GLASGOW UNIVERSITY

DEPARTMENT OF

AERONAUTICS & FLUID MECHANICS

A DESIGN PROCEDURE TO MODIFY THE TRAILING EDGE UPPER SURFACE PRESSURE GRADIENT OF A GIVEN AEROFOIL

by

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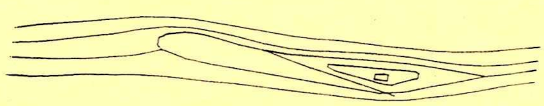

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SYMBOL GLOSSARY

γ	-	vorticity
L	-	panel length
W	-	velocity on aerofoil surface
U_∞	-	freestream velocity

SUBSCRIPTS AND SUPERSCRIPTS

a	-	actual value
d	-	designed value
err	-	error
i	-	index of surface element corner point
ic	-	control point
m	-	modification curve
NC	-	value at chosen control point
o	-	value on 23012
r	-	requested value
TE	-	value at trailing edge control point

SUMMARY

Little is known about the detailed flow on the upper surface of aerofoils, prone to trailing edge separation, during the process of dynamic stall.

The present report describes a method whereby the pressure gradient on the trailing edge upper surface of a given aerofoil may be modified to either enhance or reduce such separations, for a given section, whilst retaining the leading edge pressure distribution.

1. INTRODUCTION

The effect and importance of trailing-edge separation on the dynamic stall onset of typical rotor sections is at present unclear. It has, however, been suggested (1) that a certain amount of flow reversal takes place within the boundary layer prior to the onset of separation.

Further investigation into the effects of trailing-edge separation on dynamic stall onset may be carried out if a standard aerofoil (for which there are experimental data available) is modified and re-tested. The chosen aerofoil was the NACA 23012 and the required modification was one which would enhance the boundary layer separation at the aerofoil trailing-edge.

The type of modification was restricted to those that did not significantly alter the leading edge pressure distribution.

The description herein is of a numerical method for the modification of a standard aerofoil section. The method centres on the postulation that to enhance separation a more severe and sustained adverse pressure gradient must be imposed on the boundary layer.

2. METHOD

The complete modification procedure was essentially three algorithms; (i) a potential flow panel method allowing calculation of the original pressure gradient at any angle of attack, (ii) a procedure allowing the modification of this gradient and (iii) an inverse potential flow panel method (A.A. method) to calculate a new profile from the modified vorticity distribution.

Full details of algorithms (i) and (iii) are given in references (2) and (3) respectively. As observed by Leishman (2) the optimum number of panels was 50.

The pressure gradient was calculated using the formula :

$$\frac{1}{\rho}\frac{dp}{ds} = - U \frac{dU}{ds} \qquad (1)$$

This was easily converted into a form suitable for a panel method calculation. Hence using the notation used in figure (1) we have :

$$\frac{1}{\rho}\frac{dp}{ds}\bigg|_{ic} = \gamma ic \left(\frac{\gamma i{+}1 - \gamma i}{L_i}\right)$$

$$= \frac{\gamma_{i+1}{}^2 - \gamma i^2}{2L_i} \qquad (2)$$

Since $\gamma ic = \dfrac{\gamma i{+}1 + \gamma i}{2}$

The method used to modify the pressure gradient was essentially a curve fitting procedure conforming to a maximum of three boundary conditions. If, for instance, the pressure gradient between x_1 and x_2 was to be altered (see figure 2) then the three boundary conditions would be :

(i) $f\left(\frac{x_1}{c}\right) = \frac{1}{\rho}\frac{dp}{ds}\bigg|_{NC}$

(ii) $f\left(\frac{x_2}{c}\right) = \frac{1}{\rho}\frac{dp}{ds}\bigg|_{TE}$ (3)

(iii) $f'\left(\frac{x_1}{c}\right) = \frac{1}{\rho}\frac{d^2p}{ds^2}\bigg|_{NC}$

where $\left(\frac{1}{\rho}\frac{dp}{ds}\right)^m = f\left(\frac{x}{c}\right)$ is the modification curve.

Three types of modification were chosen for investigation: (i) a conic parabola, (ii) a combination of a straight line and a tangency circle (see figure 3) and (iii) the simplest modification, a straight line. These particular modifications were chosen because they gave similar curves to that of the original gradient.

(i) The parabolic solution

Based on the three b.c's, a curve of the form:

$$\left(\frac{1}{\rho}\frac{dp}{ds}\right)^m = a\left(\frac{x}{c}\right)^2 + b\left(\frac{x}{c}\right) + d$$

can be solved for values of a, b and d. However, this led to unpredictable shapes (see figure 4).

Therefore, it was decided to restrict the choice of curve to a conic parabola of the form:

$$\left[\left(\frac{1}{\rho}\frac{dp}{ds}\right)^{m} - a\right]^{2} = 4A\left[\frac{x}{c} - b\right]^{2} \qquad (4)$$

shere (a, b) is the vertex position.

The procedure adopted to solve this equation was:

(i) Positioning of the vertex at a chosen upstream control pt (i.e. NC in figure 2). Thus (a,b) is found.

(ii) Choice of an initial value of the pressure gradient for the trailing edge. This was used as a boundary condition to find A.

(iii) Determination of a position, G, on this parabola where the gradient equals $\left.\frac{1}{\rho}\frac{d^2p}{ds^2}\right|_{NC}$

(iv) Movement of the vertex so G now lies at NC.

(v) Re-calculation of the trailing edge pressure gradient.

This procedure was adopted because it was easily computable and always led to a solution.

(ii) <u>Tangency circle solution</u>

This modification was different from the parabola inasmuch as it gave a constant value of $\frac{1}{\rho}\frac{d^2p}{ds^2}$ over the majority of the modified region. The tangency circle allowed the satisfaction of all three boundary conditions. The procedure adopted to solve for the circle was :

(i) Specification of an upstream control pt (NC) and a value for the trailing edge pressure gradient.

(ii) Calculation of the gradient of the line through these two pts (L_1).

(iii) Calculation of the gradient of the tangent to control pt NC + 1 (L_2).

(iv) Determination of the intersection point between L_1 and L_2.

(v) Erection of the perpendiculars N_1 and N_2 and determination of their intersection pt. Thus giving the centre of the tangency circle.

(iii) The Straight Line Solution

This modification was chosen because it was the simplest and could be used to assess any merits gained by increasing the complexity of the solution (i.e. the two previous methods).

Once the type of modification was chosen the new vorticity distribution could be calculated. The method of calculation was carried out from NC towards the trailing edge using the equation :

$$\gamma_i^2 = \gamma_{i+1}^2 - 2L \left(\frac{1}{\rho}\frac{dp}{ds}\right)_{ic}^{m} \qquad (5)$$

This obviously gave a different value of γ_1 than the original and therefore to satisfy the kutta condition γ_{N+1} had to be altered accordingly.

Two conditions were used to estimate the success of any one modification:

(i) As in reference (2) a velocity error was used as a measure of the convergence of the A.A. method. This was defined as :

$$e = \left|\frac{Ur-Ua}{U_\infty}\right| \qquad (6)$$

(ii) The departure from the original leading edge conditions on the new profile was estimated by a defined error

$$\gamma_{err} = \left| \frac{\gamma_o - \gamma_d}{\gamma_o} \right| \qquad (7)$$

The procedure adopted to solve equation (7) was :

(i) Choice of an angle of attack range (here this was 0°, 10° and 20°).

(ii) Calculation of the vorticity distributions for both 23012 and modified profile using the forward panel algorithm.

(iii) Calculation of equation (7) for those panels forward of the point x/c = x/c(NC), followed by an averaging over the range of angles.

A FORTRAN program was written allowing any one of the above modifications to be implemented complete with calculation of the new vorticity distribution.

This was then called the requested vorticity distribution and was used as input data to the inverse panel program for calculation of the new profile. The output from this program was called the designed vorticity distribution.

