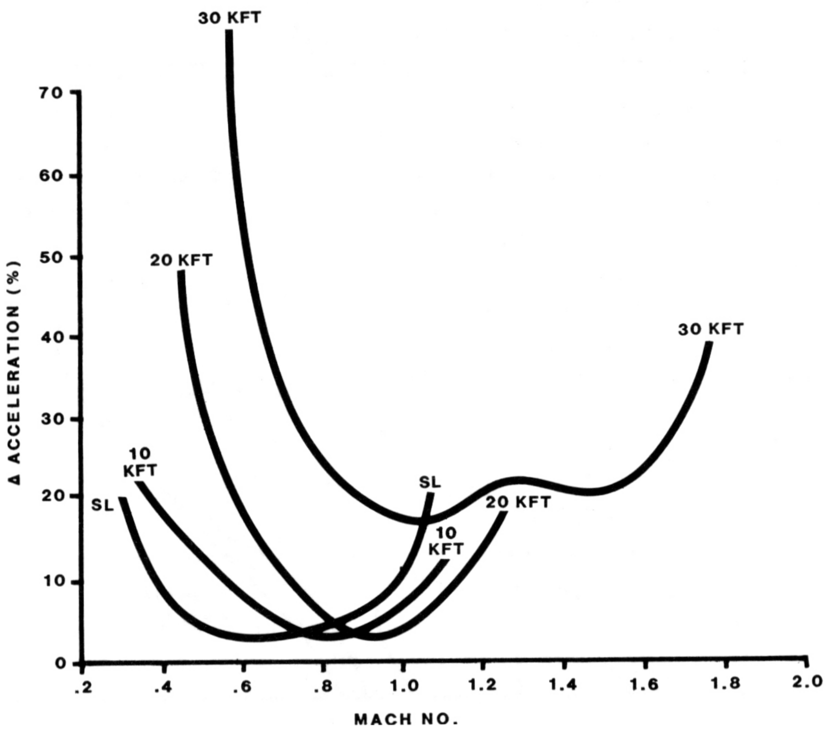

Figure A-16. Effects of Unloading on Acceleration turn performance (i.e., rate and radius) improves, but total aircraft drag also increases. Eventually a load factor is reached at which the entire thrust of the engines is needed just to offset this drag, leaving no excess power for a simultaneous climb or for acceleration. Equation 4 indicates that when thrust equals drag, P_S is zero. Figure A-14 shows how the zero-P_S line reacts by shrinking and deforming under increased G. This process is further illustrated by Figure A-17.

This figure consists of H-M plots of the same supersonic jet fighter at load factors of 3 G sand 5 Gs. The outer curve in each case is the 1-G $P_S = 0$ line for reference. Within this 1-G envelope are speciflc-excess-power values (in ft/sec) for the two sample load factors. Note that the zero-Ps envelope shrinks considerably in the 3-G plot, and even farther under 5 Gs.

