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NASA TECHNICAL
MEMORANDUM

INPUT DESCRIPTION FOR JAMESON'S THREE-DIMENSIONAL

TRANSONIC AIRFOIL ANALYSIS PROGRAM

By Perry A. Newman and Ruby M. Davis
February 7, 1974

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16. Abstract This paper describes the input parameters for a computer program which has been developed by Antony Jameson of the Courant Institute of Mathematical Sciences, New York University under NASA Grant NGR-33-016-167. The program performs calculations for inviscid isentropic transonic flow over 3-D airfoils with straight (may be yawed but not swept) leading edges. The free-stream Mach number is restricted only by the isentropic assumption. Weak shock waves are automatically located where ever they occur in the flow. The finite-difference form of the full equation for the velocity potential is solved by the method of relaxation, after the flow exterior to the airfoil is mapped to the upper half plane. The mapping procedure allows exact satisfaction of the boundary conditions and use of supersonic free stream velocities. The finite difference operator is "locally rotated" in supersonic flow regions so as to properly account for the domain of dependence. The relaxation algorithm has been stabilized using criteria from a time-like analogy. The brief description contained in this paper should enable one to use the program until a formal user's manual is available.

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INPUT DESCRIPTION FOR JAMESON'S THREE-DIMENSIONAL

TRANSONIC AIRFOIL ANALYSIS PROGRAM

By Perry A. Newman and Ruby M. Davis

Langley Research Center

SUMMARY

This paper describes the input parameters for a computer program which has been developed by Antony Jameson of the Courant Institute of Mathematical Sciences, New York University under NASA Grant NGR-33-016-167. References 1 and 2 describe the method and give several sample results; however, a user's manual (ref. 3), is not yet available. A version of the program which was successfully demonstrated on the CDC system here at NASA Langley is available as Langley Program A4231. This paper gives a description of the input parameters and a listing of input data cards and some output results for a sample case. It should enable one to use this program until a final version with its formal user's manual is available.

A brief description of the program and type of problems it will handle is given in the computer program abstract which is reproduced as Figure A1 of Appendix A. Further details concerning the method are given in references 1 and 2. An overlay diagram and a list of subroutine names and functions are given as Figures A2 and A3 respectively.

Computer storage and time requirements for a three-dimensional problem limit what can reasonably be done on present computers. Therefore, in practice, this 3-D program does not have the flexibility (with respect to grid size, number of grid halvings, and multiple case runs) of similar 2-D analysis programs (refs. 4-7) which are based on the full nonlinear potential formulation. In this program, the potential function G is a large three-dimensional array which, in essence, determines both the central memory storage and the computational time. Typical runs, at the dimensions stored on the data cell, require (a) 15-30 minutes CPU time on a CDC 6600 (using a run compiler) to reach a convergence criterion of about 10^{-5} and (b) 322K (base 8) central memory storage. These runs would start on a coarse grid (64 x 8 x 16) and be halved only once. Iterations take very close to 8 times as long on the resulting fine grid (128 x 16 x 32). The maximum values quoted here and on the following pages are those consistent with the data cell dimensioning and one halving of the grid; these, of course, can be changed somewhat. In practice there is little advantage in using the multiple case capability; thus it is recommended that single cases be run.

INPUT DESCRIPTION

Read Order	Number Cards	Description and Comments
1	1	TITLE. - Descriptive title of case or sequence; Format (8A10) Appears on Varian Plots and beginning of output.
2	1	DESC. - Description for card in Read Order 3 Format (8A10).
3	1	FNX, FNY, FNZ, FPLOT Format (8E10.7)

FNX, FNY, FNZ, FPLOT
Format (8E10.7)

Note: A number of quantities are read in as floating-point numbers and converted to integers within the program.

FNX. - Number of computational grid points in "chordwise direction" from downstream infinity, around the leading edge and back to downstream infinity on coarsest mesh. Maximum is 64 (128 with no grid halving).

FNY. - Number of computational grid points in "normal direction" from airfoil surface to infinity on coarsest mesh. Maximum is 8 (16 with no grid halving).

FNZ. - Number of computational grid points in "spanwise direction" from infinity, across the wing span and to infinity on coarsest mesh. Maximum is 16 (32 with no grid halving).

FPLOT. - Plot trigger. Selects type of plot for chordwise surface pressure coefficients. FPLOT = 0. Printer plots, one at each spanwise grid plane section with CP versus the computational grid chordwise variable.