To allow the calculation of the leading edge errors another FORTRAN program was written and used in conjunction with the forward panel program as described above.

To show that the modified profile did, indeed, enhance trailing edge separation, Garner's method (4) for the prediction of the separation pt was used. A Glasgow University FORTRAN program utilising this method was already available for use.

Appendix (1) illustrates the program procedure which includes program filenames and corresponding data input/output for the pressure modification program is listed in Appendix (3).

3. RESULTS AND DISCUSSION

During modification all vortices, except γ_1 to γ_{NC} inclusive and γ_{N+1}, were held constant at their original values. As a consequence of this condition a large modification would cause one of the two following errors:

(i) A noticeable discontinuity in pressure gradient over the Nth panel.

(ii) The left hand side of equation (5) would become negative before the trailing edge was reached.

Therefore, in order to achieve a sensible distribution of vorticity and hence a reasonable designed profile, only small modifications in pressure gradient were carried out.

To allow for a comparison between different modifications, a design criterion was used; this stated that the modification must be such that the requested trailing edge vorticity was similar to that of the original 23012. This modification was then termed the maximum.

Since the modification procedure could be carried out any any angle of attack, three angles were chosen, namely 10°, 14.2° and 18°. Each resulted in a pressure gradient which could be modified three ways.

After the nine modifications were carried out, it was found that each converged to a reasonable profile. It was therefore concluded that this method was highly suitable for small modifications in pressure gradient.

However, in order to select a final design method, a more thorough investigation was carried out and, in general, the following points were noted:

(i) The best angle to carry out any modification was at 14.2°. It was observed that at low angles any change in pressure gradient was relatively large with respect to the original.

This consequently affected the convergence of the A.A. method. Also, it was noted that at 18° the original pressure gradient decreases rapidly after the peak thus leaving a limited amount of vorticity over the rear of the aerofoil. Consequently equation (5) sligthly restricted the amount by which the pressure gradient could be increased (see figure 5).

(ii) With increased modification of the constant $\frac{1}{\rho}\frac{d^2p}{ds^2}$ of the straight line, the larger was the vorticity error.

Based on the stringent conditions above the best overall modification was the parabolic solution at 14.2°. The velocity error was 1.3% and the average leading edge error was 1.1%. Figure 8 shows a graph of the predicted separation point at various angles of attack.

4. CONCLUSIONS

A method for the modification of a standard aerofoil to enhance boundary layer separation has been developed. This method was applied to the NACA 23012. The resulting profile can now be tested under static and dynamic conditions and the data obtained compared to that of the NACA 23012.

Acknowledgements

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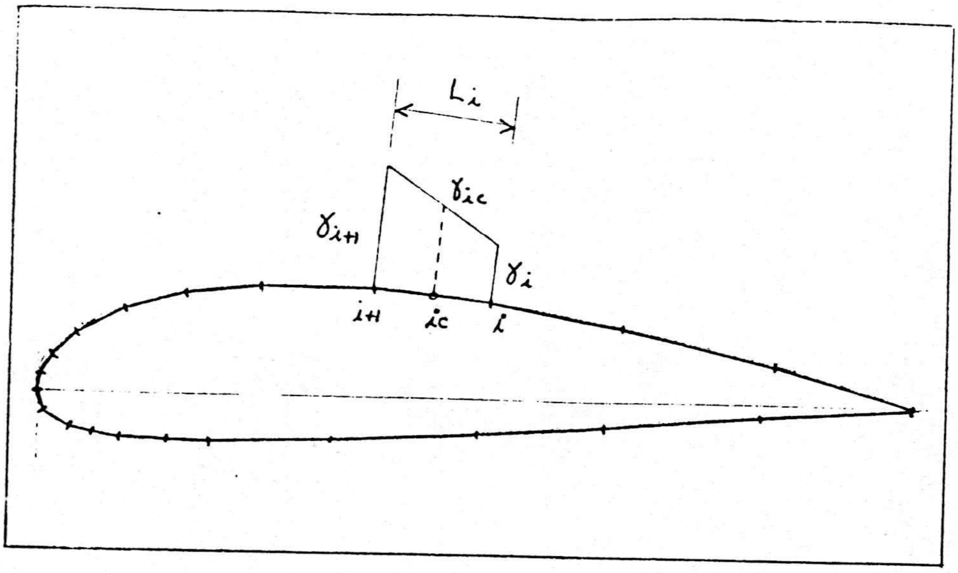


