# Interference-Free Wind-Tunnel Flows by Adaptive-Wall Technology

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**The adaptive-wall or self-correcting wind tunnel has been proposed for such regimes as transonic and V/STOL where wall effects are large and cannot be corrected for. The power and generality of the concept are pointed out. In a two-dimensional transonic embodiment in the Calspan 1-ft tunnel, the scheme has been shown to work at lower transonic Mach numbers. Several practical problems are cited, including instrumentation, the nature of the wall modification, and convergence of the iterative procedure. Moreover, questions of shock-wave neutralization at the wall and probable configuration of three-dimensional embodiments are discussed.**

## Nomenclature

$c$ = airfoil chord
$C_d$ = drag coefficient
$C_l$ = lift coefficient
$C_m$ = pitching-moment coefficient about quarter-chord
$C_p$ = pressure coefficient
$E_\pm$ = operators for exterior flow
$h$ = normal distance from airfoil to interface
$k_\pm$ = relaxation factors
$M_\infty$ = ambient Mach number
$p$ = pressure
$q$ = $\rho U_\infty^2/2$
$U_\infty$ = longitudinal freestream velocity
$v_n$ = normal disturbance-velocity component
$v_x$ = longitudinal disturbance-velocity component
$W_\pm$ = operators for the interior flow
$x$ = longitudinal coordinate
$\alpha$ = angle of attack
$\beta$ = $\sqrt{1-M_\infty^2}$
$\rho$ = density

*Subscripts*

$c$ = calculated
$m$ = measured

## Introduction

THE undesirable effects of the finite dimensions of wind tunnels have been a problem as long as there have been wind tunnels. "Corrections," based on simple theoretical considerations, have long been applied to measured data to account for boundary effects. Unfortunately, there are categories of wind-tunnel tests for which such simple corrections cannot be used, and these include the most interesting and challenging regimes of modern aeronautics, namely those of transonic flight and of V/STOL.

In the transonic regime, boundary corrections are not usually possible for two reasons: first, transonic tunnels are "ventilated" (they have slotted or perforated walls whose effects are complicated and do not lend themselves to simple theoretical descriptions) and, second, transonic flow is inherently nonlinear, so that effects like boundary interference are not additive and the idea of "corrections" fails. All aeronautical engineers today are aware of alarming cases of poor agreement between wind-tunnel and flight measurements at transonic speeds, some of which are most probably related to unknown boundary effects.

In the V/STOL regime, there is again the matter of nonlinearity. The aerodynamics of a V/STOL vehicle is profoundly affected by the energized, vortical wake of its lift/propulsion system. The effects of such wakes are not simply additive, so that again meaningful corrections cannot be applied. In V/STOL testing of high-lift, low-speed configurations, in fact, it is often obvious that tunnel boundaries grossly deflect the wake and well recognized by aerodynamicists that the experiment is, therefore, meaningless.

These are flight regimes where theoretical methods are especially difficult and wind-tunnel testing is badly needed. The transonic case (at least) is also one in which high accuracy is often required of wind-tunnel results. In principle, boundary effects can always be minimized by testing smaller models in larger tunnels, but in both the transonic and V/STOL regimes this would have to be carried to rather alarming extremes; moreover, reduction of model size reduces test accuracy and Reynolds number.

These problems have been growing continually more serious for at least a decade, and have attracted the attention of concerned aeronautical engineers in several countries (see, for example, Ref. 1). It is not surprising, therefore, that a number of these engineers have independently come up with proposed solutions based upon the same logical principles. Namely, they have observed that, by measuring certain flow perturbations in the flowfield in the presence of any model configuration, one can ascertain whether boundary interference exists. If the tunnel boundaries (walls) can then be modified, it should be possible to approach, iteratively, interference-free flow in the tunnel.

This concept, which we called the "self-correcting wind tunnel," was first proposed in the open literature by Ferri and Baronti.[2] It was also the subject of the Sixteenth Lanchester Lecture and was set forth there in considerable detail.[3] A more general name for the concept is "adaptive-wall," which terminology describes categorically the research and development work being carried out by a number of individuals and organizations in several countries, some of which will be referred to, briefly, in this paper.

In application, the self-correcting concept can be described as an iterative procedure that provides a matching of an inner

Presented as ICAS Paper No. 76-02 at the Tenth Congress of the International Council of the Aeronautical Sciences, Ottawa, Canada, Oct. 3-8, 1976; submitted March 3, 1977; revision received June 23, 1977.

Index categories: Testing, Flight and Ground; Transonic Flow; Subsonic Flow.

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region and an outer region that comprise the total field about the vehicle under test. The flow chart for this scheme is illustrated in Fig. 1. The inner region lies entirely within the wind tunnel, encloses the model under test, and is reproduced in the experiment. The outer region extends from a suitable interface out to arbitrarily great distances and is simulated in the computer, i.e., by numerical modeling. The essential feature of the scheme is to match the two regimes at their interface (which, as already stated, is inside the tunnel) by iterative adjustment of the shape and/or properties of the tunnel's walls.

In its original concept, this process would be automated, so that the measurement of flow perturbations, the computation of the outer flowfield, and the mechanical adjustment of the walls would be continually updated. Readings of forces, moments, etc., at the model would be carried out only when the matching of conditions at the interface had been achieved to a specified accuracy, i.e., when a "green light" came on. We will mention, in this paper, some possible modifications of this wholly-automated embodiment of the concept.

This concept would seem to have a great deal of generality as regards the nature of the outer flow; there is no reason why this region has to be limited to the case of the infinite, unbounded, body of air in uniform motion. For example, the presence of the ground, provided only that it lies outside the interface, can be accounted for in choosing boundary conditions for the outer region. In principle, the earth's boundary layer could also be simulated; this might be necessary for accurate tests of surface vehicles and ground-effect machines.

Clearly, the scheme involves essentially three major components: instrumentation, computing hard- and software, and a method of modifying wind-tunnel walls. All of these have been provided and exercised in the Calspan self-correcting wind tunnel, a 1-ft transonic tunnel that is a two-dimensional embodiment of the concept, albeit nonautomated, now operating in Buffalo, N. Y. The next section of this paper constitutes a description of its features. In subsequent sections, we undertake to discuss the experience gained during the research with the Calspan tunnel and in the light of this experience to discuss aspects of future adaptive-wall tunnels, especially three-dimensional.