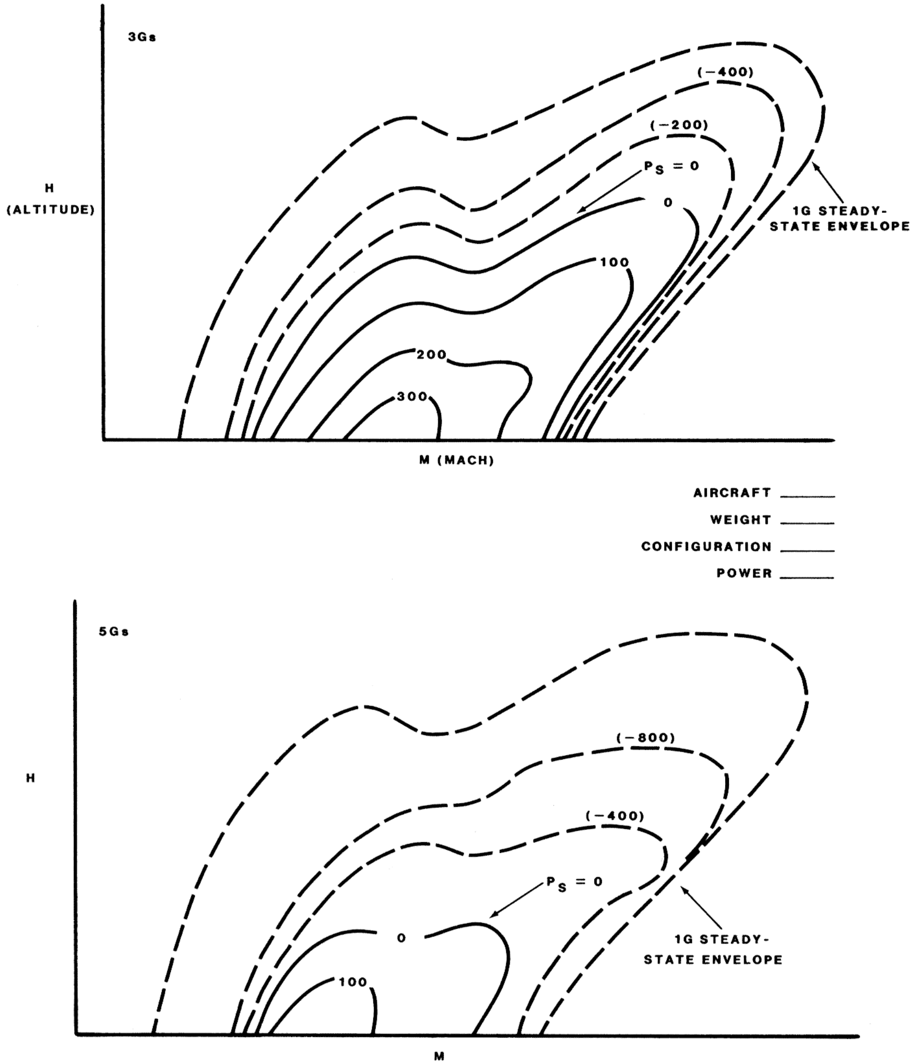

Figure A-17. H-M Diagrams for 3 Gs and 5 Gs

Outside the zero-P_S lines are negative P_S values, which indicate the rate at which energy (altitude and/or airspeed) will be lost while pulling that load factor at a given combination of speed and altitude. Inside the zero- P_S envelope are positive P_S values, which give the rate at which energy may be gained (by a climb and/or acceleration) under those conditions. The conditions under which the given load factor can just be sustained are those which lie directly on the respective zero-P_S lines. Once the sustained-G capability of a fighter is known at a given speed, its sustained turn rate and radius under those conditions may be determined mathematically or by Figure A-2.

Note that for this supersonic fighter the zero-P_S curve has two peaks. At high altitudes and fairly low G levels (less than about 5 G for this aircraft), the highest peak, and consequently the greatest sustained G, is found in the supersonic speed range. At low altitudes, where sustained G levels are higher, however, the maximum sustained G is usually achieved at speeds near the subsonic peak. Obviously, subsonic fighters would generate greatest sustained G in the subsonic region at all altitudes.

Sustained G, however, is generally of less value in air combat than the corresponding turn rate and radius are. Because of the interaction of airspeed and G, best sustained turn rate is generally achieved at a speed slightly below that for maximum sustained G at a given altitude. For supersonic fighters this speed is almost always near the subsonic-P_S peak, even at high-altitude/low-G conditions, since supersonic speeds greatly reduce turn rate. Because of the very great sensitivity of turn radius to airspeed, minimum sustained turn radius is normally achieved at fairly slow airspeed (generally 1.4 to 1.5 times power-on stall speed for jets), considerably slower than for best sustained turn rate.

