and confirms the application of the external compressibility correction to very thick sections. Poorer correlation on the upper shroud upper surface and within the ducts is probably due to the known problem of leakage in Douglas-Neumann surface singularity methods, along with deficiencies in the application of viscous effects producing an incorrect mass flow.

Conclusions

The inclusion of a surface slope correction in the external compressibility correction due to Dietrich, Oehler, and Stockman, has been shown to significantly improve the prediction of compressible velocities. This modified technique for external flow has also been combined with the Lieblein and Stockman compressibility correction for internal flow to produce accurate predictions of the compressible flow around multifoil sections.

Acknowledgment

This work was supported by the Canadian Department of National Defence.

References

[1]Whittley, D. C., "Augmentor-Wing Technology for STOL Transport Aircraft," Paper presented for High Lift Technology Course, University of Tennessee Space Institute, Tullahoma, Oct. 1975.

[2]Wilby, P. J., "The Calculation of Subcritical Pressure Distributions on Symmetrical Aerofoils at Zero Incidence," NPL Aero Rept. 1208, 1967.

[3]Labrujere, Th. E., Loeve, W., and Slooff, J. W., "An Approximate Method for the Calculation of the Pressure Distribution on Wing-Body Combinations at Subcritical Speeds," AGARD CP 71, 1970, pp. 11-0—11-15.

[4]Lieblein, S., and Stockman, N.O., "Compressibility Correction for Internal Flow Solutions," *Journal of Aircraft*, Vol. 9, April 1972, pp. 183-184.

[5]Stockman, N. O., "Potential and Viscous Flow in VTOL, STOL, or CTOL Propulsion System Inlets," AIAA Paper 75-1186, Oct. 1975.

[6]Dietrich, D. A., Oehler, S. L., and Stockman, N. O., "Compressible Flow Analysis About Three-Dimensional Wing Surfaces Using a Combination Technique," AIAA Paper 83-0183, Jan. 1983.

[7]Boerstoel, J. W., "Symmetrical Subsonic Potential Flows Around Quasi-Elliptical Aerofoil Sections," NLR TR 68016, 1968.

Applications of Adaptive-Wall Wind Tunnels

Sanford S. Davis*
NASA Ames Research Center
Moffett Field, California

Introduction

THE purpose of this Note is to introduce a new technique for processing flowfield data from an adaptive-wall wind tunnel. The basic premise is that it may not be necessary, or desirable, to force the adaptive-wall wind tunnel to simulate complete free-air conditions. There are many reasons why this may be an important consideration. For example, the control system in a ventilated wall may not be powerful enough to supply the required inflow/outflow distribution; or a new computer code needs to be validated against an experiment with well-defined, but finite boundary conditions. In three dimensions, the extremely complex mechanical and flow control systems may be an insurmountable barrier to building a facility with complete four-wall active control.

To introduce the method, the concept of a phantom wind tunnel is introduced for both two- and three-dimensional wind tunnels. This is illustrated for a two-dimensional wind tunnel in Fig. 1. The phantom wind tunnel has a solid floor and ceiling and may have an arbitrary height. The height of the phantom wind tunnel is a variable and controllable parameter. The objective is to adapt the walls of the physical wind tunnel in such a manner that the flowfield is equivalent to that in the phantom wind tunnel. By introducing the phantom wind tunnel, a continuous spectrum of flowfields ranging from the original passive and ventilated configuration to the fully adaptive may be obtained.

The three-dimensional phantom wind tunnel must be viewed in a slightly different context. The simplest approximation to three-dimensional wind tunnel interference is to consider an equivalent two-dimensional problem in the far wake or Trefftz plane. This approximation is fully described for subsonic flows in the wall interference literature.[1,2] The equivalent two-dimensional problem is usually solved by an application of the method of images. Such solutions are quite complicated, since a two-dimensional family of images requires doubly infinite summations.

An important limitation of the Trefftz plane analysis is that it does not predict streamwise variations of the interference potential. This shortcoming may be overcome by applying the method of images to the full, three-dimensional configuration. For example, the method of images for a closed-wall, rectangular wind tunnel requires successive rows of upright and inverted image aircraft to satisfy the wall boundary conditions. Consider a wind tunnel with an active floor and celing as shown in Fig. 2. If the flow can be shown to be compatible with that existing between two infinite vertical walls, then the residual interference can be computed with a single array of horizontal images, as depicted in the figure. This flow would be equivalent to a horizontal line of aircraft spaced B units apart and would seem to be a suitable candidate for computation (for a full airplane model) or for analytical studies in the Trefftz plane. In the following sections, two simple examples (in two and three dimensions) are described, followed by a discussion of several possible application areas.