Read Order	Number Cards		Description and Comments
			FPLOT = 1. Varian plots (from THREED). These are superimposed plots, with all span sections shown on two figures, an upper surface and a lower surface plot of CP versus physical space chordwise variable.
			FPLOT = 2. Varian plots (from THREED) as above plus section plots (from GRAPH). These latter plots, one per section, give upper and lower surface CP versus physical space chordwise variable.
			Defaults to zero
4	1	DESC. –	Description for card in Read Order 5 Format (8A10).
5	1 card for each computational grid. Maximum essentially 2, dimensioned 3.	FIT, COVO, P10, P20, P30, BETAO, STRIPO, FHALF Format (8E10.7)	
		FIT. –	Maximum number of iterations on this gird, called MIT in program.
		COVO. –	Convergence criterion on the maximum change in reduced velocity potential (G) from one iteration cycle to the next on this grid.
		P10. –	Subsonic point relaxation factor on this grid; must be <2.. Typically 1.6 on coarse grid.
		P20. –	Supersonic point relaxation factor; must be ≤ 1.. Should use 1.0 for stability on all grids.
		P30. –	Circulation relaxation factor. May be > 1.0 .
		BETAO. –	Stabilization factor used at supersonic points in finite difference operator if BETAO > 0. Most needed when $M_\infty > 1.$, many cases operate satisfactorily with BETAO = 0. Convergence is slowed but stability enhanced when BETAO > 0.

3

Read Order	Number Cards		Description and Comments
		STRIPO. -	Line relaxation control. Computational X-Y planes are relaxed by horizontal lines (YSWEEP) in central strip, vertical lines (XSWEEP) in outer strips. STRIPO specifies the fraction of computational plane included in central strip: $0. \leq STRIPO \leq 1.$, where STRIPO=1. gives all horizontal line relaxation.
		FHALF. -	Grid halving trigger. $\|FHALF\| \geq 1.$ read another card (Read Order 5 format) containing computational parameters to be used on grid with mesh size halved in all directions. $\|FHALF\| < 1.$ must appear on finest grid card (last one read). Calculation proceeds automatically through the sequence of computational grids.
6	1	DESC. -	Description for card in Read Order 7 Format (8A10).
7	1	FMACH, YA, AL, CDO	Format (8E10.7)
		FMACH. -	Freestream Mach number.
		YA. -	Yaw angle (in degrees).
		AL. -	Angle of attack (in degrees) measured in plane normal to leading edge, not in plane containing freestream direction.
		CDO. -	Drag coefficient due to skin friction (CD FRICTION on output). This input number is added to the drag coefficient obtained by integrating the surface pressures (CD FORM on output).

Read Orders 8 through 19 are used to specify the wing geometry (in physical space, of course). One can define the wing at up to 11 span stations. A set of airfoil coordinates must be read in at the first station. It need not be read in at other stations, if one is changing only combinations of the following three airfoil section parameters: chord, thickness ratio or angle of attack (twist). The wing shape at intermediate span positions (i.e., the computational grid planes for example) is obtained by linear interpolation in the spanwise direction in the physical space.

Read Order	Number Cards	Description and Comments

A multiple run capability for the same wing geometry at several flow conditions is available and controlled by the parameter FNC in Read Order 9. One does not have to re-read the wing geometry to use it. The following description of Read Orders 8 through 19 is that required for a single case.

Read Orders 8 and 9 are read only once: 10 and 11 are read FNC (see 9) times; 12 through 17 (19 if non-symmetric airfoil section) must be read at first section and may be required at other sections, depending on the wing geometry.

Read Order	Number Cards	Description and Comments
8	1	DESC. - Description for card in Read Order 9 Format (8A10).
9	1	FNC Format (8E10.7)

FNC.   -   Number of span stations at which the wing is described or specified. Maximum is 11. Must be at least 2 for a single case or the first of a sequence. If FNC < 2. geometric wing data is assumed to be the same as in previous case and calculation begins for the new flow conditions reading <u>no</u> further input cards.

Read Order	Number Cards	Description and Comments
10	1	DESC. - Description for cards in Read Order 11 Format (8A10).
11	1	ZS(K), CHORD, THICK, AL, FSEC Format (8E10.7)

ZS(K).   -   Spanwise coordinate of the wing section being specified. It is in the same units as CHORD. These stations are ordered from tip-to-tip, in ascending algebraic order of ZS(K).

CHORD.   -   Section chord length. The chord of the airfoil coordinates to be read in (or already read in at the prior station) will be scaled to this value.

THICK.   -   Section thickness ratio relative to that of the airfoil coordinates to be read in (or already read in at the

5

Read Order	Number Cards			Description and Comment

prior station). Note, this is a <u>ratio</u> of thickness/chord ratios. The thickness of the airfoil coordinates will be scaled with this value.

AL.   -   Section angle of attack or twist (in degrees). Airfoil coordinates will be rotated through this angle.

FSEC.   -   Section airfoil coordinate trigger. FSEC = 0. Do not read airfoil coordinates. Last set of airfoil coordinates read will be used at this section. They may be scaled by any combination of CHORD, THICK, or AL read above. Skip Read Orders 12 through 19 for this section.

