N90-17648

NONLINEAR TRANSONIC WALL-INTERFERENCE ASSESSMENT/CORRECTION (WIAC) PROCEDURES AND APPLICATION TO CAST-10 AIRFOIL RESULTS FROM THE NASA 0.3-M TCT 8- X 24-INCH SLOTTED WALL TEST SECTION (SWTS)

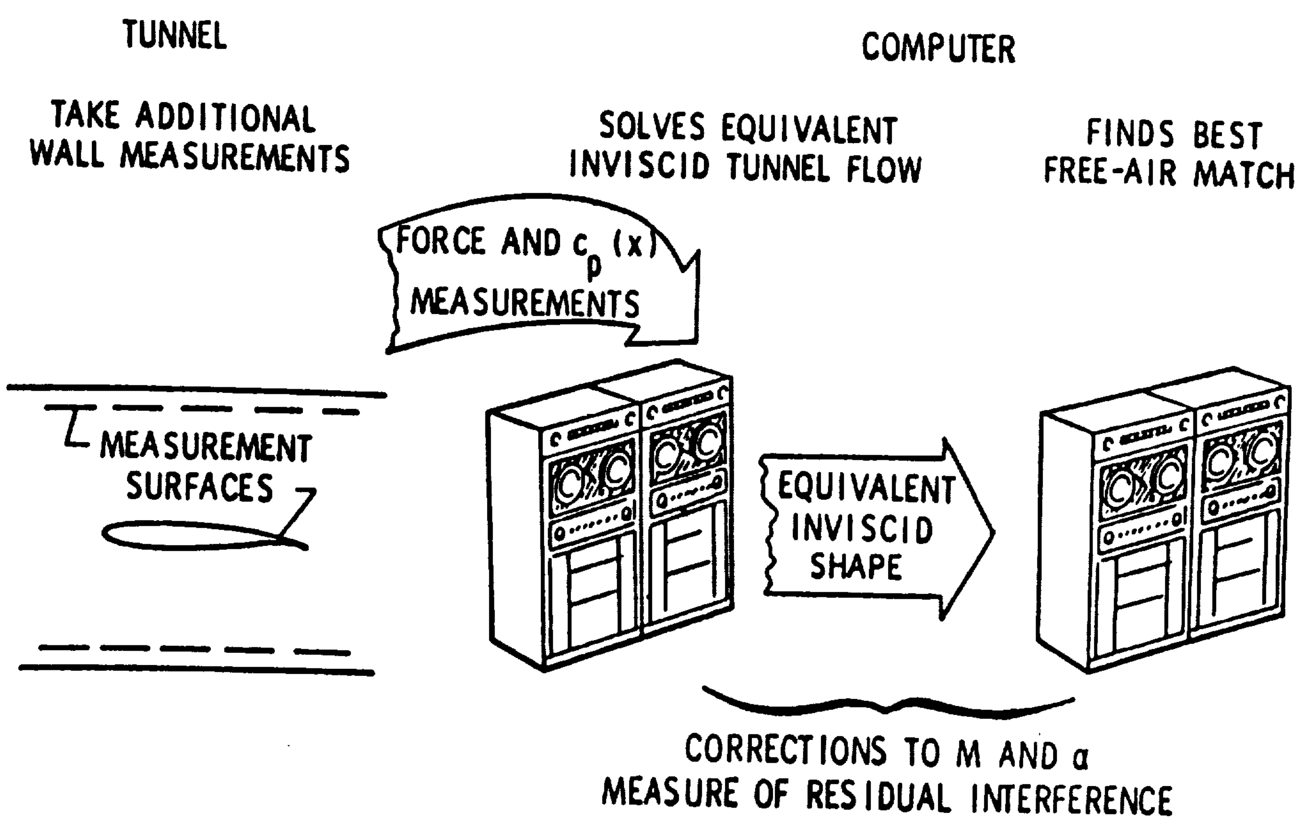
Clyde R. Gumbert,
Lawrence L. Green, and
Perry A. Newman
NASA Langley Research Center
Hampton, Virginia

Introduction

From the time that wind tunnel wall interference was recognized to be significant, researchers have been developing methods to alleviate or account for it. Despite the best efforts so far, it appears that no method is available which completely eliminates the effects due to the wind tunnel walls. This report will discuss procedures developed for slotted wall and adaptive wall test sections of the Langley 0.3-m TCT to assess and correct for the residual interference by methods consistent with the transonic nature of the tests.

WIAC Concept

The underlying concept of both procedures is depicted below. There are two basic elements: the wind tunnel which generates the flow in which measurements are made, and the computer which now solves two related flow problems. In the full nonlinear correction procedure at least two transonic flow problems are solved on the computer. The first is an equivalent inviscid tunnel flow where measured pressures near the wall and on the model are used as boundary conditions. The result of this first calculation is an equivalent inviscid model defined in terms of either its shape or its distribution of singularities. The second problem to be solved on the computer is a sequence of inviscid transonic calculations in which the equivalent model is used as the inner boundary condition and free-air conditions are used at the outer boundaries. The freestream Mach number and angle of attack are perturbed during this sequence in order to satisfy a best-fit criterion for the calculated model pressures and the measured model pressures. The two results obtained from these computer calculations are: corrections to the freestream conditions M and α, and a measure of residual interference.



Transonic WIAC Codes

This WIAC concept was conceived by Kemp (ref. 1), developed into the TWINTAN code for slotted wall test sections (ref. 2) and extended by Kemp and Adcock (ref. 3) to include the effects of the tunnel sidewall boundary layer. The resulting code, TWINTN4, was enhanced by Green (ref. 4) to allow data on shaped walls to be used as the outer boundary condition for the equivalent tunnel flow calculation.

- Transonic flows
- Broad range of lift coefficient
- Nonlinear TSDE
- Uses measured wind tunnel data in BC's
  - Airfoil C_p, C_l and C_d
  - Top & bottom wall C_p
  - Tunnel empty SWBL δ^* and H
- Three SWBL approximations
  - 2-wall (top & bottom only)
  - Barnwell-Sewall SWBL approximation
  - Murthy SWBL approximation
- Two codes
  - Kemp's TWINTN4 for slotted wall
  - TWNTN4A for adapted wall

Nonlinear TSDE for WIAC

The TWINTN4 code (and Green's derivative) performs the flow calculations using the nonlinear Transonic Small Disturbance Equations (TSDE). The three dimensional effects of the sidewall boundary layer are incorporated into the two dimensional TSDE after Barnwell and Sewall (ref. 5) by the term, S. The effect of model aspect ratio was determined by Murthy (ref. 6) as a simple modification to the Barnwell-Sewall method.

- Solves 2-D Transonic Small Disturbance Equation (TSDE)

$$\Lambda\phi_{xx} + \phi_{yy} = 0$$

$$\Lambda = 1 - M_\infty^2 + S - (\gamma+1)M_\infty^2 \frac{U_R}{U_\infty}\phi_x \left[1 + \frac{U_R}{2U_\infty}\phi_x\right]$$

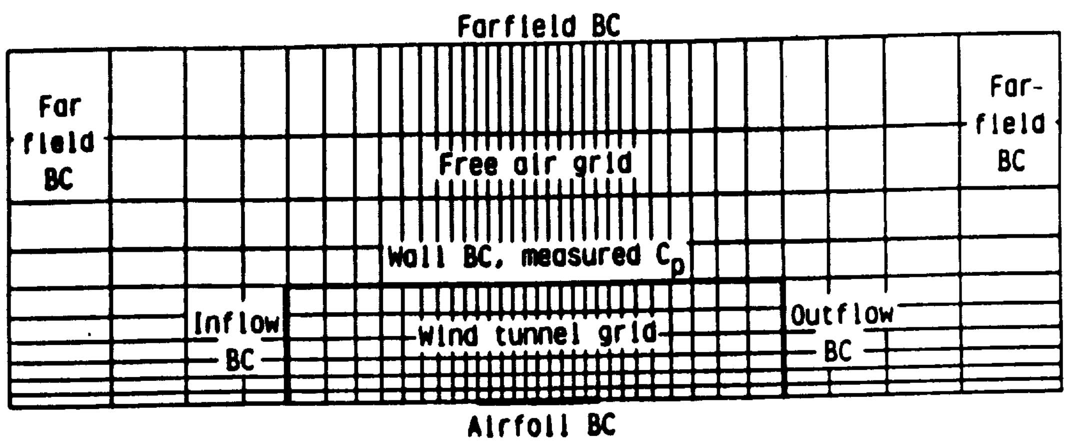
$$S = \frac{2\delta^*}{b}\left[2 + \frac{1}{H} - M_T^2\right]\left[\frac{k_2}{\sinh(k_2)}\right]$$

$$k_2 = \frac{\pi(1-M_T^2)b}{c}$$

- Three VLOR solutions
  - — In-tunnel → effective inviscid body
  - — Free-air → M_{cor} and α_{cor}
  - — Free-air → interference field

