A Method for Evaluation of Stability Matrix Elements

Report No. GD/C DDF 65-004
Contract No. NAS8-11479

J. W. Evans
Project Leader

GENERAL DYNAMICS/CONVAIR

A DIVISION OF GENERAL DYNAMICS CORPORATION

Huntsville Engineering
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Prepared for

GEORGE C. MARSHALL SPACE FLIGHT CENTER
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Abstract

This document presents the results of a study which leads to the formulation of a digital computer program system. The study consisted of evaluating the various methods of obtaining and compiling that basic data required for stability analysis. The computer program system formulated provides a means of evaluating the elements of a 25 x 25 second order matrix for use in stability analysis.

This report constitutes the final report under contract NAS8-11479, titled "Optimum Dynamic Data Flow - A Digital Computer Program System".

FIGURES

NOMENCLATURE

Aij	"Acceleration" coefficient
Alt	Height above earth's surface
Bij	"Velocity" coefficient
Cij	"Position" coefficient
Cpz	Aerodynamic center of pressure
Cz	Aerodynamic normal force coefficient
C_1	Specific aerodynamic restoring torque
C_2	Specific control torque
F	Total thrust
Fs	Swivel thrust
K_1	Specific thrust lateral acceleration
K_2	Specific aerodynamic lateral acceleration
K_3	Specific control lateral acceleration
ICORR	Correction of inertia due to propellant oscillations
Ip	Propellant total inertia
M	Total vehicle mass
MACH	Mach number

NOMENCLATURE (CON.)

Mp	Propellant mass
Msp	Sloshing mass
N'z	Specific aerodynamic normal force
q	Dynamic pressure
R'	Specific control force normal to vehicle longitudinal axis
TIME	time
V	Velocity
X_A	Accelerometer moment arm
X_E	Gimbal engine moment arm
X_R	Rate gyro moment arm
X_V	Angle of attack meter moment arm

INTRODUCTION

Dynamic analysis of large, liquid fueled, flexible launch vehicles and the stability problems arising from the interaction between automatic control problems is one of the main tasks of the Stability and Control Engineer. In order to meet this task, he must rely heavily on the use of large, high speed, digital computers.

It is the purpose of this report to present a method of formulating that basic data required in these stability analyses. This formulation is restricted to that data required in the Elastic Vehicle Response Program (MSFC No. 345980) and the Stability Analysis - Pitch Oscillations Program (MSFC No. 345780) as used by the Dynamics Analyses Branch at the George C. Marshall Space Flight Center of the National Aeronautics and Space Adminstration.

The Elastic Vehicle Response Program provides a time varying response for a system of dynamical equations. These equations represent the dynamics of:

1. Four bending modes
2. Translation
3. Rotation
4. Five propellant sloshing modes
5. Swivel engine
6. Control

The Stability Analysis - Pitch Oscillation Program provides a time instant stability study and consists of;

1. Six bending modes
2. Translation
3. Rotation
4. Ten propellant sloshing modes
5. Two rate gyros
6. Two accelerometers
7. Angle-of-attack meter
8. Swivel engine
9. Control

INTRODUCTION (CON.)

The time varying coefficients used in the Elastic Vehicle Response Program contains the same parameters as the elements of the matrices in the Stability Analysis-Pitch Oscillation Program.

1/DATA REQUIREMENTS

The types of data required for the Elastic Vehicle Response Program and the Stability Analysis-Pitch Program can be divided into the following catagories:

1. Vibration and bending mode data.
2. Propellant sloshing data.
3. Rigid body data (translation and rotation).
4. Control engine data.
5. Control system sensor dynamic data.
6. Trajectory data.

This data forms the coefficients of the dynamic equations of motion as presented in Reference 1.

In the Stability Analysis-Pitch Program, these coefficients form the elements of a 25 x 25 matrix with second order elements. (The last row of this matrix can contain rational fraction polynomial elements of up to a ninth degree over a tenth degree).

The Vehicle Response Program, which uses the same dynamic equations as the Stability Analysis Program, used coefficients which are presented as functions of time. These coefficients are usually evaluated from a polynomial curve fit of the parameters as a function of time.

2/METHOD OF COEFFICIENT EVALUATION

Since the elements of the matrix and the coefficients of the dynamic response equations at the same time instant are equal, our discussion of their evaluation will be restricted to the matrix elements. Obtaining the coefficients of a polynomial which best describes the time varying dynamic response coefficients will be treated later in this report.

The various parameters which make up these elements are not always readily available for direct element evaluation. It is necessary, therefore, to formulate a program which will provide the parameters evaluated and ready to be used in element evaluation.

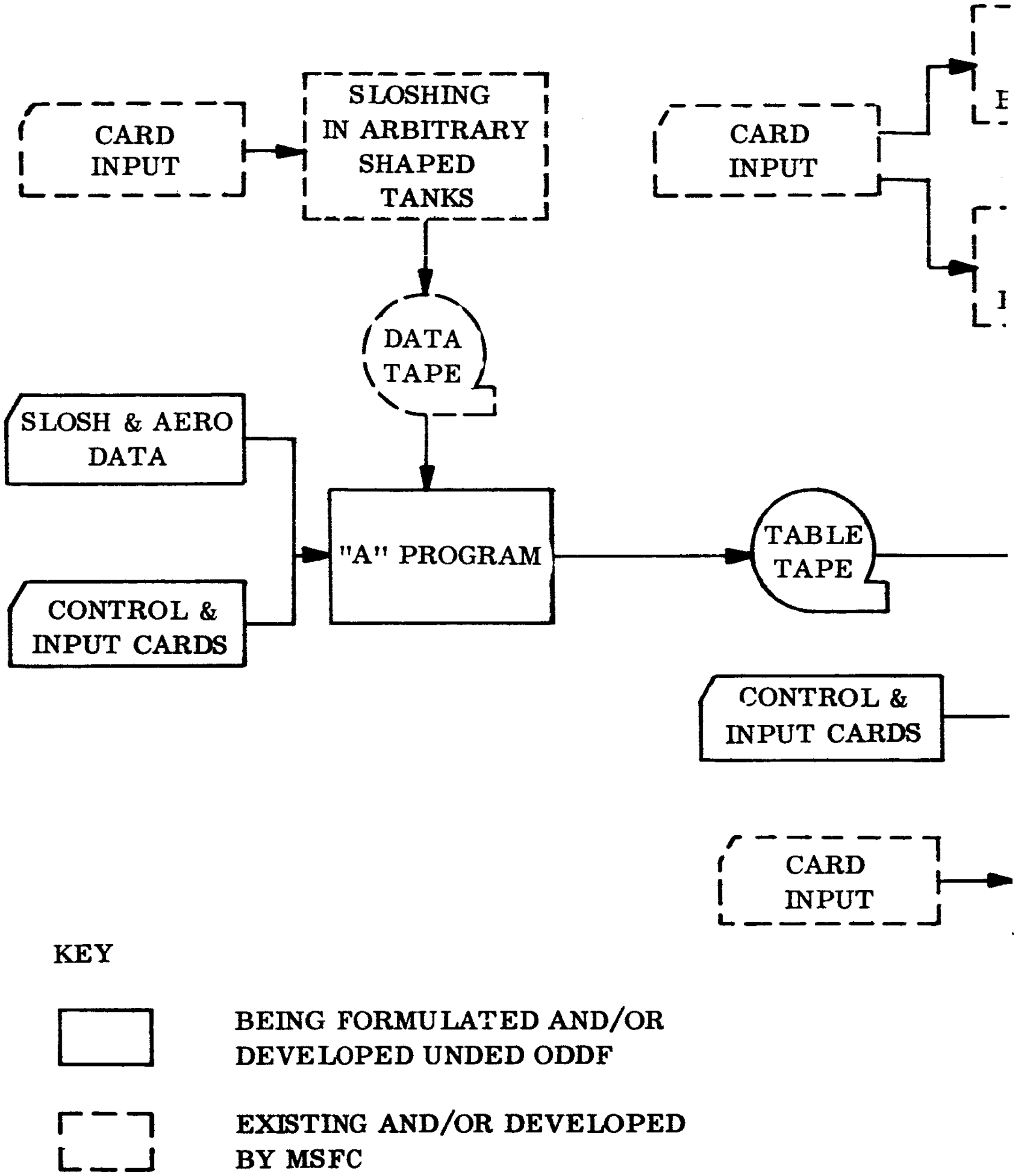
It is also desirous to have a method of reevaluating, updating the matrix elements, and rearranging or compressing the matrix after all of the elements have been computed.

The overall data flow logic for these computations is shown in Figure 1. Sources of the various parameters used and possible uses of the computed elements are shown. The purpose of, and data flow of each of the three programs required for this computation will be discussed in turn.

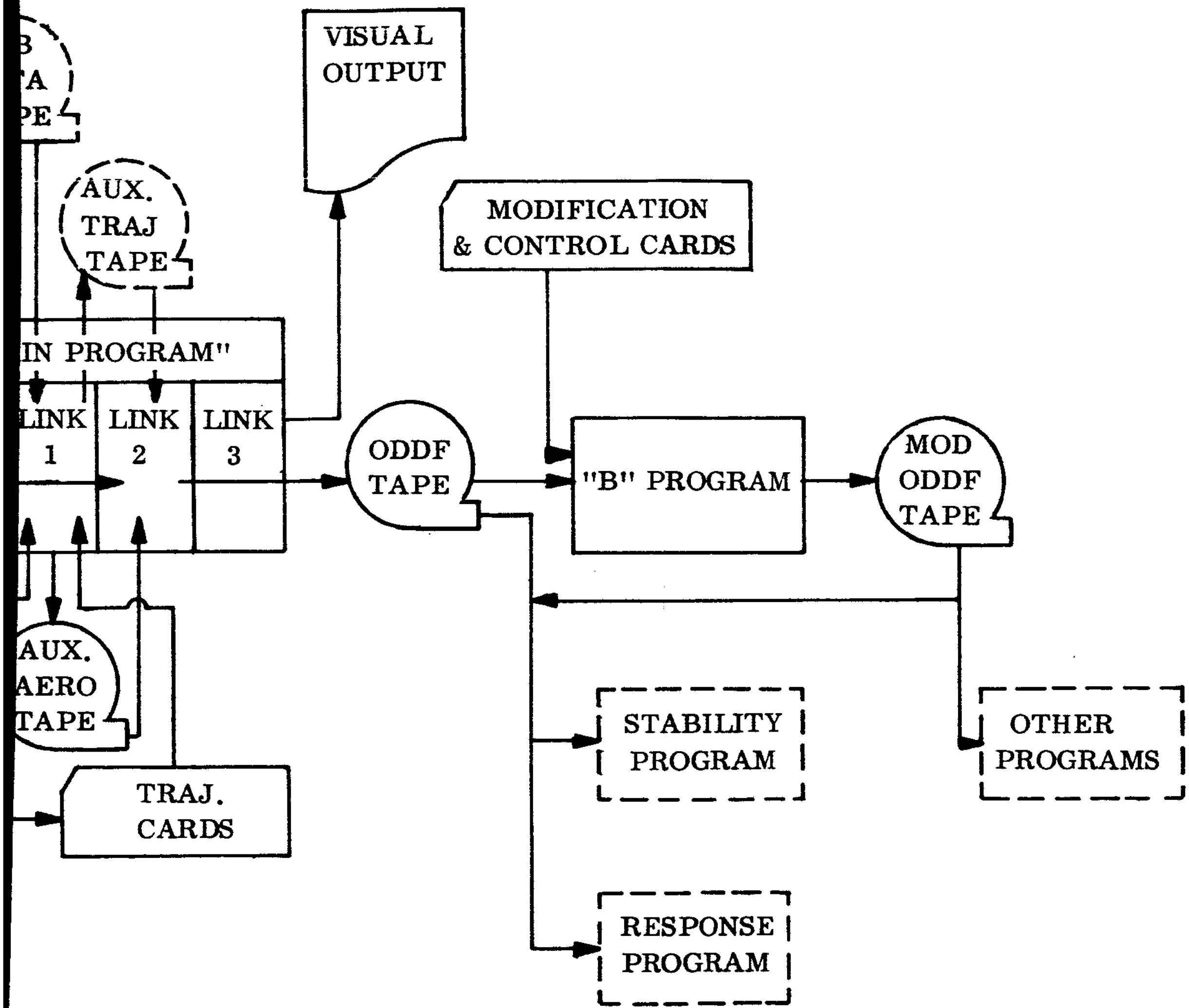
2.1 "A" PROGRAM

This program receives aerodynamic and propellant sloshing data from card input. This data is first rearranged, if required, so that the arguments are increasing monotonically. Values determined by linear interpolation are inserted in those positions of a function which may have been left blank on input. The revised tables are then stored on the "Tables Tape" for use by the "Main" Program.