Examples

One method of compatibility assessment for adaptive wall application requires the upwash distribution to be known at two levels in the flow.[3] With respect to the geometrical arrangement depicted in Fig. 3, the two-dimensional algorithm for the case of a cylinder in a wind tunnel follows the following three-step procedure. The upwash v at the selected source level Y_{SL} is measured (or simulated). The next step is to use this source level upwash as a boundary condition to compute a fictitious flow from the source level outward. The domain for this fictitious flow is cross-hatched in Fig. 3. The upwash satisfies a Laplace equation in the case of low-speed or subsonic flows. Whereas conventional adaptive wall algorithms would compute this fictitious flow from Y_{SL} to infinity, the finite domain represented by the phantom wind tunnel allows the physical fluid to be related to the flow in a wind tunnel of semiheight h_{PWT}. The final step is to compare the measured (or simulated) upwash at $y = Y_{FL}$ with that computed from the Laplace equation solution. This comparison is shown in Fig. 4, which shows, as expected, that the flow is not compatible with that in the phantom wind tunnel.

The procedure was repeated once again with a new upwash at Y_{SL}, which simulated the exact analytical solution for

Received March 10, 1985; revision received Oct. 22, 1985. This paper is declared a work of the U.S. Government and therefore is in the public domain.

*Chief, Fluid Dynamics Research Branch. Associate Fellow AIAA.

flow in a closed wind tunnel of height h_{PWT}. The results, shown in Fig. 5, indicate that the flow computed from the three-step procedure is compatible with the given input flow.

A three-dimensional example is considered next. Here it will be shown how the method can be used to develop a flow with a relatively simple residual boundary constraint. The flow is considered in the far wake or Trefftz plane. Only a two-dimensional flow needs to be considered and the lifting wing is approximated by a point vortex doublet. The adapted flow is unconfined in the vertical direction and is confined in the lateral direction only.

A sketch of the streamlines for the unconfined and confined doublets are shown in Fig. 6 as dashed and solid lines, respectively. The procedure follows the two-dimensional case in most respects. The measured (or simulated) upwash at Z_{SL} is used as a boundary condition to solve a Laplace equation in the cross-hatched region in Fig. 6. The other boundary conditions are that the flow decays at infinity and the velocities normal to the side walls vanish. The resulting solution at Z_{FL} is compared with measured (or simulated) velocities to assess the flow compatibility. The process is iterated by blowing/suction through the physical wind tunnel boundaries until the process converges. A simulation using a laterally confined vortex doublet has demonstrated the validity of the method.[4] This method is slightly different than other reported techniques that use streamwise control in two-dimensional wind tunnels for three-dimensional testing.[5,6]

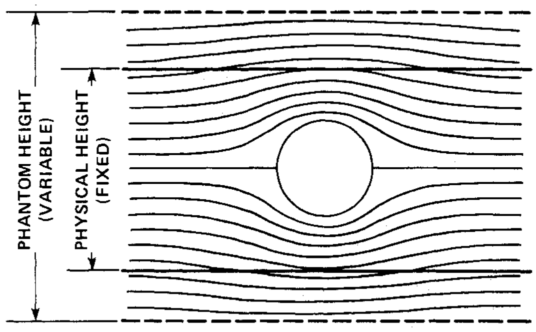

Fig. 1 Two-dimensional phantom wind tunnel.

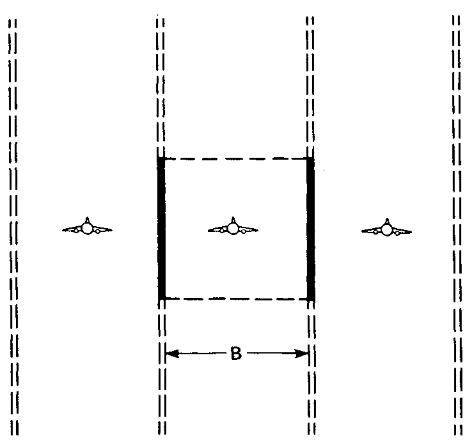

Fig. 2 Three-dimensional phantom wind tunnel.

