CALCULATION OF SIDEWALL BOUNDARY-LAYER PARAMETERS
FROM RAKE MEASUREMENTS FOR THE LANGLEY 0.3-METER
TRANSONIC CRYOGENIC TUNNEL

A. V. Murthy

Vigyan Research Associates, Incorporated
Hampton, Virginia

contract NAS1-17919
FEBRUARY 1987

(NASA-Cr-178241) CALCULATION OF SIDEWALL BOUNDARY-LAYER PARAMETERS FROM RAKE MEASUREMENTS FOR THE LANGLEY 0.3-METER TRANSONIC CRYOGENIC TUNNEL (Vigyan Research Associates, Inc.) 36 p CSCL 01A G3/02 44006
Summary

Correction of airfoil data for sidewall boundary-layer effects requires a knowledge of the boundary-layer displacement thickness and the shape factor with the tunnel empty. To facilitate calculation of these quantities under various test conditions for the Langley 0.3-m Transonic Cryogenic Tunnel, a computer program has been written. This program reads the various tunnel parameters and the boundary-layer rake total head pressure measurements directly from the Engineering Unit tapes to calculate the required sidewall boundary-layer parameters. Details of the method along with the results for a sample case are presented.

INTRODUCTION

The presence of boundary-layers on the sidewalls of a two-dimensional wind tunnel are known to affect the test data on the airfoils. Recently, methods have been proposed to account for this sidewall boundary-layer interference. A summary of these correction methods may be found in reference (1). For application of these methods, it is necessary to have a knowledge of the values of the empty test-section sidewall boundary-layer displacement thickness and the shape factor. These values are generally deduced from the total head pressure measurements across the boundary-layer, during the calibration phase of the tunnel.

For the Langley 0.3-m Transonic Cryogenic Tunnel, the sidewall boundary-layer measurements were recently made using a wall mounted boundary-layer rake in the newly installed adaptive wall test-section. To calculate the boundary-layer displacement thickness and the shape factor from these measurements, a Fortran computer program was written. The present report gives a brief description of the program developed and its use for calculating
the required sidewall boundary-layer characteristics directly from the tunnel data stored on the Engineering Unit tapes.

Nomenclature

\[ b \quad : \quad \text{Test-section width} \]
\[ H \quad : \quad \text{Boundary-layer shape factor} \]
\[ L \quad : \quad \text{Length scale} \]
\[ M \quad : \quad \text{Mach number} \]
\[ n \quad : \quad \text{Index in power-law for the velocity profile} \quad (U \alpha y^{1/n}) \]
\[ P \quad : \quad \text{Total pressure} \]
\[ Pr \quad : \quad \text{Prandtl number} \]
\[ p \quad : \quad \text{Static pressure} \]
\[ r \quad : \quad \text{Boundary-layer recovery factor} \]
\[ T \quad : \quad \text{Static temperature} \]
\[ U \quad : \quad \text{Velocity} \]
\[ y \quad : \quad \text{Coordinate normal to the sidewall} \]
\[ \gamma \quad : \quad \text{Ratio of specific heats} \]
\[ \delta \quad : \quad \text{Boundary-layer thickness} \]
\[ \delta'^* \quad : \quad \text{Boundary-layer displacement thickness} \]
\[ \theta \quad : \quad \text{Boundary-layer momentum thickness} \]

Subscripts

\[ e \quad : \quad \text{refers to conditions outside the boundary-layer} \]
\[ bl \quad : \quad \text{refers to boundary-layer} \]
\[ \infty \quad : \quad \text{refers to freestream conditions} \]

Description of the Method

The details of calculation of the boundary-layer displacement thickness and the shape factor are given in reference (2). First, the measured total head pressures in the boundary-layer are converted to Mach numbers using the isentropic relation, and assuming the static pressure across the boundary-layer to be
constant at the freestream value. The isentropic relation for
the Mach number is given by (for $\gamma = 1.4$)

$$M_{bl} = \left[5\left(\frac{P_{bl}}{p}\cdot 2.857 - 1\right)\right]^{0.5}$$  \hspace{1cm} (1)

Knowing the Mach number across the boundary-layer, the
velocity variation can be calculated using the relation

$$\frac{U_{bl}}{U_e} = \left(\frac{T_{bl}}{T_e}\right)^{1/2}\left(\frac{M_{bl}}{M_e}\right)$$  \hspace{1cm} (2)

The temperature measurements are generally not made, and
hence it is necessary to assume a suitable variation acrosss the
boundary-layer. For the adiabatic wall, the relation between the
velocity and temperature profiles can be expressed by the
crocco's relation (reference 3) given by (for $\gamma = 1.4$),

$$\frac{T_{bl}}{T_e} = 1 + 0.2rM_e^2\left[1 - \left(\frac{U_{bl}}{U_e}\right)^2\right]$$  \hspace{1cm} (3)

where $r$ is boundary-layer recovery factor. The value of $r$
depends on the nature of the boundary-layer, and the value of
the Prandtl number (Pr). For the turbulent boundary-layer,
this value is approximately $Pr^{1/3}$. Using Crocco's relation,
the velocity and temperature variation across the boundary-layer
can be calculated. The boundary-layer displacement thickness,
momentum thickness and the shape factor are then calculated by
integrating the expressions:

$$\delta^* = \int_{0}^{\delta} \left[1 - \left(\frac{T_e}{T_{bl}}\right)\left(\frac{U_{bl}}{U_e}\right)\right] dy$$  \hspace{1cm} (4)

$$\theta = \int_{0}^{\delta} \left(\frac{T_e}{T_{bl}}\right)\left(\frac{U_{bl}}{U_e}\right)[1 - \left(\frac{U_{bl}}{U_e}\right)] dy$$  \hspace{1cm} (5)

and

$$H = \left(\frac{\delta^*}{\theta}\right)$$  \hspace{1cm} (6)

For calculating the incompressible values of the displace-
ment and momentum thickness, the factor $\left(\frac{T_e}{T_{bl}}\right)$ is set equal to
unity, in equations (4) and (5).
Program Description

The method described above has been incorporated into a Fortran computer program called BOUNLAY. The program reads the required input data either from the Engineering Unit tapes or from user input. The boundary-layer rake tubes are connected to scanivalve. The values of the tunnel stagnation pressure, stagnation temperature and the static pressure are read at each instant the boundary-layer pressure is measured. These instantaneous values are used in the calculation of the boundary-layer parameters.

