RESEARCH AT HIGH SUPERSONIC SPEEDS

by

10- BY 14-INCH SUPERSONIC WIND TUNNEL

A. Fundamental Properties of Flow About Bodies and Wings, and
Flow Through Channels

For the first part of our program, we would like to discuss,
briefly, some of the fundamental properties of air flow about
bodies and wings, and air flow through channels. It is, of course,
necessary to understand the flow about bodies and wings in order
to design aircraft suitable for flight. It is also important to
understand flow through channels or wind tunnels since such
devices provide the most effective means of experimentally solving
these design problems. We will concern ourselves with air flows
from low subsonic speeds up to supersonic speeds many times
greater than the speed of sound. The speed of sound is signifi-
cant because it is the speed at which pressure disturbances
travel outward from a moving object.

First we will consider flow about bodies. We have chosen
for discussion a shape similar to a high-speed bullet since it
is typical of the nose section of a body required for flight at
subsonic as well as supersonic air speeds. We will consider
only the effect of changing speed while holding the scale of
the flow, that is the Reynolds number, constant. The first
chart illustrates the flow at subsonic speeds as it would appear
to us if we were moving along with the body.

You will notice that at low subsonic speeds the presence of the body does not alter the streamlines or flow paths of the air particles very far in the lateral direction. They are, however, distorted some distance in front of the body. We may think of the air in this case as being incompressible. The boundary layer, that region immediately adjacent to the surface where air-friction effects are most pronounced, is thin compared to the body diameter, and the low energy wake is relatively steady. At intermediate subsonic speeds the compressibility of air begins to influence the flow. In the lateral direction the streamlines are more distorted but the distortion ahead of the body is decreased. The boundary-layer thickness has increased and the wake has become somewhat unsteady.

At high subsonic speeds the lateral distortion of the streamlines becomes even greater and the distortion ahead of the body becomes even less. The boundary layer is considerably thicker, and the wake becomes very unsteady. At these speeds a more pronounced effect of the compressibility of air appears in the form of the shock waves at the rear of the body. These waves may be attributed to the occurrence of local regions of supersonic flow near the rear of the body. The shock waves are the mechanism by which the air is decelerated back to subsonic speeds. Physically they cause sudden changes in pressure, density, and flow velocity.

Summarizing briefly then, as the speed increases through the subsonic range the lateral distortion of the streamlines

increases while the distortion ahead of the body decreases.
The boundary-layer thickness and the unsteadiness of the wake
both increase, and finally the shock waves appear. These
phenomena, particularly the latter two, account in a large part
for the difficulties encountered in flight at near-sonic speeds,
including the now familiar increase in drag, or resistance of
the body to forward motion.

We will now turn our attention to the behavior of air
flowing about the body at supersonic speeds. At low supersonic
speeds a shock wave is formed at the nose. As the body is
moving faster than the compression disturbances it creates,
these disturbances cannot move ahead of the body and therefore
they coalesce to form the shock wave. The streamlines are not
distorted ahead of this shock wave as the region where the flow
is influenced is now entirely behind this wave. The boundary
layer is somewhat thicker than in the case of subsonic flow.
The air expands around the base of the body and forms a converg-
ing and then diverging wake, which is characteristic of a super-
sonic stream decelerating to rest. A trailing shock wave forms
approximately at the minimum section of the wake due to the
deflection of the main air stream by the diverging wake.

At intermediate supersonic speeds the inclination of the
nose shock wave decreases. This decrease results because the
body's speed is now even more in excess of the propagation
speed of the disturbances. The lateral extent of the region
where the flow is influenced is reduced. The boundary-layer

thickness increases further due to the increase in friction forces at the surface. In addition, the minimum section of the wake moves closer to the base of the body and the trailing shock wave has a much reduced inclination.

At high supersonic, or hypersonic, speeds where the speed of the body is far in excess of the speed of sound, the nose shock wave has such a reduced inclination that it lies almost along the surface and becomes intermixed with the boundary layer to form what is sometimes referred to as a hypersonic boundary layer. The body's effect on the air is now confined to a region very close to the surface. The pressure in the wake has been reduced to near vacuum.

Again summarizing briefly, as the speed of the body increases through the supersonic range, the nose shock wave decreases in inclination confining the region where the flow is influenced closer and closer to the surface. This region is eventually restricted to the hypersonic boundary layer. The pressure in the wake decreases and at high supersonic speeds approaches a vacuum. Although we have confined our discussion to flow about a body, similar phenomena occur in the flow about wings.

Formation of the hypersonic boundary layer indicates an increased effect of friction forces at high supersonic speeds. This increase is one of the most important problems encountered as the flow speed increases through the supersonic range. We can show its importance by studying the effect of friction on

the efficiency or lift to drag ratio of a wing. The lift-drag ratio of two representative wings is plotted on this chart for various angles of attack. The solid curve at low supersonic speeds is faired through data obtained for one wing in the Ames Laboratory 1- by 3-foot supersonic wind tunnel at one and one-half times the speed of sound. The solid curve at high supersonic speeds is faired through data obtained for the other wing in the Langley Laboratory 11-inch hypersonic wind tunnel at seven times the speed of sound. These curves, of course, include friction. The dashed curves represent the highest ratios that can theoretically be obtained in the absence of friction. The reduction in the maximum lift-drag ratio caused by friction at low supersonic speeds is only about 15 percent, whereas, at high supersonic speeds it is about 35 percent. This increased effect of friction at high supersonic speeds is serious because it represents an increase of about 50 percent in the power required to carry a given load.

We have discussed the changes in the flow about a body or wing from low subsonic to high supersonic speeds. Now let us consider the changes in the shape of channels or wind tunnels used to produce these speeds. In a nozzle designed for subsonic speeds the maximum or test speed occurs at the section of mini- mum cross-sectional area, as shown in the top diagram. To increase the test speed, the speed of the driving fans is increased. A fundamental change must be made in the shape of the channel to produce supersonic flow. The maximum or test

speed will no longer occur at the minimum section, but rather downstream of this section at an expanded area. The speed can no longer be varied by varying the speed of the drive equipment but it is fixed by the ratio between the cross-sectional area of the test region and the area of the minimum section. To vary the speed, this ratio must be changed. A group of shock waves which terminate the region of supersonic flow occur in the diverging channel downstream of the test region. These shock waves produce losses in energy and therefore the power required to drive the air through the channel increases with increasing intensity of these waves. At high supersonic speeds as shown in the lower diagram, the minimum section or throat area becomes very much smaller than the cross-sectional area of the test region. To illustrate this point, the throat area in a nozzle designed to give seven times the speed of sound is less than 1 percent of the cross-sectional area of the test region. If the channel were merely diverged after the test region as in the low supersonic speed nozzle, the terminal shock waves would become extremely intense and the operating power required would become excessively high. This problem is solved by employing a converging-diverging diffuser. The air is decelerated to a moderate supersonic velocity at a second throat and then the walls are diverged again. The terminal shock waves stand downstream of this throat and occur at a speed considerably lower than the test-section velocity. These shock waves have a reduced intensity and the power required to operate the wind tunnel is therefore lowered.