AD-A 128 041

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TECHNICAL REPORT ARBRL-TR-02485

GRID NETWORK GENERATION WITH ADAPTIVE BOUNDARY POINTS FOR PROJECTILES AT TRANSONIC SPEED

Chen-Chi Hsu

April 1983

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS
BEFORE COMPLETING FORM

1. REPORT NUMBER TECHNICAL REPORT ARBRL-TR-02485	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)

GRID NETWORK GENERATION WITH ADAPTIVE BOUNDARY
POINTS FOR PROJECTILES AT TRANSONIC SPEED

5. TYPE OF REPORT & PERIOD COVERED
Final

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
Chen-Chi Hsu

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
U.S. Army Ballistic Research Laboratory
ATTN: DRDAR-BLL
Aberdeen Proving Ground, Maryland 21005

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
1L161102AH43

11. CONTROLLING OFFICE NAME AND ADDRESS
US Army Armament Research & Development Command
US Army Ballistic Research Laboratory (DRDAR-BLA-S)
Aberdeen Proving Ground, MD 21005

12. REPORT DATE
April 1983

13. NUMBER OF PAGES
35

14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release, distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Computational Aerodynamics
Projectile Aerodynamics
Hyperbolic Grid System
Transonic Flow
Elliptic Grid System
Adaptive Boundary Grid Points

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The existing grid generation package GRIDGEN for projectile aerodynamics problems has been modified for an additional option to provide grid systems with adaptive boundary grid points. An improvement on hyperbolic grid generation is also made for more accurate finite-difference computations. The modifications made to GRIDGEN have been discussed and documented. The resulting package of computer programs named ADAPTGD has been tested successfully for generating a number of two-dimensional grid networks for a projectile.

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I. INTRODUCTION

In the field of computational mechanics it is well known that the accuracy of finite-difference approximations depends on the fineness of the grid system; moreover, the accuracy of solutions also depends upon the resolution of solution gradients. For use of a uniform grid system the local truncation error in the difference approximation to derivatives can be the largest at the location where the solution gradient is the largest. Hence, one can expect to obtain greater overall accuracy for the solution if more grid points are concentrated at places where the solution gradient is very large.

For a transonic viscous flow past a slender projectile with sting, the variation of the solution characteristics in the direction normal to the body surface is somewhat predictable qualitatively for most of the flow region; consequently, a rather well-suited grid size distribution in the normal direction can be predetermined and fixed. However, the solution characteristics of a transonic flow problem in the streamwise direction are more complex; the location of nearly normal shocks changes with the value of free-stream Mach number as well as with the number of iterations used in the process of convergence. It is known that in association with the formation of shock waves there exist extremely steep solution gradients. Therefore, a proper distribution of the boundary grid points can be very crucial to the accuracy of the computed forces acting on the projectile in transonic flows.

For an axisymmetric flow, the grid system generation code available at BRL can provide a good grid network for the transonic flow problem if the boundary grid points are properly generated. Presently, the boundary points required for the grid generation are specified and clustered in accordance with the user's intuition and experience; the resulting grid systems have provided accurate results for a number of different flow conditions. It seems, however, that the accuracy and efficiency of the solution method can be further improved if the boundary grid points required for grid generation are adaptively determined according to a relevant solution gradient distribution along the body surface. Moreover, for certain flow problems, the development of an adaptive boundary grid point generation is essential for improving the overall accuracy of solutions, for the maximum number of boundary points allowable in numerical simulation is often limited by the capacity of an existing computer system.

The objective of this development is to modify the existing grid generation code GRIDGEN so that the user will have an option to generate the boundary grid points adaptive to an input control function. The resulting grid generation code named ADAPTGD has been tested successfully.

II. IMPLEMENTATION TO GRIDGEN

In modifying GRIDGEN for adaptive boundary grid point generation, efforts have been made to minimize the changes. In fact, only insertions of executable statements are made to GRIDGEN; consequently, the resulting grid generation code ADAPTGD will make a number of unnecessary computations in the process of redistributing the boundary grid points. A substantial modification not related to the adaptive boundary grid generation has been made to subroutine

RHS (---) so that the resulting hyperbolic grid system exhibits more desirable characteristics for finite-difference computations. The modifications made to GRIDGEN and the relevant information required for using ADAPTGD are described and discussed in the following sections.

A. Input Data

In order to run the grid generation code ADAPTGD, the user must provide two data cards in addition to the regular input data file for GRIDGEN at the very beginning of the input data file. The data cards provide information and instruction for the redistribution of boundary grid points. Definition and comments for the input data can be found in the first part of the program MAIN in ADAPTGD. A listing is provided in Appendix A.

B. Program MAIN

Only insertions of executable statements have been made to the program MAIN of GRIDGEN. The first two executable statements now read the two additional input data cards. The program then continues as before to generate inner boundary grid points by calling appropriate subroutines. However, the generated boundary grid points will be overridden if the user calls for an adaptive boundary grid point generation.

In order to generate adaptive boundary grid points, a tape or file FOR007 which contains the grid points to be redistributed as well as the control function (e.g., pressure) at grid points must be provided. The tape FOR007 must be written in the format

```
FORMAT (1H ,I5,5E15.7)
```

and contains, in order, the variables

J, XX(J), YY(J), XS(J), YS(J), FF(J)

where XX(J) and YY(J) are the coordinates of Jth grid point on the inner boundary, while XS(J) and YS(J) are those of the outer boundary. FF(J) is the value of the control function (e.g., computed pressure on the body) at Jth node. The redistribution of the inner boundary grid points and the outer boundary grid points are determined according to a linear function of the gradient of FF(J) by calling the subroutine HADAPT (---), which is described in Section III. Note that the same control function is used for both inner and outer boundary grid points redistribution.

C. Subroutine OUTER (---)

In GRIDGEN the subroutine OUTER is called upon to generate outer boundary grid points for elliptic grid generation. If adaptive boundary grid points are called for a grid generation, then the call for subroutine OUTER can be avoided. In order to maintain the versatility of ADAPTGD to reproduce the capability of GRIDGEN as well as to maintain the format of input data file used in GRIDGEN, the call for subroutine OUTER by subroutine ELPGRD has not been modified; however, if an adaptive boundary grid point distribution is called for a grid generation, then the final computation for XS(J) and YS(J) in subroutine OUTER is bypassed. Hence, the adaptive outer boundary grid points generated earlier are intact for an elliptic grid generation. Only one COMMON statement and one IF statement have been added to the original subroutine OUTER.

III. SUBROUTINE HADAPT (F, X, Y, JI, JE)

The subroutine HADAPT (---) is developed for the redistribution of nodal points (X(J), Y(J)) on a segment of curve (e.g., inner or outer boundary) between nodes JI and JE according to the characteristics of an input control function F(J) along the curve. The redistribution of the nodal points can be iterated for INO times; the iteration is desirable if the discrete value of the control function is used for determining the new nodal point distribution. Consequently, an interpolation function subprogram ATKN (---) has been called by subroutine HADAPT to provide more accurate values for F(J) at the new location. Note that INO = 3 has been set in the current version of subroutine HADAPT, which has been found by a number of numerical experiments to be a good choice.