The boundary-layer rake used in the 0.3-m TCT (figure 1) has fifteen tubes and the total height is about 0.6". The tube closest to the wall is about 0.024" from the wall. Hence, to evaluate the boundary-layer thickness, it is necessary to extrapolate the velocity profile up to the wall in a suitable manner. Also, under certain flow conditions, it is probable that the outermost tube may not be positioned within the boundary-layer edge. This requires suitable extrapolation of the measured data from the outermost tube to the outer edge of the boundary-layer. Hence, a power-law variation was assumed for the turbulent boundary-layer velocity profile. The velocity profile was represented by the equation

\[ \left( \frac{U_{b1}}{U_e} \right) = \left( \frac{y}{\delta} \right)^{1/n} \]  

or

\[ \log \left( \frac{U_{b1}}{U_e} \right) = \frac{1}{n} \log \left( \frac{y}{L} \right) + \frac{1}{n} \log \left( \frac{L}{\delta} \right) \]  

where 'δ' is the boundary-layer thickness, 'n' is the index of the power-law variation and L is a length scale. The values of 'δ' and 'n' are determined by making a least square fit to the calculated values of \( \left( \frac{U_{b1}}{U_e} \right) \) at different heights across the boundary-layer. The least square fit is accomplished by using the library subroutine LSQPOL. An example of this least square fit result is shown in figure 2. The slope and the intercept
of the least square fit determine the values of 'n' and 'δ' respectively.

After determining the index of power-law variation for the velocity, the integrals for the displacement thickness and the momentum thickness are evaluated by using the library subroutine CADRE.

It was recognised that the readings of some of the tubes may be erroneous due to extraneous effects during tests. These measurement points need to be omitted to avoid erroneous calculation of the sidewall boundary-layer parameters. Hence, provision has been made to skip up to three tube locations.

Program Input

The input data to the program BOUNLAY is through the namelist PARAM and the relevant parameters with their default values are given in Appendix A. The value of the parameter IDATA, either '0' or '1', specifies whether the required tunnel parameters are to be read from the Engineering Unit tapes, or are given directly as input by the user. The tube heights from the wall are specified through the parameter Y. The default values shown correspond to the recent measured data, and can be changed through the namelist, if new measurements are made, or if a new rake is used. Corresponding to the default option of IDATA=0, if the tunnel parameters are to be read from the Engineering Unit tapes, the values of the array numbers where the various parameters are stored are to be specified through the namelist. These parameters and other control parameters required are indicated in Appendix A.

A typical set of input data along with the control cards required are shown in Appendix B. Following the namelist PARAM, the test, run and point numbers are specified in 3I3 format, when the tunnel parameters are to be read from the Engineering Unit
tapes. Specifying '0', for the point number allows the program to calculate the sidewall boundary-layer parameters for all the points in the specified run number. For termination of the calculation, the run number is specified as '999', in the last record.

If the tunnel parameters are given directly as input data, following the namelist PARAM, the program reads a title card in the format 10A8. After this, the values of the stagnation pressure(psia), stagnation temperature(degree K), height of the tube from the wall(inches), boundary-layer pressures(psia) and tunnel static pressure (psia) are specified in format 5F10.6. These are repeated corresponding to the value of NBL specified in the namelist PARAM.

Results for a Sample Case

The use of the computer program developed is demonstrated by applying it to one of the runs conducted recently during empty test section calibration (Test 200). The sample output shown in Appendix C, corresponds to the results obtained with the data in Appendix B. The corresponding nominal freestream Mach number and Reynolds number are 0.7 and 30 million/ft, respectively (Run number 19 and Point number 6).

First, the values of the various parameters in namelist PARAM are printed. Following this, the title, and the test, run and point numbers are printed. Subsequently, the tunnel conditions averaged over the time interval of the boundary-layer measurements, the calculated values of the boundary-layer parameters are printed. At the end, the variation of the pressure, temperature, velocity and Mach number across the boundary-layer are tabulated.

If the value of the parameter IPLOT is not equal to zero, the calculated velocity profiles are written on a temporary file
on Tape 10. These are then plotted using the program UPLLOT, and the corresponding control cards required for plotting are shown in Appendix A. The program UPLLOT uses the library subroutine INFOPLT and plots both the measured velocities and the calculated power-law profile for comparison (see Figure 3).

For the sample case considered, it is seen that the value of the displacement thickness and the shape factor at the model location are .0713" and 1.4595 respectively. For the testsection width of 13", the value of the parameter \(2\delta^*/b\) which is one of the parameters characterizing the extent of sidewall boundary-layer correction is about 0.01. The corresponding correction for the test Mach number on long chord models is about -0.008. However, for short chord models, it is likely the sidewall boundary-layer correction will be much smaller. The detailed calculation of the sidewall boundary-layer parameters, and the corresponding corrections over the operating range of the 0.3-m TCT will be dealt in a future report.

