WIND TUNNEL WALL INTERFERENCE

Perry A. Newman, Raymond E. Mineck, Richard W. Barnwell
NASA Langley Research Center
Hampton, Virginia

William B. Kemp, Jr.
College of William and Mary
Williamsburg, Virginia
About a decade ago, interest in alleviating wind tunnel wall interference was renewed by advances in computational aerodynamics, concepts of adaptive test section walls, and plans for high Reynolds number transonic test facilities. Selection of the NASA Langley cryogenic concept for the National Transonic Facility (NTF) tended to focus our renewed wall interference efforts. A brief overview and current status of some Langley sponsored transonic wind tunnel wall interference research are presented. Included are continuing efforts in basic wall flow studies, wall interference assessment/correction (WIAC) procedures, and adaptive (flexible) wall technology. It should be pointed out that for transonic flow conditions, wind tunnel wall interference is coupled to other tunnel flow phenomena not generally associated with subsonic flow and classical (linear) wall interference theory. Some of these related phenomena, such as flow quality, support interference, flow diagnostics, and transition studies, are discussed in other papers in this compilation. Understanding these phenomena is basic to proper unbounded-flow simulation in wind tunnels; however, it is not appropriate to repeat the material in this brief overview. Furthermore, much of what should be included here cannot be; a list of publications from Langley sponsored research over the past decade or so is included in order to summarize the total effort and to identify some of the individual researchers who have been involved.

**NASA Langley focus is transonic**

- Basic wall flow studies
- Assessment/correction procedures - WIAC
- Adaptive wall technology - flexible
In order to emphasize specific wall interference aspects, the basic wall flow studies summarized here have been grouped as slotted wall test sections, sidewall boundary-layer phenomena, wall interference data bases, and tunnel simulator code development. Activities pertaining to slotted test section walls include parametric studies of wall properties, use of such information in NTF test section design, and subscale design verification tests. These efforts are considered as customary wall interference research. Activities dealing with the response of the (solid) sidewall boundary layer to the model pressure field and its resulting influence on the test conditions are not so customary. It is primarily observed in airfoil testing and should be accounted for or alleviated; its influence is much less in 3-D. NASA Langley work in this area includes theory, experiment, and applications. Wall interference data bases and numerical wind-tunnel flow simulator codes are required for the development and verification of assessment/correction (WIAC) procedures; in addition, these pursuits have their own intrinsic value. Both 2-D and 3-D data bases, including wall pressure signature data, are being generated. Tunnel simulator CFD codes are being continually developed; governing flow equations include linear, transonic potential, and nonpotential approximations. The paper by South et al. in session 1 of this compilation is an example of our work in this area.

- Slotted test section walls
  - 6- by 19-inch TT parametric studies
  - NTF design/subscale NTF tests
- Sidewall boundary layer phenomena
  - Theory and experiment
  - Applications
- Wall interference data bases
  - 2D and 3D
  - Wall pressure data
- Tunnel simulator code development
  - Linear and transonic potential
  - Nonpotential
SLOTTED WALL PARAMETRIC STUDIES

6- by 19-Inch TT

The experimental phase of Langley's most recent parametric slotted wall flow study was conducted by Joel Everhart throughout 1984 in the 6- by 19-inch Transonic Tunnel (TT). His experimental setup is shown in the photograph; the single-slot test section wall configuration standing at the right has been removed, exposing the airfoil and opposite wall. A flow angularity probe is visible in the slot of the far wall, just ahead of the leading edge of the model. Pressure data were taken on the walls and model; flow angularity data were also taken in the test section. Variation of wall parameters was by means of readily interchangeable test-section "upper and lower" slotted-wall configurations. Wall parameters varied in this study include geometric openness ratio, number of slots at fixed openness, slat thickness, slat lip radius-of-curvature, and sidewall boundary-layer thickness. This was done using a 6-inch-chord NACA 0012 airfoil over a range of angles of attack (-4° to +4°) and tunnel Mach numbers (0.1 to 0.95). Data from this study are now being reduced; hopefully these data will aid in understanding the role of such parameters in the slotted-wall boundary condition.
The 0.3-m TCT sidewall boundary layer removal hardware consists of a pair of perforated panels inserted (flush-mounted) in the tunnel sidewalls upstream of the model location. These perforated panels extend from the floor to the ceiling of the test section and are approximately 6 inches wide, as shown in the top view photograph of the test section (top of the plenum chamber and the slotted wall removed). Visible in this photograph are the airfoil model, boundary layer bleed ducting, one of the four boundary layer sidewall rakes, and one of the two perforated panels. The holes in it were drilled using an electron beam technique and the surface was etched; this results in an unusually smooth surface considering the large number of holes in the plate. Two different hole configurations giving different porosities have been tested. The amount of the boundary layer mass flow removed from either of the sidewalls is controlled independently by two digital flow control valves and discharged directly to the atmosphere (passive system). At a Mach number of 0.76, the maximum bleed flow rate is about 2 percent of the test section mass flow rate; this amount of bleed capability is sufficient to significantly reduce the sidewall boundary layer displacement thickness. Recently, a cryogenic reinjection compressor (active system) has been installed and validated; the sidewall boundary layer mass removal capability has been expanded to cover the entire operating envelope of the 0.3-m TCT.
EFFECT OF SIDEWALL BOUNDARY LAYER BLEED

