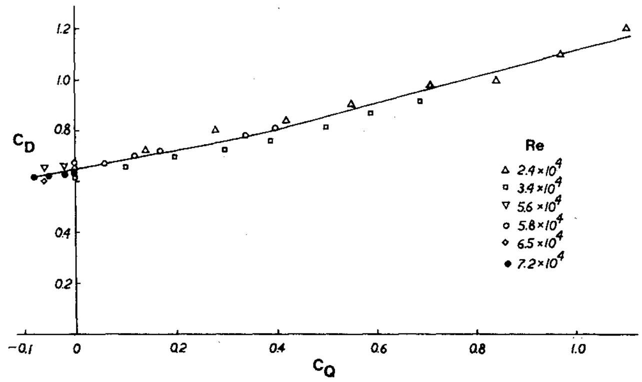

Fig. 3 Effect of suction on drag of two-dimensional model.

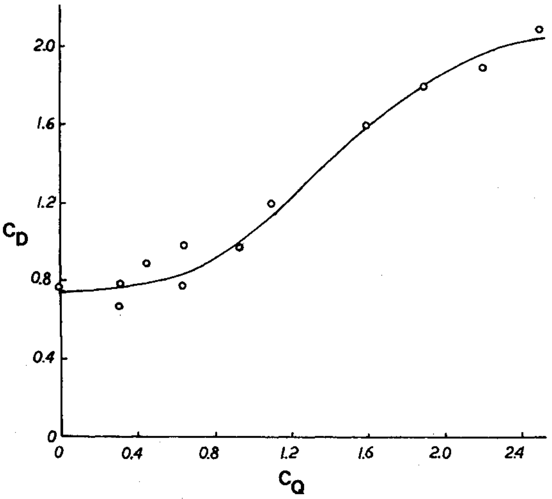

Fig. 4 Effect of high suction coefficients on two-dimensional model, $Re = 1.1 \times 10^4$.

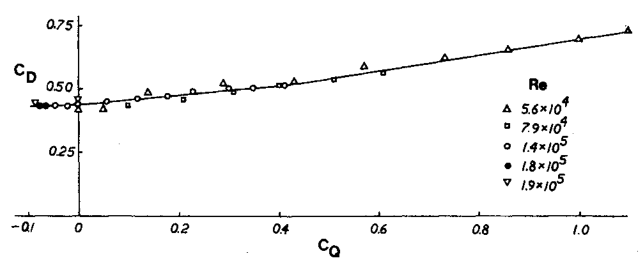

Fig. 5 Effect of suction on drag of three-dimensional model.

For the two-dimensional model, a steady increase in drag coefficient resulted as the base suction rate increased (Fig. 3). Base bleed, i.e. negative C_Q, did result in a decrease in drag, but the reduction was less than that reported by Wood. Suction coefficients larger than 1 could only be obtained for the lowest Reynolds numbers. For the two-dimensional model, the drag continues to increase for $C_Q > 1$ but at a decreasing rate (Fig. 4).

The drag coefficient for the three-dimensional model (Fig. 5) is lower than for the two-dimensional case, since the three-dimensional model has a smaller surface area relative to its base area. Thus the skin friction contribution is much less for the three-dimensional model. Again base suction causes a drag increase but at a lower rate for suction coefficients less than 1. However, for higher values of C_Q (Fig. 6) the drag increases more rapidly than for the two-dimensional model.

Conclusion

These tests show that base suction always results in a drag increase. However, at the Reynolds numbers tested, a clearly defined shed vortex is not produced. At lower base Reynolds numbers, where a distinct Karman vortex street is present, vortex trapping by base suction may indeed produce drag reduction.

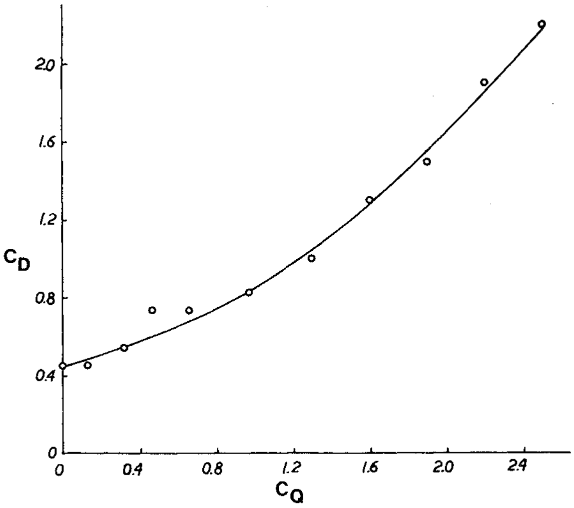

Fig. 6 Effect of high suction coefficients on three-dimensional model, $Re = 2.5 \times 10^4$.

