

AIAA 2001-2472

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Two NASA Langley Wind Tunnels**

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**19th AIAA Applied Aerodynamics Conference
11-14 June 2001
Anaheim, CA**

APPLICATION OF PRESSURE-BASED WALL CORRECTION METHODS TO TWO NASA LANGLEY WIND TUNNELS

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ABSTRACT

This paper is a description and status report on the implementation and application of the WICS wall interference method to the National Transonic Facility (NTF) and the 14x22-ft subsonic wind tunnel at the NASA Langley Research Center. The method calculates free-air corrections to the measured parameters and aerodynamic coefficients for full span and semispan models when the tunnels are in the solid-wall configuration. From a data quality point of view, these corrections remove predictable bias errors in the measurement due to the presence of the tunnel walls. At the NTF, the method is operational in the off-line and on-line modes, with three tests already computed for wall corrections. At the 14x22-ft tunnel, initial implementation has been done based on a test on a full span wing. This facility is currently scheduled for an upgrade to its wall pressure measurement system. With the addition of new wall orifices and other instrumentation upgrades, a significant improvement in the wall correction accuracy is expected.

1. INTRODUCTION

Wall interference in a wind tunnel is traditionally defined as a correction to be applied (added, as per usual convention) to the measured forces and moments and

to the tunnel parameters to approximate the free-air condition. The in-tunnel conditions and measurements are different from the free-air values due to the constraining effect of the walls, wall boundary layers and a number of second order effects such as flow non-uniformity, model support interference and measurement errors. In the computational approach, the free-air and the in-tunnel solutions are two distinct spatially varying flows, and the corrections correspond to a measure of the difference in the two solutions (called interference solution). The classical treatment of the problem is to lump the correction as a blockage effect producing an effective higher speed flow in the tunnel, and a lift-induced effect producing an asymmetric effect in the lift vector direction, equivalent to a change in the angle of attack. Based primarily on linear potential theory, closed form expressions are available to compute these corrections as is well documented in Reference 1. More refined models have been developed to treat blockage due to attached and separated wakes separately using the drag coefficient variation (see Reference 2, for example). However, these methods rely mostly on the model geometry and averaged measurements such as forces and moments.

Classical methods have served well as a simple and dependable way of computing

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wall corrections, expressed as bias corrections on the model coefficients and test parameters (Mach number, dynamic pressure, angle of attack, etc.). However, stringent accuracy requirements imposed by the user community (airframe and components manufacturers, in-house researchers) have necessitated a more accurate calculation of wall corrections. For example, an accuracy of 1 drag count demanded by the customer cannot be typically met by a facility with a classical wall correction method with its higher uncertainty on the corrections, especially at high angle of attack. Research work on improving the accuracy of wall corrections has focused on the use of the measured wall-pressure boundary condition, which incorporates a more realistic characterization of the in-tunnel flow into the correction method and hence a tighter control on the accuracy of corrections. The current wall correction effort at NASA Langley Research Center (LaRC) is therefore to implement more advanced computational methods in combination with measured boundary data to improve the quality of experimental results.

The two NASA LaRC tunnels extensively employed for subsonic and transonic testing of transport and fighter aircraft models in cruise or high-lift configurations are the 14x22-ft subsonic tunnel and the National Transonic Facility (NTF). Both these tunnels are slotted facilities that are also capable of being run with the slots closed, i.e., in a solid-wall configuration. The typical test section geometry for the 14x22-ft tunnel is to conduct experiments with the slots closed, while that of the NTF is to test with the slots open. The NTF conducts high Reynolds number testing in a cryogenic, pressurized environment

with slotted tunnel walls to alleviate transonic wall interference effects. The facility has also the capability to run tests on large high-lift models at subsonic speeds with the tunnel wall slots covered. In contrast, the 14x22-ft tunnel is an atmospheric tunnel used extensively for subsonic testing of advanced fixed wing and rotor craft configurations with simulations of ground effects and propulsion elements. In the past, customers have used classical correction methods or no corrections for these tunnels, especially in the slots open configuration based on the assumption of negligible wall interference effects or because of lack of a better method. As mentioned previously, with tighter tolerances on the measured data imposed by the customer, it is necessary to apply more advanced methods based on the measured wall signature. It is also a frequent requirement that these corrections be made available using an efficient and robust calculation procedure in a post-point (i.e., on-line) or post-run mode so that set points can be adjusted accordingly, if necessary.

Currently, the effort at NASA LaRC on wall interference assessment and correction (WIAC) is aimed at implementing, validating and establishing standards for wall corrections using measured pressure boundary information. As is elaborated in Reference 3, there is a hierarchy of methods starting from classical to linear to non-linear that needs to be implemented in these tunnels using an incremental approach. In the present strategy, the first phase is the implementation of linear methods for solid wall tunnels, followed by methods for porous or slotted walls and eventually

the application of non-linear methods in the transonic cruise regime. As a progress report on the work accomplished to date on the first phase of this action plan, the present paper deals with the application and validation of a pressure-based linear method known as WICS (see References 4, 5) to the NTF and 14x22-ft tunnels. Further studies addressing the sensitivity of the method to measurement uncertainty, testing techniques, and theoretical modeling issues are presented in References 6, 7.

2. THE WICS CORRECTION METHOD

The WICS wall correction method is a wall signature method, first developed by Hackett (Reference 8). Ulbrich (Reference 4) introduced modifications to this idea by developing a strategy of globally fitting the wall signature thereby adding more robustness to the method. Reference 5 discusses additional facility-specific modifications made during implementation of the code at the NTF. A brief summary of the method is given below.