In the preparation of data for entry into this program where more than one function is presented per argument, blanks may appear anywhere in the function list with the following restrictions.


CARD
INPUT
SLOSHING
IN ARBITRARY
SHAPED
TANKS
CARD
INPUT
DATA
TAPE
SLOSH & AERO
DATA
"A" PROGRAM
TABLE
TAPE
CONTROL &
INPUT CARDS
CONTROL &
INPUT CARDS
CARD
INPUT
KEY
BEING FORMULATED AND/OR
DEVELOPED UNDED ODDF
EXISTING AND/OR DEVELOPED
BY MSFC

FIGU


B
A
PE
AUX.
TRAJ
TAPE
VISUAL
OUTPUT
MODIFICATION
& CONTROL CARDS
IN PROGRAM"
LINK 1
LINK 2
LINK 3
ODDF
TAPE
"B" PROGRAM
MOD
ODDF
TAPE
AUX.
AERO
TAPE
TRAJ.
CARDS
STABILITY
PROGRAM
OTHER
PROGRAMS
RESPONSE
PROGRAM
M

FORTRAN CODING

PROBLEM "A" PROGRAM INPUT FORMAT

CODER | EXT. | DATE

```
         1111111111222222222233333333334
1234567890123456789012345678901234567890
     (NREAD)   (NDELETE)
       (ID1)
         o
         o    N=NDELETE
         o
       (IDN)
 (AERO ID)             A(N COMMENTS)
(COMMENTS FOR N=N COMMENTS CARDS
  (MACH1)      (CZA1)      (CPZ1)
     o           o           o
     o           o           o    N=
     o           o           o
  (MACHN)      (CZAN)      (CPZN)
 (TANK ID)             S(N COMMENTS)
(COMMENTS FOR N=N COMMENTS CARDS
  (MAS1)       (MS1)       (WS1)      (I
     o           o           o
     o           o           o
     o           o           o
  (MASSN)      (MSN)       (WSN)      (I
 (DIST ID)             D(N COMMENTS)
(COMMENTS FOR N=N COMMENTS CARDS
              (MACH1)     (MACH2)     (M
  (MACH6) ooo                         (M
    (X1)       (CZ∝1,1)    (CZ∝1,2)    (
   (CZ∝1,6)ooo                         (
      o          o           o
      o          o           o
    (XM)       (CZ∝M,1)    (CZ∝M,2)    (
   (CZ∝M,6 ooo                         (
```

FIGURE 2

AND DATA FORM

AWO

EWO

PAGE

OF

```
41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80

(N ARGS)
                                                  ──────────►)


NARGS


(N ARGS)
                                                  ──────────►)
CORR1)         (XCM1)          (ICM1)  ┐
 o              o               o      │
 o              o               o      ├N = NARGS
 o              o               o      │
CORRN)         (XCMN)          (ICMN)  ┘
(N STAS)       (N MACHS
                                                  ──────────►)
ACH3)        (MACH4)         (MACH5)
ACHN) }N = N  MACHS
CZ∝1,3)      (CZ∝1,4)        (CZ∝1,5)
CZ∝1,N) }N = N  MACHS
 o              o               o
 o              o               o
CZ∝M,3)        (CZ∝M,4)        (CZ∝M,5)
CZ∝M,N) }M = N  STAS,N = NMACHS
```

As can be seen in Figure 1, the "Main" Program is subdivided into four (4) sections or links as specified under the overlay feature of IBJOB (IBM terminology). This feature is required because the large amount of data handled and calculations performed exceeds the capacity of the IBM 7094 digital computer.

2.2.1 LINK 0. This link serves as the driver for other links, calling them into core as required and providing storage allocations for those variables common to all links. Link 0 remains in core during the entire execution time of the program.

2.2.2 LINK 1. This link establishes a vector which specifies the table IDs and trajectory ID required during the run. This is done by reading in each ID required or by reading a unique ID which establishes an internally stored array of IDs to be used. This will allow the user to specify only one control card requiring the program to use the data available on a specified magnetic tape.

Using the TRAJ ID from this array, the time varying trajectory parameters are read in and written out on the "Auxilliary Trajectory Tape". A vector of TIME and MACH are saved in core. Other control and input data cards are read in at this time.

The aerodynamic normal force distribution tables are then read in, ordered, and stored on disk or magnetic tape for ready access in computing the aerodynamic coefficients.

For each time instant (T_V) available on the "Vibration Data Tape", the aerodynamic coefficients are computed utilizing the MACH vs TIME vector to determine the normal force distribution at that T_V (a vector of T_Vs is also established at this time). Interpolation between distributions at different MACHs may be required. These coefficients and the vibration data at each T_V is then stored on the "Auxilliary Aero Tape".

2.2.3 LINK 2. This link utilizes the data stored on the "Auxilliary Trajectory Tape" and the "Auxilliary Aero Tape" for computation of the Aij, Bij, and Cij matrices at each T_V available from the "Vibration Data Tape". Additional data in the form of rocket engine parameters, sensor locations, etc. has been read in LINK 1 (see Figure 3 - Mavrik input).

An additional feature of LINK 2 will be the computation of "General Basic Data" at each time instant (Tn) available from the trajectory. This data will consist of:

MNEMONIC	MATHEMATICAL SYMBOL	DEFINITION	UNITS	ARRAY	VALUE ASSUMED IF NOT LOADED
*XHPS	X_{HPS}	SWIVEL ENGINE HINGE POINT			
X SUBK	X_K	STA. NO. FOR RIGID BODY B.M		10	
X SUBA	X_{ai}	STA. NO. LOCATION			
		OF ACCELEROMETER		2	
X SUBE	X_E	ENG. SWIVEL			
X REF	X_{REFi}	ITH TANK		30	
X SUBS	$X_{s,j}$	CG OF jTH STRU.		10	
X SUBR	X_{Ri}	RATE GYRO			
ZETA A	ζ_{ai}	% CRITICAL DAMP-ACCELEROMETER		2	
B	ζ_{bi}	BENDING		6	
E	ζ_E	ENGINE			
F	ζ_{fi}	SLOSHING		30	
M	ζ_m	α-METER			
		(MECHANICAL)			
R	ζ_{ei}	RATE GYRO		2	
V	ζ_v	α-METER			
		(VISCOUS)			
AEROID		ID FOR AERODYNAMIC NORMAL FORCE			
		COEFFICIENT DATA TABLES			
CONID		ID TO DESIGNATE A SPECIFIC DATA			
		ARRAY			
	*NOT REQUIRED FOR COMPUTATION OF [A], [B] & [C]				

FIGURE 3 MAIN PROGRAM INPUT DATA

MNEMONIC	MATHEMATICAL SYMBOL	DEFINITION	UNITS	ARRAY	VALUE ASSUMED IF NOT LOADED
ISUBOE	I_{OE}	MOMENT OF INERTIA OF SWIVEL ENGINE ABOUT ITS C.G.			
IYYS	I_{yysi}	MOMENT OF INERTIA OF iTH STRUCTURE		10	
MSUBE	M_E	MASS OF SWIVEL ENGINE		10	
MSUBS	M_s	MASS OF iTH STRUCTURE			
MPO	M_{poi}	MASS OF PROPELLANT IN iTH TANK AT $t < 0$		30	
OMEGA A	W_{ai}	NATURAL FREQ. - ACCELEROMETER		2	
OMEGA B	W_{bi}	NATURAL FREQ. - BENDING		6	
OMEGA E	W_E	NATURAL FREQ. - SWIVEL-ENG.			
OMEGA R	W_{Ri}	NATURAL FREQ. - RATE GYRO		2	
OMEGA V	W_v	NATURAL FREQ. - α-METER		2	
STRUNO		STRUCTURE NUMBER ASSOCIATED WITH iTH TANK		30	
TANKID		TANKID FOR SLOSHING PARAMETERS OF iTH TANK		30	
VIYY	ΔI_{yy}	MULTIPLIER FOR VARYING I_{yy}		10	
VXCG	ΔX_{cg}	MULTIPLIER FOR VARYING X_{cg}		10	
VXA1	ΔX_{a1}	MULTIPLIER FOR VARYING X_{a1}		10	
VXA2	ΔX_{a2}	MULTIPLIER FOR VARYING X_{a2}		10	
VXR1	ΔX_{R1}	MULTIPLIER FOR VARYING X_{R1}		10	
VXR2	ΔX_{R2}	MULTIPLIER FOR VARYING X_{R2}		10	
VXV	ΔX_v	MULTIPLIER FOR VARYING X_v		10	
VCZA	$\Delta C_{z\alpha}$	MULTIPLIER FOR VARYING $C_{z\alpha}$		10	
VCPZ	ΔX_{cpz}	MULTIPLIER FOR VARYING X_{cpz}			

FIGURE 3 MAIN PROGRAM INPUT DATA

1. Mass, center of gravity, and inertia data for each structure (stage) making up the vehicle. The total mass, center of gravity, and inertia for the entire vehicle (less expendable propellants) is also presented.

At each time instant (Tn);

2. Trajectory parameters from the "Auxilliary Trajectory Tape", TIME, F, Fs, X, M, MACH, ALT, q, and V.
3. Aerodynamic normal force coefficients and the center of pressure from the "Tables Tape",
   Cz and Cpz
4. Sloshing parameters for each tank from the "Table Tape",
   Mp, Msp, Ws, ICORR, Isp, and Ip.
5. Rigid body parameters,
   N'z, R', C_1, C_2, K_1, K_2, K_3, X_E, X_A, X_V, and X_R.

For some stability analysis, it is desired to evaluate the overall system stability under conditions when certain parameters have values other than nominal. LINK 2, therefore, has the capability of evaluating the matrix elements for various numerical values of these parameters.

2.2.4 LINK 3. This link will store the elements of the Aij, Bij, and Cij matrices on a magnetic tape ("ODDF Tape") in a format readily useable by the "Stability Analysis - Pitch Plane" Program. Ploynomial curve fits of each element as a function of time (T_V) will be generated and stored on the magnetic tape for use in the "Vehicle Response Program".

Visual output in the form of tabular listings and automatic SC4020 plots of desired parameters as function of time (T_V and/or T_n) will be available.

2.3 "B" Program

This program will be the "utility" program of the system. Its function will be to edit, correct, and modify the stability coefficients data tape for use in other programs. This editing and correcting will consist of changing individual elements or entire rows or columns in the data matrix. Modification would consist of reordering the rows and columns and compressing the matrix to agree with the input format of other programs.

Provisions are also made to generate polynomial curve fits of selected elements of the modified matrices as a function of time and/or automatic SC4020 plots as a function of time for any or all of the elements.

