Convergence Schemes for an Adaptive-Wall Wind Tunnel

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A series of experiments was carried out to demonstrate the feasibility of using the side-wall pressure distribution as the flow variable in the wall-interference compatibility assessment, and to exploit a one-step method in a ventilated adaptive-wall wind tunnel. The iterative and one-step convergence methods were applied using different flow variables to investigate their relative merits. It was shown that the number of iterations could be reduced to a minimum with the application of the one-step convergence scheme. The same unconfined conditions obtained with the streamwise and normal velocity components could be achieved using the resultant velocity from side-wall pressure. Side-wall pressure measurements require simple instrumentation and reduce the total testing time, which are some of the major requirements in production testing. The one-step scheme reduces the testing time by eliminating the intermediate experimental iterations. In the present research, wall corrections were determined using measured influence coefficient matrices, which were evaluated at two control levels. The effects of Mach number, model, suction, and blowing on the influence coefficients were investigated along with the superposition and linearity characteristics. Experiments were carried out at velocities from $M = 0.5$ to 0.75 and at angles of attack from $\alpha = 0$ to 4 deg.

Nomenclature

a_0	= speed of sound at standard atmospheric conditions
c	= airfoil chord
C_{ij}	= element of the influence coefficient
C_p	= pressure coefficient
M	= Mach number
N	= number of control points
p	= pressure
P_t	= total pressure
u	= streamwise disturbance velocity component
u_r	= $U_r - U_{ref}$
U_r	= resultant velocity
U_{ref}	= longitudinal freestream velocity
x	= airfoil longitudinal axis, origin at $X/c = -0.25$
X	= longitudinal coordinate
Y	= normal coordinate
α	= angle of attack, deg
Δp	= pressure change in a plenum compartment
ΔV	= disturbance velocity change at a control point

Subscripts

c	= calculated
i	= ith control point
j	= jth plenum compartment
k	= number of plenum compartments
m	= measured

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Introduction

WALL interference has been a long-standing problem in wind-tunnel testing. Over the years, various mathematical methods have been developed based on potential theory to correct the wind-tunnel data. However, at high subsonic speeds and especially in transonic flow, wall corrections become very large and wind-tunnel data may not be corrected simply by using methods based on small perturbations. Since the introduction of the adaptive-wall wind-tunnel concept[1,2] as an alternative method to eliminate or minimize the wall interference by actively controlling the flow near the walls, extensive research has been done to develop such tunnels.[3]

In general, assessment of the wall interference and proposed correction schemes for adaptive-wall wind tunnels requires measurement of two flow variables along the control levels at or near the walls of the test section. Any two conveniently measured variables can be used in the adaptive-wall process. In ventilated test sections, the flow variables can be measured using either intrusive techniques, such as probes,[4] or nonintrusive techniques, such as Laser Doppler Velocimetry (LDV)[5] or side-wall static pressure measurements.[6] Depending on the method and type of the variables to be measured, complexity of the instrumentation and the total testing time may vary considerably. At NASA Ames Research Center, the LDV system is currently used for the velocity measurements. Although this measurement technique is nonintrusive and accurate, its instrumentation is complex and collection of velocity data takes a long time. The LDV system has to be moved from one control point to the other to get the velocity distribution along the control level. If the ventilated adaptive-wall wind tunnels are to be used for production testing, total testing time should not be excessive. The purpose of the present research was to provide solutions to the just-mentioned problems by developing fast and accurate schemes with nonintrusive measurement techniques with simple instrumentation.

To simplify the instrumentation and to reduce the data-taking time, side-wall pressure has been proposed as the flow variable.[6,7] One of the major goals of the present experiments is to validate the use of side-wall pressure distribution in the assessment of wall interference. Side-wall pressure measurement is a nonintrusive technique similar to LDV. Moreover, it is faster and requires simple instrumentation.

One of the alternatives to reduce the testing time is to minimize the number of iterations, preferably to a single iteration, in the convergence process. For this reason, a one-step convergence scheme was developed and applied experimentally. The main purpose of the one-step scheme is to eliminate the intermediate experimental iterations by simulating them on the computer. Once the corrections are determined, new distributions of the flow variables at the control levels are predicted using the influence coefficients instead of taking the measurements of the flow variables again. Cumulative pressure corrections are determined and applied in the plenum compartments as the final experimental step.

In the present study, the emphasis was given to the convergence schemes with two-level compatibility assessment,[8] which requires the measurement of one flow variable at two levels, unlike the one-level method,[2] in which two flow variables have to be measured at one control level. Adaptive-wall experiments were carried out using both the one-step and the iterative convergence schemes to determine their relative merits.

In the iterative and one-step methods, influence coefficients were employed for a systematic estimation of the pressure corrections. In previous experiments at NASA Ames Research Center,[5] only the normal velocity components were used to implement the idea of using the influence coefficients for rapid convergence to an interference-free flow. In the present research, influence coefficients were evaluated at different Mach numbers, with and without the presence of a nonlifting model, for both suction and blowing, using the side-wall pressure, and the streamwise and normal velocity components. Superposition and linearity of the influence coefficients were investigated. In the application of the convergence schemes, separate influence coefficients were used for suction and blowing. One aspect of the present research was to determine the limitations and effectiveness of the influence coefficients at different Mach numbers and model angles of attack.