0.3-M TCT

The adverse influence of the sidewall boundary layer/model pressure field interaction on an airfoil test is most pronounced at supercritical flow conditions. Barnwell and Sewall have shown that for attached flow on the sidewall, the Mach number correction is approximately $-26 \times /b$, where $b$ is the tunnel span. When the airfoil shock waves intersecting the sidewall separate the sidewall boundary layer, then the resulting flow is very 3-D in nature; one tries to prevent this situation. In the 0.3-m TCT airfoil tests, the effect of upstream sidewall boundary layer bleed is most easily observed at supercritical flow conditions with high lift. Shown in the figure are midspan chordwise and several spanwise pressure distributions on an airfoil at the nominal tunnel conditions shown in the subtitle. Results are for tests without (O) and with (□) bleed (passive system); test section Mach numbers ($M_t$) and their corrected values ($M_c$), using Barnwell-Sewall approximations, are also given. As can be seen on the left, with bleed applied, there is an improvement of the midspan pressure recovery on the upper surface near the trailing edge of the airfoil; this suggests that with bleed the separation on the upper surface is significantly reduced. The more downstream location of the shock wave and higher normal force coefficient for the lower test section Mach number also indicate less separation. The spanwise distributions are on the right; at $x/c = 0.5$ it is seen that the separation induced by the shock is at the sidewalls. The flow appears to be less 3-D with bleed applied.

0.3 m TCT, $M_\infty, t = 0.76, R_c = 6 \times 10^6, \alpha = 4^\circ$

- $M_t = 0.759, c_n = 0.9, M_c \approx 0.74$
- $M_t = 0.743, c_n = 1.0, M_c \approx 0.73$

- No bleed $26^*/b = 0.022$
- With bleed $26^*/b = 0.012$
Suction requirements under the turbulent boundary layer of the contoured test-section liner near the model and on the model surfaces near the liner were determined as part of the liner-design procedure. This was done in the process of determining the effective displacement correction which had to be accounted for in the liner shape. Determination of the suction requirements in these turbulent-flow regions is not to be confused with what is required to determine the laminar-flow-region suction rates over most of the model. Suction is required on the liner "endplates" near the model juncture in order to keep the turbulent boundary layer attached through the adverse pressure-gradient regions which occur in the following regions: on approaching the model leading edge, through the aft-portion pressure-recovery regions, and near the concave corners on the lower surface. The liner blocks in these regions form a collar about the model containing suction panel blocks with slot/plenum/duct construction very similar to that used on the wing. These blocks are metal, but with molded fiberglass outer skin; they move with the model through angle-of-attack adjustments. The figure is a photograph looking downstream through the channel "above" the wing surface, and the suction panel blocks are the dark areas on the top and bottom liner "endplates."
SIDEWALL BOUNDARY LAYER CONTROL