FIGURE 1

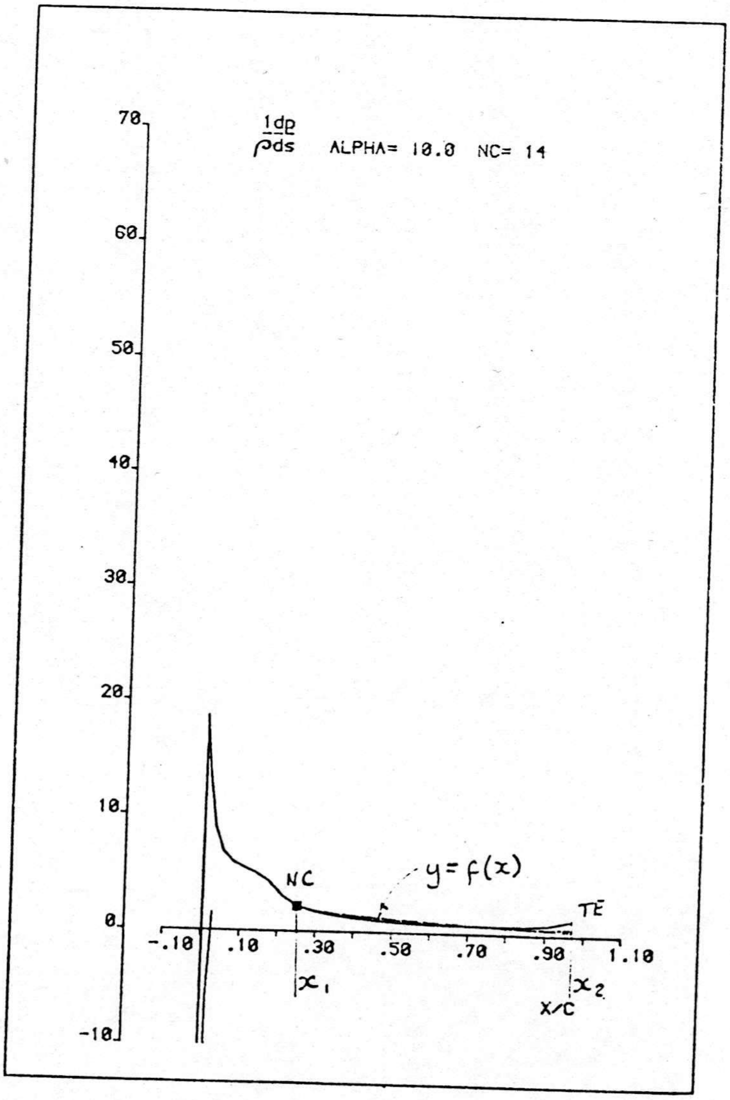


FIGURE 2

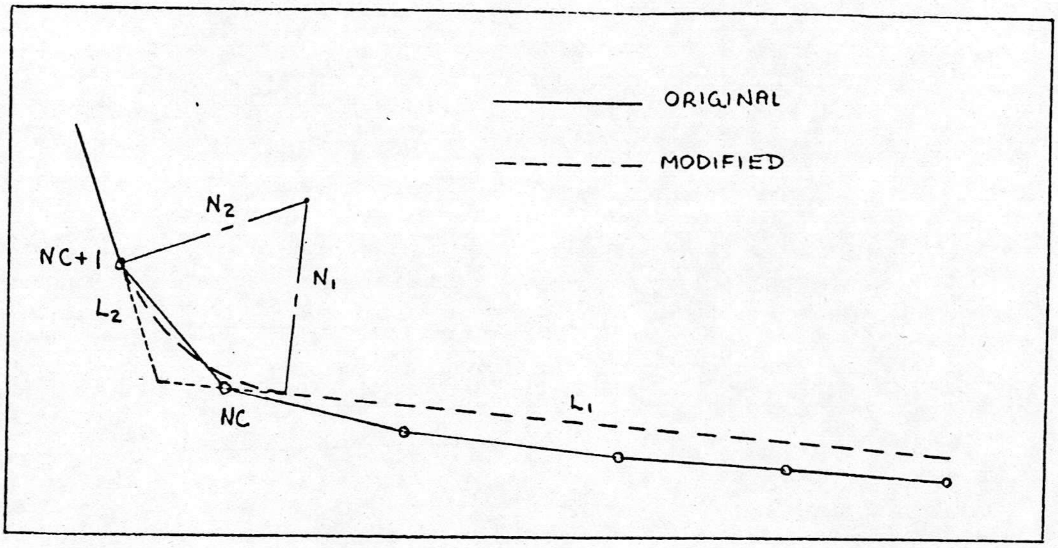


FIGURE 3 Tangency Circle Solution

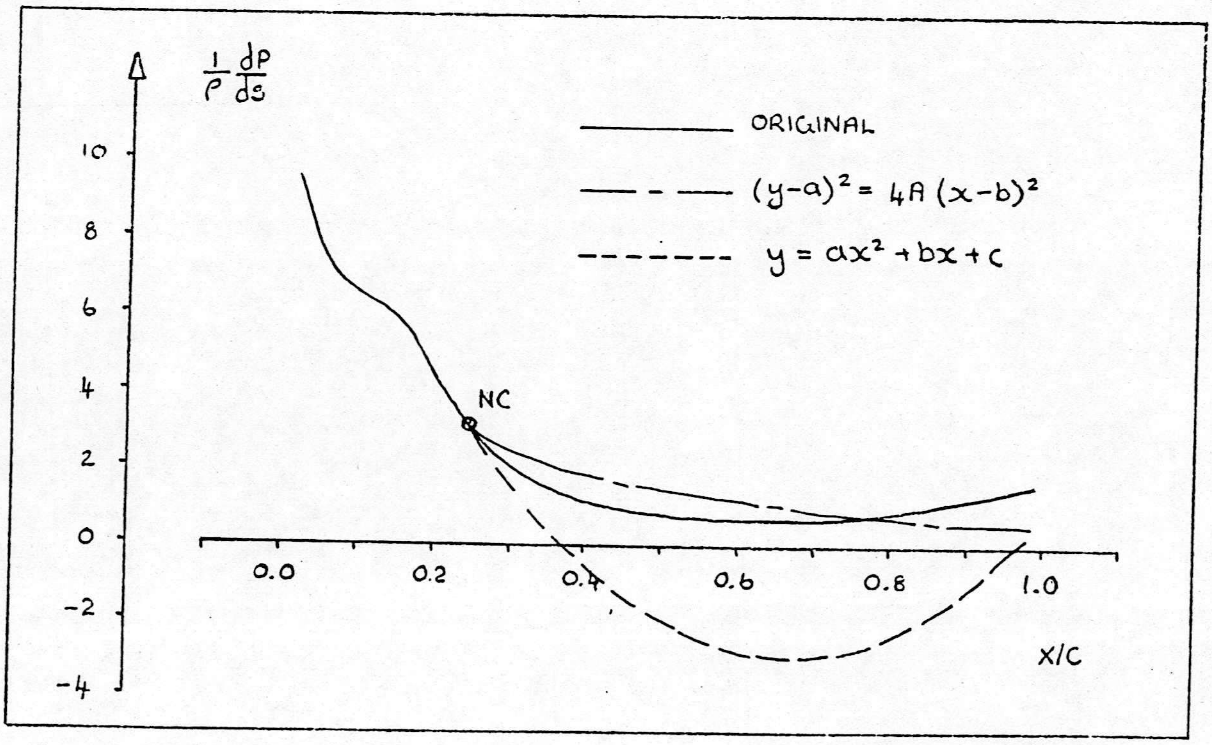
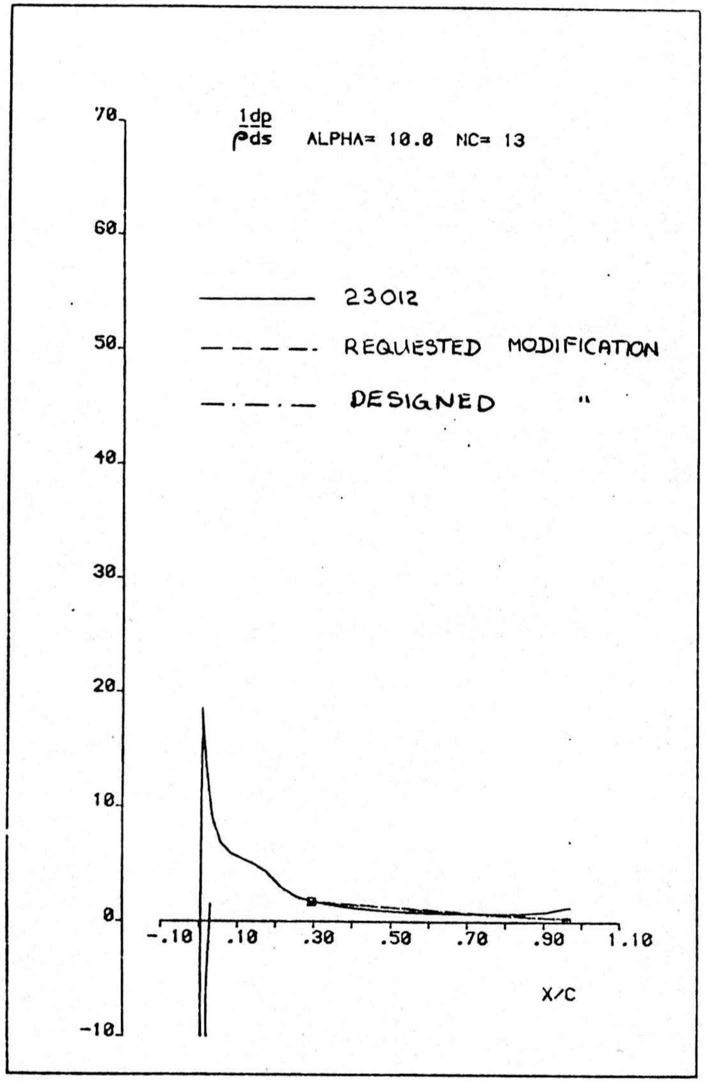
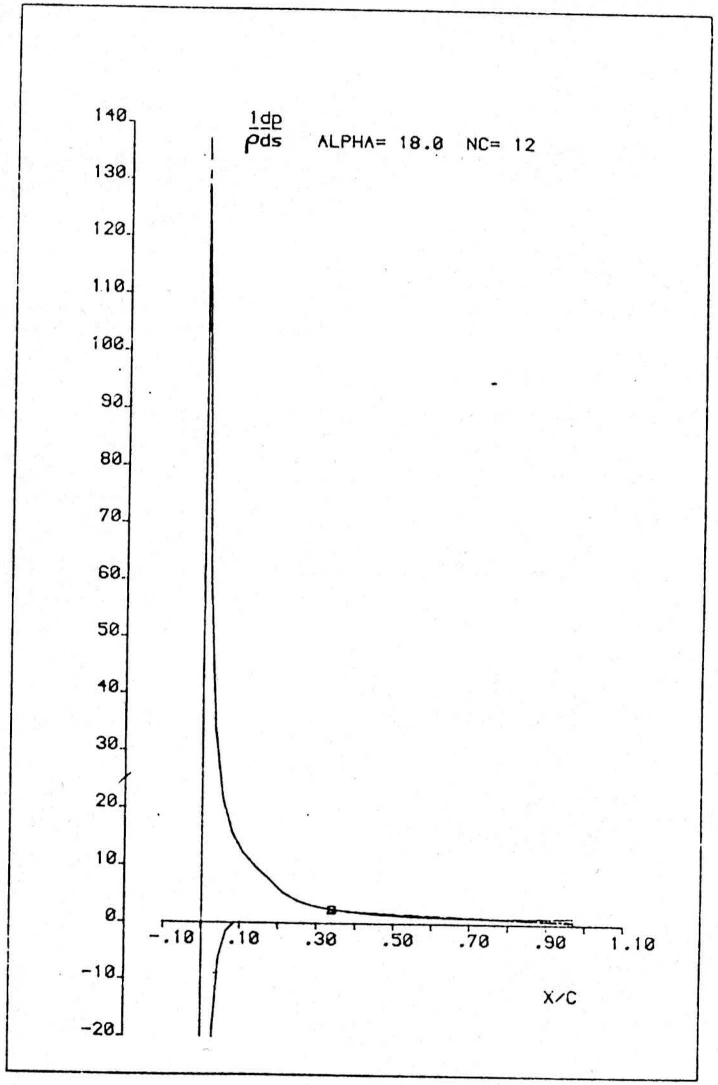


