THE SYNTHESIS OF SPEECH USING A DIGITAL COMPUTER

by

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SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
BACHELOR OF SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June, 1959

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ABSTRACT

A program has been written for the IBM-704 digital computer to synthesize speech. The input requires detailed specification of the speech spectrum as a function of time. The output is audible samples of 2.4 seconds duration with a signal-to-noise ratio up to 36 db and a frequency response up to 7 kc. Included is a complete SAP listing and flow--charts of the program. The synthesis of each sample takes from 6 to 10 seconds. The IBM-704 "Direct-Data" attachment and a digital-to-analog converter is required.

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Introduction

The purpose of this work is the development of a device to synthesize speech which will be able to manipulate the acoustic "building blocks" of speech in a very flexible manner. Today a synthesizer is primarily useful for studying speech by testing various hypotheses about the interactions of various speech sounds and the nature of our perception of speech. Eventually it is hoped that speech may be added to our methods of communicating with machines. Before this can be done we need to have a fairly detailed knowledge of the acoustics of speech.

Acoustics of the Vocal Tract

The vocal tract begins at the vocal cords in the larynx and then divides, one section terminating at the mouth approximately 17 cm. away and the other section terminating at the nose a slightly greater distance away as shown in Fig. 1.

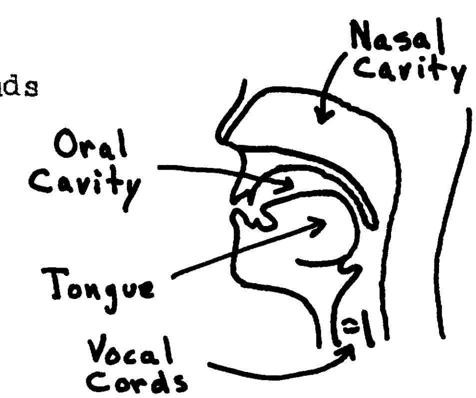


Fig.1

For a large class of speech sounds we need only consider the oral cavity, as the nasal cavity is virtually isolated from the system. Thus in essence the vocal tract can be considered to be a tube of fixed length and variable cross-sectional area. The area varies from 0 to 15 $cm.^2$.

Electrical Analogy

If we define an acoustical impedance as the ratio of the applied pressure to the volume velocity (cm.^{3}/sec.), we find that the vocal tract is analogous to an electrical transmission line with distributed inductance $L=p/S$ and capacitance $C=S/c^2p$ per unit length. Here p is the density of air, c is the velocity of sound and S is the cross-sectional area of the tract at the corresponding point.

A transmission line may be simulated by lumped elements, inductors and capacitors, provided the wavelength λ is long compared to the section being represented. For speech the highest frequency of normal interest is of the order of 6 kc. with a corresponding wavelength of $\lambda=c/f$ which is $3x10^2/6x10^4 = 0.05$ m. or 5 cm. Thus the vocal tract can be adequately represented by approximately 15 sections. In this analogue the pressure in the system corresponds to the voltage and the current to the volume velocity. The source (for vowels) is represented by a high impedance (current) generator. The output is taken as the pressure (voltage) at the lips which are loaded by a dissipative impedance representing the loss of energy to the surrounding air. See Fig. 2 below.

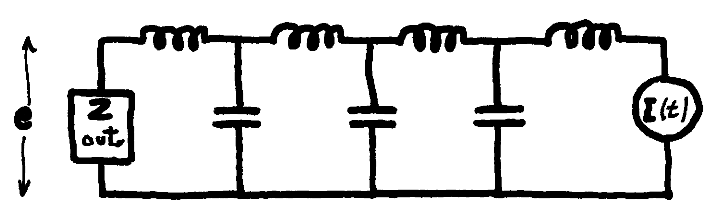


Fig. 2

Solution of the Circuit Equations

The elements in the circuit obey the simple equations:

$$i = C\frac{de}{dt} \quad , \quad e = L\frac{di}{dt} \quad , \quad e = iR.$$

By ordinary circuit analysis we obtain a differential equation of the form:

$$b_n \frac{d^n e}{dt^n} + b_{n-1}\frac{d^{n-1}e}{dt^{n-1}} + \ldots + b_0 e = i$$

