Experimental Results for Reynolds Number Effects on Trailing Vortices

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Nomenclature

c	= mean aerodynamic chord
Re_c	= Reynolds number based on c
u, v, w	= axial, radial, and tangential velocity, respectively
V	= mean velocity vector
V_F	= freestream velocity
V_X	= axial velocity
V_Z	= tangential velocity
x, y, z	= axial, horizontal, and vertical coordinate, respectively
α	= angle of attack

Introduction

THIS work is a study of tip vortices, such as trail from wings or control surfaces on airplanes, surface ships, or undersea vehicles. The near-wake behavior of the vortices trailing from low aspect ratio lifting surfaces mounted on either side of a larger, nonlifting, streamlined strut was investigated in a wind tunnel. The simulation of vortices by small-scale model testing in wind tunnels and towing tanks presents a problem, since the history of vortices is known to be sensitive to Reynolds number. The present test program was designed to obtain a high Reynolds number by using a large-scale model of a part of a vehicle configuration. The rest of the vehicle was "simulated" by mounting the model on the floor of the wind tunnel. At a tunnel speed of 220 ft/s, this gave an Re_c of 1.5×10^6, which is greater than the usual tests with complete vehicle configurations in wind tunnels and towing tanks. Tests were also conducted at $Re_c = 2.1 \times 10^5$ and 6.7×10^5 to clarify the Reynolds number dependence. Mean flow properties were measured with a five-port yaw-head probe, and axial turbulence intensity was obtained by a straight, hot-wire anemometer.

Apparatus and Instrumentation

The tests were conducted in the Virginia Tech 6×6 ft tunnel. Figure 1 shows the model. The aspect ratio of the lifting surfaces was 2.7 ($\mathcal{R}$ ≡ span/mean chord). The lifting surface section was NACA 0012.

Figure 2 describes the coordinate system. A straight, five-port yaw-head probe (⅛ in. diam) was used to obtain the mean-flow measurements. For the axial turbulence intensity measurements, a single-normal hot wire was used. Mason and Marchman[1] found that a probe of a size small compared to the vortex core moving slowly (1-2 in./min) would not perturb the vortex seriously enough to affect the velocity profiles.

A difficulty for this type of measurement is the occasional, aperiodic fluctuations in readings caused by unsteady movement of the vortex. For pressure probes, this fluctuation is believed to be damped by the slower response caused by the long leads, and the problem is not as severe. For these reasons, a seemingly stable vortex measured by a yaw head may show large fluctuations in hot-wire readings, especially when the vortex is not strong. Occasional fluctuations of 30-50% were detected for the higher angle-of-attack case, but repeated fluctuations up to 100% were observed around the vortex centers at $x/c = 6$ and 9 with the lower angle of attack, which rendered the turbulent measurements impossible in those cases.

Test Procedure

Test speeds were chosen as 20, 95, and 220 ft/s. A positive angle of attack was chosen to be 5 deg for fear of influence from the tunnel floor. A second angle of attack was −10 deg. Measurements were made at three stations: 3.5, 7.0, and 10.5 ft behind the trailing edge of the lifting surfaces. The last station corresponded to $x/c = 9$.

Results and Discussion

Mean flow surveys were carried out at all test conditions with the exception of the low-speed case at $x/c = 9$, for which the vortex center could not be located with the needed ac-

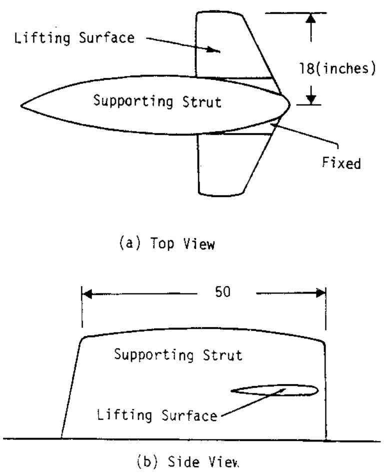

Fig. 1 Model description.

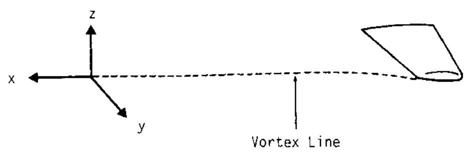

Fig. 2 Coordinate system for experimental study.