References

1. Murthy, A. V.: A Simplified Fourwall Interference Assessment Procedure for Airfoil Data Obtained in the Langley 0.3-Meter Transonic Cryogenic Tunnel. (NASA CR under publication)


Appendix A
Parameters in Namelist PARAM

IDATA : = 0, Tunnel parameters are read from EU tapes, (0)*
        = 1, Tunnel parameters are given as input data
ICOMP : = 0, Incompressible values of $\delta^*$ and $\theta$ calculated, (1)
        = 1, Compressible values of $\delta^*$ and $\theta$ calculated
IPILOT : = 0, Plot files are not generated, (1)
         = 1, Plot files are generated
L : Reference length scale, (1.0)
NBL : Number of tubes in the boundary-layer rake,
     Maximum value = 30, (15)
Y : Tube heights from the wall (.024,.06,.10,.14,.18,
    .22,.26,.30,.34,.38,.42,.46,.50,.55,.59)
ISKIP : Number of tubes to be omitted calculation, Max. 3 (1)
IBL : Port number of the tubes to be omitted (1, 0, 0)
IPRINT : = 0, Only final results are printed (0)
         = 1, Intermediate results also printed
IOPT : = 1, $\delta^*$ and $\theta$ calculated using the power-law for
       the entire profile.
       = 2, $\delta^*$ and $\theta$ calculated using the power-law only
       upto first tube, and using trapezoidal rule
       for the remaining profile
NTEST : Array number for the test+ (3)
NRUN : Array number for the run+ (5)
NPOINT : Array number for the point+ (6)
NPORT : Array number for the port+ (10)
NBLSCAN : Array number for the boundary-layer rake pressure+ (117)
NPTINF : Array number for the tunnel total pressure+ (107)
NPRT : Array number for the tunnel total temperature+ (217)
NPTC : Array number for the tunnel static pressure+ (108)

* Numbers within paranthesis refer to default values
+ to be specified only when IDATA = 0.
Appendix B
Control Cards and Sample Input Data

PROBOUN,T1000,CM170000.
USER,username,password.
CHARGE,chgnum,LRC.
ATTACH,TAPE7=D*****/UN=username.
GET,BOUNLAY.
FTN,I=BOUNLAY,L=0,PL=10000.
ATTACH(FTNMLIB/UN=LIBRARY,NA)
LDSET(LIB=FTNMLIB,PRESETA=INDEF)
MAP,OFF.
LGO.
REWIND,TAPE10.
RETURN(*,TAPE10)
GET,UPL0T
FTN,I=UPL0T,L=0.
ATTACH,LRCGOSF/UN=LIBRARY,NA.
LDSET(LIB=LRCGOSF,PRESETA=INDEF)
LGO.
DELIVER.bldgnum name
PLOT.VARIAN,FF
/eor
$PARAM IDATA=0,IOPT=2,$END
200019000
200099000
$PARAM IDATA=1,IOPT=2,$END
TEST NO: 200. RUN: 19. POINT: 6. SAMPLE INPUT DATA
35.5818 129.6503 .0240 29.1408 25.6570
35.5475 129.8012 .0600 30.9015 25.6787
35.5341 129.8498 .1000 31.5694 25.5685
35.6083 129.8417 .1400 31.9734 25.4811
35.6049 129.8197 .1800 32.5464 25.5275

continued
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<th>Value 2</th>
<th>Value 3</th>
<th>Value 4</th>
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<td>129.7544</td>
<td>.2200</td>
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<td>129.6764</td>
<td>.5500</td>
<td>35.4686</td>
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<td>35.6374</td>
<td>129.5828</td>
<td>.5900</td>
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</tr>
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</table>

/eor
/eof
Appendix C
Sample Output from the Program

$PARAM
NTEST = 3,
NRUN = 5,
NPOINT = 6,
NBL = 15,
NPORT = 10,
NBLSCAN = 117,
NPTINF = 107,
NPTC = 108,
NPRT = 217,
ICOMP = 1,
IPLT = 1,
Y = .24E-01, .6E-01, .1E+00, .14E+00, .18E+00,
    .22E+00, .26E+00, .3E+00, .34E+00, .38E+00,
    .42E+00, .46E+00, .5E+00, .55E+00, .59E+00,
    I, I, I, I, I, I, I, I, I, I, I, I,
L = .1E+01,
ISKIP = 1,
IBL = 1, 0, 0,
IDATA = 0,
IPRINT = 1,
IOPT = 2,
$END

continued
Sample Output from the Program

0.3-M TCT STREAMLINED WALL TEST SECTION
RIGHT SIDEWALL BOUNDARY-LAYER MEASUREMENTS

TEST:200      RUN: 19      POINT: 6

AVERAGE MACH NUMBER : .7049
AVERAGE REYNOLDS NUMBER/FT : .295E+08
AVERAGE STAGNATION PRESSURE PSIA : 35.6035
AVERAGE STAGNATION TEMPERATURE K : 129.7217
PRANDTL NUMBER : .7600
RATIO OF SPECIFIC HEATS : 1.4000
RECOVERY FACTOR : .9126
REFERENCE LENGTH SCALE L : 1.0000
VALUE OF N IN POWER LAW PROFILE : 7.9196
BOUNDARY-LAYER THICKNESS DELTA/L : .5642
DISPLACEMENT THICKNESS DELTASTAR/L : .0713
MOMENTUM THICKNESS THETA/L : .0488
SHAPE FACTOR : 1.4595

A: DISPLACEMENT AND MOMENTUM THICKNESS REFER TO COMPRESSIBLE VALUES.
B: DISPLACEMENT AND MOMENTUM THICKNESS CALCULATED USING POWER-LAW FROM WALL TO FIRST TUBE.

continued
<table>
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<th>NO.</th>
<th>Y/L</th>
<th>M/MINF</th>
<th>P/PT</th>
<th>T/TINF</th>
<th>U/UINF</th>
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<td>1.0239</td>
<td>.8590</td>
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<td>.9063</td>
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<td>1.0057</td>
<td>.9678</td>
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<td>1.0022</td>
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<td>.9945</td>
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<td>.5900</td>
<td>.9932</td>
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<td>1.0011</td>
<td>.9938</td>
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</tbody>
</table>
PROGRAM CRYOTBL(INPUT,OUTPUT,TAPE5=INPUT,TAPE7,TAPE10)

* * * * * * * * * * * * * * * * * * * * * *
0.3-M TCT BOUNDARY-LAYER CALCULATION

THIS PROGRAM CALCULATES THE SIDEWALL BOUNDARY-LAYER
DISPLACEMENT THICKNESS, MOMENTUM THICKNESS AND THE
SHAPE PARAMETER FROM THE TOTAL HEAD PRESSURE MEASUREMENTS IN THE BOUNDARY-LAYER.