## The Calspan Self-Correcting Wind Tunnel

The Calspan self-correcting wind tunnel is a modification of an existing transonic tunnel. The original facility was a closed-circuit variable density tunnel with a nominal 1×1-ft test section. The modifications to make it self-correcting consisted of removing the aerodynamic test section, installing a two-dimensional test section with perforated top and bottom walls, and providing for auxiliary blowing and suction at the top and bottom walls.

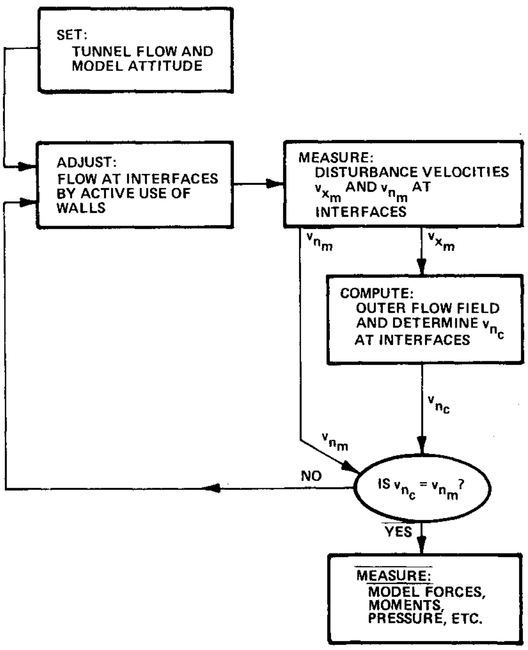



Fig. 1 Self-correcting wind-tunnel scheme.

The test section is 12 in. high, 10 in. wide, and 66 in. long, and the plenum chamber behind each perforated wall is divided into a total of 18 individual plenum chambers, ten on the top and eight on the bottom wall. The rationale for this design has been described previously;[3,4] briefly, it provides a means for approximating, in a stepwise fashion, the flowfield for a lifting two-dimensional airfoil. As shown in Fig. 2, each individual plenum is connected to vacuum and pressure lines, through individual control valves, to obtain either inflow or outflow through the walls. The vacuum source is an auxiliary compressor, the compressor discharge is vented into the wind tunnel pressure shell, and the flow is reintroduced into the mainstream in the diffuser. The pressure source is the wind-tunnel stilling chamber.

A view of the model and test section instrumentation is shown in Fig. 3. The airfoil model is an NACA 0012 section with a 6-in. chord and completely spans the test section. It has a 2.5 in. wide metric section, supported by a three-component force balance on the tunnel centerline, and there is an adjacent row of orifices to measure the airfoil pressure distribution. The test section instrumentation, partially visible in Fig. 3, consists of two static pressure pipes each with 50 pressure orifices to measure the static pressure distribution outside of the wall boundary layers. In addition, 18 probes, each above the center of a plenum, are used to measure the flow angle outside the wall boundary layer.

The model flowfield inside the test section can be adjusted by auxiliary suction (or blowing) through the control valves until either the local static pressure or the local flow angle agrees with a desired value. This illustrates one of the basic features of the self-correcting wind tunnel, i.e., flowfield control is achieved without the necessity of knowing the complex flow processes that occur at and through the walls.

The Calspan self-correcting wind tunnel has been used extensively to establish modes of operation, to calibrate it as a conventional wind tunnel, to utilize wall control to improve tunnel-empty characteristics, and to perform iteration experiments to minimize wall interference effects on models. These results are summarized in Ref. 4. The results obtained in one series of iteration experiments, at $M_\infty = 0.725$ with the model at $\alpha = 2$ deg, are presented in Fig. 4. The data labeled "8-ft tunnel" were obtained in two-dimensional tests with the 6-in.-chord model in the Calspan 8-ft tunnel, and the results of those experiments have been reported in Ref. 5. These data are regarded as essentially free from wall interference effects and are used to check the accuracy of the data obtained in the self-correcting wind tunnel.

The data labeled "1-ft tunnel (simulating conventional tunnel)" are data obtained in the 1-ft tunnel operated with wall control to approximate a conventional tunnel. That is, wall control was used to establish a uniform axial pressure distribution in the empty tunnel. The model was then installed and tested with the control valves set in the same position.

A comparison between the 8-ft-tunnel data and the data obtained in the 1-ft tunnel illustrates the wall interference on a 6-in.-chord model in a 12-in. test section. It should be noted that the airfoil is supercritical at all angles of attack and there is a shock wave present. The wall interference effects on lift are moderate, on pitching moment are large, and each is consistent with solid wall interference for lift coefficients greater than 0.1. The effects on drag are appreciable and indicate open-jet interference for subcritical conditions. If the available porous-wall theoretical and experimental corrections[6,7] were applied to these data, wall interference equal to about one-fourth the solid-wall interference would be predicted. The data shown here are contradictory as to open-

