Engineering Notes

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Effect of Air Injection into the Core of a Trailing Vortex

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Nomenclature

C_Q = mass flow coefficient, $m/\pi\rho_o U_o r_o^2$
m = mass flow through jet
r_1 = radius at which $\bar{w} = \bar{w}_1$
r_o = value of r_1 at $x = 218''(U_o x/\Gamma_o = 160)$
U_o = freestream velocity
$\bar{u}^2$ = mean square turbulent fluctuation in axial velocity
$\bar{u},\bar{w}$ = mean velocity perturbation due to vortex, in x- and z-directions, respectively
$\bar{w}_1$ = maximum value of $\bar{w}$
x = axial distance downstream of point of generation of vortex
y,z = distance along and normal to the horizontal diameter of the wind tunnel, respectively
Γ_o = maximum circulation around vortex

Introduction

THE complex radial distribution of axial velocity in the core of a trailing vortex has been well documented and distributions which are typical of wakes, jets and combinations of the two have been observed in full scale experiments.

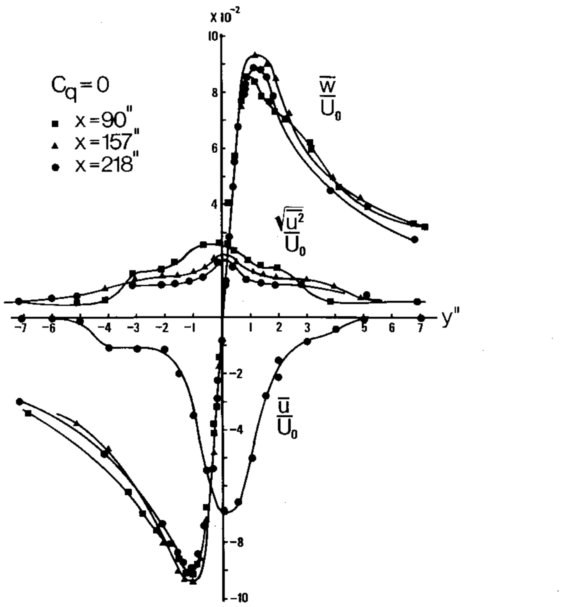

Fig. 1 Velocity distribution in core of vortex, without air injection.

The sort of distribution which occurs in the wake of any given aircraft clearly depends on the manner in which the vortex is generated, and the overall axial-momentum balance for the fluid that ultimately constitutes the core of the vortex. If some of the jet efflux is entrained in the vortex, we may expect profiles with velocities greater than freestream, while if the core consists entirely of air from the wing boundary layer, a wake-like velocity deficit is to be expected. Consequently, the axial flow in the trailing vortex in the wake of an aircraft with outboard engines may differ considerably from that of an aircraft with engines clustered near the centerline.

Solutions of the linearized equation for quasi-cylindrical laminar vortices show that the circumferential velocity distribution is independent of the axial flow (see Ref. 1, for example). It is likely that the same will be true for a turbulent vortex. The assumptions upon which such analyses are based are valid only for vortices of considerable age, however, and it is possible that, if air is injected along the axis in the early stages of the formation of the vortex, its subsequent behavior may be modified by thus changing conditions in the nascent core. This Note describes briefly some results of preliminary experiments aimed at investigating this possibility. A more complete account of this work appears in Ref. 2.

Details of Experiment

The McGill 30-in. diam blower tunnel[3] was used for the present tests, with the working section extended to a length of 21 ft.

The vortex was generated at the throat by two vanes, set at equal but opposite angles of attack, attached to the tunnel wall at one end and to a jet-pipe of $\frac{3}{8}$ in. diam on the tunnel centerline.

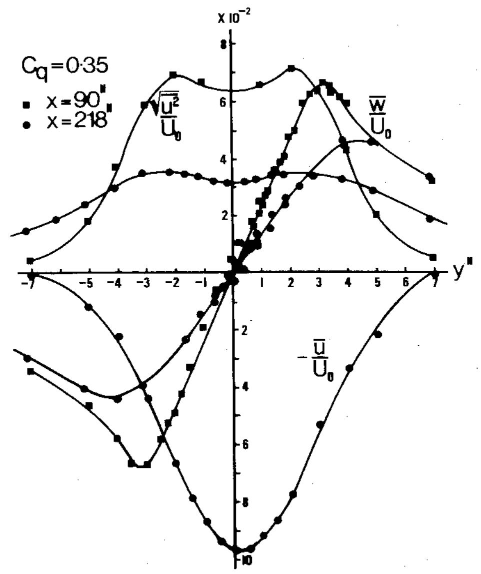

Fig. 2 Velocity distribution in core of vortex, with air injection.

