Calculation of formant frequencies of twin-tube and n-tube approximations of the vocal tract.

- J.G.Blom, E.O.Kappner -

Contents.

1. Summary

In this report two programs in Basic Fortran IV are described, which calculate the formant frequencies of models of the vocal tract. The first program calculates the formant frequencies of the so-called twin-tube model. The second, which can be considered as a further development of the twin-tube program, takes a series of 20 connected tubes, each with uniform cross-area, as an approximation of the vocal tract. In both programs the calculations are based on the theory of four terminal networks and the bi-section iteration method of Bolzano. The programs are primarily written for an IBM 1130 system, but can easily be modified for other systems. The console typewriter is used for the input of the parameters. The programs are self-instructing.

2. Introduction

The literature on the calculation of formant frequencies mentions several models of the vocal tract. They all are one-dimensional models. In most cases the boundary conditions are: $u = 0$ (u = velocity) at the vocal cords, and $p = 0$ (p = sound pressure) at the lips. Two types of models can be distinguished:

(a) models in which the cross area is a continuous function of place,
(b) models in which the vocal tract is approximated by a number of tubes with uniform cross-areas.

Examples of type (a) are presented in calculations based on Webster's horn equation, as done, for example, by Ungeheuer (1). A well-known model of type (b) is the so-called twin-tube, which was presented first by Dunn (2), and later by Fant (3). Mol's formula (4), which is built on other parameters, is easier to handle. Since the twin-tube equation is trancendental, in the general case its solution can only be found by numerical methods.

In the case of vocal tract models consisting of a greater number of tubes, it is hardly possible to derive manageable equations. Using a computer, it is possible to avoid the derivation of the equation, as will be shown later on (4.2.6.).

In this report two programs are presented. Both are written in Basic Fortran IV for an IBM 1130 system, but can easily be modified for other systems. The first program, written by Blom, is a numerical solution of the twin-tube equation. The second, the n-tube program,

written by Blom and Kappner, uses an algorithm to determine the formant frequencies of a chain of an arbitrary number of tubes. For practical reasons the number of tubes is limited to 20 in this program. In modifications for other computing systems this limit can be adapted to the precision of the system.
Further work in this field is in progress, and will be reported upon later.
In this report the following notations are used:
S is the cross-area of the tube,
u is the velocity of the air particles,
v is the volume velocity (v = S.u) ,
c is the velocity of sound propagation,
p is the sound pressure,
ρ is the density,
f is the frequency,
ω is the angular frequency (ω = 2πf) .

3. Basic Principles

3.1. Four-pole theory.

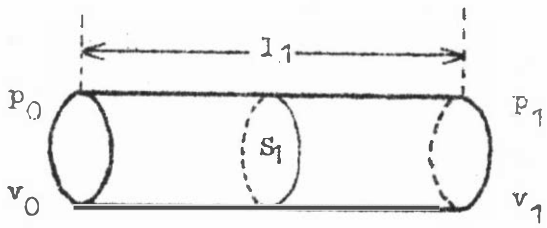


Fig.1

For a tube with uniform cross area, which has a length l_1 and a cross area S_1 , the relation between pressure and volume velocity at both ends (p_0, v_0 and p_1, v_1 respectively) is given by:

$$\begin{bmatrix} p_0 \\ v_0 \end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \begin{bmatrix} p_1 \\ v_1 \end{bmatrix}$$

where A_1 , B_1 , C_1 and D_1 are the four-pole coefficients:

$$A_1 = \cos\frac{\omega l_1}{c} \quad , \quad B_1 = i\,\frac{\rho c}{S_1}\sin\frac{\omega l_1}{c} \quad ,$$

$$C_1 = i\,\frac{S_1}{\rho c}\sin\frac{\omega l_1}{c} \quad , \quad D_1 = \cos\frac{\omega l_1}{c} \quad .$$

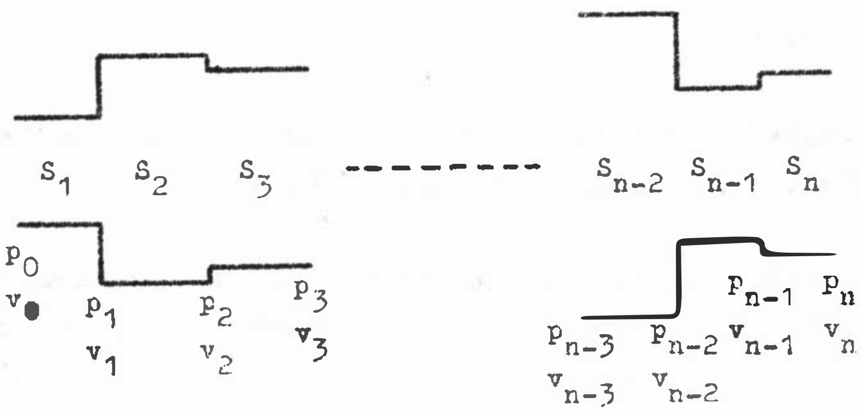


Fig. 2

For n connected tubes with uniform cross areas, with lengths and cross areas respectively l_1, $l_2, l_3, \ldots, l_n$ and S_1, $S_2, S_3, \ldots, S_n$, and pressure and volume velocity at the end of each as given in fig. 2, we have:

$$\begin{bmatrix} p_0 \\ v_0 \end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix} \cdots\cdots \begin{bmatrix} A_{n-1} & B_{n-1} \\ C_{n-1} & D_{n-1} \end{bmatrix} \begin{bmatrix} A_n & B_n \\ C_n & D_n \end{bmatrix} \begin{bmatrix} p_n \\ v_n \end{bmatrix} .$$

If we define: $$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \prod_{i=1}^{n} \begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix} ,$$

then we have $$\begin{bmatrix} p_0 \\ v_0 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} p_n \\ v_n \end{bmatrix} .$$

Assuming that the closed ending (vocal cords) is at the first tube, and the open ending (lips) at the n'th, we have as boundary conditions:

$$v_0 = 0 \qquad \text{and} \qquad p_n = 0 \quad .$$

Thus:

$$\begin{bmatrix} p_0 \\ 0 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} 0 \\ v_0 \end{bmatrix} \quad .$$

Then the condition :

$$D = 0 \qquad (1)$$

must be fulfilled. This is an equation in ω ; the solutions give us the resonance frequencies of the system.

For a small number of tubes, the matrix multiplication can easily be carried out. In the case $n = 2$ (twin-tube) , the condition (1) becomes:

$$C_1 B_2 + D_1 D_2 = 0 \ ,$$

or:

$$i \frac{S_1}{\rho c} \sin \frac{\omega l_1}{c} \cdot i \frac{\rho c}{S_2} \sin \frac{\omega l_2}{c} + \cos \frac{\omega l_1}{c} \cos \frac{\omega l_2}{c} = 0$$

$$\cos \frac{\omega l_1}{c} \cos \frac{\omega l_2}{c} - \frac{S_1}{S_2} \sin \frac{\omega l_1}{c} \sin \frac{\omega l_2}{c} = 0$$

Introducing the parameters:

l = total length = $l_1 + l_2$,

k = ratio of the cross areas = $\frac{S_2}{S_1}$,

Δ = excentricity = $\frac{1}{2} |l_1 - l_2|$ (see fig. 3) and

β = relative excentricity = $\frac{\Delta}{\frac{1}{2} l}$

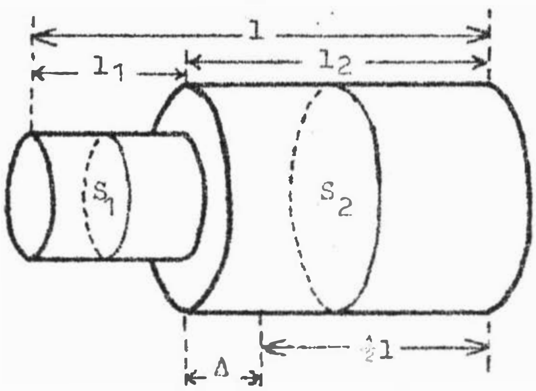
this equation can be reduced as follows:

$$\tfrac{1}{2}\left[\cos\frac{\omega l}{c} + \cos\frac{\omega(l_1-l_2)}{c}\right] + \frac{S_1}{2S_2}\left[\cos\frac{\omega l}{c} - \cos\frac{\omega(l_1-l_2)}{c}\right] = 0$$

$$\left(1+\frac{S_1}{S_2}\right)\cos\frac{\omega l}{c} + \left(1-\frac{S_1}{S_2}\right)\cos\frac{\omega(l_1-l_2)}{c} = 0$$

$$\cos\frac{\omega l}{c} - \frac{1-k}{1+k}\cos\frac{2\omega\Delta}{c} = 0$$

or: $$\cos\frac{\omega l}{c} - \frac{1-k}{1+k}\cos\frac{\omega\beta l}{c} = 0 \qquad (2)$$



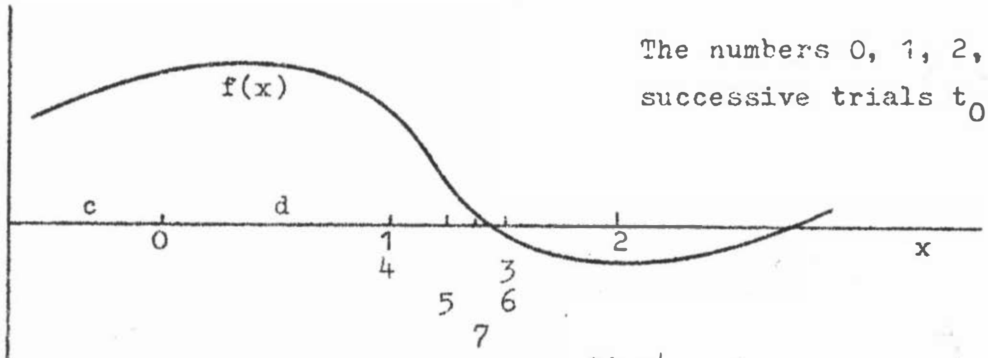
$$\Delta = \tfrac{1}{2}l - l_1 = \tfrac{1}{2}(l_1 + l_2) - l_1 = \tfrac{1}{2}(l_2 - l_1)$$

Fig. 3

Δ has been introduced as an absolute value. Since it only appears under the cosine function, its sign is of no consequence.
The equation (2) is the well-known twin-tube equation in the form given by Mol. The twin-tube program starts from this equation.
Since the complexity of the expression D increases rapidly with the number of tubes, a slightly different approach must be chosen for the n-tube program (see 4.2.5).