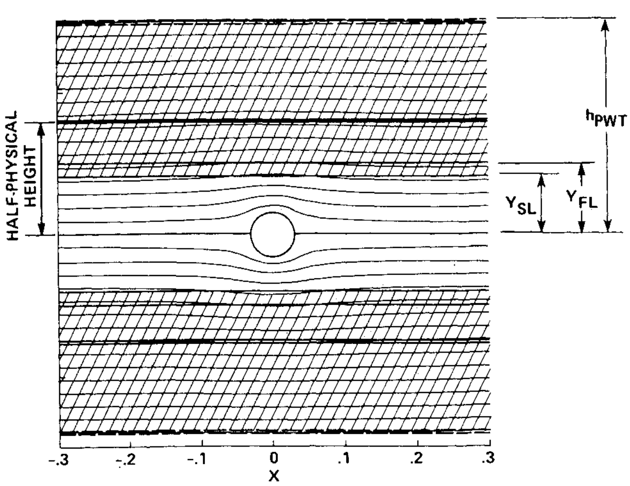

Fig. 3 Solution domain for two-dimensional adaptive-wall wind tunnel.

Applications

The elementary results presented in the previous section may be used as the basis for describing some possible applications. Modern two-dimensional interference assessment schemes can be used in conjunction with the described method to great advantage. For example, an initial measurement in a wind tunnel adapted to some phantom height h_{PWT}, coupled with an interference assessment method such as that developed by Schairer,[7] would yield a blockage correction. Another adaptation, to say 2 h_{PWT}, would yield another correction. With some experience, the rate of decay of interference could be assessed and even used to extrapolate to unconfined flow conditions. It may turn out that

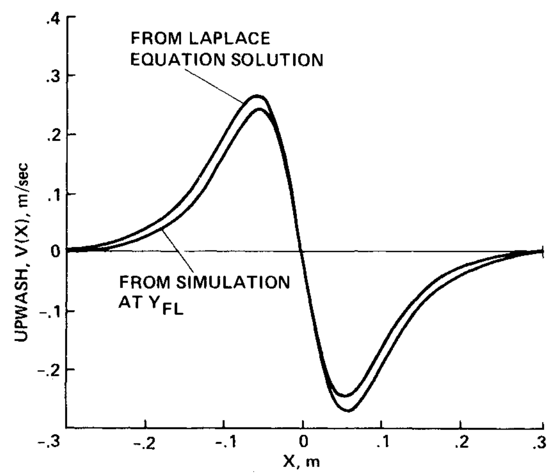

Fig. 4 Comparison between Laplace equation solution and simulation at $y = Y_{FL} = 0.10$ m ($h = 0.15$ m, $Y_{SL} = 0.08$ m, and $h_{PWT} = 0.30$ m).

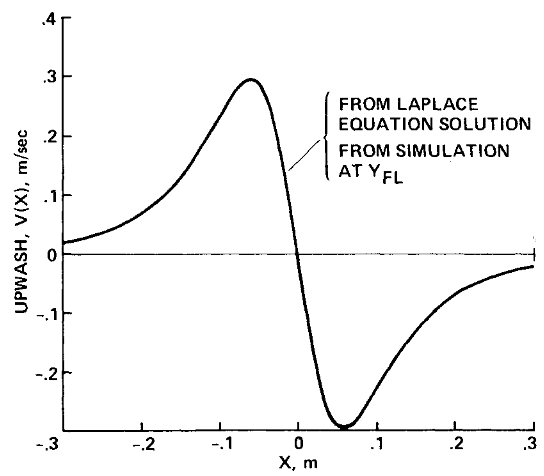

Fig. 5 Comparison between Laplace equation solution and simulation at $y = Y_{FL} = 0.10$ m ($h = 0.15$ m, $Y_{SL} = 0.08$ m, and $h_{PWT} = 0.30$ m). Exact solution used at Y_{SL}.