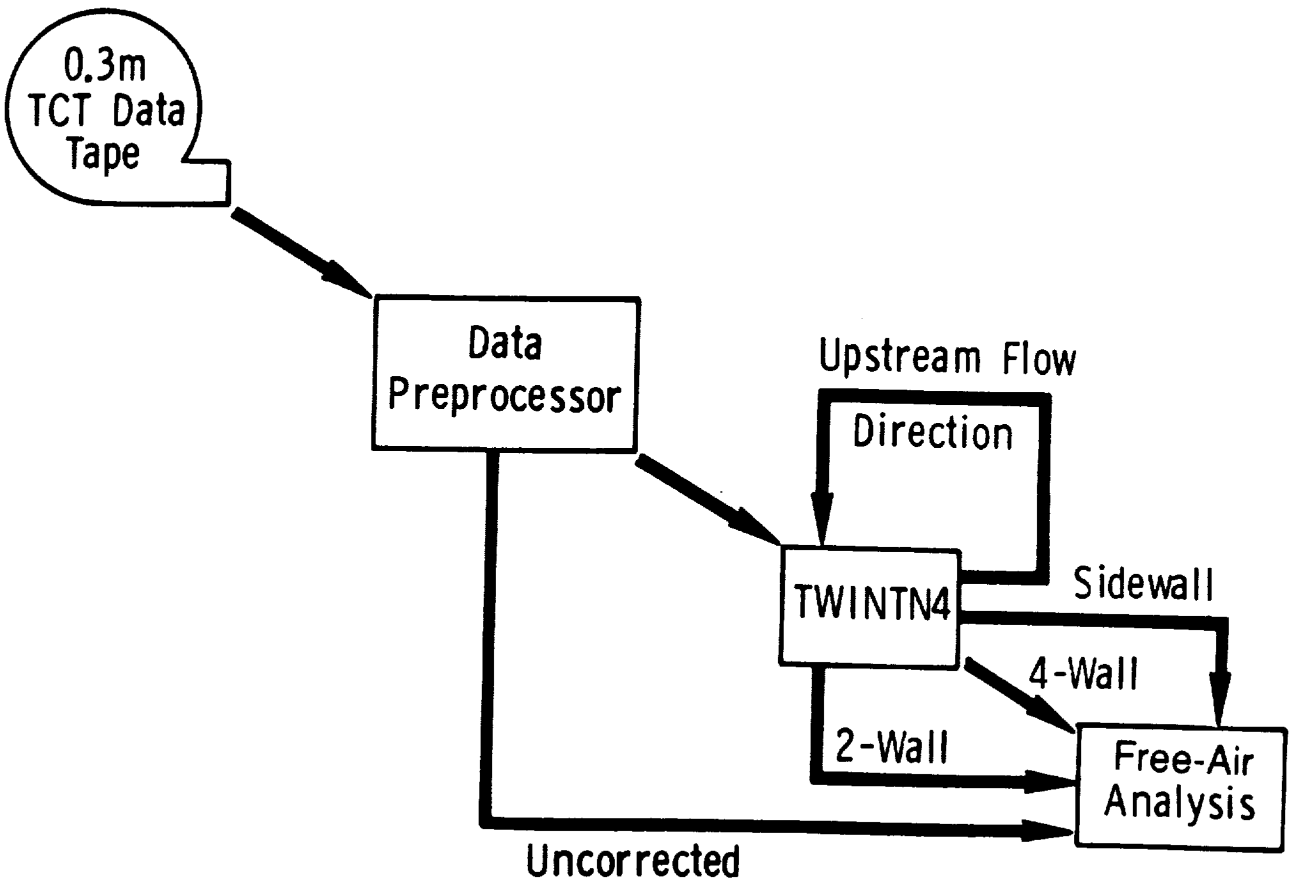
Cartesian Grid for WIAC

The flow field is discretized onto a Cartesian grid which is similar for both the tunnel flow calculation and the free air calculations. The top and bottom wall data is applied on grid lines included in the free air grid at the mean location of the walls. The data on the airfoil surface is applied at the slit on the tunnel centerline (or mean location of the model). The boundary condition at the inflow plane of the wind tunnel was left undetermined from wind tunnel data. This remaining boundary condition is assumed during the first pass through the correction code and approximated by iteration based on the difference between the computed inclination of the equivalent inviscid model and the geometric model according to the method devised by Gumbert et al (ref. 7). The first approximate iterated value is used in the second pass through the correction code; a third pass may be required.



WIAC Procedure

In order to more easily apply the individual codes to the data, they were incorporated into a procedure by Gumbert, et al (refs. 7 and 8) to pass data from one code to the next in a somewhat automated manner. This procedure was first used for making corrections to several data sets in order to validate the procedure and the individual codes.



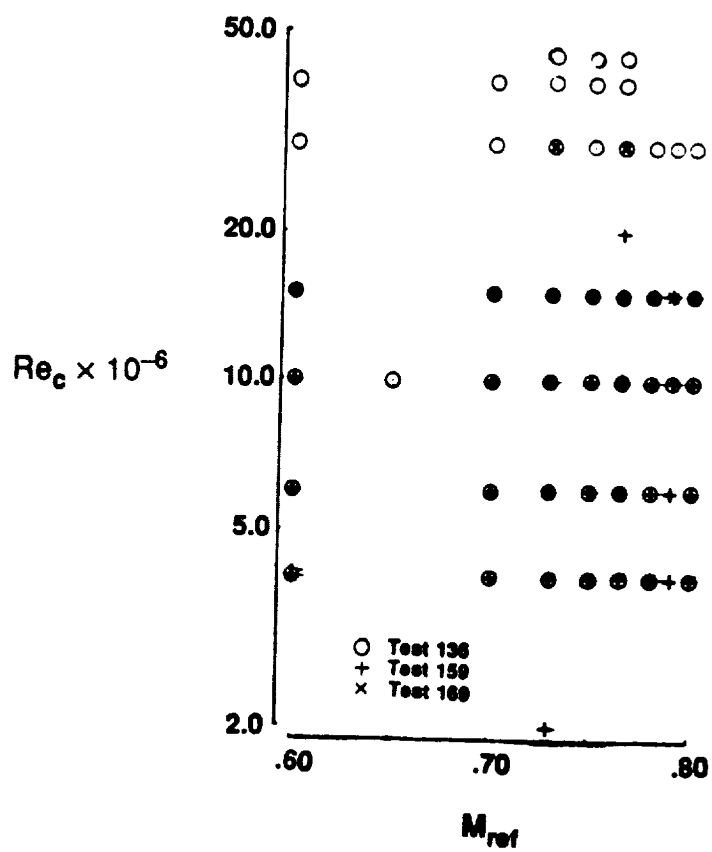
Validation of WIAC Procedure

The validation of the WIAC procedures (refs. 4 and 9) was accomplished by two types of comparisons. First, the corrected data was compared to the best available independent free-air computer code solutions. For the earlier slotted wall data comparisons (ref. 9), solutions from the conservative, transonic, full-potential equation (with viscous/inviscid interaction) GRUMFOIL code (ref. 10) were used. For the latter adaptive wall data comparisons, solutions from a Navier-Stokes code (ref. 11) were used. Second, the corrected data from several tests of the same airfoil shape were compared for consistency.

- Comparison of Corrected Data With Independent Free-Air Calculations
- Consistency of Corrected Data From Separate Tests of Common Airfoil

Test Data Matrix

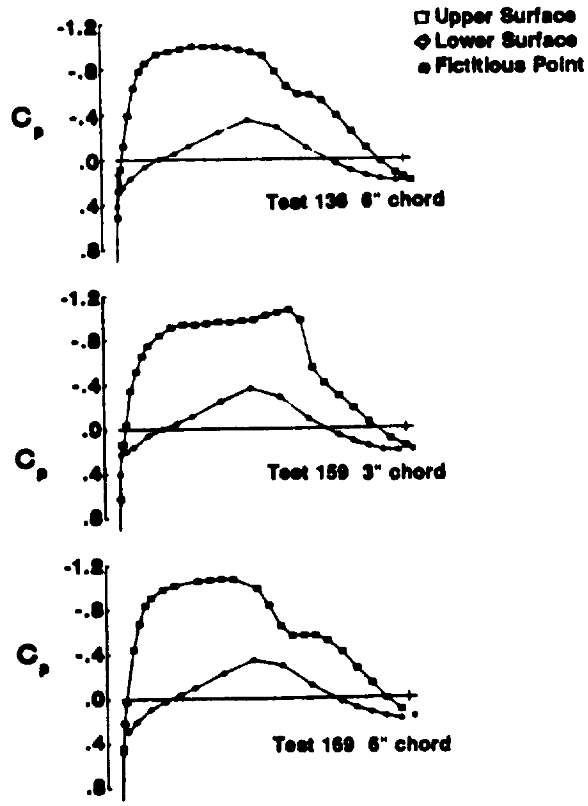
The three tests of the CAST 10 airfoil under consideration here were conducted in the 8- X 24-inch slotted wall test section over a span of several years. Two of the tests were conducted using a six-inch-chord model. During the period between the two tests, several changes were made to the test section to accommodate different instrumentation and flow visualization techniques. The other test used a three-inch-chord model. It was the only non-six-inch chord model tested in the 8- X 24-inch slotted wall test section. More specific information about the tests can be found in references 12 through 15. The figure shows the ranges of Mach number and Reynolds number over which the three tests were run. The WIAC procedure was applied to data for the three tests at those conditions which are similar for all three tests. These eleven common points are denoted as ● in the figure below.