FSEC = 1. Read a new set of airfoil coordinates which will be used at this station and perhaps at other stations. They may be scaled by any combination of CHORD, THICK, or AL read above for this section. At first station (K = 1) FSEC is ignored; one <u>must</u> supply Read Orders 12 through 17.

12   1   DESC.   -   Description for cards in Read Order 13 Format (8A10).

13   1   FSYM, FNU, FNL
                           Format (8E10.7)

FSYM.   -   Airfoil symmetry trigger.

$FSYM \geq 1$. Symmetric airfoil. Read in only upper surface airfoil coordinates, ordered leading edge to trailing edge.

$FSYM < 1$. Non-symmetric airfoil. Read in upper and lower surface airfoil coordinates, respectively, each set ordered leading edge to trailing edge. Note that leading-

Read Order	Number Cards	Description and Comments

		edge points are included in both sets.
		FNU. – Number of coordinates read in for upper surface of airfoil.
		FNL. – Number of coordinates read in for lower surface of airfoil.
14	1	DESC. – Description for cards in Read Order 15 Format (8A10).
15	1	TRL, SLT, XSING, YSING Format (8E10.7)
		TRL. – Included angle of trailing edge of airfoil (in degrees).
		SLT. – Slope of airfoil mean camber line at trailing edge.
		XSING. – X coordinate of the origin of the mapping referenced to the airfoil leading edge. Recommend approximately X(LE) + 1/2 leading edge radius.
		YSING. – Y coordinate of the origin of the mapping referenced to the airfoil leading edge. Recommend approximately Y(LE).
16	1	DESC. – Description for cards in Read Order 17 Format (8A10).
17	FNU	XP(I), YP(I) Format (8E10.7)
		XP(I). – X coordinate of airfoil upper surface, ordered leading edge to trailing edge.
		YP(I). – Y coordinate of airfoil upper surface, ordered leading edge to trailing edge. Note that there is only one pair of coordinates per card.

If airfoil section is not symmetric (FSYM<1.) the airfoil lower surface coordinates must be read here. For symmetric airfoil (FSYM≥1.), skip the two Read Orders 18 and 19.

Read Order	Number Cards	Description and Comments
18	1	DESC. – Description for cards in Read Order 19 Format (8A10).
19	FNL	VAL, DUM - Format (8E10.7)
		VAL. – X coordinate of airfoil lower surface, ordered leading edge to trailing edge.
		DUM. – Y coordinate of airfoil lower surface, ordered leading edge to trailing edge. Note that there is only one pair of coordinates per card.

Read Orders 10 through 19 complete the input for one span station. As indicated above Read Order 8, at least Read Orders 10 and 11 must be repeated for the remaining FNC-1 sections when FNC $\geq$ 2.

The above Read Orders complete the input for a computational case or a sequence of cases if obtained by having FNC < 2. Additional cases requiring different input are obtained by repeating the above Read Orders. Recommend that cases be run one at a time.

The program terminates by reading the first three Read Orders with FNX<1.; that is, last three cards for a normal stop should be:

1	1	TITLE. – End of Calculation
2	1	DESC. – Description for card in Read Order 3
3	1	0. . . . .

SAMPLE CASE

A simple wing, shown in Figure 1, is used here for the sample case; more realistic wing shapes are considered in references 1 and 2. This wing has a rectangular planform of aspect ratio 32/9 with a NACA 63A006 airfoil section (ref. 8) at all span stations. The free stream, at Mach number .9, is at 2° incidence and 0° yaw with respect to the wing. Note that the freestream direction is consistantly indicated by a large open arrow on the figures.

Figure 2 depicts how the wing section planes are transformed from physical space to computational space for the present sample case. In Figure 3, a portion of the equally spaced computational grid in the wing section plane is plotted in physical space. This plot, however, was obtained

from a separate program, supplied by J. D. Keller of NASA Langley Research Center.

Appendix B is a listing of the input cards for the sample case. Read Order notations on the right side identify these cards with the input description of the last section.

Appendix C is a collection of figures which show some typical output results for the sample case. Note that FPLOT was 2 in the input (Appendix B) so there are two types of plots: those from THREED and those from GRAPH.

The bottom line of printing is common to all plots and contains the NASA LRC computer process number, date and time of run. Another line common to all plots contains the freestream Mach number (M), yaw angle (YAW), and incidence angle (ALF). Figures C1, C2, and C3 show the plots obtained from subroutine THREED. The first shows interpolated airfoil sections at each of the spanwise computational planes for the fine grid. (For this sample case, all sections are identical.) This plot serves to locate the CP origins on the second and third plots, where curves for all sections are superimposed but shifted with respect to one another. Figure C2 shows the chordwise distributions of (negative) surface pressure coefficient on the upper surface of the wing at all spanwise computational planes of the fine grid, whereas Figure C3 gives that for the wing lower surface. The sharp downward breaks in the curves (at about 50-60% chord) are shock waves. On these plots L/D, CL and CD are for the entire wing; CL is the inviscid lift coefficient, CD is the drag coefficient (composed of that obtained from integrating the inviscid pressures plus that read in as input (CDO) due to skin friction, and L/D is the ratio CL/CD. A set of plots like these is obtained on each grid refinement; for the sample case there were two grids so two sets were obtained.

