While the fundamental physical laws governing flight at supersonic speeds are the same as those for subsonic flight, the nature of the flow about the airplane and, as a consequence, the various aerodynamic forces and moments acting on the vehicle at these higher speeds are substantially different than those at subsonic speeds. Basically, these variations result from the fact that at supersonic speeds the airplane moves faster than the disturbances of the air produced by the passage of the airplane, such effects being propagated at roughly the speed of sound. As a result, these disturbances influence only a region primarily behind the vehicle.

The primary effect of the change in the nature of the flow at supersonic speeds is a marked increase in the drag, resulting from the formation of shock waves about the configuration. (See section on shock waves.) These strong disturbances, which may extend for many miles from the airplane, cause significant energy losses in the air. At supersonic flight speeds these waves are swept back obliquely, as shown in figure (1), the angle of obliqueness decreasing with speed. For the major parts of the shock waves produced by a well designed airplane, the angle of obliqueness, \( \mu \), is such that \( \sin^{-1}(1/M) \) where \( M \) is the Mach number, the ratio of the flight velocity to the speed of sound.

The shock waves are associated with
outward diversions of the airflow by the various elements of the airplane. Part of this turning is caused by the leading and trailing edges of the wing and control surfaces and by the nose and aft end of the fuselage and other bodies. Major proportions of these effects also result from the wing incidence required to provide lift. At the lower supersonic speeds, the wave drag at the zero lift condition is usually more significant than the drag due to wing incidence. However, when the Mach number is increased, the relative magnitude of wave drag at the zero lift condition gradually decreases, while the drag associated with wing incidence progressively increases, so that at the higher supersonic speeds the wave drag due to lift is usually considerably more important than the zero lift value. The wave drag at the zero lift condition is reduced primarily by decreasing the thickness-to-chord ratios for the wings and control surfaces and by increasing the length-to-diameter ratios for the fuselage and bodies. Also, the leading edge of the wing and the nose of the fuselage are made relatively sharp. (See figure (2).) With such changes, the severity of the diversions of the flow by these elements is reduced, with a resulting reduction of the strength of the associated shock waves. The wave drag has been further lessened by sweeping the wing back as discussed in the section on transonic flight. Some supersonic wings have a large amount of leading-edge sweep with little or no trailing-edge sweep. Such planforms are
referred to as "delta" or "modified delta". Also, the supersonic drag wave has been reduced by shaping the fuselage and arranging the components on the basis of the area rule. (See section on transonic flight.) For supersonic speeds, the airplane cross-sectional areas utilized in the application of this rule are obtained in planes inclined at the angle of the shock waves.

The most effective means for reducing the drag associated with incidence is to sweep the wing leading edge back. With such a procedure, the flow over the wing with incidence is more like that at lower speeds. (See section on transonic flight.)

When the speed is increased to supersonic values, an airplane at a given attitude and altitude experiences large increases in drag, in addition to those associated with the different nature of the flow, because of the higher dynamic pressure at these higher speeds. (See section on fluid mechanics.) To offset this effect, supersonic airplanes usually fly at considerably higher altitudes than subsonic vehicles. For example, for efficient flight at a Mach number of 3, an airplane must fly at an altitude of about 60,000 feet.

Even with the improvements just described, the aerodynamic efficiencies, or lift-drag ratios, for supersonic airplanes are substantially less than those for subsonic
machines. The best lift-drag obtainable with feasible configurations at moderate supersonic Mach numbers, 2 to 3, are about one-half of the values measured for comparable subsonic airplanes. However, the efficiency of the jet engine is higher at supersonic than at subsonic speeds. At Mach numbers between 2 and 3, the increase is about equal to the decrease of aerodynamic efficiency, so that the overall flight efficiency may be as high at such speeds as at subsonic velocities.

At supersonic speeds the center of lift on the wing is well aft of the position for subsonic speeds. As a result, the control forces required to maintain level flight at these speeds may be substantially different from those for subsonic speeds. In addition, the effectiveness of control surfaces at supersonic speeds is substantially less than at subsonic speeds for the same reason that such effectiveness is reduced at transonic speeds. (See section on *transonic flight*.) Consequently, flap-type controls are made relatively large on supersonic airplanes. Also, special spoiler-type controls may be used to augment the effect of the flap. Further, the entire horizontal or vertical stabilizing fins may be moved to provide longitudinal and directional control.

For supersonic airplanes with wings having a delta or highly swept planform, the lateral controls near the tips of the wing may also be used for longitudinal control. For such wings, the controls are sufficiently far aft of the airplane center of gravity so that forces
associated with control deflections provide adequate pitching moments. A supersonic airplane may have the horizontal stabilizing and control surface forward of the wing, rather than in the conventional rearward location. Such an arrangement, called a canard, offers a number of advantages for supersonic airplanes. For example, the tail does not operate in the strong downwash field of the wing or the exhaust of the jet engines.

At the higher supersonic speeds, an improperly designed airplane may become directionally unstable; that is, unstable about a vertical axis. This effect results from the fact that effectiveness of the aft-located vertical stabilizing surface decreases with an increase in Mach number, while the destabilizing force on the forward part of the fuselage usually does not. Also, the influence of the reduction in directional stability may interact with the wing dihedral effect to cause a severe compound instability usually referred to as "roll coupling". To provide sufficient directional stability to eliminate the possibility of such effects, the vertical stabilizing surfaces of supersonic airplanes are made relatively large.

One of the major problems associated with supersonic flight, particularly at the higher supersonic speeds, is that of taking air into the engines. This air must be decelerated from the flight velocity to a relatively low speed at the compressor of the engine, without excessive energy losses. With a simple inlet, such as used on
Subsonic and transonic airplanes, a strong normal shock wave forms ahead of the forward face at supersonic speeds. This shock causes very severe loss of energy in the air reaching the engine, which leads to losses of engine performance. In addition, the drag of the airplane is increased. To reduce these losses, special inlets and diffusers which decelerate the airflow to the engine by a series of weak disturbances are used. (See section on supersonic diffusers.)

Since the shock waves produced by an airplane at supersonic speeds are very extensive, they reach to the ground to produce rapid changes in atmospheric pressure when the airplane passes. At a considerable distance from the airplane, the shock waves produced by the various airplane components converge to form two distinct fronts, as shown in figure 1. The resulting changes in pressure on the ground appear as shown in figure 3. The human ear hears these pressure changes as two explosive sounds in rapid succession. These sounds are referred to as "sonic booms" because of their similarity to the effects produced by airplanes maneuvering near the speed of sound. (See section on sonic boom.) When the airplane is flying at low altitudes, the pressure changes may be sufficiently great to break windows. As might be expected, the severity of the boom is greatly reduced for airplanes flying at higher altitudes. However, an airplane must usually fly at an altitude of at least 40,000 feet to reduce the noise to an unobjectionable
level. Because of this fact, supersonic airplanes must climb to the supersonic cruise altitude primarily at subsonic speeds.
BIBLIOGRAPHY


FIGURE LEGENDS FOR ARTICLE ON SUPersonic FLIGHT BY R. T. WHITCOMB

Figure 1.— Shock waves about airplane at supersonic speeds.

Figure 2.— Comparison of airfoil sections for subsonic and supersonic flight.

Figure 3.— Effect of shock waves on pressure at ground.