It should be noted that the order of editing, correcting, or modifying is not fixed. These functions may be performed in any order desired. A suggested input format is shown in Figure 4.

MNEMONIC	MATHEMATICAL SYMBOL	DEFINITION	UNITS	ARRAY	VALUE ASSUMED IF NOT LOADED
COMP	-	COMPRESS MATRIX SAVING ROWS			
		& COLUMNS INDICATED			
I	i	ROWS TO BE SAVED			
J	j	COLUMNS TO BE SAVED			
MOD	-	MATRIX IS TO BE MODIFIED			
TIME (I)	Tv(i)	TIMES TO BE MODIFIED			
A^RC (J)	A_{cj}	ELEMENTS IN ROWS TO BE			
B^RC (J)	B_{cj}	MODIFIED			
C^RC (J)	C_{cj}				
ACC (J)	A_{ic}	ELEMENTS IN COLUMNS TO BE			
BCC (J)	B_{ic}	MODIFIED			
CCC (J)	C_{ic}				
REORD	-	MATRIX IS TO BE REORDERED			
ROW 1		RENUMBERING OF ROWS			
ROW 2					
↓					
ROW 25					
COL 1		RENUMBERING OF COLUMNS			
COL 2					
↓					
COL 25					
FIT		ELEMENTS TO BE CURVE FITTED			

FIGURE 4 "B" PROGRAM INPUT FORMAT

MNEMONIC	MATHEMATICAL SYMBOL	DEFINITION	UNITS	ARRAY	VALUE ASSUMED IF NOT LOADED
A (I, J)		ELEMENTS TO BE CURVE FITTED			
B (I, J)					
C (I, J)					
PLOT		PLOTTING REQUESTED			
A (I, J)		ELEMENTS TO BE PLOTTED			
B (I, J)					
C (I, J)					

FIGURE 4 "B" PROGRAM INPUT FORMAT

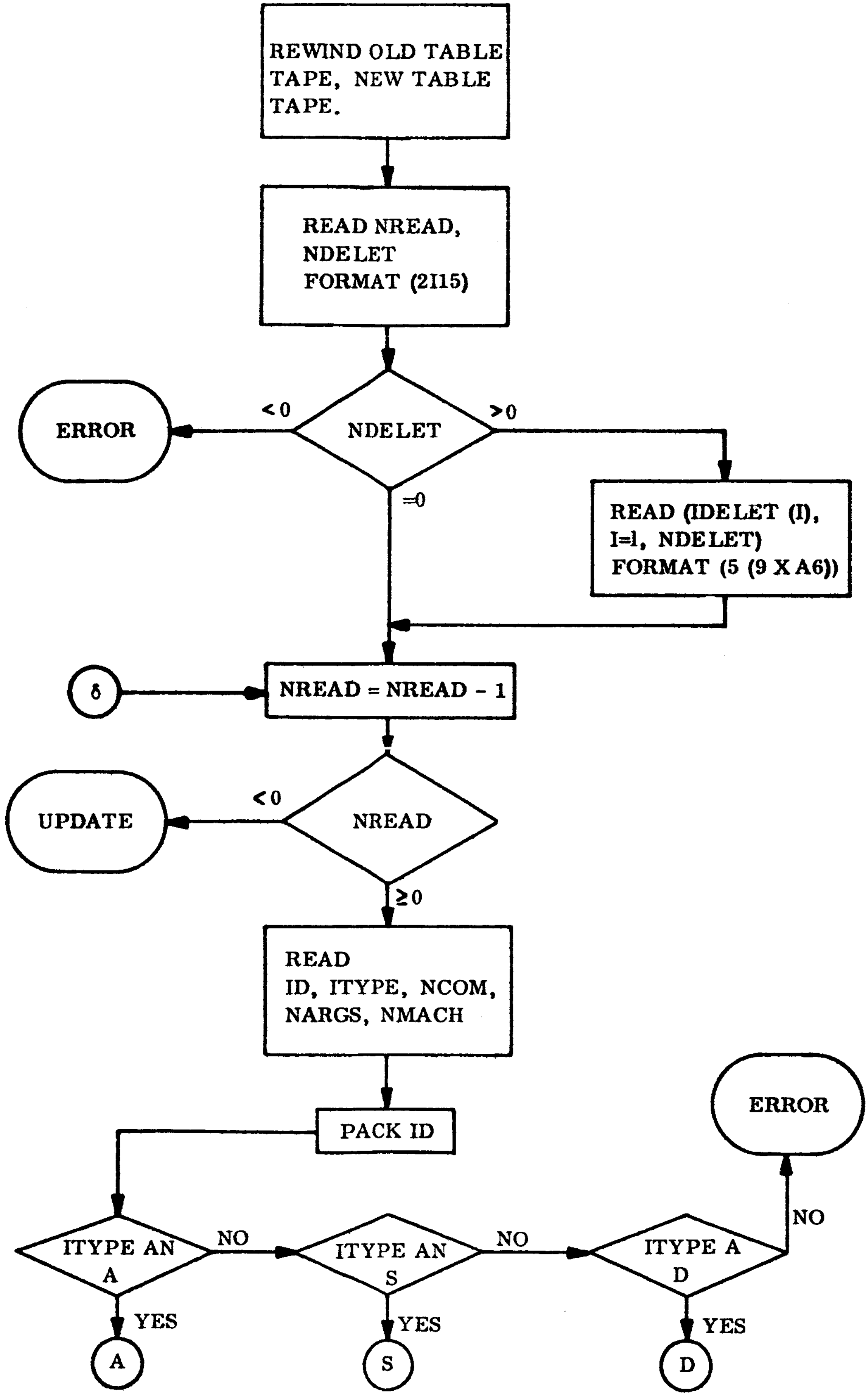
3/CONCLUSIONS

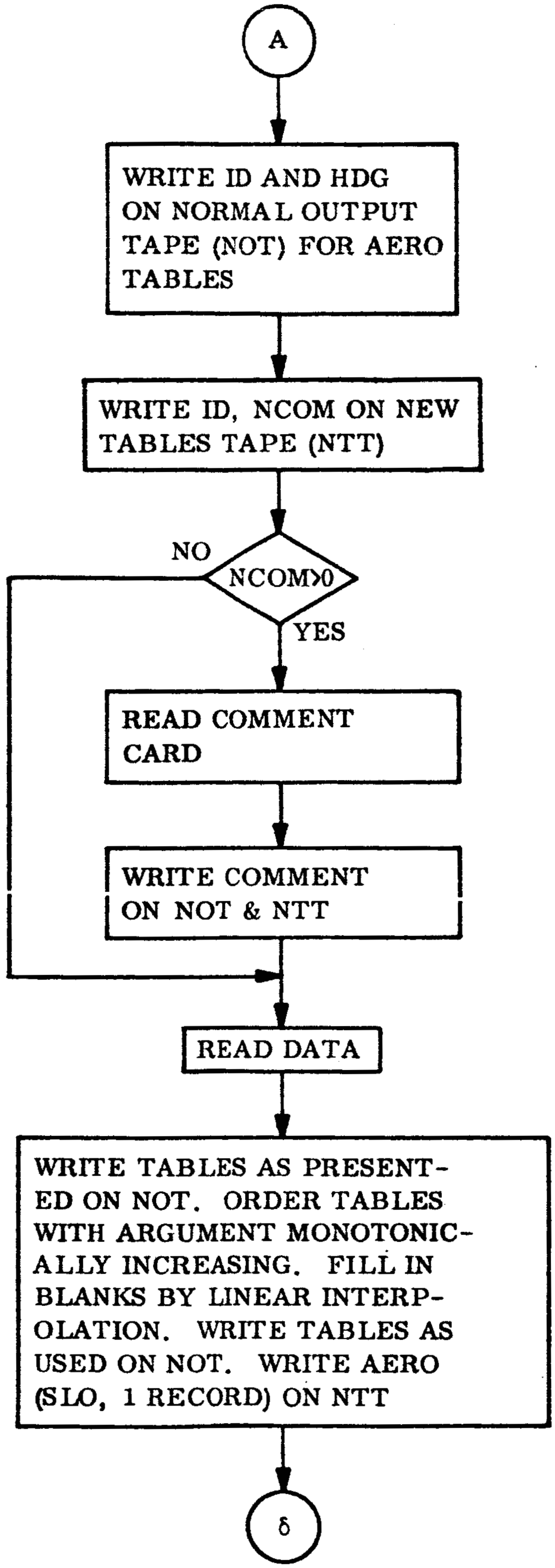
Logic and data flow charts for the three programs ("A", "Main", and "B" Program) which comprise the Optimum Dynamic Data Flow System are presented in the Appendix. These flow charts are detailed to the extent that a working program system could be generated. Input formats and data sources are indicated by the input formats and discussion throughout the text.

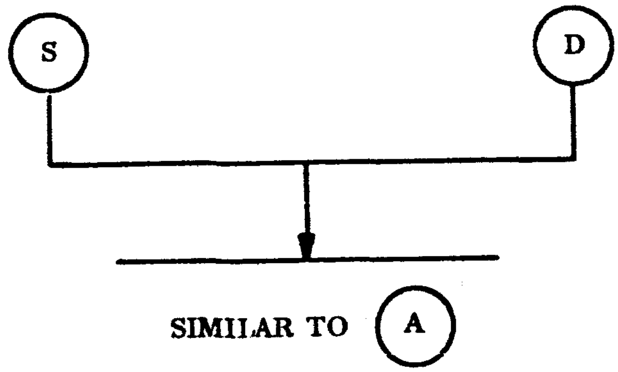
4/REFERENCES

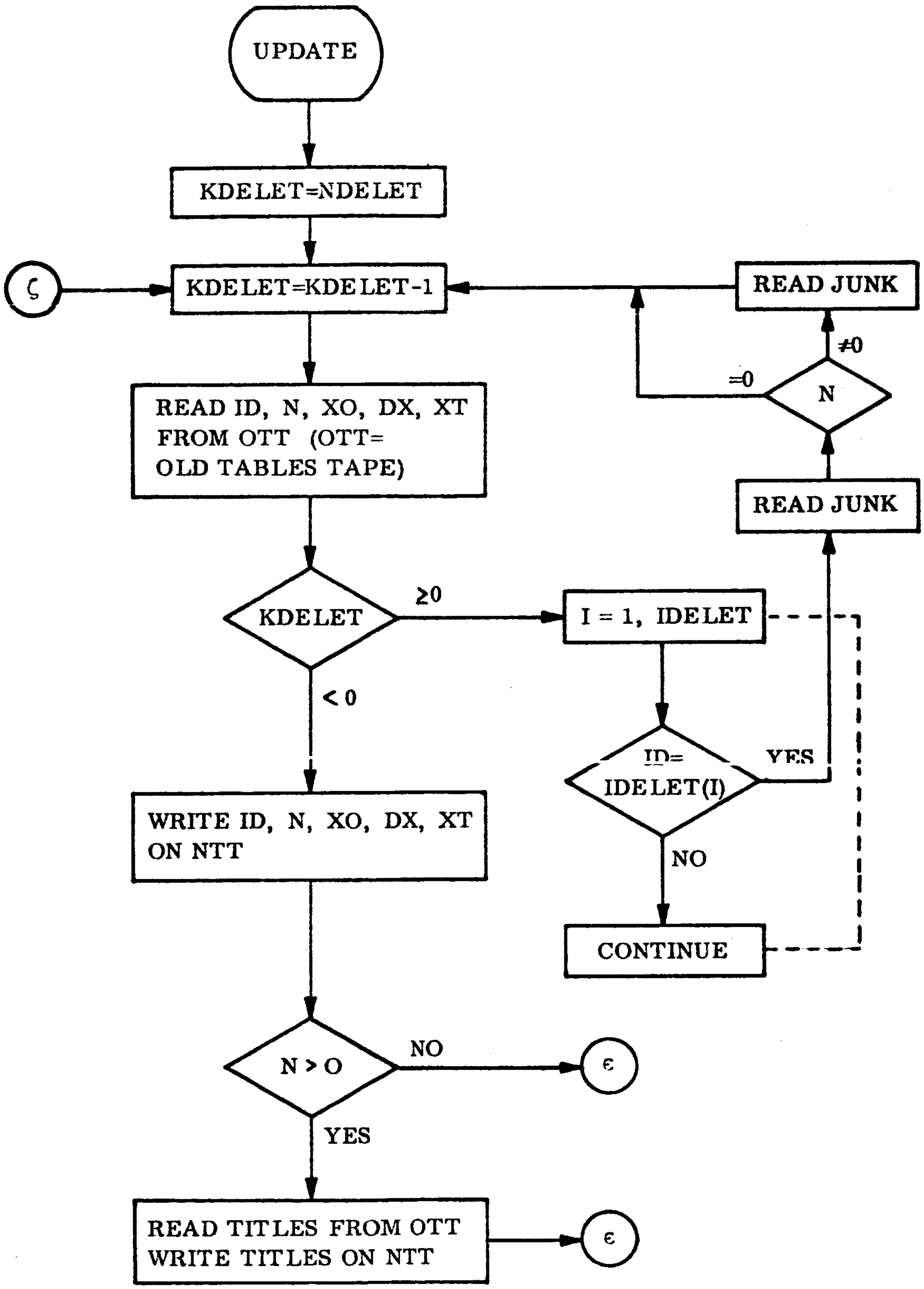
1. NASA TMX-53109, "Numerical Procedures for Stability Studies" by Robert S. Ryan, dated August 19, 1964.

