When the velocity of an airplane approaches the speed of sound (roughly 660 miles per hour at 35,000 feet altitude) the flight characteristics become radically different from those at subsonic speeds. The drag increases greatly, the lift at a given attitude decreases, the moments acting on the airplane change abruptly, and the vehicle may shake or buffet. Such phenomena usually persist to flight velocities somewhat above the speed of sound. These flight characteristics, as well as the speeds at which they occur, are usually referred to as transonic. The extent of the speed range of these changes depends on the form of the airplane; for configurations designed for subsonic flight they may occur at velocities from 70 percent to 110 percent of the speed of sound (Mach numbers of 0.7 to 1.1); for airplanes intended for transonic or supersonic flight they may be present only at Mach numbers from 0.95 to 1.05.

The transonic flight characteristics result from the development of shock waves about the airplane. (See section on shock waves.) Because of the accelerations of airflow over the various surfaces, the local velocities become supersonic while the airplane itself is still subsonic. (The flight speed at which such local supersonic flows first occur is called the critical speed.) Shock waves are associated with deceleration of these local supersonic flows to subsonic flight velocities. The usual forms of these waves at speeds just above the critical values are illustrated by the photograph (1) in
which the rates of change of pressure in the flow about an airfoil section are made visible by an optical system called Schlieren. The shock wave is the nearly vertical line near the midchord of the section. Such shock waves in the position shown cause abrupt streamwise increases of pressure on the airplane surfaces. These gradients may cause a reversal and separation of the flow in the boundary layer on the wing surface in roughly the same manner as do similar pressure changes at lower subcritical speeds. (See section on boundary layer flow.) When the wing carries lift, the shock-induced separation is particularly strong on the upper surfaces. As for boundary layer separation at lower speeds, the flow breakdown in this case leads to increases of drag, losses of lift, and changes of aerodynamic moments. The unsteady nature of the separated flow results in an irregular change of the aerodynamic forces acting on the airplane with resulting buffeting and shaking. As the Mach number is increased the shock waves move aft, so that at Mach numbers of about 1.0 or greater, depending on the configurations, they reach the trailing edges of the surfaces. With the shocks in these positions, the associated pressure gradients have relatively little effect on the boundary layer and the shock-induced separation is greatly reduced.

When the speed is increased to the higher transonic range, at and just above the speed of sound, the energy losses in the shock waves about an airplane result
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quite large. As a result, the drag may increase to many times the subsonic value. At these speeds shock waves, in addition to those present near the aft parts of the surfaces, form ahead of the components. The various waves extend outward, interact and merge to form two shock waves at a distance from the airplane. (See figure (2).)

These two waves are relatively strong and very extensive; they may extend for miles from the airplane.

As the speed is increased through the transonic range the changes of the distribution of load on the wing, resulting from first the boundary layer separation and then the rearward movement of the shock wave, cause a marked rearward shift of the center of lift. This shift causes a nose-downward moment on the airplane which must be corrected by an increase of the negative lift on the usual tail to maintain trim. Also, the effectiveness of the usual flap-type elevator and aileron control surfaces used on subsonic airplanes decreases greatly at transonic speeds. At subcritical speeds, deflections of such flaps provide differences in the pressures on upper and lower parts of the main surface ahead of flap, as well as on the flap itself. At transonic speeds, the effects of the flap on the pressures on the main surface are greatly reduced because of the presence of local supersonic flows on this surface. As a result, the total forces produced by the flap are diminished. In addition, the hinge moments required to deflect the control may be
greatly increased at transonic speeds.

A number of means are used to delay and reduce the adverse transonic characteristics. Among these are sweepback, that is, turning the wing or tail panels back to an oblique angle with the flight direction; reductions of the thickness-to-chord and span-to-chord ratios (aspect ratio) for the wing or tail; additions on the wing; special fuselage contours; and rearrangement of the airplane components.

Sweepback is the most effective means for improving the overall transonic characteristics. The action of sweep may be most readily understood by considering the airflow over a very long swept surface such as shown in the figure (3). Fundamentally, only the component of airflow normal to swept elements of this panel is effective in determining the nature of flow over the surface. Thus, on such a swept surface the onset of a shock wave, with the associated separation, is delayed until the reduced component of local velocity normal to the swept elements becomes supersonic. For substantial amounts of sweep, the flight speed may be quite high before this condition is reached. The use of sweep also greatly reduces the magnitude of the changes in the aerodynamic characteristics, once they occur.