Speed control is quite important for prolonged sustained turn performance. Pulling too great a load factor will cause speed to bleed off below the optimum value, resulting in reduced sustained turn. This lost speed can be regained only by relaxing G (further reducing turn performance) until the aircraft accelerates back to the desired speed, or by diving, which allows gravity to provide the needed acceleration.

The sustained-G capability of a fighter is proportional to its ratio of thrust to weight (T/W) at its particular altitude and airspeed. High T/W is analogous to low "power loading" (weight/horsepower) for prop-powered fighters. Just as important for sustained-G performance, however, is the lifting efficiency of the wing-airframe combination of the fighter, which is measured by the lift-to-drag ratio (L/D) at sustained-G levels. Therefore a relatively low-powered fighter with high L/D may possess a greater sustained-G capability. For two fighters with roughly the same sustained-G performance, the one that achieves its optimum sustained turn capability at the lower airspeed will have better sustained turn rate and radius. This superior low-airspeed performance is generally achieved by designing a larger wing for a given aircraft weight, which results in lower "wing loading" (aircraft weight/wing area), or by providing greater L/D for the wing by use of slots, slats, flaps, etc.

The fighter pilot can optimize his sustained turn performance by controlling airspeed, keeping weight and drag to a minimum, and configuring his aircraft to provide maximum L/D for the high-G condition. Still another technique is to maintain the aircraft CG at the rearmost position practicable (assuming a tail-configured fighter) in order to minimize trim drag, as explained earlier.

A feature that is less well known among fighter pilots is a phenomenon known as "gyroscopic precession," which may cause a fighter's turn performance to vary depending on the direction of its turn. High-speed rotational components, such as propellers or jet compressor and turbine rotors, behave as large gyroscopes when the aircraft turns. Gyroscopic precession generates a torque about an axis that is perpendicular to both the rotational axis of the gyroscope (generally near the fuselage axis of the aircraft) and the axis about which the fighter is turning (i.e., the vertical axis for a level turn). For a level turn this results in a gyroscopic nose-up or nose-down moment (relative to the earth) which must be compensated for by increased upward or downward lift from the pitch-control surfaces, and by use of the rudder. Whenever this gyroscopic moment must be offset largely by the pitch controls, there will be an increase or decrease in trim drag, depending on the turn direction. This phenomenon affects both sustained and instantaneous turn performance in a manner that is similar to the effect of an actual weight change in the aircraft.

The significance of the gyroscopic effect is increased by large, heavy rotating parts (high moment of inertia) in relation to total aircraft weight, and by faster rotational speeds. Faster turn rates, slower speeds, level skidding turns, lower G, and shorter distances between the CG and the pitch-control surface also increase the impact of the gyroscopic effect on turn performance.

As fighters have developed over the years they have generally become larger, heavier, faster, and capable of developing more G but less turn rate. All these factors have served to reduce the impact of the gyroscopic effect to the point where it may be insignificant to a modern fighter. This was certainly not the case, however, during World War I, when many fighters of both sides, including some Sopwiths, Nieuports, and Fokkers, were powered by rotary engines. The rotary engine was an air-cooled design with cylinders arranged radially around a central crankshaft. The prop was connected directly to the cylinders, and the cylinders and prop rotated as a unit around the fixed crankshaft. With more than one-quarter of their total weight comprised of rotating parts, some of these fighters earned reputations for being extremely maneuverable—at least in one direction. This same characteristic, however, made these fighters very tricky to handle, and they probably killed nearly as many of their own pilots as they did those of the enemy.