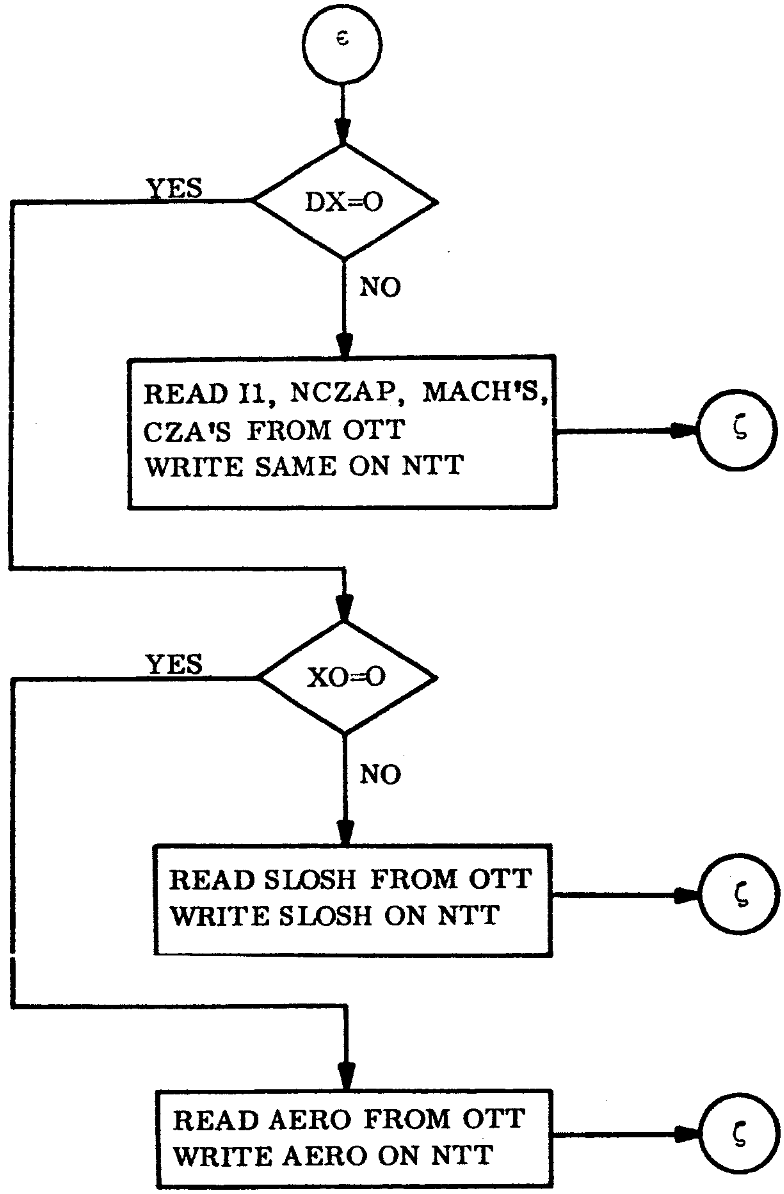
Appendix


REWIND OLD TABLE TAPE, NEW TABLE TAPE.
READ NREAD, NDELET FORMAT (2I15)
NDELET
< 0
ERROR
> 0
=0
READ (IDELET (I), I=1, NDELET) FORMAT (5 (9 X A6))
δ
NREAD = NREAD - 1
NREAD
< 0
UPDATE
≥ 0
READ ID, ITYPE, NCOM, NARGS, NMACH
PACK ID
ITYPE AN A
NO
ITYPE AN S
NO
ITYPE A D
NO
ERROR
YES
A
YES
S
YES
D


A
WRITE ID AND HDG ON NORMAL OUTPUT TAPE (NOT) FOR AERO TABLES
WRITE ID, NCOM ON NEW TABLES TAPE (NTT)
NO
NCOM>0
YES
READ COMMENT CARD
WRITE COMMENT ON NOT & NTT
READ DATA
WRITE TABLES AS PRESENTED ON NOT. ORDER TABLES WITH ARGUMENT MONOTONICALLY INCREASING. FILL IN BLANKS BY LINEAR INTERPOLATION. WRITE TABLES AS USED ON NOT. WRITE AERO (SLO, 1 RECORD) ON NTT
δ


S
D
SIMILAR TO
A


UPDATE
KDELET=NDELET
KDELET=KDELET-1
READ ID, N, XO, DX, XT FROM OTT (OTT= OLD TABLES TAPE)
KDELET
≥0
<0
I = 1, IDELET
ID= IDELET(I)
YES
NO
CONTINUE
READ JUNK
N
=0
≠0
READ JUNK
WRITE ID, N, XO, DX, XT ON NTT
N > O
NO
YES
READ TITLES FROM OTT WRITE TITLES ON NTT


ε
DX=O
YES
NO
READ I1, NCZAP, MACH'S,
CZA'S FROM OTT
WRITE SAME ON NTT
ζ
XO=O
YES
NO
READ SLOSH FROM OTT
WRITE SLOSH ON NTT
ζ
READ AERO FROM OTT
WRITE AERO ON NTT
ζ

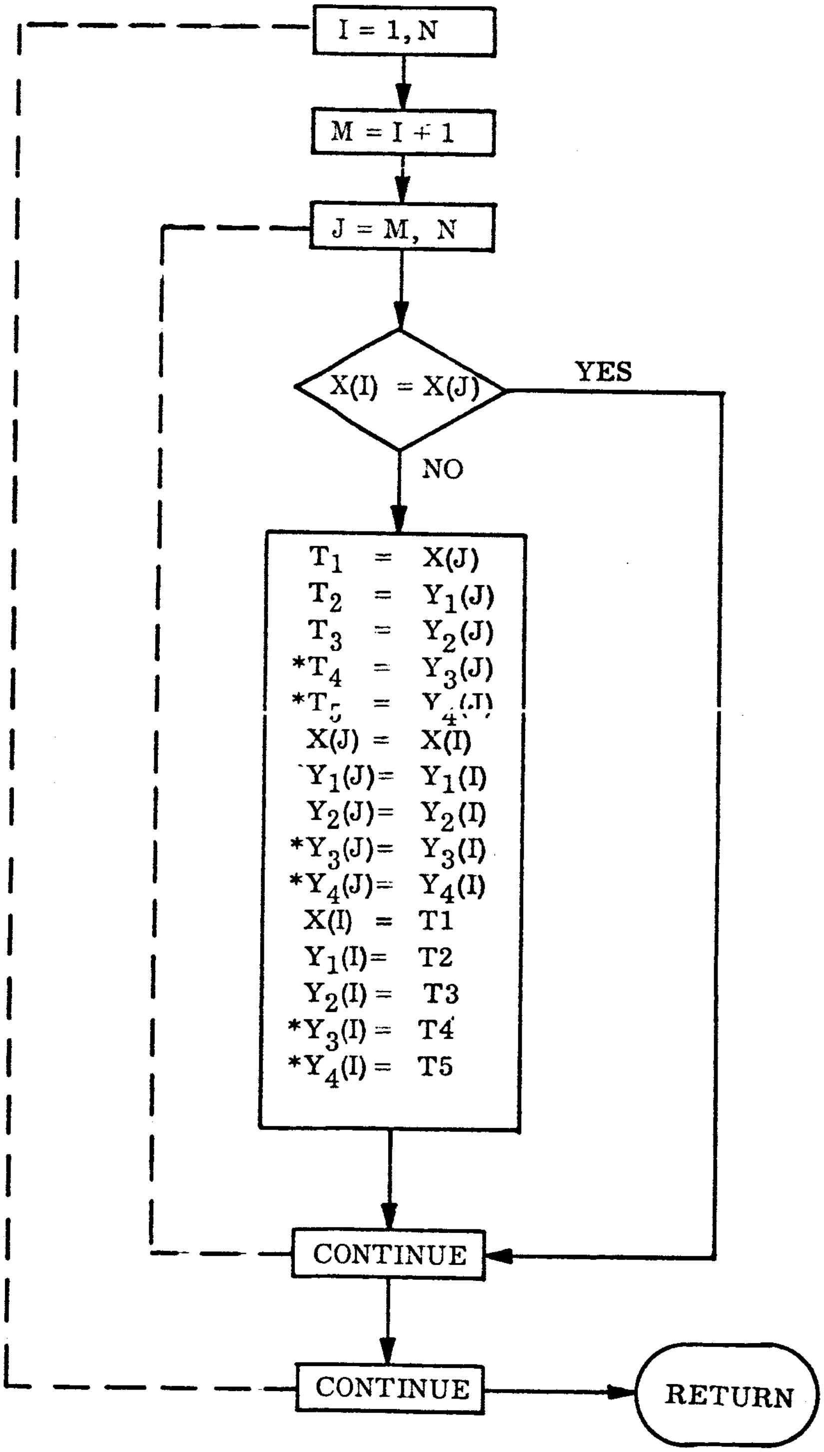
ARRANGE TABLES WITH ARGUMENT INCREASING MONOTONICALLY

SLOSH TABLES

(N, X, Y_1, Y_2, Y_3, Y_4 COMMUNICATED THROUGH COMMON)