Figures C4 and C5 are typical of the plots obtained from subroutine GRAPH. In these, the chordwise distribution of surface pressure coefficient for both the upper and lower wing surfaces is shown on one figure, a separate figure for each spanwise computational plane. The value of Z, shown on the next to last line at the bottom of the plot, is the spanwise coordinate in the physical plane (See Fig. 1) and thus identifies the section location. The values of CL and CD shown on these plots are the inviscid <u>section</u> lift and drag coefficients, respectively. Figure C4 is for the root section (Z = 0.0) while Figure C5 is for the tip station (Z = 160.0). The long tick mark on the ordinate is the sonic value of pressure coefficient. A set of plots (one for each spanwise station) is obtained for each grid refinement.

Figures C6, C7, and C8 are charts which show the local Mach number (multiplied by 100) in various computational planes. Figure C6 is at the root section of the wing (Z = 0.0); minus signs on it denote the lower half plane. A solid line outlines that portion of computational grid shown in Figure 3. The supersonic bubbles on both upper and lower wing surfaces are

clearly visible. Figures C7 and C8 show the Mach charts in the wing plane at the upper and lower surfaces, respectively. The wing planform (in the computational plane) is outlined on each figure and again the supersonic bubbles on both surfaces of the wing are clearly visible. One set of these charts is made on each grid refinement. Those for the fine grid of the sample case have been given in figures C7 and C8.
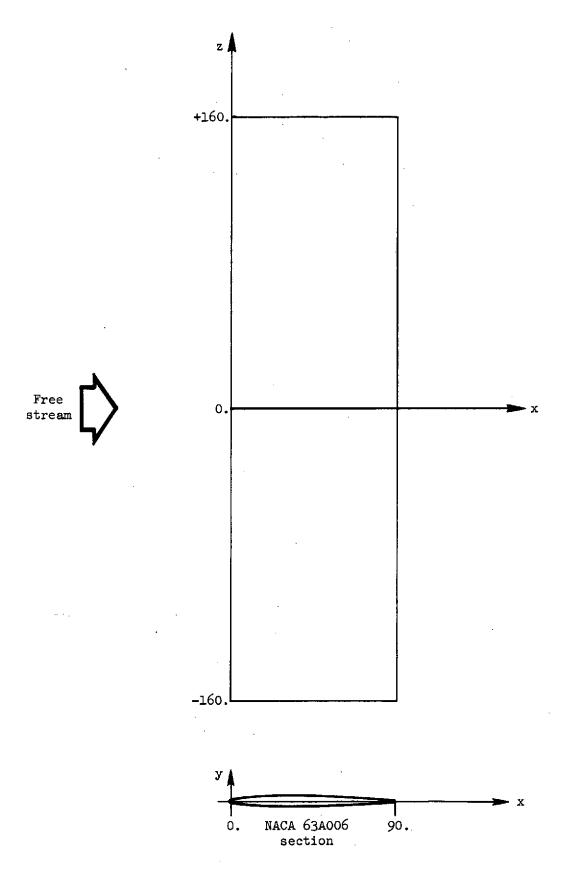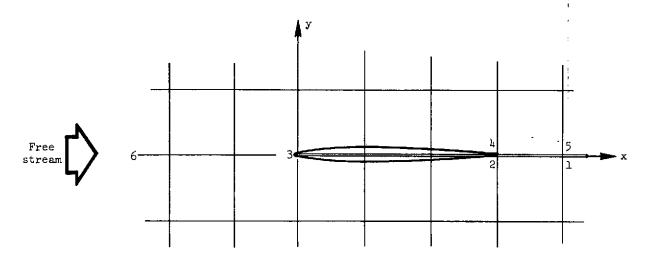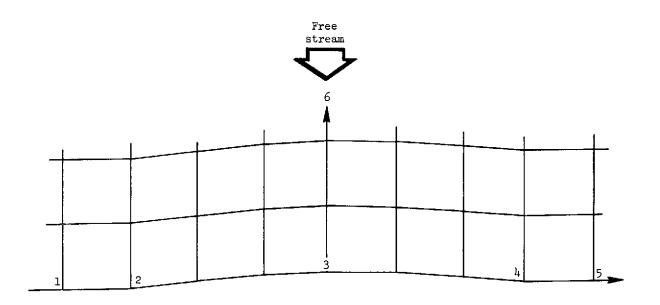
Figure 1.- Geometry of wing for sample case.