* * * * * * * * * * * * * * * * * * * * * *

REAL MBL,MBLBMIN,MINF,L,MAV

NAMELIST /PARAM/

600 CONTINUE
C

SET DEFAULT VALUES OF THE NAMELIST PARAMETERS

IDATA = 0
NTEST = 003
NRUN = 005
NPOINT = 006
NBL = 015
NPORT = 010
NBLSCAN = 117
NPRT = 217
NPTINF = 107
NPTC = 108
ICOMP = 001
IPLLOT = 001
Y( 1) = 0.024
Y( 2) = 0.060
Y( 3) = 0.100
Y( 4) = 0.140
Y( 5) = 0.180
Y( 6) = 0.220
Y( 7) = 0.260
Y( 8) = 0.300
Y( 9) = 0.340
$Y(10) = 0.380$
$Y(11) = 0.420$
$Y(12) = 0.460$
$Y(13) = 0.500$
$Y(14) = 0.550$
$Y(15) = 0.590$
$L = 1.000
ISKIP = 1
IPRINT = 0
IBL(1) = 1
IBL(2) = 0
IBL(3) = 0
I OPT = 1

C SET ERROR FLAG TO ZERO
I ERR = 0

C READ INPUT DATA FROM NAMELIST

140 READ(5, PARAM)
   IF(EOF(5)) 120, 130
120 STOP 120
130 CONTINUE
   IF(IDATA .LE. 0) PRINT PARAM

C STORE Y VALUES
DO 1600 II = 1,NBL
   YM(II) = Y(II)
1600 CONTINUE
ENBL = NBL
ISKP = ISKP

IF(IDATA .LE. 0) GO TO 700

C READ TITLE CARD
READ 650, (HEADING(I),I=1,8)

C READ INPUT DATA
DO 710 I=1, NBL
   READ 720, PTINF(I), TTINF(I), Y(I), PBL(I), PTC(I)
   PRINT 720, PTINF(I), TTINF(I), Y(I), PBL(I), PTC(I)
720 FORMAT(5F10.6)
710 CONTINUE
   PRINT 660, (HEADING(I),I=1,8)
GO TO 15

C TUNNEL AND BOUNDARY-LAYER PARAMETERS ARE READ FROM EU TAPES

700 CONTINUE
FIRST TWO FRAMES CONTAIN NON-DAT, INFO SUCH AS UNITS AND LABELS
DO 1000 I=1,2
READ(7)KEY,N,(ARRAY(I),I=1,N)
1000 CONTINUE

SET REQUIRED INPUT DATA TO VARIABLES USED IN THE PROGRAM
NSVO = NBLSCAN

READ 4, IT, IR, IP
IF(IR.EQ.999) GO TO 110

READ THE TUNNEL VARIABLES FROM THE EU TAPE
READ(7)KEY,N,(ARRAY(I),I=1,N)
IF(EIF(7))2,6
6 CONTINUE

SELECT THE REQUIRED PARAMETERS
IF (IP. NE. 0) GO TO 1500
IF (ARRAY(NRUN) .GT. IR) GO TO 2
1500 CONTINUE
ITEST=ARRAY(NTEST)
IRUN=ARRAY(NRUN)
IPOINT=ARRAY(NPOINT)
IF(IRUN .EQ. 0) GO TO 7
IF(IRUN .LT. IR) GO TO 5
IF(IP .EQ. 0) GO TO 7
IF(IPOINT .NE. IP) GO TO 5
7 IPORT=ARRAY(NPORT)
IF(IPORT .EQ. 0) GO TO 5
IF(IPORT .GE. 16) GO TO 5
IORF1(IPORT)=ARRAY(NPORT)
PBL(IPORT)=ARRAY(NSVO)
PTINF(IPORT)=ARRAY(NPTINF)
PTC(IPORT)=ARRAY(NPTC)
TTINF(IPORT)=ARRAY(NPRT)
IF (IPORT.EQ.1) GO TO 10
IF (IPORT.EQ.NBL) GO TO 15
GO TO 5
10 PRINT 40
PRINT 100,ITEST,IRUN,IPOINT
13 GO TO 5
15 CONTINUE
IF(ISKIP .NE. 0)
CALL SKIP(NBL,ISKIP,IBL,Y,PBL,PTINF,TTINF,PTC,IPRINT,IERR)
SIGMA=0.76
GAMMA=1.4
N=NBL

C CALCULATE BOUNDARY-LAYER PROFILES

CALL BLPROFL(NBL,Y,PBL,PTC,PTINF,TTINF,L,GAMMA,SIGMA,
SYN,PBLNON,MLBMIN,UBLBUIN,TBLBTIN,MAV,PTINFAV,TTINFAV,
$REYAV,REC,IPRINT,IERR)
IF(IERR .NE. 0) GO TO 600

C FIT A POWER-LAW CURVE TO THE VELOCITY PROFILE

CALL LSFIT(NBL,YN,UBLBUIN,L,IPRINT,EN,DELTA,IERR)
IF(IERR .NE. 0) GO TO 600

C CALCULATE DISPLACEMENT THICKNESS AND MOMENTUM THICKNESS

CALL THIKNES(NBL,YN,UBLBUIN,TBLBTIN,L,ICOMP,DELTA,EN,IOPT
$,MAV,REC,GAMMA,DELS,THETA,IPRINT,IERR)

C PRINT FINAL RESULTS
PRINT 500, MAV
PRINT 501, REYAV/3.2808
PRINT 502, PTINFAV
PRINT 503, TTINFAV
PRINT 504, SIGMA
PRINT 505, GAMMA
PRINT 506, REC
PRINT 507, L
PRINT 508, EN
PRINT 509, DELTA/L
PRINT 510, DELS
PRINT 511, THETA
PRINT 512, DELS/THETA