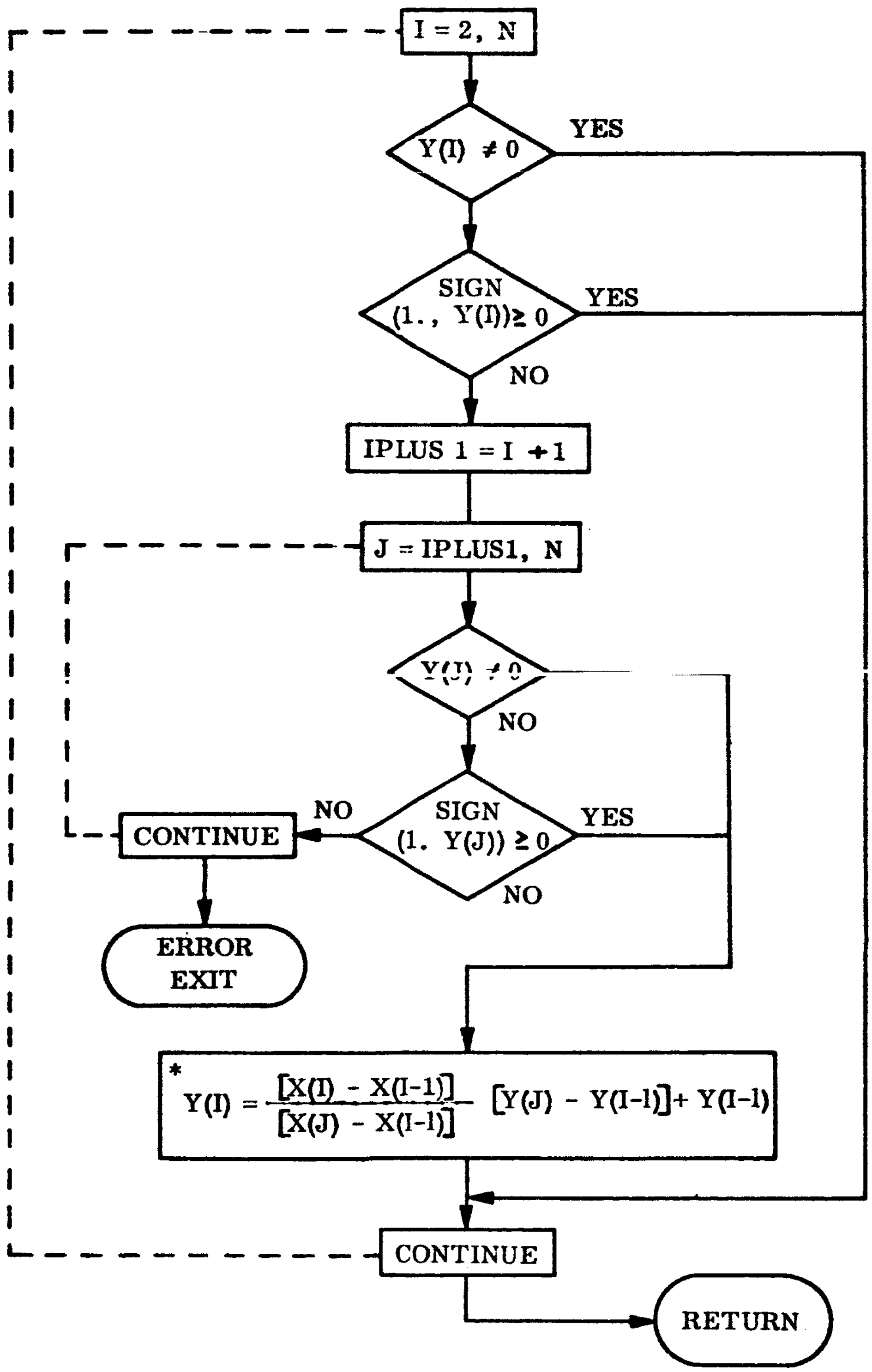
AERO TABLES

(SAME AS SLOSH EXCEPT OMIT *)



FILL IN - 0.S FOR Y_1's, Y_2's, Y_3's, Y_4's

AERO & SLOSH TABLES (CALL ONCE FOR EACH FUNCTION) DISTRIBUTION TABLES ARE THE SAME EXCEPT AS NOTED (COMMUNICATION: X, N THROUGH COMMON, Y THROUGH ARGUMENT LIST.)



*SEE PAGE A8

* FOR DISTRIBUTION TABLES

```
XJ = XO + FLOAT (J-1) * DX
XIM1 = XO + FLOAT (I-2) * DX

Y(I) ={DX/ [XJ-XIM1]}*
       [Y(J) - Y(I-1)]  + Y(I-1)
```

NOTES:

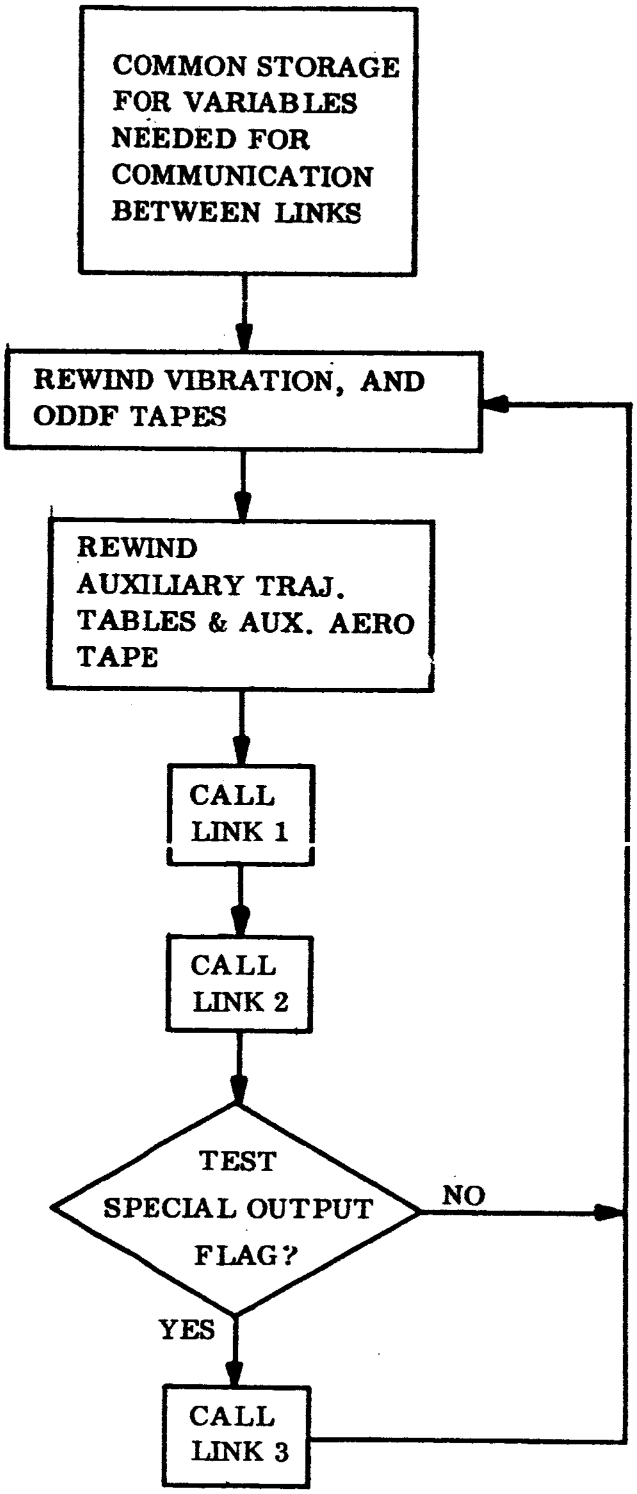
1) VARIABLE TAPE NAME POSSIBLE SHOULD BE USED FOR TABLES TAPE TO AID IN PREPARING AN UPDATED TABLES TAPE.