The theoretical background for the subroutine HADAPT (---) is briefly given in the following. Let s be the distance measured along a curve in xy-plane. Assume that a segment of the curve is divided into n elements with node at s_i or (x_i, y_i) for i = 1, 2, ..., n+1. Suppose that f(s) is the control function for element size distribution on the segment, in the sense that higher resolutions are required for higher gradient of f(s). It is then assumed in subroutine HADAPT (---) that the element size must be inversely proportional to a linear function of $\frac{df}{ds}$ for an adaptive nodal point distribution. Therefore, one has

$$\Delta s_j \equiv s_{j+1} - s_j = \frac{\alpha}{1 + \beta\left(\frac{df}{ds}\right)_j} \equiv \alpha\, w_j \tag{1}$$

where α is the proportional constant and β is the weight parameter for the gradient of control function f(s).

The proportional constant α is determined by equating the sum of n elements to the total segment length. Hence, one obtains

$$\alpha = (s_{n+1} - s_1) / \sum_{j=1}^{n} w_j \tag{2}$$

With the input data $f_i \equiv f(s_i)$ and (x_i, y_i) at nodes, the gradient of f(s) for a given element Δs_j can be approximated by

$$\left(\frac{df}{ds}\right)_j \approx (f_{j+1} - f_j)/\Delta s_j, \ \Delta s_j = [(x_{j+1} - x_j)^2 + (y_{j+1} - y_j)^2]^{1/2} \qquad (3)$$

The value for $\beta \equiv BW$ can be selected by the user. It is clear that a constant element size distribution will result if one chooses to set $\beta \equiv BW = 0$. It is mentioned in passing that the ratio of the largest element to the smallest element increases with increasing value of β. A value of $\beta \rightarrow BW = 5.0$ has been set in the current version of the program. Note that higher resolutions for the highest gradient region can be achieved by taking a larger value of β, but then poor resolutions will result in the smallest gradient region if the number of nodal points on the line segment of interest is fixed.

The function subprogram ATKN (---) called by subroutine HADAPT (---) is a general purpose interpolation program for one-dimensional problems. Both subprograms HADAPT (---) and ATKN (---) which are placed at the end of ADAPTGD package are also given in Appendix A for reference.

IV. OTHER MODIFICATION TO GRIDGEN

The hyperbolic grid network generated from GRIDGEN for a projectile has some undesirable characteristics in the region upstream of the nose. For example, Figure 1 shows rather large grid sizes upstream of a projectile nose and, consequently, poor orthogonal characteristics at the line of symmetry result. The objective of this modification is then to reduce the size of those large grids as well as to improve their orthogonal property at the line of symmetry.

In GRIDGEN the subroutine RHS (---) is called upon by subroutine HYPGRD (---) to provide the right-hand side of the reduced finite difference equations for hyperbolic grid generation. The subroutine RHS (---) has been modified, after a number of numerical experiments, by introducing a weight function for controlling the area of the grid network. With the same input data of Figure 1, the modified GRIDGEN produces a hyperbolic grid network shown in Figure 2. It is clear that the modified subroutine RHS (---) does give a more desirable hyperbolic grid network for projectile aerodynamics computations.

V. GRID NETWORK GENERATED BY ADAPTGD PACKAGE

The modified GRIDGEN named ADAPTGD has been tested successfully for generating a number of two-dimensional grid networks for a projectile. In these numerical experiments the same tape file FOR007, which is given in Table 1, for controlling the boundary grid point distribution has been employed. The control function FF(J) used is the discrete value of a computed pressure coefficient distribution on a projectile and the size of grid network chosen is 60 by 28. Two of the grid networks generated are presented and discussed briefly in the following.

An elliptic grid network generated with the adaptive boundary grid points is shown in Figures 3(a) and 3(b). The input data used for the grid system are given in Table 2. Recall that only the first two lines of the data file are new to the data file for GRIDGEN. In the first line the first integer "1" implies that adaptive boundary grid points are called for the grid network generation while the second integer "4" indicates that there are four segments of boundary grid points with segment end points fixed to be redistributed. The starting point and the ending point of each segments selected for redistribution are specified in the second line of the input data file. As indicated in the input data file, the first four boundary points from the nose of the projectile have not been moved; it shows that the user can choose rather arbitrarily any segments of boundary points for redistribution.

The same input data have also been employed to generate a hyperbolic grid network with adaptive boundary points; the resulting grid network is given in Figures 4(a) and 4(b) for reference. The comparison of Figure 4(b) against Figure 3(b) shows clearly that the hyperbolic network has better overall orthogonality characteristics which can be advantageous to the accuracy of solutions to be obtained in the transformed space.

VI. CONCLUSIONS

The modification of GRIDGEN for generating grid networks with adaptive boundary grid points specified has been described. The resulting package of computer programs named ADAPTGD has been tested successfully for two-dimensional straight ray grid systems, elliptic grid systems and hyperbolic grid systems. It should be pointed out again that in ADAPTGD the same input control function has been employed to redistribute the inner boundary points as well as the outer boundary points for generating an elliptic grid network.

The modification made to subroutine RHS (---) for a hyperbolic grid generation seems to have made the hyperbolic grid network competitive to the elliptic grid network. An axisymmetric transonic flow past a projectile is being solved with an elliptic grid system similar to the one shown in Figure 3(a) as well as with a hyperbolic grid system similar to that shown in Figure 4(a). The results obtained under the same conditions and at iteration number = 1000 show that both grid systems give the pressure coefficient distribution of the same order of accuracy. A straight ray grid system had also been used for the flow problem; however, a number of difficulties had been encountered, apparently due to large truncation errors resulted from high skewness of the grid system.

For the application of ADAPTGD, the required input data tape FOR007 for adaptive boundary grid point generation can be created in the computer program package for the governing equations of the flow problem. For example, in the axisymmetric thin-layer Navier-Stokes code, the tape FOR007 can be created in the main program of the package.