Preprocessor Plots of Airfoil C_p

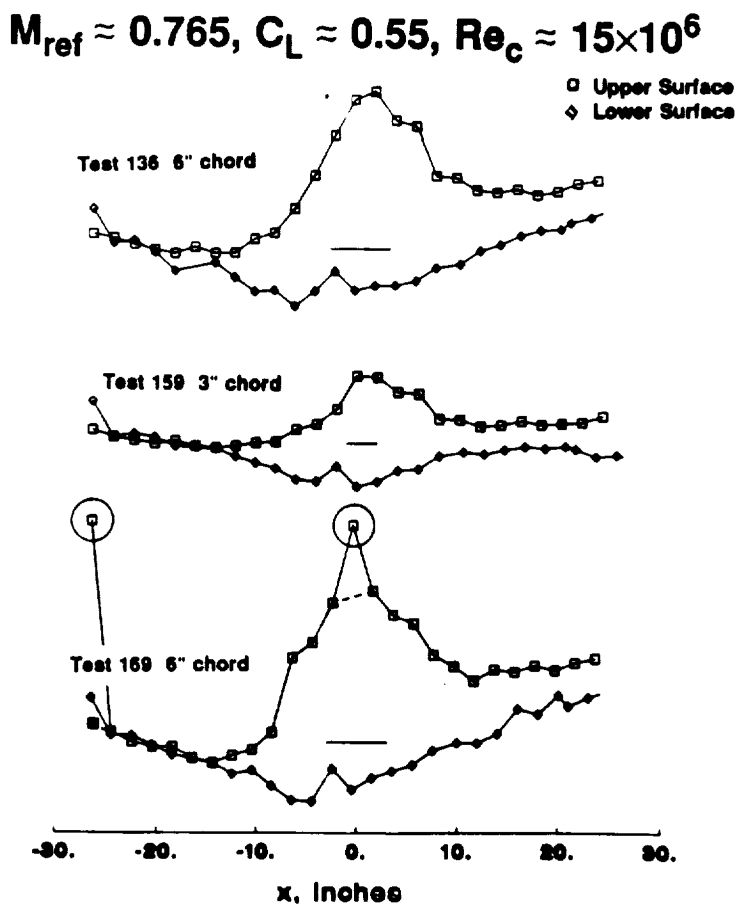
The first step in the WIAC procedures is the preprocessor code where the primary function is to select only the pertinent information from the data tapes and generate an input file for TWINTN4. In the process it generates plots of the uncorrected data which are to be used as inner boundary conditions for the WIAC code solutions. Shown in the figure are the uncorrected pressure coefficient distributions on the model for each test at nearly the same conditions: $Re_c = 15$ million, $M_{ref} = 0.765$, and $C_L = .55$.

$M_{ref} \approx 0.765$, $C_L \approx 0.55$, $Re_c \approx 15\times10^6$



Preprocessor Plots of Wall C_p

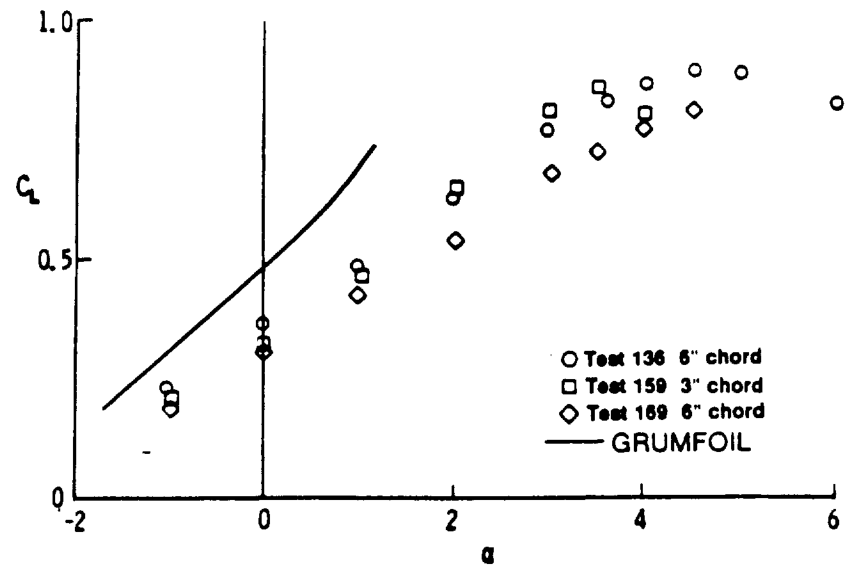
The preprocessor also generates plots of the pressure coefficient distribution on the center slats of the top and bottom walls as shown in the figure. The circled points in the bottom figure indicate data that was conspicuously inconsistent. The data point over the leading edge was removed and the data point ahead of the model was modified as shown by the filled square symbol. These are the data to be used as outer boundary conditions for the WIAC code solutions.



Uncorrected Lift Curves

The correction to the angle of attack can best be shown in plots of the lift coefficient versus angle of attack. Shown in the figure is the comparison of the uncorrected lift curves for the three tests at $M_{ref}=0.73$ and $Re_c=10$ million. For comparison, the results from GRUMFOIL are shown.The data from the three tests are quite scattered and each shows a different slope.

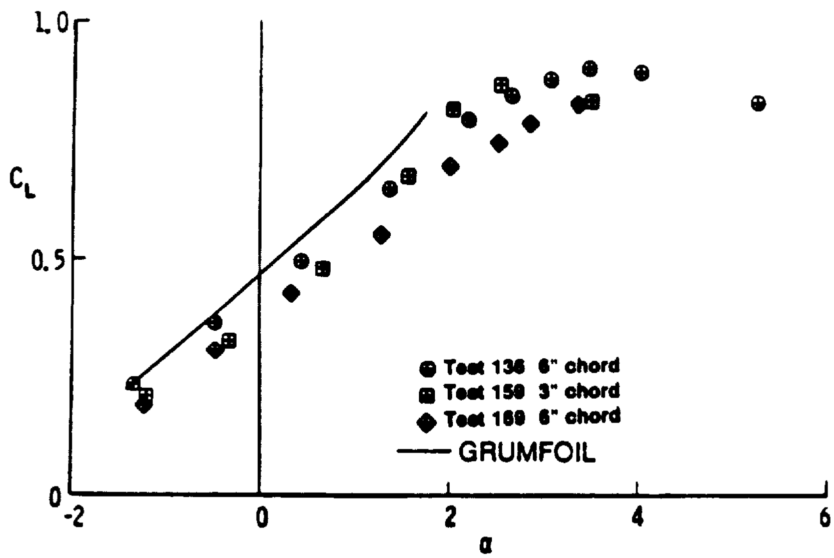
$M_{ref} \approx 0.730$, $Re_c \approx 10\times10^6$



First Pass WIAC Lift Curves

The results from the first pass through the correction code, TWINTN4, are shown below. The lift curve slopes seem more consistent between the three tests, yet there is an unresolved shift between the data sets and with respect to the GRUMFOIL curve.

