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A Wall Correction Program Based on Classical Methods for the National Transonic Facility (Solid Wall or Slotted Wall) and the 14x22-Ft Subsonic Tunnel at NASA LaRC

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List of Symbols

AR	wing aspect ratio
a	slot width
B	tunnel effective breadth
b	wing span
b_e	effective vortex span
b_v	vortex span
C	tunnel effective cross section area
C_D	drag coefficient
$C_{D,a}$	apparent drag coefficient
$C_{D,0}$	minimum drag coefficient
C_L	lift coefficient
C_M	pitching moment coefficient
$\bar{c}$	wing mean aerodynamic chord (MAC)
d_{eq}	equivalent fuselage diameter
d_{max}	maximum fuselage diameter
F	slot parameter
H	tunnel effective height
K	slot parameter (non-dimensional)
K^*	slot parameter (dimensional)
$K_{1,w}$	wing shape factor
$K_{3,f}$	fuselage shape factor
l_f	fuselage length
l	slat width
M	Mach number
P	slot parameter
Q	dynamic pressure
S_{ref}	wing reference area
V_{ref}	reference velocity
V_f	fuselage volume
V_w	wing volume

Greek:

α	angle of attack
β	compressibility factor $\sqrt{1-M^2}$
$\Delta\alpha_1$	angle of attack correction at ¼ chord
$\Delta\alpha_{sc}$	angle of attack correction due to streamline curvature
δ_0	correction factor 1 for upwash
δ_1	correction factor 2 for upwash
ε	blockage parameter
ϕ	potential function
γ	ratio of specific heats
τ	tunnel shape factor

Ω_s	slotted tunnel blockage factor

Prefixes:

$\Delta\$$	correction to the quantity $\$$

Subscripts:

f	fuselage
n	normal to stream
ref	reference value
u	uncorrected
w	wing
wk	wake
wkb	wake buoyancy
x	streamwise

Abbreviations:

MAC	mean aerodynamic chord
MGC	mean geometric chord
AR	wing aspect ratio

Abstract

A Fortran subroutine CMWALL is described, which is an implementation of the collective information from classical methods-based wall corrections. These methods use established closed-form expressions which were developed based on simple linear potential-based methods. Since both the NASA LaRC 14x22-Ft Subsonic Tunnel and the National Transonic Facility (NTF) are rectangular in cross-section, this commonality has been taken advantage of in the implementation of the method. This is a simple and rapid tool to calculate corrections due to wall interference, designed to be easily implemented in the existing tunnel data reduction programs, either as real-time or post-point. It is however important to realize that the method is based on the simplifying assumptions of linearity, small model and attached flow. The computed results are thus to be viewed as 'first-cut' estimates, to be refined further using more complex methods based on measured wall pressures (known as wall signature methods).

The inputs required for CMWALL relate to the tunnel configuration and model geometry (assumed to be constant for a test) and test point measurements of tunnel reference parameters, model forces and moments. The geometry inputs are provided as a data block which can be easily set up prior to the test. Test data are provided and transmitted to CMWALL in the subroutine call list.

Three test cases are presented to illustrate the application of the method. A summary of results in each case is presented in a composite plot of the corrections.

1. Introduction

Classical methods-based wall corrections can be calculated using established closed-form expressions which were developed based on simple linear potential-based methods, subsequently enhanced empirically from experimental data and test experience. Literature on the subject from 1970 and earlier is available in the form of various reports, papers, charts and tables. A Fortran subroutine CMWALL has been developed, which is an implementation of the collective information contained in these sources, resulting in a simple and rapid tool to calculate corrections due to wall interference. Since both the NTF and 14x22-Ft Subsonic Tunnel are rectangular in cross-section, there is considerable amount of commonality in implementation.

The inputs required for CMWALL are of two types: (1) tunnel configuration and model geometry inputs (which are assumed to be constant for a test) and, (2) test point measurements of tunnel reference parameters, model forces and moments. Inputs of type (1) are provided as a data block which can be easily set up prior to the test. Inputs of type (2) are provided and transmitted to CMWALL in the subroutine call list. The subroutine is thus designed to be easily implemented in existing tunnel data reduction programs. It is, however, important to realize that the method is based on the simplifying assumptions of linearity, small model and attached flow. The computed results are thus to be viewed as 'first-cut' estimates, to be refined further using more complex methods based on measured wall pressures (known as wall signature methods).

2. Wall Correction Basics

The subject of wall correction is an important part of wind tunnel experimentation and has been extensively studied for the last 50 years. Key concepts in wall correction, important in the use of CMWALL, are summarized below.

Wall interference refers to the changes in the measured tunnel and model parameters due to the model being enclosed in a tunnel. In the case of solid or ventilated walls, the streamlines in the wall region are constrained to a shape that is different from what exists in free air. This in turn changes the boundary conditions, which makes the tunnel flow around the model substantially different from the free-air flow. The tunnel-measured values represent this changed flow, which needs to be corrected to remove the effect of the walls. In other words, corrections are applied to the measured and derived values to get the equivalent free-air values (i.e., when the walls are removed). References 1 and 2 (AGARD reports AG-109 and AG-336) give a comprehensive review on the topic of wall interference. The first report is a collection of work, mostly of classical nature, prior to 1966. The second report summarizes subsequent work until 1998 which includes more advanced computational methods.