FIGURE 4 The parabolic Solution





<u>FIGURE 5</u> Presure Gradient $\alpha = 10^\circ$, $\alpha = 18^\circ$

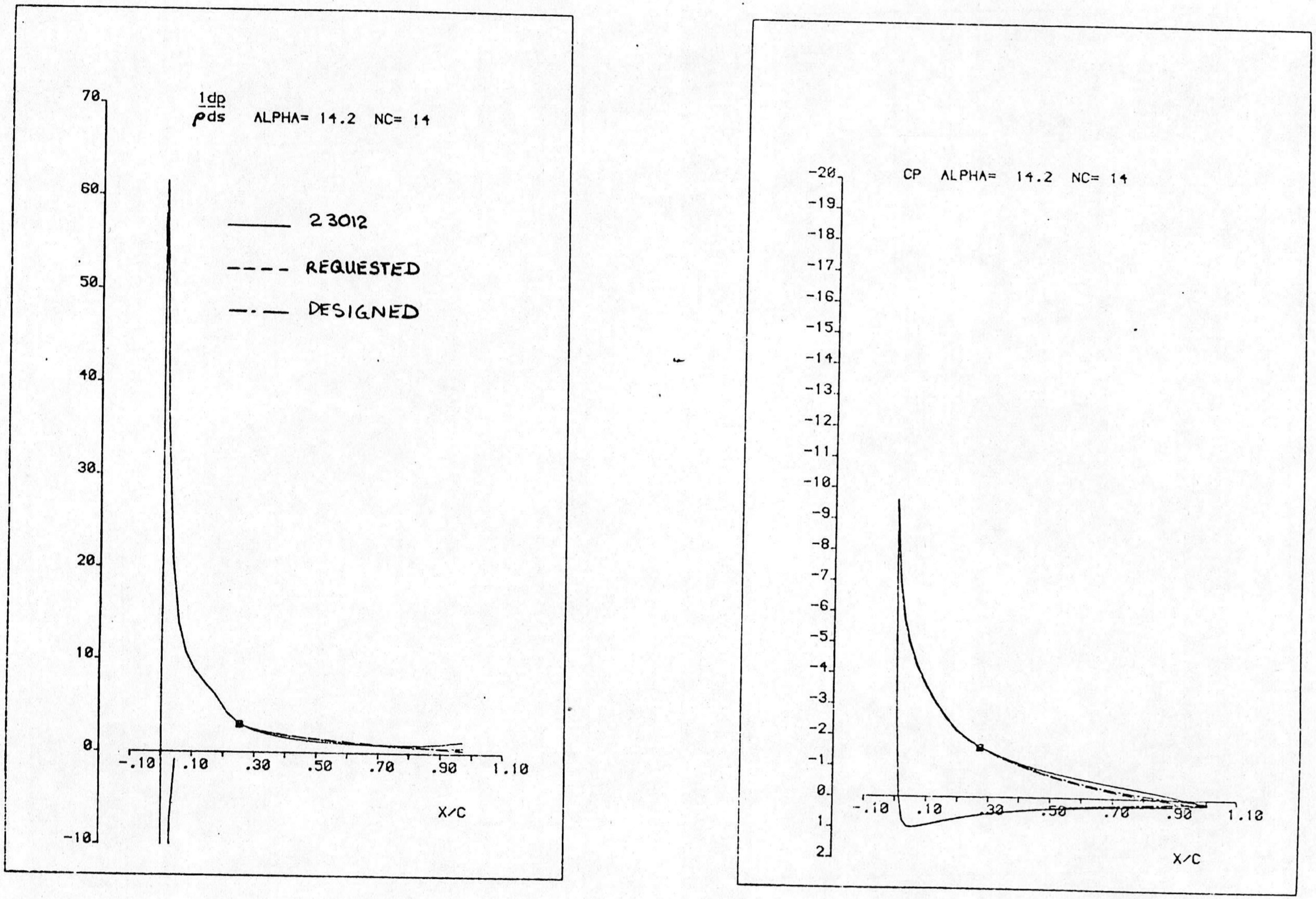
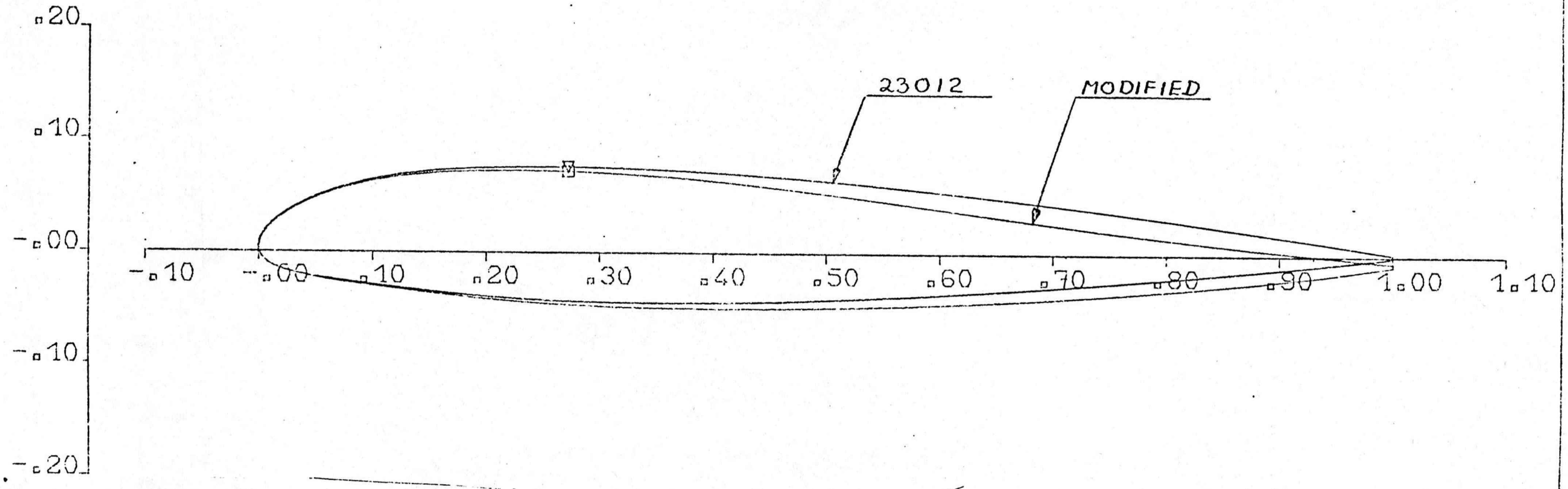


