Engineering Notes

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Effect of Air Injection on the Torque Produced by a Trailing Vortex

RICHARD S. SNEDEKER*
Aeronautical Research Associates of Princeton Inc., Princeton, N. J.

Nomenclature

a = lift curve slope of torquemeter vanes
b = span of torquemeter vanes
c = chord of torquemeter vanes
c_{vg} = chord of vortex generator airfoils
C_l = torquemeter rolling moment coefficient = $L/\frac{1}{2}\rho_\infty W_\infty{}^2 Sb$
$C_{\dot{M}}$ = jet momentum flux coefficient
$C_{\dot{m}}$ = jet mass flux coefficient
d_j = diameter of central jet
d_{ts} = diameter of test section
d_v = local diameter of vortex core
L = rolling moment
p = rolling velocity
r = radial coordinate
S = area of torquemeter vanes
v = local tangential velocity component
w = local axial velocity component
W_j = exit velocity on centerline of central jet
W_∞ = freestream velocity in test section
z = axial distance downstream of the vortex generators
α_{vg} = angle of attack of vortex generator airfoils
ρ_j = density at exit of central jet
ρ_∞ = density in test section

Introduction

RECENT studies of the aircraft vortex wake involve two complementary approaches to the task of reducing its danger potential to encountering aircraft. First, a means is sought to classify vortex wakes according to characteristics of the aircraft which generate them and thereby to set up guidelines for operations in areas where wake encounter is likely to occur.[1] The second approach makes use of techniques for modifying the wake as it forms. Such modification, it has been argued, might so alter the development and decay of a wake that its danger potential could be substantially reduced. Indeed, it has been observed[2-4] that when, for example, an axial jet of air is introduced near the starting point of a vortex in a wind tunnel, a marked change is noted downstream in both the turbulence characteristics of the vortex and the tangential and axial velocity profiles. These effects may be interpreted to mean 1) that the increased turbulence level promotes more rapid decay and 2) that the modified velocity profiles, especially the lower tangential velocities, represent a less severe hazard in terms of the aerodynamic moment that might be imposed upon an encountering aircraft. While these would seem to be encouraging conclusions, there has been heretofore no direct experimental evidence that a vortex wake which has been modified by a jet is actually less hazardous at a given point than one which is unmodified. The experiment to be described suggests that the value of a jet in modifying a vortex wake may be less than anticipated.

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* Research Engineer. Member AIAA.

The Experiment

The experiment was conducted in the A.R.A.P. 18-in. diam vortex tube tunnel. A vortex was produced on the tunnel centerline by a pair of airfoils of symmetric section (chord = 3.38 in.) which were set at equal but opposite angles of attack. The arrangement was similar to that used by Hoffmann and Joubert[5] and Poppleton.[2] A jet pipe of $\frac{1}{4}$-in. i.d. was mounted on the centerline within a fairing between the airfoils. Jet air was supplied from an external source through a tube inside one of the airfoils.

To make a direct measurement of the rolling moment or torque induced by the vortex on a typical wing, a simple torquemeter was built (Fig. 1). It consisted of two flat vanes held at zero angle of attack with respect to the undisturbed flow. The vanes were mounted on a pivoted arm assembly, the hub of which was restrained from rotating by a nylon monofilament attached, through a spring, to the tunnel wall at each end. (The vanes were made in two pieces so that there would be no central portion which might cause the vortex to move off-center.) The angular position of the vanes was calibrated against a known torque applied with weights. Thus, when a vortex was present, the deflection of the vanes indicated the induced torque directly. Mean velocity profiles were measured with a five-hole, conical tip, directional pitot-static probe.

