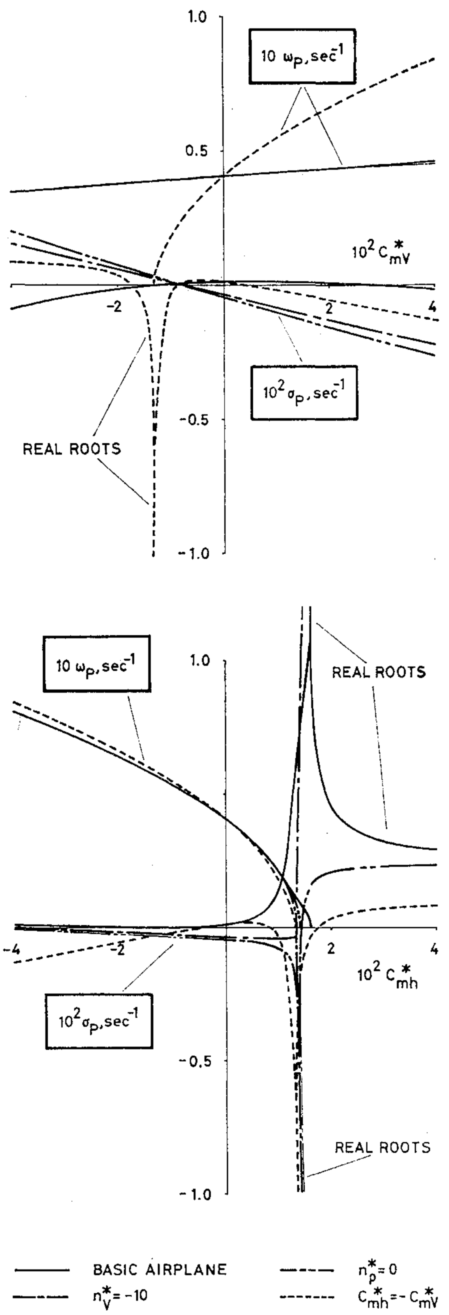

Fig. 3 Effect of C_{mV}* and C_{mh}* on phugoid mode.

It becomes very strong when $C_{mh}^* \rightarrow \beta_\rho \mu \bar{c}_h \rho_h C_L C_{m\alpha}/C_{L\alpha}$. These effects corresponding to a variation of n_V^* are also shown in Figs. 2 and 3 where $n_V^* = -10$ is equivalent to $\Delta n_V^* = -12$.

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Response of a Trailing Vortex to Axial Injection into the Core

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Introduction

TRAILING vortices behind lifting surfaces create serious problems; e.g., aeroelastic loads and noise in the case of helicopter blades, and turbulent gusts for airplanes following large aircraft. The severity of these problems is determined by the intensity and persistence of the vortices. A simple method of quickly and effectively dispersing the vorticity in these vortex cores without penalizing the performance has been the object of several investigations.[1–3] Various methods like the use of swept and porous tips (Ref. 1), twisted swept tips (Ref. 2) and vortex dissipators (small spanwise fences placed at the wing tip on the suction side—Ref. 3) have been tried with varying success. This Note describes briefly some preliminary qualitative results of an investigation into the effects of axial air injection into a vortex core. A more detailed account appears in Ref. 4.

Other investigations[5–8] on the effect of injection on vortex flows have appeared recently. Rinehart et al.[5] used a set-up essentially similar to the present one and their photographs of the vortex obtained by the hydrogen bubble technique and vorticity contours indicate that injection can indeed spread out the vorticity concentrated in the core. However his theory[6] indicates that the phenomenon is governed by the mass-flow-rate of injection contrary to our evidence presented herein that it is governed by the momentum-rate. Poppleton's investigations (Ref. 7) though not exactly on a trailing vortex core (his experiments were conducted on a swirling flow in a tube) confirm the fact that injection is effective. His measurements clearly show decreases in peak tangential velocities and increases in the size and turbulence level in the core, and the axial decay rate of tangential velocities. Monnerie and Tognet[8] have also investigated the effect of injection, not axially but vertically down along the chord at the wing tip.