3.2. Bi-section method of Bolzano.

Suppose $f(x)$ is a continuous and bounded function on $(0, \infty)$. We want to approximate the values of x, for which $f(x) = 0$. (Let us assume that such values exist.) Let these values be denoted as x_1, x_2, ..., x_n, ... successively. Suppose that we can find a certain value d, $(d > 0)$, such that for each pair of successive zeroes holds : $x_n - x_{n-1} > d$, and a value c $(c > 0)$, such that $x_1 > c$. Then we construct a series of trials, denoted as $x = t_0, t_1, t_2, \ldots, t_n, \ldots$ in the following way.



The numbers 0, 1, 2, ... denote the successive trials t_0, t_1, t_2, ...

Fig.4

The first trial is : $t_0 = c$. We determine the sign of $f(t_0)$.
The next trial is: $t_1 = c + d$, and the sign of $f(t_1)$ is determined. If this sign is the same as the sign of $f(t_0)$, the next trial is: $t_2 = c + 2d$. In this way we continue, every time determining the sign of $f(t_n)$. As long as this sign is the same as that of $f(t_0)$, the next trial is obtained by adding d to the preceding.
We assume that $f(t_n) \neq 0$ for each n. (If $f(t_n)=0$ for a certain n, the zero is found, and the process is stopped.)
We continue, until we have got a trial $t_k = c + kd$, for which the sign of $f(t_k)$ is opposite to the sign of $f(t_0)$. Then the zero x_1 must be between the last two trials, t_{k-1} and t_k. We now "go backward" in steps of $\frac{1}{2}d$ (that means: $t_{k+1} = t_k - \frac{1}{2}d$; $t_{k+2} = t_k - d$), again determining the sign of each t_n, until the first trial t_{k+i} for which the sign of $f(t_{k+i})$ is opposite to the sign of $f(t_k)$. (Thus: $i = 1$ or $i = 2$.) Then x_1 must be between the last two trials, and we "go forward" in steps of $\frac{1}{4}d$. This process is continued until x_1 is approximated sufficiently accurately.
To approximate the value of x_2, we repeat this process: we start from the approximated value of x_1 and take as the first trial $x_1 + d$, and so on. The decision " go forward " or " go backward " must now depend on signs opposite to those, determining this decision when approximating x_1.

It is clear that the error in the approximated value of x_2 is independent of that of x_1.
The iteration method here described is known as the bi-section method of Bolzano. It is well suited to high speed computers.

4. Flow-chart narratives.

Both programs are self-instructing. The instructions are printed on the console printer. The keyboard is used for the input of the parameters, the punching of data decks thus being avoided.

4.1. Twin-tube program.

Appendix III is a listing of the twin-tube program. Appendix I consists of:

(1) a flow-chart of the twin-tube program,

(2) a separate flow-chart of the calculations carried out in the twin-tube program ("CALCULATE" in flow-chart (1)).

Observing the following remarks, the course of the program can easily be read from these appendices.

4.1.1. c is defined as 35000 cm/sec, a normal value for the warm air in the vocal tract. By means of data entry switch 14 this parameter can be changed (statements 130 ff.). In statement 145 a test is built in for extreme values of c.

4.1.2. If data switch 15 is on, the program stops.

4.1.3. Every time when reading parameter values, the program tests the field. This is realised by reading all the places out of field; if a value $\neq 0$ is encountered, an error message is produced.

4.1.4. The counter INT causes the instruction in statement 255 to be printed once only, namely after the first run of calculations.

4.1.5. Three tests for the values of the twin-tube parameters are built in (statements 195, 205, 215.) . In the case of extreme values, the program gives error messages. The tests are the following:

(a) l must be between 10 and 25 cm. This is only because of the practical object of the program: calculating models of the vocal tract. Technically the program could go beyond these limits. Difficulties only arise at very great values for l, for example: a model having k = 8 and $\beta = 0$, would produce, at an l-value of more than 1 meter, frequencies of the first and second formant so close to each other, that they would come within one single approximation step (see 3.2. and 4.1.7.).

(b) k must be between 0.1 and 10. This limitation is for mathematical reasons.

Writing the twin-tube equation (3.1.,(2)) as:

$$\cos \frac{\omega l}{c} = \frac{1-k}{1+k} \cos \frac{\omega \beta l}{c} \quad ,$$

the solutions can be found as the intersection points of two cosine functions, one having maximal and minimal values of +1 and -1, the other of $\frac{1-k}{1+k}$ and $-\frac{1-k}{1+k}$. Both for great and small values of k, the value of $\frac{1-k}{1+k}$ is close to 1.

In this case, in the neighbourhood of those values for ω for which both functions are about maximum (or minimum) , there are two intersection points close to each other (see fig.5). It now may happen that these points come within one approximation step,which means that two formant frequencies may be missed.

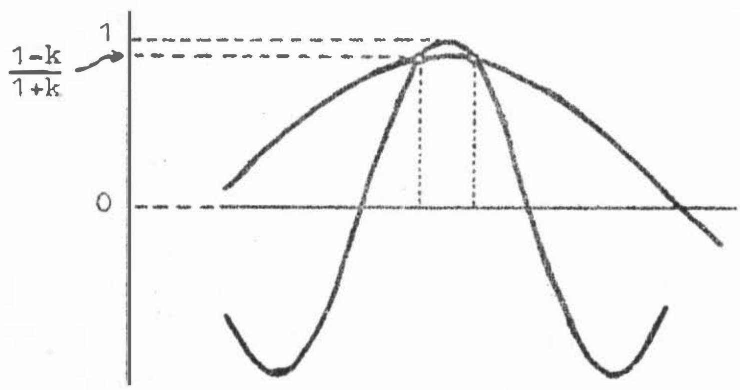


Fig.5

(c) β must be between -1 and +1 . By definition, β has no physical meaning for other values.

4.1.6. Statement 245 + 1 tests for the sign of the expression D (3.1.,(1)), which for the twin-tube has the form of 3.1.,(2). Two parameters T_1 and T_2 are used, each of which is either +1 or -1.

The sign of T_2 changes every time that the sign of D is changed; the sign of T_1 changes every time the program starts to approximate another formant frequency. This is the way in which the decision "go forward/go backward" is governed.
Since $0.1 \leq k \leq 10$, (see 4.1.5.,(a)), it follows that:

$$0 < \frac{1-k}{1+k} < 1 ,$$

and:

$$\cos\frac{\omega l}{c} - \frac{1-k}{1+k}\cos\frac{\omega \delta l}{c} > 0 \text{ for small values of } \omega .$$

The first trial t_0 (see 3.2.), which only served to determine the sign of the expression D for small values of ω , can be omitted. Both T_1 and T_2 are first defined as -1 .

4.1.7. The value of F (trial frequency) is first defined as zero, and DF (increment of F) as 32 Hz. Therefore the trials t_0, t_1 , t_2,.... are: 32, 64,96, ...Hz, until the sign of D changes. In other words, our assumption is that the difference between two successive formant frequencies is more than 32 Hz, and the first formant frequency is more than 32 Hz.

4.1.8. In statement 235 the step length is devided by 2, and 235 + 1 tests for the step length: if this is less than ¼ Hz, the process is stopped. Statement 250 represents a rounding-off procedure: ½ Hz is added to the last trial, and the figures to the right of the decimal point are deleted. This deletion is effected by the FORMAT-statement; this is not mentioned in the flow-chart. In this way we round off to the nearest whole number of Hz. If the fractional part of the last trial is exactly .5, rounding off occurs to the next greater whole number of Hz.

4.2. n-tube program.

Appendix IV is a listing of the n-tube program. Appendix II contains the flow-chart, and, just as in the case of the twin-tube program, a separate flow-chart for the calculations. The following remarks refer to these appendices.

4.2.1. In three places the flow-chart has the words: WRITE INSTRUCTION, followed by a number in brackets. These numbers refer to the sections of Appendix VI where the respective instructions are shown.

4.2.2. There are two input modes:
mode 1: all tubes have the same length,
mode 2: there are tubes which have different lengths.

4.2.3. The following table gives a survey of the parameters to be entered through the keyboard and of the data entry switches by means of which the parameter values can be changed.

Name of parameter	meaning	data entry switch
MODE	input mode, see 4.2.2	1
NMB	number of tubes (≤ 20)	2
KTOT	number of formant frequencies to be calculated (≤ 4)	3
C	velocity of sound	4
S(I)	diameter of the Ith tube	9, to change diameters of all tubes
	(I=1, ...,NMB)	8, to change diameter of one tube only
In the case of mode 1:		
LN	length of each tube	5
In the case of mode 2:		
LNGTH(I)	length of the Ith tube (I= 1,...., NMB)	7, to change lengths of all tubes
		6, to change length of one tube only

If data switch 6 or 8 is on, the program first inquires which tube must be changed.
Data switch 15 causes the program to stop.
The course of the program when testing for the different data switches can easily be read from the flow-chart.

Contrary to the twin-tube program, no tests are built in for parameter values and for the field. The program, therefore, is supposed to work in an error-free environment. Errors in the calculated formant frequencies are data-dependent.

4.2.4. The diameters of the tubes are specified in the input. Since the calculations are in terms of cross areas, the diameters have to be converted accordingly. Only the ratios of the cross areas are of importance, so it is sufficient to square the diameters (statements 205-210).

4.2.5. Contrary to the twin-tube program we do not have an equation to start from. We therefore proceed as follows. The trial frequency is filled in in the four-pole coefficients of the different tubes, so that these become constants. With these constants, the matrix multiplication is carried out, which gives us the numerical value of the expression D for this trial.Depending on this value we take the next trial as described in 3.2.
In the program this is realised as follows.
After defining the trial frequency, the unit matrix is loaded in a buffer AMAT (360 ff.).
A matrix BMAT is defined as the four-pole matrix of the first tube in which the trial frequency is filled in (depending on the mode: statements 365 ff. and 375 ff, or 380 ff.). Subsequently AMAT x BMAT is calculated (385 ff.), and this product is stored in buffer AMAT (385+4). Now BMAT is defined as the four-pole matrix of the second tube, and AMAT x BMAT is calculated again, and this product is stored buffer AMAT, and so on. When this loop is ended, the buffer AMAT contains the product of the four-pole matrices of all the tubes. Statement 410 + 1 tests for the lower-right element of this product matrix.