IF(ICOMP .EQ. 0) PRINT 521
IF(ICOMP .NE. 0) PRINT 522
IF(IOPT .EQ. 1) PRINT 523
IF(IOPT .EQ. 2) PRINT 524

PRINT 530

DO 550 I = 1, NBL
PRINT 531, I,YN(I),MLBMIN(I),PBLNON(I),TBLBTIN(I),UBLBUIN(I)
550 CONTINUE

C WRITE PLOT FILE
IF(IPLOT .EQ. 0) GO TO 570
WRITE(10, 533) NBL, EN
IF(IDATA .EQ. 0) WRITE(10, 534) ITEST, IRUN, IPOINT
IF(IDATA .NE. 0) WRITE(10, 535) HEADING(1), HEADING(2)

DO 560 I = 1, NBL
WRITE(10, 536) Y(I)/DELTA, UBLBUIN(I)
560 CONTINUE

570 PRINT 532
IF(IDATA .NE. 0) GO TO 600
NBL = ENBL
ISKIP = ISKP
C RESET Y VALUES
DO 1700 I = 1, NBL
Y(I) = YM(I)
GO TO 5
1700 CONTINUE

500 FORMAT(10X,*AVERAGE MACH NUMBER :*, F10.4)
501 FORMAT(10X,*AVERAGE REYNOLDS NUMBER/FT :*, E10.3)
502 FORMAT(10X,*AVERAGE STAGNATION PRESSURE PSIA :*, F10.4)
503 FORMAT(10X,*AVERAGE STAGNATION TEMPERATURE K :*, F10.4)
504 FORMAT(10X,*PRANDTL NUMBER :*, F10.4)
505 FORMAT(10X,*RATIO OF SPECIFIC HEATS :*, F10.4)
506 FORMAT(10X,*RECOVERY FACTOR :*, F10.4)
507 FORMAT(10X,*REFERENCE LENGTH SCALE L :*, F10.4)
508 FORMAT(10X,*VALUE OF N IN POWER LAW PROFILE :*, F10.4)
509 FORMAT(10X,*BOUNDARY-LAYER THICKNESS DELTA/L :*, F10.4)
510 FORMAT(10X,*DISPLACEMENT THICKNESS DELTASTAR/L :*, F10.4)
511 FORMAT(10X,*MOMENTUM THICKNESS THETA/L :*, F10.4)
512 FORMAT(10X,*SHAPE FACTOR :*, F10.4)

521 FORMAT(/10X,*A: DISPLACEMENT AND MOMENTUM THICKNESS REFER*,
$/10X,* TO INCOMPRESSIBLE VALUES.*)
522 FORMAT(/10X,*A: DISPLACEMENT AND MOMENTUM THICKNESS REFER*,
$/10X,* TO COMPRESSIBLE VALUES.*)
523 FORMAT(10X,*B: DISPLACEMENT AND MOMENTUM THICKNESS CALCULATED*,
$ /10X,* USING POWER-LAW FOR WHOLE PROFILE.*)
524 FORMAT(10X,*B: DISPLACEMENT AND MOMENTUM THICKNESS CALCULATED*,
$ /10X,* USING POWER-LAW FROM WALL TO FIRST TUBE.*)

530 FORMAT(/10X,*NO.*,6X,*Y/L*,4X,*W/MINF*,6X,*P/PT*,4X,
$*Y/TINF*,3X,*U/UpINF*,/)
531 FORMAT(10X,12,5F10.4)
532 FORMAT(/30X,*- - - - - - - - *)
533 FORMAT(15, F10.6)
534 FORMAT(*17UH/UE *,314,* Y/DELTA *)
535 FORMAT(*17 U/UE *,2A10,* Y/DELTA *)
536 FORMAT(2F10.6)
4 FORMAT(3I3)
40 FORMAT(1H1/10X,"0.3-M TCT STREAMLINED WALL TEST SECTION",
        $/10X,"RIGHT SIDEWALL BOUNDARY-LAYER MEASUREMENTS")
101 FORMAT(3I10)
110 CONTINUE
   GO TO 140
   STOP
   END
SUBROUTINE SKIP(NBL, ISKIP, IBL, Y, PBL, PTINF, TTINF, PTC, IPRINT, IERR)

DIMENSION IBL(3), Y(30), PBL(30), PTINF(30), TTINF(30), PTC(30)
DIMENSION P1(30), P2(30), P3(30), P4(30), P5(30)

C
C NBL : NUMBER OF TUBES IN BOUNDARY-LAYER RAKE
C ISKIP : NUMBER OF POINTS TO BE SKIPPED (MAXIMUM 3)
C IBL(3) : PORT NUMBERS TO BE SKIPPED
C Y : DISTANCE OF TUBES FROM WALL
C PBL : TOTAL PRESSURE IN THE BOUNDARY-LAYER
C PTINF : FREE-STREAM STAGNATION PRESSURE
C TTINF : FREE-STREAM STAGNATION TEMPERATURE
C PTC : FREE-STREAM STATIC PRESSURE
C IPRINT : NOT USED
C IERR : NOT USED
C
C NOTE : ON RETURN, NEW VALUES OF NBL,Y,PBL,PTINF,TTINF,PTC
C WILL BE AVAILABLE.
C
JS = 0
300 DO 100 I=1, NBL
   DO 200 J=1, ISKIP
      IF(I .EQ. IBL(J)) GO TO 150
   CONTINUE
   GO TO 250
200 CONTINUE
   GO TO 250

150 JS = JS + 1
   GO TO 100

250 II = I - JS
   P1(II) = PBL(I)
   P2(II) = PTINF(I)
   P3(II) = TTINF(I)
   P4(II) = PTC(I)
   P5(II) = Y(I)
100 CONTINUE

NBL = NBL - ISKIP

DO 400 I=1, NBL
   PBL(I) = P1(I)
   PTINF(I) = P2(I)
   TTINF(I) = P3(I)
   PTC(I) = P4(I)
   Y(I) = P5(I)
400 CONTINUE
IF(IPRINT .EQ. 0) RETURN
PRINT 500
DO 550 I=1, NBL
   PRINT 600, I,Y(I),PTINF(I),TTINF(I),PTC(I),PBL(I)
550 CONTINUE