2) X, Y_1, Y_2 SHOULD BE EQUIVALANCED WITH <u>AERO</u> FOR SHORT LISTING TABLES ON TAPE

3) X, Y_1, Y_2, Y_3, & Y_4 SHOULD BE EQUIVALANCED WITH <u>SLOSH</u> FOR SHORT LISTING TABLES ON TAPE

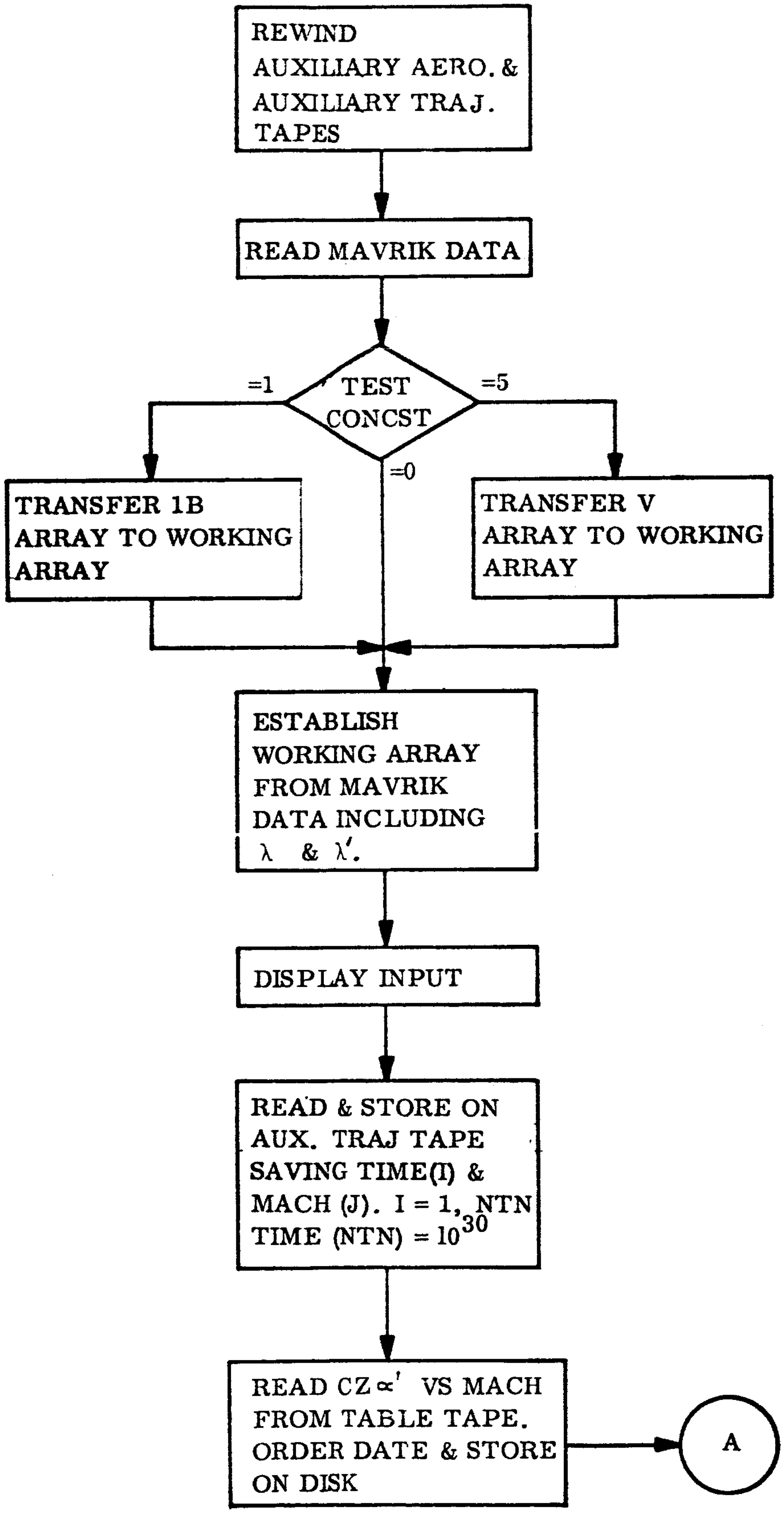
"MAIN" PROGRAM

LINK 0



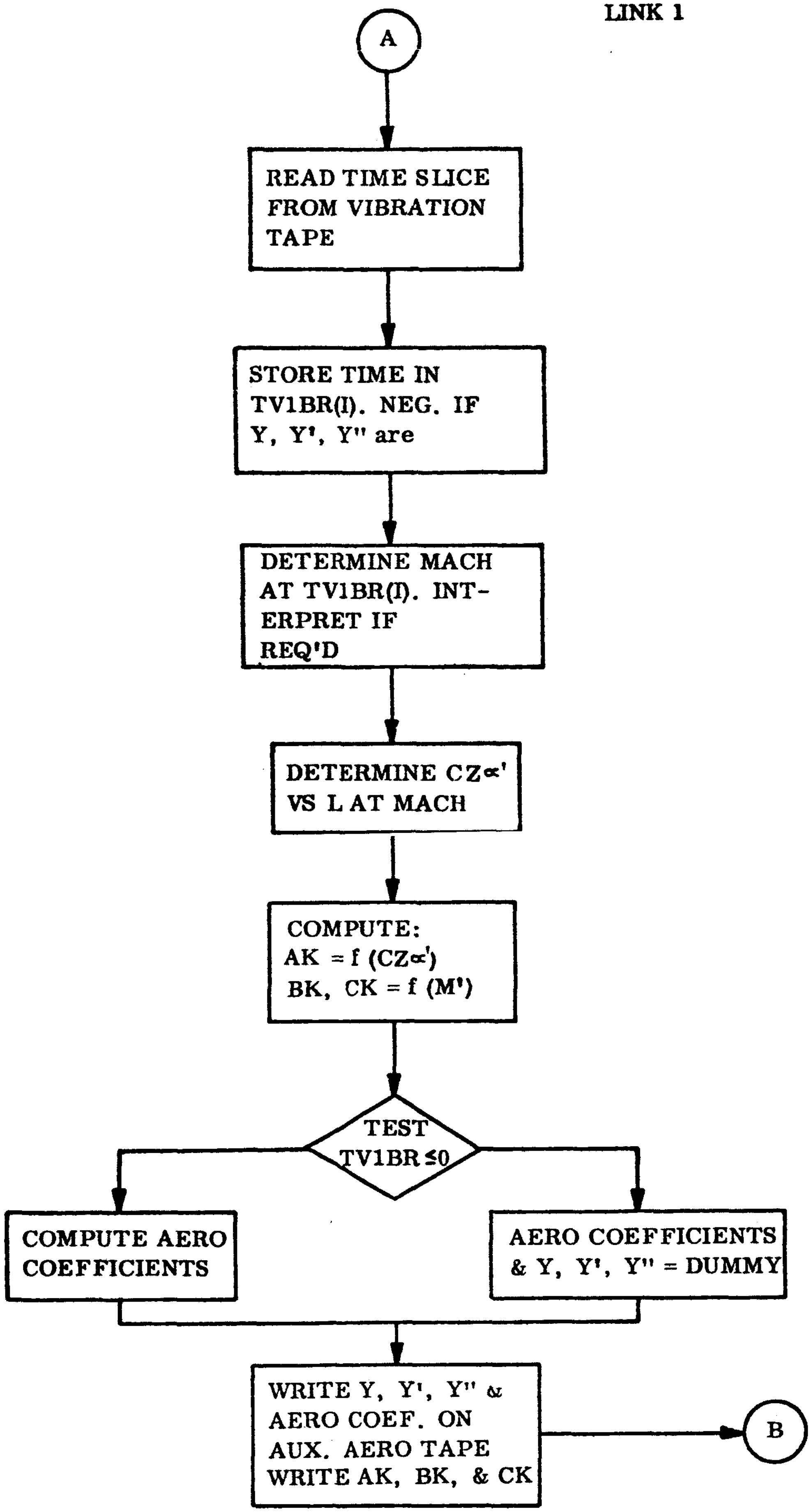
"MAIN" PROGRAM

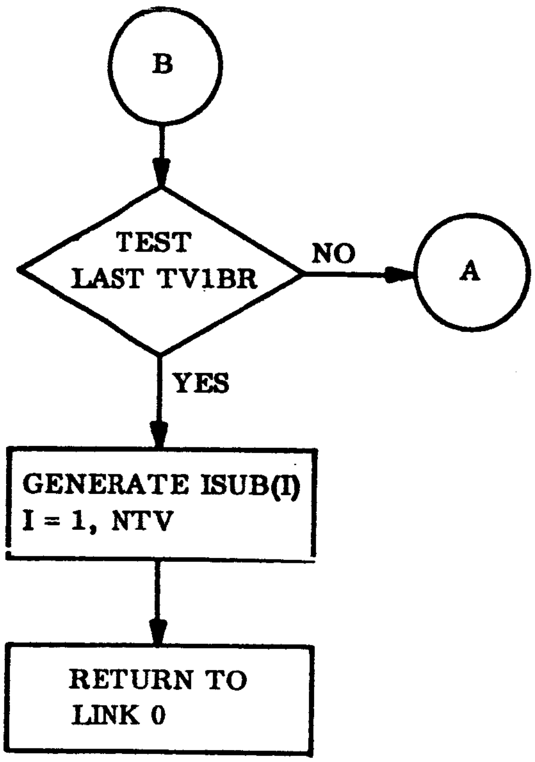
LINK 1



"MAIN" PROGRAM

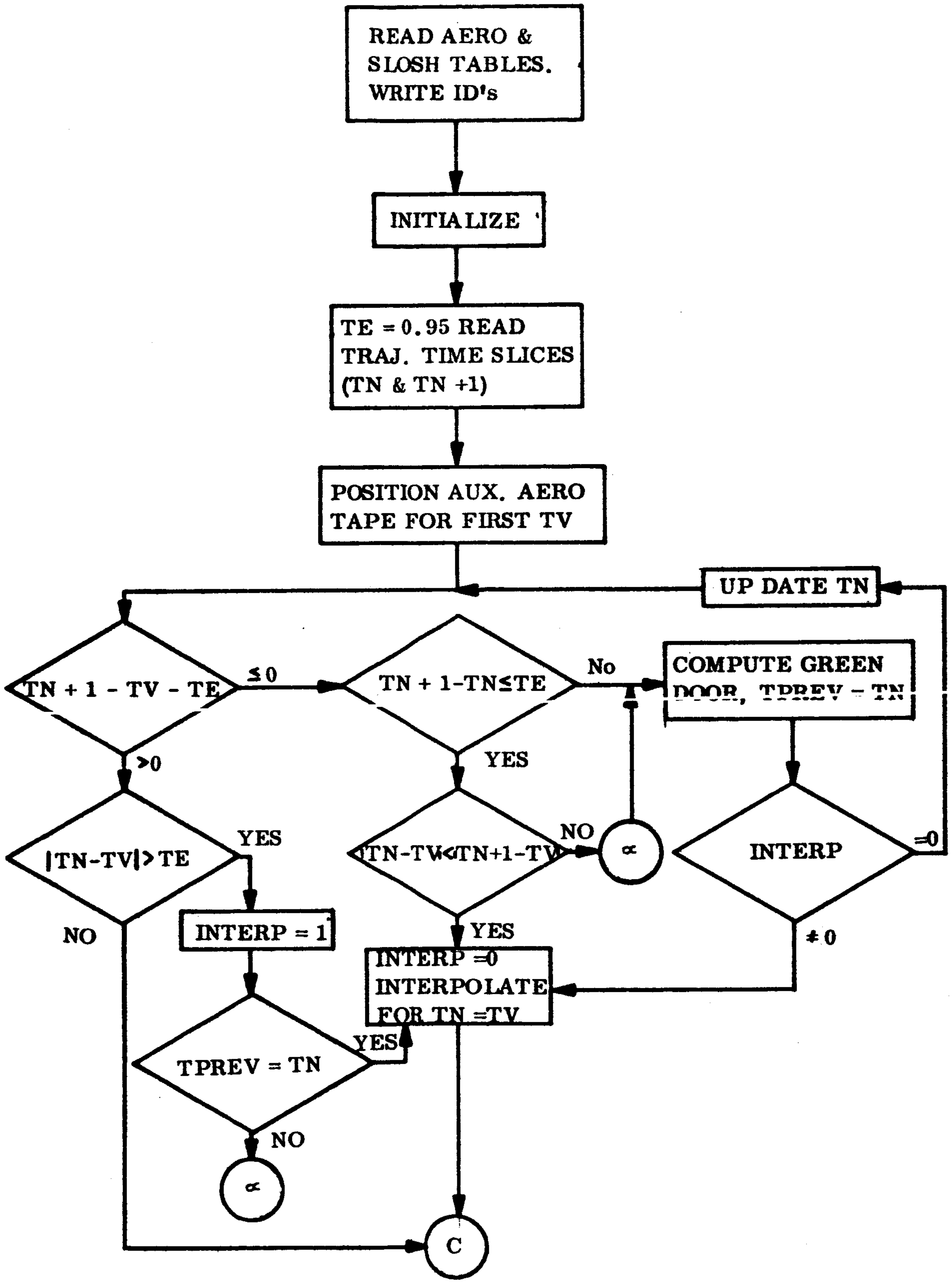
LINK 1

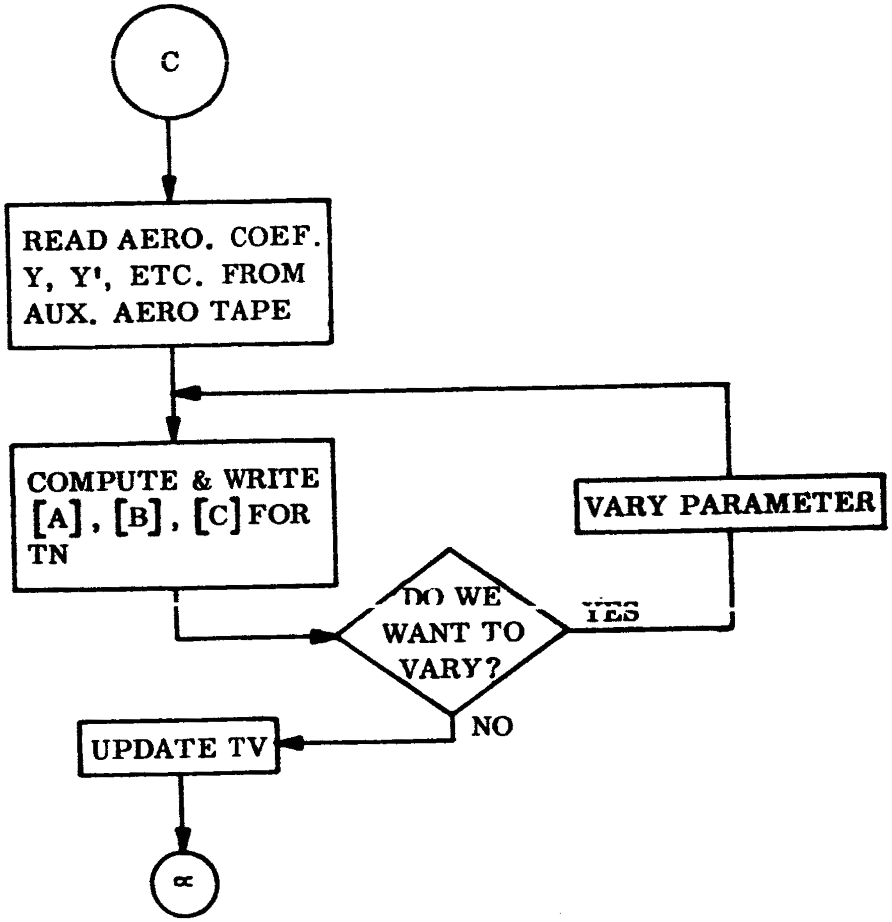



B
TEST
LAST TV1BR
NO
A
YES
GENERATE ISUB(I)
I = 1, NTV
RETURN TO
LINK 0

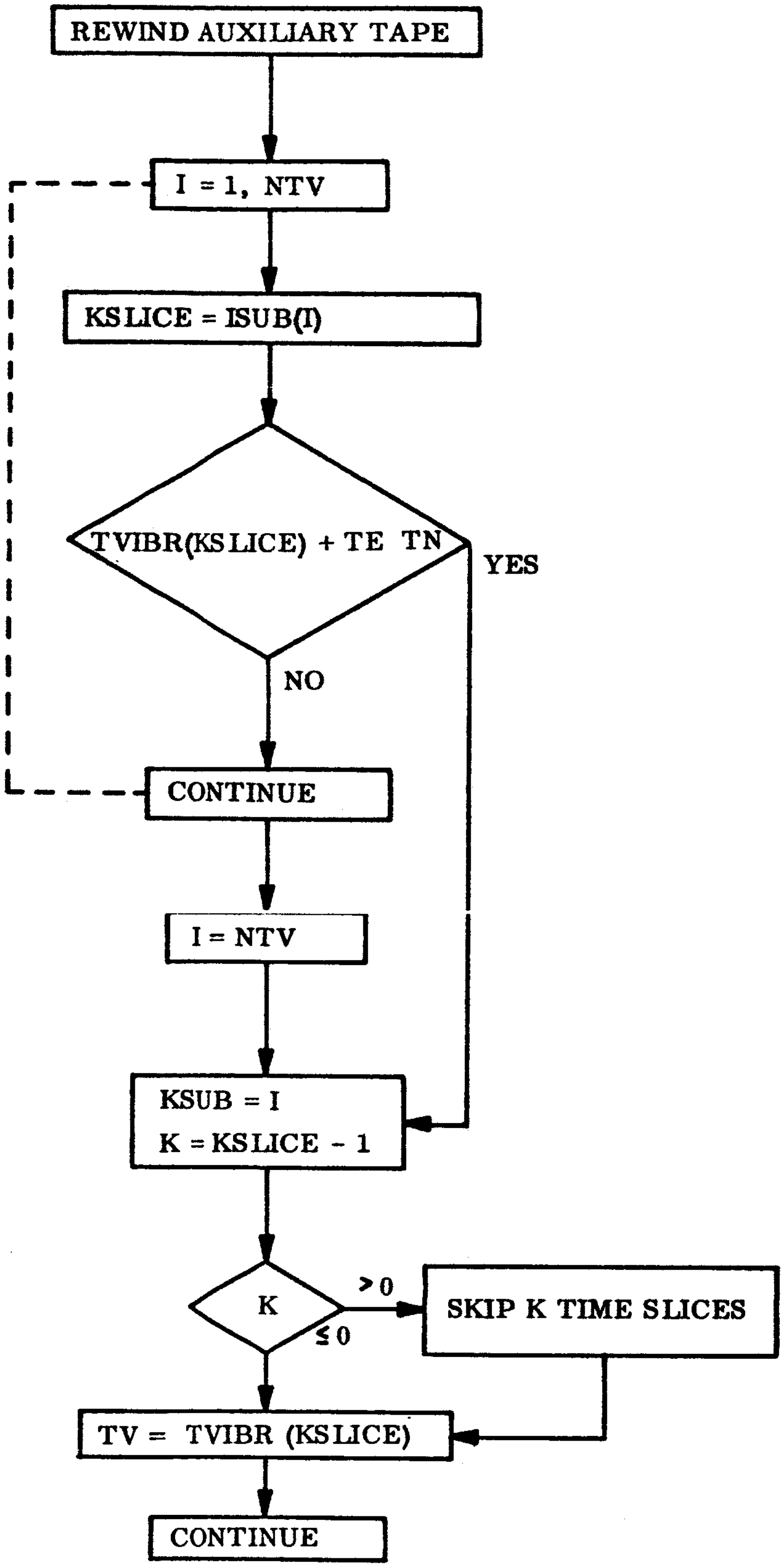
"MAIN" PROGRAM

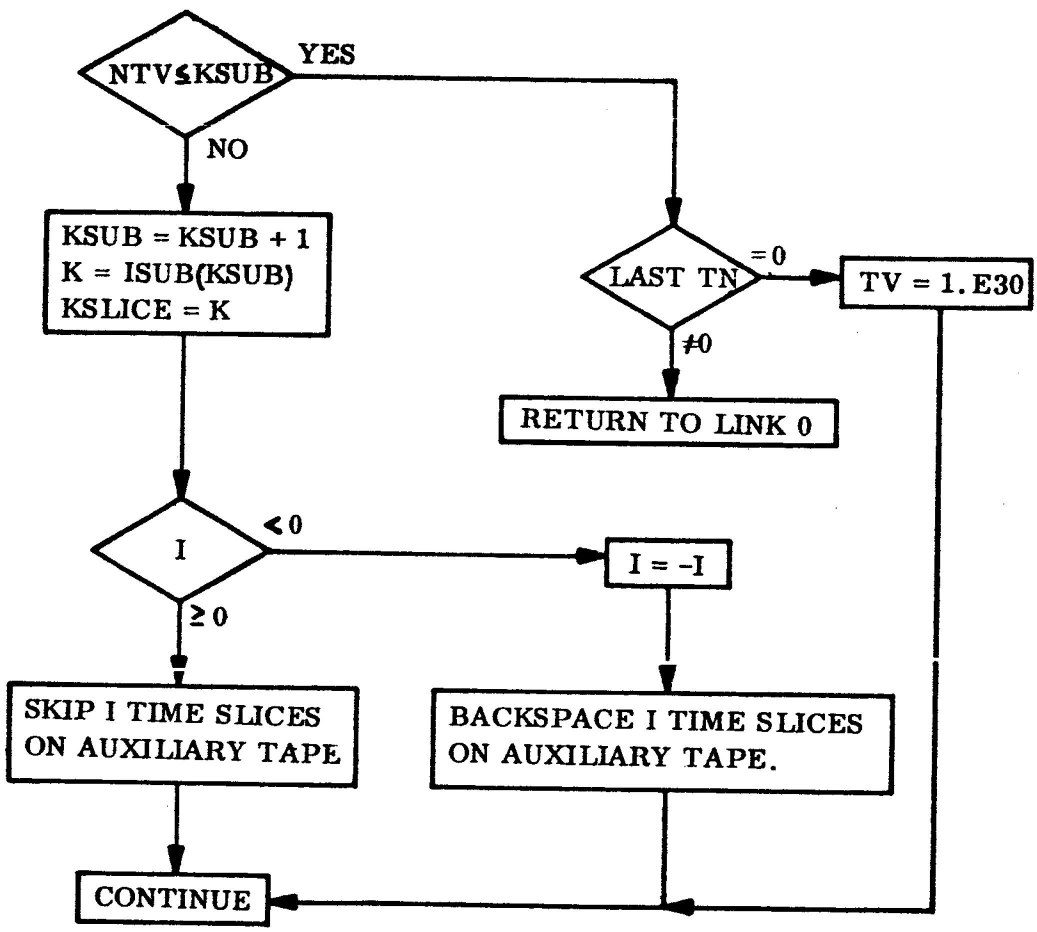
LINK 2

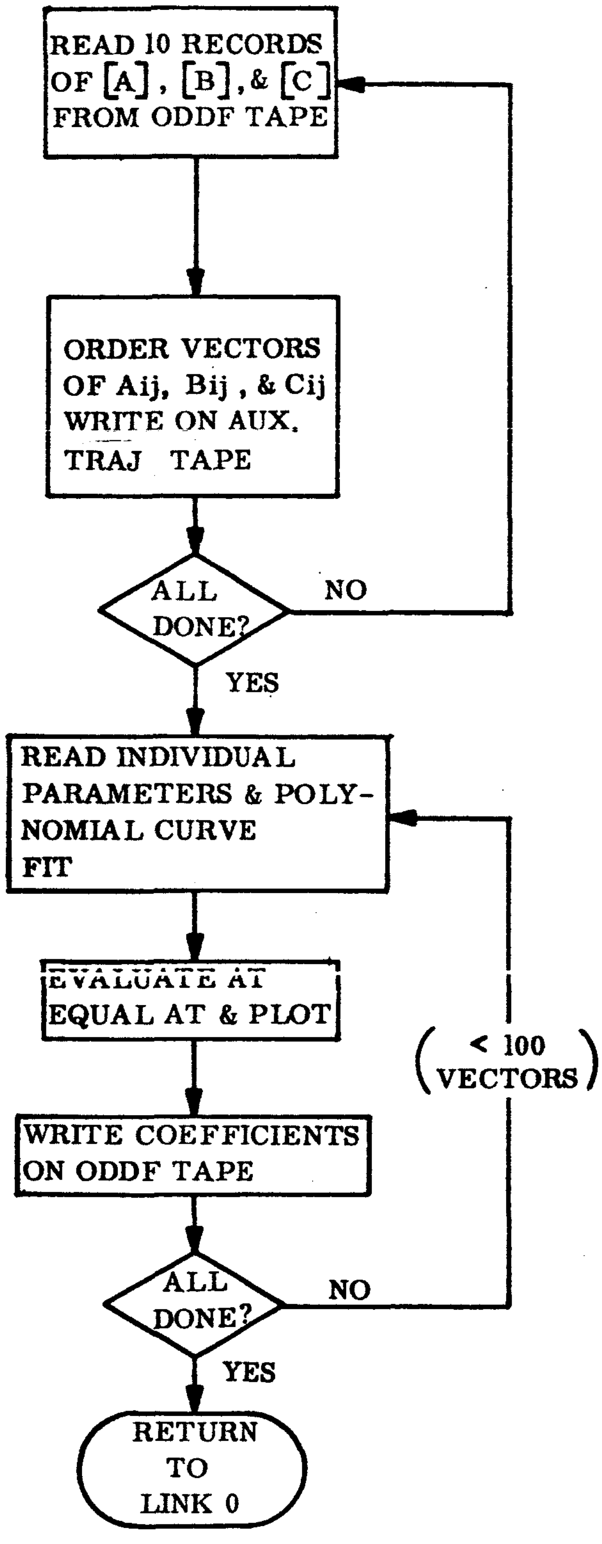