4.2.6. The 2x2-matrices to be multiplied contain real numbers in the principal diagonal, the other two elements being imaginary.The product of two of such matrices is of the same form again. Only the lower-right element of the product matrix is used, which is real. As a consequence of the imaginary numbers, certain terms in the product have minus signs.These are stated in the matrix multiplication in the statements 385 ff.; the factors i themselves are omitted.

4.2.7. In the lower-right element of the product matrix, the factors ρc from the four-pole coefficients cancel each other out. This is why they are left out in the calculations.

4.2.8. F (trial frequency) is first defined as 32 Hz, and DF (increment) as 64 Hz. The assumption, therefore, is that the first formant frequency is more than 32 Hz, and the difference between two successive formant frequencies is more than 64 Hz.

4.2.9. Two parameters T1 and T2 are used in the same way as in the twin-tube program (see 4.1.6.). For the twin-tube the sign of the expression D for small values of ω is known beforehand. In the n-tube program this sign is determined in the first trial (32 Hz) and depending on this sign a parameter TT is set to +1 or -1 (395 ff.).

5. Applications.

5.1. Twin-tube program.

Appendix V shows an output of the twin-tube program.

5.1.1. In the first section , marked (1), the twin-tube parameters are defined on the basis of a print-plotted twin-tube model and an instruction is printed, prescribing how to enter the parameters. When the "program start"-key is pressed, three pairs of brackets are printed, in which the parameter values have to be filled in. After pressing the "end of field"-key the calculations are carried out and the formant frequencies are printed on the next line. By pressing the "program start"-key once again, new parameter values can be entered.

5.1.2. In section (2), the parameters of the model for [ə], a tube with a constant cross area, are filled in. The formant frequencies are the odd harmonics, produced by an organ pipe closed at one side and open at the other, and having a length of 17.5 cm (the average length of the male vocal tract).

5.1.3 In section (3) the parameter values of the model of Dutch [a] are filled in (see Mol, (4)).

5.1.4. In section (4) the velocity of sound is defined as 34000 cm/s (data switch 14), and the same twin-tube parameters as those in section (3) are filled in. As is to be expected, a lower value for c results in lower formant frequencies.

5.1.5. In sections (5), (6) and (7), the parameter l, k and β, respectively, are out of their specified ranges (see 4.1.5.). In each case an error message is produced and new brackets are printed. In section (8) all the parameters are within the specified ranges again.

5.2. n-tube program.

The following remarks refer to the output of the n-tube program, reproduced in appendix VI.

5.2.1. In section (1) , an instruction is printed and some of the parameters are defined. After pressing the "program start"-key , brackets are printed to specify the mode, the number of tubes, the desired number of formant frequencies, and the velocity of sound.

5.2.2. In the case of mode 1,the instruction in section (3) is printed. After this, brackets are printed for the specification of the dimensions of the tubes. In section (4) the model for [ə] is calculated. Section (5) shows the output when calculating the twin-tube model for Dutch [a], first for c = 35000 cm/s and then for c = 34000 cm/s, just as is appendix V.
Whereas in the twin-tube program the ratio of the cross areas is used as a parameter, in the n-tube program it is the diameters of the tubes that have to be specified.

5.2.3. In section (6) LN is changed by means of data switch 5. The computer calculates again, the other parameters remaining unchanged. A comparison with section (5) shows that greater lengths result in lower formant frequencies (the "law of proportional growth" , see Ungeheuer (1)).

5.2.4. If data switch 1 is on, the program branches to the beginning, immediately after the first instruction (section (7)). The mode is now defined as 2. An instruction is printed which is slightly different from that printed in the case of mode 1.

5.2.5. As can be seen in section (8) , the specification of the dimensions of the tubes takes two lines when the number of tubes is more than 10. First ten pairs of brackets are printed on one line, and after the values for the first ten tubes have been filled in and the "end of field"-key has been pressed, the remaining pairs of brackets are printed on the next line.

5.2.6. Section (9) is produced by setting data switch 8 on. Only the diameter of the 18th tube is changed; the remaining parameter values are left unchanged.

References.

(1) Ungeheuer G.: Elemente einer akustischen Theorie der Vokalartikulation. (Springer 1962)

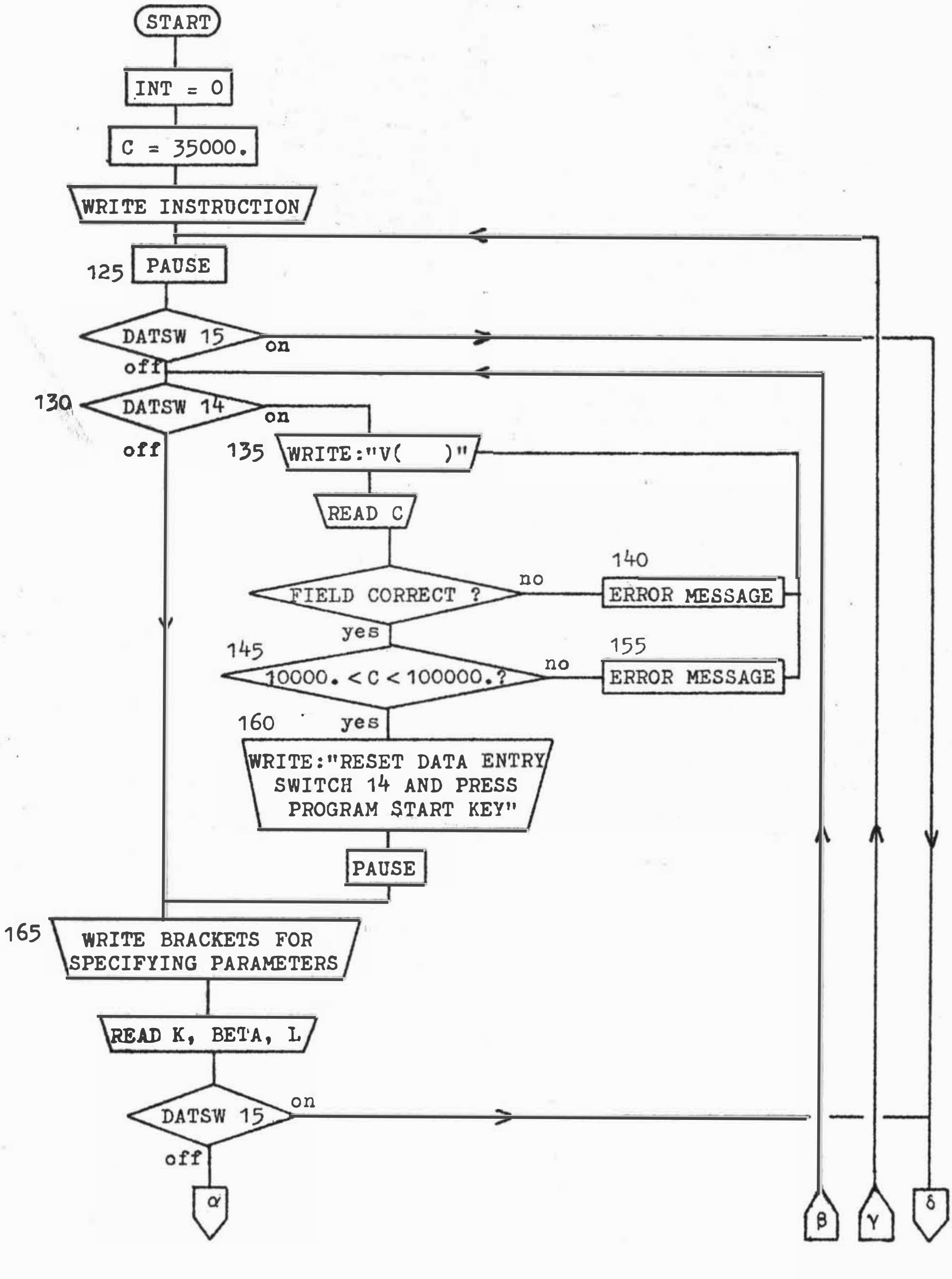
(2) Dunn H.K.: The calculation of vowel resonances, and an electrical vocal tract. (J.A.S.A.,vol.22,p.740 ff.,1950)

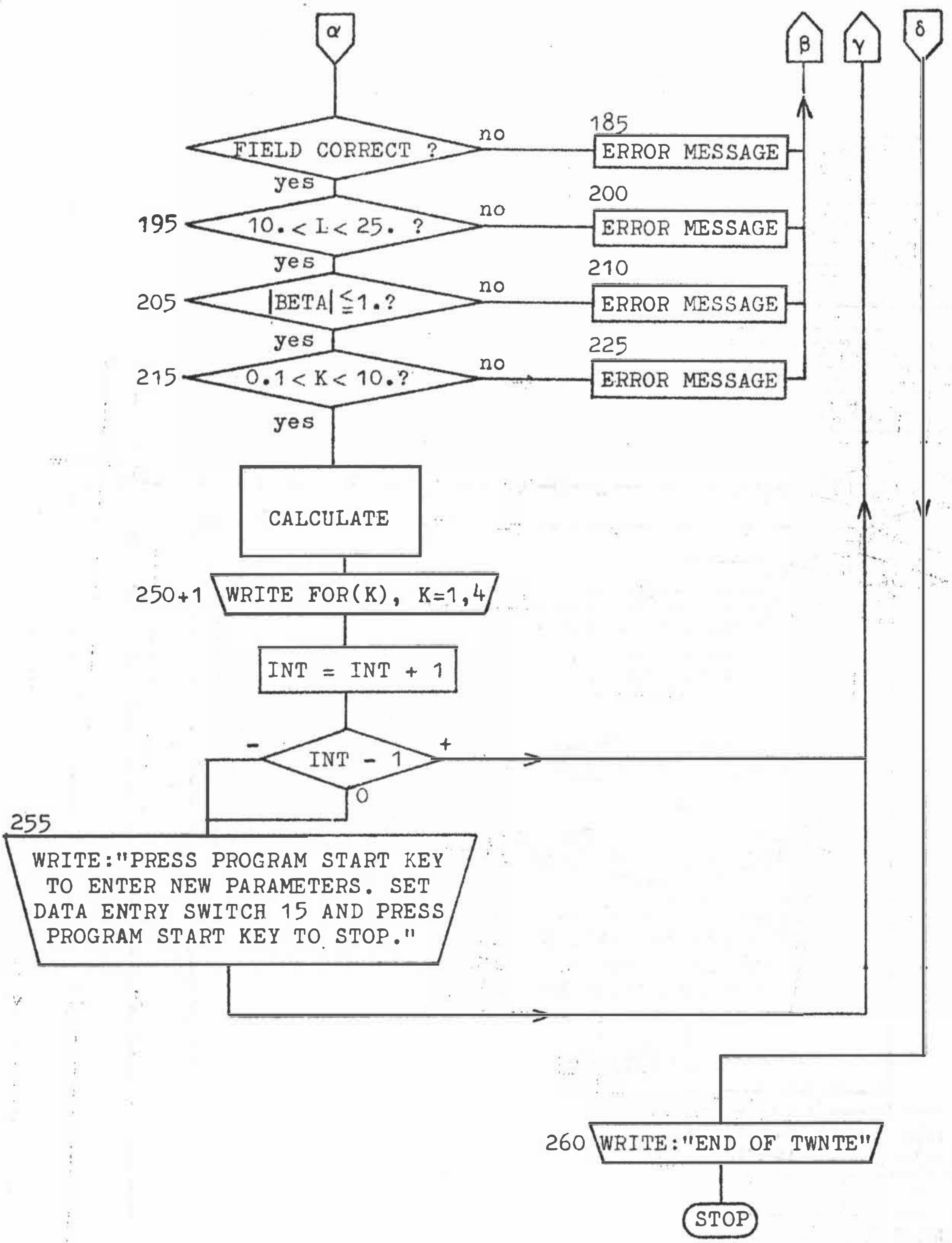
(3) Fant G.: Acoustic theory of speech production. (Mouton 1960)