Torque may also have an effect on turn performance, particularly with high-powered prop fighters at slow speed. The effects of engine torque must generally be offset by rudder power to maintain balanced flight. Normally under these conditions considerable right rudder will be required to balance the torque of a prop turning clockwise (when viewed from behind), and vice versa. Another consideration here is called "P-factor," which is the tendency of a propeller to produce more thrust from one side of its disc than from the other. P-factor usually affects the aircraft in the same manner as torque, and it is exacerbated by slow speeds and hard turning. Since even more rudder is usually required in the direction of a turn to maintain balanced flight, there may be conditions under which sufficient rudder power is just not available. The resulting unbalanced flight (slip) may cause loss of aircraft control. Generally the high wing (i.e., the outside wing in a turn) will stall, causing the aircraft to "depart" controlled flight with a rapid roll toward the stalled wing.

This phenomenon has been used to good effect in combat, since it is more pronounced in some fighters than in others, and because prop-rotation direction may be reversed between combatants. The following World War II combat example of this tactic involves the P-38J Lightning versus the German Fw 190. The P-38 is a twin-engine fighter with counter-rotating props and essentially no net torque or P-factor.

> My flight of four P-38s was bounced by twenty-five to thirty FW-190s of the yellow-nose variety from Abbeville. A string of six or more of them got in behind me before I noticed them, and just as No. 1 began to fire, I rolled into a right climbing turn and went to war emergency of 60 inches manifold pressure. As we went round and round in our corkscrew climb, I could see over my right shoulder the various FW-190 pilots booting right rudder attempting to control their torque at 150 mph and full throttle, but one by one they nipped over to the left and spun out.[1]

Gravity Effects on Turn Performance

The acceleration of gravity has a very significant effect on turn performance. Figure A-18 illustrates the influence of gravity on a level turn. In this example the aircraft is flying out of the page in a level left turn. The acceleration of gravity tends to pull downward on the aircraft, and for level flight gravity must be balanced by lift, which is represented by the load-factor vector. Load factor, however, is oriented perpendicular to the fighter's wings, so only the vertical component of this acceleration can oppose gravity. This leaves only the horizontal component of load factor, labelled "radial G," to turn the aircraft. Because load factor must offset

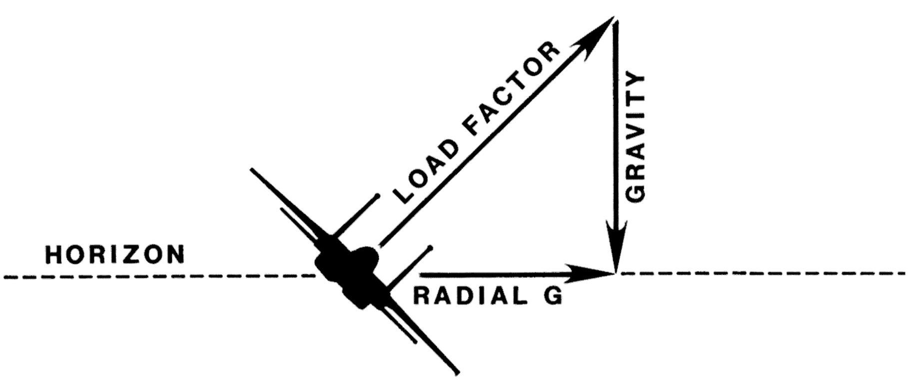

Figure A-18. Level-Turn Accelerations

gravity, radial G will be smaller than the full load factor experienced by the aircraft, and turn performance will suffer.

Gravity also affects vertical maneuvers, such as the loop illustrated in Figure A-19. In this case the fighter is executing a loop at a constant speed and a load factor of 4 Gs. At the bottom of the loop the downward pull of gravity reduces radial G to only 3 Gs, causing a large turn radius and a low turn (in this case "pitch") rate. At the top of the loop, when the fighter is inverted, gravity adds to load factor, producing a 5-G turn, smaller radius, and faster rate. When the aircraft is vertical, both nose-high and nose-low, there is no component of gravity in the direction of lift, so load factor becomes radial G, resulting in intermediate turn performance. The effect of gravity on turn radius during vertical maneuvers causes the flight path to be noncircular, giving rise to the term "tactical egg." In practice the fighter's airspeed is usually very much slower at the top of the maneuver than along the bottom, which serves to accentuate the variation in turn radius even more.