The classical approach to wall correction is based on replacing the model in the tunnel by equivalent singularities and the principle of superposition. Consider a three-dimensional point source in free-stream simulating a Rankine forebody. The free-air solution is given by the sum of the free-stream potential and the source potential. The perturbation velocities in free-air are simply the derivatives of the source potential. When this singularity is enclosed by four solid walls, flow tangency is imposed at the boundaries which is obtained by placing an infinite number of singularities at reflection locations off the walls, following the well-known method of images. Therefore, the additional perturbation potential introduced by the walls is the sum of all the image potentials. Correction for wall interference thus corresponds to the sum of reflection potentials, which can be evaluated once the original singularity strength is known.

Wall interference correction is thus a spatially varying function. The traditional assumption is that the perturbation velocity field can be approximated by a change in the angle of attack and the tunnel velocity (wall interference-induced gradient effects in the flow such as axial buoyancy and streamline curvature are also accounted for in an approximate manner). Any left-over differences are usually second-order effects. However, when they become significantly large such as in the case of a large model, the measured data may become uncorrectable by traditional methods.

The perturbation velocity field is usually computed using a simplified representation of the model consisting of potential singularity elements such as point sinks, point sources, and point or line doublets. Once the perturbation velocity solution with the appropriate boundary condition imposed is known, wall corrections can be quantified by averaging the interference flow field along model or tunnel reference lines. Primary wall interference corrections are given in terms of a blockage correction ε and an angle of attack correction $\Delta\alpha$.

The blockage correction ε is obtained as the average of streamwise perturbation velocities (normalized by tunnel reference velocity) along the model axis. This is proportional to the ratio of the maximum model frontal cross section area to the tunnel cross section area. This correction is applied to the measured values of Mach number M and dynamic pressure Q. The corrections for M and Q are obtained as

$$\frac{\Delta M}{M} = \left(1 + \frac{\gamma - 1}{2} M^2\right)\varepsilon \qquad (1)$$

$$\frac{\Delta Q}{Q} = \left(2 - M^2\right)\varepsilon \qquad (2)$$

The angle of attack correction is obtained as a weighted average of the perturbation velocity in the lifting direction. The wing ¼ chord line is the reference line customarily used for this averaging. An additional term is added to include the effect due to streamline curvature. These primary mean corrections translate to equivalent corrections on force and moment coefficients. A buoyancy correction (on C_D) due to wall interference is also computed from the wake blockage gradient. Pitching moment correction is computed based on the change in flow curvature calculated from the change in the angle of attack correction from ¼ chord to ¾ chord.

To summarize, classical wall corrections for a test point are reported as follows:

1. A blockage parameter, ε and an angle of attack correction, $\Delta\alpha$; these are the primary corrections obtained by averaging the perturbation flow field.
2. Corrections on tunnel Mach number and dynamic pressure, which are functions of the blockage parameter, ε.
3. Corrections on lift, drag and moment coefficients which result from the changed tunnel reference velocity, angle of attack and flow gradients. These are derived corrections obtained from the primary corrections and the uncorrected coefficients.

The free-air or corrected values are obtained by adding the corrections to the measured values. For a lifting model in a solid-walled tunnel, the free-air or corrected values of M, Q, α, C_D are larger than the measured values; free-air C_L is usually decreased. In general, slotted-wall corrections tend to be much smaller than the solid-wall corrections.

3. Elements of the Classical Method

The tunnel configuration (height, width, cross section area) is first set depending on the facility and model type (full- or semispan), which are input to CMWALL. For a semispan model, the mounting wall becomes a reflection plane resulting in effectively doubling the tunnel cross section perpendicular to the reflection wall. Tunnel height (H), breadth (B) and cross section (C) are thus redefined based on the model type and orientation.

The model blockage parameter is first calculated assuming solid tunnel wall boundaries. This consists of three parts, viz., blockage due to wing volume ε_w, blockage due to fuselage volume ε_f, and blockage ε_{wk} due to the model wake region. Details are given in the next section. Total blockage is obtained by summing the three parts (as in Ref. 3, Barlow, Rae and Pope).

The downwash or angle-of-attack correction is obtained from the boundary correction factors δ_0 and δ_1 as a function of effective jet width, which is in turn a function of wing aspect ratio, taper ratio and tunnel aspect ratio (see Ref. 3). The force and moment coefficients are then corrected based on the blockage and the angle of attack correction. Pitching moment correction is calculated based on the streamline curvature. Details are again given in the next section.

For the NTF slotted-wall case, the additional parameter Ω_s as well as new values of δ_0, δ_1 are obtained from the work of Pindzola and Lo (Ref. 4). These are slotted-wall results in the form of tables as a function of the tunnel openness parameter and the tunnel aspect ratio. The solid-wall blockage and upwash corrections are then adjusted based on these interpolated values.

A schematic of the calculation sequence in CMWALL is shown in Fig. 1. Detailed expressions are given in the next section.