We are primarily interested in the homogeneous or force-free ($i=0$) solution. The standard method for solving the above linear, homogeneous, differential equation with constant coefficients is to make the substitution $e = \epsilon^{st}$. Doing this we obtain the algebraic equation:

$$b_n s^n + b_{n-1} s^{n-1} + \ldots + b_0 = 0$$

Denoting the roots of this equation by s_n we have the homogeneous solution:

$$e = B_n \epsilon^{s_n t} + B_{n-1}\epsilon^{s_{n-1}t} + \ldots + B_0$$

where the values of the constants, B_n, are determined by the initial conditions.

The actual system has distributed losses due to viscosity, cavity wall absorption and due to the fact that the process is not adiabatic as the calculations suppose. In the case of losses the roots are in general complex numbers, $s_i = \sigma_i + j\omega_i$, and the solution for the force-free condition can be written in the form:

$$e = B_n \epsilon^{\sigma_n t}\sin(\omega_n t + \alpha_n) + B_{n-1}\epsilon^{\sigma_{n-1}t}\sin(\omega_{n-1}t + \alpha_{n-1}) + \ldots$$

The Production of Vowels and Consonants

Vowels: The current source can be thought of as delivering impulses spaced at intervals of $1/f_0$ where f_0 is the fundamental pitch or voicing frequency. The impulse determines the initial conditions and for the remainder of the interval the circuit decays by the force-free solution above. See Fig. 3 below.

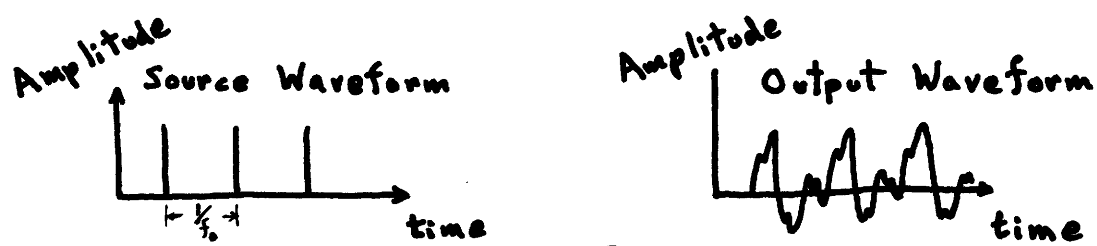


Fig. 3

In general the acoustic network acts as a filter on whatever source spectrum is present, as shown in Fig. 4 below.

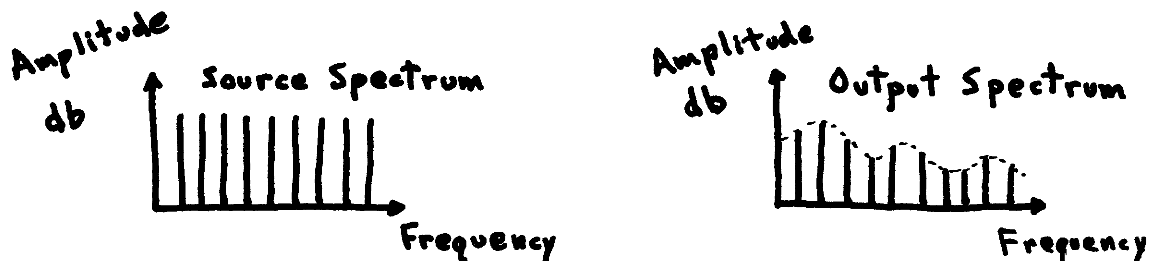


Fig. 4

Consonants: The production of a fricative consonant such as (s) proceeds in this manner: A constriction, in this case caused by the tongue pressing against the front of the roof of the mouth, causes a high velocity, turbulent flow of air. This is a source of noise which is filtered by the cavities ahead of it, around the teeth and to some extent by those back of it, giving a spectrum of the type shown in Fig. 5 on the next page.