The two maneuver planes discussed (horizontal and vertical) are only two of an infinite number available to the fighter pilot. All other maneuver planes are called "oblique turns." Gravity affects these turns in the same manner, depending on the steepness of the maneuver plane. Whenever the fighter's lift vector is oriented above the horizon, gravity detracts from turn performance; conversely, gravity enhances turn performance when the lift vector is pointing below the horizon.

Roll Performance

The foregoing discussions of fighter performance concerned the aircraft's ability to change the orientation of its velocity vector and its energy state, that is, to turn, accelerate, or climb. This ability is "maneuverability" or "energy maneuverability." There are other important measures of fighter performance which do not fit this definition.

Roll performance, for example, is the ability of an aircraft to change the lateral direction of its lift vector. Since the lift force is primarily responsible for turning an aircraft, roll performance indicates the ability of a fighter to change its plane of maneuver. Therefore, although roll performance is not, in a strict sense, maneuverability, it does have a direct relationship with maneuverability. Roll performance may be defined as a measure of the aircraft's "agility."

> A big aerial barge is too clumsy for fighting. Agility is needed.
>
> Baron Manfred von Richthofen

The rolling motion of an aircraft is produced by the action of its lateral control system. These systems vary from fighter to fighter, but presently the most common controls are ailerons, spoilers, and differential tails. Since all control systems are more effective in some situations than in others, many modern fighters are designed with more than one type control to avoid problems throughout the flight envelope of the aircraft.

Aerodynamic roll controls operate by increasing lift on one side of the aircraft relative to that on the other, producing a rolling moment. When this condition occurs, a roll will commence, accelerate to a maximum value, and then stabilize at that rate. A stabilized roll rate is attained when a balancing, or "damping," moment is generated which offsets the torque of the roll controls. This damping moment is produced primarily by lift differences between the two wings caused by one wing moving upward and the other downward, and is proportional to the roll stability of the aircraft. In general, the more stable a fighter is about the roll axis, the slower its roll rate will be.

Figure A-20 graphically illustrates the effects of speed on steady roll performance. The charts in the figure discount both compressibility, which may reduce the effectiveness of roll controls or even cause rolls opposite to the intended direction (called "roll reversal"), and "aeroelastic effects," which may cause similar problems as a result of the wings twisting under the torque of the roll-control deflections. Note that as speed increases, the force (F_r.) required from the pilot to maintain full control deflection (δ_r.) increases until reaching the limits of his physical ability, after which further speed increases result in reduced control deflection. In the range of maximum-control deflection, roll rate increases almost linearly with speed, reaching a maximum at the highest speed at which full control deflection (δ_{rMAX}) can be maintained. Roll-rate capability then decreases with further speed increase, possibly to very low values at high speeds. To maintain roll performance at high speeds, power-boosted or fully powered controls are often employed to enable the pilot to attain full control deflection. With powered controls the pilot's control inputs usually position valves that allow hydraulic fluid pressure to move the control surfaces. The effects of such systems are shown by the dashed lines. For supersonic fighters it is also desirable to make these controls irreversible, so that variations in airloads on the control surfaces are not transmitted back to the pilot. Shock waves moving around on these surfaces can lead to some very distracting and misleading feel cues, making aircraft control difficult. With such controls, artificial-feel systems are usually provided so that control forces vary as the pilot would expect.