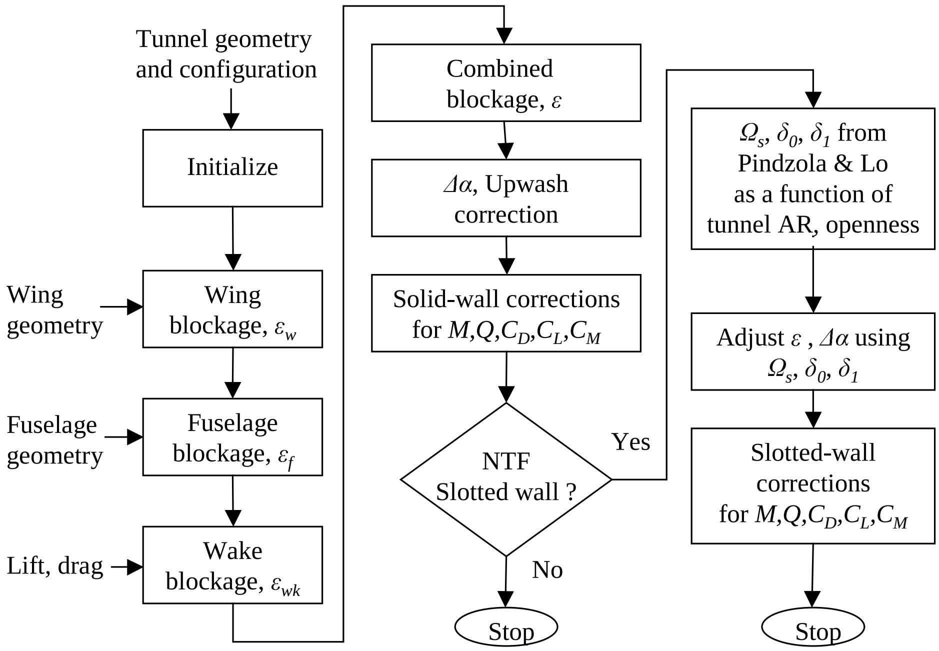

Figure 1. Schematic of the Calculation Sequence in CMWALL.

4. Detailed Formulation for Blockage

Ref. 3 has the generally-accepted formulation for model blockage based on earlier work, especially Herriot (Ref. 5).

As stated in Ref. 1 (AGARD 109), "…the model and its wake occupy a certain volume within the tunnel stream. The streamline pattern about the model is thereby distorted compared with free-air conditions…interference associated with the model itself is called "solid blockage", and that due to the wake, "wake blockage". For most purposes, it is sufficiently accurate to assume that the two blockage components are independent both of each other and of the model lift." The important assumptions are that the model is small compared to the tunnel section and that the lift is not too large. Blockage is assumed to influence only the longitudinal component of the flow about the model. The model is assumed to be mounted in the center of the tunnel.

Blockage due to the model support and its wake should be accounted for separately and added to model blockage. This is not an issue usually for semispan models since there are no support elements in the tunnel stream. If a semispan standoff plate is used, it can be considered as a part of the fuselage unless the lift coefficients with and without the standoff plate are significantly different (see Ref. 6). For full-span models, blockage due to the aft sting (NTF), canon and post or floor-mounted post (14x22-Ft Subsonic Tunnel) is to be accounted for separately. This blockage may be a function of the pitch angle. It is preferable to measure this directly, or estimate it using a wall signature method such as the Transonic Wall Interference Correction System (TWICS, Ref. 7).

The corrections due to solid-wall boundaries are described here. Adjustments required for slotted walls are given in a separate section.

Blockage due to the wing:

The method is based on summation of a series of doublet images representing the model (Ref. 3). For a semispan wing, calculations are based on the equivalent full-span wing in the equivalent doubled test section. The wing shape factor $k_{1,w}$ is first obtained from a table as a function of the wing cross section geometry type (selected as the section closest to the NACA 4-digit series, 64, 65 or 66 series; choice of NACA 4-digit series should be sufficiently accurate in most cases) and the average wing thickness ratio $(t/c)_{av}$. The data for the table is taken from Ref. 3, Fig. 10.2, p.369. The tunnel shape factor τ_w is then obtained from a table as a function of the wing span to tunnel breadth ratio and the tunnel aspect ratio. Note that breadth and height are defined in directions perpendicular and parallel respectively, to the lift vector direction. The data for the table is taken from Ref. 3, Fig. 10.3, p.369. The incompressible blockage ε_w due to the wing is then calculated as

$$\varepsilon_w = \frac{k_{1,w}\tau_w V_w}{C^{3/2}} \qquad (3)$$

where V_w is the wing volume (a good approximation is $0.7\,(t/c)_{av}\,S_{ref}\,C$, where S_{ref} is the wing planform area) and C is the test section area equal to BH.

Blockage due to the fuselage:

The body shape parameter $k_{3,f}$ is obtained from a table as a function of the ratio $\frac{d_{eq}}{l_f}$, where d_{eq} is the equivalent fuselage diameter and l_f is the fuselage length. The data for the table is taken from Ref. 3, Fig. 10.2, p.369. The blockage factor τ_f is obtained from a table (based on Ref. 3, Fig. 10.3, p.369) as a function of the tunnel aspect ratio with fuselage diameter to tunnel width ratio assumed to be zero. The blockage ε_f due to the fuselage is then calculated as

$$\varepsilon_f = \frac{k_{3,f}\tau_f V_f}{C^{3/2}} \qquad (4)$$

where V_f is the fuselage volume (a good approximation is $0.45\,l_f\,d_{\max}^2$).
Note that both ε_w and ε_f are equal to a constant times the corresponding volumes divided by $C^{3/2}$. The constant is in the range 0.9 to 0.96 depending on the geometry.