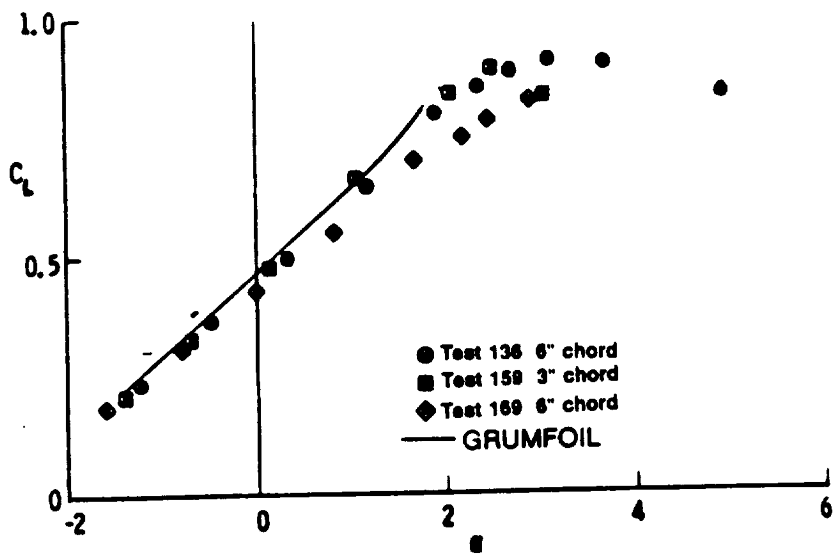
$M_{ref} \approx 0.730$, $Re_c \approx 10 \times 10^6$



Second Pass WIAC Lift Curves

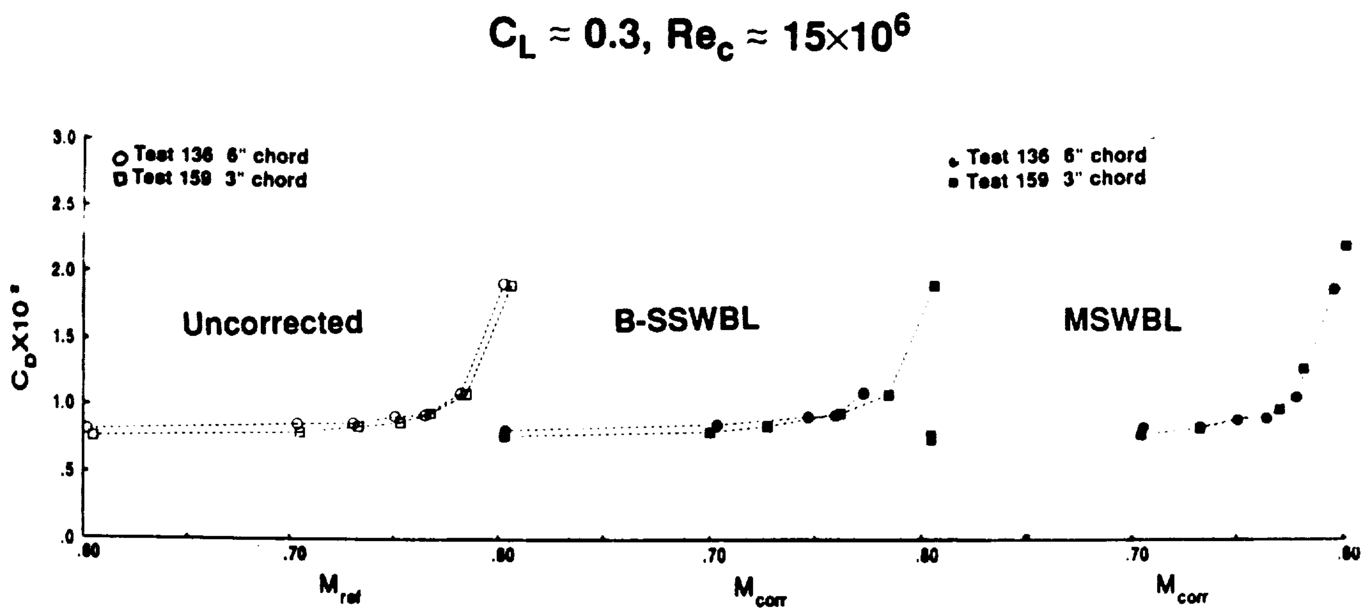
The results from the second pass through the correction code are shown below. All three tests show good agreement over the low lift range and the comparison with the independent free-air code is good. However, the data from test 169 tend to be inconsistent at moderate lift and all three data sets show different behavior near maximum lift. The early breakdown of the test 169 data and its correction may be due to the known inaccuracy of the top wall pressure data in the vicinity of the model. Subsequent correction comparisons will involve data from test 136, the early test of the six-inch-chord model and test 159, the test of the three-inch-chord model.

$M_{ref} \approx 0.730$, $Re_c \approx 10\times10^6$



Drag Rise Curves, $C_L = 0.3$

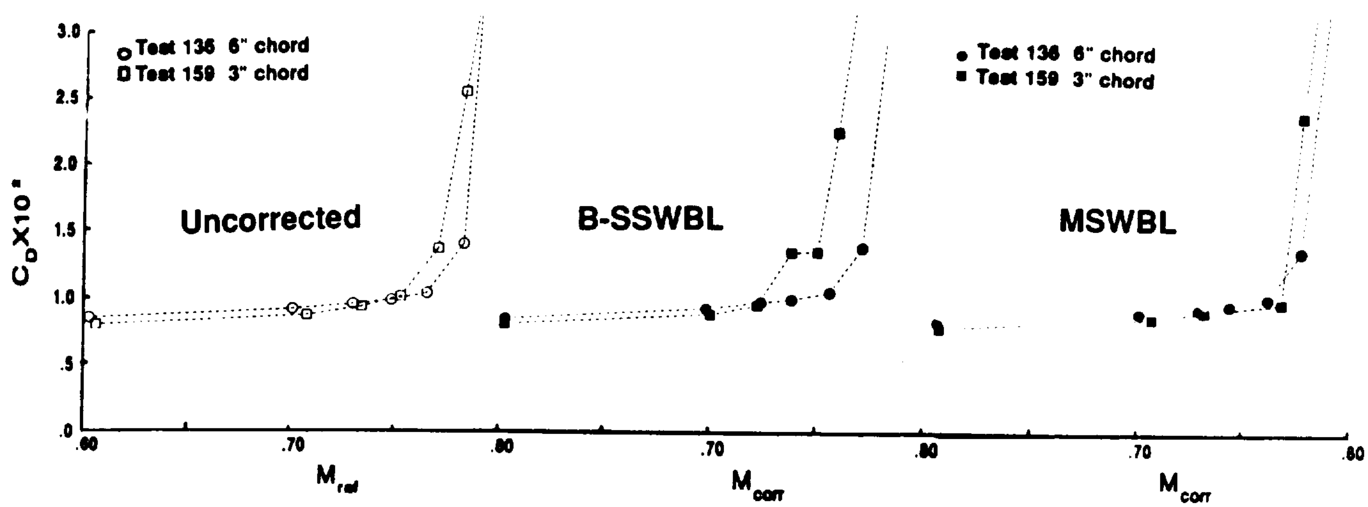
The following three figures show the Mach number correction in the form of uncorrected and corrected drag rise curves. The corrections are shown with and without the Murthy aspect ratio factor (ref. 6) on the Barnwell-Sewall sidewall boundary layer term (refs. 3 and 5). The first figure below shows the comparison for $Re_c = 15$ million at $C_L = 0.3$.



Drag Rise Curves, $C_L = 0.5$

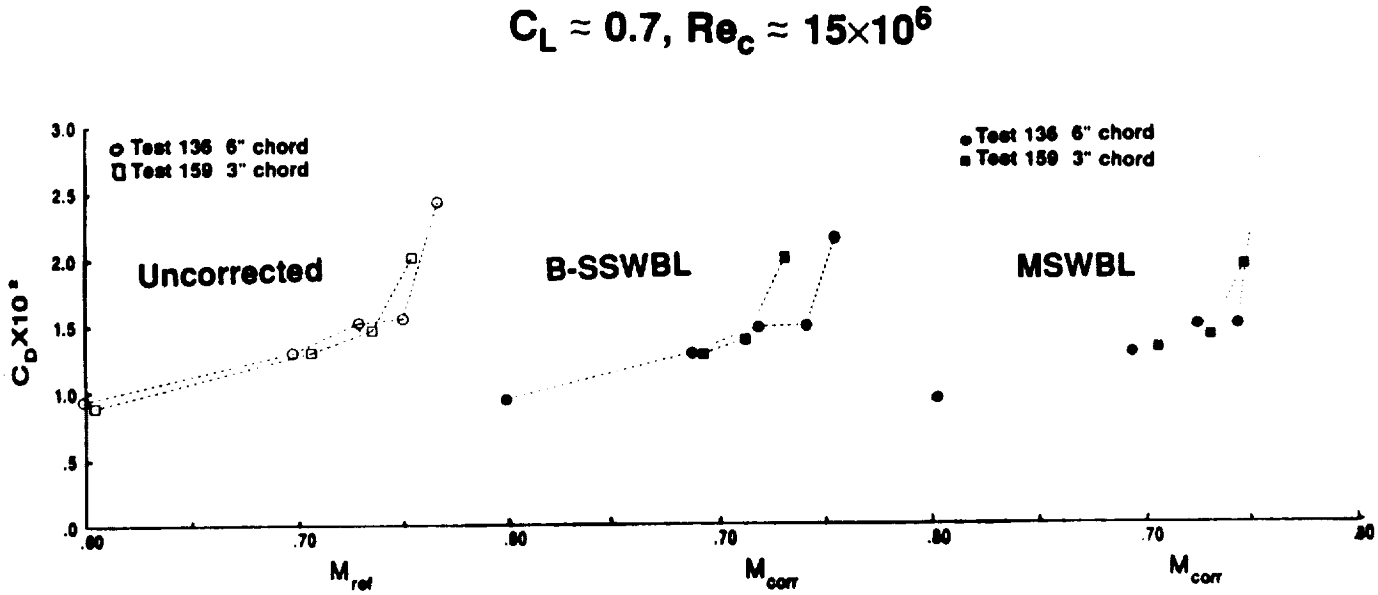
Uncorrected and corrected drag rise curves are shown here for $C_L = 0.5$.