11

Physical space - Cartesian coordinates

Computational space - sheared parabolic coordinates

Figure 2.- Physical and computational coordinate systems in wing section planes for sample case.
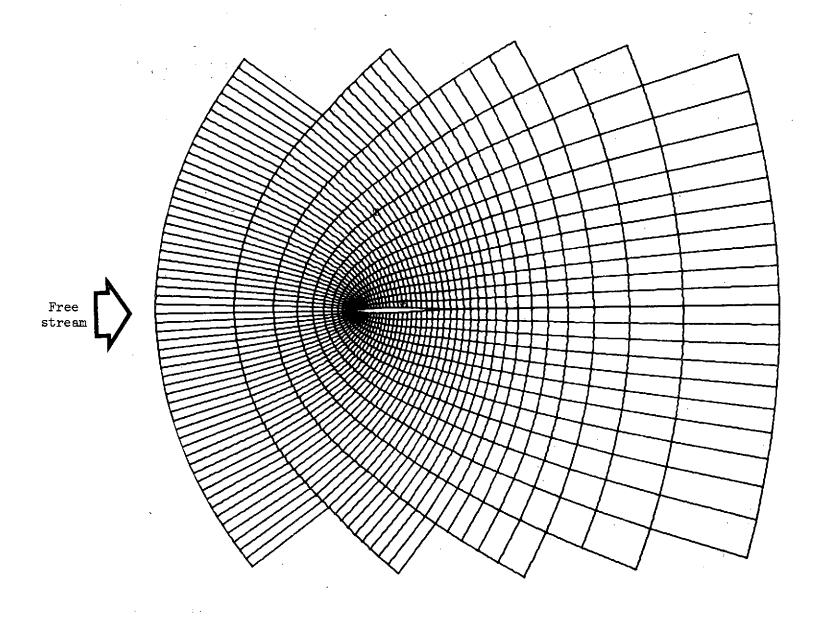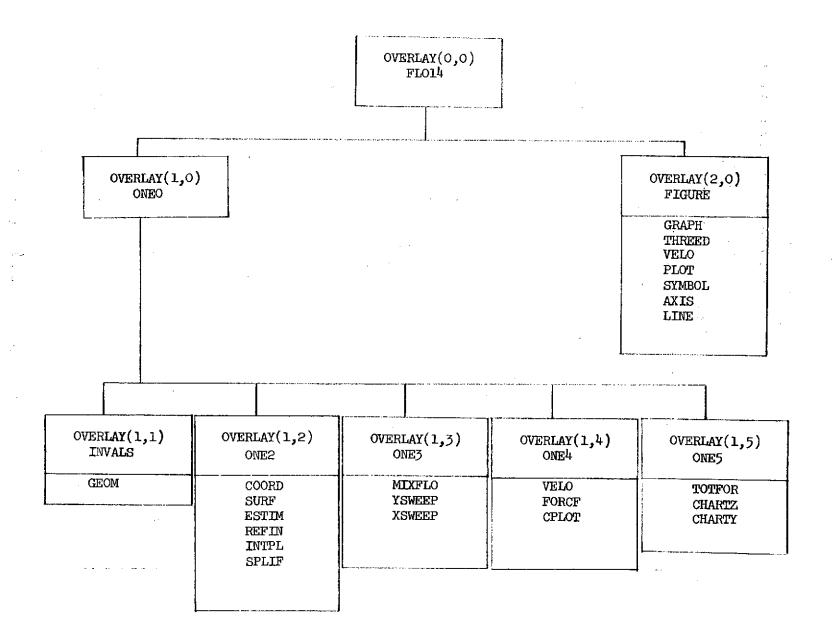
Figure 3.- Portion of wing section computational grid plotted in physical space.

NASA-LANGLEY RESEARCH CENTER

01 3 LAR	01 7 PROGRAM NO A4231	COMPUTER PROGRAM ABSTRACT		01 14 DATE 081073

01 20 TITLE OF PROGRAM (61 CHARACTERS MAXIMUM)		PARENT PROGRAM		
Transonic Flow Analysis-3D airfoils/Jameson(parabolic)		02 14 CATEGORY I	02 15 SITE NYU	02 18 PROGRAM NO.

02 26 CATEGORY	02 27 LANGUAGE NO. 1	02 32 LANGUAGE NO. 2	02 37 KEY WORDS (8 MAXIMUM, SEPARATED BY COMMAS)
I	FØR6M		transonic flow, embedded shocks, isentropic supersonic flow, subsonic flow

WHO TO CONTACT ABOUT THE PROGRAM

05 14 CONTACT RMDavis	05 28 SITE LAR	05 31 ORGN CODE 33.300	05 39 PROJECT NO R2564	05 45 NASA CENTER

STATUS 05 48:
- ☐ A. UNDER DEVELOPMENT
- ☒ B. OPERATIONAL
- ☐ C. COMPLETED

05 49: ☐ A THIS PROGRAM IS NOT FOR SHARING.