FIGURE 6 Modification at $\alpha = 14.2$

FIGURE 7 : NACA 23012 : Parabolic modification at $\alpha = 14.2°$

50 PANELS NC= 14



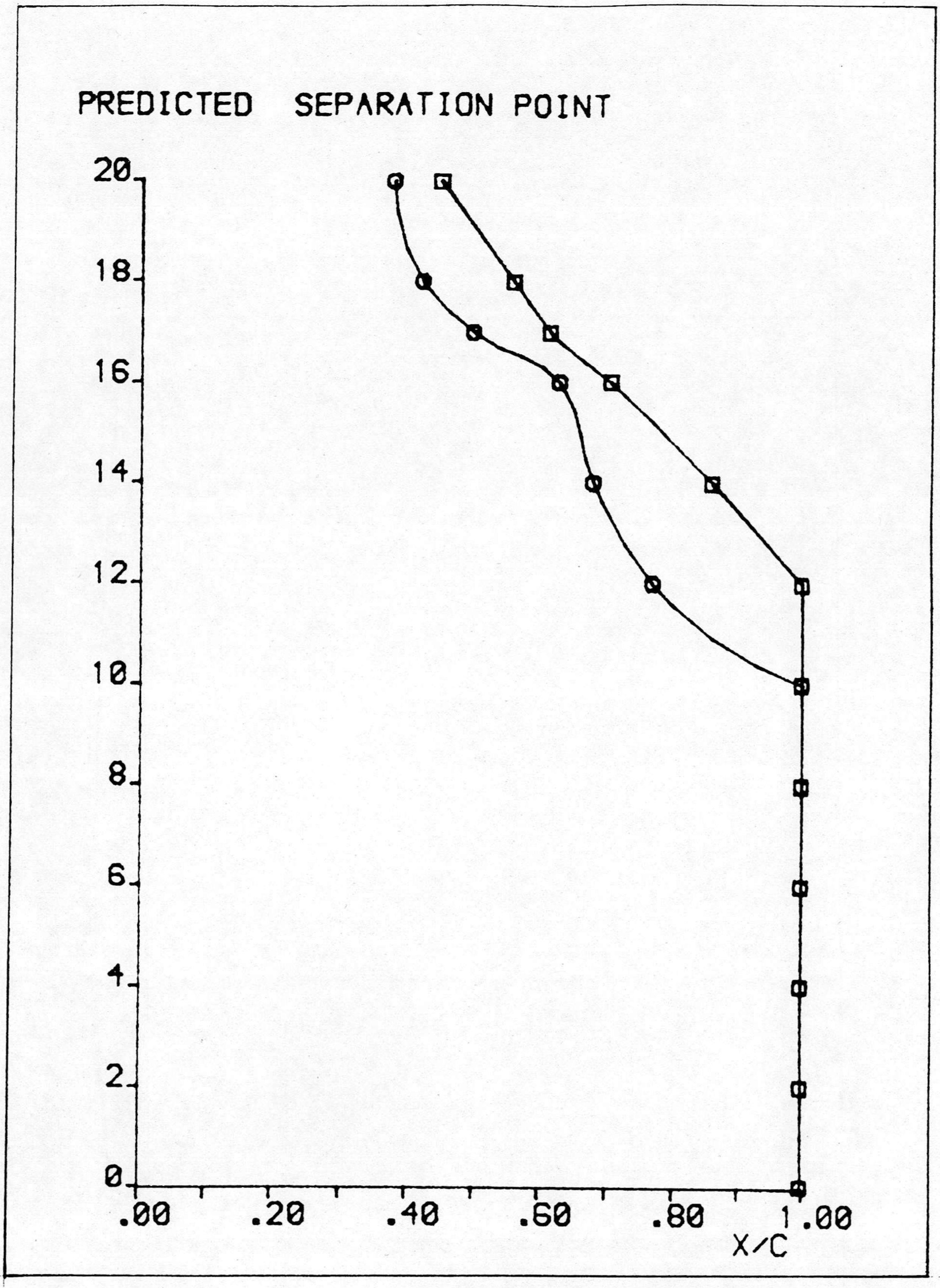
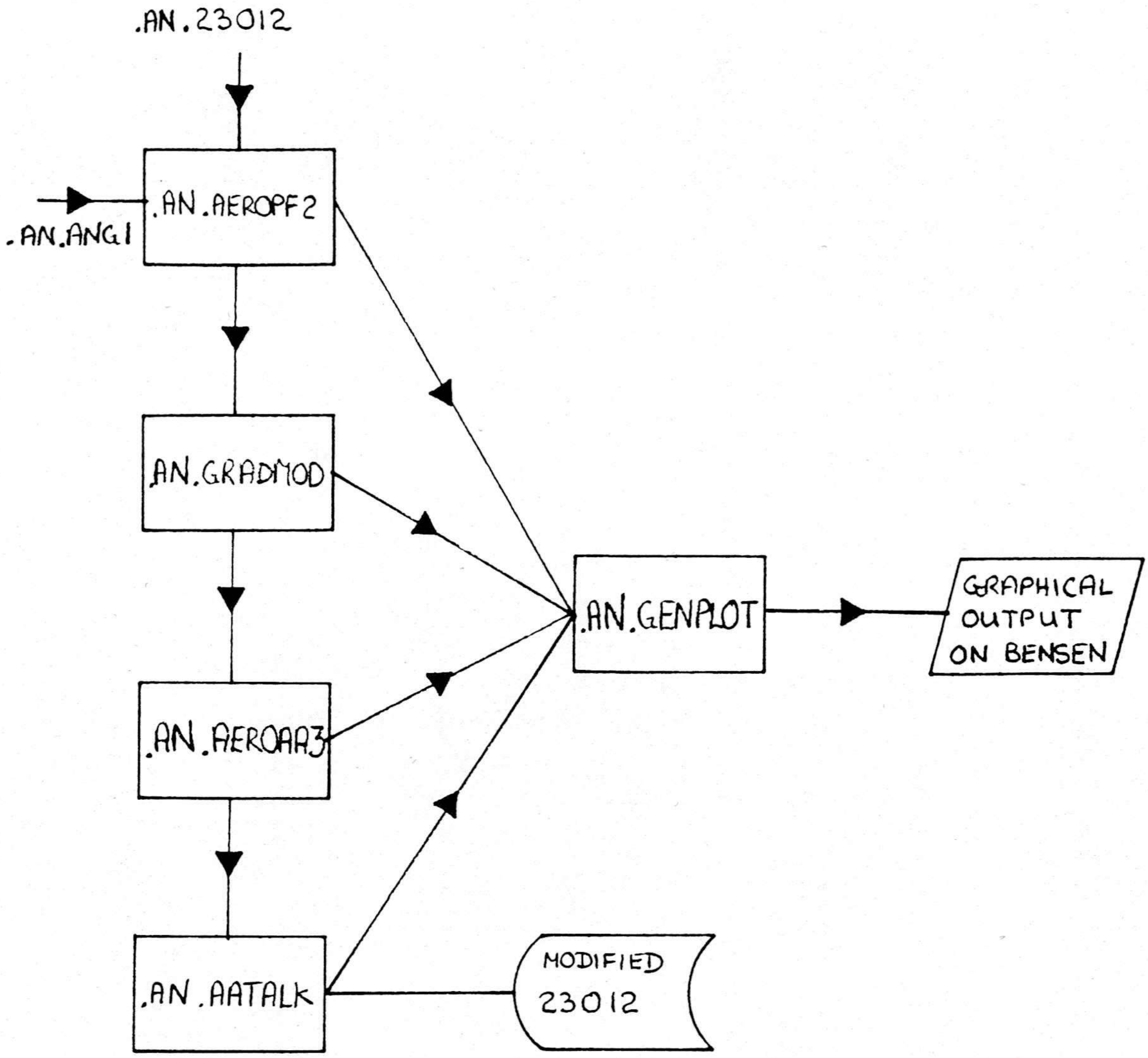


