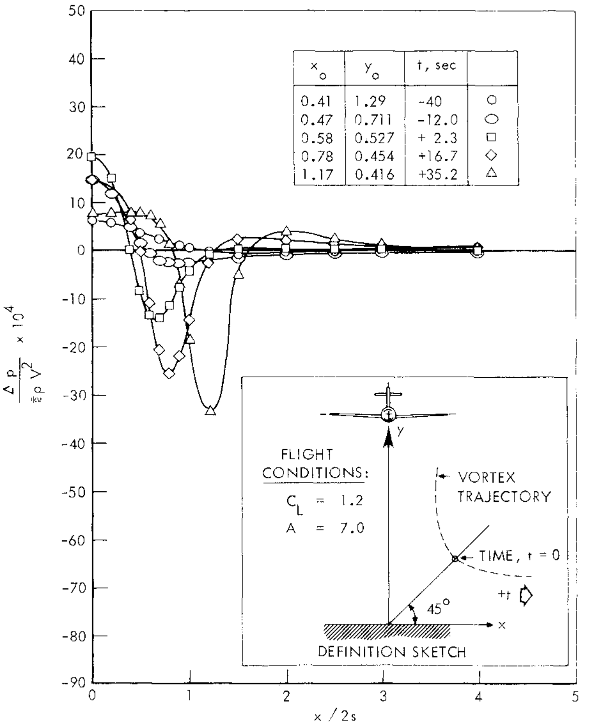

Fig. 1 Ground pressure under a symmetrical descending vortex pair.

the flight speed, lift coefficient and aspect ratio but the length scale of the pressure distribution is proportional to the span.

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Effect of Heating on Leading Edge Vortices in Subsonic Flow

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LEADING edge vortices are the primary source of lift on delta wings at high angles of attack.[1] The suction resulting from these vortices and the associated three-dimensional flow delays separation on delta wings to very high angles of attack and usually results in a relatively smooth stall for the wing. The space shuttle vehicle will employ a thick delta wing which will (like all delta wing vehicles) assume high angles of attack upon landing. A unique problem for the space shuttle, however, will occur due to the heating it will experience during re-entry. The subsequent glide and landing maneuvers will be conducted with a hot wing surface. It is therefore of interest to know how this heating from the wind surface will effect the wing's low speed aerodynamics, and in particular, the leading edge vortex.

During re-entry the shuttle wings should reach soak temperatures of 1000°F or more. To study the effects of such wing surface temperatures on a delta wing an experimental study was conducted in the Virginia Tech Six Foot Stability Wind Tunnel. An aluminum, 60° sweep, double delta wing (Fig. 1) was cast using a wood model which has been previously tested at NASA Langley Field.[2] This wing was tested in the wind tunnel using a six component mechanical balance system to avoid heating errors which would be experienced with strain gage balances. Heating was accomplished by the use of a special 70,000 BTU/hr infrared gas burner system. With this system the wing could be heated to over 600°F, making possible surface temperature to freestream absolute temperature ratios up to two.

Extensive testing was performed on the unheated wing to verify the nature of the flow and check out the balance system. Flow visualization tests showed the classic leading edge vortex formation with increasing angles of attack and a highly three-dimensional flow at higher angles.[3] Force and moment data were taken over a wide range of angle of attack and yaw angle. This data essentially duplicated that reported in Ref. 2 for the same wing.[3]

Heated wing tests were conducted by heating the wing to at least twice the absolute ambient temperature, removing the external heaters while accelerating the tunnel to the desired speed, and recording forces, moments, and wing surface temperature as the tunnel speed remained steady and wing temperature dropped. Temperature data were obtained from ten thermocouples imbedded in the wing surface. This procedure was repeated for all desired angles of attack and yaw. All tests were run at a Reynolds number of approximately 1.6 x 10,^{6} representing a speed of 148 fps.

