18,000-lb thrust of the engine is only 2% of the momentum flux of the freestream flow. Thus, it appears that the value $C_{\dot{M}} = 0.049$ represents a jet of considerable strength. The relative strength of the vortex itself may be estimated by observing that, if the rolling moment coefficient for this aircraft were the same as that measured by the torquemeter ($\alpha_{vg} = 6°$), then a roll rate of approximately 90°/sec would result. The lateral control power necessary to cope with this roll rate under the specified conditions is $pb/2W_\infty \approx 0.05$. Since these values are representative of high performance aircraft, it would appear that the vortex is a strong one.

The conclusions to be drawn from this experiment are limited, of course, to what can be determined from measurements at a single axial station. Thus, it is not possible to gauge what ultimate effect the jet may have on the decay of the vortex far downstream; nor have the effects of the tunnel wall been assessed. Additional measurements which are now in progress should help to clarify these questions. It has been shown, however, that in spite of the modified tangential velocity profiles caused by the jet, the torque induced by the vortex on a typical wing changes very little in the near field. Unless the injected air results in a greatly enhanced diffusion of vorticity in the far field, it seems premature to conclude on the basis of changes in the velocity profiles alone that a jet is of significant value in reducing the hazard potential of a strong vortex wake.

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Effect of Several Wing Tip Modifications on a Trailing Vortex

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Introduction

AIRCRAFT trailing vortices have become of considerable interest to the aviation industry, NASA and the FAA in recent years. The jumbo jet class aircraft has forced the aviation community to take strong new precautions to avoid the consequences of wake-aircraft interaction. In this light, considerable research has been undertaken to provide a better understanding of the trailing vortex in an effort to learn means of accelerating its decay and breakup. Some recent research in this area has been that of Chigier and Corsiglia at NASA Ames[1] and Mason and Marchman at Virginia Polytechic Institute and State University.[2] It has been shown by several studies[2,3] that mass injection at the wing-tip exhibits much promise in efforts to artifically induce early vortex decay. In addition to mass injection, other studies with various wing-tip modifications have been conducted with varying degrees of success.[4,5] These modifications have included plates on the wing-tip, porous wing-tips, wing-tip drogue chutes, etc. In an effort to continue the examination of wing-tip modifications and their effect on the vortex the present study was undertaken.

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Experimental Procedure

An experimental investigation of the velocity field in the trailing vortex of a NACA 0012 wing with four different nonpower-augmented wing-tip modifications was conducted in the Virginia Tech six-foot subsonic wind tunnel. The tunnel's 28-ft-long test section permits investigation of the vortex up to 30 chordlengths downstream of the wing. Velocities were reduced from the pressure data obtained from a five-hole yawhead type pitot tube.

The wing used in the experiment was an 8-in-chord, brass, NACA 0012 wing 4 ft in length. This is the same wing used in a previous investigation reported in Ref. 2 and was mounted in exactly the same manner, hung from the top of the wind tunnel with a $7\frac{1}{2}°$ angle of attack used to produce a strong vortex. The wing was unswept and untapered and gave an effective 8-ft span with the mounting system used. All tests were run at the same angle of attack and at a dynamic pressure of 1 in. of water to permit comparison with the results of Ref. 2.

Four wing modifications as well as the plain wing case were tested. These consisted of: 1) a crossed blade (*X*-pattern), 4 in. across and 2 in. deep, fixed immediately behind the wing-tip, 2) a second crossed blade, 8 in. across and 2 in. deep, 3) the same 8 in. crossed blade attached to permit free rotation in the vortex, and 4) two, 1-in.-high fences, angled 30° relative to the wing-tip, one each placed on the upper and lower surface of the wing in such a manner as to produce a swirl which rotates counter to the normal vortex. The first two modifications were investigated and when these gave satisfactory results the third was used to test the possibility of using the blade both to reduce the effect of the vortex and to power a small auxiliary generator or other such device simultaneously.

