

HIGH ALTITUDE AERODYNAMICS

CRITICAL ASPECTS OF MACH FLIGHT In recent years, a number of corporate jet airplanes have been involved in catastrophic loss of control during high-altitude/high-speed flight. A significant causal factor in these accidents may well have been a lack of knowledge by the pilot regarding critical aspects of high-altitude/MACH flight.

a. Maximum operating altitudes of general aviation turbojet airplanes have now reached 51,000 feet. It is, therefore, logical to expect these types of accidents to continue unless pilots learn to respect the more critical aspects of high-altitude high-speed flight and gain as much knowledge as possible about the specific make and model of aircraft to be flown and its unique limitations.

b. From the pilot's viewpoint, MACH is the ratio of the aircraft's true airspeed to the local speed of sound. At sea level, on a standard day (59°F / 15°C) the speed of sound equals approximately 660 KIAS or 1,120 feet per second. MACH 0.75 at sea level is equivalent to a TAS of approximately 498 KIAS (0.75 x 660 K) or 840 feet per second. The temperature of the atmosphere normally decreases with an increase in altitude. The speed of sound is directly related only to temperature. The result is a decrease in the speed of sound up to about 36,000 feet.

c. The sleek design of some turbojet airplanes has caused some operators to ignore critical airspeed and MACH limitations. There are known cases in which corporate turbojet airplanes have been modified by disabling the airspeed and MACH warning systems to permit intentional excursions beyond the FAA certificated V_{mo} / M_{mo} limit for the specific airplane. Such action may critically jeopardize the safety of the airplane by setting the stage for potentially hazardous occurrences.

d. The compulsion to go faster may result in the onset of aerodynamic flutter, which in itself can be disastrous, excessive G-loading in maneuvering, and induced flow separation over the ailerons and elevators. This may be closely followed by a loss of control surface authority and aileron buzz or snatch, coupled with yet another dangerous phenomenon called MACH tuck, leading to catastrophic loss of the airplane and the persons onboard.

e. MACH tuck is caused principally by two basic factors:

(1) Shock wave-induced flow separation, which normally begins near the wing root, causes a decrease in the downwash velocity over the elevator and produces a tendency for the aircraft to nose down.

(2) Aftward movement of the center of pressure, which tends to unbalance the equilibrium of the aircraft in relation to its center of gravity (CG) in subsonic flight.

f. The airplane's CG is now farther ahead of the aircraft's aerodynamic center than it was in slower flight. This dramatically increases the tendency of the airplane to pitch more nosedown.

g. Pressure disturbances in the air, caused by an airfoil in high-altitude/high-speed flight, result from molecular collisions. These molecular collisions are the result of air that moves over an airfoil faster than the air it is overtaking can dissipate. When the disturbance reaches a point at which its propagation achieves the local speed of sound, MACH 1 is attained. One hundred

percent (100%) of the speed of sound at MSL with a temperature of 15°C is 760 statute or 660 nautical miles per hour. This speed is affected by temperature of the atmosphere at altitude. Thus, optimum thrust, fuel, and range considerations are significant factors in the design of most general aviation turbine-powered airplanes which cruise at some percentage of MACH 1.

h. Because of the critical aspects of high-altitude/high-MACH flight, most turbojet airplanes capable of operating in the MACH speed ranges are designed with some form of trim and autopilot MACH compensating device (stick puller) to alert the pilot to inadvertent excursions beyond its certificated M_{mo} . This stick puller should never be disabled during normal flight operations in the aircraft.

i. If for any reason there is a malfunction that requires disabling the stick puller, the aircraft must be operated at speeds well below M_{mo} as prescribed in the applicable Airplane Flight Manual procedures for the aircraft.

j. An airplane's IAS decreases in relation to TAS as altitude increases. As the IAS decreases with altitude, it progressively merges with the low-speed buffet boundary where pre-stall buffet occurs for the airplane at a load factor of 1.0 G. The point where high-speed MACH, IAS, and low-speed buffet boundary IAS merge is the airplane's absolute or aerodynamic ceiling. Once an aircraft has reached its aerodynamic ceiling, which is higher than the altitude limit stipulated in the Airplane Flight Manual, the aircraft can neither be made to go faster without activating the design stick puller at MACH limit nor can it be made to go slower without activating the stick shaker or pusher. This critical area of the aircraft's flight envelope is known as coffin corner.