(4) Mol H.: Fundamentals of phonetics II. (Mouton 1970)

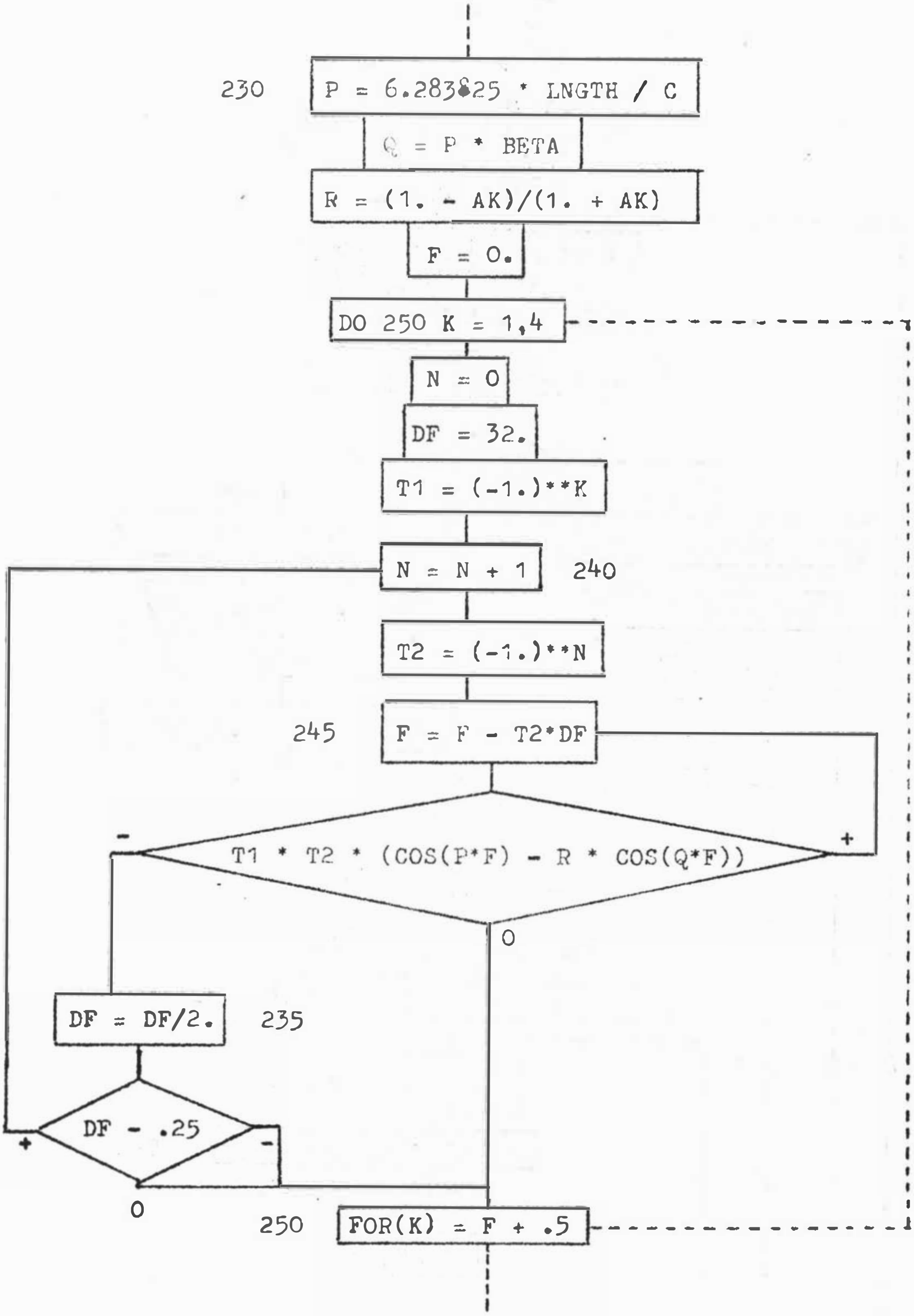
Appendix I.

(1) Flow-chart twin-tube program.



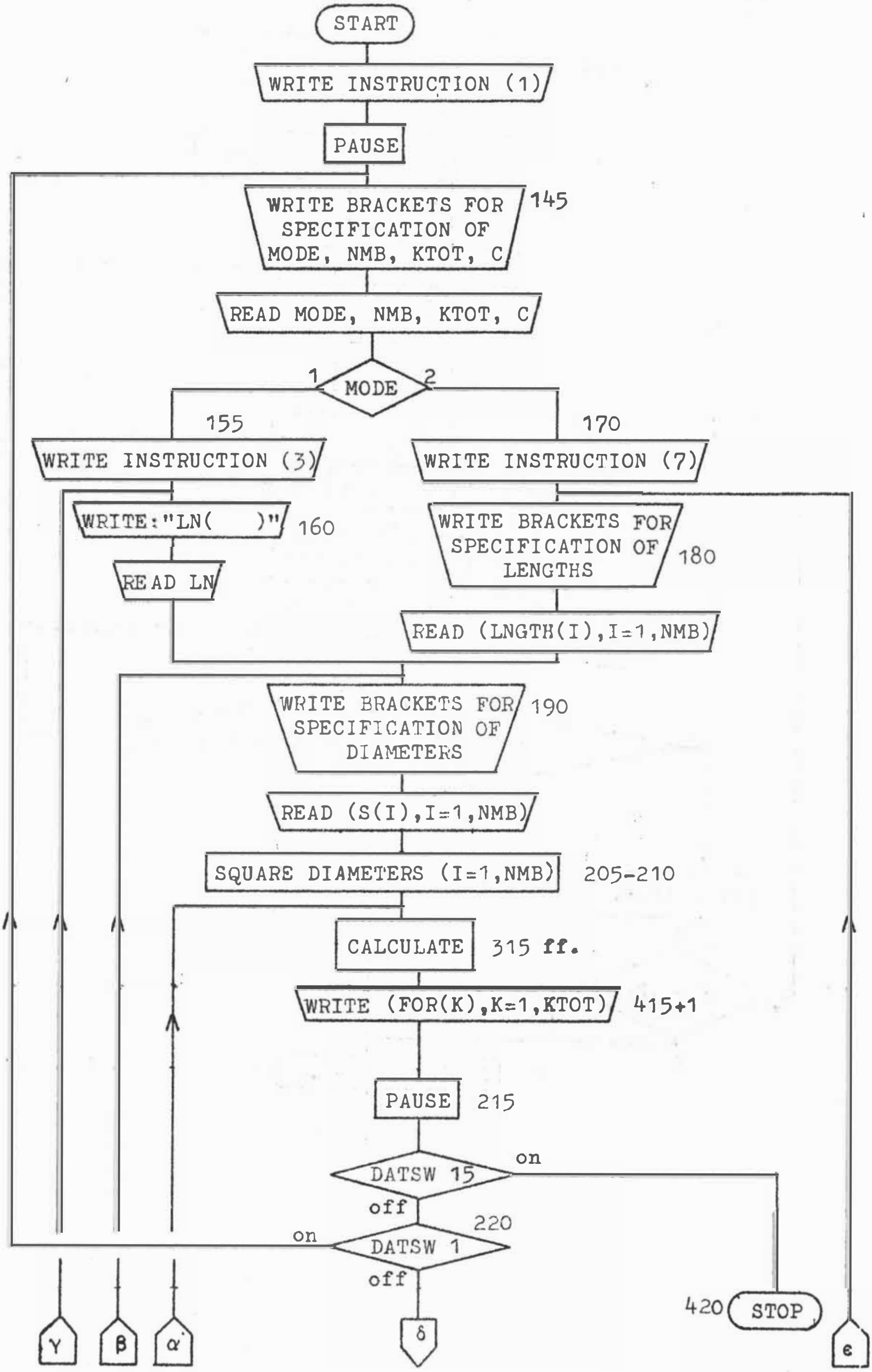

α
β
γ
δ
185
FIELD CORRECT ?
no
ERROR MESSAGE
yes
200
195
10. < L < 25. ?
ERROR MESSAGE
210
205
|BETA| ≦ 1.?
ERROR MESSAGE
225
215
0.1 < K < 10.?
ERROR MESSAGE
CALCULATE
250+1
WRITE FOR(K), K=1,4
INT = INT + 1
INT - 1
-
+
0
255
WRITE:"PRESS PROGRAM START KEY TO ENTER NEW PARAMETERS. SET DATA ENTRY SWITCH 15 AND PRESS PROGRAM START KEY TO STOP."
260
WRITE:"END OF TWNTE"
STOP