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They report substantial decreases in peak tangential velocities and increases in the core size with injection. It is interesting to note that they present their data in terms of a momentum-rate parameter rather than a mass-flow parameter.

Experimental Details

Experiments were conducted in the 7 1/2 ft × 10 ft Wright Brothers Subsonic Wind Tunnel at MIT. The tip vortex was produced by a 7.75 in. × 31.5 in. rectangular wing (with symmetric NACA 0012 profile) mounted vertically on the floor of the wind tunnel. The wing had provisions for introducing smoke at the wing tip for purposes of visualizing the tip vortex. The smoke particles emerging from the tip arrange themselves in a characteristic tube-like pattern in the vortex, with the radius of the tube believed to be roughly indicative of the viscous core of the vortex. The wing also had provisions for injecting air at the tip. The exit diameter of the injection tube could be changed for independent control of the mass and momentum-rate of injection. The tip of the injection tube was adjusted such that it was approximately at the center of the vortex core. The vortex streaming out of the tip could be photographed with a sideward-looking camera. The experiments were conducted at freestream velocities of 44 fps (corresponding to Re of 1.8×10^5) and 88 fps ($Re = 3.6 \times 10^5$, where Re is the Reynolds number based on freestream velocity and wing chord). The angle of attack of the wing was kept constant at 8° and the trailing vortex core was photographed at various injection rates. The tests were also conducted with two different injection tip sizes to permit injection mass-flow rate and momentum rate to be independently varied.

Discussion of Results

Figures 1 and 2 show the trailing vortex core without ($\alpha = 0$) and with ($\alpha = 0.40$) injection. The momentum-rate parameter α is defined as the ratio of the momentum-rate of injection (or the thrust of the injection jet) to the total drag of the wing (in the present case, equal to $6.2 \times 10^{-5}\ U_\infty^2$ lbf with U_∞ in fps). It can be seen that injection has appreciably altered the appearance of the core. The edge of the core presents a familiar discrete eddy-like appearance with injection suggesting that the change may be stability oriented. The size of the core has increased and so also the axial rate of decay of the vortex, as indicated by the decrease in persistence of the vortex core. The changes in the vortex core begin to be significant at around $\alpha \approx 0.2$ and there seems to be an injection point, roughly equivalent to $\alpha \approx 0.35$, above which further increase in injection does not produce equally substantial changes in the behavior of the core. Peak vorticity measurements made with a standard vorticity-meter at various distances downstream of the vortex also indicate a decrease in peak vorticity of more than 50% at an approximate value of α of 0.35. Also increases in α beyond approximately 0.35 produce little further substantial decreases in peak vorticity. The data correlate fairly well with α.

Figures 3 and 4 show the vortex core at the same value of α (0.35), but different values of β (1.46 and 3.20), where β is the mass-flow-rate parameter defined as $\dot{M}U_\infty/\rho\Gamma^2$, where $\dot{M}$ is the mass-flow-rate of injection, U_∞ is the freestream velocity, ρ is the density and Γ is the theoretical value of circulation around the trailing vortex (in the present case $\Gamma = 0.247\ U_\infty$ ft²/sec, with U_∞ in ft/sec). The qualitative appearance of the vortex core is essentially the same. On the other hand, Figs. 3 and 5 show substantial differences in the appearance of the core at the same value of β (1.46), but different values of α (.35 and .1). Thus within the limitations of the qualitative nature of the data, the phenomenon seems to be more nearly governed by the momentum-rate of injection rather than by the mass-flow-rate.

Comparison of the present data with that of Rinehart et al.[5] shows a rough agreement in the trend of the decrease in peak vorticity with increase in α. Their data are presented in terms of dimensional mass-flow rates, some of which correspond to very high values of α. The only discrepancy appears to be the good agreement they achieve between their data and their mass-flow theory.[6] Monnerie and Tognet[8] show a reduction in peak vorticity of approximately 90% about 9 chords downstream of the tip but this is achieved with an excessively high value of $\alpha \approx 3.5$.