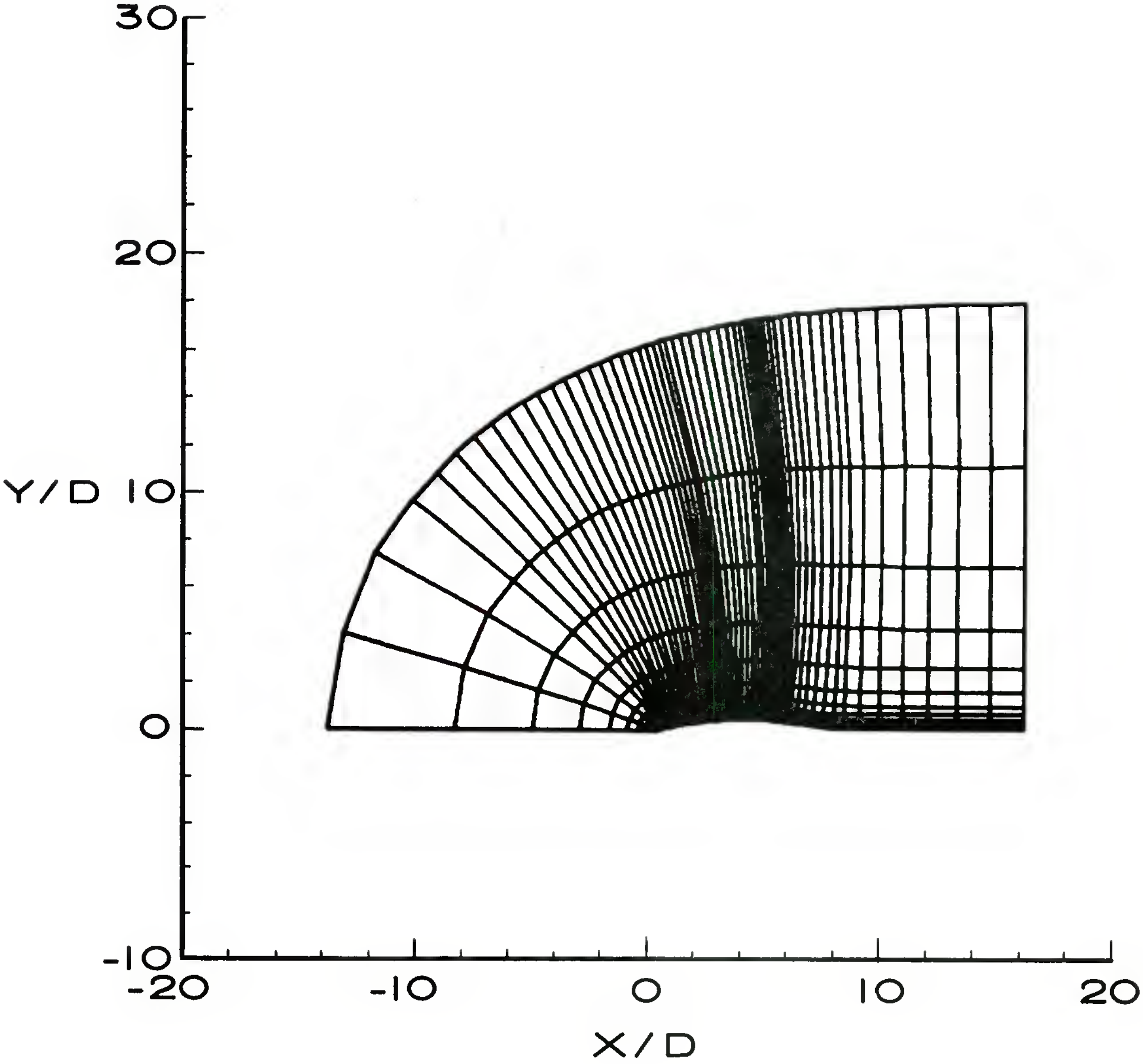

Figure 1. A Hyperbolic Grid Network Obtained from Original GRIDGEN

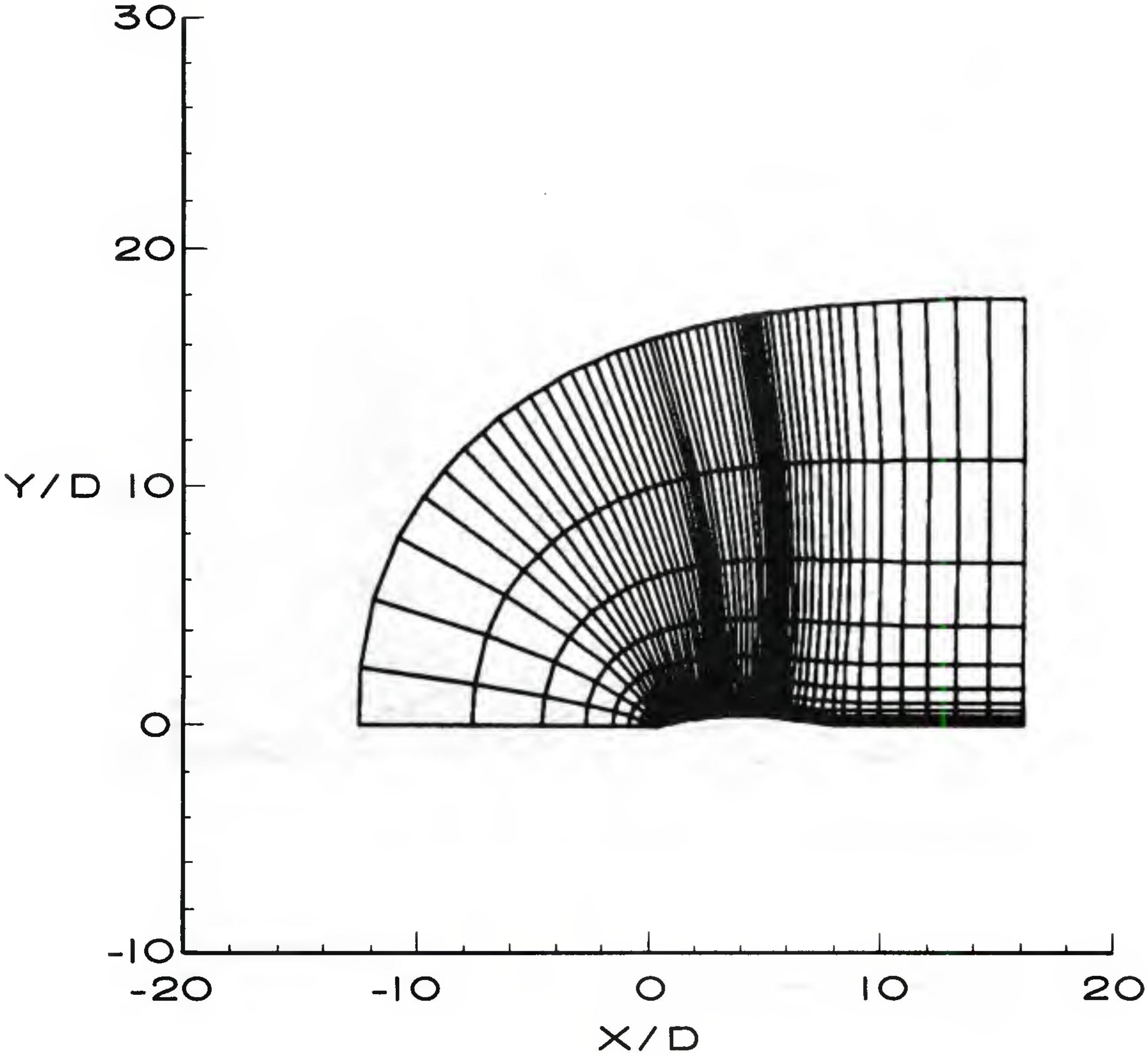

Figure 2. A Hyperbolic Grid Network Obtained from Modified GRIDGEN

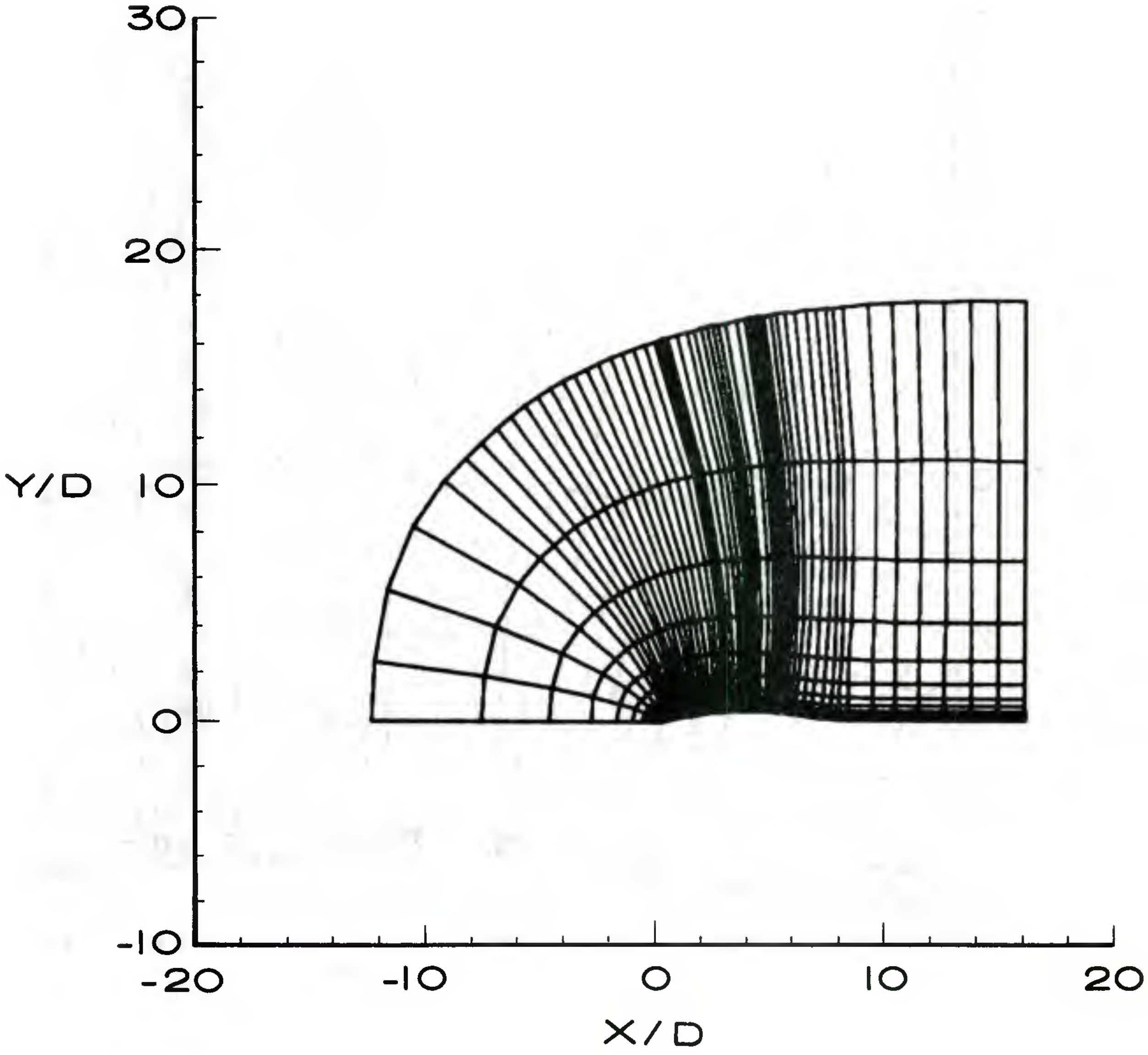

Figure 4a. A Hyperbolic Grid Using ADAPTGD - Total Flow Field

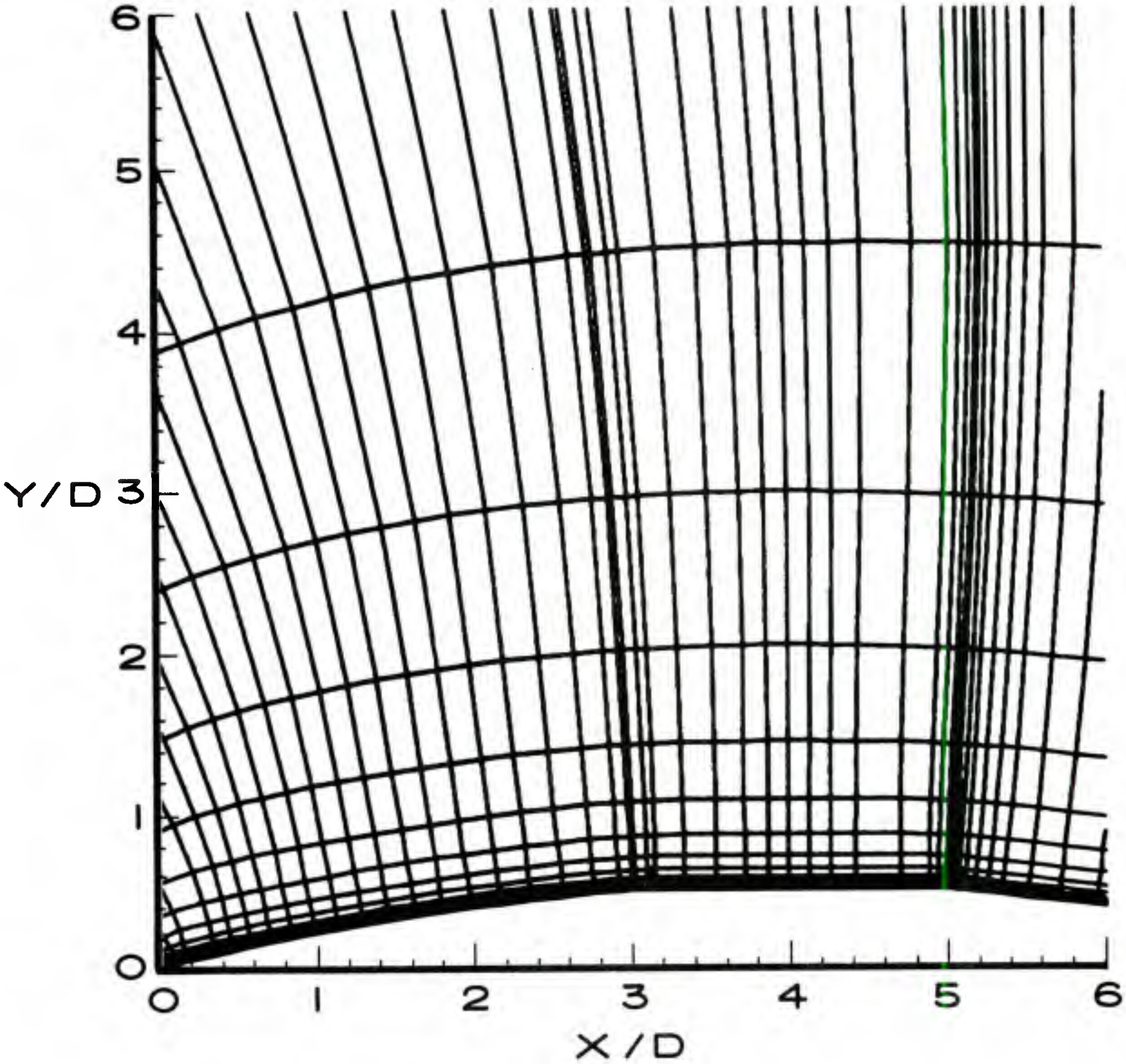

Figure 4b. Detailed Hyperbolic Grid Near Body Surface

TABLE 1. DATA FILE FOR007 FOR ADAPTIVE BOUNDARY GRID POINT DISTRIBUTION

J	XX(J)	YY(J)	XS(J)	YS(J)	FF(J)
1	0.3903E-01	0.5394E-05	-0.1800E+02	0.0000E+00	0.5133E+00
2	0.4903E-01	0.1305E-01	-0.1799E+02	0.1010E+00	0.3318E+00
3	0.9390E-01	0.2409E-01	-0.1799E+02	0.5755E+00	0.1522E+00
4	0.1701E+00	0.4258E-01	-0.1796E+02	0.1381E+01	0.2076E+00
5	0.2744E+00	0.6732E-01	-0.1789E+02	0.2485E+01	0.2075E+00
6	0.4033E+00	0.9702E-01	-0.1773E+02	0.3846E+01	0.1793E+00
7	0.5532E+00	0.1303E+00	-0.1743E+02	0.5414E+01	0.1396E+00
8	0.7208E+00	0.1661E+00	-0.1695E+02	0.7132E+01	0.1010E+00
9	0.9026E+00	0.2032E+00	-0.1623E+02	0.8928E+01	0.6669E-01
10	0.1095E+01	0.2404E+00	-0.1521E+02	0.1071E+02	0.3519E-01
11	0.1295E+01	0.2768E+00	-0.1390E+02	0.1238E+02	0.7091E-02