Results and Conclusions

The primary results from the heated delta wing tests are given in Figs. 2-4 as plots of lift, drag, and pitching moment coefficient vs wing surface to freestream absolute temperature ratio for various angles of attack from 0 to 36°. All data shown are for zero yaw (the results were similar for yaw angles of 6 and 10°). It is seen that temperature ratios up to two have virtually no effect on either lift or pitching moment; however, the effect on drag is strong and increases with angle of attack. This leads to the conclusion that heating has virtually no effect on the leading edge vortices for the delta wing

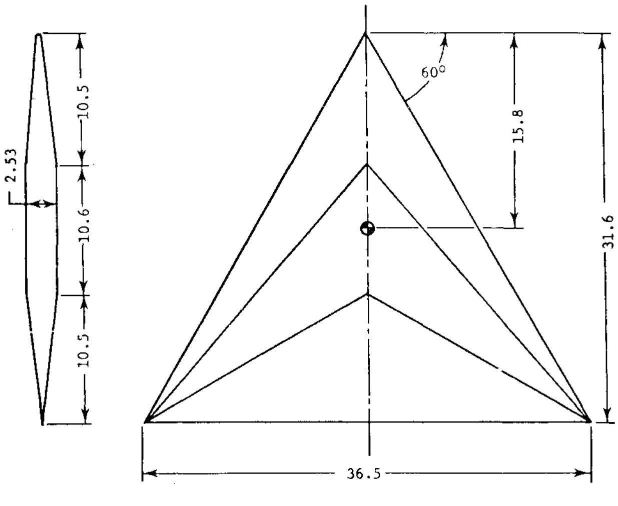

Fig. 1 Test model (dimensions in inches).

Received September 26, 1974.

Index categories: Aircraft Aerodynamics (Including Component Aerodynamics); Subsonic and Transonic Flow.

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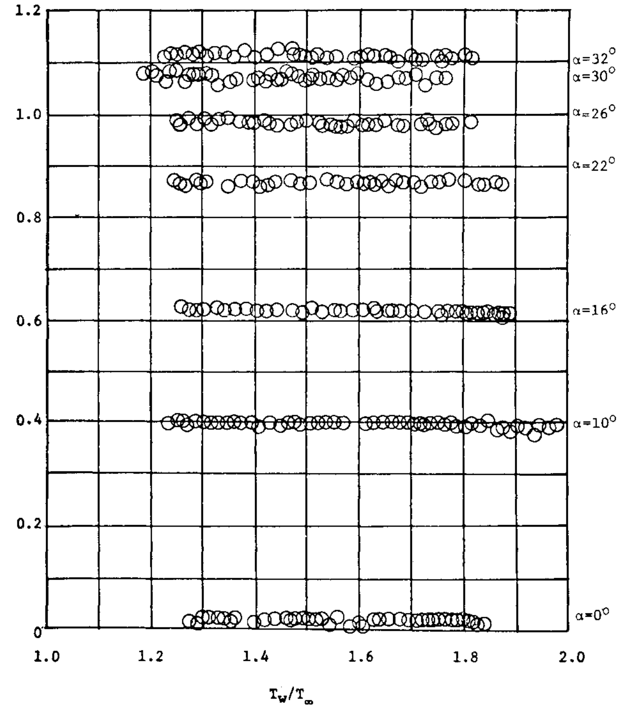

Fig. 2 Effect of surface temperature on lift, $\beta = 0°$.

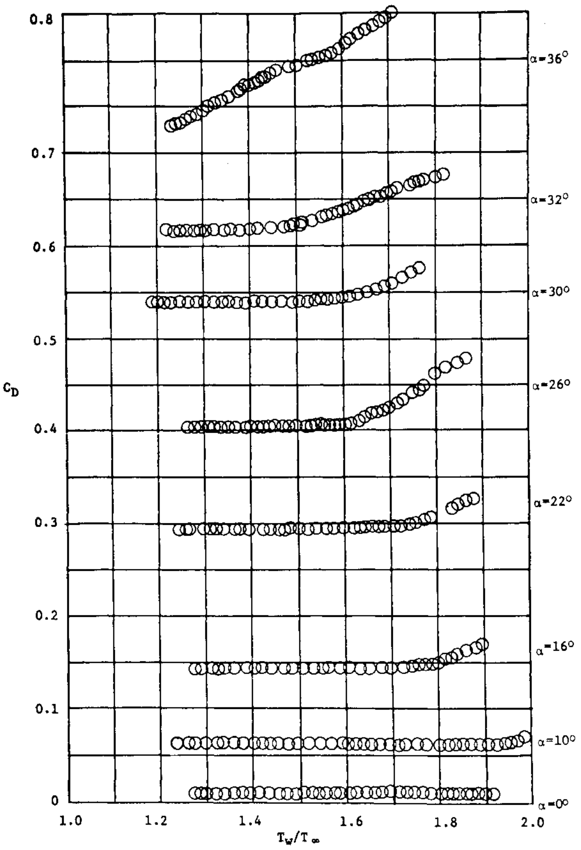

Fig. 3 Effect of surface temperature on drag, $\beta = 0°$.