Detailed measurements of the vortex were made using a yawhead pressure probe and a series of inclined manometers. The probe and other instrumentation was the same reported in earlier work by Mason and Marchman[2] and has been proved to be a very stable and accurate system for the investigation of trailing vortices. Measurements of the vortex were made at two positions downstream, 10 and 30 chordlengths from the wing, by first locating the vortex center and then making a vertical traverse through the entire vortex. All data were then reduced to tangential, axial and radial velocity components assuming incompressible flow and a constant static pressure throughout the vortex. Although the constant static pressure assumption may lead to errors in the axial velocity calculations, as pointed out by Marchman[6] it was felt that since the present tests were for comparative purposes only, the tedious static pressure measurements could be omitted.

Results and Discussion

The data from the investigation is presented in Figs 1–4 as plots of tangential and axial velocities at both 10 and 30 chordlengths downstream of the wing. Figure 1 shows

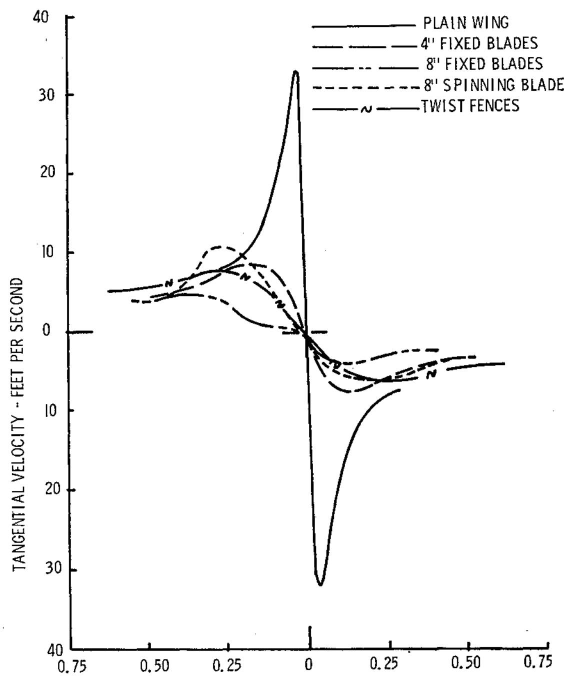

Fig. 1 Tangential velocity profiles 10 chordlengths downstream.

the tangential velocity profiles at 10 chordlengths for the plain wing and the four modifications. Figure 2 gives the same plots at 30 chordlengths downstream. In these figures one notes that all the modifications exhibit the same basic effect of reducing the maximum tangential velocity and spreading the core of the vortex. The spinning blade has the least effect on the maximum tangential velocity but appears to spread the core as well as the other devices. The large crossed blades, the fences, and the small blades gave the best reductions in tangential peak velocity in that order. In all cases the tangential velocity peaks tended to decay slightly between the 10 and 30 chordlength positions. In all cases the tangential velocity profile returns to the plain wing case at large radii since the wing circulation is conserved. There is also a slight tendency for the core to spread as the vortex goes downstream. It should be noted that the plain wing case prefectly matches that found on the same wing by Mason and Marchman[2] indicating the repeatability and accuracy of the experimental system.