Convergence Schemes

Basically, the adaptive-wall concept requires an iterative process in which two independent flow variables are measured; unconfined flow is calculated using the convenient functional relationships; calculated and measured flow variables are compared to determine the wall interference; and wall boundary conditions are modified to eliminate the wall interference to achieve interference-free flow conditions.

The iterative process can be entirely experimental or it can be carried out computationally by using a one-step convergence scheme.[6,7] The one-step scheme applied in the present study is similar to that proposed by Dowell[9] using the influence coefficients to determine the new distributions of the flow variables at the control levels after adjusting the control variables. However, the present scheme is not subject to the assumption of linearity and simulates the experimental iterative steps numerically on the computer rather than trying to compute the required pressure corrections in one calculation. Another difference compared to the other proposed single-step convergence schemes[9,10] is that the unconfined flow solution and the pressure corrections are determined at each computational step. Influence coefficient matrices may vary depending on the wall interference for different model and flow configurations. Since this situation is not known prior to the experiments, and experimental conditions may force the use of different combinations of influence coefficients for suction and blowing, the present method is more suitable for practical applications by comparison.

In the iterative method with the two-level compatibility assessment,[5,8] one flow variable is measured at two control levels. The flow variable at the first level is used to evaluate the functional relationships at the second level applying far-field boundary conditions for unconfined flow. The effect of wall interference is determined by comparing the measured flow variable with the unconfined solution at the second level. Once the wall-interference assessment is made, pressure corrections are calculated using influence coefficients for the second level, and local plenum pressures are adjusted to achieve interference-free flow. New values of the flow variable are measured. If they are not consistent with the interference-free flow conditions, the process just described is repeated until the results agree within the range of experimental error. In the one-step method, after the pressure corrections are evaluated, new values of the flow variables are not measured unlike the iterative scheme; instead, they are predicted at two control levels using influence coefficients. This eliminates the intermediate flow measurements and the application of the pressure corrections in the plenum compartments, which are the contributing factors to the large testing time.

The success of the one-step convergence scheme depends on how accurately the velocities are predicted at control surfaces for given pressure changes. Therefore, the influence coefficients should be determined precisely if the number of iterations during the experiment would be reduced to one. If the influence coefficients are not very accurate, this method will probably not create one-step convergence. Even then, the number of iterations will be reduced considerably compared to the pure experimental iterative method.

Unconfined Flow Solution

In the adaptive-wall concept, a suitable functional relationship has to be evaluated to find the unconfined flowfield in the chosen domain. As noted previously, one of the purposes of this study was to use the side-wall pressure distribution as the flow variable. Since the flow angle was not measured in the present experiments, the resultant velocity calculated from the side-wall pressure could not be resolved into its components. Therefore, unconfined flow calculations were carried out approximately by neglecting the normal velocity component. To find the error introduced with this assumption and the feasibility of this approach in the adaptive-wall concept, the iterative steps of the schemes with the streamwise velocity distribution were reconstructed computationally implementing the resultant velocity distribution in the unconfined flow calculations. In this case, the resultant velocity distributions were calculated from streamwise and normal velocity components, which were measured using the LDV system. It was determined that the error was about 4% in the assessment of the wall interference.

In the present experiments, the linearized compressible potential flow equations were used to solve the unconfined flowfield. The control levels were chosen far enough away from the model and top and bottom wall boundary layers so that the regions of complicated flow patterns and viscous effects were avoided. The undisturbed freestream flow was always subsonic, and the disturbances at the control surfaces were assumed to be sufficiently small so that the small disturbance equations would be a valid approximation. At zero angle of attack, since the flow is symmetrical with respect to the centerline of the test section, only the upper half of the computational plane was used to solve the unconfined flowfield. In the lifting cases, unconfined flow calculations were performed in the upper and lower computational planes separately.

Influence Coefficients

For the present ventilated tunnel, adaptive-wall control is produced by using the local plenum pressure control. Plenum pressure corrections required to eliminate the wall interference are determined using the influence coefficients. An influence coefficient is defined as the change in the velocity at a control point for a unit change of pressure in the active plenum compartment.

By assuming that the superposition is valid, it is possible to form the influence coefficient matrices from the following equation:

$$\Delta V_i = \sum_{j=1}^{j=k} C_{ij}\Delta p_j, \quad i = 1,\ldots,N \tag{1}$$

In Eq. (1), ΔV_i is the total change in the velocity due to the pressure changes in more than one plenum compartment. Each element of the influence coefficient matrix is denoted as C_{ij}, which is the influence coefficient at a control point. Δp_j is the pressure change in an active plenum compartment.