12	0.1499E+01	0.3117E+00	-0.1230E+02	0.1385E+02	-0.1890E-01
13	0.1703E+01	0.3444E+00	-0.1050E+02	0.1507E+02	-0.4226E-01
14	0.1905E+01	0.3743E+00	-0.8582E+01	0.1603E+02	-0.6226E-01
15	0.2100E+01	0.4012E+00	-0.6629E+01	0.1674E+02	-0.7971E-01
16	0.2285E+01	0.4248E+00	-0.4720E+01	0.1724E+02	-0.9396E-01
17	0.2457E+01	0.4450E+00	-0.2920E+01	0.1757E+02	-0.1058E+00
18	0.2612E+01	0.4619E+00	-0.1280E+01	0.1778E+02	-0.1154E+00
19	0.2747E+01	0.4756E+00	0.1533E+00	0.1791E+02	-0.1268E+00
20	0.2858E+01	0.4861E+00	0.1337E+01	0.1797E+02	-0.1472E+00
21	0.2943E+01	0.4937E+00	0.2231E+01	0.1799E+02	-0.1916E+00
22	0.2997E+01	0.4983E+00	0.2805E+01	0.1799E+02	-0.2839E+00
23	0.3017E+01	0.5000E+00	0.3016E+01	0.1800E+02	-0.3720E+00
24	0.3047E+01	0.5000E+00	0.3046E+01	0.1800E+02	-0.4440E+00
25	0.3141E+01	0.5000E+00	0.3142E+01	0.1800E+02	-0.4150E+00
26	0.3288E+01	0.5000E+00	0.3290E+01	0.1800E+02	-0.3793E+00
27	0.3476E+01	0.5000E+00	0.3479E+01	0.1800E+02	-0.3468E+00
28	0.3692E+01	0.5000E+00	0.3697E+01	0.1800E+02	-0.2998E+00
29	0.3925E+01	0.5000E+00	0.3932E+01	0.1800E+02	-0.2241E+00
30	0.4161E+01	0.5000E+00	0.4171E+01	0.1800E+02	-0.1311E+00