WICS uses the pressure signature at the walls (actually the incremental value relative to tunnel empty signature) as the basis for computing wall interference corrections. The model is represented by a number of point sources, point sinks (to model blockage and wake flow) and line doublets (to model effects due to lift). The far-field effect due to the assumed singularity distribution is matched with the wall signature. This is done in a global fitting procedure, which yields the strengths of the singularities as the solution. The wall interference corrections are then computed based on superposition

of standard solutions of sources, sinks and doublets. Pre-computed databases of elemental signatures and corrections due to individual singularities are used in an interpolation procedure in WICS to compute corrections for each test point in near-real time computational speeds. Compressibility is modeled using Prandtl-Glauert scaling which gives acceptable accuracy for Mach numbers of 0.75 or less.

The inputs for WICS are described below:

1. Tunnel empty signature: For the NTF, the wall signature is defined in terms of 12 selected rows with 30 ports in each. For the 14x22-ft tunnel currently, this consists of wall measurements from three rows (two from the sidewalls and one on ceiling). This calibration data is required in a test matrix of a range of Mach numbers (and additionally total pressures for the NTF). For full span models, the signature with the model support at several states (α , for example) is also required at various operating conditions. For the 14x22-ft tunnel, several such calibration sets are required depending on the model cart used and whether the floor boundary layer suction system (BLRS) is used or not. An effort is currently under way (Reference 9) to use modern design of experiments (MDOE) to optimally select the number of test points required to define the empty tunnel wall signature as a function of all the relevant tunnel configuration variables and test parameters.
2. Wall signature for a given test point.
3. Test point values of uncorrected force and moment values, Mach number, reference velocity at model center of rotation and a number of other test and model attitude parameters.

4. Perturbation velocity database: This is a large table of pre-computed perturbation velocities used in signature matching and wall interference computation. The database depends on the wall ports layout, tunnel section, Mach number and lift vector direction.
5. Model singularity distribution and geometry data.
6. Reference lines along which weighted averages of interference are to be computed and planes along with local values of wall interference are to be computed.
7. Port flags used to de-select specific ports that are not to be used in the calculation for a given test. In addition to this, the code rejects additional ports based on statistics of the fit.

The calculation steps used in WICS are described below:

1. Read tunnel empty signature and sort it for table lookup based on tunnel parameter states (total pressure and Mach number, for example) and model support states (pitch and roll angles for full span support configuration).
2. Read test data: Subsequently, the corresponding tunnel empty signature is obtained from the sorted database and subtracted to get the incremental or 'tared' wall signature.
3. Compute the equivalent line doublet strength from measured lift and model geometry: The strength is then distributed along the span as per input or computed weights. These weights are based on the wing loading distribution.
4. Perform interpolation from the perturbation velocity database (PVD): This is done to estimate the lifting effect part of the signature at each port. It is

then subtracted from the tared signature to get the blockage effect at each port.

5. Use least squares fitting and interpolation from PVD to calculate the strengths of sources and sinks.
6. Use interpolation from PVD to compute wall interference at any point in the test section (within reference grid limits) by superposition of all singularities and ports.
7. Compute mean corrections using weighted averaging; force and moment coefficient corrections are then computed. The buoyancy correction is then computed based on the streamwise distribution of blockage.
8. Iterate steps above using corrected tunnel parameters, if necessary.

Corrections are computed for each point in a polar independently. The primary mean correction due to blockage is applied as corrections on Mach number, M and dynamic pressure, Q (added to corresponding measured values). Upwash correction is applied as correction on the angle of attack. Corrections on C_L , C_D and pitching moment are based on the primary mean corrections of blockage and upwash. In addition, model-induced buoyancy correction is also reported as a correction to be applied to C_D . The method also computes local variations of interference corrections, which are useful in determining if the averaging assumption is truly representative of the interference field in the model region.

3. APPLICATION AND VALIDATION OF WICS AT THE NTF

Results presented below are for a large semispan model recently tested at the

NTF. Results from previous tests were presented in Reference 5.

The semispan model considered here is a large model (tunnel cross section area to model reference area ratio of 0.093) in a high-lift configuration. The strategy used in the application and validation of the WICS code with reference to this test is as below. The majority of the runs in this test were done in cryogenic conditions. A few additional runs were conducted in the air mode at a Mach number M of 0.21 with the slots open. Subsequently, runs were also made with the slots covered (i.e., solid-wall configuration) under identical conditions. This permits a comparison of the solid-wall corrected data with the slots-open uncorrected values. The hypothesis is two-fold, (a) slots-open results under these conditions have negligible corrections and hence are close to the free-air values, (b) corrected slots-closed data will nearly reproduce slots-open data and can even be a better approximation to the free-air since the corrections are precisely known. In any case, it is interesting to see how the corrected data compares with the uncorrected slots-open data as a way of mutual validation of these results.

Figure 1 shows the initial placement of the singularities used in the WICS computation for this test. The singularities move with the model as it is pitched. The line doublets along the 1/4 chord line produce the lifting effect due to the model; a source-sink pair simulates the body blockage; a number of sources capture the wake blockage. A more optimum placement of the singularities is usually not necessary. In fact, the simplicity of the method is based on the assumption of far-

field effect, which is insensitive to precise placement of the singularities. The span loading of the model is an input used in the WICS method to distribute the line doublet strength, as well as to compute weighted average of the local values of upwash correction. An elliptic loading distribution is usually acceptable, although the true loading distribution was used in the present case. The model cross-sections, used in the computation of the model-induced buoyancy correction for drag is also a required input.