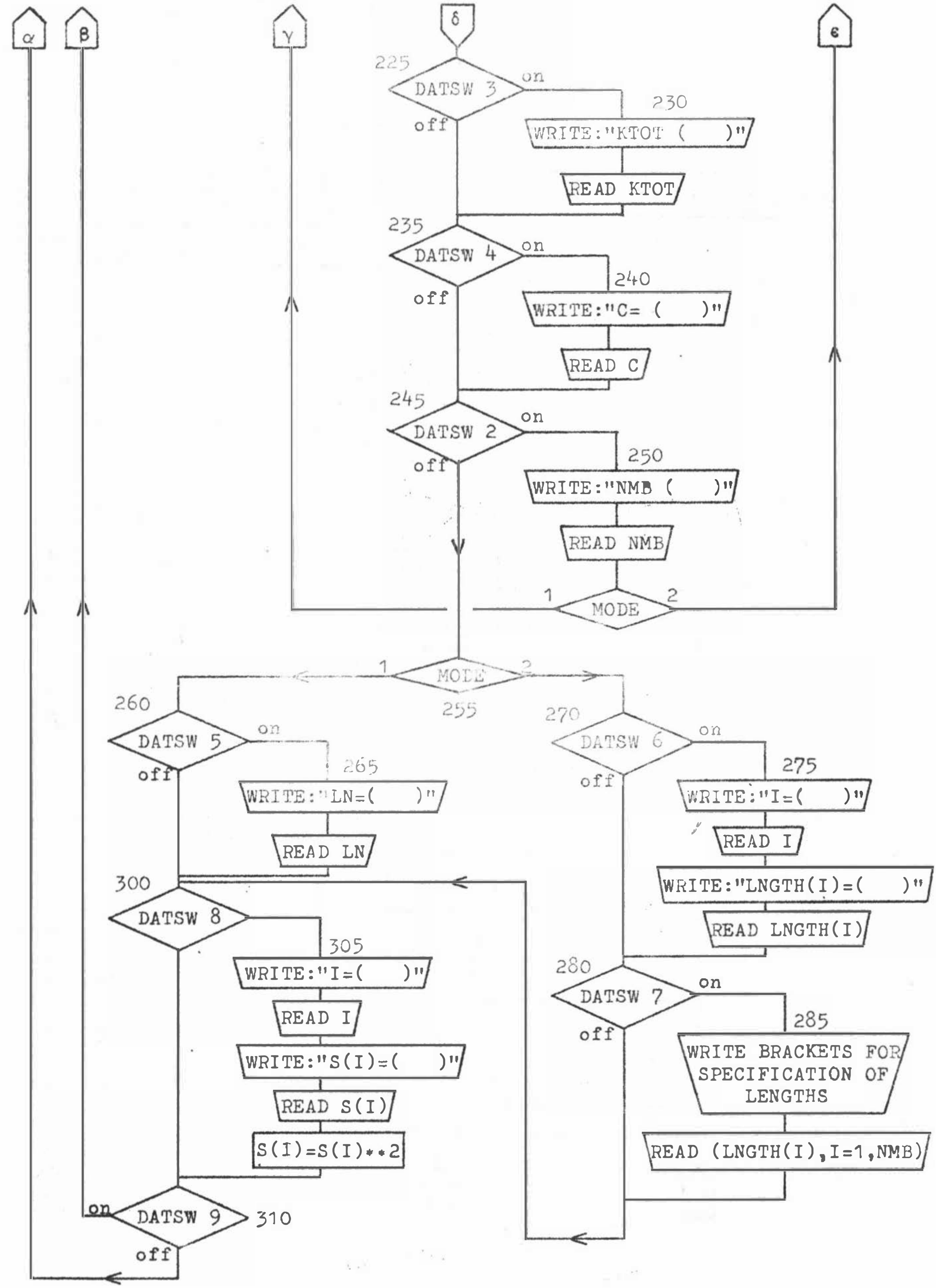
(2) Flow-chart calculations twin-tube program.



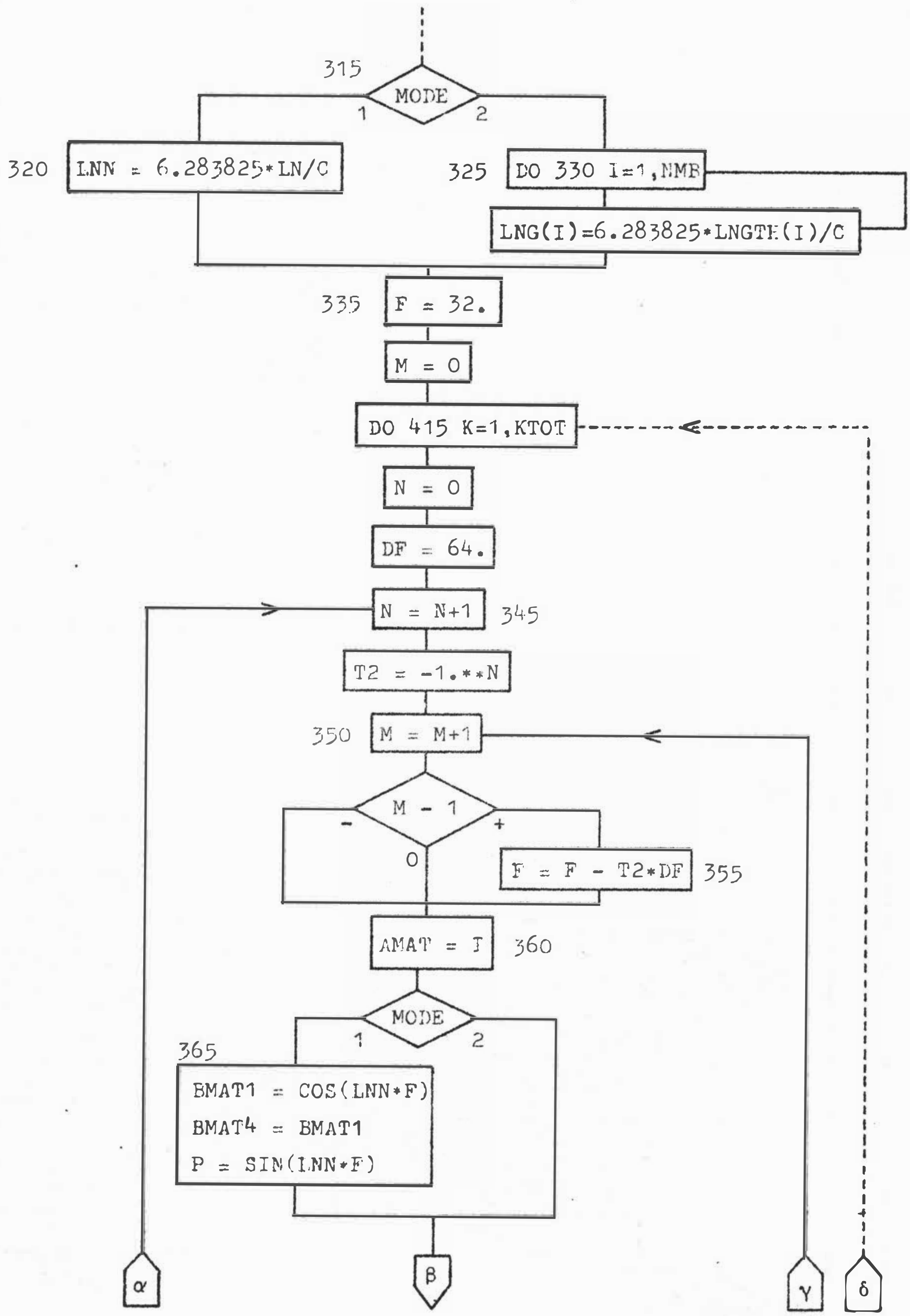
Appendix II.

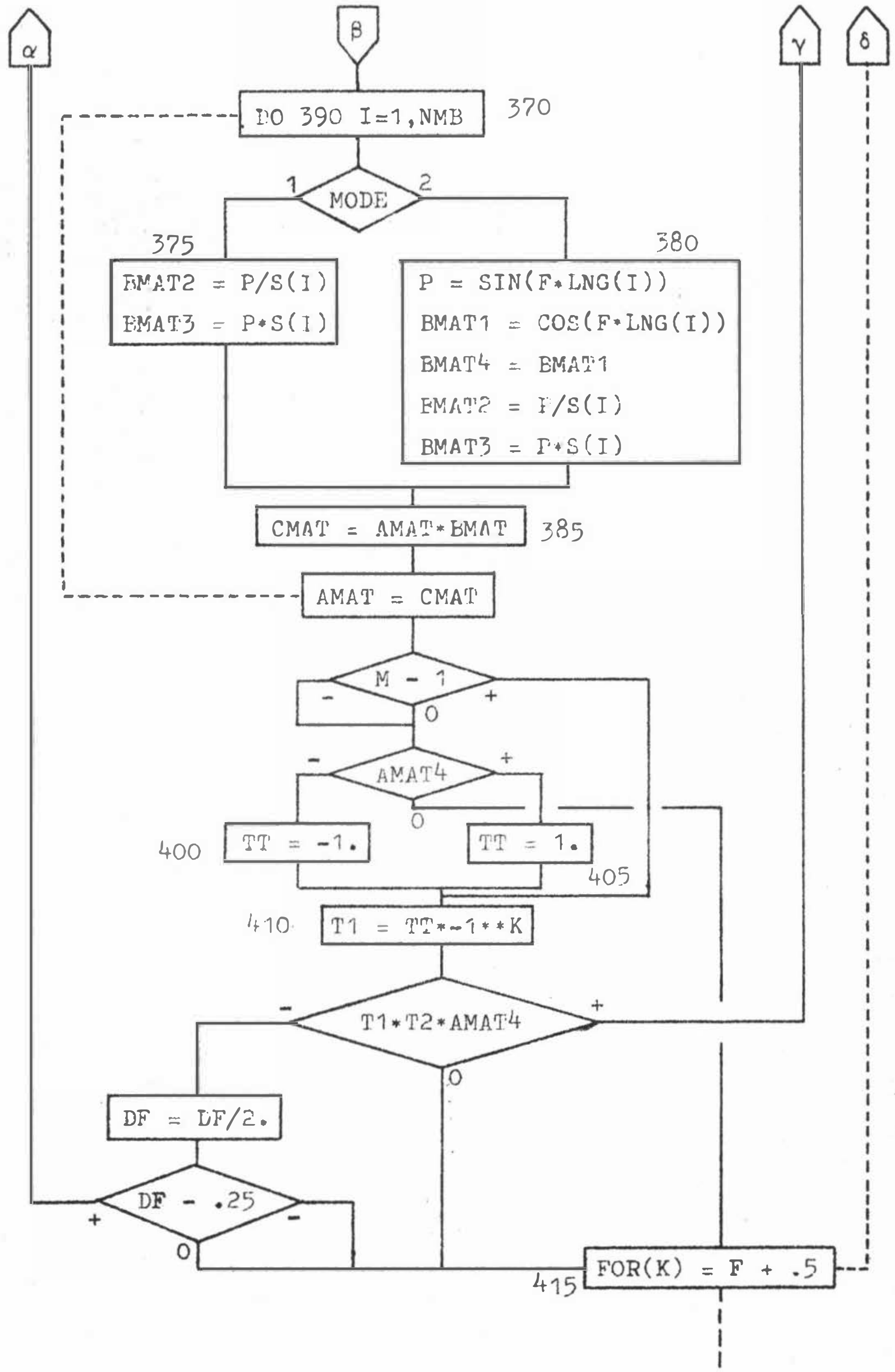
(1) Flow-chart n-tube program.