Experimental Apparatus

Experiments were conducted in the ventilated adaptive-wall tunnel at NASA Ames Research Center. It is a continuous-flow, indraft wind tunnel equipped with a flexible downstream throat to vary the test section Mach number and an auxiliary system to provide suction and blowing of air through plenum chambers. The adaptive-wall test section with slotted walls was of rectangular cross section, 25- × 11-cm area, and 61 cm long. The test section had separate top and bottom plenums, and each was divided into 10 plenum compartments with variable partitions. Upper and lower walls each had 10 slots with an open area ratio of 12%. Eight out of 10 plenum compartments were used actively. The first plenum compartment was chosen as the reference plenum for freestream values. The last one was shown to be ineffective for the control of the flow. A schematic of the test section arrangement of the adaptive-wall wind tunnel is illustrated in Fig. 1.

In the present experiments, a 7.62-cm-chord NACA 0012 airfoil model without a boundary-layer trip was used. The blockage ratio of the model in the test section was 8.3% and it was expected to create significant wall interference effects at high speeds. Experimental data and numerical codes available in the literature were used to compare with the measured model pressure distributions.

Standard instrumentation was used to measure tunnel total pressure and total temperature. Static pressure distributions in the plenum compartments, on the model, and at the control levels were measured using a six-unit Scanivalve. At the control levels, side-wall pressure distributions were measured through a number of pressure tappings located on one of the side-walls.

The LDV system was used to measure the streamwise and normal velocity distributions at the control points. Measurements were taken at the centerline of the test section along the streamwise direction. When the LDV system was used, the sidewall with the static pressure tappings was replaced by a clear sidewall. The maximum number of control points at each level was 15 in the LDV experiments. The number of control points and their location were the same as those used in the side-wall pressure measurements. At each point, 1000 samples/measurement were typical for mean velocity calculations in the LDV experiments and the accuracy was about 1 m/s. Flow was seeded with 0.5-μ-diam polystyrene spheres. The seeding technique avoids the deposition of the seeding material on the test section windows.[11]

Evaluation of the Influence Coefficients

For each plenum compartment and control point, influence coefficients were evaluated for suction and blowing, which were applied symmetrically in the top and bottom plenum compartments. The validity of superposition and the effects of the Mach number and the model on the influence coefficients are crucial for practical applications. The degree of dependency and the limitations should be explored carefully. For this reason, various experiments were carried out to investigate the characteristics of the influence coefficients. The complete set of influence coefficients was determined at $M = 0.5$.

Effect of Suction and Blowing

Experiments showed that the disturbance velocity distribution at the control surfaces could be altered significantly by varying the local plenum pressures. In the case of normal velocity distribution, the greatest velocity changes occur directly under the active plenum compartment. As compared to the normal velocity component, completely different velocity distributions were observed for resultant and streamwise velocities. The effect of suction or blowing is greatest at the control points downstream of the active plenum compartment; it is practically negligible at the upstream stations. The effect of suction is to produce a negative disturbance velocity, although blowing produces a positive disturbance.

Effect of Mach Number

The effect of the Mach number on the influence coefficients at a downstream control point when suction and blowing are applied into plenum 4 is illustrated in Fig. 2. In this typical example, ΔV, the change in u_r, was calculated from side-wall pressure in the presence of a nonlifting model. For blowing, the influence coefficients change very little with Mach number. However, some differences are observed in the suction case. Figure 3 shows the influence coefficients from the streamwise component u without the model created by approximately the same blowing and suction. In the Mach