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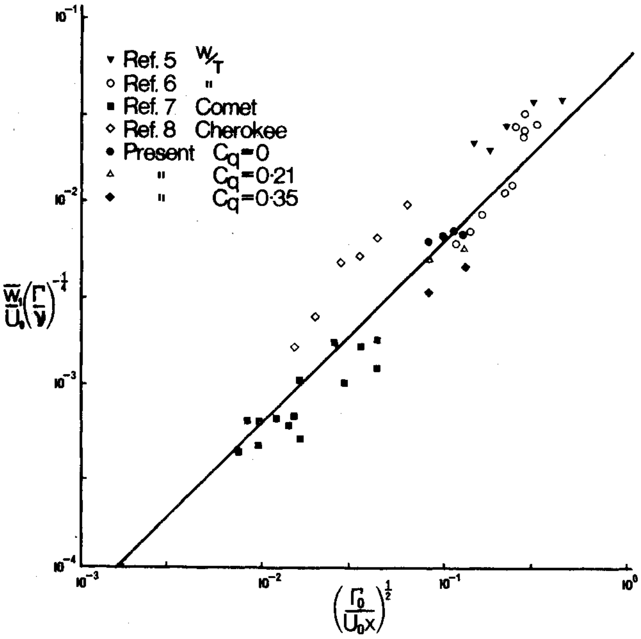

Fig. 3 Variation of maximum circumferential velocity with axial distance.

A probe, comprising a static tube, a hot-wire and a pitot tube, mounted in the vertical plane at 1-in. pitch was attached to a mechanism that allowed horizontal traverses to be made through the vortex at any required vertical position. A normal hot-wire was used to measure axial velocities and an inclined wire that could be rotated remotely about an axis parallel to the tunnel axis was used to measure the radial and circumferential components of the instantaneous velocity.

All the measurements were made with a tunnel speed of about 70 fps and with $\Gamma_o/\nu = 5 \times 10^4$.

The McGill DATAC system was used for data acquisition and reduction.

Effect of Jet Flow on Circumferential Velocity

The results of two sets of measurements are shown in Figs. 1 and 2.

Those for the basic vortex flow (Fig. 1) indicate a rather slow rate of decay of the vortex in the length investigated. The measurements at $x = 90$ in. show a rather irregular profile near the radius of maximum velocity and it is conceivable that the rolling-up process is not complete at this station. Also illustrated are the radial variation of the rms value of the axial component of the velocity perturbation at three stations, and the axial velocity defect in the core at $x = 218$ in.

The effect of blowing through the central jet pipe is shown in Fig. 2. There has been a remarkable decrease in circumferential velocity and an increase in core radius at $x = 90$ in. The rate of decay in the axial direction has been increased considerably. The turbulence has been increased by a large amount in the core and its rate of decay is correspondingly greater. The flow through the jet is admittedly quite large in this case, and it is estimated that, on a full scale large aircraft at take-off, this would be of the order of the maximum flow through a large engine, like the JT9D. The jet-like distribution of axial velocity increment is also shown in Fig. 2 (plotted with sign reversed).

Comparison with Other Work

It is interesting to see how the basic profiles obtained here compare with trends exhibited by other measurements, and how the jet flow modifies this trend.

Two sets of wind-tunnel results[4,5] are collected in Fig. 3, together with those of the present tests and some of the full-scale results of Refs. 6 and 7. They are presented in a form suggested by the work of Owen[8], and also shown on the figure is the equation proposed in Ref. 8 for the maximum circumferential velocity, in a turbulent vortex which has reached an equilibrium structure. In the present notation, this may be written

$$(\bar{w}_1/U_o)(\Gamma_o/\nu)^{-1/4} = 0.065(\Gamma_o/U_o x)^{1/2}$$

Some reasonable assumptions had to be made in reducing the results of Refs. 6 and 7 to the present form. For those of Ref. 6 a standard atmosphere was assumed, while, for those of Ref. 7 the circulation was calculated from the given data, assuming that it was the same as that at mid-span. This differed considerably from the apparent asymptotes of Fig. 12 of Ref. 7.

All the results group fairly well about the line given by the above equation, although there is considerable scatter. The four results of the present tests with no jet flow, exhibit a very low rate of decay, as mentioned above, and, taken by themselves, would indicate a very different behavior from that of the proposed equation. However, they group about the line, well within the scatter of other measurements.

The effect of blowing through the jet is effectively to 'age' the vortex prematurely. It is not possible to say anything quantitative about its subsequent asymptotic behavior, however, due to the paucity of the present preliminary results. Presumably the equation given above should again describe the flow when equilibrium has been reached.

Concluding Remarks

The presentation of results in the form shown in Fig. 3 has brought some order to measurements made over a very wide range of Reynolds number ($10^7 < \Gamma_o/\nu < 10^8$). However, the figure includes vortices at various stages of their development and a number of these have not reached the state of self-preservation assumed by Owen in deriving the above equation. As a consequence, probably most of the results should actually be represented as points on different curves which become asymptotic to the given line, as the time since the generation of the vortex increases.

The effect of injecting air into the vortex is quite marked and deserves further investigation. These investigations should attempt to separate the effect on the decay of a) increasing the turbulence of the core and b) introducing an air mass of zero angular momentum; a) and b) occurred simultaneously in the present tests.

It should be possible to design model experiments (in the McGill tunnel, for instance) which reach into the full scale range of $(\Gamma_o/U_o x)$.

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