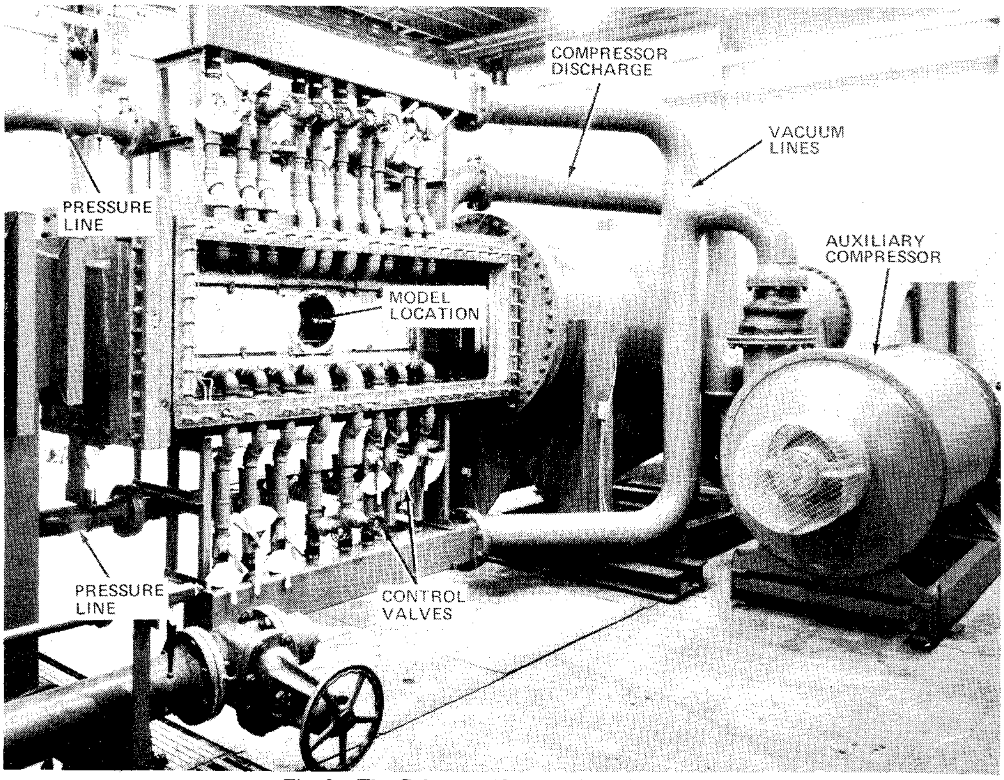



**Fig. 2 The Calspan self-correcting wind tunnel.**

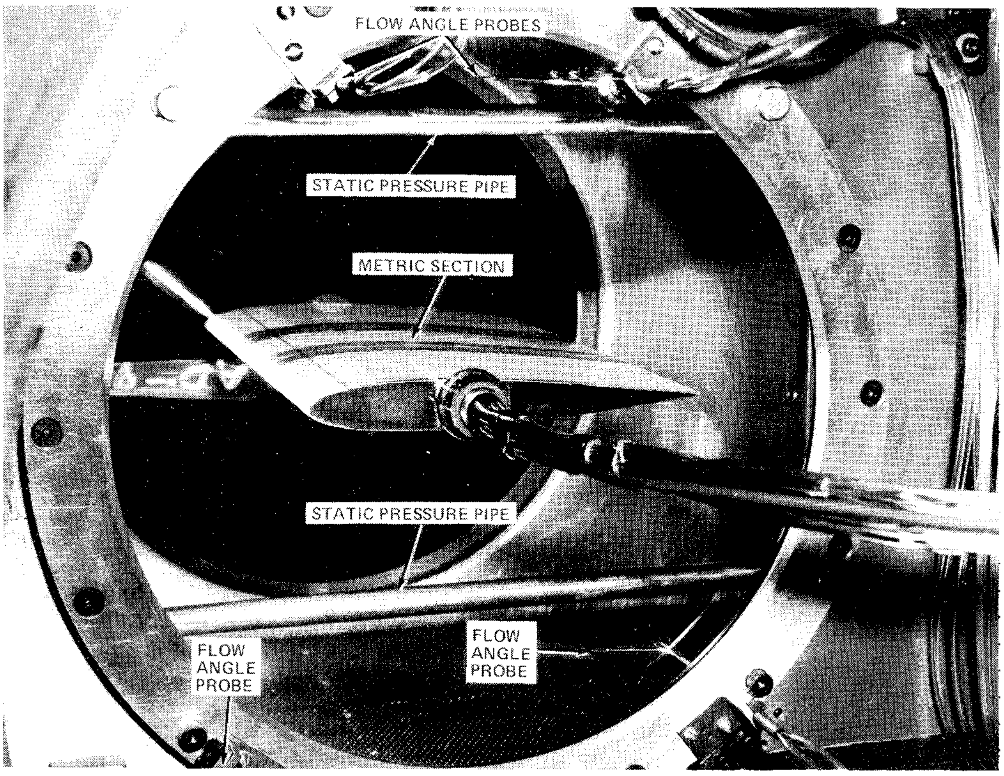



**Fig. 3 Test section of the self-correcting wind tunnel.**

jet or solid-wall interference, and this probably reflects the fact that it is an oversimplification to attempt to categorize these results within the usual concepts of solid-wall or open-jet interference. The interference includes important effects such as changes in the separation point and changes in the shock-wave position at supercritical conditions.

The data obtained in the successive iteration experiments at $\alpha = 2$ deg are indicated in Fig. 4 by numerals, and the comparable data point in a simulated conventional facility is indicated by a solid symbol. The first iteration experiment was to set the flowfield to the values predicted by an approximate theory,§ and it can be seen that it overcorrected the lift, but it brought the drag and pitching moment into much closer

§Prandtl-Glauert theory using a vortex, a doublet, and a source to model the airfoil.