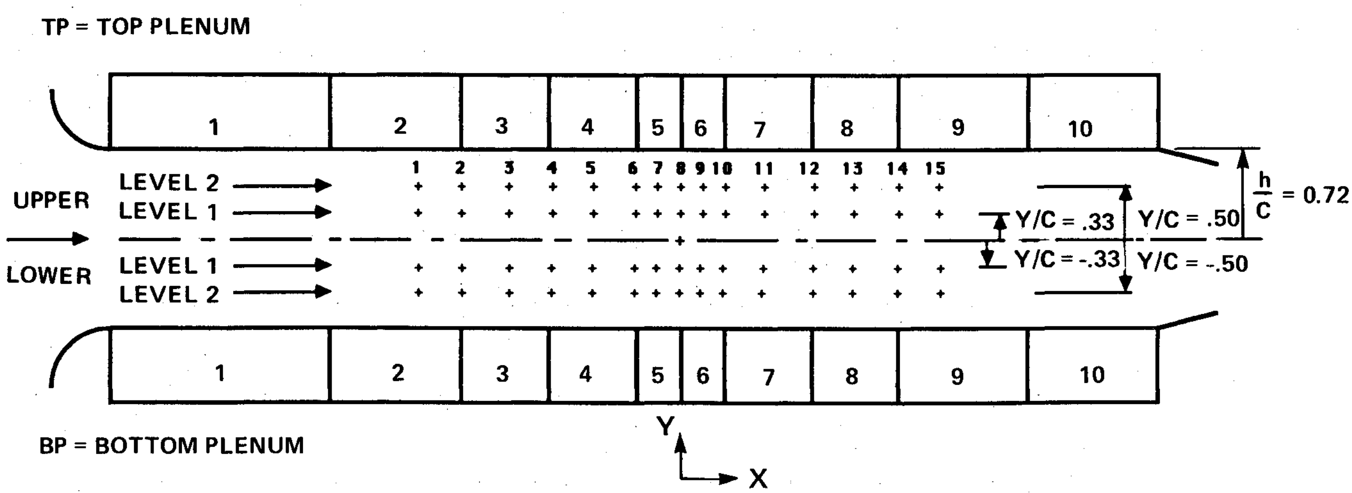

Fig. 1 Test section arrangement for the adaptive-wall wind-tunnel experiments.

number range of interest, the effect of Mach number on the influence coefficients is negligible in both cases.

Effect of Model

The effect of the presence of a nonlifting model is presented for the resultant velocity u_r at different Mach numbers in Fig. 4. The effect of the model is negligible for blowing, although some discrepancies are observed for suction. Some of the differences are attributed to the changes in the freestream velocity because of the movement of the normal shock at the downstream throat and the variation in the suction pressure. Since all of the influence coefficients were evaluated at zero angle of attack, the effect of a lifting model remained unknown. Experiments for the application of the convergence schemes were carried out at angles of attack up to 4 deg to determine the effectiveness and limitations of the influence coefficients.

Superposition

The velocity change produced at any control point due to the pressure changes in more than one plenum was assumed to be equivalent to the sum of velocity changes produced at that point by the same pressure changes in each plenum if applied separately. A superposition check for resultant disturbance velocity is given in Fig. 5. In this case, the top and bottom plenum compartments were treated separately. Suction and blowing were first applied in the top plenum compartment (plenum 6). The same procedure was repeated for the corresponding bottom plenum compartment while the others were kept closed. Influence coefficients were calculated for each case and superimposed to compare with those obtained when the top and bottom plenum compartments were opened to suction and blowing together. A good agreement is observed between two influence coefficients, which validates the assumption of superposition in the range of experimental error.

Linearity

Over the Mach number range of interest, the influence coefficients are approximated as piecewise linear for suction and blowing. For suction, nonlinearity is observed at low Mach numbers. However, a linear fit is found as a good approximation. As the Mach number increases, the linear approximation gets better for both suction and blowing. Since suction and blowing created different effects, two separate sets of influence coefficients were used in the construction of the influence coefficient matrices. The effects of the nonlinear coefficients were not investigated theoretically or experimentally because the linear approximation was found satisfactory for practical applications.

Application of the Convergence Schemes

Adaptive-wall experiments were performed at Mach numbers ranging from 0.5 to 0.75 and at angles of attack of 0, 2, and 4 deg. The existing auxiliary system provided insufficient suction and blowing of air for the control of the flow at higher Mach numbers. In the adaptive-wall experiments with the

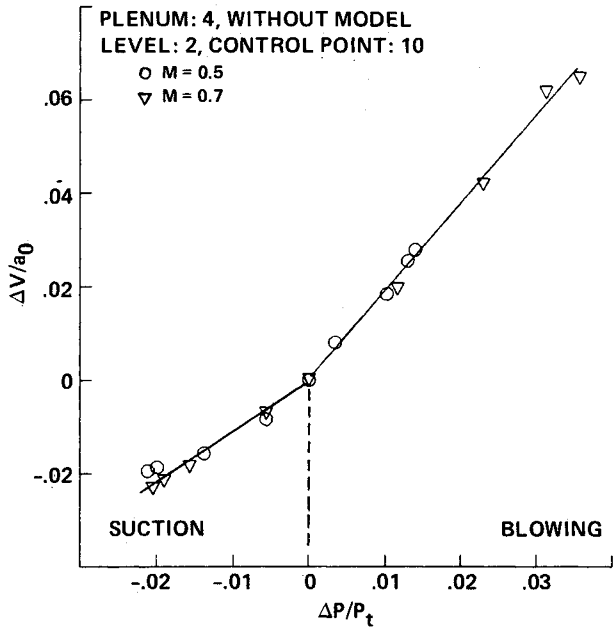

Fig. 3 Effect of Mach number on the influence coefficients determined from the streamwise velocity.