FIGURE 8 □ = 23012 O = MODIFIED

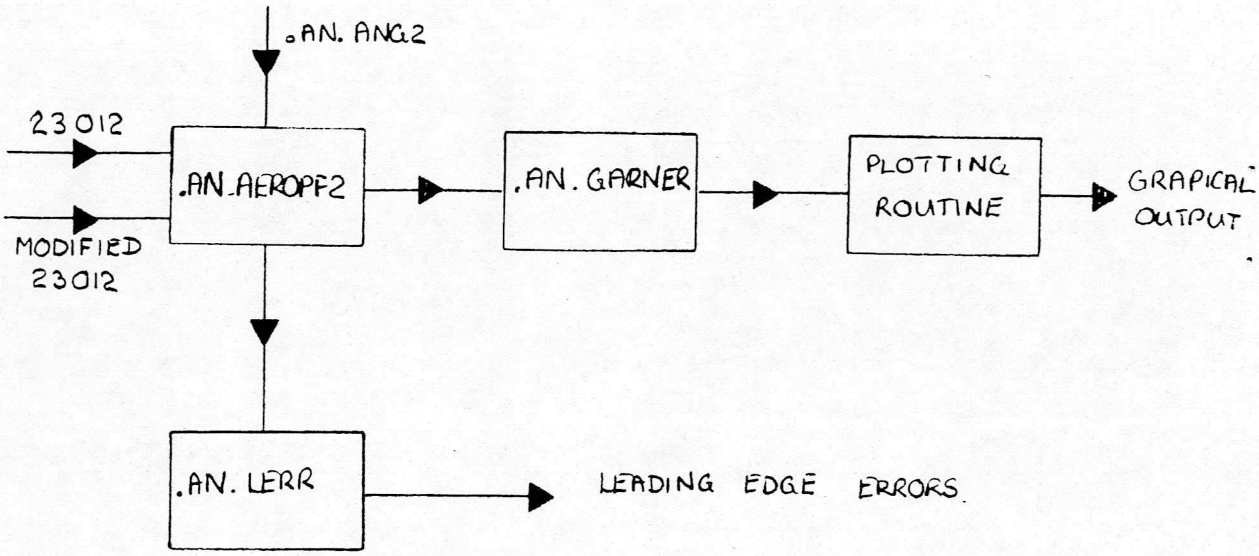
APPENDIX 1

(a) PROGRAM SEQUENCE FOR PROFILE MODIFICATION



.AN.23012	File containing coordinates of a 50 panel NACA 23012
.AN.ANG1	File containing the angles of attack at which the pressure gradient modification is to implemented (3 maximum)
.AN.AEROPF2	Forward potential flow panel program
.AN.GRADMOD	Pressure gradient modification program
.AN.AEROAA3	Inverse potential flow panel program
.AN.AATALK	Program to calculate modified C_p and $\frac{1}{e}\frac{dP}{ds}$
.AN.GENPLOT	Plotting Routine.

(b) PROGRAM SEQUENCE FOR SEPARATION POINTS AND LEADING EDGE ERRORS



.AN. GARNER	Program utilizing Garners method
.AN. LERR	Program to calculate leading edge errors
.AN. ANG2	Range of angle of attacks

APPENDIX 2

```
Listing of file .GRADMOD by LF 4 on 17 APR 1984 at 14:55:48
File created on THU 02 FEB 1984  :  file last modified on MON 16 APR 1984

C***********************************************************************
C PROGRAM TO MODIFY PRESSURE GRADIENT
C WRITTEN TO USE OUTPUT FROM .AEROPF2
C NOTE:HERE SOL IS +VE CLOCKWISE
C WRITTEN BY A.NIVEN
C JAN 1984
C***********************************************************************


      REAL X(100),XC(100),Y(100),LEN(100)
      REAL SOL(100),VT(100),CP(100),CPC(100),PGRAD(100)
      REAL SOLD(100),PGRADD(100)

C READ IN AEROFOIL GEOMETRICAL DATA AND NO. OF ANGLES
      READ(3,*)N,NA
      WRITE(4,*)NA
      WRITE(6,*)N,NA
      DO 100 M=1,N+1
      READ(3,*)X(M),XC(M),Y(M),LEN(M)
      WRITE(6,*)X(M),XC(M),Y(M),LEN(M)
  100 CONTINUE

C START CALCULATION FOR EACH ANGLE HERE
      IRUN=0
  120 IRUN=IRUN+1
      WRITE(10,*)'THE MODIFICATION ANGLE IS='


C READ IN INITIAL AEROFOIL VELOCITY DATA
      READ(3,*)ANGLE,JP
      WRITE(2,*)ANGLE,JP
      WRITE(10,*)ANGLE,JP
      DO 160 M=1,N+1
      READ(3,*)SOL(M),VT(M),CP(M),CPC(M),PGRAD(M)
  160 CONTINUE

C CHOOSE TYPE OF MODIFICATION
  170 WRITE(2,175)
      WRITE(10,175)
  175 FORMAT(' (A)  CHOOSE:PARABOLA=1,STRAIGHT LINE=2,CIRCLE+LINE=3')
      READ(1,*)ICH
      WRITE(10,*)ICH
      WRITE(2,180)
      WRITE(10,180)
  180 FORMAT(' (B)  CHOOSE:PGRAD RETURN=1.PGRAD REDUCTION=2')
      READ(1,*)IPRO
      WRITE(10,*)IPRO
      WRITE(2,250)
      WRITE(10,250)
```

```
  250 FORMAT(' (C)  INPUT DOWNSTREAM BOUNDARY CONDITION PRESSURE GRAD')
      READ(1,*)YTE
      WRITE(10,*)YTE
      WRITE(2,260)
      WRITE(10,260)
  260 FORMAT(' (D)  INPUT UPSTREAM BOUNDARY CONDITION CONTROL PT')
      READ(1,*)NC
      WRITE(10,*)NC
      IF(ICH.NE.1) GOTO 510

C**********************************************************************
C CALCULATE NEW PRESSURE GRADIENT FROM PARABOLA
C**********************************************************************
C USE YTE FOR INTIAL VERTEX POSTION
      YV=PGRAD(NC)
      XV=XC(NC)
      P4A=((YTE-YV)**2)/(XC(1)-XV)

C GRADIENT BOUNDARY CONDITION AND VERTEX SHIFT
      DYDXP=(PGRAD(NC)-PGRAD(NC+1))/(XC(NC)-XC(NC+1))
      YG=P4A/(2.0*DYDXP)+YV
      XG=((YG-YV)**2)/P4A+XV
      SHIFTY=YV-YG
      SHIFTX=XV-XG
      YV=YV+SHIFTY
      XV=XV+SHIFTX

C CALCULATE NEW PRESSURE GRADIENT VALUES
C SOLVE QUADRATIC USING -VE SQRT
      DO 470 M=1,N-1
      IF(M.GE.NC) GOTO 460
      A0=YV**2-P4A*(XC(M)-XV)
      A1=2.0*YV
      PGRADD(M)=(A1-SQRT(A1**2-4.0*A0))/2.0
      GOTO 470
  460 PGRADD(M)=PGRAD(M)
  470 CONTINUE

C OUTPUT VALUE OF YTE FOR 2 & 3
      WRITE(2,480)
      WRITE(10,480)
  480 FORMAT(' (E)  PARABOLA T.E PRESSURE GRADIENT IS:-')
      WRITE(2,*)PGRADD(1)
      WRITE(10,*)PGRADD(1)
      GOTO 960

C*********************************************************************
C CALCULATE NEW PRESSURE GRADIENT FROM STRAIGHT LINE
C*********************************************************************
  510 IF(ICH.EQ.3) GOTO 590
```