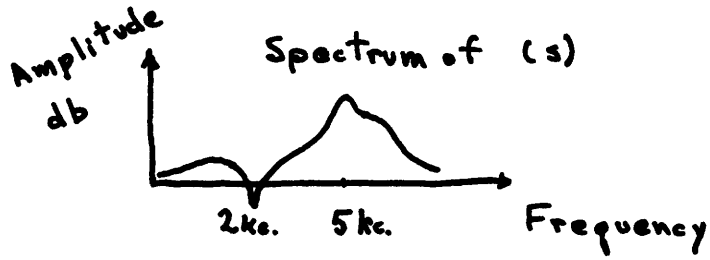


Fig. 5

The equivalent circuit for the production of fricative consonants seems to involve a noise voltage source at the place of the constriction as shown in Fig. 6 below.

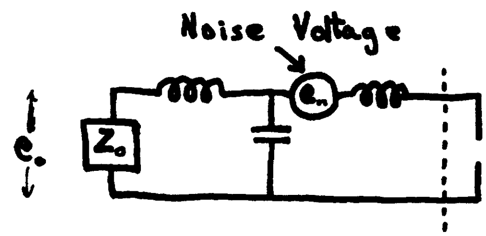


Fig. 6

Previous Methods of Synthesis

For the synthesis of speech a number of methods have been used. Probably the two most flexible ones are those at MIT[16*] and the Haskins Laboratory.[4] The first uses a dynamic analog vocal tract. It is an electrical analogy in which the "cross-section" of the tract is continuously adjustable by purely electrical means (saturable reactors and reactance tube circuits.) The other at the Haskins Laboratory in New York is a device allowing playback of hand drawn speech patterns. The patterns are drawn to any desired complexity and the sound is reproduced by the playback device.

A number of other devices have been built[9,10,11,13,14,15], but they all suffer in being difficult to "program" for complex or rapidly changing speech sounds.

*Superscripts refer to the bibliography on pgs. 16 - 18.

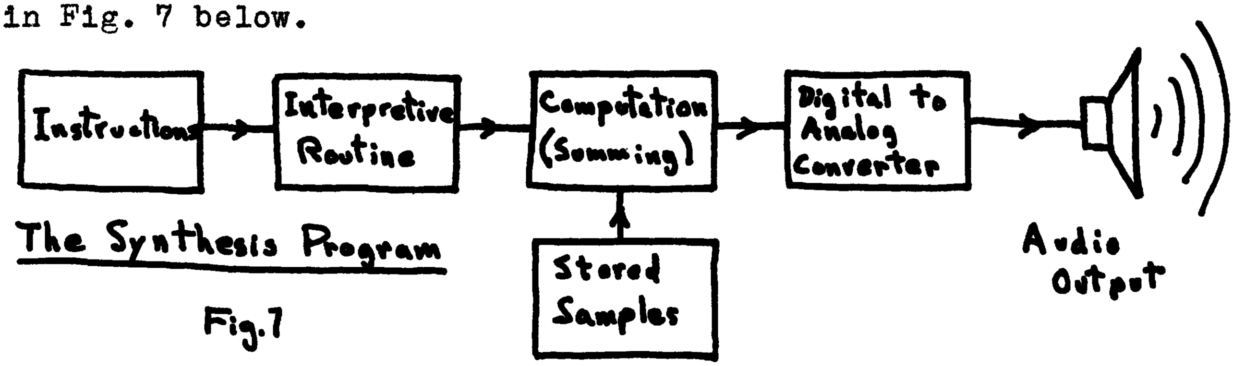
DIGITAL COMPUTER METHODS

Introduction

It is possible with certain high speed digital computers both to compute the waveforms and to have the waveforms presented at a loudspeaker in their normal audible form, i.e., as speech sounds. The computer can also manipulate at high speed the instructions specifying the nature of the waveforms.