500 FORMAT(/10X,*REARRANGED VALUES OF THE PARAMETERS Y,PTINF,*,
        *TTINF,PTC,PBL BY SUBROUTINE SKIP ARE AS FOLLLOWS*,/)
600 FORMAT(110,5F12.6)
RETURN
END
SUBROUTINE LSFIT(N,Y,U,L,IPRINT,EN,DELTA,IERR)

* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

THIS SUBROUTINE FIT A POWER-LAW CURVE TO THE VELOCITY PROFILE TO
DETERMINE THE CONSTANTS EN AND DELTA

N : NUMBER OF POINTS IN VELOCITY PROFILE
Y(N) : VALUES OF Y
U(N) : VALUES OF NON-DIMENSIONALIZED VELOCITY
L : LENGTH SCALE
IPRINT : NOT EQUAL TO ZERO, PRINTS OUTPUT PARAMETERS
IERR : EQUAL TO ZERO, NORMAL RETURN
EN : INDEX IN POWER-LAW VELOCITY PROFILE
C2 : CONSTANT TERM DELTA = L/EXP(C2/C1)

THE CURVE FIT IS OF THE TYPE
LOGN(U/UINF) = C1 * LOGN(Y/L) + C2

* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

REAL L
DIMENSION Y(30),U(30)
DIMENSION XX(30),YY(30)
DIMENSION W(30),RESID(30,1),SUM(1),A(30,1),B(30,1),WK(30,2)

DO 100 I = 1, N
XX(I) = ALOG(Y(I))
YY(I) = ALOG(U(I))
W(I) = 1
100 CONTINUE

SET PARAMETERS FOR LEAST SQUARE FIT

NMAX = 30
N = N
LL = 1
MMAX = 4
M = 2

LEAST SQUARE FIT FOR N READINGS

CALL LSQPOL(NMAX,N,XX,LL,YY,W,MMAX,M,RESID,SUM,A,B,WK,IERR)
IF(IERR .NE. 0) PRINT 500
500 FORMAT(/10X,*ERROR IN SUBROUTINE LSQPOL: CHECK VELOCITY DATA*)
IF(IERR .NE. 0) RETURN
C DETERMINE EN AND DELTA
EN = 1./B(2,1)
DELTA = L/EXP(B(1,1)/B(2,1))

IF (IPRINT .EQ. 0) GO TO 300

C PRINT INPUT TO AND OUTPUT FROM SUBROUTINE LSQPOL

PRINT 1000, NMAX,N,LL,MMAX,M
DO 200 I = 1, N
   PRINT 2000, I,W(I),Y(I),U(I),XX(I),YY(I),RESID(I,1)
200 CONTINUE

PRINT 2020, IERR, EN, DELTA, SUM(1)

300 CONTINUE

1000 FORMAT(10X,515)
2000 FORMAT (5X,15,6F9.4)
2020 FORMAT(10X,*IERR =*,12,5X,*EN =*,F8.4,5X,*DELTA=*,F8.4, $5X,*SUM(1)=*,F8.4)
2030 FORMAT(/10X,F10.6,/10X,5E10.4)
RETURN
END
SUBROUTINE BLPROFL(N,Y,PBL,PS,PTINF,TTINF,L,GAMMA,SIGMA,
SYN,PBLNON,MBLBMN,UBLBUIN,TBLBTIN,MAV,PTINFAV,TTINFAV,
$REYAV,REC,IPRINT,IERR)
REAL MBL,MBLBMN,MINF,L,MAV
DIMENSION Y(30),PBL(30),PS(30)
DIMENSION PTINF(30),TTINF(30),MINF(30),MBL(30)
DIMENSION YN(30),PBLNON(30),MBLBMN(30),UBLBUIN(30),TBLBTIN(30)

* * * * * * * * * * * * * * * *

* N : NUMBER OF TUBES IN THE BOUNDARY-LAYER RAKE
* Y : PROBE HEIGHTS FROM THE WALL
* PBL : TOTAL PRESSURE IN THE BOUNDARY-LAYER
* PS : STATIC PRESSURE (FREE-STREAM)
* PTINF : TUNNEL STAGNATION PRESSURE
* TTINF : TUNNEL STAGNATION TEMPERATURE
* L : LENGTH SCALE FOR NON-DIMENSIONALISING Y
* GAMMA : RATIO OF SPECIFIC HEATS
* SIGMA : PRANDTL NUMBER

* YN : VALUES OF Y NORMALISED BY L
* PBLNON : VALUES OF PBL NORMALISED BY PTINF
* MBLBMN : RATIO OF MACH NUMBER IN BOUNDARY-LAYER TO FREE-STREAM
* UBLBUIN : RATIO OF VELOCITY IN BOUNDARY-LAYER TO FREE-STREAM
* TBLBTIN : RATIO OF TEMPERATURE IN BOUNDARY-LAYER TO FREE-STREAM
* MAV : AVERAGE MACH NUMBER
* PTINFAV : AVERAGE STAGNATION PRESSURE
* TTINFAV : AVERAGE STAGNATION TEMPERATURE
* REYAV : AVERAGE REYNOLDS NUMBER/METER
* REC : RECOVERY FACTOR
* IPRINT :
* IERR :

* * * * * * * * * * * * * * * *

RECOVERY FACTOR

R = SIGMA**(1./3.)
REC = SIGMA**(1./3.)