Listing of file .GRADMOD by LF 4 on 17 APR 1984 at 14:55:48

```
C GRADIENT OF LINE
      DYDXL=(YTE-PGRAD(NC))/(XC(1)-XC(NC))

C NEW PGRAD VALUES
      DO 580 M=1,N-1
      IF(M.GE.NC) GOTO 570
      PGRADD(M)=YTE+DYDXL*(XC(M)-XC(1))
      GOTO 580
  570 PGRADD(M)=PGRAD(M)
  580 CONTINUE
      GOTO 960

C*****************************************************************
C CALCULATE NEW PRESSURE GRADIENT FROM CIRCLE TANGENCY
C*****************************************************************
C FIND GRADIENT OF LINE BETWEEN 1 & NC
  590 DYDXVT=(YTE-PGRAD(NC))/(XC(1)-XC(NC))
      THETA=ATAN(DYDXVT)
  630 NC=NC+1
      WRITE(2,650)NC
      WRITE(10,650)NC
  650 FORMAT(' (E)  UPSTREAM BOUNDARY CONDITION PT NC=',I4)

C FIND GRADIENT OF TANGENT TO NC
      DYDXNC=(PGRAD(NC)-PGRAD(NC+1))/(XC(NC)-XC(NC+1))

C FIND PT OF INTERSECTION
      D1=PGRAD(NC)-YTE+DYDXVT*XC(1)-DYDXNC*XC(NC)
      XI=D1/(DYDXVT-DYDXNC)
      PGRADI=YTE+DYDXVT*(XI-XC(1))
      WRITE(2,*)'(F)  INTERSECTION AT:-'
      WRITE(10,*)'(F)  INTERSECTION AT:-'
      WRITE(2,*)XI,PGRADI
      WRITE(10,*)XI,PGRADI

C GRADIENT OF PERPENDICULAR FROM NC
      DYDXCP=-1.0/DYDXNC

C LENGTH FROM NC TO (XI,PGRADI)
      DISI=SQRT((PGRAD(NC)-PGRADI)**2+(XC(NC)-XI)**2)

C FIND FOOT OF PERPINDICULAR N INPUTED LINE
      PGRADF=PGRADI+DISI*SIN(THETA)
      XF=XI+DISI*COS(THETA)

C GRADIENT OF PERPENDICULAR FROM (XF,PGRADF)
      DYDXVP=-1.0/DYDXVT

C FIND PT OF INTERSECTION OF PERPENDICULARS.......
```

```
C........GIVING THE CENTRE OF THE CIRCLE
      D2=PGRADF-PGRAD(NC)+DYDXCP*XC(NC)-DYDXVP*XF
      XS=D2/(DYDXCP-DYDXVP)
      PGRADS=PGRADF+DYDXVP*(XS-XF)
      WRITE(2,*)'(G)  CIRCLE CENTRE IS:-'
      WRITE(10,*)'(G)  CIRCLE CENTRE IS:-'
      WRITE(2,*)XS,PGRADS
      WRITE(10,*)XS,PGRADS

C FIND RADIUS OF CIRCLE
      RAD2=(XS-XF)**2+(PGRADS-PGRADF)**2

C WE NOW HAVE ALL THE PARAMETERS TO FIND NEW PGRAD'S
C FROM INPUTED STRAIGHT LINE OR TANGENCY CIRCLE
C USING -VE SQRT
      DO 910 M=1,N-1
      IF(M.GE.NC) GOTO 900
      IF(XC(M).LT.XF) GOTO 840
      PGRADD(M)=YTE+DYDXVT*(XC(M)-XC(1))
      GOTO 910
  840 AC=PGRADS**2+(XC(M)-XS)**2-RAD2
      B=2.0*PGRADS
      D3=B*B-4.0*AC
      IF(D3.LT.0.0) GOTO 920
      D7=1.0
      IF(PGRADS.LT.0.0) D7=-1.0
      PGRADD(M)=(B-D7*SQRT(D3))/2.0
      GOTO 910
  900 PGRADD(M)=PGRAD(M)
  910 CONTINUE
      GOTO 960
  920 WRITE(2,930)IRUN
      WRITE(10,930)IRUN
  930 FORMAT(' *****NO CIRCLE SOLUTION AT ITERATION=',I4)
      WRITE(2,*)'***************TRY AGAIN***************'
      WRITE(10,*)'***************TRY AGAIN***************'
      GOTO 170

C*****************************************************************
C CALCULATION OF NEW VORTICIES
C*****************************************************************
  960 SOLD(N)=-1.0*SOL(N)
      DO 1120 M=N-1,1,-1
      IF(M.GT.NC) GOTO 1110
  990 D4=SOLD(M+1)**2-2.0*LEN(M)*PGRADD(M)
      IF(D4.LT.0.0) GOTO 1040
      SOLD(M)=SQRT(D4)
      WRITE(2,*)M,PGRADD(M),SOLD(M)
      WRITE(10,*)M,PGRADD(M),SOLD(M)
      GOTO 1120
```

Listing of file .GRADMOD by LF 4 on 17 APR 1984 at 14:55:48

```
 1040 IF(IPRO.EQ.1) GOTO 1140
      D5=SOLD(M+1)**2/(2.0*LEN(M))
      D6=D5/1000
      PGRADD(M)=D5-D6
      IF(M.EQ.1) PGRADD(M)=D5
      WRITE(2,*)D5
      WRITE(10,*)D5
      IF(PGRADD(M).LT.0.0) GOTO 1130
      GOTO 990
 1110 SOLD(M)=-1.0*SOL(M)
 1120 CONTINUE
      GOTO 1200
 1130 WRITE(2,*)'*****PRESSURE GRADIENT HAS BECOME -VE BY REDUCTION'
 1140 WRITE(2,1150)
      WRITE(10,1150)
 1150 FORMAT(' *****NO VORTICITY DISTRIBUTION FOR THESE CONDITIONS')
      IF(ICH.NE.3) GOTO 1180
      WRITE(2,*)THETA,YTE
      WRITE(10,*)THETA,YTE
      GOTO 1190
 1180 WRITE(2,*)NC,YTE
      WRITE(10,*)NC,YTE
 1190 WRITE(2,*)'***************TRY AGAIN***************'
      WRITE(10,*)'***************TRY AGAIN***************'
      GOTO 170

C CALCULATION OF SOLD(N+1) & PGRADD(N)
 1200 SOLD(N+1)=-1.0*SOLD(1)
      PGRADD(N)=(SOLD(N+1)**2-SOLD(N)**2)/(2.0*LEN(N))
      WRITE(2,*)'PGRADD(N) IS:-'
      WRITE(2,*)PGRADD(N)
      WRITE(10,*)'PGRADD(N) IS:-'
      WRITE(10,*)PGRADD(N)

C CHOICE OF WHETHER TO KEEP THIS MODIFICATION
      WRITE(2,1210)
      WRITE(10,1210)
 1210 FORMAT(' !!!!!OKAY SO FAR? - 1=YES,0=NO!!!!!')
      READ(1,*)IO
      WRITE(10,*)IO
      IF(IO.EQ.0) GOTO 170

C CALCULATION OF TANGENTIAL VELOCITIES & PRESSURE COEFFICIENTS
C AT CONTROL PTS
      DO 1250 M=1,N
      VT(M)=ABS((SOLD(M)+SOLD(M+1))/2.0)
      CPC(M)=1.0-VT(M)**2
 1250 CONTINUE

C AT CORNER PTS
```

```
      DO 1280 M=1,N+1
      CP(M)=1.0-SOLD(M)**2
 1280 CONTINUE

C OUTPUT TO FILES
      WRITE(6,*)ANGLE,JP,NC
      WRITE(4,*)ANGLE
      WRITE(4,*)N
      DO 1350 M=1,N+1
      WRITE(6,*)SOLD(M),VT(M),CP(M),CPC(M),PGRADD(M)
      WRITE(4,*)X(M),Y(M),SOLD(M)
 1350 CONTINUE

C RETURN FOR ANOTHER ANGLE
      IF(IRUN.LT.NA) GOTO 120
      STOP
      END
```

```
Listing of file .LERR by LF 4 on 17 APR 1984 at 14:55:08
File created on WED 22 FEB 1984  :  file last modified on TUE 13 MAR 1984

C*****************************************************************
C PROGRAMM TO CALCULATE LEADING EDGE ERRORS
C WRITTEN BY A.NIVEN
C FEB 1984
C*****************************************************************

      REAL SOLM(70),VTM(70),CPM(70),CPCM(70),PGRADM(70)
      REAL SOLA(70),VTA(70),CPA(70),CPCA(70),PGRADA(70)
      REAL SERR(70),CERR(70),PERR(70),XA(70),XCA(70)
      TSAVE=0.
      TCAVE=0.
      TPAVE=0.

C READ IN PROFILE DATA:D IS A DUMMY ARGUMENT

      WRITE(2,*)'TYPE IN NC'
      READ(1,*)NC
      READ(3,*)N,NA
      WRITE(6,*)N,NC,NA
      DO 10 M=1,N+1
      READ(3,*)XA(M),XCA(M),D,D
   10 CONTINUE
      READ(5,*)N,NA
      DO 20 M=1,N+1
      READ(5,*)D,D,D,D
   20 CONTINUE

C START LOOP FOR EACH ANGLE

      IANG=0
   30 IANG=IANG+1

C READ IN VELOCITY DATA : M=MODIFIED:A=23012

      READ(3,*)ANGLE,JPM
      READ(5,*)D,JPA
      WRITE(6,*)ANGLE,JPM,JPA
      DO 50 M=1,N+1
      READ(3,*)SOLM(M),VTM(M),CPM(M),CPCM(M),PGRADM(M)
      READ(5,*)SOLA(M),VTA(M),CPA(M),CPCA(M),PGRADA(M)
   50 CONTINUE

C CALCULATE ERRORS

      DO 60 M=NC+1,N-NC
      SERR(M)=((ABS(SOLA(M))-ABS(SOLM(M)))*100.)/ABS(SOLA(M))
      CERR(M)=((ABS(CPA(M))-ABS(CPM(M)))*100.)/ABS(CPA(M))
      PERR(M)=((ABS(PGRADA(M))-ABS(PGRADM(M)))*100.)/ABS(PGRADA(M))
      WRITE(6,*)SERR(M),CERR(M),PERR(M),XA(M),XCA(M)
   60 CONTINUE
```