Wake blockage:

The wake blockage is calculated by assuming an attached wake[1]. The attached wake model uses an image system based on a three-dimensional source at the trailing edge. This involves subtracting from the measured drag, the drag due to lift (induced drag), which results in the apparent drag $C_{D,a}$ defined as

$$C_{D,a} = C_{D,u} - \frac{C_{L,u}{}^2 S_{ref}}{\pi b^2} = C_{D,u} - \frac{C_{L,u}{}^2}{\pi AR} \quad (5)$$

Here the subscript u refers to uncorrected measured values. S_{ref} is the wing reference area, b is the span of the wing and AR is the wing aspect ratio. Note that for a semispan model, values corresponding to the equivalent full-span wing are used. $C_{D,a}$ should be nearly same as the minimum drag $C_{D,0}$; $C_{D,a}$ is however used here because it can be calculated directly. The wake blockage is then calculated as

$$\varepsilon_{wk} = \frac{C_{D,a} S_{ref}}{4C} \quad (6)$$

The longitudinal gradient of wake blockage along the tunnel centerline creates a buoyancy drag (Ref. 2, Section 2.2.2.6). This buoyancy drag correction (produces an increase in drag) is given by

$$\Delta C_{D,wkb} = C_{D,a} \frac{\varepsilon_w + \varepsilon_f}{(1 - M^2)^{3/2}} \quad (7)$$

Combined blockage:

The combined blockage is obtained by adding the blockages due to the wing, fuselage and wake, with a compressibility correction adjustment as

$$\varepsilon = \frac{\varepsilon_w + \varepsilon_f}{(1 - M^2)^{3/2}} + \frac{\varepsilon_{wk}(1 + 0.4M^2)}{(1 - M^2)} \quad (8)$$

5. Detailed Formulation for Downwash Corrections

The change in angle of attack at the quarter-chord location due to the walls is given by

[1] A more refined wake blockage model accounting for separated flow drag developed by Maskell (Reference 2, Section 6.2.3) is available. But it is not used here because of its need for detailed analysis, such as finding of the minimum drag, slopes, etc. from the drag polar, which would prevent its use for pre-test prediction.

$$\Delta\alpha_1 = \delta_0 \frac{S_{ref}}{C} C_{L,u} \quad (9)$$

Here $\Delta\alpha_1$ is in radians and δ_0 is a factor that is a function of the span load distribution, model span to tunnel width ratio and the test section shape, usually with a value around 0.125. The value of δ_0 is obtained as below. First, the vortex span ratio b_v / b is obtained as a function of the wing aspect ratio and wing taper from a table corresponding to Fig. 10.11, page 382 of Ref. 3. The ratio b_e / b is computed as $0.5\,(1 + b_v / b)$. The value of δ_0 is obtained from a table corresponding to Fig. 6.21 of Ref. 8 as a function of the tunnel aspect ratio and b_e / b. The angle of attack correction is then computed.

There is an additional angle of attack correction $\Delta\alpha_{sc}$ due to the change in streamline curvature produced by the walls. This is given as

$$\Delta\alpha_{sc} = \delta_1 \bar{c} \frac{S_{ref}}{C} \frac{C_{L,u}}{2\beta H} \quad (10)$$

The parameter δ_1 is obtained from a table corresponding to Fig. 3.4 of Ref. 1, which gives δ_1 / δ_0 as a function of *B/H*. The correction due to upwash on drag is computed as

$$\Delta C_{D,\alpha} = \left\{ C_{D,u} \left[\cos(\Delta\alpha_1) - 1 \right] + C_{L,u} \sin(\Delta\alpha_1) \right\} C_Q \quad (11)$$

where

$$C_Q = \frac{Q}{Q + \Delta Q} \quad (12)$$

The correction due to upwash on lift is computed as

$$\Delta C_{L,\alpha} = \left\{ C_{L,u} \left[\cos(\Delta\alpha_1) - 1 \right] - C_{D,u} \sin(\Delta\alpha_1) \right\} C_Q \quad (13)$$

The angle of attack correction is reported as the sum of the correction at the ¼ chord and the correction due to change in streamline curvature, which is

$$\Delta\alpha = \Delta\alpha_1 + \Delta\alpha_{sc} \quad (14)$$

The correction to pitching moment produced by streamline curvature is given as

$$\Delta C_M = \frac{\Delta\alpha_{sc}}{8} \left(\frac{\partial C_L}{\partial \alpha} \right) C_Q \quad (15)$$

The factor of 1/8 is true for a rectangular wing only; real wings will have larger factors.

6. Formulation for Slotted-Wall Corrections

Corrections for slotted walls have been discussed in a number of studies, both analytical as well as computational. The problem of inflow/outflow from test section to the tunnel plenum is a complex one, not easily amenable to simple image methods. Inviscid homogeneous flow near the walls is a simplifying assumption made to reduce the boundary condition to the simple form, $\phi_x + K^* \phi_{xn}^2 = 0$, where K^* is a dimensional slot parameter defined as

$$K^* = \frac{l}{\pi} \ln\left(\csc\frac{\pi a}{2l}\right) = l\,K \qquad (16)$$

where a is the slot width and l is the distance between slots. The value of K has been determined analytically as above and determined empirically as well. The empirical value depends on the viscous flow in the slots, the number of slots, the degree of openness, Mach number, etc. A value suggested for the 6% open test section of the NTF is 3.6 (Ref. 2, Fig. 5.16), which corresponds to a multiplication factor of 4.75 from the inviscid analytical value of $K = 0.76$. Recent comparisons with TWICS results indicates that this factor may even be higher (7.5 in one case). A variable called `factor` is provided in the code to specify this empirical multiplication factor.

Slot parameters F and P are defined in Ref. 4 as

$$F = \frac{2K^*}{H}; \quad P = \frac{1}{1+F} \qquad (17)$$

Ref. 4, Fig. 5.5 provides a chart of Ω_s, which is the ratio of slotted tunnel blockages to the solid wall blockages as a function of the openness ratio P and tunnel aspect ratio H/B. With the value of Ω_s known, slotted-wall blockages can be computed from the corresponding solid-wall values. Ref. 4 also provides charts of the tunnel upwash ratios δ_0 and δ_1 (Fig.s 5.12 and 5.13) as a function of P and B/H. For the slotted tunnel applications, these values are used in place of the solid-wall values in Equations 8 and 9.