LTPT

In order to reasonably approach two dimensionality in low-speed flows when testing multielement airfoils, some form of tunnel sidewall boundary layer control is needed. The large adverse pressure gradients induced by the high-lift airfoil can cause the tunnel sidewall boundary layer to separate and result in a decrease in airfoil lift. Tangential blowing was selected to provide local sidewall BLC near the airfoil; overall boundary layer thinning upstream of the model is accomplished by single suction slots on each sidewall. Five blowing boxes with tangential slots are available for each side of the tunnel and can be positioned around the airfoil within the confines of the endplates. High-pressure air is supplied to each box through a flexible hose connected to a mobile blowing-box control cart. The tangential wall blowing energizes the sidewall boundary layer, appreciably reducing its displacement thickness. The photograph is a view looking into the trailing edge of a "poor man's" split flap model. Single blowing-box tangential slots are seen on each turntable above the model in the adverse pressure recovery region above the upper airfoil surface. Ahead of the leading edge, the sidewall suction slots are visible. These span each sidewall from top to bottom. In earlier tests on an NACA 4416 airfoil with flap, it was found that tangential blowing through slots located on the model endplates eliminated flow separation at the flap and sidewall juncture. It is required to obtain useful results from two-dimensional tests of high-lift multielement airfoils.
Experimental studies on controlling the sidewall boundary layer in airfoil tests at transonic flow conditions via suction through a few discrete orifices have been initiated by Bill Sewall. The photograph shows a 3-inch-chord NACA 0012 model mounted on endplates for the 6- by 28-Inch Transonic Tunnel. Pressure orifices on the model upper surface are visible near midspan. Discrete sidewall orifices are seen on the endplate at the top of the photograph; each of these can be connected to either measure pressure or provide local sidewall boundary layer suction. The tubing stubs for this interchangeable connection are seen on the endplate at the bottom of the photograph; the tubing bundle is from the model upper-surface pressure orifices. The discrete endplate orifices are located along the model-endplate juncture, including one at the leading edge, and in the aft adverse pressure gradient region where shocks would form and tend to separate the sidewall boundary layer. The hardware has not yet been put into the tunnel.
HYPERSONIC MODELS USED IN SUBSCALE NTF INTERFERENCE EXPERIMENT

Three-dimensional transonic data bases suitable for testing and validating WIAC procedures are being taken on this pair of (previously existing) hypersonic models in a subscale NTF facility - the Diffuser Flow Apparatus (DFA). These models are the same shape but differ in size; some wall interference assessment can be made by comparing certain force and moment data between the two models. However, using the measured wall pressures as boundary data in a WIAC code, one would hope to get very similar corrected results independent of the model size. The differences caused by the inability to match the model Reynolds number at the same Mach number have been minimized by the selection of this configuration, which has a highly swept planform and a sharp nosed airfoil.
The wall pressure orifice layout on the DFA floor, ceiling, and sidewall is shown in this schematic. Location of these orifices with respect to the large hypersonic model, its supporting sting, the floor and ceiling wall slots, and reentry flaps can be seen. This particular pattern was determined by NTF slotted wall constraints and a linear theory wall interference code. The suitability of using data obtained with this particular orifice layout in existing 3-D linear and transonic simulation and WIAC codes is being analyzed at present. Another entry and additional testing is to be done in the DFA.
Sample results for Mach number distributions along the centerline of
the test section floor are given in the figure. These were for a
nominal tunnel Mach number of 0.9 and at very-near-zero lift for
both models. The tunnel was initially run empty, without either
model or sting support system, to investigate the uniformity of the
Mach number distribution in the test section and provide a Mach
number calibration for the model tests. Wall Mach number signatures
for both models are also shown; the influence of the sting flare can
be seen downstream of the model location. This effect must be
accounted for either in the WIAC procedure or by taking the sting
signature out as a tare-type correction to the wall data. Tests of
sting only have also been made.
Wind tunnel wall interference assessment/correction (WIAC) procedures have evolved over the past decade; they are based upon ideas and capabilities from classical wall interference theory, adaptive wall concepts, and computational fluid dynamics. Specific representations have varied from classical-like pretest prediction methods to adaptive-like post-test correction methods; however, it is now generally believed that some flow-field data taken during the test are required in order to make an adequate assessment of or correction for transonic wall interference. The basic idea is to first numerically simulate the tunnel flow field, subject to measured boundary data, and then to search for a corresponding numerical solution in free air. Differences between such solutions are associated with wall interference corrections. When flight Mach and Reynolds numbers are both nearly matched in the tunnel test, then the corrections deduced by this correspondence may be valid well into the transonic flow regime. A nonlinear, transonic small-disturbance equation WIAC procedure has been developed for the airfoil test section of the 0.3-m TCT. It utilizes measured wall pressure data and accounts for interference from all four test section walls. For the NTF, both linear and nonlinear 3-D correction procedures are being developed. Nine longitudinal rows of wall pressure taps are being installed in the test section, and specific wall interference experiments are scheduled. Transonic nonpotential WIAC codes are being developed in order to determine the importance of nonisentropic effects in wall corrections.