Slots-closed results:

Results presented below are from one set of runs from the slots-open and slots-closed tests, considered to be typical of other similar run pairs. Figure 2 shows the primary average corrections for the closed slots run with an α (uncorrected angle of attack) range of -5° to 26° . The blockage due to the body and wake, ϵ , is about 1% in the α range of -5° to 10° . The blockage gradually increases to about 1.5% at $\alpha=17^\circ$, which is the point of onset of stall for this model configuration under the given conditions. For higher angles, the blockage increases rapidly until it reaches a value of 3.2% at $\alpha=26^\circ$. This is obviously due to the larger contribution to the blockage from the separated wake. The corrections on Mach number and Q are directly derived from the blockage, $\Delta M \approx (1+0.2M^2)\epsilon M$; $\Delta Q \approx (2-M^2)\epsilon Q$. These corrections follow the same trend as ϵ . The correction on angle of attack $\Delta\alpha$ is large and varies approximately linearly with α until onset of stall is reached. A large maximum correction of about 1.35° on α is reached at this point. At higher angles, the angle of attack correction drops

to lower values, which is directly a result of reduced lift. Figure 3 shows the corrections on the force and moment coefficients, which are derived from the averaged and local variations of blockage and upwash. The change in C_L and C_D is mainly due to the rotation of the lift vector caused by the angle of attack correction and the increased blockage due to changes in the separated wake. The drag coefficient is additionally affected by model-induced buoyancy. Solid walls reduce the lateral expansion of the flow around the model thereby changing the curvature of the flow. The pitching moment correction is due to the wall-induced changes in streamline curvature and spanwise center of lift. Again note that the coefficient corrections are quite significant due to the large upwash correction and blockage of the model. It is interesting to note that the correction for C_L is almost linear for the entire range due to the fact that the corrections on α and Q offset each other proportionately in the entire range. The drag correction reaches a maximum value of about 460 counts at the stall onset test point.

It is obvious from these results that there are significant corrections to the measured values due to wall interference when the slots are closed. A partial validation of the accuracy of these corrections can be obtained by looking at a comparison of the wall pressures predicted by WICS with the actual pressures measured on the walls along selected rows. Figure 4 presents one such comparison for the $\alpha=15^\circ$ point (the wall signature is expressed as velocity increments above the reference value and tared with the tunnel empty values). As described in Reference 5, wall rows 5 and 7 are immediately below and above the

semispan model, and the other numbered rows are farther away. Note that the WICS results are obtained from a global fit of the measured wall pressures (i.e., it is not a row-wise fit). Considering the simplicity of the model used in the WICS code, it can be said that WICS matches the wall pressures very well. The rows in the lower wall show a larger difference in the match, possibly related to second-order wall interference effects, flow non-uniformity, etc. There are not enough tunnel characterization data at present to fully address such issues. However, it may be noted that these differences produce only a miniscule effect on the averaged correction parameters. An important advantage of pressure-based methods such as WICS is that it permits an analysis of the local variation of correction in the model region. Figure 5 is an example of an interference field around the model. The upper part of this figure shows the local variation of blockage in the image plane (model mounting plane). The lower part of the figure shows variation of the angle of attack correction for the $\alpha=15^\circ$ test point at the horizontal mid-plane of the tunnel. Contour plots like this permit the analysis of phenomena such as wing-tip stall induced by wall interference, which may not be obvious from the average correction results. For this test point for example, the wing tip and root regions have very similar interference fields. Note, also, that the wall induces a 1.2° difference in the angle of attack correction at the tail position compared to that at the wing.

Comparison with slots-open runs:

If one makes the assumption that the slots-open results in this case are closer to the

free-air results, it is then interesting to see how the corrected solid-wall data compares with the slots-open data for identical conditions and model type.

Figure 6 shows the comparison of C_L . Note that the solid wall corrected data are shown as C_L -corrected vs. α -corrected. The corresponding uncorrected solid-wall values are also shown. It can be seen that corrected data compares well with the slots-open results. Figure 7 shows the pitching moment comparison. Here again, the corrected data compares well with the slots-open data. Figure 8 shows the drag comparison. Again, the correction moves the drag polar closer to and in line with the slotted data. Although a slight departure is evident at the higher end of the α range, the overall agreement attests to the validity of the WICS corrections.

The effect of the standoff plate used for this model at the sidewall mount station is an issue that has to be considered in relation to these comparison plots. Since the standoff plate is non-metric, the lift generated by it is not included in the measurement. However, the wall signature used in the WICS calculation is due to the model and the standoff plate combined. Therefore, for consistency, WICS should be given the input of lift generated by the standoff plate also. A detailed analysis of the sensitivity of corrections to the non-metric standoff plate is given in Reference 7. In summary, the effect is to produce a small decrease in the blockage correction and a small increase in the angle of attack correction. Only very minor changes in the lift and drag coefficients are produced. Generally, the effect is to produce an even better comparison with slotted data.

The important conclusion from this analysis is that corrected solid-wall results compare well with corresponding slotted-wall results. The effect of the standoff plate is such as to further improve this agreement. This conclusion can be interpreted in two ways, (a) the slots open test section provides nearly interference-free conditions for this test and, (b) this analysis provides a validation of the WICS solid-wall corrections. It should be noted, however, that while the WICS corrections appear valid, insufficient experimental data exist to quantify the uncertainty in the corrections.

4. WICS ON-LINE IMPLEMENTATION AT THE NTF

The WICS code has recently been enhanced to add on-line application capability at the NTF (Reference 10). On-line application is defined as one where test point data and various input and calibration data are furnished by an external program, which is typically the tunnel on-line data reduction program. This external program interfaces to WICS (which may reside on a separate dedicated machine in the control room) via an RPC (Remote Procedure Call) call for real-time application. Off-line option assumes that data for a single test point or multiple points are furnished in a file. In the present version, real-time simulation can also be done in an off-line mode by using a main program simulating the external RPC call. This version has also many other improvements over the version described in Reference 11. These include simplified pre-processing, improved input formats and program structure, and a common source code for semispan and full-span applications. Provision for

future enhancements such as roll capability and new support systems is also available.