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Pressure Distribution on a Symmetrical Butterfly Wing

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I. Introduction

THE mild ogee wings are the planform of the lift surfaces frequently used in aerospace vehicles flying at supersonic and hypersonic speeds. The characteristics of these wings are:

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symmetrical planform with respect to the centerline chord, small aspect ratio of the order of $A\!\!R_0 = 1.0$, small sweepback, and small profile thickness. All these geometrical characteristics are imposed by the conditions at supersonic flight. However, it is to be noted that almost all aircraft are required to fly at subsonic speeds for landing and takeoff, during which higher lift coefficients are needed. For this reason, the supersonic wings such as delta, gothic, mild ogee, etc. are often studied in subsonic flows.[1-6]

The lifting effect of these wings can be increased during the takeoff and landing by using variable-geometry circular sectors placed on each leading edge starting at about middle point of the basic wing. In this way, a butterfly wing form with an aspect ratio of about $A\!\!R = 3$ is obtained. The two mobile sectors always keep the same form of the leading edge of the basic wing.

For the wings with a small aspect ratio, the lift and the pitching moment are nonlinear functions of the incidence angle. This nonlinear dependence increases with decreasing aspect ratio. The nonlinear dependence can be divided into linear and nonlinear parts. The linear part is associated with the flow around an aerofoil which is studied in the thin wing theory. The nonlinear part is associated with the effects of flow separation at the leading edge and the formation of two vortex sheets detaching on the upper surface. The influence of the form of sharp leading edge on the nonlinear part of aerodynamic characteristics is also well known.[2] From an aerodynamical point of view, the new wings can be studied satisfactorily by using the methods of the linear theory of lifting wings.[7,8]

II. Experimental

The mild ogee wing with aspect ratio of $A\!\!R_0 = 1.0$ and with two circular sectors having $c_s/c_0 = 0.5$ is shown in Fig. 1. The unfolding angle of the sectors can be chosen in such a way to obtain a maximum aspect ratio for the butterfly wing. From the definition of the aspect ratio, it can be expressed as a function of ϕ angle as

$$A\!\!R = f(\phi) = b^2/S = b^2/(S_0 + R^2\phi) \tag{1}$$

where b and S are the total span and lifting surface of the butterfly wing, respectively, S_0 is the lifting surface of mild ogee wing, R is the radius of the sector, and ϕ is the unfolding angle at the center of circular sector.

If σ is the auxiliary surface of the two sectors, then

$$S = S_0 + \sigma \tag{2}$$

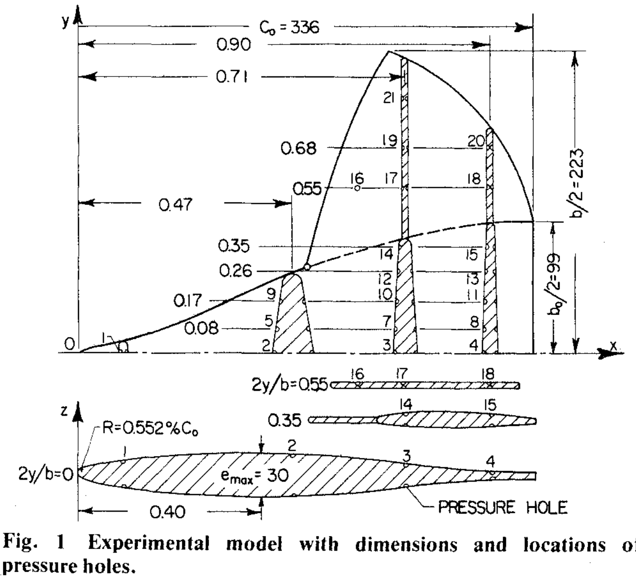

Fig. 1 Experimental model with dimensions and locations of pressure holes.

Using the curves of $A\!\!R = f(\phi)$ and $\sigma/S_0 = f(\phi)$ in Fig. 2, the butterfly wing with a maximum aspect ratio of $A\!\!R = 2.9$ and an additional lifting surface of $\sigma/S_0 = 0.77$ is obtained. These values correspond to an unfolding angle of $\phi = 60$ deg.