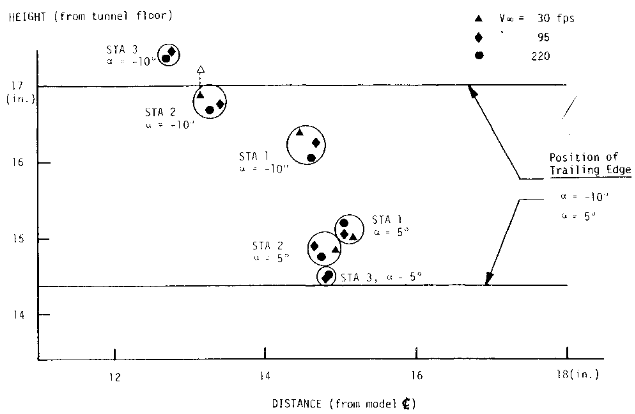

Fig. 3 Location of vortex centers.

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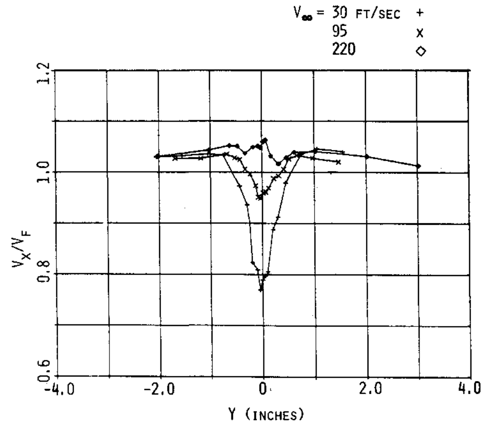

Fig. 4 Typical axial velocity profiles at $x/c=6$, $\alpha=5$ deg and various speeds; horizontal survey.

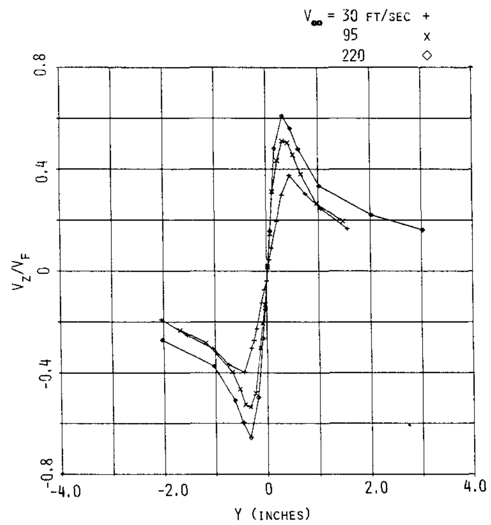

Fig. 5 Typical tangential velocity profiles at $x/c=6$, $\alpha=5$ deg and various speeds; horizontal survey.

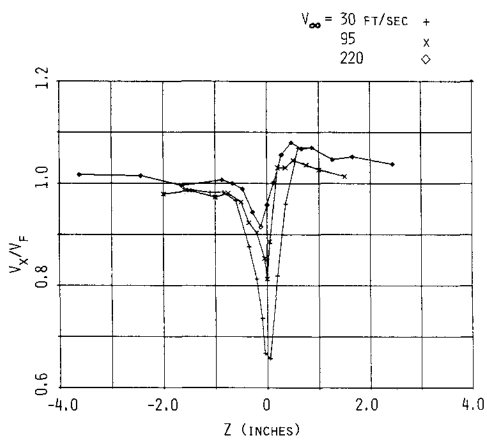

Fig. 6 Axial velocity profiles at $x/c=3$, $\alpha=-10$ deg; vertical survey.

curacy. Radial velocity profiles are not reported here as they are more susceptible to experimental errors than the axial and tangential velocity profiles. The small radial velocity can contain contributions from other velocity components if a scan is not conducted perfectly along the centerline.

Hot-wire surveys were conducted for all test conditions with $\alpha=-10$ deg, except for the low-speed case at $x/c=9$, for which yaw-head probing failed to provide the vortex center location.