31	0.4391E+01	0.5000E+00	0.4402E+01	0.1800E+02	-0.5567E-01
32	0.4600E+01	0.5000E+00	0.4614E+01	0.1800E+02	-0.2570E-01
33	0.4778E+01	0.5000E+00	0.4793E+01	0.1800E+02	-0.4884E-01
34	0.4912E+01	0.5000E+00	0.4928E+01	0.1800E+02	-0.1325E+00
35	0.4990E+01	0.5000E+00	0.5006E+01	0.1800E+02	-0.3496E+00
36	0.5000E+01	0.5000E+00	0.5016E+01	0.1800E+02	-0.4080E+00
37	0.5010E+01	0.4987E+00	0.5026E+01	0.1800E+02	-0.4410E+00
38	0.5019E+01	0.4975E+00	0.5036E+01	0.1800E+02	-0.4734E+00
39	0.5034E+01	0.4957E+00	0.5050E+01	0.1800E+02	-0.5000E+00
40	0.5057E+01	0.4928E+00	0.5072E+01	0.1800E+02	-0.4621E+00
41	0.5095E+01	0.4882E+00	0.5108E+01	0.1800E+02	-0.4096E+00
42	0.5151E+01	0.4814E+00	0.5163E+01	0.1800E+02	-0.3527E+00
43	0.5230E+01	0.4716E+00	0.5241E+01	0.1800E+02	-0.2917E+00
44	0.5338E+01	0.4584E+00	0.5346E+01	0.1800E+02	-0.2240E+00
45	0.5478E+01	0.4412E+00	0.5485E+01	0.1800E+02	-0.1611E+00
46	0.5655E+01	0.4194E+00	0.5660E+01	0.1800E+02	-0.1022E+00
47	0.5875E+01	0.3925E+00	0.5878E+01	0.1800E+02	-0.4348E-01
48	0.6141E+01	0.3598E+00	0.6143E+01	0.1800E+02	-0.8539E-02
49	0.6458E+01	0.3208E+00	0.6460E+01	0.1800E+02	0.2258E-01
50	0.6832E+01	0.2749E+00	0.6833E+01	0.1800E+02	0.3760E-01

ETC.

