Engineering Notes

ENGINEERING NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed 6 manuscript pages and 3 figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Pressure Measurements of Wake Vortices near the Ground

J. N. HALLOCK*
Department of Transportation,
Transportation Systems Center,
Cambridge, Mass.

IT has been known since the beginning of air flight that an aircraft leaves in its wake a pair of highly concentrated, counter-rotating trailing vortices. With the introduction of jumbo jets, the vortices generated by these aircraft can become a real hazard to smaller planes especially near airports where encounters are frequent. In the interest of safety and airport efficiency, it is desirable to remotely detect the vortices in order to avoid a vortex encounter.

Electromagnetic[1–4] and acoustic[5] sensors are now being used to detect vortex wake turbulence. Because these systems are inherently complex and costly, a simple pressure sensor was tested to ascertain whether it would be possible to detect the presence of a vortex. A barocel† sensor was employed. It measured the differential pressure using the motion of a metal diaphragm separating two enclosures: one enclosure is connected to an external pressure port; the other is opened to the ambient conditions and is sealed before each data run.

The tests were conducted at the National Aviation Facilities Experimental Center (NAFEC), Atlantic City, N. J., and consisted of 175 flybys: 24 DC-7, 38 B-747, 10 C-5A, 24 B-707/DC-8, 52 C-141 and 27 others (P-3, Lear Jet, DC-3, etc.). An acoustic vortex detector[5] was used to determine the height of the vortices as they drifted over the pressure sensor. All the relevant flight parameters (velocity, gross weight, flap configuration, etc.) as well as the meteorological conditions were provided for the DC-7, B-747 and B-707/DC-8 flybys. The horizontal location of the pressure sensor was varied from 150 ft (45.7 m) to 300 ft (91.4 m) from the aircraft ground track and the distance above the ground varied from 1 ft (0.3 m) to 5 ft (1.5 m).

Figure 1‡ represents a sample of the data from the DC-7 flights. The error in the theoretical points is due to the error in the acoustically measured height of the vortex (typically ±5 ft). A theoretical pressure differential for a vortex near the ground was calculated using Bernoulli's principle for a vortex of circulation Γ and its image:

$$\Delta P = \frac{\rho \Gamma^2 h^2}{2\pi^2 (h^2 - d^2)^2} \tag{1}$$

where ρ is the air density, h is the height of the vortex above the ground, and d is the height of the sensor. (One may question the applicability of Bernoulli's principle for a vortex system which includes turbulent flow, but the data and the fact that the flow is measured far from the vortex core suggests that the equation is valid.) Γ was determined assuming an elliptically loaded wing:

$$\Gamma = \frac{4W}{\pi b V \rho} \tag{2}$$

and using the known weight (W), wingspan (b) and aircraft velocity (V). The pressure differential measurements are lower than the theoretical values (within experimental error) probably because the actual Γ was less than the predicted value (due to losses occurring during the wake rollup which in turn are caused by the ambient turbulence, the flap configuration, and the consequence of wing-mounted engines). The disparities between the measured and predicted pressure differentials for vortices below 40 ft (12.2 m) probably result from the neglect of viscous decay and vortex breakdown for vortices that have been in ground effect for any length of time.

A matrix of pressure sensors could be used in an airport environment to monitor the existence and horizontal motions of wake vortices. Such a system would be limited by the ambient winds; they limit the maximum height at which a vortex can be detected. (When the winds were above 10 mph, the DC-7 vortices were not detected if the vortex was over 60 ft above the ground.) When the wind velocity is comparable to $\Gamma/\pi h$, the vortex signature is comparable to the pressure differential caused by the ambient turbulence.

Pressure sensors would be valuable for monitoring vortices between parallel runways where the vortices are well within ground effect. However, when the ambient winds are high and the use of pressure sensors becomes questionable; the problem should be minimal as the vortices should quickly sweep away and/or dissipate.

References

[1] McGowan, N. A., "NASA Aircraft Trailing Vortex Research," *Proceedings of the FAA Symposium on Turbulence*, Federal Aviation Administration, March 1971, Washington, D.C., p. 25.

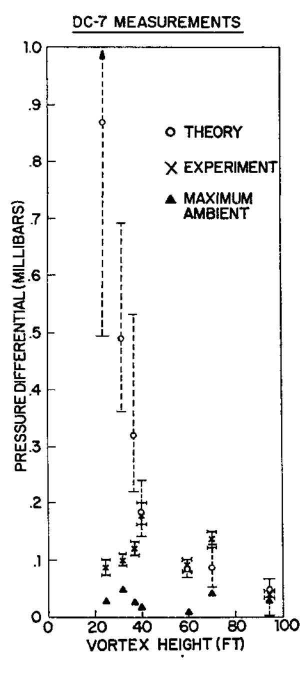

Fig. 1 Pressure differential vs height of the vortex above the ground.

Received September 20, 1971; revision received October 29, 1971.
Index category: Air Navigation, Communication, and Traffic Control Systems.

* Physicist.

† Type 1023 Barocel Electronic Manometer manufactured by CGS Datametrics, Watertown, Mass. 02172.

‡ In Fig. 1 the circles are the theoretical predictions, x's are the measured values, and the triangles are the measured maximum values of the ambient wind-induced turbulence.

[2] Francis, D. G., "Development of a Vortex Laser Doppler Velocimeter," *Proceedings of the 1971 National Aerospace Electronics Conference*, IEEE, AIAA, *1971*, Dayton, Ohio, pp. 36–40.