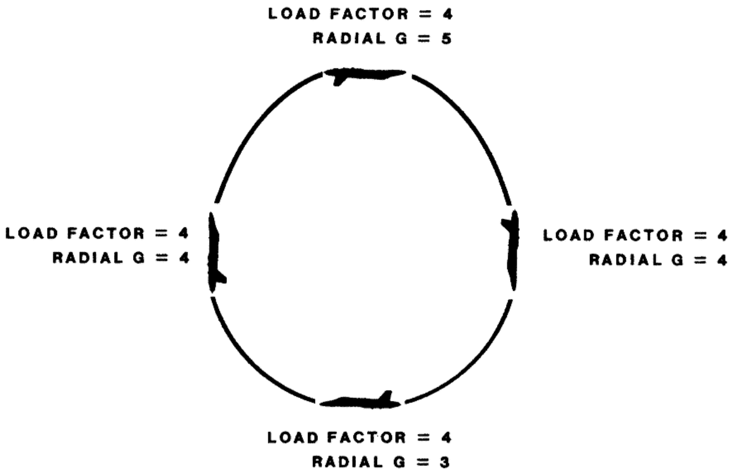

Figure A-19. Load Factor versus Radial G in Vertical Maneuvering

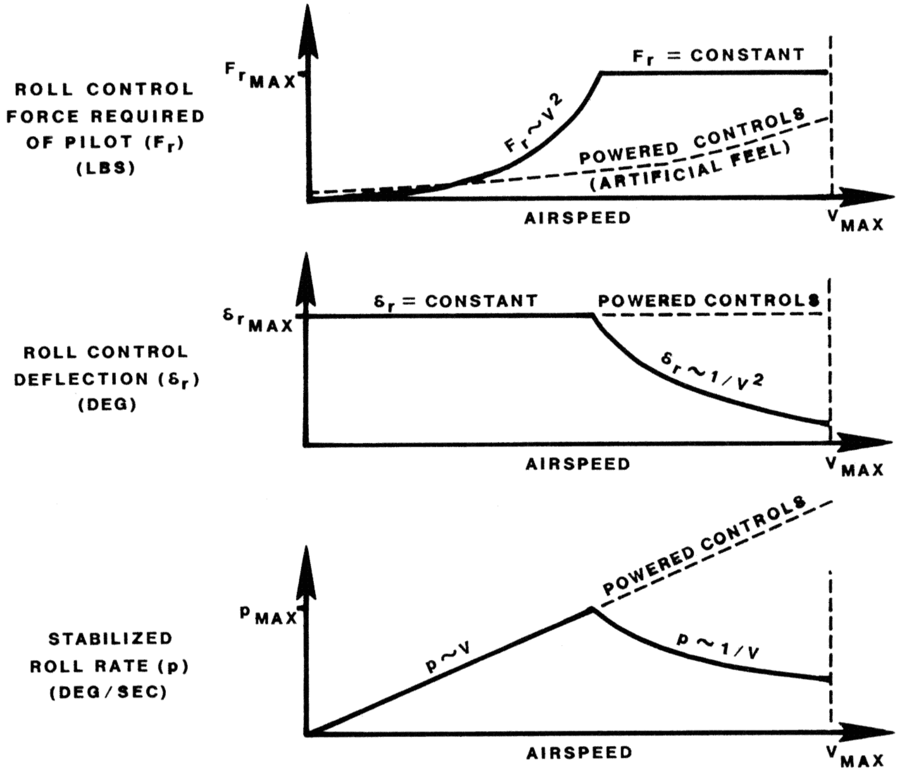

Figure A-20. Variations in Roll Rate with Airspeed

In air combat, continuous rolls of more than 180° are seldom required. Because a certain length of time is necessary to accelerate the roll rate from zero to its maximum value, maximum stabilized roll rate may not be reached during such short periods of roll. Therefore, roll acceleration is often the controlling factor in combat performance.

In addition to roll-control power, roll acceleration is a function of the "moment of inertia" of the aircraft. This moment of inertia about the roll axis depends on the aircraft weight and its distribution. The greater the total weight, and the farther it is distributed away from the fuselage axis, the greater the inertia. Large wingspan, tip-tank fuel, and wing-mounted ordnance or engines, for example, would contribute to increased roll inertia and reduced roll acceleration. In addition, roll performance may vary between left and right depending on the design of the aircraft. Prop-driven fighters, for instance, generally have better roll acceleration in the direction opposite to that of prop rotation because of engine torque effects. Cockpit configuration may also be a factor, particularly with unboosted control systems at high speeds. The pilot's ability to push the stick to the left harder than he can pull it to the right may result in a noticeable difference in roll performance.