The experimental model of the mild ogee wing is fabricated by using Bio-plastic and aluminum profiles of NACA 65-009 modified starting at $x/c = 0.8$ to the trailing edge (see Fig. 1). This modification was necessary to install and connect plastic tubes to pressure holes as well as to reduce the premature separation of the boundary layer near the trailing edge. In fact, it is well known that, at the trailing edge, the boundary layer modifies the profile in such a way as to produce an open layer – a phenomenon which explains the difference between the theoretical and experimental pressures. By modifying the NACA 65-009 profile starting at 80% of the centerline chord toward the trailing edge, the boundary-layer thickness on the major part of the profile is reduced; hence, the difference between the theoretical and experimental pressures is reduced to a minimum and the modification has given an added advantage. For the model, $(b_0/2)/c_0 = 0.3$ where b_0 is the total span and c_0 is the centerline chord of the mild ogee wing. The two circular sectors were made of 3-mm plexiglas sheet, with rounded leading edges. In order to measure the static pressures on the wing, several pressure taps and connecting tubes were prepared; on three sections, namely at $x/c_0 = 0.47$, 0.71, and 0.90, also at seven sections of the span, namely at $2y/b = 0.0$, 0.08, 0.17, 0.26, 0.35, 0.55, and 0.68 the static pressure holes were drilled on the mild ogee wing, 14 of them on the upper surface, 14 on the lower surface of the profile as shown in Fig. 1. An additional 14 static pressure holes, seven on each side, were used to measure the pressure distribution on one of the circular sectors. All the measurements were taken first with the mild ogee wing and then with the butterfly wing for angles of incidence from −14 to +30 deg with 2 deg increments, at a constant flow velocity of $U_\infty = 43$ m/s.

III. Results and Discussion

The local pressure coefficient is defined as

$$C_p = (p - p_\infty)/\tfrac{1}{2}\rho_\infty U_\infty^2 \tag{3}$$

where p, ρ, U_∞ are the pressure, mass density, and velocity respectively and the subscript ∞ indicates unperturbed flow outside the boundary layer.

The pressure distribution along the span, $C_p = 2y/b$, is shown in Fig. 3 for $\alpha = 20$ deg and $x/c_0 = 0.71$. It can be seen that the pressure distribution is more uniform on the butterfly wing than on the mild ogee wing. It is noted that for the same conditions the lift increases with increasing span, which is an indication of the importance of the sectors in the subsonic range. By using these pressure distributions, the local lift coefficient can be calculated as

$$C_{zl} = \frac{1}{c}\int_0^c (C_{pi} - C_{pe})\,\mathrm{d}x \tag{4}$$

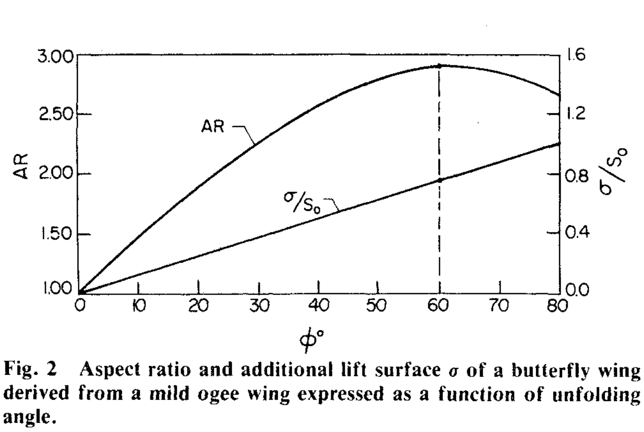

Fig. 2 Aspect ratio and additional lift surface σ of a butterfly wing derived from a mild ogee wing expressed as a function of unfolding angle.

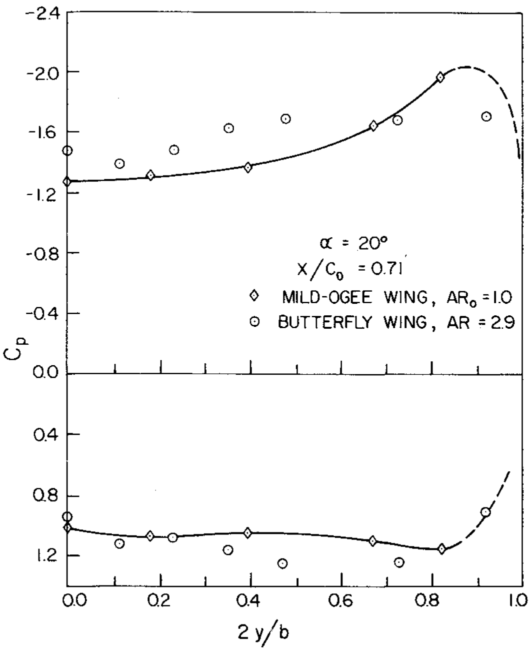

Fig. 3 Presure coefficient along the span at the section $x/c_0 = 0.71$ and incidence angle of 20 deg for mild ogee and butterfly wings.