5. WICS IMPLEMENTATION AT THE 14x22-FT SUBSONIC TUNNEL

Since the implementation of the WICS code at the NTF is sufficiently general, it is relatively easy to adapt it to a different facility, especially another rectangular tunnel. The present effort has led to an initial implementation and customization of the code to the 14x22-ft facility at NASA LaRC (Reference 12). The main differences here compared to the NTF version are: changes in the wall pressure measurement system; new perturbation velocity databases that have to be computed specifically for the 14x22-ft dimensions and test parameters; and the changes in the model kinematics used in WICS to model how the singularities move with variations in pitch, roll and yaw. In addition, tunnel empty data were acquired and processed to provide the tare wall signature based on a recent calibration performed at the facility. The calibration involved measurement of tunnel empty wall signature at various pitch and yaw positions of the support system with the Boundary Layer Removal System (BLRS) in the on and off conditions. Recently acquired data from a check standard elliptic wing test were used for the initial application of WICS at the 14x22-ft facility.

The wall signature for this facility comes from three rows of pressure orifices arrayed along the center of three walls (no pressure measurements are available on the tunnel floor). The rows are approximately in the middle of the South,

Ceiling and North walls. As shown in Figure 9, each row has 29 or fewer usable ports distributed along the 50 ft. length of the test section.

Previous analysis (Reference 6) has shown that the number of rows and ports to measure the wall signature should be of the order of 8 to 12 rows with 240 to 360 total number of ports, clustered around the model station to reduce uncertainty in the corrections due to random or precision error in the measurements. In addition to this precision error, bias error is also an important issue. To reduce error due to bias in wall pressures, the full-scale value of the wall ESP modules should be sized to as low a value as possible. The current 14x22-ft tunnel wall measurements do not satisfy these requirements. The present implementation is therefore only an ad hoc version to demonstrate the use of WICS for this tunnel. Improvements in the wall system and a dedicated validation experiment are being planned to reduce the uncertainty in the corrections. Further tunnel calibrations subsequent to wall system upgrade are also being planned.

An example of the current wall signature definition is shown in Figure 10 (only Ceiling and South wall rows are shown). These data were obtained using the elliptic wing model, a small 6.75 ft span model also used as the facility check standard model. The raw signature and the tared signature after subtraction from the tunnel empty data are plotted here in the streamwise direction. The signature definition and resolution are obviously of reduced quality compared to the NTF. The maximum Δp at Station 18 ft approx. is about 1.4 psf (0.01 psi).

In view of the reduced wall signature quality and the proposed upgrades to the facility, only a limited implementation is in place at present in order to validate the method. A full implementation is planned subsequent to the wall system improvement and calibration.

Figure 11 shows the singularity distribution used for the elliptic wing. Figure 12 shows a comparison of the WICS-fit wall pressure distribution to the original input distribution for a typical test point. There is a good match of the trend although a more detailed analysis is not possible due to limitations in the wall system. Various other runs were made with the model rolled by 90° and also at different Q values and BLRS states. Since the elliptical wing model is small (reference area less than 2% of tunnel cross section area), the computed blockage corrections are small; the angle of attack correction varied linearly at approximately 0.01° per degree of angle of attack. In all cases, the corrections computed were compromised by the lack in wall signature quality.

6. CONCLUSION

This paper^{*} gives a summary of progress made towards the application and validation of the WICS wall signature method to two NASA Langley wind tunnels. The results obtained so far have demonstrated the accuracy and robustness of the method in a number of tests. Further calibrations and validation tests are required to achieve a national standard in applying wall corrections at these facilities.

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^{*} Work in part under NASA Langley contract NAS1-00135.

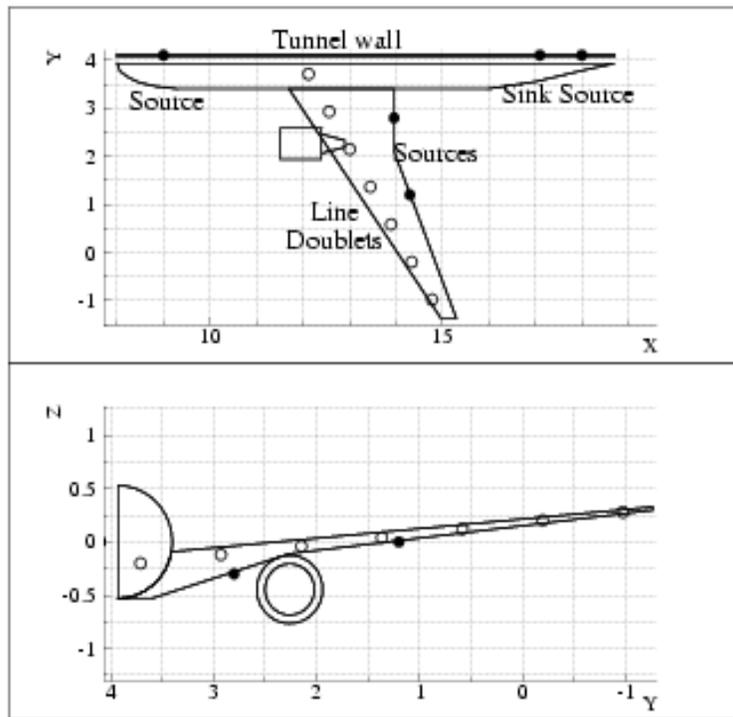


Figure 1. Model lines and singularity distribution for a semispan model.