7. Applying Corrections

All the corrections listed below are added to the uncorrected values to obtain the equivalent free-air values.

The blockage corrections for Mach number and dynamic pressure are as follows.

$$\Delta M = M(1 + 0.2M^2)\varepsilon \qquad (18)$$

$$\Delta Q = Q(2 - M^2)\varepsilon \qquad (19)$$

The reference velocity is corrected by $\Delta V = V_{ref}\,\varepsilon$

Corrections to the angle of attack $\Delta\alpha$ is given by Equation (14). The final corrected drag coefficient is obtained from Equation (11) as

$$C_{D,c} = C_{D,u} C_Q + \Delta C_{D,\alpha} + \Delta C_{D,wkb} \quad (20)$$

The final corrected lift coefficient is obtained from Equation (13) as

$$C_{L,c} = C_{L,u} C_Q + \Delta C_{L,\alpha} \quad (21)$$

The correction to the pitching moment is obtained as

$$C_{M,c} = C_{M,u} C_Q + \Delta C_M \quad (22)$$

8. CMWALL Subroutine Call Details

The CMWALL subroutine is called as

```
subroutine cmwall(amachu,qu,vrefu,alphau,clu,cdu,cmu,
          eps,dalpha,dcd,dcl,dcm,dq,dv,dm,dcdb,cdc,clc,cmc)
```

with the call list defined as below. All quantities are in conforming U.S. units (ft., lb, sec.). All the variables are REAL*4.

Input list:

`amachu`	Mach number, uncorrected for wall
`qu`	dynamic pressure, uncorrected for wall, psf
`vrefu`	tunnel velocity, uncorrected for wall, fps
`alphau`	angle of attack, uncorrected for wall
`clu`	lift coefficient (stability axis), uncorrected for wall
`cdu`	drag coefficient (stability axis), uncorrected for wall
`cmu`	pitching moment coefficient (stability axis), uncorrected for wall

Note that only `amachu`, `clu` and `cdu` are actually used in the calculation of the primary correction terms `eps` and `dalpha`.

Output list:

`eps`	combined blockage parameter
`dalpha`	wall correction on angle of attack
`dcd`	wall correction on `cdu` due to lift interference only
`dcl`	wall correction on `clu` due to lift interference only

`dcm`	wall correction on `cmu` due to streamline curvature only
`dq`	wall correction on `qu`, psf
`dv`	wall correction on `vrefu`, fps
`dm`	wall correction on `amachu`
`dcdb`	buoyancy correction on drag coefft. due to wake blockage gradient
`cdc`	drag coefficient corrected for blockage and lift interferences and wall-induced buoyancy
`clc`	lift coefficient corrected for blockage and lift interferences
`cmc`	pitching moment coefficient corrected for blockage and lift interferences

An include file called `walldata` is also required, which provides tunnel and model geometry data to the program. This file should be set up with the appropriate values prior to a test. Input data definitions are given below.

Definitions of input parameters in the file '`walldata`'

`iwdbg`	:debug flag, 0 for no detailed print,1 for detailed debug print type INTEGER
`itunl`	:1 for NTF-solid wall; 2 for NTF-slotted wall; 3 for 14x22-Ft; NTF slotted wall openness (floor and ceiling) is determined by `ivent` type INTEGER
`itsconf`	:1 for full-span model; 2 for semispan model; type INTEGER
`ivent`	:% openness (NTF slotted case only),=6 (all slots open, usual case), 4 or 2 type INTEGER
`wingvol`	:wing volume; for semispan, enter corresponding full-span value
`tcav`	:maximum thickness ratio (t/c) of the representative wing section
`naca`	:airfoil type representing the average wing section; `naca`=44 if wing section can be approximated by a 4-digit NACA section; `naca`=64, 65, or 66 for corresponding 6-digit NACA series; type INTEGER
`twob`	:wing span; for a semispan model, input the equivalent full-span value
`sref`	:wing reference area, for semispan, input full-span wing value
`ar`	:wing aspect ratio, usually this is b^2 / S_{ref} of the full-span wing
`taper`	:taper ratio (tip chord / root chord), input 0.57 for elliptical planform wing
`cbar`	:mean aerodynamic chord (MAC)
`clalpha`	:lift curve slope, $\partial C_L / \partial \alpha$ in /deg units
`dequiv`	:maximum diameter of fuselage (from an equivalent circular section)
`fusl`	:fuselage length
`fusvol`	:fuselage volume, for semispan enter full-span value

9. Test Cases

Three test cases are provided covering the range of options. The test cases are:

1. 14x22-Ft Subsonic Tunnel: Semispan wing (Trap wing), Test 506, Run 109 data.

2. 14x22-Ft Subsonic Tunnel: Full-span Elliptical wing, Test 511, Run 195 data.
3. NTF solid wall: Full-span wing (Pathfinder 1), Test 114D, Run 313 data.

The geometric data used in these examples were obtained from available sources such as drawings, test reports, etc. However, note that whenever exact data were not available, an estimate was used.