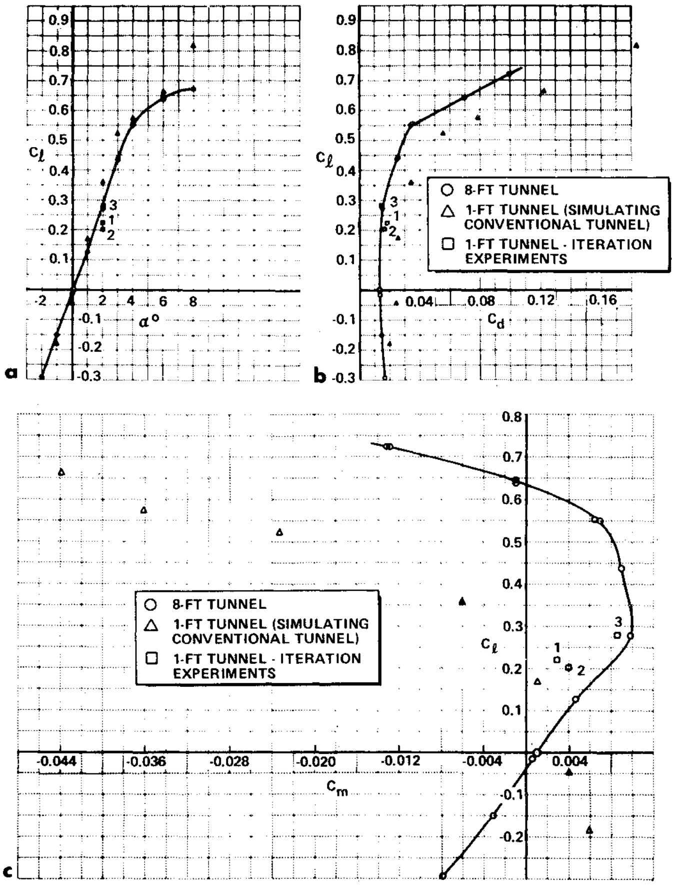
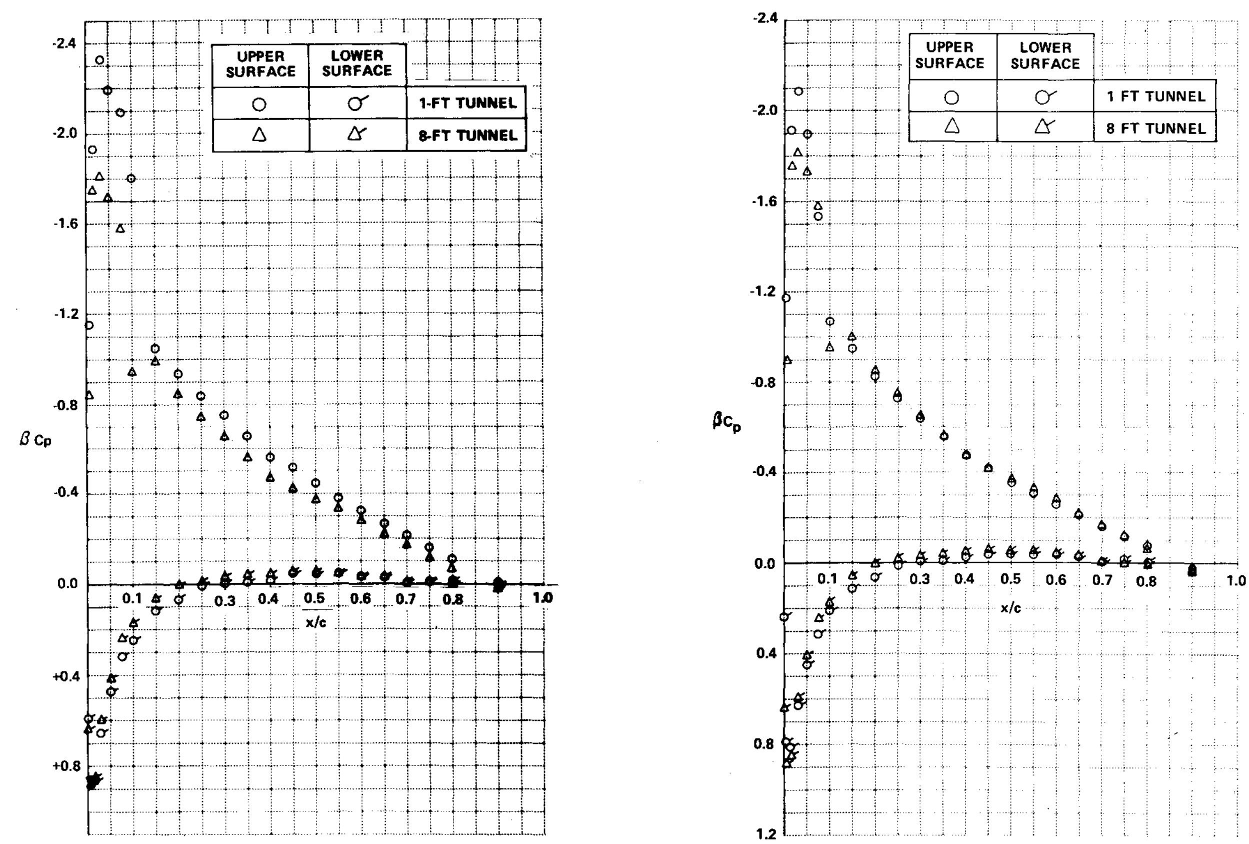



Fig. 4 The effects of wall control at $M_\infty = 0.725$, $\alpha = 2$ deg: a) lift coefficient vs angle of attack, b) lift coefficient vs drag coefficient, c) lift coefficient vs pitching-moment coefficient.

agreement with the interference-free data. The second iteration, using the theoretical methods described subsequently, improved the drag but produced further errors in the lift and pitching moment. The third iteration brought the lift and drag into excellent agreement and the pitching moment to within 5-7% of the 8-ft-tunnel data. The exterior flow functional relationship matching criteria indicated that further iterations were required. Limitations in the auxiliary pumping system precluded further wall adjustments.

Iteration experiments were made, and convergence has been achieved at other test conditions. Typical results for the pressure distributions on the airfoil in one such case are given in Fig. 5. In Fig. 5a, the comparison is shown between the 8-ft-tunnel data and the data from the 1-ft tunnel operating to simulate a conventional tunnel. The differences, including a small shift in the position of the shock wave on the upper surface, are apparent. The comparison of the 8-ft-tunnel data with the data after seven iterations in the 1-ft tunnel operating in the adaptive-wall mode is shown in Fig. 5b, and the agreement generally is excellent. The discrepancies at the nose are comparable with the repeatability of the 8-ft-tunnel data, but are consistently high. The seven iterations were carried out until convergence was obtained within the limits of resolution of the static pressure and flow inclination measurements at the interfaces, namely about 0.002 psi and 0.1 deg, respectively. At this tunnel condition these limits are equivalent to differences in $v_x/U_\infty$ of 0.0006 and in $v_n/U_\infty$ of 0.0015, which are approximately 1-2% of their peak values. It was found, however, that the airfoil data were in equally good agreement after the second or third iteration, at which point convergence had beeen obtained only within about 0.006 psi and 0.3 deg, respectively. Hence, we conclude that our initial convergence criterion may be too restrictive.

With the results presented in Figs. 4 and 5 and those reported in Ref. 4, we feel that the self-correcting concept has been demonstrated for the case of subcritical interfaces and




a) Simulated conventional tunnel

b) Self-correcting wind tunnel after seven iterations

Fig. 5 NACA 0012 airfoil pressure distributions at $M_\infty = 0.55$, $\alpha = 6$ deg.

conclude that it is practical to implement the concept. The procedures for controlling the inflow and outflow through the walls are quite simple, and a high degree of flowfield control can be achieved with existing instrumentation and techniques. To illustrate, it is feasible to control the flowfield static pressure to about 0.025% in two or three sequential wall adjustments. The computational time to evaluate the functional relationships is on the order of a few seconds. Consequently, there should be no basic difficulty in automating completely the measurements at the interfaces, the evaluation of the functional relationships, and the wall control.

## Discussion

In this section, the various components that make up the self-correcting wind-tunnel scheme are discussed, namely, wall adjustment, measurement requirements, exterior flow calculations, and control logic. The discussion is based on experience to date with the Calspan tunnel and with a view toward extending the concept to three-dimensional, automated applications.