TABLE 2. INPUT DATA FOR GENERATING FIGURE 3a BY ADAPTGD

```
   1    4                                                         ADAPT1
   4   25   25   44   44   53   53   60                           ADAPT2
   0    0   20   20                                               000001
  60   28    0  18.       .00002                                  000002
  -1   52    0    3                                               000003
  1.       1.0                                                    000004
 0.       3.017     5.0       7.76722   .5        -7.       1.    000005
 18.88    0.025     4.58                                          000006
   1   23  0.       3.017     .01       .02                       000007
  23   36  3.017    5.0       .03       .01                       000008
  36   52  5.0      7.76722   .010      .5                        000009
   1                                                              000010
   9   -1                                                         000011
   1                                                              000012
 7.76722  .16023    16.0      .16023                              000013
   1    9  7.76722  16.0      .5        1.5                       000014
   2    4                                                         000015
-18.0     0.0      3.017     18.       90.       0.               000016
 3.017    18.0     16.       18.       0.        0.               000017
   1   23  0.0      31.69825  0.1       .21                       000018
  23   36 31.69825 33.69825  .03       .01                        000019
  36   52 33.69825 36.44847  .01       .5                         000020
  52   60 36.44847 44.68125  .5        1.5                        000021
  28   99   -1    0    1    1                                     000022
 .00002   1.7                                                     000023
   1   25                                                         000024
                                                                  000025
                                                                  000026
```

APPENDIX A

Partial Program Listing

APPENDIX A. PARTIAL PROGRAM LISTING

The implementation and modification made to the grid generation package GRIDGEN are given in this Appendix. Note that the additions made are given between the comment statements CCHSU while the deletion made in Subroutine RHS (---) are commented with CCH.