<u>Test case 1: 14x22-Ft Subsonic Tunnel: Semispan wing (Trap wing), Test 506, Run 109</u>

The tunnel and model input data as specified in the file `walldata` are as below.

```
data iwdbg/0/
data itunl,itsconf,ivent/3,2,0/
data wingvol,tcav,naca/8.752,0.11,44/
data twob,sref,ar,taper/14.1765,44.056,4.561,0.395/
data cbar,clalpha/3.3,0.075/
data dequiv,fusl,fusvol/1.713,9.893,17.034/
```

The test data for 28 selected points in a run are provided in the standard TWICS format (Ref. 7) to a test program that calls CMWALL. The Mach number is a constant at 0.2 for this run. The classical correction results output from CMWALL are shown in Fig. 2. The variation of the blockage corrections ε, ΔM and ΔQ as a function of the uncorrected angle of attack α (variable `alphau`) is shown in the first 3 frames of the plot. Frame 4 shows the correction on the angle of attack due to lift-induced wall effects as a function of the uncorrected angle of attack. Frame 5 shows the correction on the lift coefficient due to lift interference. In frame 6, the correction on drag due to buoyancy produced by the wake blockage gradient is shown in addition to the lift-induced drag correction. Frame 7 shows the correction on the pitching moment due to lift, which is due to the wall-induced change in streamline curvature. Note that all corrections are added to the measured values. Finally, frame 8 shows the lift-drag curve before and after correction. The changes in C_L and C_D are both due to lift interference and also due to the change in Q due to blockage.

<u>Test case 2: 14x22-Ft Subsonic Tunnel: Full-span Elliptical wing, Test 511, Run 195</u>

The tunnel and model input data as specified in the file `walldata` are as below.

```
data iwdbg/0/
data itunl,itsconf,ivent/3,1,0/
data wingvol,tcav,naca/3.5,0.12,44/
data twob,sref,ar,taper/6.75,6.45,7.06,0.57/
data cbar,clalpha/1.20,0.10/
data dequiv,fusl,fusvol/0.60,2.80,2.5/
```

The test data for 13 points in a run is provided in the standard TWICS format to a test program that calls CMWALL. The Mach number is constant at 0.22. The classical correction results output from CMWALL are shown in Fig. 3. This is a much smaller wing compared to the trap wing in example 1 as can be seen from the much lower blockage values and lift interference values. Since the flow is attached in the small angle of attack range of –3 to 12, variation is mostly linear.

Test case 3: NTF solid wall: Full-span wing (Pathfinder 1), Test 114D, Run 313

The tunnel and model input data as specified in the file `walldata` are as below.

```
data iwdbg/0/
data itunl,itsconf,ivent/1,1,0/
data wingvol,tcav,naca/0.12,0.12,44/
data twob,sref,ar,taper/4.42,1.98,9.8,0.2/
data cbar,clalpha/0.56,0.05/
data dequiv,fusl,fusvol/0.25,4.15,0.2/
```

The test data for 15 points in a run is provided in the standard TWICS format to a test program that calls CMWALL. The Mach number is constant at 0.2. The classical correction results output from CMWALL are shown in Fig. 4. Similar to Example 2, this is a small model for this tunnel section, as can be seen from the low values of blockage and lift interference parameters. Since the flow is attached in the small angle of attack range of –2 to 10, variations are mostly linear.

10. Program Limitations

Results are based on the assumptions of *small model* and *attached flow*. CMWALL does not consider support interference or the effect of tail surfaces (which is important in the pitching moment corrections). Model is assumed to be in the center of the tunnel. Corrections for high subsonic Mach numbers may be suspect due to assumptions of linearity and the simplified Prandtl-Glauert compressibility correction factor.

11. Program Notes

The source program is `~/cm/source/cmwall.f`. Examples of the include file `walldata` are in `~/cm/source` as well as in `~/cm/testcases`. The test cases discussed above are in three sub-directories under `~/cm/testcases`. The test cases require test data input files which are also provided under `~/cm/testcases`.

The test program outputs a TECPLOT format file called `corr.plt`. Layout files are provided to plot the results shown in the figures in this report.

When input parameters are outside of allowed limits (potentially leading to extrapolation from tables), the error flag `ierr` is set to 1 and default values are used to prevent program termination. A print output such as '`ierr=1, setting ak1w=1.0`' is also produced. In such cases, debug runs with `iwdbg=1` can be made to locate the input parameter that may be out of bounds.