$C_L \approx 0.5$, $Re_c \approx 15 \times 10^6$



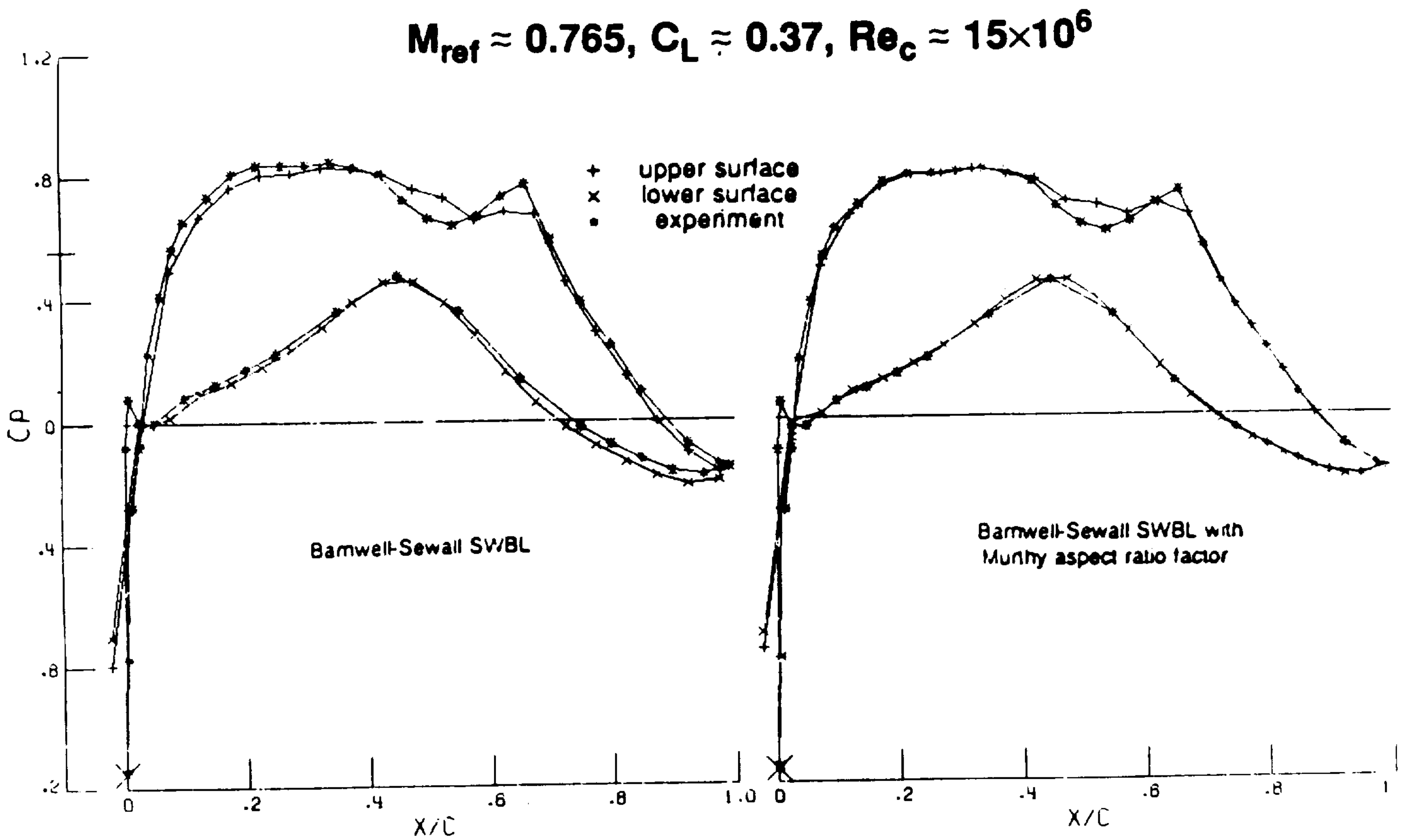
Drag Rise Curves, $C_L=0.7$

Uncorrected and corrected drag rise curves are shown here for $C_L=0.7$. In all cases, the Barnwell-Sewall Mach correction is noticeably too large for the three-inch-chord test. The agreement is pretty good for all three cases with the Murthy aspect ratio factor included; this is taken as evidence that an aspect ratio factor should appear as part of a sidewall boundary layer approximation.



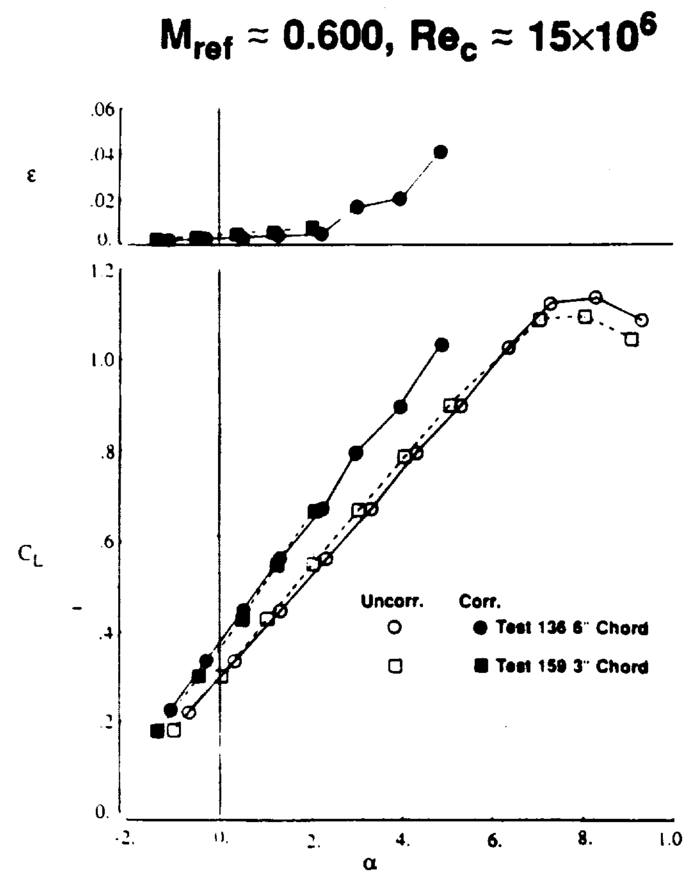
Airfoil C_p Plots

The better correction to the Mach number due to the Murthy aspect ratio factor is also evident in comparisons of the free-air calculated pressure coefficient, shown by the vertical and diagonal crosses, and the experimental pressure coefficient renormalized with the corrected Mach number, shown by the asterisks. The figure shows the comparison for the three-inch-chord model at $C_L \approx 0.37$, $M_{ref} = 0.765$, and $Re_c = 15$ million. The shift in the C_p's is eliminated by using the Murthy aspect ratio factor. Similar tendencies are found in the corrections for the six-inch-chord model but not to the same extent. All subsequent corrections will be made with the Murthy aspect ratio factor included in the sidewall boundary layer approximation.



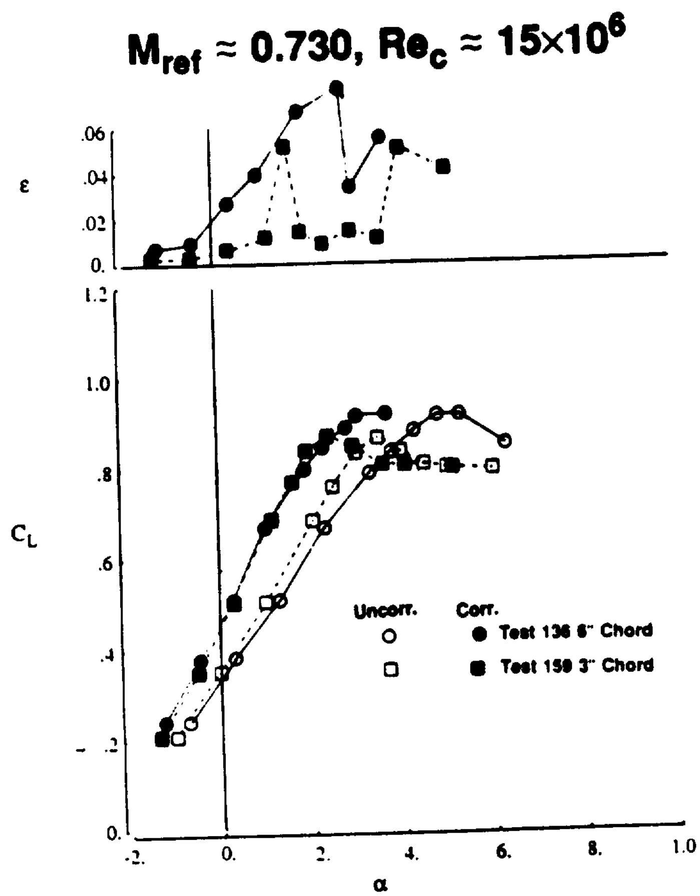
Lift Curves and Error Parameter, $M_{ref}=0.60$

The following three figures show the results of applying the WIAC procedure to data for three Mach numbers and a Reynolds number of 15 million. The corrected and uncorrected lift curves are shown for two tests. In addition, ε, the RMS matching error of the experimental and calculated airfoil surface velocity squared, is shown as an indication of the relative 'goodness' of the corrections. As the error increases the corrections are deemed to be less trustworthy. The first figure shows the lift curve and the error for $M_{ref}=0.60$.



