Surface Flowfield Induced by the Turbulent Boundary Layer on a Yawed Cone

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THE problem of the three-dimensional turbulent boundary layer over a supersonic vehicle can be approximated by using a yawed cone for that vehicle. Owing to the great development of computers, many numerical analyses have been developed based on various assumptions, the validity of which has to be demonstrated by experiment.

The present work is devoted to the experimental determination of the limiting streamlines at the surface of a 23 cm length, 9° half-angle cone. The model is sting mounted in the supersonic I.M.F.M. blowdown wind tunnel at nominal Mach number M_∞ of 4.95. Stagnation temperature T_{o_∞} of 370 K and stagnation pressure p_{o_∞} of 13 bars were used giving a freestream unit Reynolds number Re_∞ of 2.46×10^5 cm^{-1}. The cone support is held from a side wall with an automatic gear for setting it at incidence about 0.1 sec after the beginning of the run. The surface flow is visualized by oil film technique[1] and the limiting streamline angle α_p is measured from the recording of the traces by developing the cone surface on an absorbing paper after the run. In order to make the measurements more accurate, the α_p value at a point located by the distance x from the cone apex and the circumferential angle ϕ from windward generator, was taken equal to the average of the measured values within the area limited by $x \pm 1.5$ cm and $\phi \pm 5°$.

The surface flow angle has been measured at $x = 20$ cm for the range of incidence angles, i, from 0°–18°. A previous study had shown that the end of transition occurs at a maximum distance x of 15 cm on the windward side of the cone.

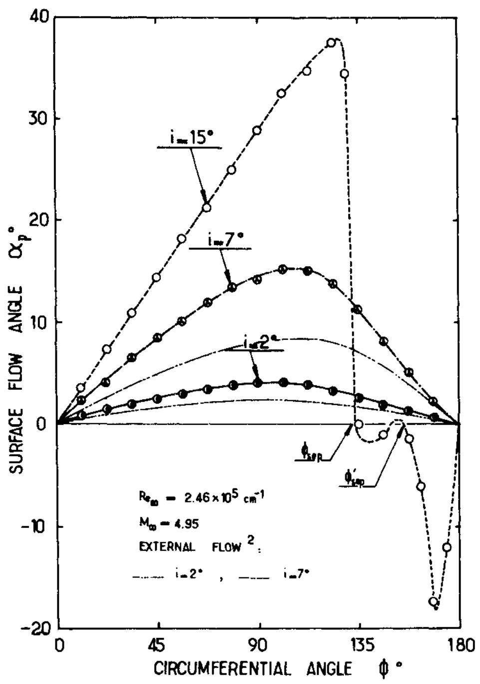

Fig. 1 Limiting streamline direction.

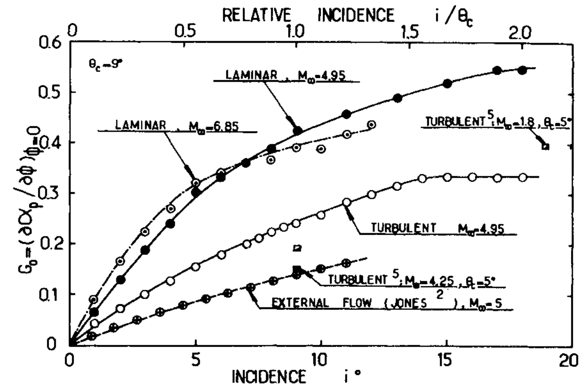

Fig. 2 Evolution of $(\partial\alpha_p/\partial\phi)_{\phi=o}$ with incidence angle.

Typical examples of the circumferential distribution of limiting streamline angle are presented in Fig. 1. The corresponding data obtained by interpolating the results of the inviscid flow computations conducted by Jones[2] are also shown in this figure. For a small incidence, below 5°, the absolute value of the gradient $\partial\alpha_p/\partial\phi$ is maximum at both windward and leeward generators. In the case of a higher incidence but less than 10°, this gradient no longer has a maximum absolute value at the leeward generator, which implies that $\partial^2\alpha_p/\partial\phi^2 = 0$ at an azimuth found to be within the range $135° < \phi < 155°$. With respect to inviscid results, it is interesting to note that $(\partial\alpha_p/\partial\phi)_{\phi=\pi}$ is maximum whatever the incidence may be.

With an increasing incidence, the gradient $(\partial\alpha_p/\partial\phi)_{\phi=\pi}$ decreases to zero obtained for the separation value i_{sep}. Beyond the separation incidence (i.e., $i = 15°$), the turbulent boundary layer is separated, according to the criterion $\alpha_p = 0$ proposed by Eichelbrenner and Oudart.[3] The separation line seems to be directed along a cone generator, at least over the distance concerned by turbulent measurements (8 cm). The surface flow pattern between the separation line and the leeward generator results from the vortical flow previously described,[4–7] with essentially divergent streamlines from the $\phi = \pi$ generator ($\alpha_p < 0$) and a secondary separation which occurs also along a cone generator.

The main purpose of the present study is to provide the evolution with incidence of characteristic parameters of surface flow angle. These parameters are given in both laminar and turbulent cases, by using the results of identical measurements obtained under laminar conditions ($Re_\infty = 0.68 \times 10^5$ cm^{-1}).