Stabilized roll rate is also affected by wingspan. For geometrically similar fighters, shorter wingspan results in higher stabilized roll rate for the same speed and control deflection.

Roll performance is highly dependent on pilot technique as well as on speed control. Many of the effectiveness problems of roll-control devices occur at slow speeds or with high load factors (i.e., when the wings are generating close to their maximum lift). Therefore, if a pilot wishes to achieve maximum roll performance from his aircraft he should whenever possible unload before beginning the roll. Load factor can be reapplied once the lift vector is pointing in the desired direction. Efficient rudder technique can also improve roll performance. Rudder may even be the most effective roll-control device available for some fighters (especially those with sharply swept wings), particularly under high-lift conditions.

A roll-performance superiority has historically been exploited as an effective tool in guns-defense maneuvers. Since for steady guns tracking of a maneuvering target the shooter must have his aircraft's wings closely aligned with those of his victim, such tracking can be rendered practically impossible by an uncooperative defender who can change his plane of maneuver more rapidly than the attacker. Poor roll performance at high speed was one of the few characteristics of the Japanese Zero which could be exploited by the generally inferior American fighters early in World War II. Similarly, hydraulically boosted ailerons improved the agility of the American F-86 Sabre jets relative to their Russian MiG-15 adversaries in Korea. Lack of hydraulic assist continued to plague the later MiG-17 in Vietnam and the Middle East.

Pitch Performance

Pitch performance is the ability of a fighter to rotate about an axis that is parallel to its wings (i.e., the "lateral" axis). In level flight this would mean rotating the nose of the aircraft upward or downward, but the upward direction is generally the more important. Like roll performance, pitch rate is a measure of the fighter's agility.

When pitch controls are applied in a nose-up direction the aircraft begins to rotate, which causes an increase in "angle of attack," as defined in Figure A-21. Angle of attack (AOA) is the angle between the "chord line" of the wing (an imaginary line that connects the wing's leading and trailing edges) and the "relative wind," which is equal in speed to, and opposite in direction to, the aircraft's motion through the air. As AOA increases, so generally do the lift produced by the wing, and load factor, which causes the aircraft to turn (i.e., change the direction of the velocity vector). The motion that is observed is therefore partially turn and partially increasing