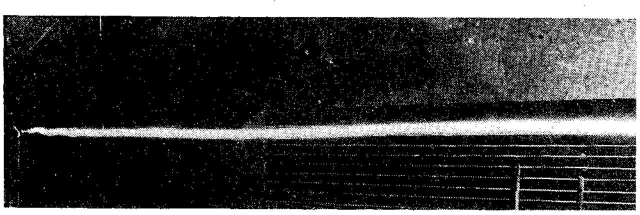

Fig. 1 Trailing vortex core without injection (momentum-rate-parameter $\alpha = 0$).

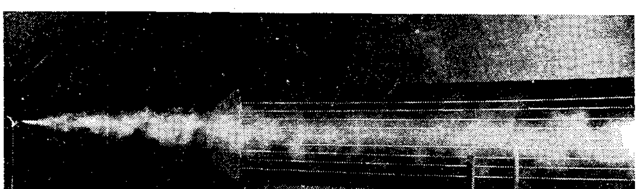

Fig. 2 Trailing vortex core with injection, corresponding to a value of momentum-rate-parameter $\alpha = 0.40$.

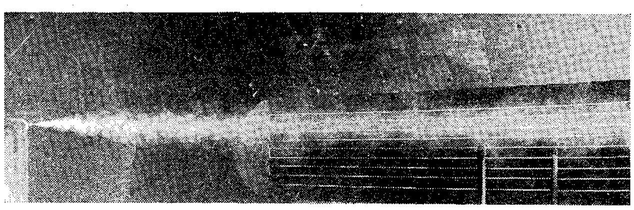

Fig. 3 Trailing vortex core with injection, corresponding to a value of momentum-rate-parameter $\alpha = 0.35$, and a value of mass-flow-parameter $\beta = 1.46$.

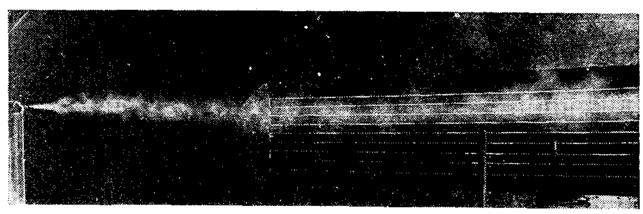

Fig. 4 Trailing vortex core with the same momentum rate of injection as Fig. 3 but for a different mass-flow-parameter $\beta = 3.20$.

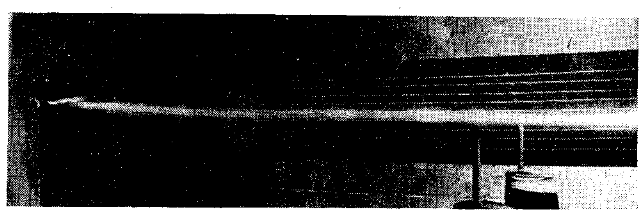

Fig. 5 Trailing vortex core with the same mass-flow-parameter as Fig. 3 but for a different momentum-rate-parameter $\alpha = 0.10$.

We believe the dispersion of the vorticity accomplished by jet injection in the present study is quite different from the phenomenon of vortex breakdown. In the vicinity of a highly loaded wing tip the tangential and axial velocities in the vortex core are of the same order of magnitude. Under this condition the vortex appears quite stable and thus persists far downstream. Vorticity diffusion can be enhanced by either sufficiently increasing or decreasing the core axial velocity. If the core axial velocity is sufficiently decelerated it is possible for downstream turbulence to propagate upstream via inertial waves to dissipate the core. Vortex breakdown represents the boundary of this upstream propagation. On the other hand, when the axial velocity is increased to be sufficiently larger than the tangential velocity, the core behaves as a turbulent jet and thus spreads relatively quickly. This latter type of diffusion is what appears to be taking place in the present experiment.

Conclusions

The present investigation demonstrates that axial injection into the core of a vortex can indeed beneficially spread out the vorticity concentrated in it and prematurely age it. It further shows that the phenomenon is more nearly governed by the momentum flux of injection than by mass flow. A suitable value of injection for which substantial changes are produced in the vortex core appears to correspond to α of roughly 0.35. Despite the relatively high value of α needed, this provides a possibly feasible way to disperse trailing vortices, since all of the injection required may be obtained by a redistribution of thrust.

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Technical Comment

Erratum: "Flight Investigation of the Influence of Turbulence on Lateral-Directional Flying Qualities"

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