### Wall Adjustment

The Calspan tunnel, as mentioned, has perforated top and bottom walls and is provided with auxiliary air for control of the pressures in subdivided plenum chambers. Obviously, several other types of wall adjustment could be proposed for the adaptable-wall scheme, such as control of the shapes of impermeable, flexible walls, and control of either wall porosity or slot width in the case of ventilated walls.[8-13]

The choice of plenum-pressure control for the Calspan tunnel was made after many years of experience at Calspan with porous-wall transonic wind tunnels. It was anticipated that both in- and outflow through the walls would be required and that these could be achieved by adequate control of plenum pressures. It should be emphasized at this point that it is control of the perturbation quantities, namely velocity components, *at the interface* that is required, and it was believed that this control would be afforded by manipulation of the plenum pressure. It is not necessary (nor, we believe, possible) to determine a wall flow-through characteristic that permits either the streamwise or normal velocity component to be related uniquely, in a predetermined way, to plenum pressure or pressure difference;[14] it is necessary to measure the quantities at the interface.

Perforated walls with variable control of pressure in subdivided plenum chambers also provide an important feature in connection with cancellation of shock waves that impinge on the tunnel walls. Clearly, in a perfect simulation of unconfined flow, none of the shock waves produced by the model would be reflected in any way from the wall; this would be one of the features assured by proper matching at the interface. Any practical wall configuration, however, provides only an approximation to this ideal situation. The wall is adjusted at only a finite number of points, and data from the inner and outer flow regions are matched at only a finite number of stations. The result is "global" cancellation of shock reflection, but not the ideal, point-by-point cancellation exhibited by a perfect simulation. In this situation, perforated plenum walls afford a minimum of local reflections, because they possess the property of admitting more, or less, through-flow where the local pressures are greater, or smaller, than the point-by-point ideal. This forgiving property is one of the reasons why porous walls have been used, for some 20 years, in transonic wind tunnels.

To put this argument into different words: By subdividing the plenum chambers and providing local control over their pressures, one retains the well-known shock cancellation property of porous wall tunnels, and one requires it to act only locally (over the dimension of one chamber), so that now "global cancellation" means cancellation within this short distance, which is relatively small compared to tunnel height and model dimensions. More detailed studies of these phenomena are being carried out at Calspan and at the University of Arizona.

The appeal of flexible, adjustable, impermeable tunnel walls presumably is twofold: 1) that one of the flow-perturbation quantities, namely the flow inclination, might easily be measured by measuring the slope of the wall; and 2) that another quantity, namely static pressure, can be measured by means of simple wall orifices. We believe that the first of these presumed advantages is illusory, because the wall has a boundary layer and the relationship between the wall slope and the slope of streamlines at the interface (which must be outside this boundary layer) is complicated and unknown, especially in the presence of wall curvature and shock impingement.

As one looks ahead toward three-dimensional applications, the appeal of flexible, impermeable walls becomes even more elusive. We foresee major difficulties in attempts to deform a flexible wall in two dimensions, to match three-dimensional flow at an interface, and in predicting the slopes of three-dimensional boundary-layer displacement surfaces.

Although, in three dimensions, the use of subdivided plenum chambers with pressure control may involve considerable plumbing, there appears to be no other disadvantage to this method. Moreover, porous walls have distinct practical advantages over impermeable, deformable walls. It is our experience that the model tends to establish its own flowfield and hence controls approximately two-thirds of the inflow and outflow at the walls. In the Calspan embodiment of the self-correcting tunnel, the auxiliary pumping system is used only to augment the control exerted by the model; in effect, to control only the adverse effects of the wall interference and not to establish the entire flowfield! Within this context, the ideal impermeable, deformable wall might be a flexible membrane, and subsequent adjustments to the membrane would compensate for the solid-wall interference.

It should be noted that the walls of several of the plenum chambers of the Calspan tunnel have linearly distributed, rather than uniform, porosities; these linear porosities are mechanically variable.[3,4] It is easy to imagine that adjustment of porosity (or slot width), area by area, could also be provided mechanically in a three-dimensional tunnel, but unfortunately this alone would not provide for both in- and outflow through the tunnel walls. One possibility is that the walls should converge in the flow direction so much as to cancel all inflow.

### Measurement Requirements

Sensor and instrumentation requirements have received continuing consideration in our research with the two-dimensional self-correcting wind tunnel, and we have examined all techniques that are known to be available. Static pressure is an obvious choice for measurements of one of the boundary values, because of the inherent simplicity. Static pressure can be resolved to $10^{-3}$ psi, using commercially available transducers, and in some instances meaningful measurements have been made with a resolution of about $3\times10^{-4}$ psi. Those accuracies are more than adequate for the present purposes. In the Calspan tunnel, static pipes are used and they extend upstream into the contraction section and downstream into the diffuser. An equally useful technique would be to utilize rails similar to those at the NRC.[15] The important point, for porous-wall wind tunnels, is that wall measurements of static pressure are not reliable because of a measurable pressure difference across the wall boundary layer when there is inflow or outflow.

There are several choices for the second, or redundant, measurement: 1) a static-pressure measurement at another interface, 2) direct measurement of a gradient, 3) mass-flow measurements through the walls to infer the normal velocity component, 4) LDV measurements of both the longitudinal and normal velocity components, and 5) aerodynamic probes to determine the local flow angle. All of these techniques were examined carefully and are discussed briefly. It was concluded that use of aerodynamic probes offered the greatest possibility for success.

A measurement of static pressure at a second interface is appealing. It has not been used in the Calspan research because the size of our tunnel and the desired accuracies limit the utility of this technique. If the interface spacing is restricted to 1/10 the airfoil chord, the pressure differences between the interfaces are comparable with the measurement resolution, and that would compromise the experiment.

There are techniques for the direct measurements of flowfield gradients. The technique is to oscillate a sensor, for example, a hot-wire anemometer,[16] and to record the output through a phase-lock amplifier. The technique can be applied to any sensor, in principle, and it should be possible to use the method to determine the normal gradient of the longitudinal disturbance velocity. However, it did not seem practical for our research because it would require excessive instrumentation, e.g., 18 oscillators, 18 phase-lock amplifiers, etc.

Measurements of the mass flow through the walls to infer the normal velocity component is appealing, and it was attempted in the present research. It was demonstrated, both theoretically and experimentally,[14] that the normal velocity component was amplified through the wall boundary layer. Moreover, the magnitude of the amplification depended on the local pressure gradient, the local boundary-layer characteristics, and gradients of the local boundary-layer characteristics. The amplification can be as large as a factor of six, and it does not seem practical to calibrate for the amplification. Consequently, this technique was discarded.