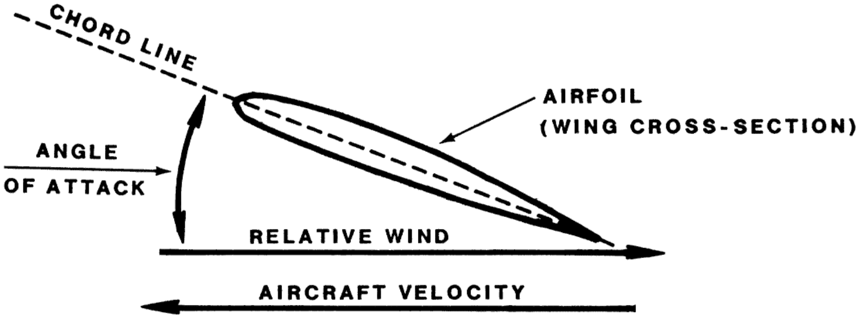

Figure A-21. Angle of Attack

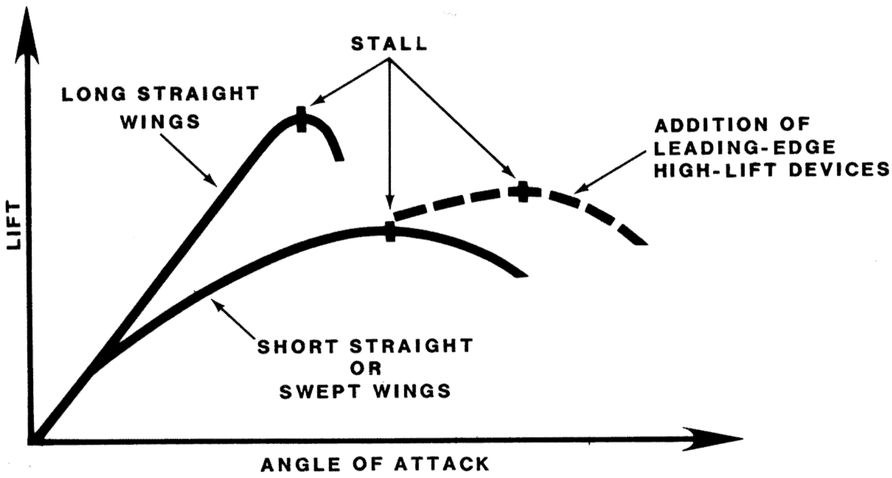

Figure A-22. Lift versus Angle of Attack

AOA. It is difficult to separate these two motions visually, so both are generally included in "pitch rate." Once AOA has stabilized, pitch rate and turn rate in a given maneuver plane are the same.

Pitch rate is important to fighters for several reasons. One of them is that the faster AOA can be increased, the more quickly a turn can begin. This can have a great effect on the early stages of maximum turn-performance maneuvers. A second reason is the influence of pitch rate on gunsight tracking. The ability simply to point the aircraft in a given direction, regardless of its direction of motion, is quite valuable. A third factor has to do with the difficulty of visually differentiating pitch rate from turn rate. Since fighter pilots must rely on visual information to assess the performance of an opponent's aircraft, large changes in AOA easily may be mistaken for increased turn performance. Such a misinterpretation often leads to mistakes in maneuver selection to counter the perceived maneuver of an adversary.

The pitch performance of a fighter, i.e., pitch rate and pitch acceleration, is a function of the effectiveness of the pitch controls and the resistance the aircraft presents to a pitching motion. The AOA contribution to pitch is limited by the maximum usable AOA (stall AOA or limits of controllability) at low speeds and by load-factor limits above corner speed. Since the range of usable AOA is rather small (about 20° to 30°) for most fighters, AOA's contribution to pitching motion is completed quickly. Therefore, as in the case of roll performance, it is pitch acceleration rather than pitch rate which is of greater importance in fighter maneuvering when the discussion is limited to AOA changes only.

Since the rate of AOA increase is on the same order of magnitude as the turn rate and is additive in producing total pitch performance, the greater the range of usable AOA, the greater its contribution will be during the early phases of a turn. Greatest pitch performance is often found near corner speed, which provides the highest instantaneous turn rate and represents the fastest possible speed (for maximum pitch-control authority) at which the full range of AOA is available. Design features such as short or swept wings and leading-edge high-lift devices can increase maximum usable AOA by increasing the stall AOA, as shown in Figure A-22.

Pitch acceleration is dependent on control power and on the aircraft's pitch stability and its inertia. The moment of inertia about the pitch axis is a function of the fighter's weight and its distribution fore and aft about the CG. Increasing total aircraft weight or moving some of this weight farther from the CG either forward or aft tends to increase pitch inertia and reduce pitch acceleration. The position of the CG also has an effect. Aft CG positions usually increase pitch performance by reducing aircraft stability.

> Know and use all the capabilities in your airplane. If you don't, sooner or later, some guy who does use them all will kick your ass.
>
> Lieutenant Dave "Preacher" Pace, USN
> U.S. Navy Fighter Weapons School Instructor

Note

1. Robin Higham and Abigail T. Siddal, eds., *Flying Combat Aircraft of the USAAF-USAF*, p. 136.