tested. Since lift in particular is very dependent on the vortices at high angles of attack and there is no decrease in lift, it must be concluded that the basic vortex structure is unaltered. The fact that pitching moment is unchanged indicates that the position of the leading edge vortex on the wing does not vary significantly with wing heating. The large increases in drag are apparently due to an increased tendency for boundary-layer separation in the essentially two-dimensional region at the rear of the wing between the vortices. Two-diemnsional boundary-layer theory would predict boundary-layer destabilization with heating. This separation evidently results in increased wake size with a resulting drag increase. This drag increase causes a change in the C_L vs C_D characteristics for the wing as shown in Fig. 5.

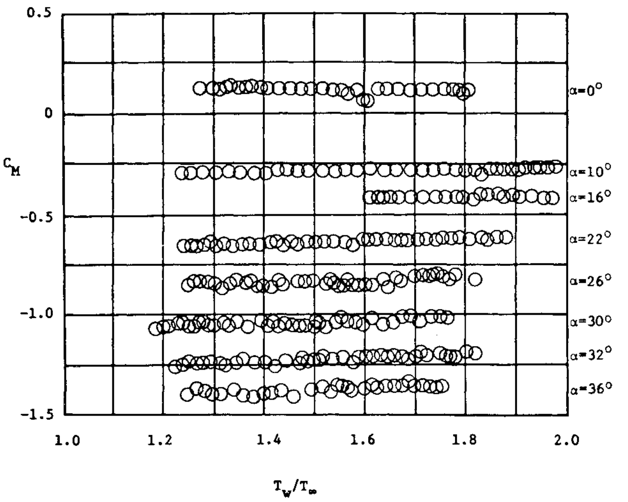

Fig. 4 Effect of surface temperature on pitching moment, $\beta = 0°$.

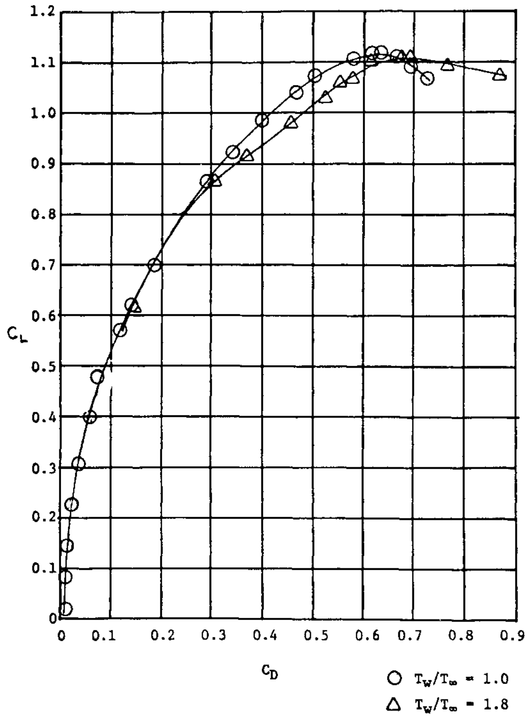

Fig. 5 C_L vs C_D.

These results are both encouraging and to a degree alarming when viewed in context of the space shuttle program. The indication that the leading edge vortices are not disturbed by the heated wing surface portends no loss of lift or stability for the delta wing vehicle after it is heated during re-entry. However, the drag change would result in drag increases up to 25% at high angles of attack such as those encountered in re-entry glide and landing.

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Aircraft Vortex Detection System Using Dual Laser Beams

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THE intense vortices generated by heavy aircraft during takeoff tend to linger over the runway on calm days or drift across adjacent runways with a cross wind. These large swirling masses of air were observed using smoke sources by Garodz.[1] Vortices are generally invisible to the human eye and can cause severe control problems for smaller aircraft attempting to land or take off.[2] Large aircraft separations are now being employed to allow the vortices to decay. This practice may be wasteful of runway use time if, for example, the generated vortices drift off quickly in a cross wind. It would appear, then, that airports are in need of a reliable vortex detection system which is relatively simple, is insensitive to runway heating effects, and does not interfere with visibility or normal airport functions. This Note reports laboratory experiments on a vortex detection system that may meet most of these requirements.