The gradient $G_o = (\partial\alpha_p/\partial\phi)_{\phi=o}$, related to the coefficient K_o computed by Jones for an inviscid flow by $G_o = \frac{3}{2}\sin\theta_c K_o$, is plotted against incidence in Fig. 2. In the turbulent case, this

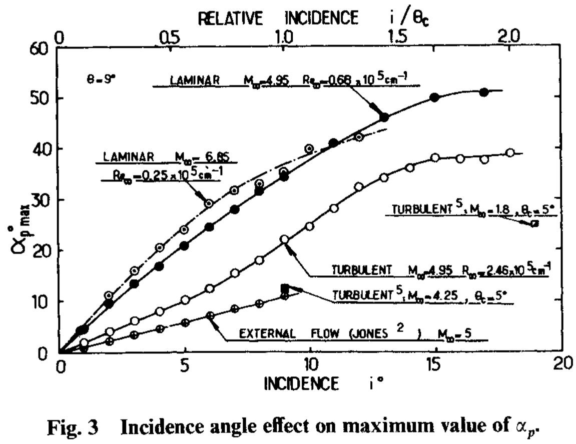

Fig. 3 Incidence angle effect on maximum value of α_p.

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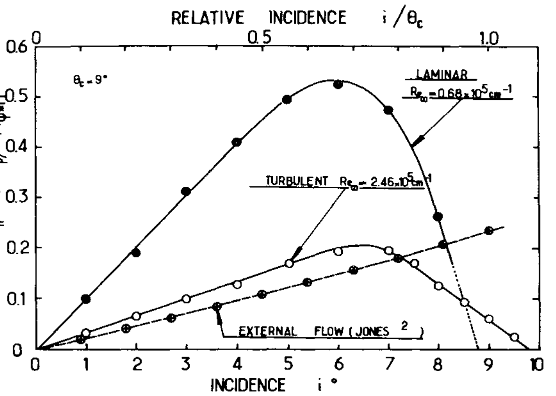

Fig. 4 Evolution of $(\partial\alpha_p/\partial\phi)_{\phi=\pi}$ with incidence angle.

parameter increases with incidence up to $i = 14°$ and becomes nearly constant beyond this value at about 0.33. The ratio of turbulent parameter G_o to the inviscid one is constant and close to 1.80 up to $i = 11°$ which is the limit value of Jones' data. The laminar values are about twice the turbulent ones and are slightly affected by Mach numbers as shown when comparing data previously obtained at $M_\infty = 6.85$, $Re_\infty = 0.25 \times 10^5$ cm^{-1} with those obtained under the present conditions.

The comparison of present results with data of Rainbird[5] for the turbulent case, shows a similar effect of Mach number. The maximum value of α_p follows the same evolution with incidence as the parameter G_o (Fig. 3). According to the results of Rainbird,[5] the Mach number effect appears to be different, whereas the present data point out a similar effect in the laminar case.

The α_p slope G at $\phi = \pi$ is particularly interesting for the determination of the separation incidence i_{sep}. Its evolution with incidence (Fig. 4), increasing linearly within $0 < i < 6°$ and decreasing linearly within $7° < i < i_{sep}$, presents a maximum value for $i = 6.5°$. Thus, the separation incidence is found equal to $9.8° = 1.09\ \theta_c$ with an accuracy estimate of $\pm 0.05°$. The laminar value obtained with less precision because of the minor frequency of measurements, is close to 8.8°, which means that the turbulent separation occurs 1° sooner than the laminar one. Furthermore, it is to be noted that the comparison between the experiments and the inviscid theory brings out a particular value of incidence angle (6°) beyond which the boundary effects are fundamental with respect to the separation phenomenon.

Finally, the separation azimuth ϕ_{sep}, deduced from the circumferential surface flow angle, decreases with incidence down to a constant value beyond $i = 14°$ (Fig. 5). This constant value seems to be slightly higher for the laminar case than for the turbulent case. In order to show the Mach number effect, some previous data have been plotted in the figure.

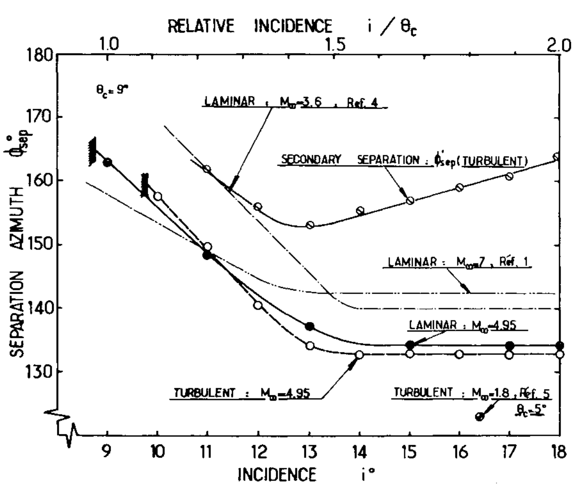

Fig. 5 Location of separation line. All data concern primary separation, except the symbol θ as indicated.

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Instantaneous Velocity Measurements in the Near Wake of a Helicopter Rotor

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A RECENT study on the near flow behind a propeller[1] has shown that the form of the mean velocities measured just downstream of the rotation plane can illustrate the significant phenomena which occur upon the blades. Such a method seemed to be applicable to a helicopter rotor wake. However, the unsteady nature of such a flow requires that the instantaneous velocities be measured.

The three instantaneous velocity components have been measured by use of a hot film wedge-shaped probe, located in the near wake of a two-bladed rotor tilted at $-10°$ as shown in Fig. 1. The untwisted blade (profile NACA 0018) has a rectangular shape. During all the tests the blade tip speed ωR (where ω is the angular frequency and R the radius of the rotor) and the wind-tunnel velocity were maintained respectively at 105 m/sec and 25 m/sec, so that the advance ratio was kept at a constant value (0.24). The sensor element of the probe was placed in the retreating blade zone at the position $0.25R$ from the rotation axis and $0.1R$ under the horizontal plane (see Fig. 1). The measurement method of the three velocity components by use of such a probe is described in Ref. 2. This method is applicable when the angle between the axis of the probe and the mean velocity direction is less than 12°. In our experiments,

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