k. MACH buffet occurs as a result of supersonic airflow on the wing. Stall buffet occurs at angles of attack that produce airflow disturbances (burbling) over the upper surface of the wing which decreases lift. As density altitude increases, the angle of attack that is required to produce an airflow disturbance over the top of the wing is reduced until a density altitude is reached where MACH buffet and stall buffet converge (*coffin corner*). When this phenomenon is encountered, serious consequences may result causing loss of control of the aircraft.

l. Increasing either gross weight or load-factor (G-factor) will increase the low-speed buffet and decrease MACH buffet speeds. A typical turbojet airplane flying at 51,000 feet altitude at 1.0 G may encounter MACH buffet slightly above the airplane's M_{mo} (0.82 MACH) and low speed buffet at 0.60 MACH. However, only 1.4 G (an increase of only 0.4 G) may bring on buffet at the optimum speed of 0.73 MACH and any change in airspeed, bank angle, or gust loading may reduce this straight and level flight 1.4 G protection to no protection. Consequently, a maximum cruising flight altitude must be selected which will allow sufficient buffet margin for the maneuvering necessary and for gust conditions likely to be encountered. Therefore, it is important for pilots to be familiar with the use of charts showing cruise maneuvering and buffet limits. Flightcrews operating airplanes at high speeds must be adequately trained to operate them safely. This training cannot be complete until pilots are thoroughly educated in the critical aspect of aerodynamic factors described herein pertinent to MACH flight at high altitudes.

AIRCRAFT AERODYNAMICS AND PERFORMANCE Pilots who operate aircraft at high speeds and high altitudes are concerned with the forces affecting aircraft performance caused by the interaction of air on the aircraft. With an understanding of these forces, the pilot will have a sound basis for predicting how the aircraft will respond to control inputs. The importance of these aerodynamic forces and their direct application to performance and the execution of aircraft maneuvers and procedures at altitude will be evident.

a. **Wing Design**

(1) The wing of an airplane is an airfoil or aircraft surface designed to obtain the desired reaction from the air through which it moves. The profile of an aircraft wing is an excellent example of an efficient airfoil. The difference in curvature between the upper and lower surfaces of the wing generates a lifting force. Air passing over the upper wing surface moves at a higher velocity than the air passing beneath the wing because of the greater distance it must travel over the upper surface. This increased velocity results in a decrease in pressure on the upper surface. The pressure differential created between the upper and lower surfaces of the wing lifts the wing upward in the direction of the lowered pressure. This lifting force is known as induced lift.

Induced lift may be increased, within limits, by:

(i) Increasing the angle of attack of the wing or changing the shape of the airfoil, changing the geometry, e.g., aspect ratio.

(ii) Increasing the wing area velocity.

(iii) Increasing the free-stream

(iv) A change in air density.

(2) The pilot may have only varying degrees of control over these factors. Thus, the pilot must keep firmly in mind that an aircraft will obey the laws of physics just as precisely at its high speed limits as it does during a slower routine flight, and that regardless of wing shape or design, MACH range flight requires precise control of a high volume of potential energy without exceeding the critical MACH number or MACH critical.

(3) MACH critical is important to high- speed aerodynamics because it is the speed at which the flow of air over a specific airfoil design reaches MACH 1, but the most important effect is formation of a shock wave and drag divergence.

(4) Sweeping the wings of an airplane is one method used by aircraft designers to delay the adverse effects of high MACH flight and bring about economical cruise with an increase in the critical MACH number. Sweep allows a faster airfoil speed before critical MACH is reached when compared to an equal straight wing. This occurs because the airflow now travels over a different cross section (camber) of the airfoil. This new cross section has less effective camber which results in a reduced acceleration of airflow over the wing, thus allowing a higher speed before critical MACH is reached. Sweep may be designed either forward or rearward; the overall effect is the same.

However, rearward sweep appears to be somewhat more desirable, since it has presented fewer problems to manufacturers of models of general aviation aircraft in terms of unwanted design side effects. In effect, the wing is flying slower than the airspeed indicator indicates and, similarly, it is developing less drag than the airspeed indicator would suggest. Since less drag is being developed for a given indicated airspeed, less thrust is required to sustain the aircraft at cruise flight.