The differential equation describing the vocal tract could be converted to difference form and solved continuously to yield the desired output. However, this involves rather high order differences and is thus time-consuming. It is intriguing because it can be made quite exact and still retains the analogue form fairly well. A faster approach, and the one utilized, is to compute a number of samples of solutions and have the program simply extract the desired sections of the solutions from its table and present them at the output. The stored solutions would contain damped sine waves of many different frequencies and filtered noise of various bandwidths and frequencies. This produces a quazi-static solution quite similar to the WKB solution of a wave equation. This approach is justified by the fact that the vocal tract parameters change much more slowly than the characteristic decay rates of the cavity responses.

A program has been written by myself to perform these operations on the MIT-IBM 704 computer. The program has been designed primarily for high speed and flexible operation. An outline of the program is shown in Fig. 7 below.



The Synthesis Program

Fig. 7

Digital to Analog Conversion

The conversion of the synthesized samples in their digital form to an analog voltage which can be recorded or reproduced in audible form is simply accomplished by a converter such as the one shown in reference 26, pg. 530. Within the machine samples are computed to six binary places of accuracy. This gives a maximum of 36 db signal-to-quantization level ratio, a rough measure of the maximum signal-to-noise ratio. Frequency response is limited by the maximum obtainable read-out rate of 14,000 points per second. The highest component that can be transmitted is 7,000 cps.; all higher are reflected into the 0 to 7,000 cps. region and appear as noise.

The Instructions

When summing a number of sine and noise samples, the instructions must specify the nature of the samples (frequency, amplitude, phase, bandwidth, etc.), the point at which the sample is to begin, and finally the duration of the sample. The four instructions used to specify this information are: "Time", "Duration," "Formant," and "Noise."

Time A marker is kept within the machine which denotes the present point of time. This point is a certain location in the 704 magnetic core memory. When any sample is specified it will begin at this point. When the Time instruction is given (abbreviated by T) the marker is moved ahead by the amount specified by the instruction. Thus a series of T instructions interspersed with other instructions might give the output shown in Fig. 8 below.

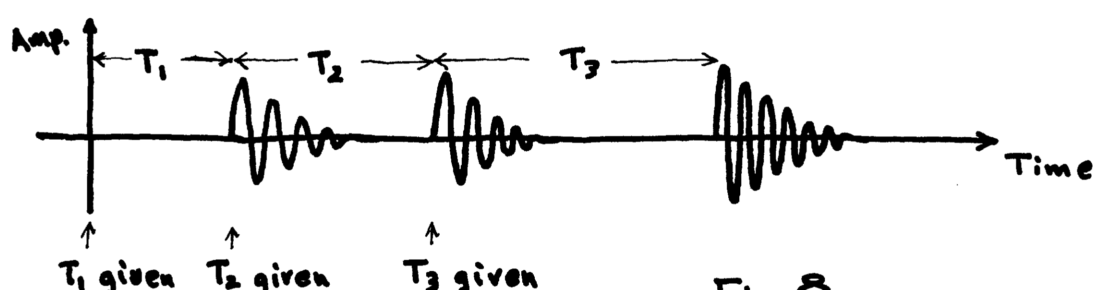


Fig. 8

Duration It is sometimes desired to limit the duration of a sample. Often a noise burst is desired which is much shorter than the particular sample in storage. By giving a duration instruction (abbreviated by D) we can accomplish this limiting. The amplitude of a noise sample is set and cannot be changed while it is being summed. Therefore, if a burst of increasing amplitude is desired, a series of short bursts of length limited by D can be specified. Each of these bursts would have a greater amplitude than the preceding one. The value of the duration is always that of the last given; it need not be stated frequently. The effect of the D instruction is shown in Fig. 9 below.