While theory and experiments indicate that the transonic characteristics are progressively delayed and reduced by increasing the sweep to relatively high values, very large amounts of wing sweep are not used
in practice, since experience has indicated that excessive sweep leads to a number of aerodynamic problems. Most importantly, a highly swept wing may have an abrupt nose-up moment at the higher lifts. This phenomenon, known as pitchup, may result in excessive aerodynamic loads or stall. Pitchup results from an initial separation of the boundary layer on the outboard part of the swept wing, with an associated loss of lift for this region. Since this portion of a sweptback wing is aft of the center of gravity, the loss of lift causes a nose-up moment. Increasing the wing sweep also reduces the lift available for takeoff and landing. Because of these limitations, most transport-type airplanes intended to fly close to the speed of sound incorporate only a moderate amount of wing sweep. Usually the obliqueness of the midchord element for such airplanes is about 30°. Such a sweep provides a delay of the onset of the adverse transonic characteristics of roughly 0.08 Mach number. Transonic and supersonic military airplanes may also incorporate as much as 45° of midchord sweep, which results in a delay of the adverse effects of approximately 0.15 Mach number.

Substantial improvements of the adverse transonic characteristics are provided by reducing the thicknesses-to-chord ratios for the wing and tail surfaces. Such changes reduce the acceleration of the flow over the surfaces with a resulting delay of the onset of local supersonic flows and the associated shock wave. Also, the
severity of the adverse longitudinal pressure gradients on the wing surface is lessened so that boundary-layer separation is reduced. However, reductions of thickness lead to considerable increases in the weight of a structurally sound wing. Thus, the wing thickness used must be a compromise between the aerodynamic and structural factors. Most high-speed transport wings have mean thickness-to-chord ratios of about 10 percent, while military airplanes may have thickness ratios as low as 3 percent.

Reductions in the aspect ratio provide delays and reductions of the transonic changes similar to those provided by reductions in thickness ratio, although the magnitude of the effect is usually considerably less. More importantly, lower aspect ratios result in improvements of the wing structural characteristics, which allows the use of smaller thickness-to-chord ratios. However, the use of reduced aspect ratios leads to increases of the subcritical drag due to lift. Most high-speed transport wings have aspect ratios of roughly 7, while transonic and supersonic military airplanes may have aspect ratios of as low as 2.

The adverse transonic characteristics may also be improved by adding streamlined bodies to the aft portion of the upper surface of the wing. Such changes provide reductions of the accelerated flows and adverse pressure gradients similar to those provided by reducing the thickness ratio.
Because of the pronounced interaction of the shock waves of various airplane components near the speed of sound, the drag increase for the airplane associated with these waves is most effectively defined and improved by considering the flow about the configuration as a whole. It has been found that for a nonlifting condition the forms of the shock waves and, as a result, the drag are primarily a function of the longitudinal development of cross-sectional area, in section normal to the airstream, for the complete airplane. This relationship, called the area rule, is illustrated by considering the transonic drag increases for the configurations shown in the figure (7). The various normal cross-sectional areas for the body of revolution, such as at BB, are the same as those for the wing-fuselage combination at the corresponding longitudinal station, such as at AA. The shock wave and the resulting drag near the speed of sound are approximately the same for the two configurations.

On the basis of the area rule, the transonic drag increment is reduced by shaping and arranging the airplane components so that area development for the airplane more nearly approaches the shape with the lowest drag, as shown in the figure (5). The magnitude of the drag associated with such a shape is greatly reduced by increasing the overall length while reducing the maximum cross-sectional area. However, because of a number of practical considerations, the lengths and cross-sectional areas of airplanes must have certain reasonable values.
be limited to values corresponding to a body of revolution with a ratio of length to diameter of about 9.

The longitudinal developments of area for conventional subsonic airplanes differ very greatly from the ideal shape and, as a result, the maximum transonic drag for such airplanes may be as much as 10 times subsonic drag values. The various wing features used for delaying and reducing the transonic characteristics, sweep, thinner sections, lower aspect ratios usually result in airplane area developments more nearly approaching the most satisfactory shape. (See figure (5).) Consequently, the transonic drag for such airplanes is reduced to roughly three times the subsonic level.

The area developments for some transonic and super- sonic airplanes have been made to approach the shape for lowest drag by specially shaping the fuselage. Such a shaping has been provided through the subtraction of fuselage volume in the region of the wing and tail, as well as by the addition of volume ahead and behind these surfaces. The transonic drag for airplanes with such shaped fuselages is as low as twice the subsonic values. The area development may also be improved by specially locating external bodies such as engine nacelles.

The jet engines used to power transonic airplanes have been placed in various locations; within the fuselage or wing, in housings flush to these components, or on struts attached to these elements. Each location offers certain individual aerodynamic and structural
advantages. For transonic airplanes, intakes for the air to the engine are usually of simple streamlined forms.

RTW: mbb
10-21-59
BIBLIOGRAPHY


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

Figure 1.- Schlieren photograph of flow about airfoil section at low transonic speeds.

Figure 2.- Shock waves about airplane near the speed of sound.

Figure 3.- Effect of wing sweepback.

Figure 4.- Area rule comparison.

Figure 5.- Longitudinal area developments for various types of airplanes.