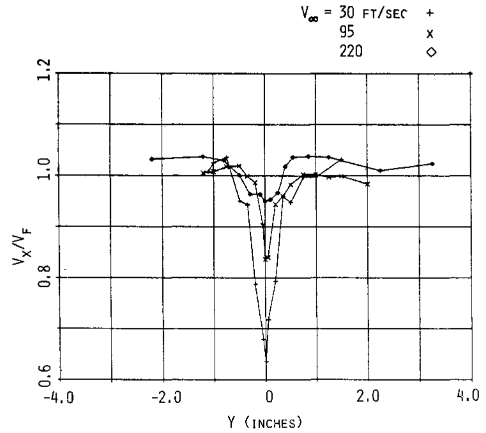

Fig. 7 Axial velocity profiles at $x/c=3$, $\alpha=-10$ deg; horizontal survey.

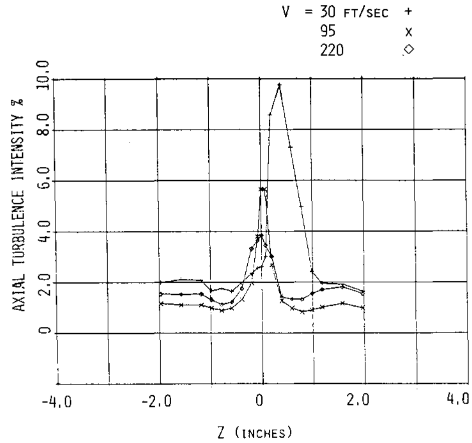

Fig. 8 Axial turbulence intensity profiles at $x/c=6$, $\alpha=-10$ deg and various speeds; vertical survey.

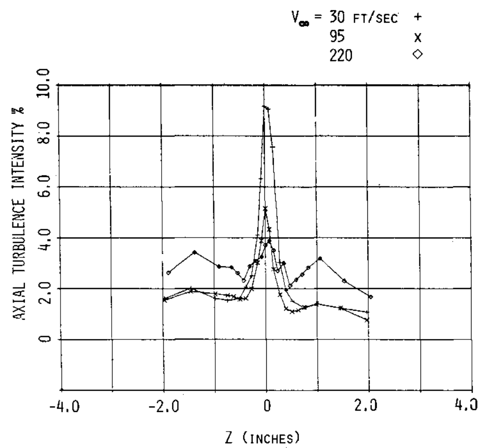

Fig. 9 Axial turbulence intensity profiles at $x/c=3$, $\alpha=-10$ deg and various speeds; vertical survey.

Figure 3 shows the location of the vortex centers. The definite grouping indicates that the path of a vortex is determined essentially by the model geometry. For $\alpha=5$ deg, there were only slight variations with changes in station. This was consistent with earlier work showing that the vortex travels parallel to the freestream after a distance of several chord lengths.[2] This was also the case for $\alpha=-10$ deg, except that the alignment occurred more slowly due to greater vortex strength.

Typical velocity profiles in the vortices at $x/c=6$ are depicted in Figs. 4 and 5. Good symmetry is exhibited, indicating that the vortices were rolled up almost completely at this station. However, this was not the case at $x/c=3$, as evidenced by Fig. 6. This asymmetry was not evident in horizontal profiles (Fig. 7), which may suggest that the asymmetry of the vortex structure during rollup is mainly in the vertical direction.

The effect of Reynolds number is apparent; an increasing Re_c corresponds to a decreasing axial velocity defect and an increasing maximum swirl velocity. Furthermore, this Reynolds number effect was found to be greater than that of downstream distance. Downstream distance had a minor effect on vortex structure and this has been observed in previous experiments.[2]

Typical profiles of axial turbulence intensity can be observed in Fig. 8. The asymmetry at low speed can be explained as the result of vortex swerving in the vertical direction at this test condition. Otherwise, good symmetry was found as evidenced by the profiles at $x/c=3$ shown in Fig. 9. The effect of Reynolds number is quite clear and is in the direction of a decrease in intensity inside the core with increasing Re_c. Downstream distance was observed to have little influence on axial turbulence intensity over this range.

References

[1]Mason, W. H. and Marchman, J. F., "Far-Field Structure of an Aircraft Trailing Vortex, Including Effects of Mass Injection," NASA CR-62078, 1972.

[2]Marshall, J. R. and Marchman, J. F., "Vortex Age as a Wake Turbulence Scaling Parameter," Virginia Polytechnic Institute and State University, Blacksburg, Va., VPI-Aero-006, 1973.