LDV techniques are relatively new and advances are still being made. In its present state of development, the LDV technique does not appear to offer any advantages over aerodynamic probes, except that it is nonintrusive, and it does have some limitations for our applications. For example, the LDV technique generally requires that the flow be seeded with an aerosol of particles to scatter the light. It has been demonstrated[17] that the particle velocity tends to lag the flow velocity if there are strong velocity gradients present, such as in shock waves. This limitation can be relaxed somewhat if the data are analyzed statistically, but that is regarded as an excessive complication for our purposes, and the LDV technique was not attempted.

Aerodynamic probes for measuring the local flow angle is a well-established technique. One method for measuring both velocity components is to use either crossed hot wires or dual thin-film anemometers. The deficiency with both of these sensors, however, is that the performance of both devices is degraded if oil films accumulate on the surface, and most closed-circuit facilities have some oil contamination. They were not considered further for that reason.

Another basic application of aerodynamic probes is to measure the local static pressure at two points on a body and to calibrate that pressure difference as a function of flow angle. The probe sensitivity depends on the body configuration, and the most sensitive is a circular cylinder in crossflow. Another configuration with a high sensitivity is a hemisphere mounted on a cylinder. Both of these are very attractive because of their high sensitivity and, in principle, it should be possible to resolve flow angles to less than 0.01 deg. However, the scale of the Calspan experiment precluded either of these configurations because the probe sizes would introduce excessive blockage if a fixed probe were used at each plenum location.

Translating probes to survey a finite length of the test section are a possible alternative, but they must be constructed carefully to prevent extraneous errors due to mechanical limitations. Weeks[13] used a translating probe to survey the normal velocity components in a slotted test section and found that corrections were required that were comparable with the measured angles. To illustrate the accuracies required, if a translating probe is used to survey a 6-in. length and if the probe resolution of 0.01 deg is to be preserved, the translating device must introduce normal deflections no larger than 0.001 in. Translating mechanisms were not used for that reason.

As noted earlier, it was concluded that the most promising technique was to use fixed probes to measure the local flow angle above each plenum section. The probes used are commercial devices and consist of two hypodermic tubes with an o.d. of 0.025 in. and an i.d. of 0.015 in. The two tubes are mounted side-by-side and the tube ends are chamfered at $\pm 45$ deg to the stream direction. These probes have been calibrated extensively, and it was determined that the probe sensitivity nominally is $\Delta p/q \approx 2\alpha$, and the probe resolution is about 0.03 deg. Probes were calibrated over an angle range of $\pm 5$ deg in ¼ deg increments and were found to be linear to within the resolution limits and with no unusual behavior in the vicinity of $\Delta p/q = 0$. They have been calibrated at Mach numbers ranging from 0.55 to 0.95, and the slopes of the calibrations change by 10-30% over that range.

Our probe measurements represent the greatest experimental uncertainty, and this stems at least in part from their small size. It was found that a microscopic oil film collects on the probe tip during long running periods. This does not affect the slope of the calibration curve but it does produce a zero-shift. A procedure has been established for setting the wall control to obtain the desired static pressure distribution and then the probes are flushed with a solvent before probe data are recorded. With these procedures, probe measurements have been repeatable with an accuracy ranging approximately 0.03-0.10 deg, depending on the individual probe. Many of the uncertainties that stem from the small scale of the experiment would be minimized in large-scale wind tunnels. For example, large-scale wind tunnels could utilize flow angle probes with a hemispherical tip 3/16 in. diam, and these are insensitive to oil film contamination.

The measurement techniques developed in our two-dimensional research can be applied directly to three-dimensional developments. As will be noted in subsequent discussion of calculation procedures, the only measurements required are the longitudinal velocity component and the velocity component normal to the interface; the same as those now being measured. Consequently, the present sensors, instrumentation, and measurement techniques could be applied directly to a three-dimensional embodiment.

The present measurement techniques would also be applicable to V/STOL wind tunnels; however, further instrumentation must be provided for that application. It presently is anticipated that the vorticity and momentum in the energized wake will have to be determined. This is not a new problem, and procedures have been reported in the literature.[18] One technique is to survey the wake with a standard pitch-yaw probe with pitot and static orifices. These measurements, the pitot-static difference and the yaw and the pitch angles, define the three velocity components and the vorticity can be determined. In this instance, it should be possible to use a traversing probe because the flow angles would be large.

#### Exterior-Flow Calculations

The principal theoretical aspect of the adaptive-wall concept is the evaluation of the functional relationships for unconfined exterior flow. This entails calculation of the flowfield exterior to the interface, with the distribution of one of the measured flow-disturbance quantities prescribed as boundary values. In connection with the Calspan self-correcting wind tunnel, techniques based on inviscid small-disturbance theory have been used throughout.

The inviscid approximation is appropriate because the measurements are made sufficiently far from the model to be well outside any of its boundary layers or wakes. Moreover, they are made far enough from the walls to be outside wall boundary layers as well. The decision to use small-disturbance theory was made early in these studies because it was believed that this would provide satisfactory accuracy for our purposes. All our experimental experience to date verifies that this is true. Consistent with the small-disturbance approximation, it was found convenient in two-dimensional flows to work in terms of the disturbance velocity components streamwise and normal to the interfaces $v_x$ and $v_n$, respectively, instead of the quantities actually measured. That is, the linear approximation was used to convert the static pressure disturbance into $v_x$ and the flow inclination into $v_n$.

In compressible two-dimensional flows that are subcritical at the interfaces, the Prandtl-Glauert equation is the appropriate form of the small-disturbance equations. All the experiments to date in the Calspan tunnel have been in this regime, so that a great deal of practical experience has been obtained with Prandtl-Glauert techniques. The basic procedure developed for the exterior-flow calculation is the so-called multipole expansion (MPE) technique.[19] One of the measured distributions, $v_{n_m}$ say, is expanded in a series, the terms of which are the normal velocity components induced by fundamental singularities that satisfy the Prandtl-Glauert equation. Our theoretical studies indicated satisfactory results over a wide range of model-to-interface-size with a six-term series that included a source, vortex, two doublets, and two quadrupoles. These singularities are all located at the model quarter chord. A least-squares fit to the measured data determines the singularity strengths, which, in turn, are used in the series expansion of the streamwise component to evaluate the corresponding unconfined-flow distribution $v_{x_c}[v_{n_m}]$. A similar procedure is used to evaluate $v_{n_c}[v_{x_m}]$ when $v_{x_m}$ is chosen as the boundary condition for the exterior flow. Thus, the MPE provides both an interpolation fit to the measured data and a convenient evaluation of the functional relationships based on that fit.