DATES		05 58 REVISION CODE	TIME AND COST FOR DEVELOPMENT			
05 50 INITIATED 0873	05 54 COMPLETED	☐ A REVISION ☐ B CANCELLATION	05 59 MANMONTHS	05 64 MACHINE HOURS	05 69 COMPUTER TYPE 6000	05 74 TOTAL COST (DOLLARS)

CARD NUMBER	ABSTRACT
06	This program performs calculations for inviscid isentropic
07	transonic flow over 3D airfoils with straight (may be yawed
08	but not swept) leading edges. The free-stream Mach number is
09	restricted only by the isentropic assumption. Weak shock waves
10	are automatically located where ever they occur in the flow.
11	The finite-difference form of the full equation for the velocity
12	potential is solved by the method of relaxation, after the
13	flow exterior to the airfoil is mapped to the upper half
14	plane. The mapping procedure allows exact satisfaction of the
15	boundary conditions and use of supersonic free-stream velocities.
16	The finite difference operator is "locally rotated" in
17	supersonic flow regions so as to properly account for the
18	domain of dependence. The relaxation algorithm has been
19	stabilized using criteria from a time-like analogy.
20	

Figure A1.- Computer program abstract.

14

```
                    ┌─────────────────┐
                    │  OVERLAY(0,0)   │
                    │     FLO14       │
                    └────────┬────────┘
                             │
          ┌──────────────────┴──────────────────────────────┐
          │                                                  │
┌─────────────────┐                              ┌─────────────────────┐
│  OVERLAY(1,0)   │                              │    OVERLAY(2,0)     │
│     ONEO        │                              │      FIGURE         │
└────────┬────────┘                              ├─────────────────────┤
         │                                       │      GRAPH          │
         │                                       │      THREED         │
         │                                       │      VELO           │
         │                                       │      PLOT           │
         │                                       │      SYMBOL         │
         │                                       │      AXIS           │
         │                                       │      LINE           │
         │                                       └─────────────────────┘
   ┌─────┴────┬──────────┬──────────┬──────────┬──────────┐
```

| OVERLAY(1,1) | OVERLAY(1,2) | OVERLAY(1,3) | OVERLAY(1,4) | OVERLAY(1,5) |
INVALS	ONE2	ONE3	ONE4	ONE5
GEOM	COORD	MIXFLO	VELO	TOTFOR
	SURF	YSWEEP	FORCF	CHARTZ
	ESTIM	XSWEEP	CPLOT	CHARTY
	REFIN			
	INTPL			
	SPLIF			

Figure A2.– Overlay diagram.

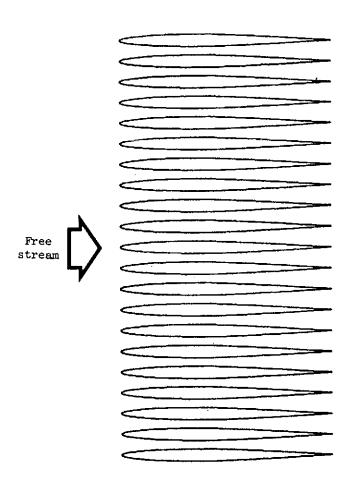|	
GEOM	reads geometric definition of wing
COORD	sets up stretched parabolic and spanwise coordinates
SURF	interpolates mapped wing surface at computational mesh points
ESTIM	computes initial estimate of reduced potential
REFIN	halves computational mesh size
INTPL	interpolates using Taylor series
SPLIF	performs cubic spline fit
MIXFLO	solves mixed-flow equations (rotated difference scheme)
YSWEEP	relaxes horizontal lines, sweeping in y-direction
XSWEEP	relaxes vertical lines, sweeping in x-direction
VELO	calculates surface velocity
FORCF	calculates section force coefficients
CPLOT	generates printer plots of CP at equal computational intervals
TOTFOR	calculates total force coefficients
CHARTZ	generates Mach number chart in plane of wing section
CHARTY	generates Mach number chart in plane of wing planform
GRAPH	generates Varian plots
THREED	generates three-dimensional plots
PLOT *	moves pen (call CALPLT)
SYMBOL *	plots symbols (call NOTATE)
AXIS *	draws axes (call AXES)
LINE *	plots arrays

* expedient modifications were made so that NYU plotting subroutines were
  compatible with NASA LRC CDC system.

Figure A3. - Function of subroutines.