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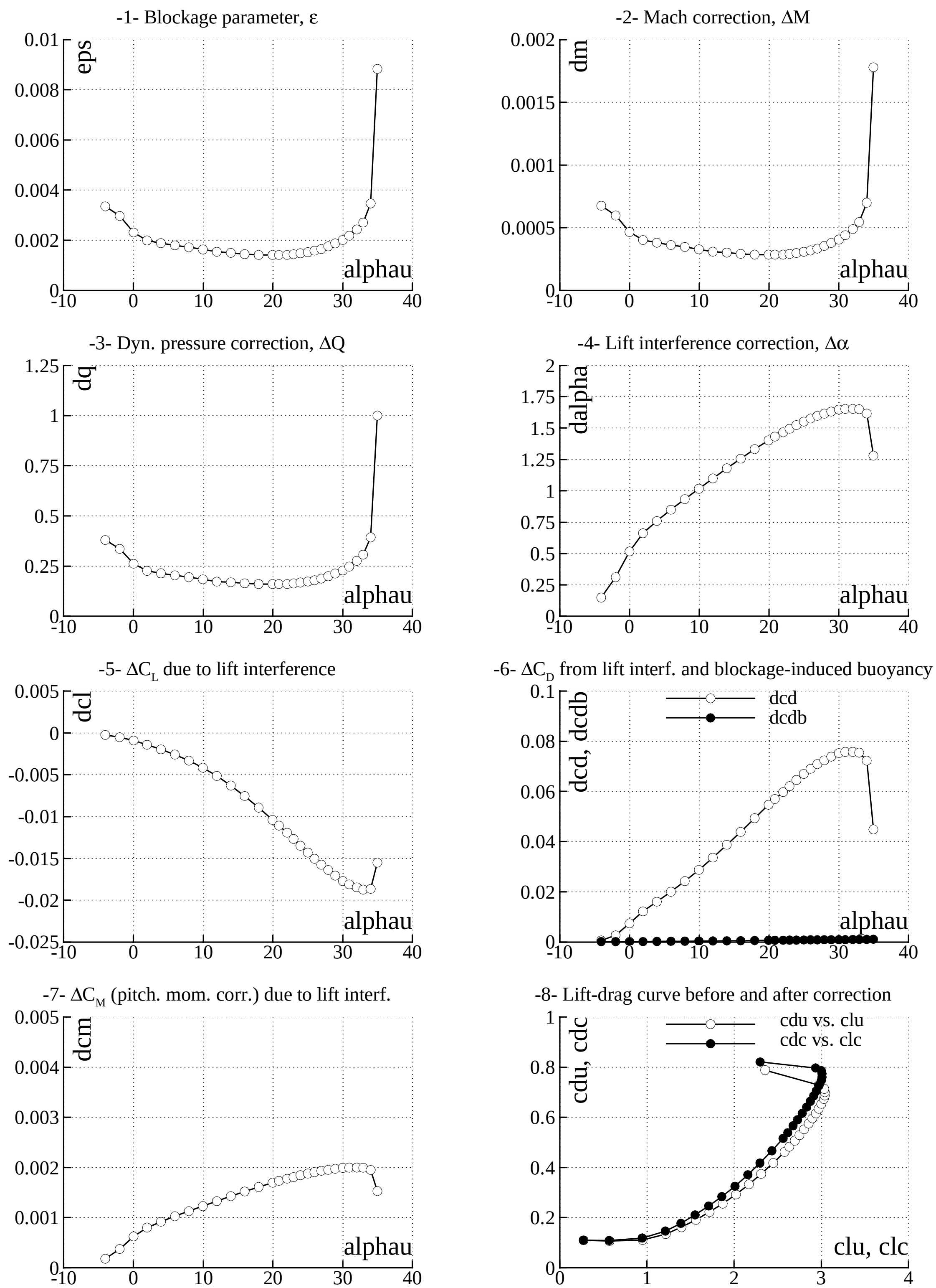

Figure 2. Classical wall correction results from CMWALL, test case 1.
NASA LaRC 14x22-Ft Subsonic Tunnel, semispan trap wing test 506, run 109.

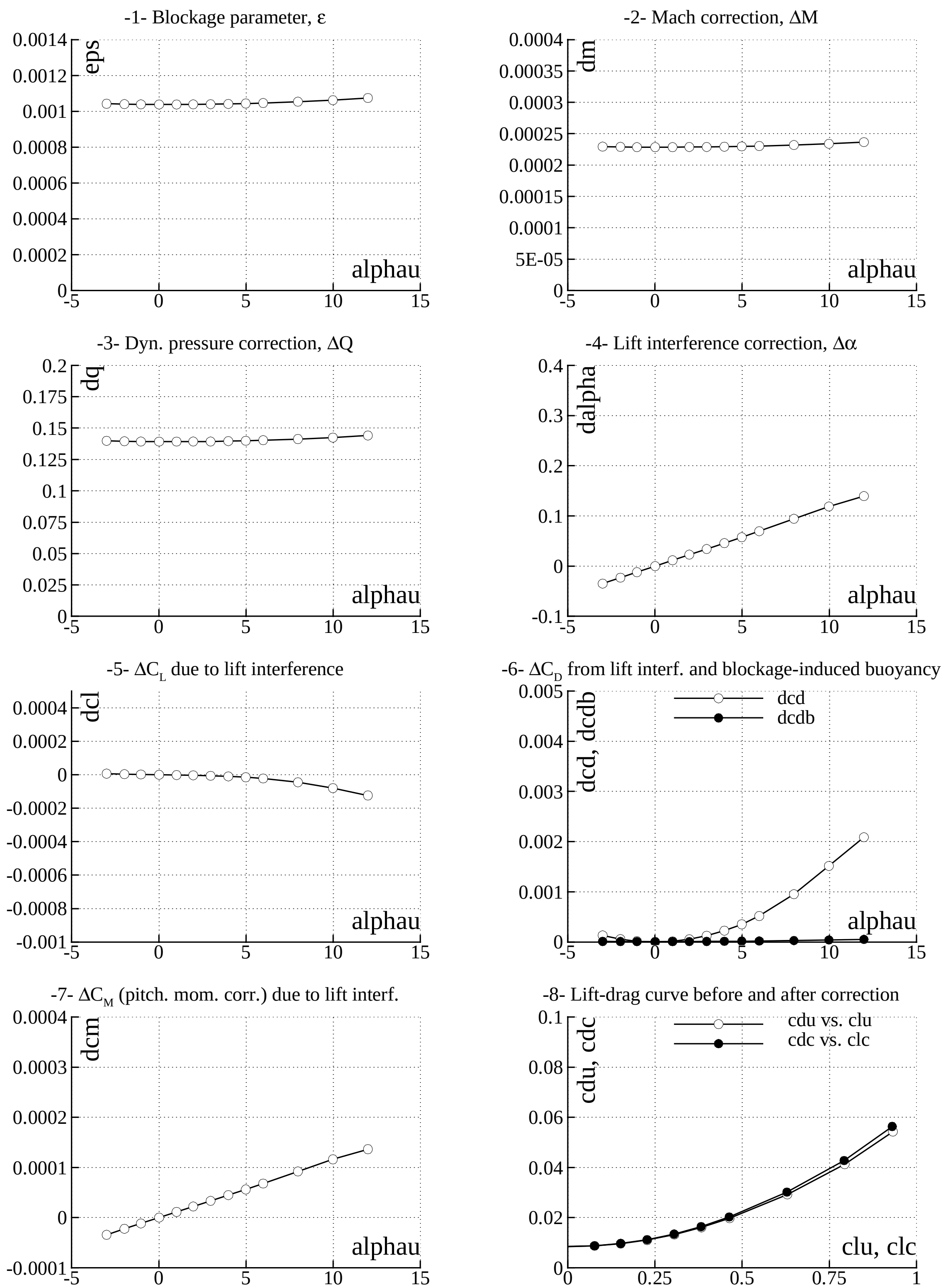

Figure 3. Classical wall correction results from CMWALL, test case 2.
NASA LaRC 14x22-Ft subsonic tunnel, full-span elliptical wing test 511, run 195.