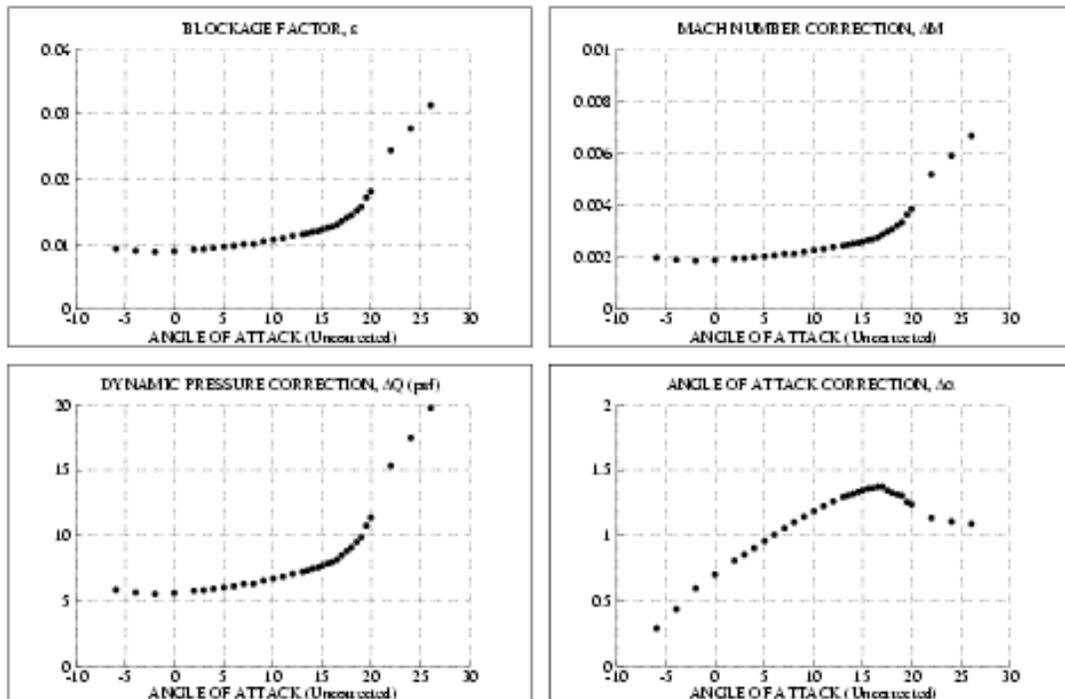


Figure 2. Wall interference corrections for a semispan model at the NTF. (ϵ , ΔM , ΔQ are the averaged values along fuselage center line; $\Delta \alpha$ is the weighted average value along 3/4 chord line)

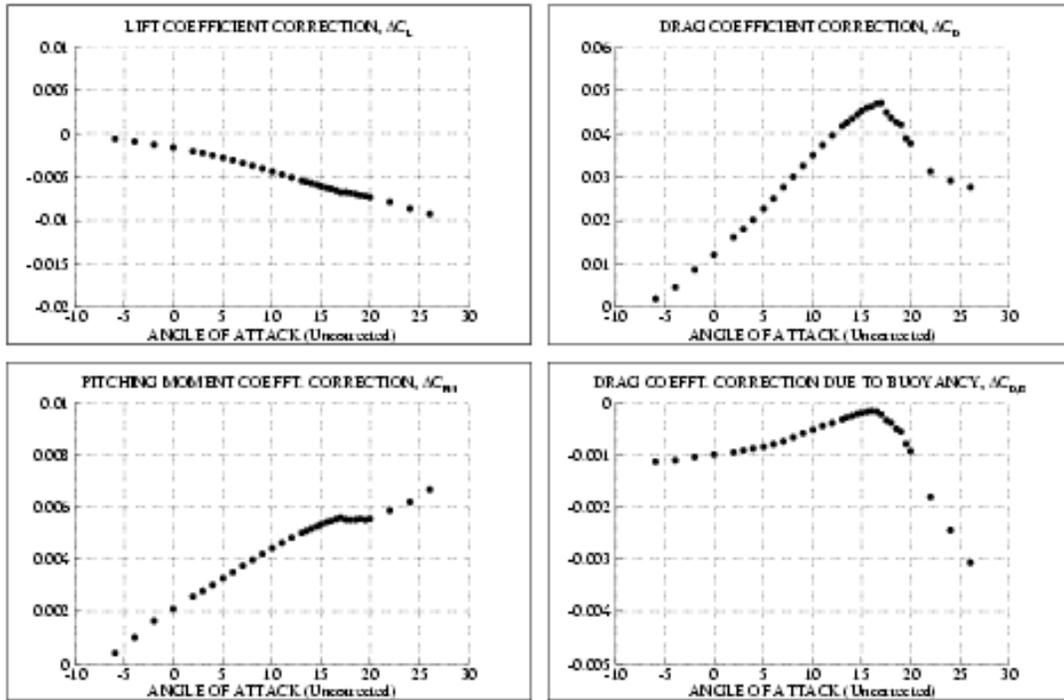


Figure 3. Coefficient corrections for a semispan model at the NTF.
 (Coefft. corrections due to wall-induced inclination of forces and moments, streamline curvature and buoyancy)

Symbols: UTUN-UCAL (Raw perturb. vel. minus tunnel empty vel.)
 Lines: UFIT-UCAL (WICS global fit of UTUN-UCAL)