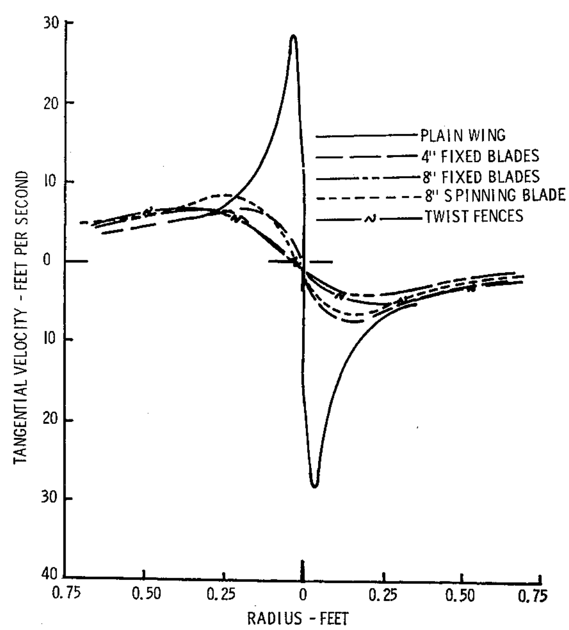

Fig. 2 Tangential velocity profiles 30 chordlengths downstream.

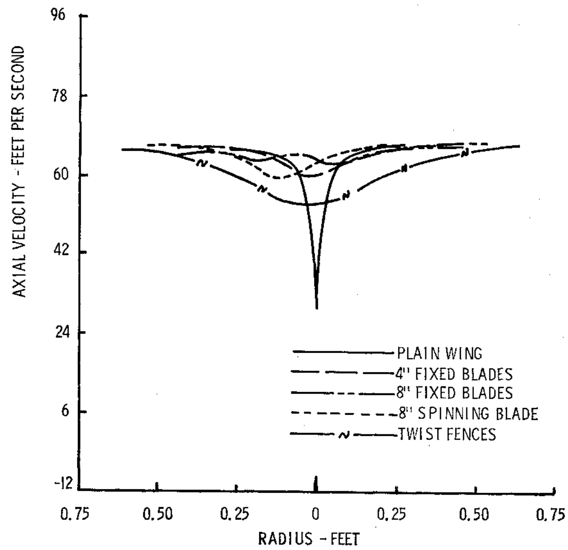

Fig. 3 Axial profiles at 10 chordlengths downstream.

The axial velocity profiles shown in Figs. 3 and 4 exhibit the same apparent large deficit noted by other investigators for the plain wing case. This is noted as an "apparent" deficit because its shape may change considerably when the actual static pressures are used in the computations instead of the constant pressure assumption.[6] However, for comparative purposes the present data serves to illustrate the effects of the wing-tip modifications on the axial velocities. Again the spreading of the core is noted in every case with dramatic changes in the velocity magnitudes. In several cases the apparent deficit is eliminated, which may indicate an excess axial velocity if the real static pressures were known.

Conclusions

Most of the previous studies of mass injection or wing-tip modifications have shown a common effect on the trailing vortex: a spreading of the core region and a reduction in the

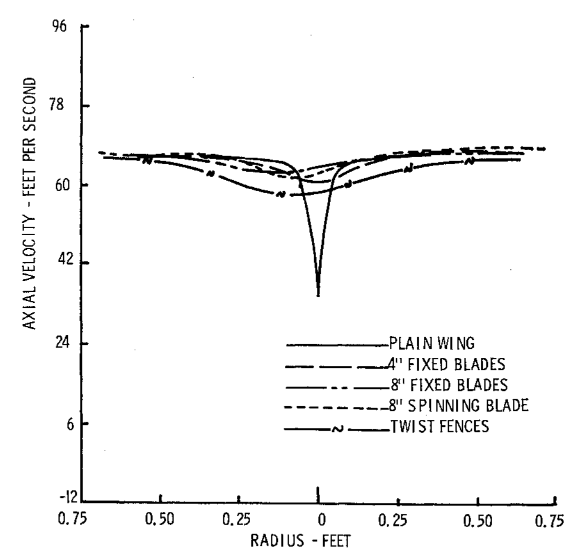

Fig. 4 Axial profiles at 30 chordlengths downstream.

maximum tangential (swirl) velocities in the flow. Based on their own study of mass injection and the results of other researchers, Mason and Marchman[2] concluded that the introduction of turbulence into the vortex by virtually any means is the dominant factor in tangential velocity reduction and the spreading of the core. The present research seems to substantiate this conclusion.