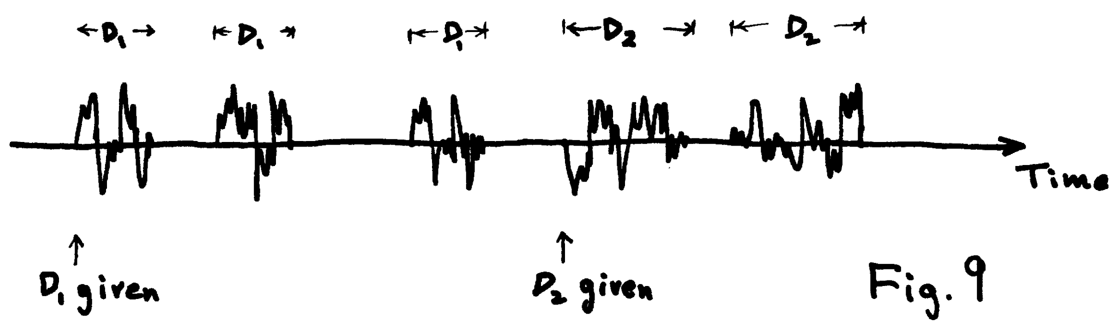


Fig. 9

Formant The Formant instruction specifies a single damped sine wave. This instruction (abbreviated F) specifies the phase(as plus or minus), the frequency, and the amplitude. There are normally about 50 frequencies available between 100 and 5,000 cps. The amplitude is adjustable in 3 db steps over a range of 36 db.

Noise The Noise instruction (abbreviated N) specifies the amplitude in 6 db steps and the frequency of the noise. The exact character of the noise samples is yet to be decided.

Summation

It is normally necessary to sum a number of different damped sines or noise. This is done very simply by letting them overlap or coincide in time, when specifying them in the instructions. Thus, if a number of different F instructions are given without an intervening T instruction the sum of the various F's will be formed, similarly for noise. There are no restrictions on the ordering of the instructions -- they are completely independent in that sense. To produce a section of a vowel we might give a sequence of the form FFFTFFFTFFF...... which would produce a sum as shown in Fig. 10 below.