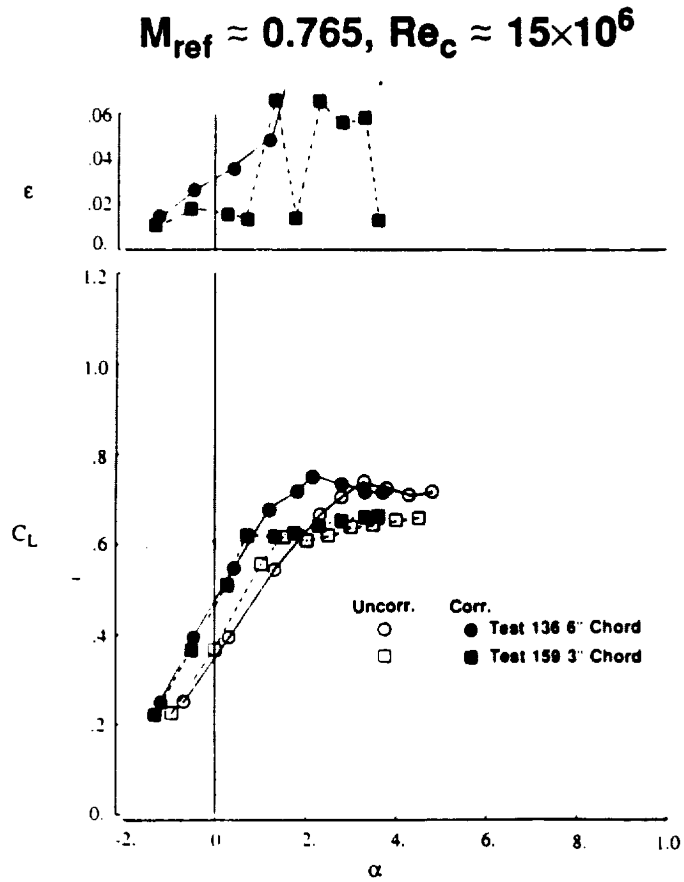
Lift Curves and Error Parameter, $M_{ref}=0.73$

This figure shows the lift curve and the error parameter for $M_{ref}=0.73$, $Re_c=15$ million. It can be seen that the error parameter, ε, becomes relatively much larger sooner with increasing α than was the case at $M_{ref}=0.60$ shown on the previous page.



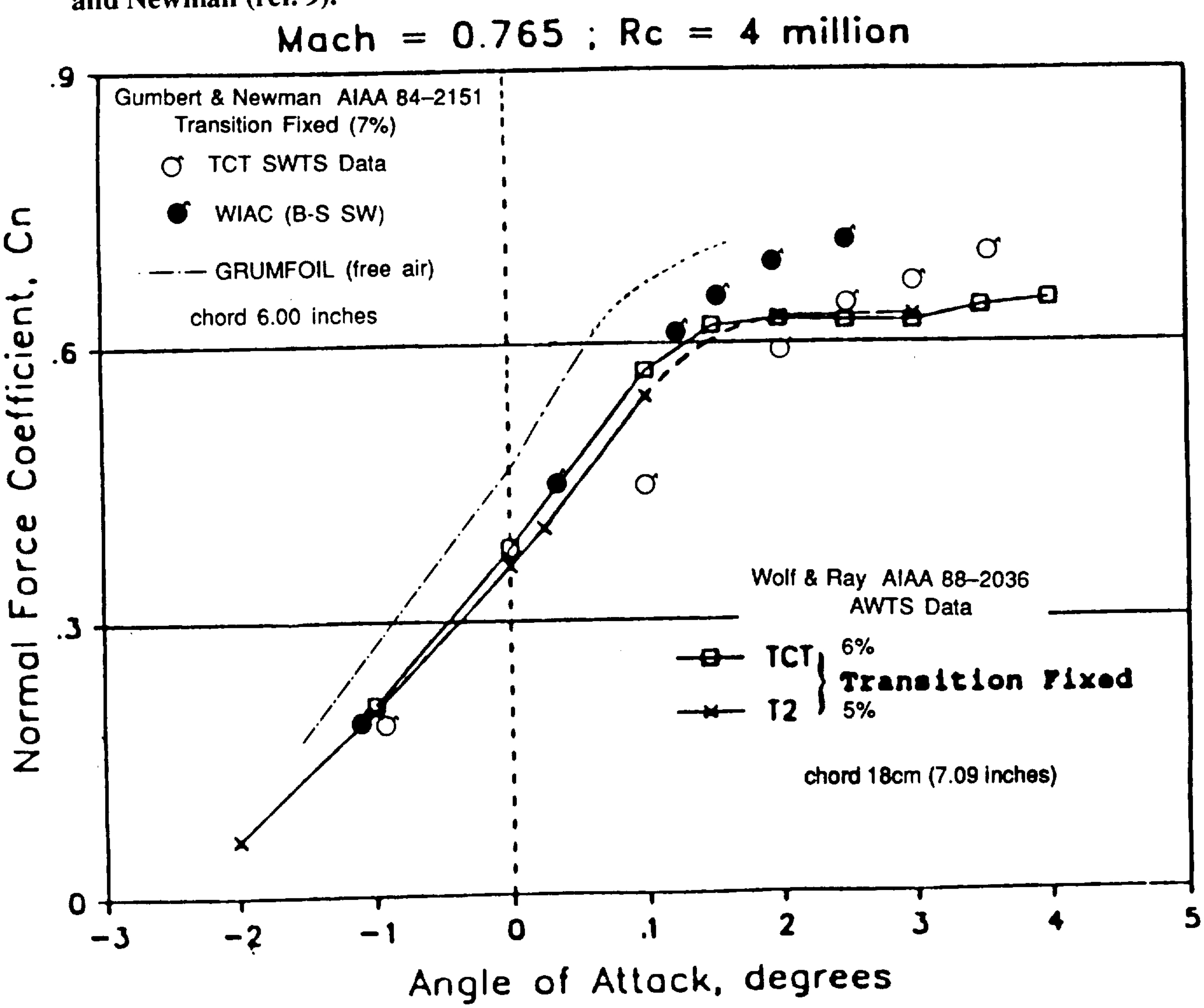
Lift Curves and Error Parameter, $M_{ref} = 0.765$

This figure shows the lift curve and the error parameter for $M_{ref} = 0.765$, $Re_c = 15$ million. It can be seen in these three figures that as the Mach number increases and the lift increases the error parameter also increases. This is due in part to the inability of the inviscid method to adequately model a flow condition greatly influenced by viscous and viscous/shock interaction phenomena. In addition, the present sidewall boundary layer/model pressure field interaction approximations may certainly become suspect at the higher transonic flow conditions.