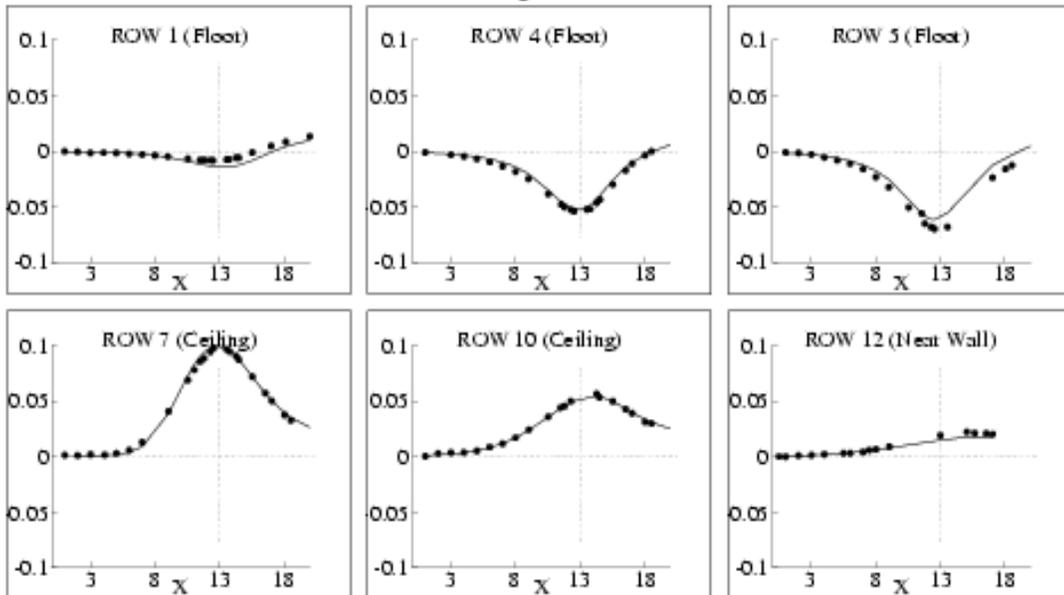


Figure 4. Wall signature, raw and fit for $\alpha=15^\circ$ test point for a semispan model at the NTF.

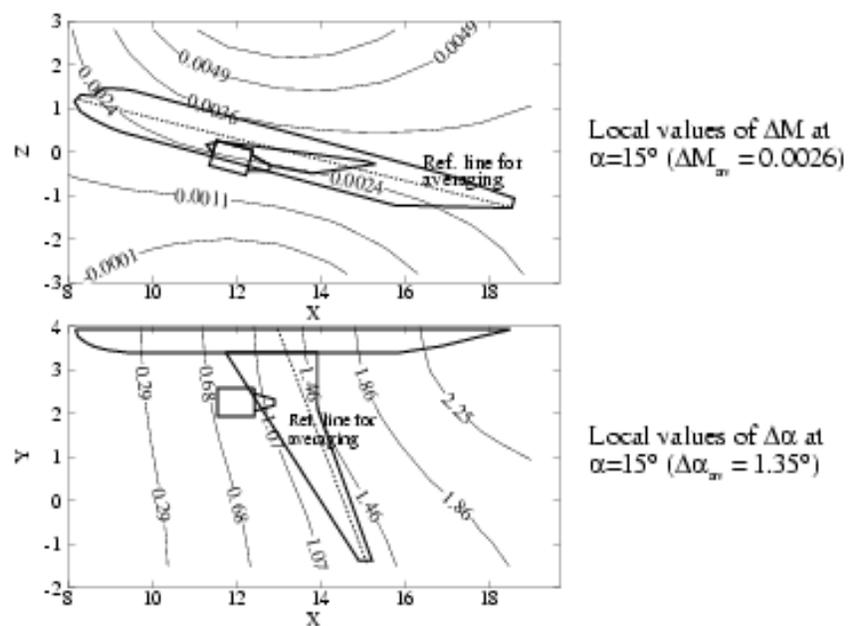


Figure 5. Local values of corrections in the model region at $\alpha=15^\circ$.

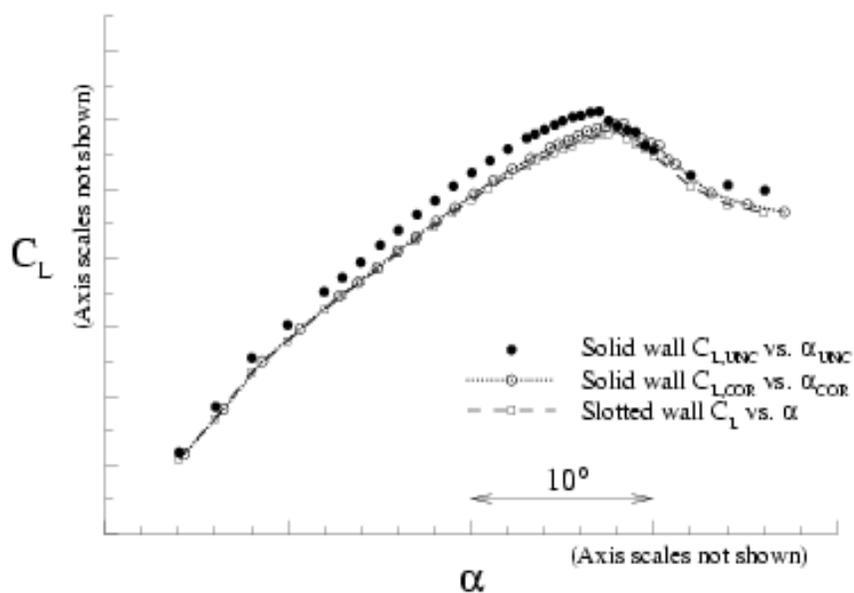


Figure 6. Lift coefficient variation for solid-wall and slotted-wall runs.