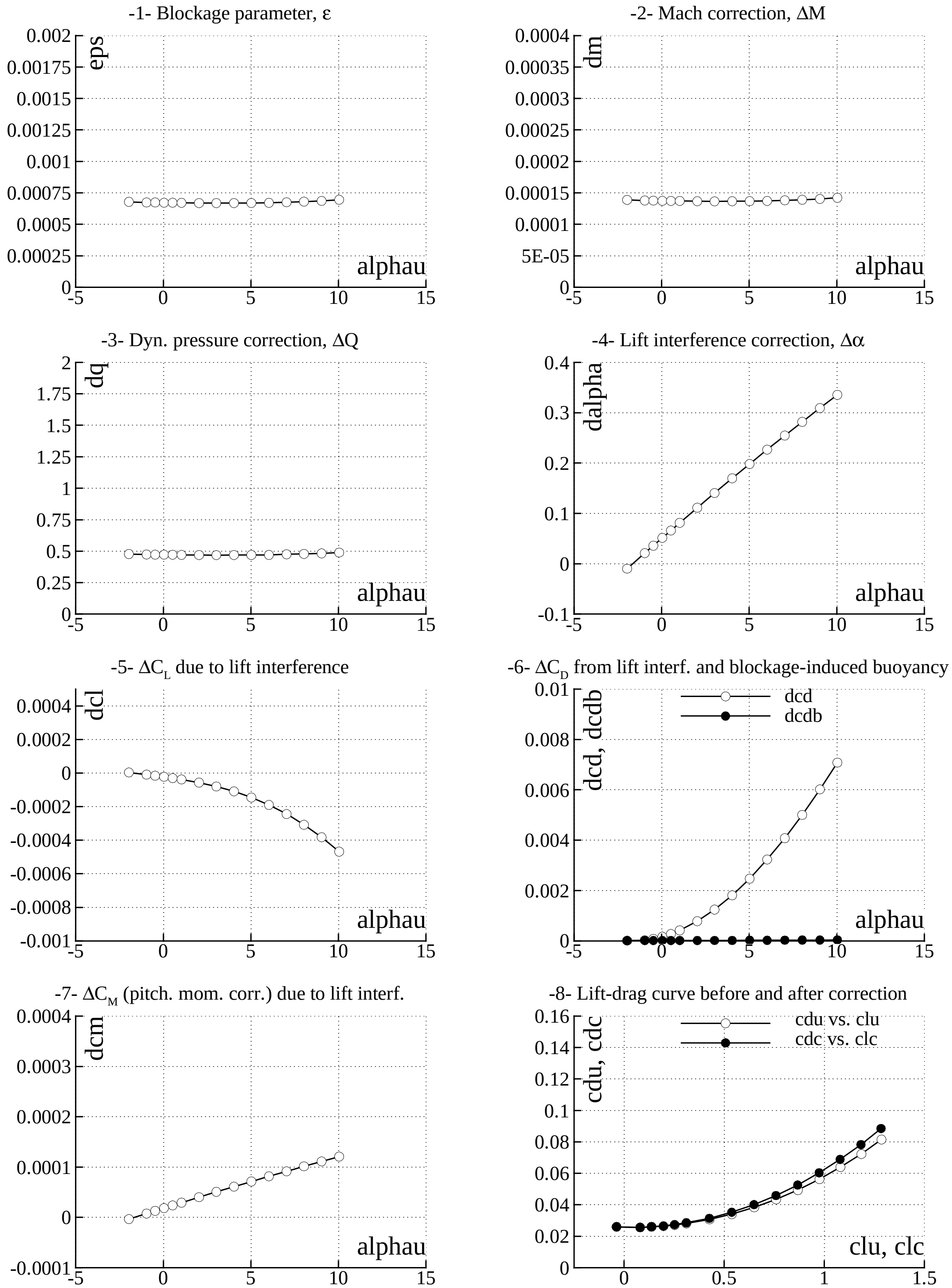

Figure 4. Classical wall correction results from CMWALL, test case 3.
National Transonic Facility, solid wall, full-span Pathfinder-1 (PF-1) test 114D, run 313.

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14. ABSTRACT
A Fortran subroutine CMWALL is described, which is an implementation of the collective information from classical methods-based wall corrections. These methods use established closed-form expressions which were developed based on simple linear potential-based methods. This is a simple and rapid tool to calculate corrections due to wall interference in the National Transonic Facility (Solid Wall or Slotted Wall) or the 14x22-Ft Subsonic Tunnel at NASA LaRC. It is designed to be easily implemented in the existing tunnel data reduction programs, either as real-time or post-point. It is however important to realize that the method is based on the simplifying assumptions of linearity, small model and attached flow. The computed results are thus to be viewed as first-cut, estimates, to be refined further using more complex methods based on measured wall pressures (known as wall signature methods).

15. SUBJECT TERMS
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