(5) There is a penalty, however, on the low-speed end of the spectrum. Sweeping the wings of an aircraft increases the landing/stall speed which, in turn, means higher touchdown speed, with proportionally longer runway requirements and more tire and brake wear as opposed to a straight-wing design. A well-stabilized approach with precise control of critical “V” speeds is necessary. In other words, to achieve a safe margin airspeed on the wing that will not result in a stalled condition with the wingtips stalling prior to the rest of the wing and possibly rolling uncontrollably to the right or left, the swept-wing aircraft must be flown at a higher actual airspeed than a straight-wing aircraft.

(6) Drag curves are approximately the reverse of the lift curves, in that a rapid increase in drag component may be expected with an increase of angle of attack with the swept wing; the amount being directly related to the degree of sweep or reduction of aspect ratio.

(7) The extension of trailing edge flaps and leading edge devices may, in effect, further reduce the aspect ratio of the swept wing by increasing the wing chord. This interplay of forces should be well understood by the pilot of the swept-wing aircraft, since raising the nose of the aircraft to compensate for a mild undershoot during a landing approach-at normal approach speeds will produce little lift, but may instead lead to a rapid decay in airspeed, thus rapidly and critically compromising the margin of safety.

(8) Another method of increasing the critical MACH number of an aircraft wing is through the use of a high-speed laminar airflow airfoil in which a small leading edge radius is combined with a reduced thickness ratio. This type of wing design is more tapered with its maximum thickness further aft, thus distributing pressures and boundary layer air more evenly along the chord of the wing. This tends to reduce the local flow velocities at high MACH numbers and improve aircraft control qualities.

(9) Several modern straight-wing, turbojet aircraft make use of the design method described in paragraph h. To delay the onset of MACH buzz and obtain a higher M_{mo} , these aircraft designs may incorporate the use of both vortex generators and small triangular upper wing strips as boundary layer energizers. Both systems seem to work equally well, although the boundary layer energizers generally produce less drag. Vortex generators are small vanes affixed to the upper wing surface, extending approximately 1 to 2 inches in height. This arrangement permits these vanes to protrude through the boundary layer air. The vortex generators deflect the higher energy airstream downward over the trailing edge of the wing and accelerate the boundary layer aft of the shock wave. This tends to delay shock-induced flow separation of the boundary layer air which causes aileron buzz, and thus permits a higher M_{mo} . The lift characteristics of straight-wing and swept-wing airplanes related to changes in angle of attack are more favorable for swept-wing airplanes. An increase in the angle of attack of the straight-wing airplane produces a substantial and constantly increasing lift vector up to its maximum coefficient of lift and, soon thereafter, flow separation (stall) occurs with a rapid deterioration of lift.

(10) By contrast, the swept wing produces a much more gradual buildup of lift with no well-defined maximum coefficient, the ability to fly well beyond this point, and no pronounced stall break. The lift curve of the short, low-aspect ratio (short span, long chord) wing used on present-day military fighter aircraft compares favorably with that of the swept wing, and that of other wing designs which may be even more shallow and gentle in profile. cruise speed. For efficiency, jet aircraft are typically operated at high altitudes where cruise is usually very close to RPM or exhaust gas temperature limits. At high altitudes, little excess thrust may be available for maneuvering. Therefore, it is often impossible for the jet aircraft to climb and turn simultaneously, and all maneuvering must be accomplished within the limits of available thrust and without sacrificing stability and controllability.

(11) Regardless of the method used to increase the critical MACH number, airflow over the wing is normally smooth. However, as airspeed increases, the smooth flow becomes disturbed. The speed at which this disturbance is usually encountered is determined by the shape of the wing and the degree of sweep.

(12) When the aircraft accelerates, the airflow over the surface of the wing also accelerates until, at some point on the wing, it becomes sonic. The indicated airspeed at which this occurs is the critical MACH number (MACH critical) for that wing.

(1) Static stability is the inherent flight characteristic of an aircraft to return to equilibrium after being disturbed by an unbalanced force or movement.

(2) Controllability is the ability of an aircraft to respond positively to control surface displacement, and to achieve the desired condition of flight.

b. Jet Engine Efficiency

(1) The efficiency of the jet engine stability at high altitudes is the primary reason for operating in the high-altitude environment. The specific fuel consumption of jet engines decreases as the outside air temperature decreases for constant revolutions per minute (RPM) and TAS. Thus, by flying at a high altitude, the pilot is able to operate at flight levels where fuel economy is best and with the most advantageous cruise speed. For efficiency, jet aircraft are typically operated at high altitudes where cruise is usually very close to RPM or exhaust gas temperature limits. At high altitudes, little excess thrust may be available for maneuvering. Therefore, it is often impossible for the jet aircraft to climb and turn simultaneously, and all maneuvering must be accomplished within the limits of available thrust and without sacrificing stability and controllability.