16

Read Order

								Read Order
RECTANGULAR WING - NACA 63A006 AR=32/9								1
FNX	FNY	FNZ	FPLOT					2
48.	8.	16.	2.					3
FIT	COVO	P10	P20	P30	BETA0	STRIP0	FHALF	4
220.	.00001	1.6	1.	1.	0.	1.	1.	5
110.	.00001	1.6	1.	1.	0.	1.	0.	
FMACH	YA	AL	C00					6
.9	0.	2.	0.					7
FNC								8
2.								9
ZS	CHORD	THICK	AL	FSEC				10
-160.	90.	1.	0.	1.				11
FSYM	FNU	FNL						12
1.	36.	36.						13
TRL	SLT	XSING	YSING					14
7.0778	0.	.1325	0.					15
XP	YP		(UPPER SURFACE)					16
0.	0.							
.055555	.16235							
.11111	.22444							
.22222	.32222							
.33333	.40111							
.44444	.46777							
.55555	.52							
.83333	.62277							
1.11111	.71111							
1.66666	.86478							
2.2222	.98961							
2.7777	1.0978							
3.3333	1.1962							
3.8888	1.2877							
4.4444	1.3696							
5.	1.447							
7.5	1.7466							
10.	1.9889							
15.	2.3622							17
20.	2.6311							(FNU cards)
25.	2.82							
30.	2.9422							
35.	2.9955							
40.	2.9844							
45.	2.9144							
50.	2.7877							
55.	2.6133							
60.	2.3955							
65.	2.1433							
70.	1.8589							
75.	1.5555							
80.	1.2478							
85.	.93889							
90.	.63							
95.	.32222							
100.	.013							
ZS	CHORD	THICK	AL	FSEC				10
+160.	90.	1.	0.	0.				11
END OF CALCULATION								1
FNX	FNY	FNZ	FPLOT					2
0.	0.	0.	0.					3

Wing data at first span station
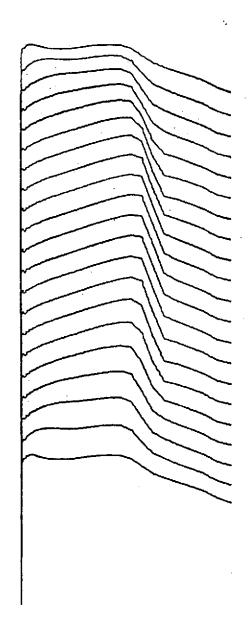
omit 18 and 19*

Wing data at last span station

* Symmetric wing section, therefore Read Orders 18 and 19 must be omitted

Note: Spanwise variable
is not scaled to
chordwise variable in
this plot. Instead, the
wing sections shown
here located the C_p
origins in the following
plots.

VIEW OF WING
RECTANGULAR WING – NACA 63A006 SECTION   AR=32/9
M =   .900   YAW =   0.00   ALF =   2.00
L/D = 23.05   CL =   .1876   CD =   .0081
LB71564   09/13/73   07.37.22.

Figure C1.– View of wing showing interpolated airfoil sections on fine grid.
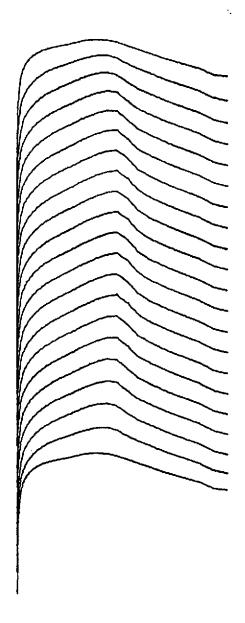
UPPER SURFACE PRESSURE
RECTANGULAR WING - NACA 63A006 SECTION   AR=32/9
M =   .900   YAW =   0.00   ALF =   2.00
L/D =   23.05   CL =   .1876   CD =   .0081
LB71564   09/13/73   07.37.22.

Figure C2.- Chordwise distributions of upper-surface wing pressure
            coefficients at spanwise computational planes of fine grid.

LOWER SURFACE PRESSURE
RECTANGULAR WING – NACA 63A006 SECTION   AR=32/9
M =   .900   YAW = 0.00   ALF = 2.00
L/D = 23.05   CL = .1876   CD = .0081
LB71564   09/13/73 07.37.22.

Figure C3.– Chordwise distributions of lower-surface wing pressure
         coefficients at spanwise computational planes of fine grid.
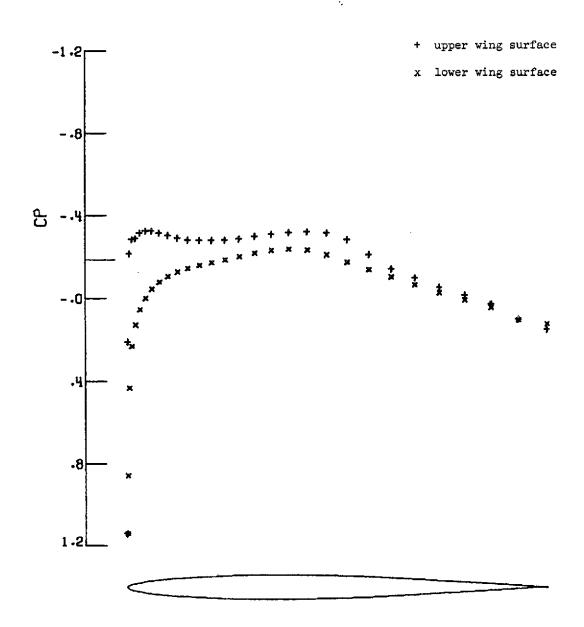
Figure C4.- Chordwise distributions of pressure coefficient at root
section of wing.