- 0.3 m TCT, 8-by 24-inch airfoil TS
  - Wall pressure taps
  - Nonlinear, four-wall correction
  - Advanced technology airfoil test data

- NTF
  - Linear and nonlinear correction codes
  - Subscale NTF (DFA) data
  - Wall pressure taps being installed
  - Planned NTF wall interference tests

- Nonpotential WIAC code development
  - Flow Industries, Inc.
  - NCSU
A sample of wall interference corrections for airfoil data taken in the 8- by 24-inch test section of the 0.3-m TCT is given in the next two figures. These data were taken in cooperation with the DFVLR as part of NASA's Advanced Technology Airfoil Test program, in which U.S. industry also participated. On the left, uncorrected lift curve data from three tests (identified in the key) are compared with an independent free-air calculation from the GRUMFOIL 2-D transonic (full-potential equation with viscous interaction) airfoil code at the uncorrected tunnel conditions. Test 136 was run about 2 years prior to the other tests, and it was later deemed to have a -0.3° bias in the tunnel angle-of-attack. This bias has been accounted for and is the only difference in the figure on the right. It can be seen that the data are not collapsed in either case; furthermore, none agree with the free-air calculation.

0.3 m TCT data, M ~ 0.73, R ~ 10 million

Test 136 data with 0.3° α shift

- Test 136
- Test 169 (6-in. chord)
- Test 159 (3-in. chord)

Grumfoil code, free air

\[ C_\ell \]

\[ \alpha \]
The transonic airfoil WIAC procedure for the 8-by-24-inch test section of the 0.3-m TCT determines corrections for the tunnel Mach number and angle-of-attack. Corrections were obtained for some of the CAST 10-2/DOA 2 airfoil data before we realized that there was an angle-of-attack bias in one of the tests; these results are shown on the left. It can be seen that the corrected data are nearly collapsed and lie very close to the GRUMFOIL free-air results calculated at the corrected conditions. WIAC corrections were then made to the shifted Test 136 data, and these latter results are shown at the right. These results are essentially the same as those on the left, indicating that the WIAC procedure accounted for the bias automatically. In this procedure, the quoted tunnel Mach number and angle-of-attack are more properly only reference values.
PLANNED NTF WALL INTERFERENCE EXPERIMENTS

NTF experiments specifically designed to study wall interference will be performed using several sizes of geometrically similar simple bodies of revolution and two sizes of Pathfinder I models. Both pointed and blunt bodies of revolution will be tested in order to study Reynolds number effects on blockage corrections and wave drag at Mach numbers near unity. The pointed bodies study will be directed toward very low supersonic flow conditions near maximum drag, whereas the blunt bodies, which are supercritical bodies of revolution, will be studied at very high subsonic flow conditions. Studies on the Pathfinder I model and a 1/2-scale Pathfinder I will evaluate combined blockage and lift interference on this general transport configuration. In all studies, tunnel wall pressures required by the wall interference assessment/correction procedures will be measured.

- Pointed bodies of revolution
- Blunt bodies of revolution
- Pathfinder I models
An uninstrumented wing was fabricated to be tested on the Pathfinder I fuselage; this model will be used in conjunction with a 1/2-scale Pathfinder I model to evaluate the wall interference techniques for the NTF. Care was taken to assure that these two models were as geometrically and structurally similar as possible. Both of the wings were fabricated from the same material with the full-sized wing having a fabrication tolerance of ±0.004 inch and the 1/2-scale model having a fabrication tolerance of ±0.002 inch. Six-component strain-gauge balance data obtained from these models will be used in conjunction with static pressures measured on the test section floor, ceiling, and one sidewall to validate wall interference assessment/correction techniques for the NTF. The primary objective of these tests will be to study Reynolds and Mach number effects on combined blockage and lift interference at high subsonic flow conditions appropriate to transport configurations.
The adaptive wall test section concept, using solid flexible walls, attempts to reduce or eliminate wall interference while providing a boundary condition more suitable for mathematical analysis than that of the ventilated wall concepts. Therefore, contouring the solid walls of the test section along free-air streamlines is the basis of the adaptive wall test section concept being pursued at Langley and the University of Southampton under an NASA grant. The concept uses a wind tunnel together with the high-speed digital computer. Both the wind tunnel and the computer are used to provide a part of the total flow field, each working in the region best suited to its unique capability. That is, the tunnel solves the real, viscous, rotational, inner flow field about the model, while the computer solves the imaginary outer flow field extending to infinity. An adaptive wall test section configured for 2-D testing is being installed in the 0.3-m Transonic Cryogenic Tunnel (TCT) circuit. The design of this test section is based upon the work undertaken at Southampton. The self-streamlining wall test section (SSW TS) of the 0.3-m TCT is 13 by 13 inches, whereas that of the transonic self-streamlining wall tunnel (TSSWT) at Southampton is 6 by 6 inches. Initial airfoil tests in the 0.3-m TCT will be for models in two sizes; early attempts at 3-D testing in it will use the AEDC wall interference model. Current research studies at Southampton concern shockwave/adaptive wall interaction control and 3-D model/2-D adaptive wall testing.