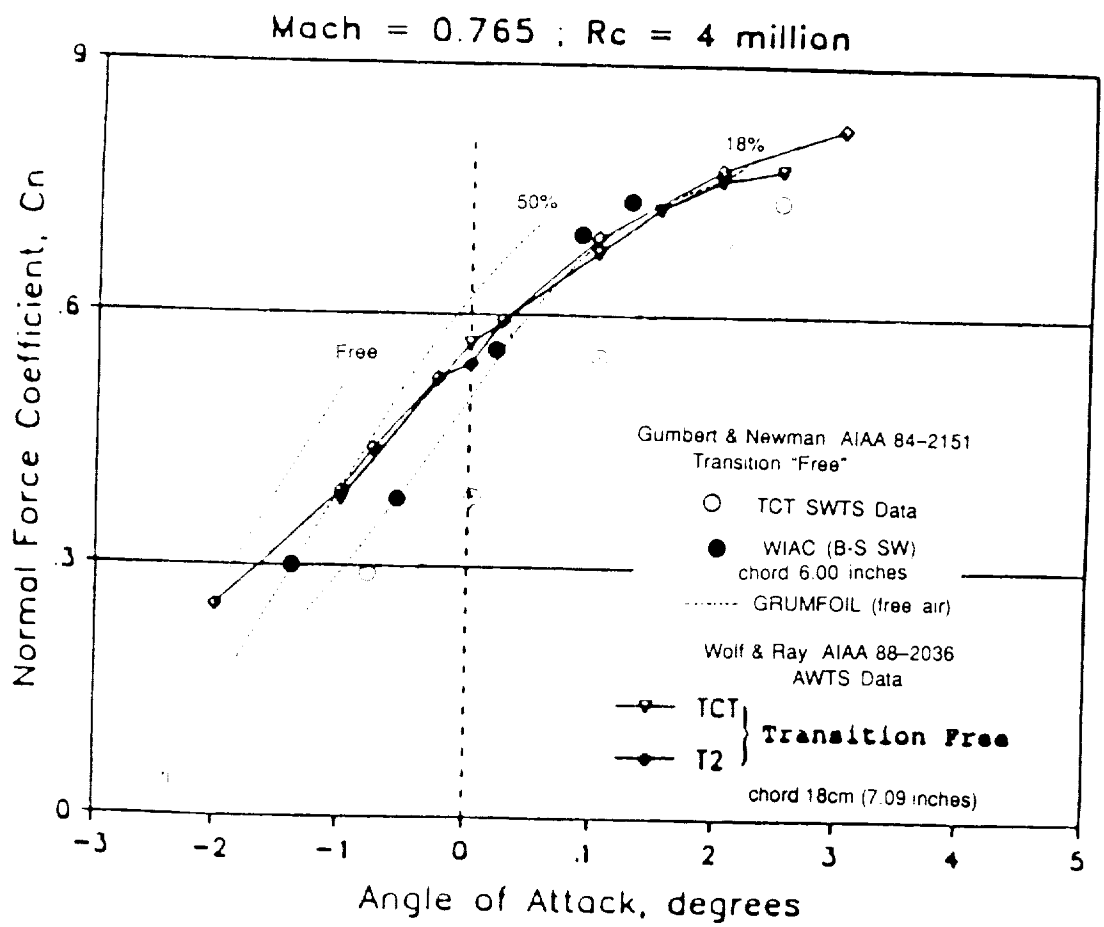
CAST 10 Airfoil Data

Comparisons of lift curve data for the French-built 18-cm (7.09 inch) chord CAST 10 model tested in both the NASA 0.3-m TCT and the ONERA/CERT T2 was recently given by Wolf and Ray (ref. 16). Both tunnels had adjusted wall test sections (AWTS) and both fixed and free transition results were given for $M_{ref} = 0.765$ and $Re_c = 4$ million. The curves shown in black by the squares and X's on the figure below denote the fixed transition data. Lift curve data shown as open and closed circles on the figure are from a 6-inch-chord model tested in the 8- by 24-inch slotted wall test section (SWTS) of the NASA 0.3-m TCT with transition fixed at 7% chord. Uncorrected data are indicated by open symbols while the (second pass, 4-wall) WIAC data are given by the solid symbols. The GRUMFOIL free-air numerical results at the corrected conditions are denoted by an alternating dash-dot line when flow is attached (until very near the trailing edge) and a dotted line for separated flow. The value of $c_{n_{max}}$ appears to be larger for the slotted wall test section results. The corrected slotted wall data and GRUMFOIL results were taken from Gumbert and Newman (ref. 9).



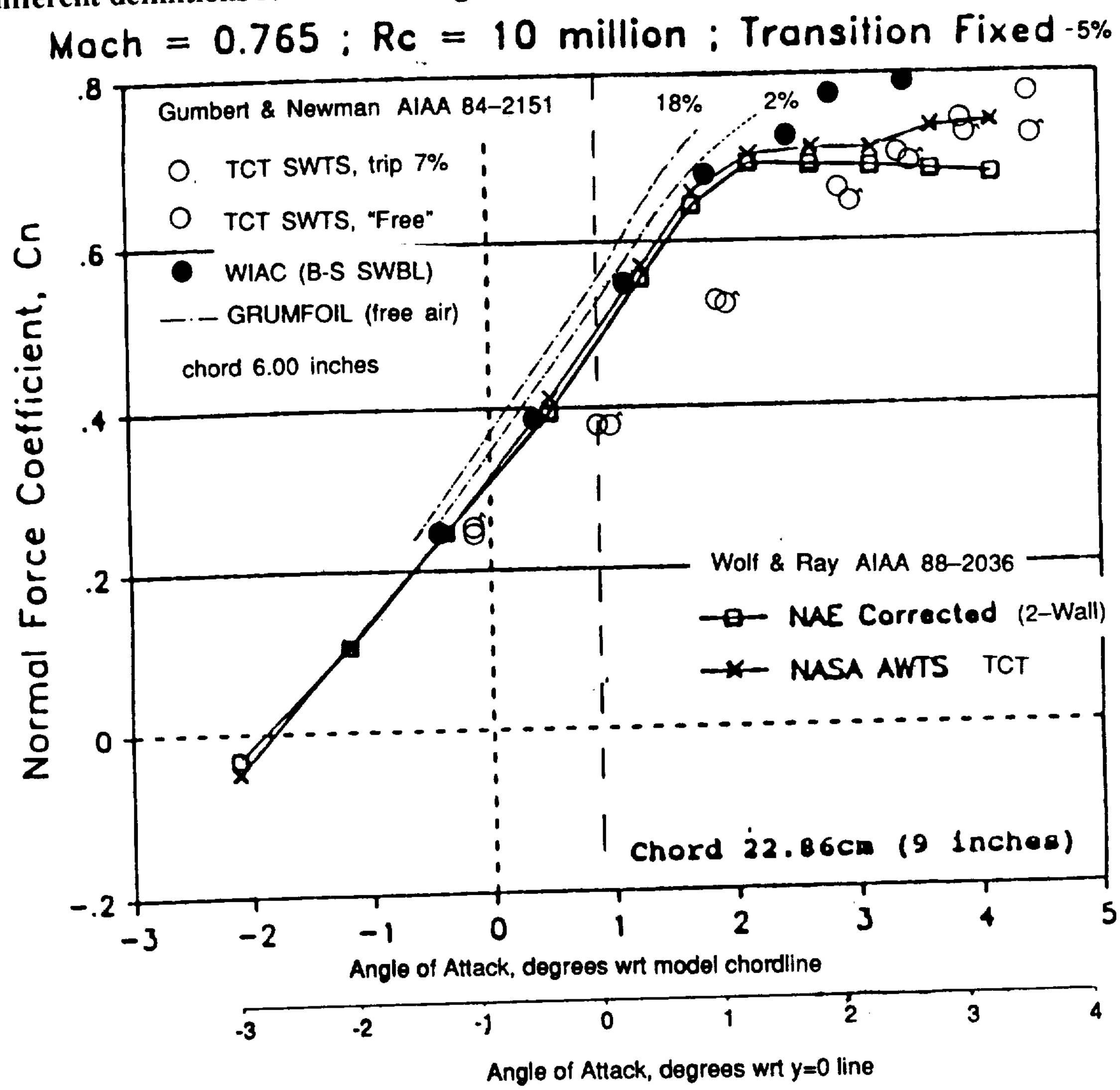
CAST 10 Airfoil Data

Lift curve data shown by the solid lines is again that from the AWTS tunnels as described on the previous page. Data shown here by the open and closed circles is for "free" transition in the slotted wall test section of the TCT. Again the open symbols are uncorrected data, the filled symbols are WIAC data and the dashed curves are for GRUMFOIL free-air results. As pointed out in reference 9, the various GRUMFOIL results are for different transition locations (denoted n% at end of line) and it appears that the transition location in the tunnel tests is changing with lift level. The relative location of the curves in the present comparison indicates that the slotted wall test section appears to cause more premature transition than the adaptive wall test section.