α
β
γ
δ
ε
225
DATSW 3
on
off
230
WRITE:"KTOT ( )"
READ KTOT
235
DATSW 4
on
off
240
WRITE:"C= ( )"
READ C
245
DATSW 2
on
off
250
WRITE:"NMB ( )"
READ NMB
1
MODE
2
1
MODE
2
255
260
DATSW 5
on
off
265
WRITE:"LN=( )"
READ LN
270
DATSW 6
on
off
275
WRITE:"I=( )"
READ I
WRITE:"LNGTH(I)=( )"
READ LNGTH(I)
300
DATSW 8
305
WRITE:"I=( )"
READ I
WRITE:"S(I)=( )"
READ S(I)
S(I)=S(I)**2
280
DATSW 7
on
off
285
WRITE BRACKETS FOR SPECIFICATION OF LENGTHS
READ (LNGTH(I),I=1,NMB)
on
DATSW 9
310
off

(2) Flow-chart calculations n-tube program.





α
β
γ
δ
DO 390 I=1,NMB
370
MODE
1
2
375
BMAT2 = P/S(I)
BMAT3 = P*S(I)
380
P = SIN(F*LNG(I))
BMAT1 = COS(F*LNG(I))
BMAT4 = BMAT1
BMAT2 = P/S(I)
BMAT3 = P*S(I)
CMAT = AMAT*BMAT
385
AMAT = CMAT
M - 1
-
0
+
AMAT4
-
+
0
400
TT = -1.
TT = 1.
405
410
T1 = TT*-1**K
T1*T2*AMAT4
-
+
0
DF = DF/2.
DF - .25
+
-
0
415
FOR(K) = F + .5

Appendix III.

Listing twin-tube program.

```
// JOB
// FOR
*LIST ALL
*IOCS(CARD,TYPEWRITER,KEYBOARD,1132PRINTER,PAPERTAPE,DISK,PLOTTER)
C
C      PROGRAM TWNTE
C
C      THIS BASIC FORTRAN IV WRITTEN PROGRAM COMPUTES
C      THE F1,F2,F3 AND F4 OF THE TWINTUBE-MODEL.
C      TWNTE IS PRIMARILY WRITTEN FOR AN IBM 1130 SYSTEM,
C      BUT CAN EASILY BE MODIFIED FOR EVERY COMPUTER
C      WITH TYPEWRITER IN AND OUTPUT.
C
C      AUTHOR  J.G.BLOM.
C
C      TWNTE
       REALLNGTH
       DIMENSIONFOR(4) ,AC(6)
     5 FORMAT('PROGRAM TWNTE,'/'TWNTE COMPUTES F1,F2,F3,F4 OF THE ',
      1'TWINTUBE MODEL OF THE VOCAL TRACT.'/
      1'DEFINITION OF PARAMETERS.'/)
    10 FORMAT(22X,'.',3X,'...............')
    15 FORMAT(22X,'.',3X,'.')
    20 FORMAT(6X,'.......................')
    25 FORMAT(6X,'.',15X,'.')
    30 FORMAT(6X,'.',5X,'O1',8X,'.',10X,'O2')
    35 FORMAT(22X,'X D X')
    40 FORMAT(6X,'X',5X,'0.5L',6X,'X',6X,'0.5L',6X,'X'//)
    45 FORMAT('K=O2/O1 (RATIO OF CROSSSECTIONS)'/
      1'BETA=D/0.5L (RELATIVE ECCENTRICITY)'/
      1'L=LENGTH IN CM'/
      1'V=35000. CM/SEC (VELOCITY OF SOUND)')
    50 FORMAT(//'TO CHANGE V SET DATA ENTRY SWITCH 14.'/'USE KEYBOARD TO
      1ENTER PARAMETER VALUES.'/'USE A DECIMAL POINT AND PRESS END OF FIE
      1LD KEY.'/'IF YOU STRIKE A WRONG KEY PRESS ERASE FIELD KEY AND REEN
      1TER PARAMETERS.'/'FIRST PRESS PROGRAM START KEY.'//)
    55 FORMAT(5X,'K',15X,'BETA',16X,'L'/
      13X,'(          )',9X,'(          )',9X,'(          )',9X,'V=',F7.0,'CM/S')
    60 FORMAT(/'PRESS PROGRAM START KEY TO ENTER NEW PARAMETERS.'/
      1'SET DATA ENTRY SWITCH 15 AND PRESS PROGRAM START KEY TO STOP.'/)
    65 FORMAT(8X,'V'/3X,'(          )')
    70 FORMAT('** PARAMETER OUT OF FIELD.')
    75 FORMAT('** ENTER PARAMETERS AND PRESS END OF FIELD KEY.')
```

```
   80 FORMAT('** L OUTSIDE RANGE 10,25,')
   85 FORMAT('** BETA OUTSIDE RANGE -1,+1,')
   90 FORMAT('** K OUTSIDE RANGE 0.1,10,')
   95 FORMAT('** V OUTSIDE RANGE 10000,100000,')
  100 FORMAT('RESET DATA ENTRY SWITCH 14 AND PRESS PROGRAM START KEY.'/)
  105 FORMAT('END OF TWNTE'//)
  110 FORMAT(3(F4.0,2F7.0))
  115 FORMAT(/4('F',I1,'=',F7.0,'C/S',3X)/)
  120 FORMAT(F4.0,F9.0,F4.0)
      INT = 0
      C = 35000.
C     C    =VELOCITY OF SOUND
      WRITE(1,5)
      WRITE(1,10)
      WRITE(1,15)
      WRITE(1,20)
      WRITE(1,25)
      WRITE(1,30)
      WRITE(1,25)
      WRITE(1,20)
      WRITE(1,15)
      WRITE(1,10)
      WRITE(1,35)
      WRITE(1,40)
      WRITE(1,45)
      WRITE(1,50)
  125 PAUSE
      CALL DATSW(15,NSTOP)
      GOTO(260,130),NSTOP
  130 CALL DATSW(14,NV)
      GOTO(135,165),NV
  135 WRITE(1,65)
      B = 0.
      BB = 0.
      READ(6,120)B,C,BB
      B = B + BB
      IF (B) 140,145,140
  140 WRITE(1,70)
      WRITE(1,75)
      GOTO 135
  145 IF (C - 10000.) 155,150,150
```

```
  150 IF (C - 100000.) 160,160,155
  155 WRITE(1,95)
      WRITE(1,75)
      GOTO 135
  160 WRITE(1,100)
      PAUSE
  165 WRITE(1,55)C
      DO 170 I=1,6
  170 AC(I) = 0.
      READ(6,110)AC(1),AK,AC(2),AC(3),BETA,AC(4),AC(5),LNGTH,AC(6)
C     AK    =RATIO OF CROSSSECTIONS
C     BETA  =RELATIVE ECCENTRICITY
C     LNGTH=LENGTH OF TWINTUBE
      CALL DATSW(15,NSTOP)
      GOTO(260,175),NSTOP
  175 DO 180 I=2,6
  180 AC(1) = AC(1) + AC(I)
      IF (AC(1)) 185,190,185
  185 WRITE(1,70)
      WRITE(1,75)
      GOTO 130
  190 IF (LNGTH - 10.) 200,195,195
  195 IF (LNGTH - 25.) 205,205,200
  200 WRITE(1,80)
      WRITE(1,75)
      GOTO 130
  205 IF (ABS(BETA) - 1.) 215,215,210
  210 WRITE(1,85)
      WRITE(1,75)
      GOTO 130
  215 IF (AK - 10.) 220,220,225
  220 IF (AK - .1) 225,230,230
  225 WRITE(1,90)
      WRITE(1,75)
      GOTO 130
  230 P = 6.283825 * LNGTH / C
      P = 6.283825 * LNGTH / C
      Q = P * BETA
      R = (1. - AK) / (1. + AK)
      F = 0.
      DO 250 K=1,4
```

```
      N = 0
      DF = 32.
      T1 = ( - 1.) * * K
      GOTO 240
  235 DF = DF / 2.
      IF (DF - .25) 250,250,240
C     STOP ITERATION IF STEP SMALLER THAN .5 C/SEC.
  240 N = N + 1
      T2 = ( - 1.) * * N
  245 F = F - T2 * DF
      IF (T1 * T2 * (COS(P * F) - R * COS(Q * F))) 235,250,245
  250 FOR(K) = F + .5
      WRITE(1,115)(I,FOR(I),I=1,4)
      INT = INT + 1
      IF (INT - 1) 255,255,125
  255 WRITE(1,60)
      GOTO 125
  260 WRITE(1,105)
      CALL EXIT
      END
```

Appendix IV.