The Subroutine HADAPT (---) developed for redistribution of points along a curve and a general purpose interpolation program ATKN (---) are also given in the Appendix for references.

```
      PROGRAM MAIN                                                       MAIN
      COMMON JMAX, KMAX, JM, KM, NBOD, JBOD                              MAIN
      COMMON /BOUDY/ XX(100), YY(100), XS(100), YS(100), SS(100), S(100) MAIN
     1   , T(100), TS(100)                                               MAIN
      COMMON /GRID/ X(80,60), Y(80,60)                                   MAIN
CCHSU
      COMMON/PYHSU/IADAPT
      DIMENSION IE(8),FF(100)
      READ (5,100) IADAPT, NSADT
      READ (5,100) IE(1),IE(2),IE(3),IE(4),IE(5),IE(6),IE(7),IE(8)
C  IADAPT=0 FOR REGULAR GRID GENERATION--GRIDGEN!
C  IADAPT=1 FOR ADAPTIVE BOUNDARY GRID POINT GENERATION
C           CONTROL DATA TO BE READ FROM FOR007
C  NSADT IS THE NO. OF BOUNDARY SEGMENTS TO BE CONSIDERED FOR REDISTRIBUTION
C        NSADT .LE. 4 IN THIS PROGRAM
C  IE(K) ARE END NODAL NO. OF NSADT SEGMENTS. FOR EXAMPLE, THE FIRST SEGMENT
C        IS BOUNDED WITH IE(1) AS THE INITIAL NODE AND ENDED WITH IE(2)
C        IF NSADT = 3, THEN ANY NUMBER CAN BE ASSIGNED TO IE(7) AND IE(8)
CCHSU
C                                                                        MAIN
C  I3D = 0 FOR 2D, NO SPIN                                               MAIN
C  I3D = 1 FOR 3D, SYM3 HALF SPIN                                        MAIN
C  I3D = 2 FOR 3D, FULL3D FULL SPIN                                      MAIN
C                                                                        MAIN
C  ISOLV = 0 FOR ELLIPTIC SOLVER                                         MAIN
C  ISOLV = 1 FOR HYPERBOLIC SOLVER                                       MAIN
C                                                                        MAIN
      READ (5,100) ISOLV,I3D,ND,LMAX                                     MAIN
      WRITE (6,70) ISOLV,I3D,ND,LMAX                                     MAIN
C                                                                        MAIN
C  READ JMAX,KMAX,IDAT,STOT,CDS FOR HYPGRD SOLVER                        MAIN
C    IDAT = 0 FOR INPUT PTS OR ANALYTIC SHAPE                            MAIN
C    IDAT = 1 FOR INPUT PTS ON "CARDS"                                   MAIN
C    IDAT = 2 FOR INPUT PTS ON XYFILE (TAPE7)                            MAIN
C    STOT = -1. FOR CONSTANT DS                                          MAIN
C .                                                                      MAIN
      READ (5,80) JMAX,KMAX,IDAT,STOT,CDS                                MAIN
      WRITE (6,90) JMAX,KMAX,IDAT,STOT,CDS                               MAIN
      JM=JMAX-1                                                          MAIN
      KM=KMAX-1                                                          MAIN
      IF (IDAT.EQ.0) GO TO 10                                            MAIN
      IF (IDAT.EQ.1) CALL INPCD                                          MAIN
      IF (IDAT.EQ.2) CALL XYFILE                                         MAIN
      GO TO 20                                                           MAIN
   10 CONTINUE                                                           MAIN
C                                                                        MAIN
C   DISTRIBUTE POINTS ALONG INNER BOUNDARY                               MAIN
      WRITE (6,110)                                                      MAIN
      CALL BODY                                                          MAIN
      READ (5,100) NFLAG                                                 MAIN
      IF (NFLAG.LT.0) GO TO 60                                           MAIN
      READ (5,100) NCGRD,NCART                                           MAIN
      WRITE (6,120) NCGRD,NCART                                          MAIN
```

```
      IF (NCGRD.GT.0) CALL STING (NCGRD)                                MAIN
      IF (NCART.GT.0) CALL CARTB (NCART)                                MAIN
CCHSU
      IF (IADAPT .EQ. 0) GO TO 19
   11 FORMAT(1H ,I5,5E15.7)
      DO 12 I=1,JMAX
   12 READ (7,11) J,XX(I),YY(I),XS(I),YS(I),FF(I)
      I1=1
      DO 13 NS=1,NSADT
      I2=I1+1
      JI=IE(I1)
      JE=IE(I2)
      CALL HADAPT(FF,XX,YY,JI,JE)
      IF (ISOLV .EQ. 1) GO TO 13
      CALL HADAPT(FF,XS,YS,JI,JE)
   13 I1=I1+2
   19 CONTINUE
CCHSU
CCHSU
      JMAX=JBOD                                                         MAIN
      JM=JMAX-1                                                         MAIN
      WRITE (6,130) JMAX                                                MAIN
   20 WRITE (6,140)                                                     MAIN
      DO 30 J=1,JMAX                                                    MAIN
      WRITE (6,150) J,XX(J),YY(J)                                       MAIN
   30 CONTINUE                                                          MAIN
C                                                                       MAIN
      IF (ISOLV.EQ.0) CALL ELPGRD                                       MAIN
      IF (ISOLV.EQ.1) CALL INITIA                                       MAIN
      IF (ISOLV.EQ.1) CALL HYPGRD (STOT,CDS,IER)                        MAIN
      IF (ISOLV.EQ.1.AND.IER.NE.0) GOTO 60                              MAIN
C                                                                       MAIN
C       FORM 3D GRID.   LMAX IS CIRCUMFERENTIAL DIRECTION               MAIN
      IF (I3D .EQ. 2) CALL SPNFUL (I3D,ND,LMAX)                         MAIN
      IF (I3D .EQ. 1) CALL GSPIN (I3D,ND,LMAX)                          MAIN
   60 STOP                                                              MAIN
C                                                                       MAIN
   70 FORMAT (1H1,21H ISOLV, I3D, ND, LMAX,4I5)                         MAIN
   80 FORMAT (3I5,2F10.0)                                               MAIN
   90 FORMAT (1H0,27HJMAX, KMAX, IDAT, STOT, CDS,3I5,2F10.5)            MAIN
  100 FORMAT (8I5)                                                      MAIN
  110 FORMAT (/1H0,36H++++++++++ INNER BOUNDARY ++++++++++)             MAIN
  120 FORMAT (1H0,13H NCGRD,NCART ,2I5)                                 MAIN
  130 FORMAT (1H0,21H FINAL VALUE OF JMAX ,I5)                          MAIN
  140 FORMAT (1H0,43H FINAL VALUES OF J,X,Y ALONG INNER BOUNDARY)       MAIN
  150 FORMAT (1H ,I5,2F13.6)                                            MAIN
  160 FORMAT (I5,6F12.5)                                                MAIN
      END                                                               MAIN
```

```
      SUBROUTINE OUTER (NSEGS,IOUTD)                                    OUTER
      COMMON JMAX, KMAX, JM, KM, NBOD, JBOD                             OUTER
      COMMON /BOUDY/ XX(100), YY(100), XS(100), YS(100), SS(100), S(100) OUTER
     1  , T(100), TS(100)                                               OUTER
      COMMON /COMP/ X(100), Y(100)                                      OUTER
      COMMON /ARRAY/ A(100), B(100), C(100), D(100), F(100), H(100)     OUTER
CCHSU
      COMMON/PYHSU/IADAPT
CCHSU
C                                                                       OUTER
C   THIS PROGRAM FORMS AN OUTER GRID BOUNDARY USING CONTIGUOUS CUBIC    OUTER
C   SEGMENTS. NUMBER OF SEGMENTS IS NSEGS.  POINT AND SLOPE ARE INPUT AT OUTER
C   THE ENDS OF A SEGMENT.  SLOPE IS AN ANGLE IN DEGRESS. PARAMETRIC    OUTER
C   CUBICS  USED TO PERMIT ANY SLOPE  (THETA = 90, -90, ETC). INITIAL   OUTER
C   LOGIC DETERMINES CUBIC COEFFICIENTS OF EACH SEGMENT. REMAINING      OUTER
C   LOGIC DISTRIBUTES POINTS ALONG OUTER BOUNDARY USING ARC LENGTH      OUTER
C   AS DISTRIBUTION FUNCTION. THUS TWO PARAMETRIC VARIABLES ARE USED.   OUTER
C   FINDING X.Y SO CUBIC SEGMENTS CAN BE DISJOINT IN SLOPE IS MESSY     OUTER