Figure C5.- Chordwise distribution of pressure coefficients at
tip section of wing.

MACH NO CHART AT Z = 0.00000

Physical
space
lower
half-plane

Lower trailing edge ●

Airfoil lower surface

Airfoil leading edge ●

Free
stream

Airfoil upper surface

Physical
space
upper
half-plane

Upper trailing edge ●

Figure C6.- Mach chart at root section of wing in computation plane.

Free
stream

UPPER SURFACE MACH NO CHART IN WING PLANE

(Mach number data grid – values ranging from approximately 19 to 127 in the central wing region, surrounded by free-stream values of 89–90.)

Figure C7.– Mach chart at upper surface of wing in computational plane.

Free
stream

```
LOWER SURFACE MACH NO CHART IN WING PLANE
89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  69  89
89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89
89  89  89  89  89  89  89  89  89  89  87  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89  89
89  89  89  89  89  89  89  89  88  88  88  88  93  88  88  88  88  88  88  88  88  88  88  88  88  89  89  89  89  89  89  89  89
89  89  89  89  88  88  88  88  88  88  87  87  87  87  87  87  87  87  87  87  87  88  88  88  88  89  89  88  89  89  89  89
89  89  89  89  89  88  87  87  87  86  86  86  86  86  86  86  86  86  86  86  86  87  87  87  88  88  89  89  89  89  89
89  89  89  88  87  87  86  86  85  85  85  85  85  84  84  64  64  85  85  85  85  85  86  86  87  87  88  89  89  89  89
90  89  89  88  87  86  85  84  84  83  83  83  83  87  83  63  83  83  83  83  83  84  84  85  86  87  38  89  89  90
90  89  89  88  86  84  83  82  82  81  91  81  81  81  81  81  81  81  81  81  82  82  83  84  36  88  89  89  93
90  89  89  88  86  82  81  80  79  79  79  79  79  78  78  78  79  79  79  79  79  80  81  82  86  88  89  90  90
90  90  89  88  85  80  77  77  76  76  76  76  76  76  76  76  76  76  76  76  77  77  80  85  88  89  90  90
90  90  89  89  86  70  68  67  67  67  67  67  67  67  67  67  67  67  67  67  67  68  70  86  89  89  90  90
90  90  90  89  87  62  60  60  59  59  59  59  59  59  59  59  59  59  59  60  60  62  96  89  90  90  90
90  90  90  89  87  47  46  46  46  46  45  45  46  46  46  46  46  46  46  46  46  47  97  89  90  90  90
90  90  90  89  87  19  21  22  23  23  24  24  24  24  24  24  24  24  23  23  22  21  19  87  89  90  90  90
90  90  90  89  87  42  38  36  36  35  34  34  34  34  34  34  34  35  36  38  42  87  89  90  90  90
90  90  90  89  87  66  62  61  60  59  59  59  59  58  59  59  59  59  60  61  62  66  87  89  90  90  90
90  90  90  89  88  77  72  71  70  70  69  69  69  69  69  69  69  70  70  71  72  77  88  89  90  90  90
90  90  90  89  88  92  78  77  76  76  75  75  75  75  75  75  75  75  76  76  77  78  82  88  89  90  90  90
90  90  90  89  89  86  83  81  80  80  79  79  79  79  79  79  79  80  81  82  86  89  90  90  90
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90  91  92  93  96  99 100 100 100  99  99  99  99  99  99  99  99  99  99 100 100  99  96  93  92  91  90
90  91  92  94  96  99 100 100 100  99  99  99  99  99  99  99  99  99  99 100 100  99  96  93  92  91  90
90  91  92  94  97 100 101 101 101 101 101 101 101 102 100 100 100 101 101 101 101 101 101 100  97  94  92  91  90
90  91  92  95  98 101 103 103 102 102 103 103 103 103 103 103 103 103 102 102 103 103 101  98  95  92  91  90
90  91  93  95  98 102 104 105 105 105 105 105 105 105 105 105 105 105 105 105 105 104 102  98  95  93  91  90
90  91  93  95  99 102 105 106 107 107 107 107 107 107 107 107 107 107 106 105 102  99  95  93  91  90
90  91  93  95  99 102 105 107 108 108 109 109 109 109 109 109 109 109 108 108 107 105 102  99  95  93  91  90
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Figure C8.– Mach chart at lower surface of wing in
computational plane.

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