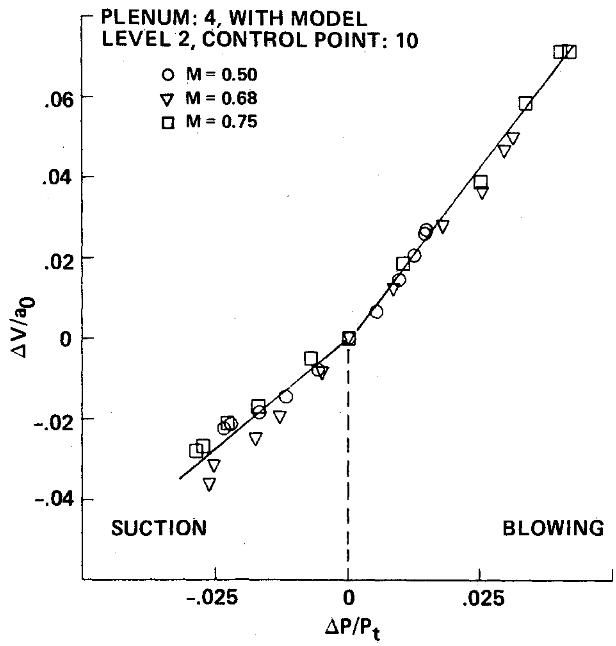

Fig. 2 Effect of Mach number on the influence coefficients determined from the side-wall pressure.

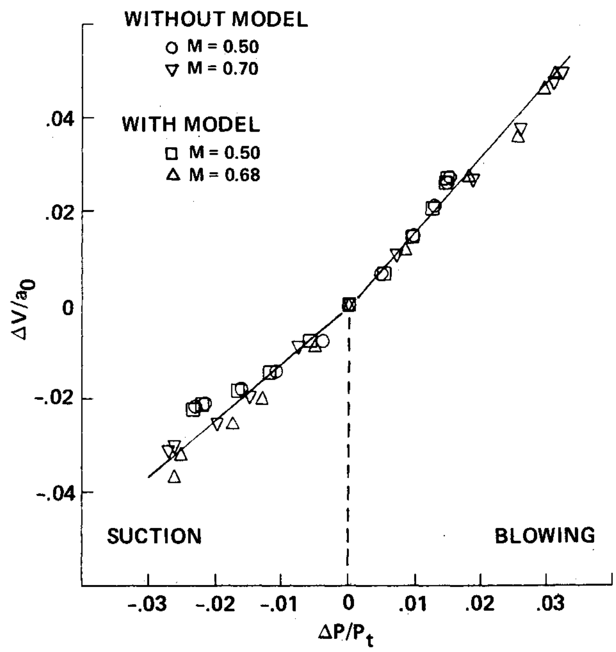

Fig. 4 Effect of the model on the influence coefficients determined from the side-wall pressure.

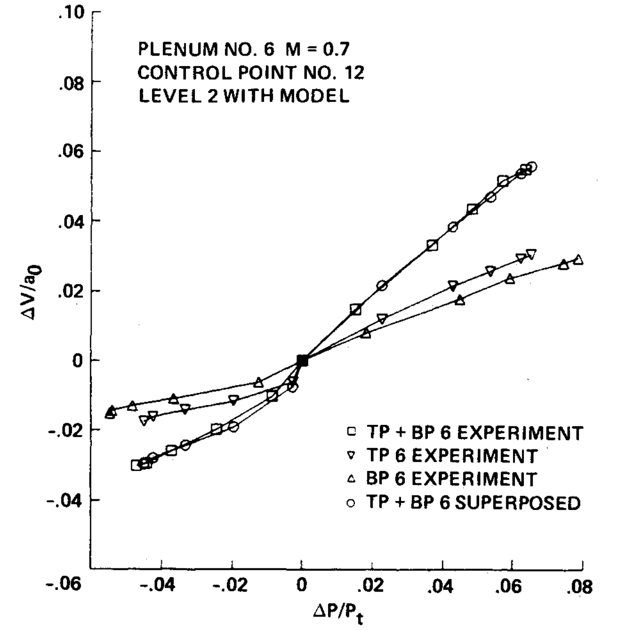

Fig. 5 Validity of the superposition for the influence coefficients.

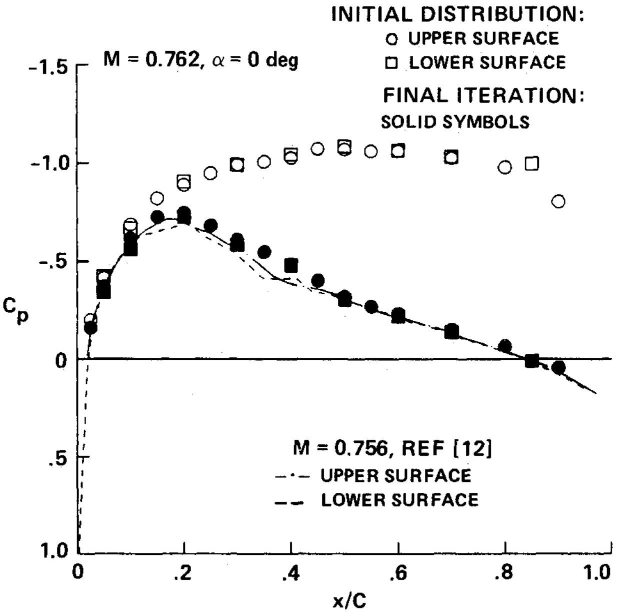

Fig. 6 Comparison of the model pressure distributions in the application of the iterative scheme using the side-wall pressure.