C   A SINGLE SPLINE INTERPOLATION CANNOT BE USED OVER THE COMBINED      OUTER
C   SEGMENTS BECAUSE OF POSSIBLE SLOPE DISCONTINUITY.                   OUTER
C                                                                       OUTER
      DIMENSION JA(8), JB(8)                                            OUTER
      DIMENSION CA0(8), CA1(8), CA2(8), CB0(8), CB1(8), CB2(8), CARC(8) OUTER
      DO 110 N=1,NSEGS                                                  OUTER
C   POINTS AND SLOPES,  -90 .LE.  THETA  .LE. 90    DEGREES USED        OUTER
      READ (5,240) X0,Y0,X1,Y1,TH0,TH1                                  OUTER
      WRITE (6,250) X0,Y0,X1,Y1,TH0,TH1                                 OUTER
      RTH0=0.017453292*TH0                                              OUTER
      RTH1=0.017453292*TH1                                              OUTER

          .
          .
          .

  190 CONTINUE                                                          OUTER
CCHSU
      IF (IADAPT .EQ. 1) GO TO 220
CCHSU
C                                                                       OUTER
C   FORM PARAMETRIC ARRAYS,FROM DISTRIBUTED PARAMETRIC ARRAY,           OUTER
C   USE IT TO DETERMINE X,Y WITHIN A OUTER SEGMENT CURVE.               OUTER
C   SPLINE REQUIRES ABOUT 5 POINTS IN AN INTERVAL                       OUTER
      S(1)=0.                                                           OUTER

          .
          .
          .

      END                                                               OUTER
```

```
      SUBROUTINE RHS (K,SY,M,N)                                         RHS
      COMMON JMAX, KMAX, JM, KM, NBOD, JBOD                             RHS
      COMMON /TRXE/ XXSI(100), YXSI(100), XADA(100), YADA(100)          RHS
      COMMON /GRID/ X(80,60), Y(80,60)                                  RHS
      COMMON /VOL/ V(100), VSTAR(100), DS(60)                           RHS
      DIMENSION SY(160)                                                 RHS
C   FILL RIGHT-HAND-SIDE VECTOR FOR HYPER SOLVER                        RHS
      MSY=1                                                             RHS
      DO 10 J=1,JMAX                                                    RHS
      SY(MSY)=XXSI(J)*X(J,K)+YXSI(J)*Y(J,K)                             RHS
      SY(MSY+1)=-(YXSI(J))*X(J,K)+XXSI(J)*Y(J,K)+V(J)+VSTAR(J)          RHS
      MSY=MSY+2                                                         RHS
   10 CONTINUE                                                          RHS
C   FRACTION OF EXPLICIT DISSIPATION THAT IS NOT PUT IN                 RHS
C   IMPLICITLY                                                          RHS
      EPS=.02                                                           RHS
C   CAUTION -- EPS IS ALSO SET IN SUBROUTINE MATRX                      RHS
CCH   JMM=JM-1                                                          RHS
CCH   DO 20 J=3,JMM                                                     RHS
CCH   MSY=2*J-1                                                         RHS
CCH   SCALE=EPS*SQRT(XADA(J)**2+YADA(J)**2)                             RHS
CCH   XX=X(J-2,K)-2.*(X(J-1,K)+X(J+1,K))+2.*X(J,K)+X(J+2,K)             RHS
CCH   YY=Y(J-2,K)-2.*(Y(J-1,K)+Y(J+1,K))+2.*Y(J,K)+Y(J+2,K)             RHS
CCH   SY(MSY)=SY(MSY)-SCALE*(XXSI(J)*XX+YXSI(J)*YY)                     RHS
CCH   SY(MSY+1)=SY(MSY+1)-SCALE*(-YXSI(J)*XX+XXSI(J)*YY)                RHS
CCH20 CONTINUE                                                          RHS
CCHSU
      L=1
      DO 30 J=1,JMAX
      AJ=J
      SCALE=EPS*SQRT(XADA(J)**2+YADA(J)**2)
      IF (J .EQ. 1) GO TO 31
      IF (J .EQ. JMAX) GO TO 32
      XX=X(J+1,K)-2.*X(J,K)+X(J-1,K)
      YY=Y(J+1,K)-2.*Y(J,K)+Y(J-1,K)
      GO TO 35
   31 XX=2.*X(J+1,K)-2.*X(J,K)
      YY=0.
      GO TO 35
   32 XX=0.
      YY=-2.*Y(J,K)+2.*Y(J-1,K)
   35 CONTINUE
      SY(L)=SY(L)-SCALE*(XXSI(J)*XX+YXSI(J)*YY)
      CHEN=(1.-60./AJ)
      IF (J .LT. 4) CHEN=(1.-(100.-AJ*10.)/AJ)
      SY(L+1)=SY(L+1)-SCALE*(-YXSI(J)*XX+XXSI(J)*YY)*CHEN
   30 L=L+2
CCHSU
      RETURN                                                            RHS
      END                                                               RHS
```

```
      SUBROUTINE HADAPT(FF,XX,YY,JI,JE)
C   FF(I) IS A FUNCTION OF BOUNDARY COORDINATE SUCH AS PRESSURE DISTRIBUTION
C      ON A PROJECTILE; ITS GRADIENT IS USED FOR REDISTRIBUTION OF THE
C      BOUDARY GRID POINTS
C   XX(I) AND YY(I) ARE (X,Y) OF THE GIVEN BOUDARY POINTS
C   JI IS THE INITIAL NODAL NUMBER WHILE JE IS THE END NODAL NUMBER
C   NOTE THAT THE BOUNDARY POINTS BETWEEN I=JI AND I=JE ARE TO BE REDISTRIBUTED
      DIMENSION FF(100),XX(100),YY(100),SX(100),SY(100),SF(100),FO(10
     10),DS(100),TX(100),TY(100),TF(100),DT(99),G(99),W(99),XO(100)
      N=JE-JI
      NE=N+1
      IF (N .GT. 99) GO TO 120
C   INO IS THE NUMBER OF ITERATION FOR REDISTRIBUTION
      INO=3
      ITER=0
      DO 10 J=1,NE
      K=JI-1+J
      FO(J)=FF(K)
      XO(J)=XX(K)
      SF(J)=FF(K)
      SX(J)=XX(K)
   10 SY(J)=YY(K)
      TF(1)=SF(1)
      TX(1)=SX(1)
      TY(1)=SY(1)
      TF(NE)=SF(NE)
      TX(NE)=SX(NE)
      TY(NE)=SY(NE)
   20 CONTINUE
C   BW IS THE WEIGHT PARAMETER FOR THE GRADIENT OF FF
C   THE EFFECT OF THE GRADIENT ON REDISTRIBUTION INCREASES WITH INCREASING BW
      BW=5.0
      ST=0.
      WT=0.
      DO 30 J=1,N
      J1=J+1
      DS(J)=SQRT((SX(J1)-SX(J))**2+(SY(J1)-SY(J))**2)
      ST=ST+DS(J)
      G(J)=(SF(J1)-SF(J))/DS(J)
      W(J)=1./(1.+BW*ABS(G(J)))
   30 WT=WT+W(J)
      ALPHA=ST/WT
      DO 40 J=1,N
   40 DT(J)=ALPHA*W(J)
      TJ=0.
      SK=0.
      K=0
```

```
      DO 80 J=1,N-1
      J1=J+1
      TJ=TJ+DT(J)
   50 K=K+1
      SK=SK+DS(K)
      IF (TJ .GE. SK) GO TO 50
      SK=SK-DS(K)
      R=(TJ-SK)/DS(K)
      K1=K+1
      TX(J1)=SX(K)+R*(SX(K1)-SX(K))
      TY(J1)=SY(K)+R*(SY(K1)-SY(K))
      TXI=TX(J1)
      TF(J1)=ATKN(XO,FO,NE,2,TXI)
      K=K-1
   80 CONTINUE
   81 FORMAT(1H1,'*** BW = ', F8.4)
      WRITE(6,81) BW
   82 FORMAT(1H0,'J',9X,'DS',9X,'DT',9X,'SF',9X,'TF',9X,'SX',9X,'TX')
   83 FORMAT(1H ,I3,6E12.4)
      WRITE(6,82)
      DO 84 J=1,N+1
   84 WRITE(6,83) J,DS(J),DT(J),SF(J),TF(J),SX(J),TX(J)
      ITER=ITER+1
      IF (ITER .GT. INO) GO TO 100
      DO 90 J=2,N
      SF(J)=TF(J)
      SX(J)=TX(J)
   90 SY(J)=TY(J)
      GO TO 20
  100 DO 110 J=2,N
      K=JI-1+J
      XX(K)=TX(J)
  110 YY(K)=TY(J)
      RETURN
  120 WRITE(6,130)
  130 FORMAT(1H1,'**** NO. OF POINTS EXCEEDS THE DIMENSION ****')
      STOP
      END
```

```
      FUNCTION ATKN(X,Y,N,K,XI)
C   AITKEN INTERPOLATING FUNCTION
C   X(I),I=1,N,--INDEPENDENT VARIABLE IN ASCENDING OR DESCENDING ORDER
C   Y(I)--TABLE OF DEPENDENT VARIABLE
C   K--DEGREE OF INTERPOLATION DESIRED; K .LE. 12
C   XI--X-VALUE WHERE THE INTERPOLATION IS DESIRED
      DIMENSION X(N),Y(N),XX(13),YY(13)
      DATA KMAX/12/
      IF (K .GT. KMAX .OR. K .LE. 0) GO TO 300
      K1=K+1
      IF (X(N)-X(1)) 100,10,10
   10 IF (XI-X(1)) 20,20,30
   20 LL=0
      GO TO 200
   30 IF (X(N)-XI) 40,40,50
   40 LL=N-K1
      GO TO 200
   50 LL=1
      LU=N
   60 IF (LU-LL-1) 180,180,70
   70 LI=(LL+LU)/2
      IF (X(LI)-XI) 80,80,90
   80 LL=LI
      GO TO 60
   90 LU=LI
      GO TO 60
  100 IF (XI-X(1)) 120,20,20
  120 IF (X(N)-XI) 130,40,40
  130 LL=1
      LU=N
  140 IF (LU-LL-1) 180,180,150
  150 LI=(LL+LU)/2
      IF (X(LI)-XI) 160,170,170
  160 LU=LI
      GO TO 140
  170 LL=LI
      GO TO 140
  180 LL=LL-(K1+1)/2
      IF (LL) 20,200,190
  190 IF (LL+K1-N) 200,200,40
  200 DO 210 I=1,K1
      I1=LL+I
      XX(I)=X(I1)-XI
  210 YY(I)=Y(I1)
      DO 220 I=1,K
      DO 220 J=I,K
  220 YY(J+1)=(1.0/(XX(J+1)-XX(I)))*(YY(I)*XX(J+1)
     1-YY(J+1)*XX(I))
      ATKN=YY(K1)
      RETURN
  300 WRITE(6,301) K
  301 FORMAT('1','POLYNOMIAL OF DEGREE K =',I3,2X,'IS
     1INCORRECT FOR THE FUNCTION SUBPROGRAM ATKN')
      RETURN
      END
```

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