- 0.3 m TCT (NASA Langley)
  - 13- by 13-inch SSW TS being installed
  - Airfoil models in two sizes initially
  - AEDC wall interference model for 3D

- TSSWT (Univ. of Southampton)
  - 6- by 6-inch test section
  - Shockwave/wall interaction studies
  - 3D model/2D adaptive testing
The 13- by 13-inch self streamlining wall test section is now being installed in the 0.3-m TCT. This new test section, shown in the photograph, is configured for two-dimensional testing. The test section is 56 inches long, and all four walls are solid with the top and bottom walls being flexible. Stepping motors, which drive the wall jacks, can be seen at the top and bottom of the photograph. Models with chords up to 13 inches can be tested over an angle-of-attack range of ±20 degrees. Windows located in the top portion of the turntable allow limited viewing of the region above the model. A traversing mechanism may be installed at several downstream locations. One of the plates for the optional sidewall boundary-layer removal system is barely visible through the test section access port.
Initial tests in the 13- by 13-inch SSW TS of the 0.3-m TCT will be for tunnel systems checkout, performance, flow quality, and wall adaptation to uniform flow at various conditions. Upon completion of these initial tests, two tests of airfoil pairs are scheduled to determine the operational capabilities of the adaptation software and to investigate 2-D wind tunnel wall interference at high Reynolds numbers. Two NACA 0012 airfoil models, one with a 6.5-inch chord and the other with a 13-inch chord, as shown in the photograph, will be tested to assess the software at values of tunnel height to model chord down to 1.0. The results from these tests can be compared with results from tests of the NACA 0012 in the 0.3-m TCT and other facilities. Two joint cooperative programs, one an NASA/ONERA/DFVLR effort and the other an NASA/NAE effort, have been established to test DOA CAST-10 airfoil models of 7- and 9-inch chords, respectively. These joint data will be used to assess the effects of model manufacturing differences and to compare the results on the same airfoil model in different facilities.
Adaptive wall work at the University of Southampton under NASA Langley sponsorship has been going on for a little more than a decade. Recent accomplishments include successful transonic testing of airfoils down to tunnel height-to-chord ratios of about one and at flow conditions where the supercritical flow region extends to the adapted walls. The facility is automated and has a reasonably rapid response. Good agreement has been seen between results from the TSSWT and several other 2-D adaptive flexible wall tunnels. Current 2-D research is toward use through Mach numbers of unity. Initial research on 3-D model testing within 2-D adaptable walls has also begun. The photograph shows a 3-D model mounted in the University of Southampton TSSWT.
The 3-D model is viewed here through the access port of the TSSWT as shown on the previous photograph. The edge of the 2-D flexible wall above the model is also seen through the port. Here, the goal of testing free from wall interference cannot be met. The philosophy adopted is to provide the test section with sufficient static pressure taps around and along its length to allow various measures of interference to be quantified. The principal interferences that the model experiences are wall-induced velocities in the streamwise and vertical directions. This induced velocity field can be manipulated by 2-D wall movement, and hence the level of interference can be reduced. Assessment of and correction for residual interference will be made using the wall pressure and location data measured for the final 2-D adapted wall setting in a given test run.
A DECADE OF RENEWED WIND TUNNEL WALL INTERFERENCE RESEARCH

This last chart characterizes NASA Langley's recently renewed wind tunnel wall interference research. In addition to the points listed, it should be added that most of our wall interference research to date has been directed toward conventional slotted-wall transonic tunnels; solid, flexible, adaptive-wall, transonic tunnels; and assessment/correction methods related to them. The publications list does not include work related to high-lift (V/STOL), supersonic-hypersonic, and unsteady wall interference research, which have also been pursued during this past decade at Langley. Furthermore, one should not assume from the number of researchers listed on the publications that our transonic effort is a large one; few are full-time wall interference players. One tends to become interested in transonic wall interference only when a promising new idea comes along or when all other explanations fail in trying to understand the test results.

- NASA Langley focus is transonic flow
- Both analytical and experimental aspects being pursued
- Applications for prediction, assessment/correction, avoidance, and verification continue
- Work best summarized by publications (list in handout)
A DECADE OF RENEWED NASA LANGLEY SPONSORED TRANSONIC
WIND TUNNEL WALL INTERFERENCE RESEARCH

I. GENERAL

A. Wall Interference


B. Langley Facilities


Unpublished:


II. BASIC

A. Slotted Walls


B. Sidewall Boundary Layers


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C. Data Bases (With Measured Wall Pressures)


D. Simulator Codes


III. WIAC


Unpublished:


IV. ADAPTED WALLS

A. Active


Unpublished:


B. Passive