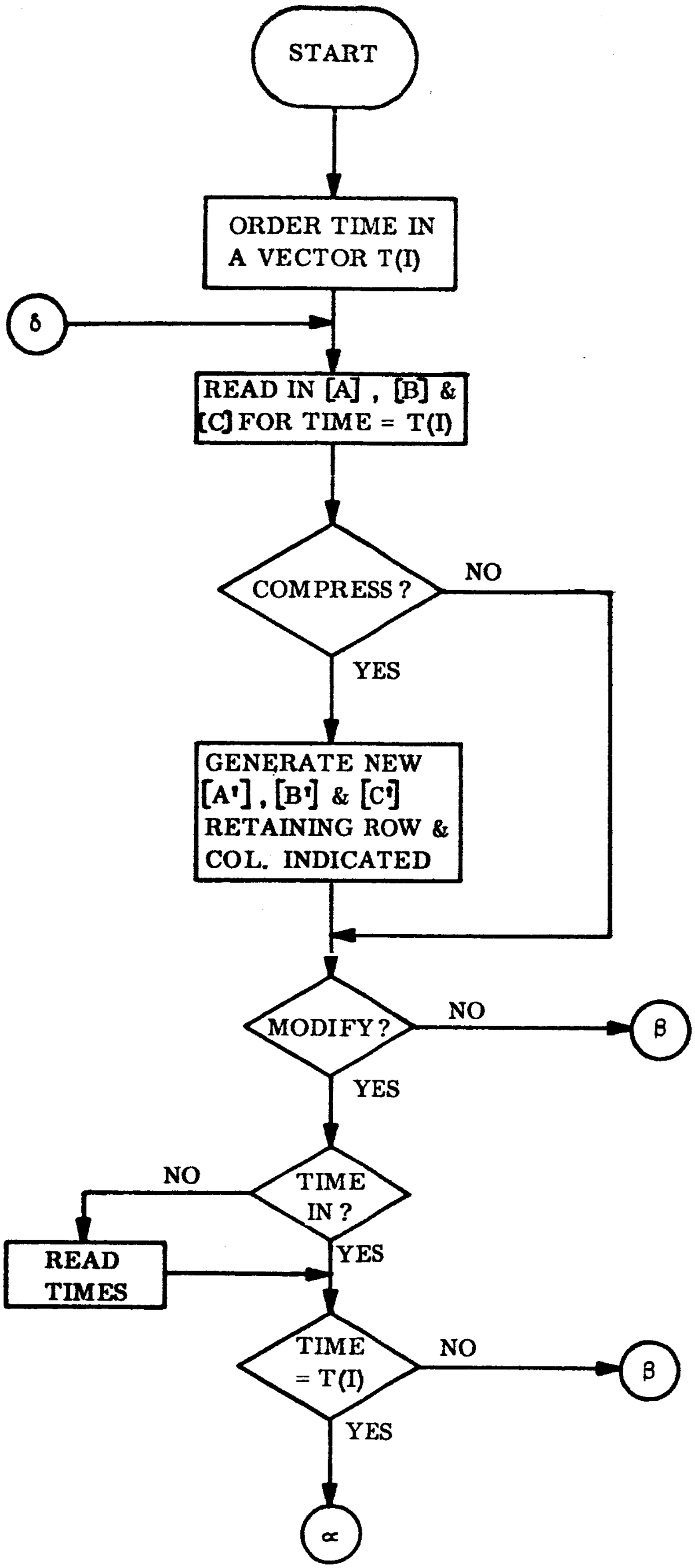

C
READ AERO. COEF. Y, Y', ETC. FROM AUX. AERO TAPE
COMPUTE & WRITE [A], [B], [C] FOR TN
VARY PARAMETER
DO WE WANT TO VARY?
YES
NO
UPDATE TV
∝

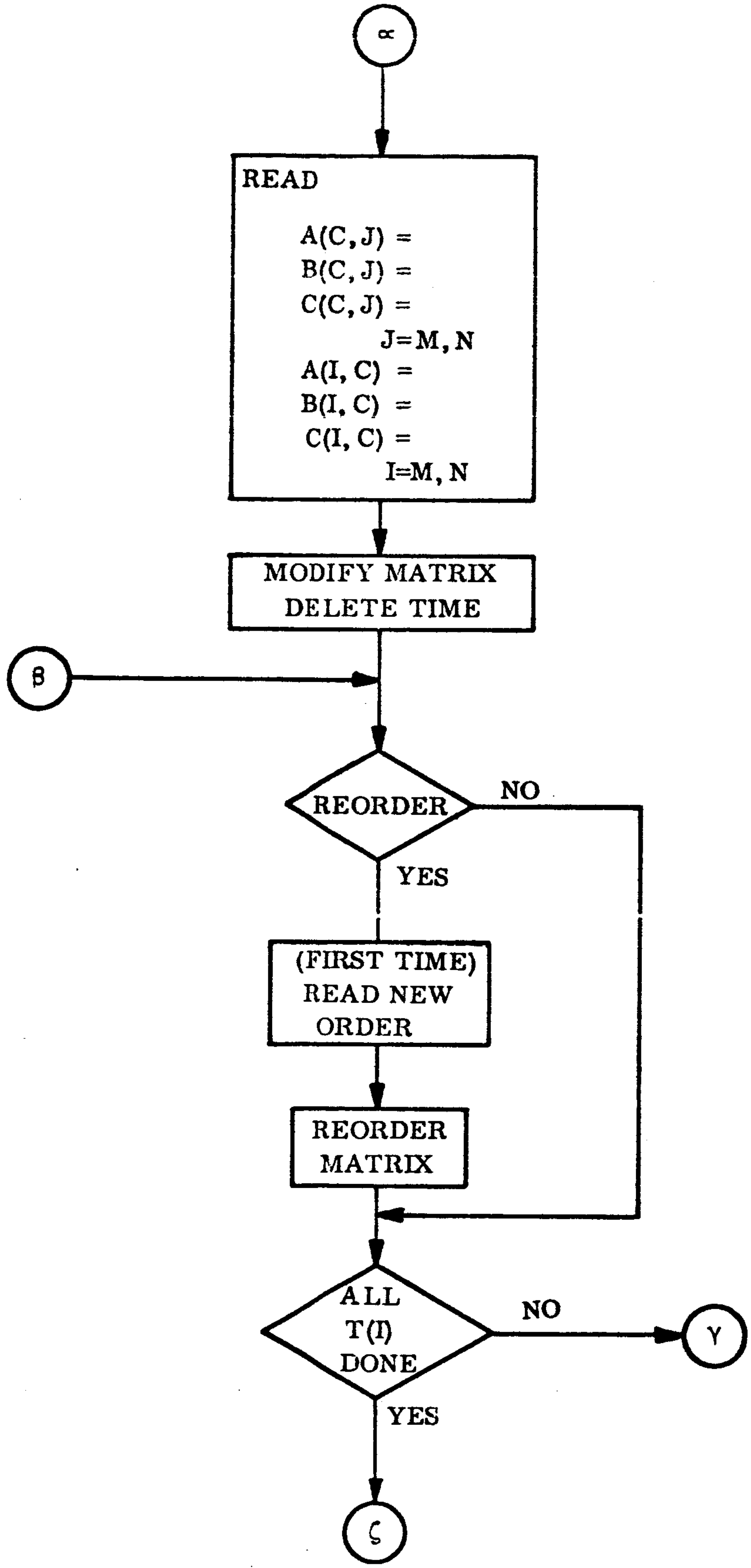
POSITION AUX. AERO TAPE

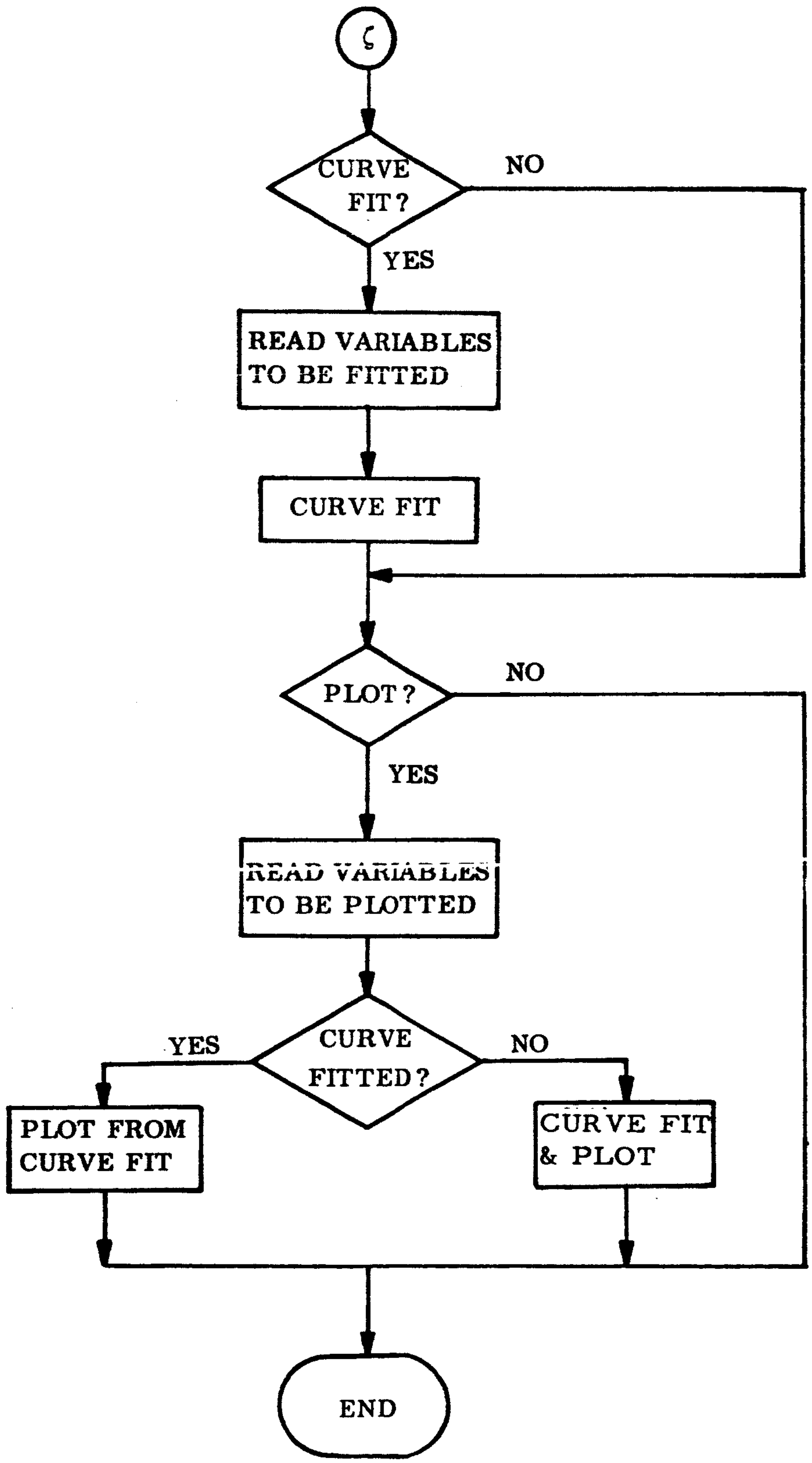



NTV≤KSUB
YES
NO
KSUB = KSUB + 1
K = ISUB(KSUB)
KSLICE = K
LAST TN
=0
TV = 1.E30
≠0
RETURN TO LINK 0
I
<0
I = -I
≥0
SKIP I TIME SLICES
ON AUXILIARY TAPE
BACKSPACE I TIME SLICES
ON AUXILIARY TAPE.
CONTINUE


READ 10 RECORDS OF [A], [B], & [C] FROM ODDF TAPE
ORDER VECTORS OF Aij, Bij, & Cij WRITE ON AUX. TRAJ TAPE
ALL DONE?
NO
YES
READ INDIVIDUAL PARAMETERS & POLY-NOMIAL CURVE FIT