CONSTANTS

G = GAMMA
G1= (G**1.)/G
G2= 1./G
G3= R*(G**1.)/2.
C CALCULATE MACH NUMBERS IN BOUNDARY-LAYER AND FREESTREAM, AND RATIO

DO 100 I = 1, N
X1 = (PBL(I)/PS(I))**G1 - 1.
X2 = (PTINF(I)/PS(I))**G1 - 1.
IF(X1 .LT. 0. .OR. X2 .LT. 0.) GO TO 1000
X1 = (2./G*1.)*X1
X2 = (2./G*1.)*X2
MBL(I) = SQRT(X1)
MINF(I) = SQRT(X2)
MBLBMIN(I) = MBL(I)/MINF(I)
PBLNONCI) = PBL(I)/PTINF(I)
100 CONTINUE

C CALCULATE RATIO OF TEMPERATURE IN BOUNDARY-LAYER TO FREESTREAM

DO 200 I = 1, N
TBLBTIN(I) = (1. + G3* (MINF(I)**2.) ) / (1. + G3* (MBL(I)**2.) )
200 CONTINUE

C CALCULATE RATIO OF VELOCITY IN BOUNDARY-LAYER TO FREESTREAM

DO 300 I = 1, N
UBLBUIN(I) = MBLBMIN(I) * SQRT(TBLBTIN(I))
300 CONTINUE

C NON-DIMENSIONALIZE RAKE PROBE HEIGHTS TO LENGTH SCALE L

DO 400 I = 1, N
YN(I) = Y(I)/L
400 CONTINUE

C CALCULATE AVERAGE QUANTITIES

SUMM = 0.
SUMP = 0.
SUMT = 0.
DO 500 I = 1, N
SUMM = SUMM + MINF(I)
SUMP = SUMP + PTINF(I)
SUMT = SUMT + TTINF(I)
500 CONTINUE

MAV = SUMM/N
PTINFAV = SUMP/N
TTINFAV = SUMT/N

IF(IPRINT .EQ. 0) GO TO 1010
PRINT 1020
DO 1030 I = 1, N
PRINT 1040, I, MINF(I), MBL(I), UBLBUIN(I), TBLBTIN(I)
1010 CONTINUE

25
1030 CONTINUE
1020 FORMAT(/1X,* I MINF NBL U/UINF T/TINF*)
1040 FORMAT(1X,15,4F10.6)
C   CALCULATE AVERAGE REYNOLDS NUMBER/METER
1010 CONTINUE
   C = 1. + ((G - 1.)/2.) * (MAV**2.)
   A1 = PTINFAV/(TTINFAV**1.4)
   A2 = MAV/(C**2.1)
   A3 = (64314./14.696)*(10.**6.)
   Z = COMP(PTINFAV,TTINFAV)
   REYAV= A3*A2*A1*Z
   IF(IPRINT .NE. 0) PRINT 1050, MAV, PTINFAV, TTINFAV, Z, REYAV
1050 FORMAT(/10X,*MAV, PTINFAV, TTINFAV, Z, REYAV: *, /10X,
   $4F10.4,E14.4)

RETURN
1000 PRINT 1100
1100 FORMAT(/10X,*ERROR IN CALCULATING BOUNDARY-LAYER VELOCITY*,
   $* PROFILE: CHECK INPUT PRESSURE DATA*)
RETURN
END
SUBROUTINE THIKNES(N,Y,U,T,L,ICOMP,DELTA,EN,IOPT $,MINF,REC,GAMMA,DELS,THETA,IPRINT,IERR)
REAL MINF, L
DIMENSION Y(30),U(30),T(30),F(30),G(30)

* * * * * * * * * * * * * * * * * * * * * * * * * * *

N : NUMBER OF POINTS IN THE BOUNDARY-LAYER
Y : RAKE PROBE HEIGHTS
U : NON-DIMENSIONALISED VELOCITY PROFILE AT N POINTS
T : NON-DIMENSIONALISED TEMPERATURE PROFILE AT N POINTS
L : LENGTH SCALE
ICOMP : = 0, CALCULATES INCOMPRESSIBLE VALUES
        : / 0, CALCULATES COMPRESSIBLE VALUES
DELTA : BOUNDARY-LAYER THICKNESS
EN : CONSTANT IN POWER-LAW VELOCITY PROFILE
MINF : MACH NUMBER
REC : RECOVERY FACTOR
GAMMA : RATIO OF SPECIFIC HEATS
IPRINT : NOT = ZERO, PRINTS INTERMEDIATE RESULTS
IOPT : = 1, DELTASTAR CALCULATED USING EN AND DELTA
        FOR THE ENTIRE PROFILE
IOPT : = 2, DELTASTAR CALCULATED USING EN AND DELTA
        ONLY UPTO FIRST TUBE, AND USING TRAPEZOIDAL
        RULE FOR OTHER POINTS.
IERR : NOT USED
DELS : DISPLACEMENT THICKNESS / L
THETA : MOMENTUM THICKNESS / L

* * * * * * * * * * * * * * * * * * * * * * * * * * *

NBL = N
IF(IOPT .EQ. 1) GO TO 680

C CALCULATE THE VELOCITY/MASS DEFECT

DO 100 I= 1, N
  IF(ICOMP .NE. 0) F(I) = 1. - U(I)/T(I)
  IF(ICOMP .NE. 0) G(I) = (U(I)/T(I))*(1. - U(I))
  IF(ICOMP .EQ. 0) F(I) = 1. - U(I)
  IF(ICOMP .EQ. 0) G(I) = U(I)*(1. - U(I))
100 CONTINUE

C INTEGRATE FROM TUBE(1) TO TUBE(N)

IF(IPRINT .NE. 0 .AND. ICOMP .NE. 0) PRINT 500
IF(IPRINT .NE. 0 .AND. ICOMP .EQ. 0) PRINT 510

27
C CONTRIBUTION FROM WALL TO FIRST TUBE

A = 0.
B = Y(1)/DELTA
CALL INCRS(MINF,REC,GAMMA,A,B,DELTA,L,EN,DELS1,THETA1,
$PRINT,IERR1,IERR2)
IF(IERR1 .LE. 2 .AND. IERR2 .LE. 2) GO TO 630
PRINT 610, IERR1, IERR2
610 FORMAT(/1X,*ERROR IN SUBROUTINE CADRE WHILE CALCULATING*,
$10X,*CONTRIBUTION FROM WALL TO FIRST TUBE:*,
$10X,*ERROR NUMBERS :*,215)
RETURN
630 DELS = DELS + DELS1 *(DELTA/L)
THETA = THETA+ THETA1*(DELTA/L)
IF(IPRINT .NE. 0)
$PRINT 660, DELS1,DELS ,THETA1,THETA
660 FORMAT(/10X,*DELS1 DELS THETA1 THETA*,4F10.6)
IF(DELTA .LE. Y(NBL)) RETURN