The MPE has been used in most of the Calspan experiments and probably is adequate because of the generally satisfactory agreement between the initial 1-ft-self-correcting-tunnel data and the 8-ft-tunnel data.[4]. Overall, experience from experiments to date confirms that evaluation methods based on small-disturbance theory are consistent with the measurement accuracy and interpolation procedures.

In two-dimensional flows that are supercritical at the interfaces, the transonic small-disturbance equations are appropriate. Although experiments have not yet been carried out in this regime, W. J. Rae of Calspan has developed a computer program for this application. This is a finite-difference method along the lines developed in Refs. 20-23 but with suitable adaptations to treat the interface geometry. The data for this program will have to be handled differently from the MPE interpolation. The most promising method, based upon initial experience in subcritical flows, is to use a smoothing spline fit[24,25] to the measured data. This should provide excellent definition of the required boundary values. The presence of shock waves, when they extend beyond the interfaces, would be taken into account in the fit.

The three-dimensional case is very similar, in principle, to the two-dimensional. The additional dimension leads to lengthier calculations, but does not add any essential differences. There are, of course, three velocity components including $v_t$ tangential to the control surface and perpendicular to $v_x$ and $v_n$. However, as shown by Erickson,[26] $v_t$ is not independent of $v_x$ at the interface and so need not be considered further. Therefore, the use of $v_x$ and $v_n$ as alternative boundary conditions will be continued.

MPE procedures have been developed[26] in three-dimensional subcritical flow along the lines discussed above, again based on solutions of the Prandtl-Glauert equation. The original three-dimensional MPE is based on point singularities all located at the same place on the model. Most of the development has been carried out for interfaces that extend upstream and downstream and have a uniform elliptical cross section. Extension to other cross sections, e.g. rectangular, can be carried out easily. Unfortunately, the original MPE does not evaluate the functional relationships accurately enough over as wide a range of model-to-interface size as does its two-dimensional counterpart. However, by replacing selected point singularities with singularity distributions, a modified MPE can be tailored to particular model configurations. For wings, the modified MPE developed by Erickson is accurate over a significantly larger range of span-to-interface width than the original point-singularity MPE.

As an alternative to the MPE in three-dimensional subcritical flow, a method has been developed[26] based on a distribution of source panels following Hess and Smith.[27-29]. This offers promise of an accurate, efficient, and less configuration-oriented way of evaluating the functional relationships. Another promising alternative would be a vortex-lattice procedure. These approaches are simply applications of well-proven contemporary calculation techniques to the exterior-flow calculation.

Three-dimensional flows that are supercritical at the interface have received only a little attention. However, finite-difference methods are applicable here, too, although the resulting calculations would probably be relatively lengthy and expensive. Ferri et al.[30] already have developed such a method for circular interface cross sections by combining a trigonometric series expansion in the azimuthal coordinate with a relaxation technique in the axial and radial directions. Similar techniques probably can be used for more practical cross sections, such as ellipses or rectangles.

The V/STOL case presents a fundamentally different problem for calculation of the exterior flow. This case is characterized by a propulsion-system efflux which generally interacts strongly with the aerodynamic surfaces to generate a highly deflected, energized trailing vortex system that exits through the interface into the exterior flow. The presence of the efflux exterior to the interface requires that it be modeled theoretically, whereas in the cases discussed previously, no exterior flowfield modeling was necessary other than the inviscid, small-disturbance approximation. Moreover, the exterior flow no longer can be assumed to have only small disturbances about the basic flight velocity. That is, near hover and during transitional flight, the disturbances introduced by the vehicle and its efflux may be comparable to, or even larger than, the flight velocity. However, the velocities involved should be low enough so that except for the interior of the efflux (which will be modeled in a simplified fashion anyway), incompressible flow should be a reasonable approximation.

We are unaware of any attention having been given to the V/STOL exterior-flow calculation with propulsion-system efflux present. It will be necessary to establish the accuracy required in modeling the efflux. However, by the time the efflux reaches the exterior flow, it should be deformed into the so-called "vortex zone" in which the trailing vorticity is the dominant feature and in which the efflux makes a relatively small angle with respect to the freestream. In this situation, it might be feasible to model the efflux realistically by relatively simple means, say, by an adaptation of three-dimensional jet-flap theory.

### Control Logic

A key aspect of the overall concept is the question of how to proceed toward unconfined flow if the functional relationships are not satisfied. That is, following Fig. 1, if the tunnel walls have been adjusted, the appropriate quantities measured, the exterior-flow calculation carried out, and it is found that $v_{n_c}$ does not agree with $v_{n_m}$, the question remains as to how the wall control should be readjusted to approach unconfined flow.

Early in our investigation of the concept, it was assumed that wall control would be available in such a way that the tunnel operator could adjust the wall porosity and plenum pressure to set up any desired $v_n$ distributions along the interfaces. Alternatively, it was assumed that he could set up any desired $v_x$ distributions. (Clearly, both $v_x$ and $v_n$ cannot be specified independently because changes in the wall porosity and/or plenum pressure will affect both components in a coupled fashion.)

The entire self-correcting wind-tunnel system can be represented in an operational notation with either $v_x$ or $v_n$ prescribed at the interfaces. The two representations differ only by exchanging $v_x$ and $v_n$ wherever they appear. For the case where $v_n$ is set, the distributions $v_{x_m}(x, \pm h)$ measured along the interfaces in the wind tunnel are

$$v_{x_m}(x,h) = W_+ [v_n(x,h), v_n(x,-h)] \quad (1)$$

$$v_{x_m}(x,-h) = W_- [v_n(x,h), v_n(x,-h)] \quad (2)$$

where $W_+, W_-$ are operators representing the interior flow in the tunnel with the model present, and $v_n(x, \pm h)$ are the distributions set up at the interfaces in the experiment.

The exterior-flow functional relationships may be expressed in a similar fashion and then rewritten in a form suitable for iteration with no loss of generality as

$$v_n(x,h) = (1-k_+) v_n(x,h) + k_+ E_+ [v_{x_m}(x,h)] \quad (3)$$

$$v_n(x,-h) = (1-k_-) v_n(x,-h) + k_- E_- [v_{x_m}(x,-h)] \quad (4)$$

where $E_+, E_-$ are the operators representing the exterior flow calculation, and $k_+, k_-$ are relaxation factors, which must be chosen so as to provide rapid convergence, as discussed below.