Listing of file .LERR by LF 4 on 17 APR 1984 at 14:55:08

```
      SAVE=0.
      CAVE=0.
      PAVE=0.
      DO 70 M=NC+1,N-NC
      SAVE=SAVE+ABS(SERR(M))
      CAVE=CAVE+ABS(CERR(M))
      PAVE=PAVE+ABS(PERR(M))
   70 CONTINUE
      T=FLOAT(N+1-2*NC)
      SAVE=SAVE/T
      CAVE=CAVE/T
      PAVE=PAVE/T
      WRITE(6,*)SAVE,CAVE,PAVE
      TSAVE=TSAVE+SAVE
      TCAVE=TCAVE+CAVE
      TPAVE=TPAVE+PAVE
      IF(IANG.LT.NA) GOTO 30
      A=FLOAT(NA)
      TSAVE=TSAVE/A
      TCAVE=TCAVE/A
      TPAVE=TPAVE/A
      WRITE(6,*)TSAVE,TCAVE,TPAVE
      STOP
      END
```

APPENDIX 3

```
Listing of file .SCREEN by LF 4 on 17 APR 1984 at 14:55:56
File created on MON 16 APR 1984  :  file last modified on MON 16 APR 1984

 THE MODIFICATION ANGLE IS=
  1.420000E+01          30
 (A)   CHOOSE:PARABOLA=1,STRAIGHT LINE=2,CIRCLE+LINE=3
          1
 (B)   CHOOSE:PGRAD RETURN=1,PGRAD REDUCTION=2
          1
 (C)   INPUT DOWNSTREAM BOUNDARY CONDITION PRESSURE GRAD
  1.670000E-01
 (D)   INPUT UPSTREAM BOUNDARY CONDITION CONTROL PT
          14
 (E)   PARABOLA T.E PRESSURE GRADIENT IS:-
  3.490386E-01
          14  3.031242E+00  1.613583E+00
          13  2.493320E+00  1.543398E+00
          12  2.194367E+00  1.474852E+00
          11  1.952983E+00  1.407532E+00
          10  1.741439E+00  1.341614E+00
           9  1.549046E+00  1.277518E+00
           8  1.370463E+00  1.215809E+00
           7  1.202630E+00  1.157156E+00
           6  1.043646E+00  1.102309E+00
           5  8.922615E-01  1.052076E+00
           4  7.476244E-01  1.007290E+00
           3  6.091375E-01  9.687672E-01
           2  4.763775E-01  9.372517E-01
           1  3.490386E-01  9.133447E-01
 PGRADD(N) IS:-
  4.600768E-01
 !!!!!OKAY SO FAR? - 1=YES,0=NO!!!!!
          1
 THE MODIFICATION ANGLE IS=
  1.420000E+01          30
 (A)   CHOOSE:PARABOLA=1,STRAIGHT LINE=2,CIRCLE+LINE=3
          2
 (B)   CHOOSE:PGRAD RETURN=1,PGRAD REDUCTION=2
          1
 (C)   INPUT DOWNSTREAM BOUNDARY CONDITION PRESSURE GRAD
  6.000000E-02
 (D)   INPUT UPSTREAM BOUNDARY CONDITION CONTROL PT
          13
          13  2.390054E+00  1.546369E+00
          12  2.231876E+00  1.476764E+00
          11  2.064754E+00  1.405590E+00
          10  1.889339E+00  1.333819E+00
           9  1.706328E+00  1.262598E+00
           8  1.516437E+00  1.193274E+00
           7  1.320409E+00  1.127427E+00
           6  1.119020E+00  1.066874E+00
           5  9.130607E-01  1.013644E+00
           4  7.033454E-01  9.699001E-01
```

Listing of file .SCREEN by LF 4 on 17 APR 1984 at 14:55:56

```
            3  4.907000E-01   9.377551E-01
            2  2.759694E-01   9.190137E-01
            1  6.000000E-02   9.148666E-01
 PGRADD(N) IS:-
  4.820266E-01
 !!!!!OKAY SO FAR? - 1=YES,0=NO!!!!!
            1
 THE MODIFICATION ANGLE IS=
  1.420000E+01          30
 (A)   CHOOSE:PARABOLA=1,STRAIGHT LINE=2,CIRCLE+LINE=3
            3
 (B)   CHOOSE:PGRAD RETURN=1,PGRAD REDUCTION=2
            1
 (C)   INPUT DOWNSTREAM BOUNDARY CONDITION PRESSURE GRAD
  3.200000E-01
 (D)   INPUT UPSTREAM BOUNDARY CONDITION CONTROL PT
           12
 (E)   UPSTREAM BOUNDARY CONDITION PT NC=  13
 (F)   INTERSECTION AT:-
  3.206354E-01  2.001260E+00
 (G)   CIRCLE CENTRE IS:-
  2.858650E+00  2.561993E+00
           13  2.390054E+00   1.546369E+00
           12  2.049975E+00   1.482559E+00
           11  1.852510E+00   1.419127E+00
           10  1.695100E+00   1.355554E+00
            9  1.555703E+00   1.291871E+00
            8  1.413174E+00   1.228931E+00
            7  1.266039E+00   1.167798E+00
            6  1.114881E+00   1.109671E+00
            5  9.602913E-01   1.055886E+00
            4  8.028830E-01   1.007893E+00
            3  6.432753E-01   9.671912E-01
            2  4.821026E-01   9.352367E-01
            1  3.200000E-01   9.132942E-01
 PGRADD(N) IS:-
  4.593484E-01
 !!!!!OKAY SO FAR? - 1=YES,0=NO!!!!!
            1
```