Listing n-tube program.

```
// JOB
// FOR
*LIST ALL
*ONE WORD INTEGERS
*EXTENDED PRECISION
*IOCS(CARD,TYPEWRITER,KEYBOARD,1132PRINTER,PAPERTAPE,DISK,PLOTTER)
C                                                                       NTUB0010
C          PROGRAM NTUBE                                                NTUB0020
C                                                                       NTUB0030
C      THIS FORTRAN IV WRITTEN PROGRAM COMPUTES F1,F2,F3 AND F4         NTUB0040
C      OF AN N-TUBE MODEL OF THE VOCAL TRACT. NTUBE IS PRIMARILY        NTUB0050
C      WRITTEN FOR AN IBM 1130 SYSTEM, BUT CAN EASILY BE MODIFIED       NTUB0060
C      FOR EVERY COMPUTER WITH TYPEWRITER IN AND OUTPUT.                NTUB0070
C                                                                       NTUB0080
      REALLN,LNN,LNGTH(20) ,LMS(20)                                     NTUB0090
      DIMENSIONS(20) ,FOR(4) ,IHAAK(8)                                  NTUB0100
    5 FORMAT(//('F',I1,'=',F6.0,'HZ')//)                                NTUB0110
   10 FORMAT('PROGRAM NTUBE'//'NTUBE COMPUTES F1,F2,F3,F4 OF AN N-TUBE MNTUB0120
     1ODEL OF THE VOCAL TRACT.'//'USE INPUT MODE 1 IF ALL TUBES HAVE THENTUB0130
     1 SAME LENGTH.'/'IF THIS IS NOT THE CASE USE INPUT MODE 2.'/'NMB=NUNTUB0140
     1MBER OF TUBES.'/'NMB SHOULD BE SMALLER THAN OR EQUAL TO 20.'/'KTOTNTUB0150
     1=NUMBER OF FORMANTS YOU WANT TO HAVE COMPUTED.'/'KTOT SHOULD BE SMNTUB0160
     1ALLER THAN OR EQUAL TO 4.'/'C=VELOCITY OF SOUND.'/)               NTUB0170
   15 FORMAT('USE KEYBOARD TO ENTER THE PARAMETERS.'/'USE DECIMAL POINTSNTUB0180
     1 AND PRESS END OF FIELD KEY.'/'IF YOU STRIKE A WRONG KEY PRESS ERANTUB0190
     1SE FIELD KEY AND REENTER PARAMETERS.'//'TO CHANGE MODE,NMB,KTOT ORNTUB0200
     1 C SET THE FOLLOWING DATA SWITCHES AND PRESS PROGRAM START KEY'/3XNTUB0210
     1,'MODE',6X,'1'/3X,'NMB',7X,'2'/3X,'KTOT',6X,'3'/3X,'C',9X,'4'/'IF NTUB0220
     1YOU CHANGE MODE,NMB KTOT AND C MUST BE REENTERED.')                NTUB0230
   20 FORMAT('SET DATA SWITCH 15 AND PRESS PROGRAM START KEY TO STOP.'//NTUB0240
     1'FIRST PRESS PROGRAM START KEY.'/)                                NTUB0250
   25 FORMAT(2X,'MODE',10X,'NMB',10X,'KTOT',10X,'C'/'(',6X,')',5X,'(',6XNTUB0260
     1,')',5X,'(',6X,')',4X,'(',10X,')'/)                               NTUB0270
   30 FORMAT(F8.0,2F13.0,F16.0)                                         NTUB0280
   35 FORMAT(//'LN=LENGTH OF EACH TUBE')                                NTUB0290
   40 FORMAT('S(I)=DIAMETER OF THE I TH TUBE'/'(I=1...NMB)'/'1=VOCAL CORNTUB0300
     1DS SIDE'/'NMB=MOUTH OPENING'/)                                    NTUB0310
   45 FORMAT('TO CHANGE LN SET DATA SWITCH 5.')                         NTUB0320
   50 FORMAT('TO CHANGE ONE SINGLE S(I) SET DATA SWITCH 8.'/'TO CHANGE ANTUB0330
     1LL THE S(I) SET DATA SWITCH 9.'//)                                NTUB0340
   55 FORMAT('LN=(',8X,')'/)                                            NTUB0350
   60 FORMAT(F12.3)                                                     NTUB0360
   65 FORMAT(//'S(I)')                                                  NTUB0370
```

```
 70 FORMAT(80A1)
 75 FORMAT(10F8.0)
 80 FORMAT('LNGTH(I)=LENGTH OF THE I TH TUBE')
 85 FORMAT('TO CHANGE ONE SINGLE LNGTH(I) SET DATA SWITCH 6.'/'TO CHAN
   1GE ALL THE LNGTH(I) SET DATA SWITCH 7.')
 90 FORMAT('LNGTH(I)')
 95 FORMAT('NMB (',6X,')'/)
100 FORMAT('KTOT (',4X,')'/)
105 FORMAT('C= (',10X,')'/)
110 FORMAT(F15.0)
115 FORMAT('I= (',10X,')'/)
120 FORMAT('LNGTH(I)=(',8X,')'/)
125 FORMAT(F20.0)
130 FORMAT('S(I)=(',8X,')'/)
135 FORMAT(I4,9I8)
    IHAAK(1) = 19789
    DO 140 I=2,7
140 IHAAK(I) = 16448
    IHAAK(8) = 23901
    WRITE(1,10)
    WRITE(1,15)
    WRITE(1,20)
    PAUSE
    NP = 0
    NPP = 0
145 WRITE(1,25)
    READ(6,30)AMODE,ANMB,AKTOT,C
    MODE = AMODE
    NMB = ANMB
    KTOT = AKTOT
    NN = NMB - 10
    GOTO(150,165),MODE
150 NP = NP + 1
    IF (NP - 1) 155,155,160
155 WRITE(1,35)
    WRITE(1,40)
    WRITE(1,45)
    WRITE(1,50)
160 WRITE(1,55)
    READ(6,60)LN
    GOTO 190
```

```
165 NPP = NPP + 1                                          NTUB0790
    IF (NPP - 1) 170,170,175                               NTUB0800
170 WRITE(1,80)                                            NTUB0810
    WRITE(1,40)                                            NTUB0820
    WRITE(1,85)                                            NTUB0830
    WRITE(1,50)                                            NTUB0840
175 WRITE(1,90)                                            NTUB0850
    IF (NN) 180,180,185                                    NTUB0860
180 WRITE(1,135)(I,I=1,NMB)                                NTUB0870
    WRITE(1,70)((IHAAK(I),I=1,8),J=1,NMB)                  NTUB0880
    READ(6,75)(LNGTH(I),I=1,NMB)                           NTUB0890
    GOTO 190                                               NTUB0900
185 WRITE(1,135)(I,I=1,10)                                 NTUB0910
    WRITE(1,70)((IHAAK(I),I=1,8),J=1,10)                   NTUB0920
    READ(6,75)(LNGTH(I),I=1,10)                            NTUB0930
    WRITE(1,135)(I,I=11,NMB)                               NTUB0940
    WRITE(1,70)((IHAAK(I),I=1,8),J=1,NN)                   NTUB0950
    READ(6,75)(LNGTH(I),I=11,NMB)                          NTUB0960
190 WRITE(1,65)                                            NTUB0970
    IF (NN) 195,195,200                                    NTUB0980
195 WRITE(1,135)(I,I=1,NMB)                                NTUB0990
    WRITE(1,70)((IHAAK(I),I=1,8),J=1,NMB)                  NTUB1000
    READ(6,75)(S(I),I=1,NMB)                               NTUB1010
    GOTO 205                                               NTUB1020
200 WRITE(1,135)(I,I=1,10)                                 NTUB1030
    WRITE(1,70)((IHAAK(I),I=1,8),J=1,10)                   NTUB1040
    READ(6,75)(S(I),I=1,10)                                NTUB1050
    WRITE(1,135)(I,I=11,NMB)                               NTUB1060
    WRITE(1,70)((IHAAK(I),I=1,8),J=1,NN)                   NTUB1070
    READ(6,75)(S(I),I=11,NMB)                              NTUB1080
205 DO 210 I=1,NMB                                         NTUB1090
210 S(I) = S(I) * * 2                                      NTUB1100
    GOTO 315                                               NTUB1110
215 PAUSE                                                  NTUB1120
    CALL DATSW(15,NSTOP)                                   NTUB1130
    GOTO(420,220),NSTOP                                    NTUB1140
220 CALL DATSW(1,NMODE)                                    NTUB1150
    GOTO(145,225),NMODE                                    NTUB1160
225 CALL DATSW(3,NKTOT)                                    NTUB1170
    GOTO(230,235),NKTOT                                    NTUB1180
```

```
230 WRITE(1,100)                                                NTUB1190
    READ(6,60)AKTOT                                             NTUB1200
    KTOT = AKTOT                                                NTUB1210
235 CALL DATSW(4,NC)                                            NTUB1220
    GOTO(240,245),NC                                            NTUB1230
240 WRITE(1,105)                                                NTUB1240
    READ(6,110)C                                                NTUB1250
245 CALL DATSW(2,NNMB)                                          NTUB1260
    GOTO(250,255),NNMB                                          NTUB1270
250 WRITE(1,95)                                                 NTUB1280
    READ(6,60)ANMB                                              NTUB1290
    NMB = ANMB                                                  NTUB1300
    NN = NMB - 10                                               NTUB1310
    GOTO(160,175),MODE                                          NTUB1320
255 GOTO(260,270),MODE                                          NTUB1330
260 CALL DATSW(5,NLN)                                           NTUB1340
    GOTO(265,300),NLN                                           NTUB1350
265 WRITE(1,55)                                                 NTUB1360
    READ(6,60)LN                                                NTUB1370
    GOTO 300                                                    NTUB1380
270 CALL DATSW(6,NL)                                            NTUB1390
    GOTO(275,280),NL                                            NTUB1400
275 WRITE(1,115)                                                NTUB1410
    READ(6,60)AI                                                NTUB1420
    I = AI                                                      NTUB1430
    WRITE(1,120)                                                NTUB1440
    READ(6,125)LNGTH(I)                                         NTUB1450
280 CALL DATSW(7,NL)                                            NTUB1460
    GOTO(285,300),NL                                            NTUB1470
285 WRITE(1,90)                                                 NTUB1480
    IF (NN) 290,290,295                                         NTUB1490
290 WRITE(1,135)(I,I=1,NMB)                                     NTUB1500
    WRITE(1,70)((IHAAK(I),I=1,8),J=1,NMB)                       NTUB1510
    READ(6,75)(LNGTH(I),I=1,NMB)                                NTUB1520
    GOTO 300                                                    NTUB1530
295 WRITE(1,135)(I,I=1,10)                                      NTUB1540
    WRITE(1,70)((IHAAK(I),I=1,8),J=1,10)                        NTUB1550
    READ(6,75)(LNGTH(I),I=1,10)                                 NTUB1560
    WRITE(1,135)(I,I=11,NMB)                                    NTUB1570
    WRITE(1,70)((IHAAK(I),I=1,8),J=1,NN)                        NTUB1580
```

```
      READ(6,75)(LNGTH(I),I=11,NMB)
  300 CALL DATSW(8,NS)
      GOTO(305,310),NS
  305 WRITE(1,115)
      READ(6,60)AI
      I = AI
      WRITE(1,130)
      READ(6,110)S(I)
      S(I) = S(I) * * 2
  310 CALL DATSW(9,NS)
      GOTO(190,315),NS
  315 GOTO(320,325),MODE
  320 LNN = 6.283825 * LN / C
      GOTO 335
  325 DO 330 I=1,NMB
  330 LNG(I) = 6.283825 * LNGTH(I) / C
  335 F = 32.
      M = 0
      DO 415 K=1,KTOT
      N = 0
      DF = 64.
      GOTO 345
  340 DF = DF / 2.
      IF (DF - .25) 415,415,345
  345 N = N + 1
      T2 = ( - 1.) * * N
  350 M = M + 1
      IF (M - 1) 360,360,355
  355 F = F - T2 * DF
  360 AMAT1 = 1.
      AMAT2 = 0.
      AMAT3 = 0.
      AMAT4 = 1.
      GOTO(365,370),MODE
  365 BMAT1 = COS(LNN * F)
      BMAT4 = BMAT1
      P = SIN(LNN * F)
  370 DO 390 I=1,NMB
      GOTO(375,380),MODE
  375 BMAT2 = P / S(I)
      BMAT3 = P * S(I)
```

```
      GOTO 385
  380 P = SIN(F * LNG(I))
      BMAT1 = COS(F * LNG(I))
      BMAT4 = BMAT1
      BMAT2 = P / S(I)
      BMAT3 = P * S(I)
  385 CMAT1 = AMAT1 * BMAT1 - AMAT2 * BMAT3
      CMAT2 = AMAT1 * BMAT2 + AMAT2 * BMAT4
      CMAT3 = AMAT3 * BMAT1 + AMAT4 * BMAT3
      CMAT4 = AMAT4 * BMAT4 - AMAT3 * BMAT2
      AMAT1 = CMAT1
      AMAT2 = CMAT2
      AMAT3 = CMAT3
  390 AMAT4 = CMAT4
      IF (M - 1) 395,395,410
  395 IF (AMAT4) 400,415,405
  400 TT = - 1.
      GOTO 410
  405 TT = 1.
  410 T1 = TT * ( - 1.) * * K
      IF (T1 * T2 * AMAT4) 340,415,350
  415 FOR(K) = F + .5
      WRITE(1,5)(K,FOR(K),K=1,KTOT)
      GOTO 215
  420 CALL EXIT
      END
```