(2) Compressibility also is a significant factor in high-altitude flight. The low temperatures that make jet engines more efficient at high altitudes also decrease the speed of sound. Thus, for a given TAS, the MACH number will be significantly higher at high altitude than at sea level. This compressibility effect due to supersonic airflow will be encountered at slower speeds at high altitude than when at low altitude.

c. Controllability Factors

(1) Static stability is the inherent flight characteristic of an aircraft to return to equilibrium after being disturbed by an unbalanced force or movement.

(2) Controllability is the ability of an aircraft to respond positively to control surface displacement, and to achieve the desired condition of flight.

(3) At high-flight altitudes, aircraft stability and control may be greatly reduced. Thus, while high-altitude flight may result in high TAS and high MACH numbers, calibrated airspeed is much slower because of reduced air density. This reduction in density means that the angle of attack must be increased to maintain the same coefficient of lift with increased altitude. Consequently, jet aircraft operating at high altitudes and high MACH numbers may simultaneously experience problems associated with slow-speed flight such as Dutch roll, adverse yaw, and stall. In addition, the reduced air density reduces aerodynamic damping, overall stability, and control of the aircraft in flight.

(I) Dutch roll is a coupled oscillation in roll and yaw that becomes objectionable when roll, or lateral stability is reduced in comparison with yaw or directional stability. A stability augmentation system is required to be installed on the aircraft to dampen the Dutch roll tendency when it is determined to be objectionable, or when it adversely affects the control stability requirements for certification. The yaw damper is a gyro-operated autocontrol system installed to provide rudder input and aid in canceling out yaw tendencies such as those in Dutch roll.

(ii) Adverse yaw is a phenomenon in which the airplane heading changes in a direction opposite to that commanded by a roll control input. It is the result of unequal lift and drag characteristics of the down-going and up-going wings. The phenomena are alleviated by tailoring the control design by use of spoilers, yaw dampers, and interconnected rudder and aileron systems.

(4) Supersonic flow over the wing is responsible for:

(i) The formation of shock waves on the wing which result in drag rise.

(ii) An aft shift in the center of lift resulting in a nosedown pitching moment called MACH tuck.

(iii) Airflow separation behind the shock waves resulting in MACH buffet.

(5) Swept wing and airfoil design alone, with boundary layer energizers such as the vortex generators described earlier, has reduced the hazardous effect of the problems described above. However, these problems are still encountered to some extent by the modern turbojet airplane in high-altitude flight.

(6) In general, this discussion has been confined to normal level, unaccelerated 1.0 G-flight. When turning or maneuvering about the pitch axis, however, acceleration of G-forces can occur while maintaining a constant airspeed. As G-forces increase, both the aircraft's aerodynamic weight and angle of attack increase. The margin over low-speed stall buffet decreases, as well as the margin below MACH buffet, because of the increased velocity of the air over the wing resulting from the higher angle of attack. This, in effect, could lower the aerodynamic ceiling for a given gross-weight. Increased G-loading can also occur in non maneuvering flight because of atmospheric turbulence or the lack of fine-touch skill by the pilot. Pilots flying at high altitudes in areas where turbulence may be expected must carefully consider acceptable safety margins necessary to accommodate the sudden and unexpected vertical accelerations which may be encountered with little or no warning. How wide is the safety margin between low-speed and high-speed buffet boundaries for an altitude and weight in a 300 bank? The answer may be easily determined by reference to the Cruise Maneuver/Buffer Limit Chart for a particular aircraft. For example, in a typical jet aircraft, the 1.0 G buffet-free margin at FL 350 is 135 kts; at FL 450 this speed is reduced to a mere 26 kts. Thus, the safety margin in airspeed spread diminishes rapidly as the aircraft climbs and leaves little room for safety in the event of a air turbulence encounter or accidental thunderstorm penetration.

(7) If a thunderstorm cannot be avoided, follow high-altitude thunderstorm penetration procedures and avoid over-action of thrust levers. When excessive airspeed buildup occurs, pilots may wish to use speed brakes. The use of aerodynamic speed brakes, when they are a part of the lateral control system, may change the roll rate any time there is a lateral control input.