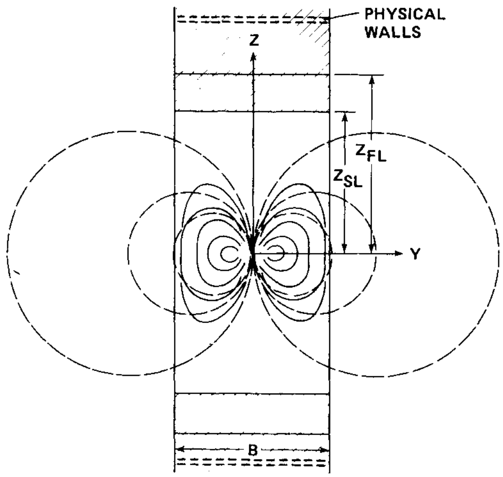

Fig. 6 Solution domain for three-dimensional adaptive-wall wind tunnel.

wall adaptation requirements need not be as severe as the wall control needed to go "all the way" to unconfined flows. This would relieve the hardware requirements for a fully adaptive wall wind tunnel.

In the difficult transonic flow regions, simple corrections in the Mach number and angle of attack are not applicable. An application of the procedure would be to place the confining effect of the walls far enough away so that classical source and vortex interference methods are sufficient for correcting data in the transonic flow regime. Thus, the flow would be made "correctable" in the manner defined by Kemp.[8]

An additional application is to the simulation of cascades. A cascade of cylinders, for example, can be tested over a wide range of cylinder spacings with only one cylinder model. Here, h_{PWT} is interpreted as the half-spacing between the cylinders. Application to nonlifting airfoil cascades is also feasible; and the procedure should be applicable to staggered arrays of cylinders or to lifting cascades.

Finally, there is much current interest in computing high-speed flows using the Navier-Stokes equations of motion. It has been very difficult to separate the viscous and wall interference effects when the computations are compared with experimental data. Another difficulty with unconfined flows has been the appropriate modeling of the conditions at infinity. With the current method, well-defined boundary conditions can be imposed at a variable height (h_{pWT}), which may help to sort out viscous-dominated effects in complex flows.

In three-dimensional flow, an obvious application is to hybrid adaptive-wall wind tunnels. For many practical reasons, ranging from optical access to mechanical complexity, solid side walls are useful features in wind tunnels. In order to implement the procedures described in this Note, active control is limited to the floor and ceiling. Within the approximation of classical Trefftz plane theory, ventilation control would be axially uniform but variable in the transverse direction. It is recognized that this procedure captures only a portion of the wall interference—streamwise curvature effects are disregarded—but the relative ease of accounting for the residual side wall effects using imaging methods and the simpler control system requirements may make this a feasible method for "first-order" studies.

For more refined calculations, a complete three-dimensional imaging system can be used. Of course, implementation of such a method requires extensive computational capability, but it is far less work than simulating both the horizontal and vertical arrays of image aircraft. The trade-off to be considered here is that two-dimensional (lateral and streamwise) wall control on the floor and ceiling is needed, in contrast to the one-dimensional lateral control illustrated in Fig. 6.

Conclusion

In this Note, applications of adaptive-wall wind tunnels were introduced and demonstrated using simple analytical methods. More work remains to be done in the demonstration and subsequent acceptance of conventional adaptive-wall technology. Once this milestone has been reached, the methods described above may be useful tool for both precision aerodynamic testing and for the development and validation of advanced computational techniques.

References

[1]Glauert, H., "Wind Tunnel Interference on Wings, Bodies, and Airscrews," British Aeronautics Research Council, R&M 1566, 1933.

[2]Garner, H. et al., "Subsonic Wind Tunnel Wall Corrections," AGARDograph 109, Oct. 1966.

[3]Davis, S., "A Compatibility Assessment Method for Adaptive Wall Wind Tunnels," *AIAA Journal*, Vol. 19, Sept. 1981, pp. 1169-1173.

[4]Davis, S., "Generalized Adaptive Wall Wind Tunnels," AIAA Paper 85-0225, Jan. 1985.

[5]Wedemeyer, E., "Wind Tunnel Testing of Three Dimensional Models in Wind Tunnels with Two Adaptive Wall," Von Kármán Institute, Brussels, Rept. VKI TN 147, 1982.

[6]Smith, J., "A Theoretical Exploration of the Capabilities of 2D Flexible Wall Test Sections for 3D Testing," National Aerospace Laboratory, NLR, Amsterdam, Rept. NLR MP 84018U, 1984.

[7]Schairer, E., "Two-Dimensional Wind-Tunnel Interference from Measurements on Two Contours," *Journal of Aircraft*, Vol. 21, June 1984, pp. 414-419.

[8]Kemp, W., "Transonic Assessment of Two-Dimensional Wind Tunnel Wall Interference Using Measured Wall Pressures," NASA CP-2045, 1979, pp. 473-486.