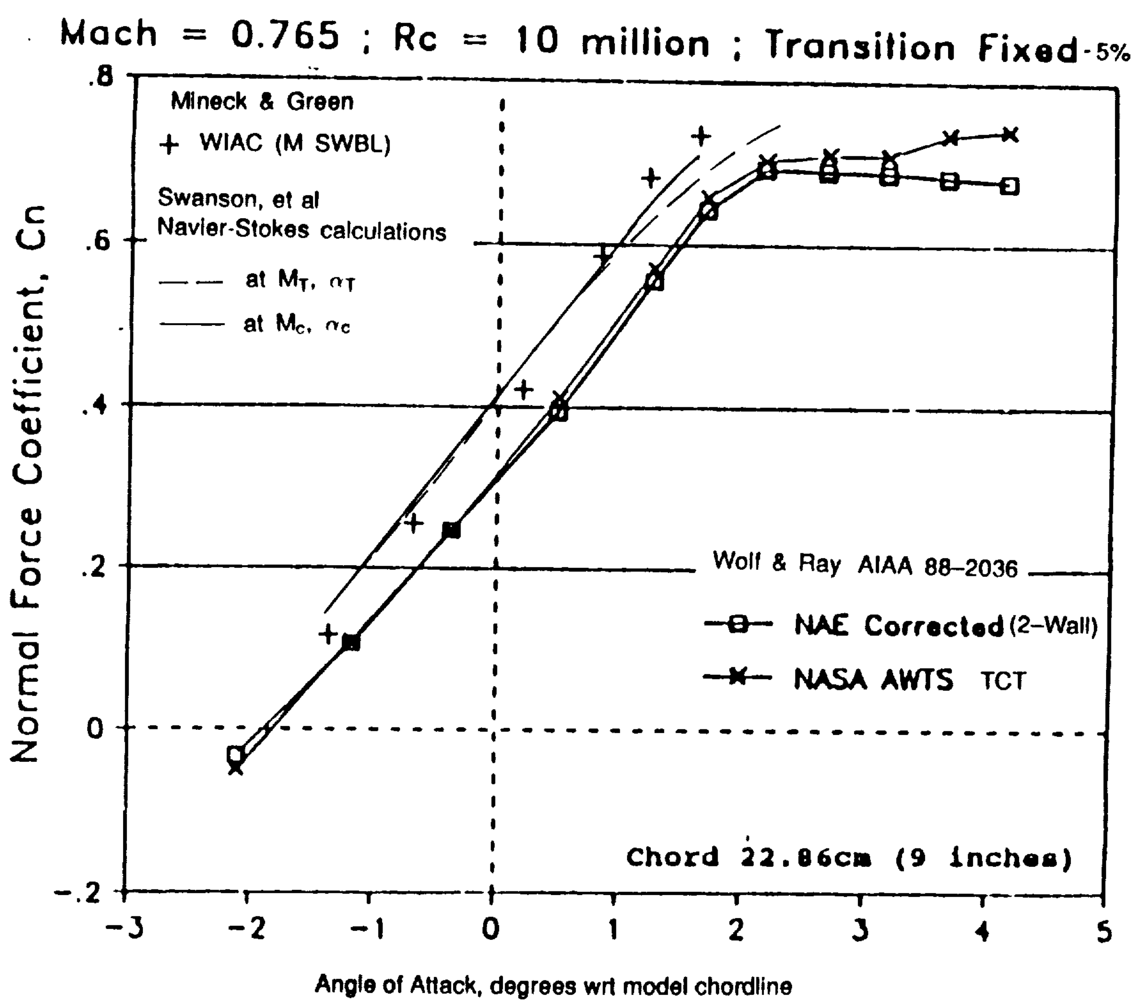
CAST 10 Airfoil Data

Comparison of lift curve data for the Canadian-built 9-inch chord CAST 10 model tested in the NASA 0.3-m TCT AWTS with that from the NAE 5-foot by 5-foot Blowdown Wind Tunnel with perforated top and bottom wall airfoil test section (15- by 60-inch) were also given by Wolf and Ray (ref. 16). These results, shown by the X's and the squares on the viewgraph below, are for transition fixed at 5% chord at $M_{ref} = 0.765$ and $Re_c = 10$ million. The Canadian data have been corrected for the top and bottom perforated wall interference. Lift curve data shown as circles are from a 6-inch-chord model tested in the 8- by 24-inch slotted wall test section of the NASA 0.3-m TCT with transition fixed (flagged symbols) and "free" (open symbols). The filled symbols represent the (second pass, 4-wall) WIAC data for free transition. Broken line curves are again GRUMFOIL free-air results with transition denoted at the end of the curve. The shift in the angle of attack scale was simply due to different definitions for the zero angle of attack.



CAST 10 Airfoil Data

Lift curve data shown by the X's and squares is again that from the NAE perforated and NASA AWTS tunnels as described on the previous page. Data shown here by the "plus" symbol are for the 4-wall AWTS WIAC (ref. 4) applied to the NASA AWTS data by Mineck using the Murthy sidewall boundary layer option. The Navier-Stokes results denoted by the solid and dashed lines are due to Swanson et al and are discussed in the final talk of this workshop. At the higher lift levels for this Mach number, the Mach number corrections appear to be too large; apparently the subsonic wavy-wall solution invoked by Murthy (ref. 6) to approximately model the sidewall boundary layer effect is no longer valid for extensive supercritical flow and certainly not for large separated flow regions. This will also be discussed by Swanson.



CONCLUDING REMARKS

PREMISE: All "airfoil tunnel" data contains some wall interference

- Conclusions Concerning Data
  - **Wall interference assessment must be made**
  - **Wall interference corrections have been required to date**
  - **Corrections smaller for AWTS data than for SWTS data**
  - **SWBL influence can be significant at transonic high-lift conditions**
  - **Airfoil and tunnel-wall C_p data required for TWINTN4**
  - **Transition location needs to be known**

- Conclusions Concerning WIAC
  - **Transonic 4-wall approximations are required**
  - **Multiple passes needed to assess upstream flow angle**
  - **SWBL approx. needs to contain aspect ratio effect**
  - **Reasonable corrections seem to be obtained**
  - **Fairly easy to use**
  - **SWBL approx. may be inadequate for extensive supercritical flow**
  - **Interpretation of error parameter not yet established**

References

1. Kemp, W. B., Jr.: Transonic Assessment of Two-Dimensional Wind Tunnel Wall Interference Using Measured Wall Pressures. Advanced Airfoil Technology Research - Volume I, NASA CP-2045, Part 2, 1979
2. Kemp, W. B., Jr.: TWINTAN: A Program for Transonic Wall Interference Assessment in Two-Dimensional Wind Tunnels, NASA TM-81819, 1980
3. Kemp, W. B., Jr. and Adcock, J. B.: Combined Four-Wall Interference Assessment in Two-Dimensional Wind Tunnel Tests, AIAA Paper 82-0586, March 1982
4. Green, Lawrence L. and Newman, Perry A.: Transonic Wall Interference Assessment and Corrections for Airfoil Data from the 0.3-m TCT Adaptive Wall Test Section, AIAA 87-1431, June 1987
5. Barnwell, R. W. and Sewall, W. G.: Similarity Rules For Effects of Sidewall Boundary Layer in Two Dimensional Wind Tunnels, Paper 3, AGARD CP-335, 1982
6. Murthy, A. V.: Effect of Aspect Ratio on Sidewall Boundary Layer Influence in Two-Dimensional Airfoil Testing, NASA CR-4008, 1986
7. Gumbert, C. R.; Newman, P. A.; Kemp, W. B.; Adcock, J. B.: Adaptation of a Four-Wall Interference Assessment/Correction Procedure for Airfoil Tests in the 0.3-m Transonic Cryogenic Tunnel, Paper 25, NASA CP-2319, 1984
8. Gumbert, C. R.: User Manual for 0.3-m TCT Wall Interference Assessment/Correction Procedure: 8- by 24-Inch Test Section, NASA TM-87582, 1985
9. Gumbert, C. R. and Newman, P. A.: Validation of a Wall Interference Assessment/Correction Procedure for Airfoil Tests in the 0.3-m Transonic Cryogenic Tunnel, AIAA Paper 84-2151, August 1984.
10. Melnik, R. E.; Mead, N. R.; and Jameson, A.: A Multi-Grid Method for the Computation of Viscid/Inviscid Interaction on Airfoils, AIAA Paper 83-0234, January 1983
11. Swanson, R. C. and Turkel, Eli, "A Multistage Time-Stepping Scheme for the Navier Stokes Equations," AIAA Paper 85-0035, January 1985
12. Dress, D. A.; Johnson, C. B.; McGuire, P. D.; Stanewsky, E.; and Ray, E. J.: High Reynolds Number Tests of the CAST 10-2/DOA 2 Airfoil in the Langley 0.3-m Transonic Cryogenic Tunnel - Phase I, NASA TM-84620, 1983
13. Stanewsky, E.; Demurie, F.; Ray, E. J. and Johnson,C. B.: High Reynolds Number Tests of the CAST 10-2/DOA 2 Transonic Airfoil at Ambient and Cryogenic Temperature Conditions, Paper 10, AGARD CP-348, 1984

14. Murthy, A. V.; Johnson, C. B.; Ray, E. J.; Stanewsky, E.: Investigation of Sidewall Boundary Layer Removal Effects on Two Different Chord Models in the Langley 0.3-m Transonic Cryogenic Tunnel, AIAA Paper 84-0598, March 1984

15. Dress, D. A.; McGuire, P. D.; Stanewsky, E.; Ray, E. J.: High Reynolds Number Tests of the CAST 10-2/DOA 2 Airfoil in the Langley 0.3-m Transonic Cryogenic Tunnel - Phase II, NASA TM-86273, 1984

16. Wolf, Stephen W. D. and Ray, Edward J.: Highlights of Experience with a Flexible Walled Test Section in the NASA Langley 0.3-Meter Transonic Cryogenic Tunnel, AIAA 88-2036, May 1988