Results and Discussion

In Fig. 2, the measured mean tangential and axial velocities are shown for two cases, one with no central jet and one with the jet at its maximum flow. In both cases, $W_\infty = 50$ fps

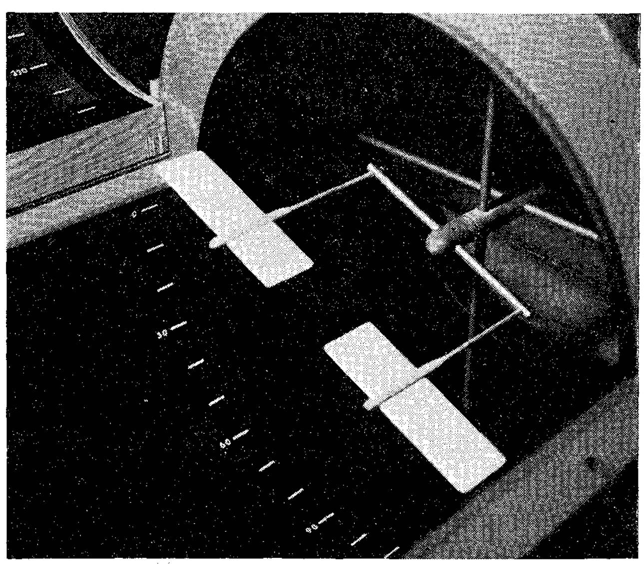

Fig. 1 The torquemeter mounted in the test section of the vortex wind tunnel.

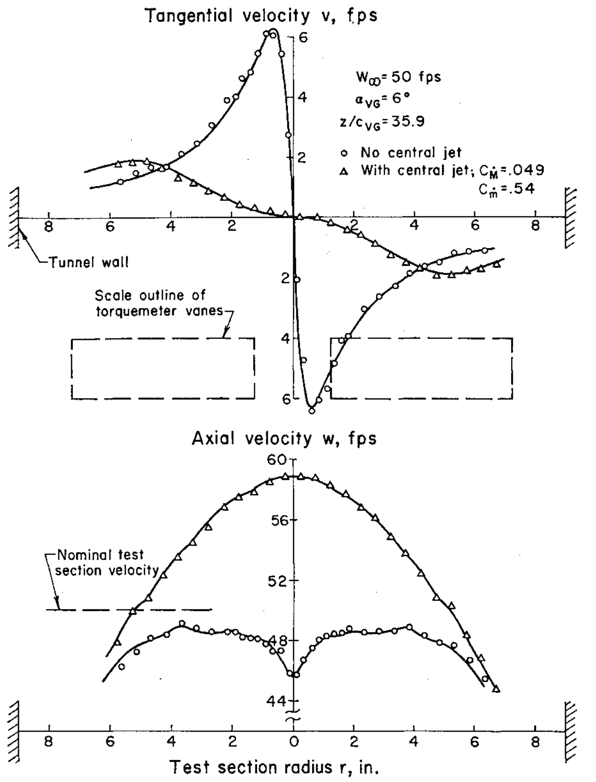

Fig. 2 Measured tangential and axial mean velocity profiles showing the effects of a strong central jet.

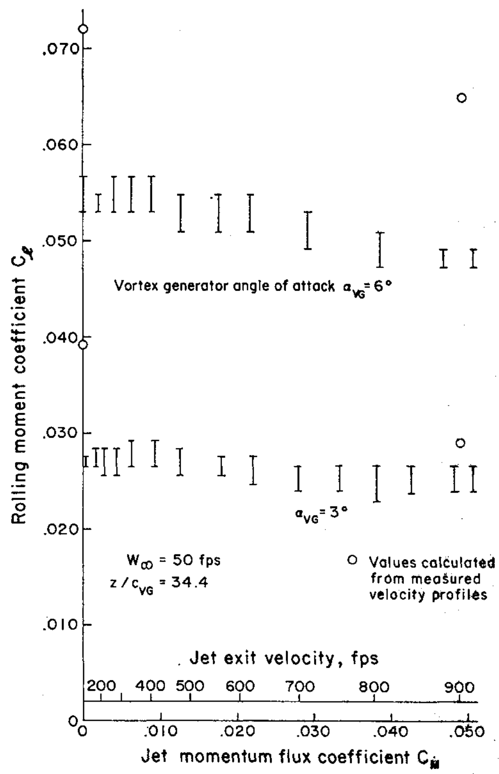

Fig. 3 Effect of the central jet on torquemeter rolling moment coefficient for two settings of the vortex generators; the size of the vortex relative to the torquemeter is as shown in Fig. 2.

and $z/c_{vg} = 35.9$. The angle of attack α_{vg} of the vortex generator airfoils was 6°. The outline of the torquemeter vanes is drawn to scale in the figure to show their size in relation to the vortex. The jet flow is expressed in terms of a momentum flux coefficient $C_{\dot M}[=(49/72)(\rho_j/\rho_\infty)(W_j/W_\infty)^2(d_j/d_{ts})^2]$ and a mass flux coefficient $C_{\dot m}[=(49/60)(\rho_j/\rho_\infty)(W_j/W_\infty)(d_j/d_v)^2]$. In these formulas, the numerical coefficients are a result of assuming a turbulent pipe flow profile for the jet exit flow. ($C_{\dot m}$ is the equivalent of Poppleton's C_Q.)