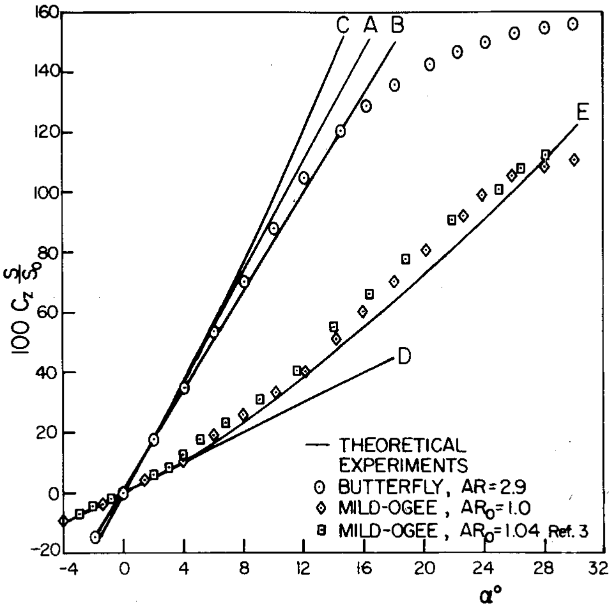

Fig. 5 Total lift coefficient as a function of incidence angle: (A) butterfly wing, linear method[7]; (B) butterfly wing, potential flow[5]; (C) butterfly wing, potential flow and vortex lift[6]; (D) mild ogee, potential flow[5]; (E) mild ogee, potential flow and vortex lift.[6]

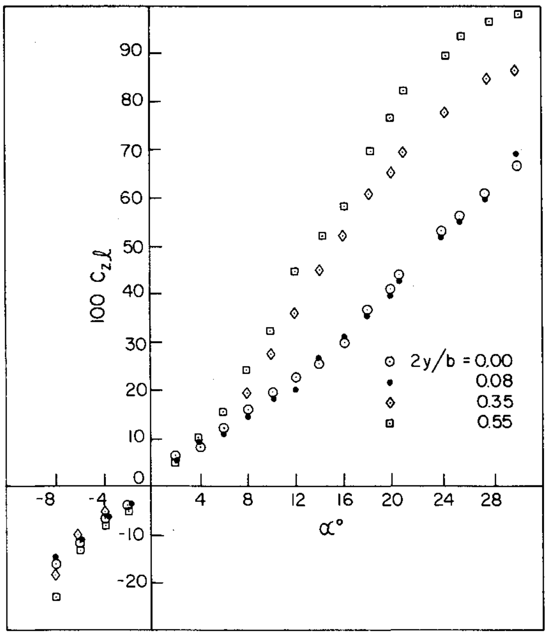

Fig. 4 Local lift coefficient as a function of incidence angle.

The results of this calculation for four sections are presented in Fig. 4, which shows that the local lift coefficient of the other sectors is much higher than that of other sections.

The total lift coefficient is calculated by integrating C_{zl} along the total span of the wing. In order to show the advantages of a butterfly wing in comparison to a basic mild ogee wing, the lift coefficients versus incidence angle for both wings are presented in Fig. 5, where the increase of the lift surface of the butterfly wing is accounted for by using 100 $C_z S/S_0 = f(\alpha)$. It should be noted that the lift is increased due to an increased aspect ratio from $AR_0 = 1.0$ to $AR = 2.9$, as well as to an increased lifting surface from S_0 to $S = 1.77\ S_0$. The lift coefficients are calculated using the linear theory,[7] the potential flow theory,[5] and the potential flow and vortex lift theory,[6] and are shown in Fig. 5 for the mild ogee and butterfly wings. It can be seen that all three methods give satisfactory results for the butterfly wings with a medium aspect ratio at small incidence angles and that the potential flow and vortex lift theory gives a good agreement in the case of mild ogee wing with small aspect ratio. It can also be seen that at incidence angles of takeoff and landing, $\alpha = 18 - 21$ deg, an almost twofold increase in lift can be obtained with butterfly wings in comparison to basic mild ogee wings. It is clear that utilization of an additional lift surface such as described in this paper does not cause a technological problem and can easily be adapted in an existing supersonic aircraft by using a flexible sheet for the part corresponding to the sectors.

Acknowledgment

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