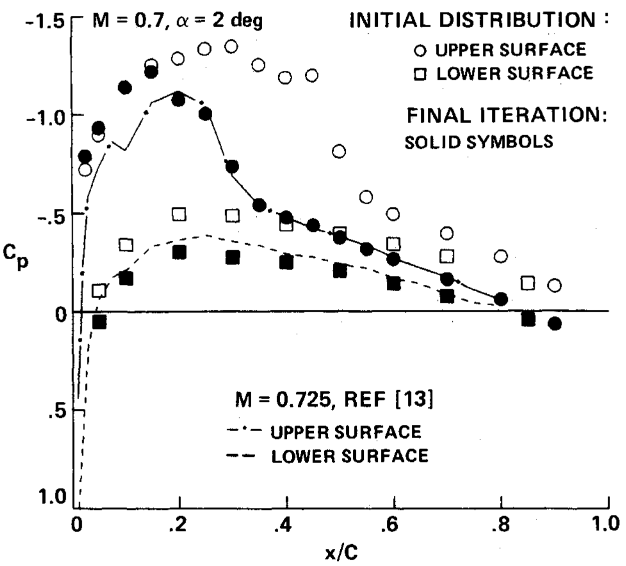

Fig. 7 Comparison of the model pressure distributions in the application of the iterative scheme using the side-wall pressure.

ventilated-wall tunnel, test section Mach number varied when suction and blowing were applied in the plenum compartments. During the experimental iterative process, after each iteration, test section Mach number was approximately adjusted back to the initial value. In the one-step method, a first-order correction, which was deduced from calibration tests, was applied to simulate this change in the test section Mach number.

In the present experiments, the root-mean-square (rms) error criterion was used as a measure for convergence. It was defined as

$$\text{rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(u_{m,i} - u_{c,i})^2} \tag{2}$$

where $u_{m,i}$ and $u_{c,i}$ are the measured and the calculated velocity components at the ith control point, respectively. N is the number of measurement points.

Experiments Using the Side-Wall Pressure Distribution

Velocity components were measured with the LDV system along the centerline of the test section away from the side-wall boundary layers. However, side-wall pressure measurements were subject to the viscous effects caused by the presence of boundary layers. In the subcritical case, comparison of resultant velocity distributions from side-wall pressure measurements with those from LDV showed that the boundary-layer assumption holds fairly well. At supercritical speeds on the model or in a lifting case, a complex flowfield may exist on the side walls. To explore these effects and to validate the feasibility of the velocity simplification, the iterative and one-step convergence schemes were applied using side-wall pressure distributions.

The typical results are given in the form of airfoil pressure coefficients. It should be noted that the present experiments were not designed to create a data base a NACA 0012 airfoil section. Instead, the model pressure distributions were measured and compared with the other experimental and numerical data to demonstrate the consistency of the results and the applicability of the methods presented in this research.

Subcritical Nonlifting Case ($M \sim 0.75$, $\alpha = 0$ deg)

Because of the blockage effect, the maximum Mach number attained in the test section was limited to approximately $M = 0.75$ with a nonlifting model when there was no wall control. At these flow conditions, the iterative scheme was applied with the side-wall pressure distribution. Initially, the flow was supercritical at some points of both control levels. Although the model was not at incidence, wall effects were very severe on the velocity distributions and the model pressure coefficients at this Mach number. Convergence to the interference-free flow was achieved in three iterations. The comparison of the measured model pressure distributions before and after the convergence with the experimental data from ONERA[12] shows the drastic improvement (Fig. 6).

Supercritical Lifting Case ($M \sim 0.70$, $\alpha = 2$ deg)

In this lifting case, a weak shock wave was initially present at the control level closer to the model in the upper half. The comparison of this case to the one with the streamwise velocity distributions at the same Mach number and angle of attack indicated that the side-wall pressure measurements underestimate the velocity distributions at the control levels. Using the

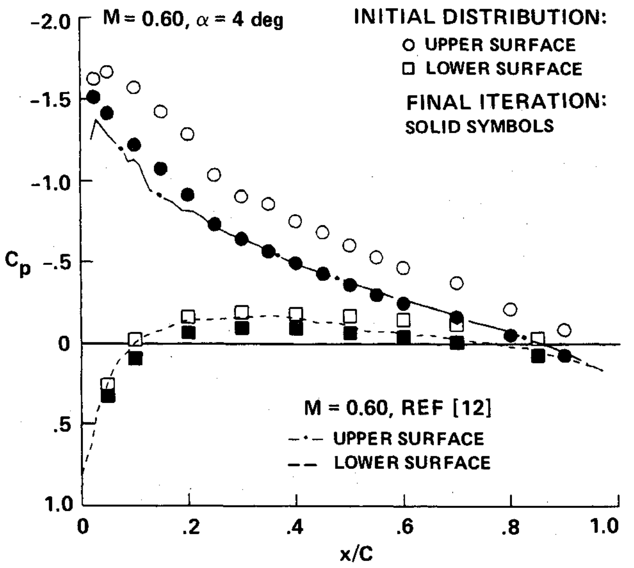

Fig. 8 Comparison of the model pressure distributions in the application of the iterative scheme using the side-wall pressure.