The iterative procedure begins by setting estimated interface $v_n$ distributions for a given model configuration. Measurements in the tunnel flowfield then give $v_{x_m}$ [the operations expressed in Eqs. (1) and (2)], which enable the exterior-flow calculations to be carried out [as expressed in Eqs. (3) and (4)] to determine the new $v_n$, say $v_{n_c}[v_{x_m}]$. These are set up in the next tunnel test, etc., until unconfined flow conditions are achieved by satisfying Eqs. (1)-(4) simultaneously.

Studies of this procedure before the self-correcting test section was built – in particular, attempts to find suitable choices of the relaxation factors $k_\pm$ – required the interior flow to be simulated theoretically. Ferri and Baronti,[2] in their early paper, asserted that for a linear system $k_+$ and $k_-$ should be 0.5. However, they did not consider the problem in the same iterative framework as that considered above. Our early theoretical studies of the control logic were carried out by simulating the flow within the tunnel numerically with appropriate computer programs. These simulations were carried out both at low speeds and under supercritical flow conditions for which shock waves in unconfined flow extended beyond the tunnel wall locations. The results of these studies are described fully elsewhere,[4,19] but it suffices here to say that for low-speed lifting and nonlifting flows with either $v_x$ or $v_n$ prescribed at the interfaces, it was found empirically that convergence was achieved most rapidly with $k_+$ and $k_-$ equal to 0.25. For supercritical nonlifting flows with $v_n$ prescribed at the interfaces, on the other hand, $k_+$ had to be varied from step to step, and values between 0.1 and 0.3 were used. Evidence from additional supercritical numerical experiments indicates that the constant values of $k_\pm$ should be replaced by distributions of $k_\pm$ as functions of distance $x$ along the interfaces, varying from 0.1 far upstream and downstream to 0.5 near the airfoil.

The assumption of suitable controllability was borne out by subsequent experiments. Systematic procedures were developed for setting the desired distributions, particularly $v_x$, which has been used in most of the subcritical flow experiments to date. Values of $k_\pm$ of about 0.25 were used in the experiments although smaller values were used at the lower interface in some iterative steps.

Recent studies by Lo and Kraft[31] have demonstrated convergence numerically for the range $0 < k_\pm \leq 1.0$ in supercritical flow and have found rapid convergence for $k_\pm = 0.5$. Also, they have carried out analytic studies showing that values of $k_\pm$ near 0.5 are optimum for nonlifting two-dimensional bodies in the linear, Prandtl-Glauert formulation for subcritical flow. In a related theoretical study, Sears[32] has carried out an analysis for lifting and nonlifting bodies similar to that of Lo and Kraft and has obtained consistent results. The difference between the analytic result that $k_\pm$ should be near 0.5 for most rapid convergence and our numerical simulation result of $k_\pm = 0.25$ is not understood. The experimental determination of the best choice remains to be carried out.

The control logic in three dimensions should be similar to that in two dimensions. Lo and Kraft have extended their two-dimensional subcritical analysis to the axisymmetric case. In addition, Sears,[32] in the theoretical study mentioned above, has carried out the analysis of subcritical axisymmetric flow about a corrugated cylinder with a sinusoidally-varying radius, as well as about an infinite-chord lifting wing with downwash that varies sinusoidally in the streamwise direction. In these cases, the interface has a circular cross section. The resulting optimum relaxation factors are found to be functions of wavelength, but lie roughly between 0.5 and 0.7. Thus, there is every indication that the iterative properties in three dimensions are closely related to those in two dimensions.

## Conclusions

Experience to date with the two-dimensional self-correcting transonic tunnel at Calspan has convincingly confirmed the power of the concept. Specifically, two-dimensional transonic flow, with imbedded shocks, about a lifting airfoil, exhibiting gross wall-interference effects, has routinely been converted into substantially unconfined flow by straightforward application of the procedure for iterative matching of inner and outer flow regions at the interface. This experience, together with studies under way, leads to the conclusion that three-dimensional applications can be made in both the transonic and V/STOL flight regimes.

Demonstrations of the abilities of the Calspan tunnel at higher Mach numbers await modifications of that tunnel to provide more auxiliary air for plenum control.

The adaptive-wall procedure seems to offer, uniquely, a way to assess the accuracy of simulation of flight conditions in transonic and V/STOL wind tunnels and a basis for eliminating boundary interference when the simulation is found to be faulty. Carried to its consistent conclusion, the scheme would be used as an integral part of each experiment, automatically adapting the walls to the requirements of each configuration, Mach number, power setting, angle of attack, etc., before any test results are recorded.

It is easy to imagine, however, that the adaptive-wall equipment of any given tunnel would be turned off during many experiments, where great accuracy is not required and where a convenient, approximate wall configuration has previously been arrived at and appears adequate for the test in question. This suggests to us a "hierarchy" of applications of the scheme; for example:

1) It might be used only as a part of the calibration procedure of a new wind tunnel, to determine a standard wall configuration, subsequently to be fixed, by carrying through the measurements, calculations, and iterations with a model of typical dimensions and properties at a typical Mach number.

2) It might be used as in 1, but to predetermine schedules of wall configuration as functions of the major test variables:

flow speed, total lift, model power output, etc. Neither 1 nor 2 would involve permanent instrumentation, automation, or permanent dedication of elaborate computer equipment to the wall-interference problem.

3) Finally, it might be embodied in permanent installations of hard- and software as described above. The tunnel operator would retain the options of switching the equipment off, truncating the iterations ("coarse setting"), or carrying them through to all available accuracy.

## Acknowledgments

This research has been sponsored by the Office of Naval Research and the Air Force Office of Scientific Research under Contract No. N00014-72-C-0102, with supplemental support by the NASA/Langley Research Center; by the ONR and AFOSR under Contract No. N00014-77-C-0052; and by the NASA/Ames Research Center under Contract No. NAS2-8777. The authors wish to acknowledge the sustained contributions of their colleagues W. J. Rae, J. P. Nenni, and P. A. Catlin to this overall program of research in adaptive-wall technology. Special recognition is given to J. Nemeth Jr. and A. F. Gretch for their unique contributions to mechanical design and tunnel operation, respectively. Finally, the authors have benefited in large measure from the constructive criticism and advice of Morton Cooper of ONR and Milton Rogers of AFOSR.

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