Funk and Johnston[3] have proposed an optical vortex detection system dependent upon the deflection of individual laser beams that cross the runway. In order to sample the complete length of the runway it was proposed that a series of beams be used between towers that line both sides of the runway. The vortex detection system reported in this note differs from that of Ref. 3 in two important ways. First, the laser beams are to be directed along the length of the runway, and second, the laser beams are to be used in pairs to detect the difference in the deflection of these beams. These changes make the dual beam system less susceptible to runway heating effects and they eliminate the need for towers along both sides of the runway.

The experimental system used in this study consisted of two parallel laser beams, each about 1 mm in diameter, which were relayed down the center of a wind-tunnel test section (see Fig. 1). A 2-mw helium-neon laser located at the wind tunnel entrance was used to produce the two beams of equal intensity by passing the laser output beam through a beam-splitter. The two beams were positioned in a horizontal plane just below a horizontally held NASA 65_3-618 airfoil with a chord of 9.5 cm and a span of 25 cm. One end of the airfoil was fastened to the tunnel wall while the free end shed the vortex approximately in the center of the wind tunnel. The lateral position of the two beams was adjusted so that the midpoint between the two beams was located at the center of the trailing vortex. The location of the trailing vortex within the wind tunnel was determined by a velocity traverse and was confirmed by smoke visualization tests.

At the end of the test section a system of plane mirrors, shown as a single long mirror in Fig. 1, deflected the two beams out of the wind tunnel approximately 370 cm behind the airfoil and directed them to an optical receiver composed of a photomultiplier, a pair of knife edges, and a light filter. At the optical receiver, the two beams of light first encounter two knife edges that faced in opposite directions, thereby blocking off about half of each beam. The remaining light which passed by the two knife edges was focused by a positive lens through a pinhole mask and a narrow-band optical filter whose transmission was centered at the 632.8-μm wavelength of the laser. The light then illuminated a photomultiplier tube. The purpose of the pinhole mask and filter was to minimize room light and to avoid saturation of the photomultiplier. The total amount of light that passed by the knife edges and reached the photomultiplier tube was proportional to the anode current which was measured with a slow response micro-micro ammeter.

The optical beam alignment was made while the tunnel was not in operation. The knife edges were then adjusted to block half of each beam. The ammeter reading, I_0, for the no-wind reference conditions was carefully noted. When the wind-tunnel fan was turned on, producing a mean velocity of 13.7 m/sec in the tunnel, the ammeter reading increased above I_0 and remained higher as long as there was air flow in the wind tunnel. The ammeter reading returned to the same initial value when the air flow was reduced to zero. When the airfoil was removed from the tunnel, the photomultiplier current was essentially the same whether or not there was air flow in the tunnel. Typical current readings as a function of the lateral beam separation for a 10° angle of attack are shown in Fig. 2. It can be seen that there is a measurable increase in the photomultiplier current due to the wing tip vortex. This current increase is shown to be strongly dependent on the lateral separation between the two laser beams.

The response of the dual laser beam detection system to thermal convection was tested by inserting a 750 w hot plate into the wind tunnel directly beneath the airfoil assembly. For these tests the airfoil was removed and there was no air flow in the wind tunnel. The 15 cm diam hot plate, which was located about 14 cm below the dual laser beams, produced a strong vertical thermal plume that visibly perturbed the light that traversed it. The photomultiplier current, however, was not affected by the presence of the hot plume, as shown in Fig. 2.

When one of the two beams was blocked off completely, the resulting single beam system showed a substantial change in the photomultiplier output due to the presence of the hot plate. The normalized current, I/I_0, for the single beam system varied from 1.02 to 1.05. This is considerably greater than the dual beam response shown in Fig. 2.

The optical vortex detection system works on the same principal as the schlieren system, i.e., the principal of light refraction. The individual laser beams act as schlieren system beams which are cut off by their own knife edge. Because of the orientation of the knife edges shown in Fig. 1, changes in the amount of light that is allowed past the knife edges can occur only when the light beams are deflected in the vertical plane within the wind tunnel. Vertical deflections in the light beam are, of course, caused by vertical density gradients along the path of the light beam. When both beams are deflected in the same direction, for example vertically, one beam is cut off more and the other less because the knife edges are facing in opposite directions. As a result, there is little net change in the total amount of light reaching the photomultiplier, and no change in the ammeter reading. If one beam deflects up and the other deflects down, then both beams experience the same change at the knife edges (for example, both may be cut off less), and a net change would result in the total amount of

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Received July 22, 1974; revision received September 16, 1974. Sponsored in part by the Mechanical, Industrial, and Aerospace Engineering Department.

Index categories: Aircraft Navigation, Communication, and Traffic Control.

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