With the jet at maximum flow, a substantial change is induced in the velocity profiles. The maximum tangential velocity is reduced to less than a third of its undisturbed value, and its location moves outward to a point roughly seven times its original distance from the center. The axial velocity also shows a distinct effect due to the jet. The original velocity decrement on the centerline is replaced by an increment caused by the jet mass flux. Because of their symmetry, it appears that the irregularities in the axial profiles are associated with the rolling up vortex sheets which, at this axial distance, are still recognizable.

The results of the torquemeter measurements are shown in Fig. 3. The torque is expressed as a rolling moment coefficient C_l based on the dimensions of the torquemeter vanes. The rolling moment was measured at $z/c_{vg} = 34.4$ for the full range of jet velocities and for two settings of the vortex generator angle of attack, $\alpha_{vg} = 3°$ and 6°. For the case of $\alpha_{vg} = 6°$, maximum flow from the central jet reduces the rolling moment by only 13%. The effect for the case of $\alpha_{vg} = 3°$ is hardly noticeable. To help understand this result, a simple formula was derived for calculating the rolling moment from the measured velocity profiles. The total rolling moment on both torquemeter vanes is

$$L = a\rho_\infty c\int_{r_1}^{r_2} w(r)v(r)r\,dr$$

where a is the lift curve slope of a vane, c is the chord of a vane, and r_1 and r_2 are the radii at the inner and outer tips of the vanes, respectively. For a simple approximation, $a = 2\pi$ was chosen, i.e., the lift curve slope for a two-dimensional flat plate. Values of C_l calculated from this formula are shown in Fig. 3. They appear to be quite consistent with the direct torque measurements. That they are higher than the torquemeter values stems in part from the use of $a = 2\pi$, since the lift curve slope for a torquemeter vane would be somewhat lower than the two-dimensional value. This comparison brings out the point that although the tangential velocity profile is "flattened" by the action of a jet, the new distribution, when coupled with the augmented axial flow, results in very little change in the integrated product of the two components. In terms of the torque-producing lift on a vane, the reduction of the effective local angle of attack (v/w) tends to be offset by the increase in local dynamic pressure, $\rho_\infty w^2/2$. (It should be realized, of course, that these results are characteristic of a torquemeter or "wing" which bears a particular size relationship to the vortex. In the present case this relationship, which is shown in Fig. 2, is felt to be physically realistic in terms of full-scale encounter possibilities. If the wing were of much larger scale than the vortex, the rolling moment coefficients would be small to begin with, and the effect of a modification due to a central jet such as that observed in this experiment would be truly negligible. The other extreme case, in which the wing is entirely immersed in the vortex core, would appear to be unlikely in a full-scale encounter.)

It is instructive to compare the test conditions with more familiar full-scale quantities. Note, first, that the maximum momentum flux of the jet—which reduced the rolling moment by 13%—is about 5% of the momentum flux of the entire freestream flow within the wind tunnel ($C_{\dot M} = 0.049$). Consider now a full-scale wind tunnel, 40 ft in diameter and containing a jet aircraft of 40-ft span, powered by a J-79 engine. If the wind speed in the tunnel is 600 fps, the

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

JAMES F. MARCHMAN III* and JOSEPH N. UZEL†
Virginia Polytechnic Institute and State University, Blacksburg, Va.

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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* Associate Professor of Aerospace Engineering; Department of Aerospace Engineering. Associate Member AIAA.

† Undergraduate Student, Department of Aerospace Engineering; presently with Martin Marietta Corp., Orlando, Fla. Student Member AIAA.

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 7½° 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