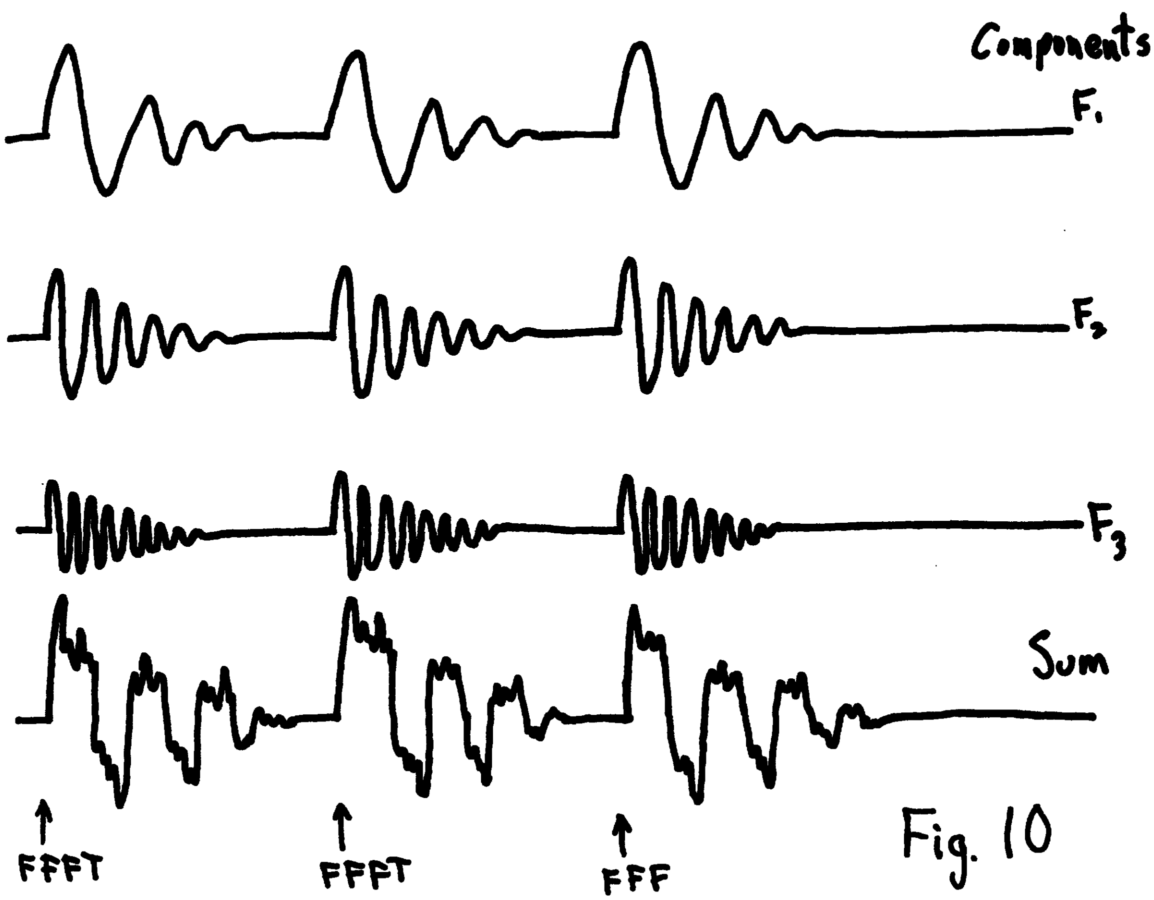


Fig. 10

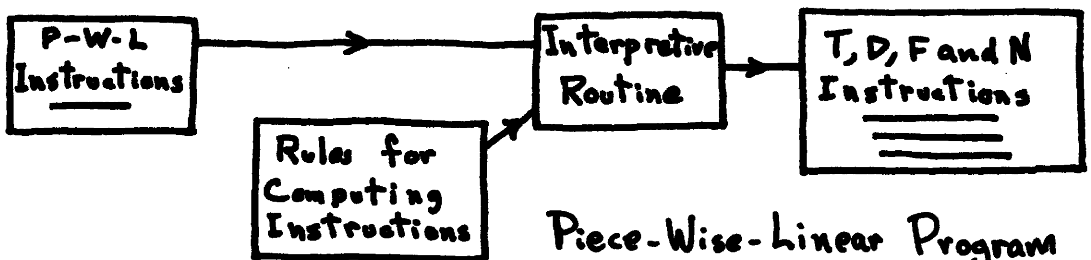
Preparation of Instructions

The instructions are punched on IBM cards to be read into the machine. Once a large number of cards is punched they need not be re-punched, they need only be re-ordered to form new sounds. If a number of identical cards are required they can simply be reproduced from a "master" (cf. the last 15 instructions in Appendix F.)

The program considers the instructions in order, one-by-one. It is designed so that the parameters such as the frequencies and the bandwidths of the samples can easily be altered. The noise samples are actually computed by the synthesis program itself using random numbers, and the T, D, and F instructions. The noise can thus be made to have almost any spectral characteristics desired. The program is also designed to be readily modified to receive new instructions that might be wanted to store the samples on magnetic tape, display the samples on an oscillograph screen or present them at the audio output for recording.

The Piece-wise-linear Program

The primary disadvantage of the program outlined above is that we must write too many instructions for each sample we wish synthesized. Often there is a great deal of redundancy in these many detailed instructions because the sounds are changing slowly or in some very regular way, e.g., the fundamental pitch or some of the formants may be changing approximately linearally with time during some interval. For cases such as these we use a coding scheme to eliminate a great deal of this redundancy. Even simple schemes can reduce the number of instructions necessary for a 2 second sample from many hundred to easily less than one hundred. The method of doing this is to write a second program which accepts the more concise instructions and translates them into a series of many more of the T, D, F, and N instructions. This operation is outlined in Fig. 11 below.



Piece-Wise-Linear Program

Fig. 11

At this point it is useful to discuss a convenient representation of the speech we want to synthesize.

A common way to represent the dynamic acoustical properties of speech is by "visible speech" patterns[21]. These are produced by certain devices used for the analysis of speech. The patterns are constructed so that the vertical axis represents frequency, the horizontal time, and the density of the shading represents intensity. Vowels then appear as horizontal bars called formants and fricatives appear as grey regions of no very definite structure in the high frequency region. This is shown in Fig. 12 at the top of the next page.