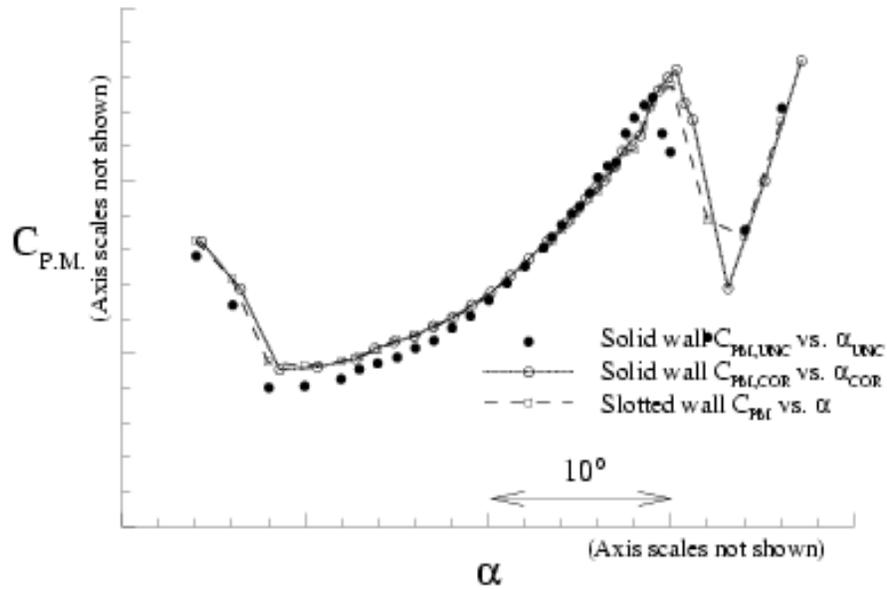


Figure 7. Pitching moment coefficient variation for solid-wall and slotted-wall runs.

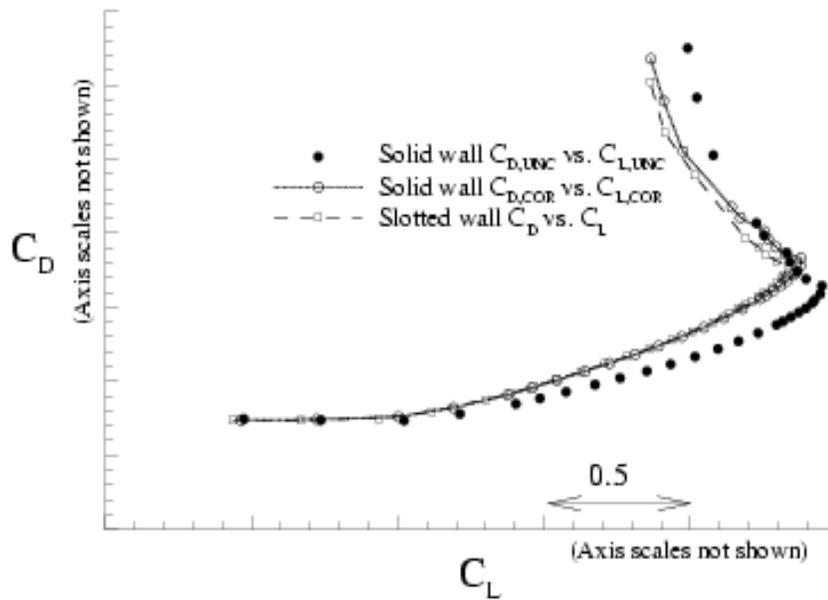


Figure 8. Drag coefficient variation for solid-wall and slotted-wall runs.

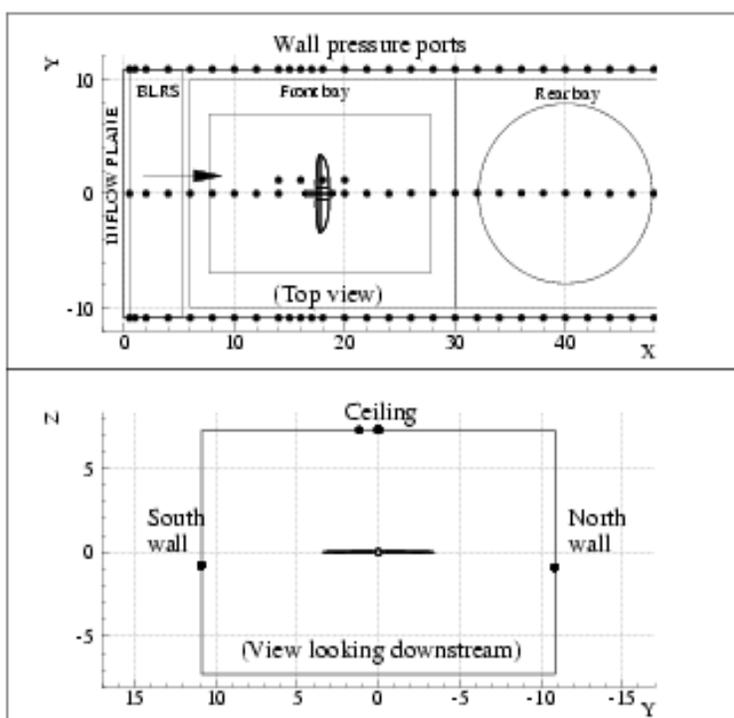


Figure 9. Elliptical wing and wall pressure ports in the 14x22-ft tunnel test section.