Appendix V.

Output twin-tube program.

(1)

```
PROGRAM TWNTE,
TWNTE COMPUTES F1,F2,F3,F4 OF THE TWINTUBE MODEL OF THE VOCAL TRACT.
DEFINITION OF PARAMETERS.

                       .    ..............
                       .    .
     ....................
     .                 .
     .    01           .          02
     .                 .
     ....................
                       .    .
                       .    ..............
                       X D X
     X     0.5L        X      0.5L        X


K=02/01 (RATIO OF CROSSSECTIONS)
BETA=D/0.5L (RELATIVE ECCENTRICITY)
L=LENGTH IN CM
V=35000. CM/SEC (VELOCITY OF SOUND)


TO CHANGE V SET DATA ENTRY SWITCH 14.
USE KEYBOARD TO ENTER PARAMETER VALUES.
USE A DECIMAL POINT AND PRESS END OF FIELD KEY.
IF YOU STRIKE A WRONG KEY PRESS ERASE FIELD KEY AND REENTER PARAMETERS.
FIRST PRESS PROGRAM START KEY.
```

(2)

```
       K                  BETA                 L
  (         )         (          )        (         )      V= 35000.CM/S
     1.                                      17.5

F1=   500.C/S   F2=  1500.C/S   F3=  2500.C/S   F4=  3500.C/S


PRESS PROGRAM START KEY TO ENTER NEW PARAMETERS.
SET DATA ENTRY SWITCH 15 AND PRESS PROGRAM START KEY TO STOP.
```

```
        K                   BETA                  L
   (          )        (          )        (          )        V= 35000.CM/S
      8.                                       17.5                              (3)

F1=    784.C/S    F2=   1217.C/S    F3=   2784.C/S    F4=   3217.C/S

        V
   (          )
    34000.
RESET DATA ENTRY SWITCH 14 AND PRESS PROGRAM START KEY.
                                                                                 (4)
        K                   BETA                  L
   (          )        (          )        (          )        V= 34000.CM/S
      8.                                       17.5

F1=    762.C/S    F2=   1182.C/S    F3=   2704.C/S    F4=   3125.C/S
        K                   BETA                  L
   (          )        (          )        (          )        V= 34000.CM/S
    5.                        .5                   30.                           (5)
** L OUTSIDE RANGE 10,25,
** ENTER PARAMETERS AND PRESS END OF FIELD KEY.
        K                   BETA                  L
   (          )        (          )        (          )        V= 34000.CM/S
     12.                                       17.5                              (6)
** K OUTSIDE RANGE 0.1,10,
** ENTER PARAMETERS AND PRESS END OF FIELD KEY.
        K                   BETA                  L
   (          )        (          )        (          )        V= 34000.CM/S
     8.                      2.                17.5                              (7)
** BETA OUTSIDE RANGE -1,+1,
** ENTER PARAMETERS AND PRESS END OF FIELD KEY.
        K                   BETA                  L
   (          )        (          )        (          )        V= 34000.CM/S
     .125                    .25                  15.                            (8)

F1=    252.C/S    F2=   1792.C/S    F3=   2968.C/S    F4=   3709.C/S


 END OF TWNTE
```

Appendix VI.

Output n-tube program.

```
PROGRAM NTUBE

NTUBE COMPUTES F1,F2,F3,F4 OF AN N-TUBE MODEL OF THE VOCAL TRACT.

USE INPUT MODE 1 IF ALL TUBES HAVE THE SAME LENGTH.
IF THIS IS NOT THE CASE USE INPUT MODE 2.
NMB=NUMBER OF TUBES.
NMB SHOULD BE SMALLER THAN OR EQUAL TO 20.
KTOT=NUMBER OF FORMANTS YOU WANT TO HAVE COMPUTED.
KTOT SHOULD BE SMALLER THAN OR EQUAL TO 4.
C=VELOCITY OF SOUND.

USE KEYBOARD TO ENTER THE PARAMETERS.
USE DECIMAL POINTS AND PRESS END OF FIELD KEY.
IF YOU STRIKE A WRONG KEY PRESS ERASE FIELD KEY AND REENTER PARAMETERS.

TO CHANGE MODE,NMB,KTOT OR C SET THE FOLLOWING DATA SWITCHES AND PRESS PROGRAM START KEY
   MODE        1
   NMB         2
   KTOT        3
   C           4
IF YOU CHANGE MODE,NMB KTOT AND C MUST BE REENTERED.
SET DATA SWITCH 15 AND PRESS PROGRAM START KEY TO STOP.

FIRST PRESS PROGRAM START KEY.
```

(1)

```
  MODE          NMB           KTOT          C
(      )      (      )      (      )    (        )

   1.           1.            4.          35000.
```

(2)

```
LN=LENGTH OF EACH TUBE                                   ┐
S(I)=DIAMETER OF THE I TH TUBE                           │
(I=1...NMB)                                              │
1=VOCAL CORDS SIDE                                       │
NMB=MOUTH OPENING                                        (3)
                                                         │
TO CHANGE LN SET DATA SWITCH 5.                          │
TO CHANGE ONE SINGLE S(I) SET DATA SWITCH 8.             │
TO CHANGE ALL THE S(I) SET DATA SWITCH 9.                ┘

LN=(          )                                          ┐
                                                         │
        17.5                                             │
                                                         │
S(I)                                                     │
   1                                                     (4)
(       )                                                │
   1.                                                    │
                                                         │
F1=  500.HZ                                              │
F2= 1500.HZ                                              │
F3= 2500.HZ                                              │
F4= 3500.HZ                                              ┘

NMB (         )                                          ┐
                                                         │
        2.                                               │
LN=(          )                                          │
                                                         │
       8.5                                               │
                                                         │
S(I)                                                     │
   1         2                                           │
(       )(       )                                       │
   1.    2.828427                                        │
                                                         (5)
F1=  807.HZ                                              │
F2= 1252.HZ                                              │
F3= 2865.HZ                                              │
F4= 3311.HZ                                              │
C= (             )                                       │
                                                         │
      34000.                                             │
                                                         │
F1=  784.HZ                                              │
F2= 1216.HZ                                              │
F3= 2783.HZ                                              │
F4= 3216.HZ                                              ┘
```

```
LN=(          )

      8.75

F1=  761.HZ
F2= 1181.HZ
F3= 2704.HZ
F4= 3124.HZ
```

(6)

```
  MODE             NMB            KTOT           C
(      )       (       )       (       )      (          )

   2.              18.            4.          35000.
LNGTH(I)=LENGTH OF THE I TH TUBE
S(I)=DIAMETER OF THE I TH TUBE
(I=1...NMB)
1=VOCAL CORDS SIDE
NMB=MOUTH OPENING

TO CHANGE ONE SINGLE LNGTH(I) SET DATA SWITCH 6.
TO CHANGE ALL THE LNGTH(I) SET DATA SWITCH 7.
TO CHANGE ONE SINGLE S(I) SET DATA SWITCH 8.
TO CHANGE ALL THE S(I) SET DATA SWITCH 9.
```

(7)

```
LNGTH(I)
   1        2        3        4        5        6        7        8        9        10
(      )(       )(       )(       )(       )(       )(       )(       )(       )(       )
  .6       .6       .6       .6       .6       .6       .6       .6       .6       .6

  11       12       13       14       15       16       17       18
(      )(       )(       )(       )(       )(       )(       )(       )
  .6       .6       .6       .6       .6       3.       3.       3.
```

(8)

```
S(I)
    1          2          3          4          5          6          7          8          9         10
(       )(         )(         )(         )(         )(         )(         )(         )(         )(         )
   1.        1.2        1.4        1.6        1.8        2.        2.2        2.4        2.3       2.1        (8)

   11         12         13         14         15         16         17         18
(       )(         )(         )(         )(         )(         )(         )(         )
  1.9        1.7        1.6        1.5        1.4        1.3        1.2        1.3

F1=  377.HZ
F2= 1677.HZ
F3= 2744.HZ
F4= 3482.HZ


I= (             )

        18.
S(I)=(          )                                                                                              (9)

          1.1

F1=  357.HZ
F2= 1613.HZ
F3= 2735.HZ
F4= 3510.HZ
```