[3] Huffaker, R. M., Jelalian, A., Keene, W., Sonnenschein, C. and Thomson, J. A. L., "Applications of Laser Droppler Systems to Vortex Measurement and Detection," *Aircraft Wake Turbulence and its Detection*, 1st ed., Plenum Press, New York, 1971, pp. 113–124.

[4] Easterbrook, C. C. and Joos, N. W., "The Utility of Doppler Radar in the Study of Aircraft Wingtip Vortices," *Aircraft Wake Turbulence and its Detection*, 1st ed., Plenum Press, New York, 1971, pp. 97–112.

[5] Kodis, R. D., "Wake Vortex Sensors," *Proceedings of the FAA Symposium on Turbulence*," Federal Aviation Administration, March, 1971, Washington, D.C., p. 28.

Compressibility Correction for Internal Flow Solutions

S. Lieblein* and N. O. Stockman†
NASA Lewis Research Center Cleveland, Ohio

THERE are many instances in internal aerodynamics where high subsonic or local transonic flows are present. Examples of such configurations include engine nacelle inlets, lift fan and lift engine inlets, compressor and turbine blade rows, diffusers, transition ducts, and thrust deflection devices. Fairly accurate solutions of the flow distributions along the surfaces or across the flow passage are frequently desired for design and analysis purposes.

Unfortunately, accurate general compressible solutions are not readily available for these situations. However, incompressible potential flow solutions are generally tractable for many of these configurations. It would be helpful, therefore, if some simple general compressibility correction could be developed for use with these methods that would produce a relatively good approximation to the compressible flow behavior.

Compressibility corrections of various forms based on upstream freestream Mach number are in frequent use for flow around submerged bodies such as airfoil sections. Recent developments[1,2] have indicated the importance of including geometry factors in the compressibility correction relations. It is expected that similar geometry factors exist for compressibility effects in channels. Thus, the derivation of an effective compressibility correction for a wide range of internal flow configurations comparable to that for a submerged body[1,2] is likely to be a complex matter. It appeared expedient therefore to explore the possibility of devising a simple correction relation based on empirical observation.

This Note proposes a simple compressibility correction for internal flow solutions that may have promise as a preliminary approach to enlarging the usefulness of incompressible potential flow calculations. The correction equation was deduced from inspection of the exact solution for the compressible flow in a turbine nozzle passage as described in Ref. 3. The blade profile is shown in Fig. 1, and the exact compressible and incompressible surface velocities, as obtained from the method of Ref. 3, are plotted in Fig. 2. It is seen that the compressibility effect is not the same in magnitude for the suction and pressure surfaces.

A correction function for the local compressible velocity,

Received October 4, 1971.

* Chief, VTOL Propulsion Branch. Associate Fellow AIAA.

† Aerospace Research Engineer. Member AIAA.

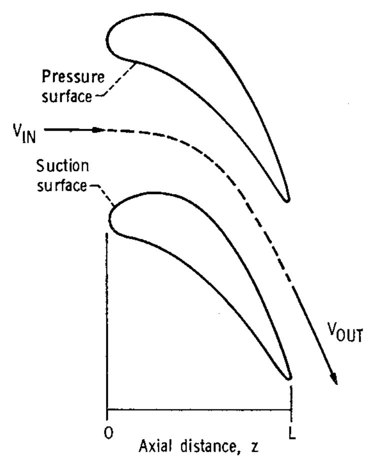

Fig. 1 Accelerating stator blade passage.

V_c, at any point as a function of the incompressible velocity, V_i, at the point was established as

$$V_c = V_i(\rho_i/\bar{\rho}_c)^{V_i/\bar{V}_i} \tag{1}$$

where: $\bar{V}_i$ = the average incompressible velocity across the flow passage at the given station; ρ_i = incompressible density, which is equal to the stagnation density, ρ_t; $\bar{\rho}_c$ = average compressible density across the flow passage.

In Eq. (1), the density ratio term represents the effect of average Mach number, while the passage surface geometry is reflected in the magnitude of the exponent $V_i/\bar{V}_i$. For the suction surface of the passage in Fig. 1, the exponent is greater than unity, while for the pressure surface, the value is less than unity.

The compressibility correction was applied to the geometry of Fig. 1 based on the incompressible values of surface velocity shown in Fig. 2. Average incompressible velocity, $\bar{V}_i$, was obtained from averaging the local values of V_i across the passage at each Z/L position. Figure 3 shows the comparison between the exact compressible velocities and the values given by Eq. (1) for the case where the average compressible density, $\bar{\rho}_c$, was also obtained from averaging the local values of exact ρ_c across the passage at each Z/L position. This actual average compressible density (which would not be available in a practical case) was used to assess the basic accuracy of the relation. The agreement is seen to be excellent

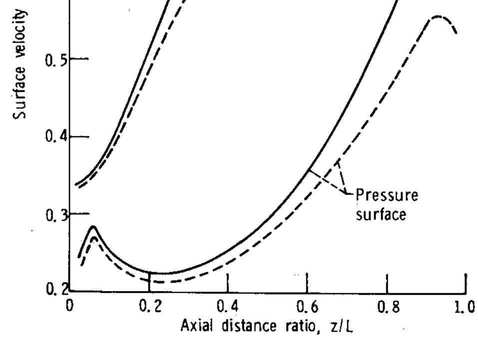

Fig. 2 Exact compressible and incompressible surface velocities for blade passage of Fig. 1 (method of Ref. 3).