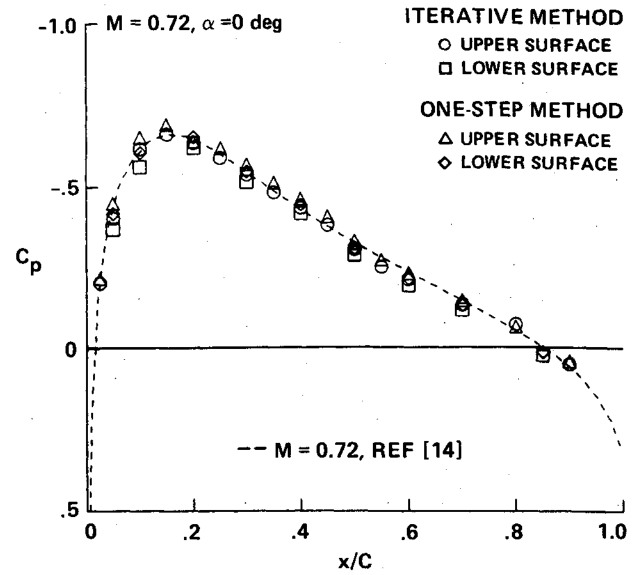

Fig. 10 Comparison of the model pressure distributions obtained from the application of the iterative and one-step schemes, subcritical flow.

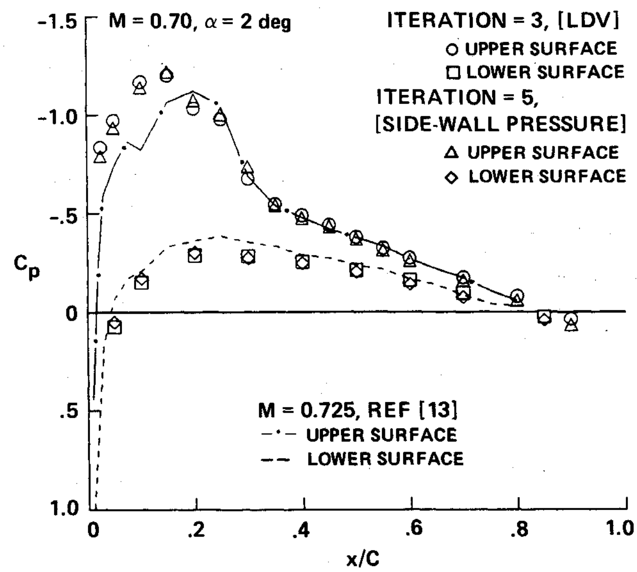

Fig. 9 Comparison of the model pressure distributions in the application of the iterative scheme using the LDV and the side-wall pressure.

estimated resultant velocity distributions, the iterative scheme was applied and wall interference was eliminated after five iterations. Model pressure distributions measured after the initial and final iterations are compared with the Calspan[13] data in Fig. 7. The initial position of the shock wave is at 50% chord of the model. In the final iteration, it was moved to a position where it is in good agreement with other results.

Supercritical Lifting Case ($M \sim 0.60$, $\alpha = 4$ deg)

In this typical example, model incidence was set to a maximum of $\alpha = 4$ deg, which was considered sufficiently high for the purpose of these experiments. It took six iterations to arrive at the unconfined flow solutions. Figure 8 shows the initial and final model pressure distributions and the experimental data from ONERA[12] for comparison. In general, the agreement between the final distribution and the other data is good, and the discrepancies are attributed to the differences in the angle of attack ($\alpha_{\text{ONERA}} = 3.94$ deg).

Comparison of the Convergence Schemes

LDV Scheme vs Side-Wall Pressure Scheme

The iterative and one-step convergence schemes were applied using both streamwise velocity (measured with the LDV system) and side-wall pressure distributions. The experiments have shown that the two-level compatibility assessment method can be applied successfully with the side-wall pressure distribution and converges to unconfined flow conditions.

In Fig. 9, the comparison of the measured model pressure distributions shows the consistency of the results from both applications in the supercritical lifting case ($M \sim 0.7$, $\alpha = 2$ deg). Both experiments were conducted at about the same Mach number and angle of attack. Although the number of iterations is higher in the experiments with the side-wall pressure measurements, the testing time for each iteration was about 5 to 8 times shorter compared to the experiments with the LDV measurements (based on the same number of control points, including on-line analysis and adjustment of the plenum pressures).

Both pressure measurements were compared with the data from the Calspan 8-ft tunnel ($Re = 10^6$ and transition strip at $x/c = 0.10$ at the leading edge). Although it was taken at a slightly higher Mach number, it provides a good comparison for our purpose. Shock location seems to be in good agreement, and boundary-layer trip is probably the cause of the local separation and the lower pressure coefficient at the leading edge.