EVALUATE AT EQUAL AT & PLOT
(< 100 VECTORS)
WRITE COEFFICIENTS ON ODDF TAPE
ALL DONE?
NO
YES
RETURN TO LINK 0


START
ORDER TIME IN A VECTOR T(I)
δ
READ IN [A] , [B] & [C] FOR TIME = T(I)
COMPRESS ?
NO
YES
GENERATE NEW [A'] , [B'] & [C'] RETAINING ROW & COL. INDICATED
MODIFY ?
NO
β
YES
TIME IN ?
NO
READ TIMES
YES
TIME = T(I)
NO
β
YES
∝


∝
READ
A(C, J) =
B(C, J) =
C(C, J) =
J=M, N
A(I, C) =
B(I, C) =
C(I, C) =
I=M, N
MODIFY MATRIX
DELETE TIME
β
REORDER
NO
YES
(FIRST TIME)
READ NEW
ORDER
REORDER
MATRIX
ALL
T(I)
DONE
NO
γ
YES
ς



ς
CURVE FIT?
NO
YES
READ VARIABLES TO BE FITTED
CURVE FIT
PLOT?
NO
YES
READ VARIABLES TO BE PLOTTED
CURVE FITTED?
YES
NO
PLOT FROM CURVE FIT
CURVE FIT & PLOT
END