C CONTRIBUTION FROM LAST TUBE TO DELTA

A = Y(NBL)/L
B = 1.0
CALL INCRS(MINF,REC,GAMMA,A,B,DELTA,L,EN,DELS2,THETA2,
$PRINT,IERR1,IERR2)
IF(IERR1 .LE. 2 .AND. IERR2 .LE. 2) GO TO 650
PRINT 640, IERR1, IERR2
C \hspace{1em} IOPT = 2: CALCULATE DELTASTAR AND THETA FROM Y=0 TO DELTA

680 CONTINUE
A = 0.0
B = 1.0
CALL INCRS(MINF,REC,GAMMA,A,B,DELTA,L,EN,DELS,THETA,
SPRINT,IERR1,IERR2)

IF(IERR1 .LE. 2 .AND. IERR2 .LE. 2) GO TO 700
PRINT 690, IERR1,IERR2

690 FORMAT(/10X,*ERROR IN SUBROUTINE CADRE WHILE CALCULATING*,
$/10X,* FOR IOPT = 1 IN THE NAMELIST*,
$/10X,* ERROR NUMBER: *,215)

700 DELS = DELS * (DELTA/L)
THETA= THETA* (DELTA/L)
IF(IPRINT .NE. 0) PRINT 710, DELS,THETA
710 FORMAT(/10X,*DELS3 THETA3: *,2F10.6)

RETURN
END
SUBROUTINE INCRS(MINF,REC,GAMMA,A,B,DELTA,L,EN,DELS1,THETA1,  
$PRINT,IER1,IER2)

REAL MINF,L
DIMENSION EPS(3)
COMMON /AA/ C,ENP
EXTERNAL FDEL, FTHETA

MINF : FREE-STREAM MACH NUMBER
REC : RECOVERY FACTOR
GAMMA : RATIO OF SPECIFIC HEATS
A : LOWER LIMIT OF INTEGRATION
B : UPPER LIMIT OF INTEGRATION
EN : INDEX IN POWER LAW \((U/UE)=(Y/D)^{(I/N)}\)
L : LENGTH SCALE
DELTA : BOUNDARY-LAYER THICKNESS (BY POWER-LAW FIT)
DELS1 : VALUE OF DELS1/L FROM WALL TO NEAREST TUBE
THETA1 : VALUE OF MOMENTM/L FROM WALL TO NEAREST TUBE
IER1 : NOT = 0, ERROR INTEGRATING DISPLACEMENT THICKNESS
IER2 : NOT = 0, ERROR INTEGRATING MOMENTUM THICKNESS

\[
C = (REC \ast (GAMMA - 1.) / 2.) \ast (MINF \ast MINF)
\]

ENP = EN

IF(IPRINT .NE. 0) PRINT 100, MINF,REC,GAMMA,A,B,ENP,L,DELTA

100 FORMAT(8F10.6)

EPS(1) = 1.0E-10
EPS(2) = 1.0E-08
ITEXT = 0

CALL CADRE(A,B,FDEL,EPS,ITEXT,SUM,IERR)
DELS1 = SUM
IERR1 = IERR
IF(IPRINT .NE. 0) PRINT 200, SUM, IERR

200 FORMAT(10X,F10.6,15)

CALL CADRE(A,B,FTHETA,EPS,ITEXT,SUM,IERR)
THETA1 = SUM
IERR2 = IERR
IF(IPRINT .NE. 0) PRINT 200, SUM, IERR

RETURN
END
FUNCTION FDEL(YD)
COMMON /AA/ C,ENP

IF(YD .NE. 0.) U = YD**(1./ENP)
IF(YD .EQ. 0.) U = 0.

T = 1. + C* (1. - U*U)
FDEL = (1. - U/T)
PRINT 100, YD,U,T,FDEL,C,ENP
100 FORMAT(10X,6F10.6)
RETURN
END

FUNCTION FTHETA(YD)
COMMON /AA/ C,ENP

IF(YD .NE. 0.) U = YD**(1./ENP)
IF(YD .EQ. 0.) U = 0.

T = 1. + C* (1. - U*U)
FTHETA= (U/T)*(1.-U)
RETURN
END

FUNCTION COMP(P,T)
C CALCULATES COMPRESSIBILITY FACTOR Z FOR GIVEN
C PRESSURE P(PSIA) AND TEMPERATURE T(DEG K)

P=P/14.7
B0= 1.37
B1= -8.773E-02
B2= 4.703E-04
B3= -1.386E-06
B4= 1.462 E-09
C0= 5.521
C1= -1.986E-01
C2= 7.817 E-04
C3= -1.258E-06
C4= 5.333E-10
D=B0+B1*T +B2*T*T +B3*(T**3.) +B4*(T**4.)
E=C0+C1*T +C2*T*T +C3*(T**3.) +C4*(T**4.)
Z=1. -P* EXP(D) -(P*P)* EXP(E)
COMP=Z
P=P*14.7
RETURN
END
Number of tubes: 15
Outside Diameter: .02"
Inside Diameter: .01"
Spacing: .04"

Figure 1: Sketch of 0.3-Meter Transonic Cryogenic Tunnel Boundary-Layer Rake.
Figure 2: Determination of edge of boundary-layer and constant 'n' in the power-law velocity profile ($U_0 y^{1/n}$).
Figure 3: Typical plot of measured boundary-layer velocities and power-law fit.
Correction of airfoil data for sidewall boundary-layer effects requires a knowledge of the boundary-layer displacement thickness and the shape factor with the tunnel empty. To facilitate calculation of these quantities under various test conditions for the Langley 0.3-m Transonic Cryogenic Tunnel, a computer program has been written. This program reads the various tunnel parameters and the boundary-layer rake total head pressure measurements directly from the Engineering Unit tapes to calculate the required sidewall boundary-layer parameters. Details of the method along with the results for a sample case are presented.