Iterative Scheme vs One-Step Scheme

The purpose of the one-step method is to obtain the unconfined flow conditions in a single iteration if possible, or otherwise to minimize the number of iterations. Experiments were conducted to demonstrate the relative merits of the iterative scheme and the one-step convergence scheme developed in this study.

Subcritical Nonlifting Case with Side-Wall Pressure Distribution

In this case, the iterative and one-step convergence schemes were applied using the side-wall pressure distribution at $M \sim 0.72$. Experiments with both schemes produced similar pressure coefficients (see Fig. 10).

As seen from the comparison, convergence to the unconfined flow was achieved in one iteration using the one-step method, although three iterative steps were required to arrive

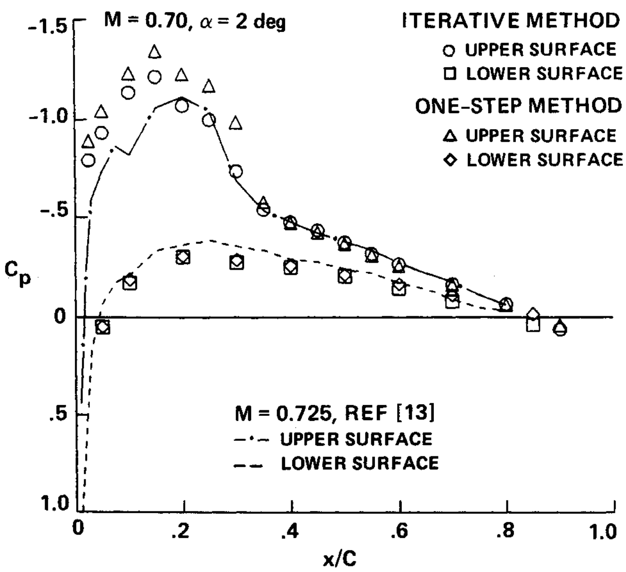

Fig. 11 Comparison of the model pressure distributions obtained from the application of the iterative and one-step schemes, supercritical flow.

at the same conditions using the iterative convergence scheme. The small discrepancies could possibly stem from the differences in the Mach numbers. Experimental data were compared with the numerical solution reported by Lock.[14] The comparison is reasonably good over the entire chord length. In general, Lock's solution is in good agreement with the Calspan wind-tunnel data[13] ($M = 0.725$, $\alpha = 0$ deg) (not presented here).

Supercritical Lifting Case with Side-Wall Pressure Distribution

In this application, experiments using the one-step convergence scheme did not produce the same results in one iteration compared to the iterative case. However, the effect of the wall interference on the model pressure distribution was reduced substantially, as seen in Fig. 11. The pressure coefficient is slightly higher in the region $0.025 \leq x/c \leq 0.30$, and the shock position is about 5% off further downstream compared to the iterative case. Imperfect matching in the velocity distributions in the same region is probably the main reason for the discrepancy. One more iteration would yield results similar to those obtained using the iterative scheme. In the application of the one-step method, the number of iterations was reduced drastically compared to the iterative case.

Testing-Time Comparisons

A comparison of the typical testing times in the application of the convergence schemes is given to determine the relative time efficiency of the preferred technique, the one-step convergence scheme using the side-wall pressure. Testing time for each iteration depended mostly on the measurement technique. Velocity measurements using the LDV system consisted of data taking, processing, and moving the LDV system along the control levels. For a total of 30 points at two control levels, collection of the LDV data took about 20 min for a nonlifting case and about 40 min for a lifting case. On the other hand, side-wall pressure measurements and data processing took about 1 min regardless of model configuration. Application of the pressure corrections in the plenum compartments contributed an average of 5 min, although the calculation of unconfined flow and pressure corrections were negligible, about 0.1 min.

Conclusions

A fast and reliable method for the elimination of the wind-tunnel wall-interference effects has been demonstrated. The main conclusions in connection with the use of this method are as follows:

1) The experiments demonstrated that it is feasible to use the side-wall pressure as a flow variable in the adaptive-wall convergence schemes. The measurement technique requires simple instrumentation and reduces total testing time considerably. The convergence schemes applied using the side-wall pressure yielded accurate and consistent results. Measurement of the model pressure distributions agrees well with the other experimental and computational data.

2) Existence of linear influence coefficients independent of Mach number and model presence permits a fast correction scheme. Influence coefficient matrices constructed using the superposition principle could be used to determine the pressure corrections at different Mach numbers, with and without the lift.

3) The use of the less complicated side-wall pressure instrumentation instead of the Laser Doppler Velocimeter measurement of velocity was found to reduce the total testing time by a factor of approximately 5. The one-step method of adapting the wall conditions to satisfy interference-free flow, using either the streamwise velocity or the side-wall pressure, further reduces the testing time by a factor of 2 to 3 when compared to the iterative scheme.

4) The adaptive-wall corrections determined by using the linearized flow equations provided sufficient control to achieve convergence to interference-free flow for both the subcritical and mildly supercritical flows.

Acknowledgments

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