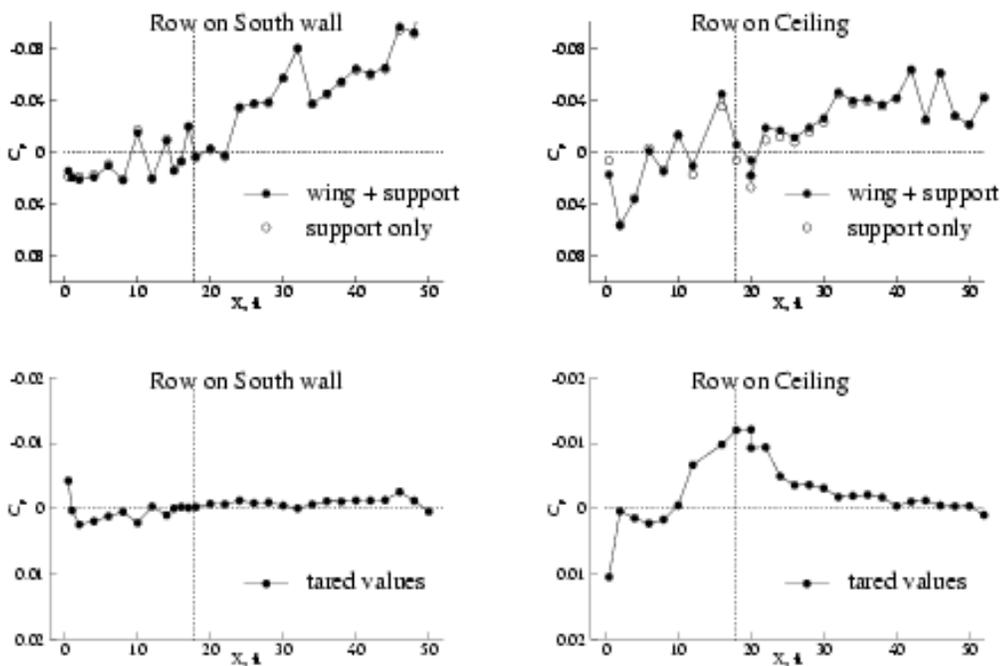


Figure 10. 14x22-ft wall pressure measurements, elliptical wing test, Wall signature for $Q = 140$ psf, α (PITCH) $=7^\circ$, BLRS off.

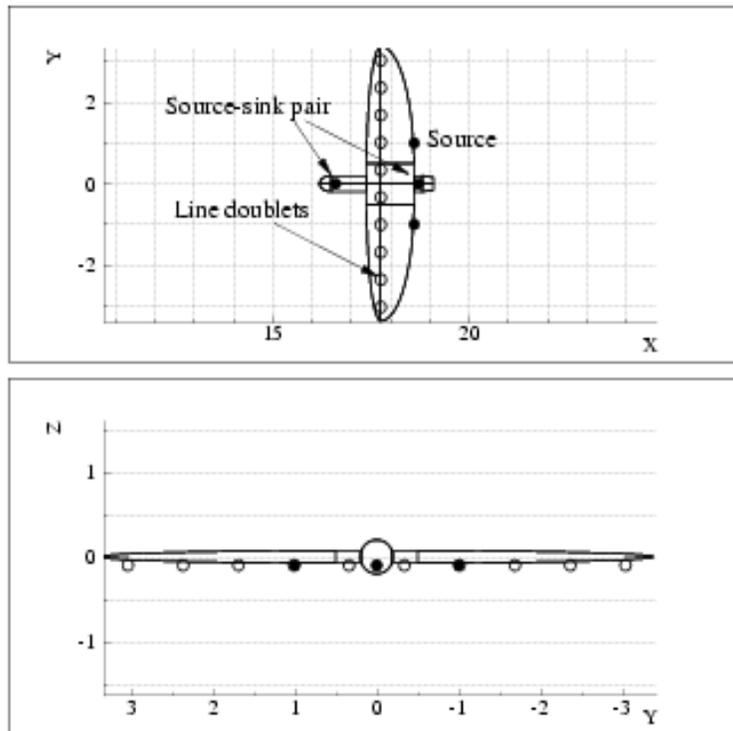


Figure 11. Model lines and singularity distribution, 14x22-ft Tunnel Elliptical wing Test.

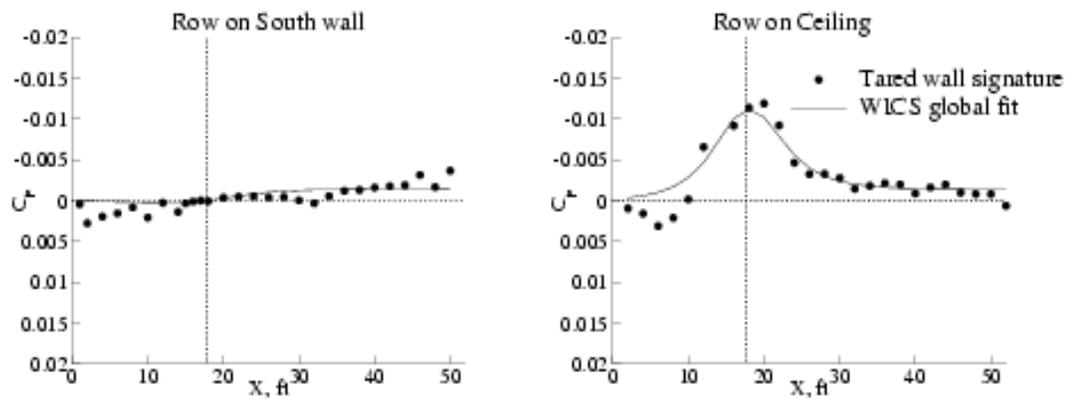


Figure 12. WICS-14x22: Wall signature fit compared to measured data, Elliptical Wing Test, α (PITCH7) = 7°, BLRS off.