These results show that vortex dissipation effects similar to those produced by mass injection can be realized without either bleeding power from the engines or using auxiliary power. In fact, using the spinning blade concept, the vortex dissipator may actually be used to produce power. Of course, such results are never free and the effects of these modifications on the wing aerodynamic characteristics as well as the vortex must be studied. The present study seems to indicate that such modifications can significantly reduce the vortex hazard to trailing aircraft without the use of auxiliary or other power and with few, if any, detrimental effects on the wing aerodynamics.

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Technical Comments

Comment on "Convergence Proof of Discrete-Panel Wing Loading Theories"

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AFTER demonstrating the convergence characteristics of the two-dimensional (2-D) Vortex-Lattice Method (VLM) in a less complete manner than had been done by James[1], DeYoung[2] makes a rather surprising recommendation. He proposes that correction factors be introduced into three-dimensional (3-D) VLM solutions based on the discrepancies between the 2-D VLM pressure distribution and the exact 2-D pressure solution, in spite of the fact that the 2-D VLM solution yields the exact values of lift and moment. The introduction of correction factors that perturb the exact results for lift and moment, and consequently the distribution of shears, bending moments, torques, and hinge moments, must be regarded as a variation of throwing the baby out with the bath water! Moreover, the use of 2-D theoretical results to correct 3-D theoretical results is naive, since experimental results deserve consideration. A technique for adjusting theoretical oscillatory aerodynamic influence coefficients (AIC's) to agree with static wind-tunnel measurements was proposed in 1962 by Rodden and Revell[3] in a survey paper on unsteady AIC's. Since that aspect of the survey has gone largely unnoticed, it is summarized below for the case in which only a limited amount of experimental data for a single deflection mode is available, e.g., the lift curve slope, and the spanwise and/or chordwise location of the aerodynamic center.

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A premultiplying real diagonal correction matrix† $\lceil W \rfloor$ is introduced to adjust the theoretical AIC's, $[C_{hs}]$ and $[C_h]$ defined in Ref. 4, to yield agreement with experimental data. The corrected static force distribution $\{F_s\}$ becomes

$$\{F_s\} = (qS/\bar{c})\lceil W \rfloor [C_{hs}]\{h\} \tag{1}$$

where q, S, and $\bar{c}$ are the dynamic pressure, reference area, and reference chord, respectively, and $\{h\}$ is the set of deflections of the AIC control points, and the corrected oscillatory force distribution for motion $\{F\}$ becomes

$$\{F\} = \rho\omega^2 b_r^2 s \lceil W \rfloor [C_h]\{h\} \tag{2}$$

where ρ, ω, b_r, and s are the density, frequency, reference semichord, and reference semispan, respectively. Equation (2) defines corrected oscillatory AIC's for use in the k method of flutter analysis, as distinguished from Hassig's p-k method of flutter analysis[5] which requires oscillatory AIC's defined as Eq. (1). If the experimental data correspond to a rigid untwisted lifting surface at angle of attack α, we set $\{h\} = \alpha\{x\}$ in Eq. (1) where $\{x\}$ is the set of streamwise coordinates of the AIC control points, and the problem is posed as the solution of

$$\{F_s\} = qS\alpha \lceil W \rfloor [C_{hs}]\{x/\bar{c}\} \tag{3}$$

for $\lceil W \rfloor$ given all the remaining terms in the equation. With only limited experimental data, there are considerably more unknowns than equations and the method of least squares may be employed, although we are now dealing with an underdetermined system of equations rather than the usual overdetermined system. The additional equations are obtained from the requirement that the changes in the theoretical load distribution shall be as uniform as possible or, in least-squares terminology, the weighted sum of the squares of the

† The matrix notation in this Comment employs [ ], $\lceil\ \rfloor$, { }, $(\ )^T$, and I to denote rectangular, diagonal, column, transposed, and unit matrices, respectively.