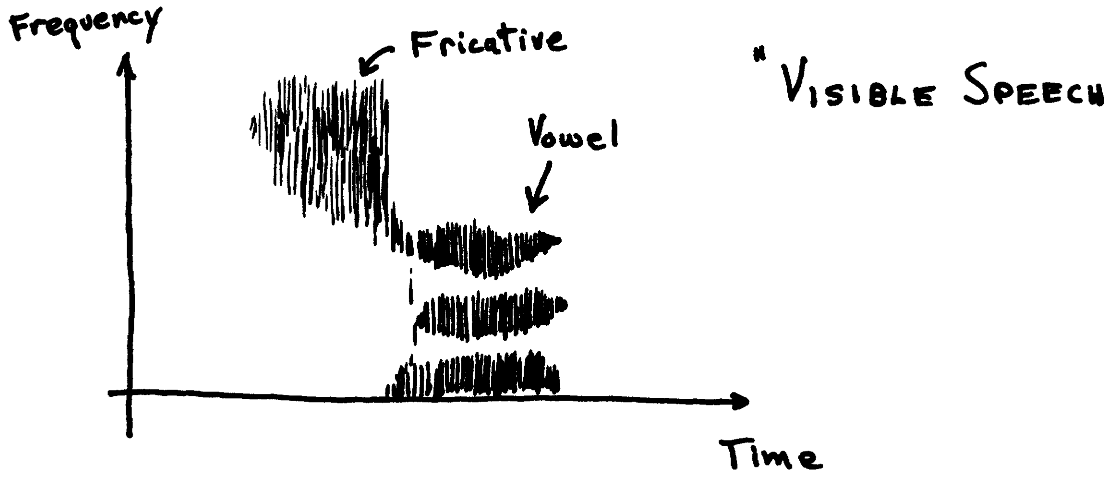


Fig. 12

To code for the piece-wise-linear program we first approximate the movements of the formants by straight-line segments. At each break-point we state the properties of the formant somewhat as an F instruction does. We do the same for the noise and for the fundamental frequency. This is shown in Fig. 13 below.

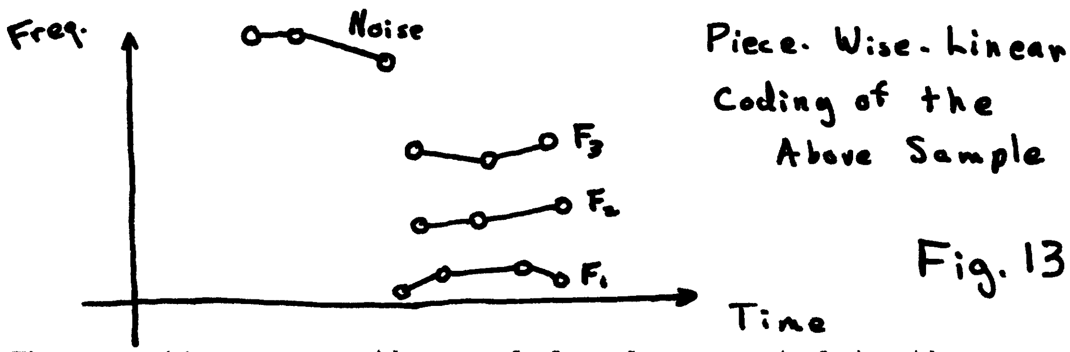


Fig. 13

These patterns are then coded and presented to the piece-wise-linear program which interprets them and composes the proper detailed instructions.

The present writer has not worked on the above program in detail but another student is studying the problem.

Pre-emphasis

By programming unnaturally large amplitudes for the higher frequencies we can, in an approximate way, pre-emphasize them. Filtering the output will bring them back to their "natural" level but now with less noise in the higher frequencies. This is done, of course, at the expense of adding noise and reducing the dynamic range in the lower frequency region. It has been found that the higher frequencies are quite important in the production and recognition of speech even though their normal amplitudes are lower than the low frequency region. The action of the noise and filtering is shown in Fig. 14 below.

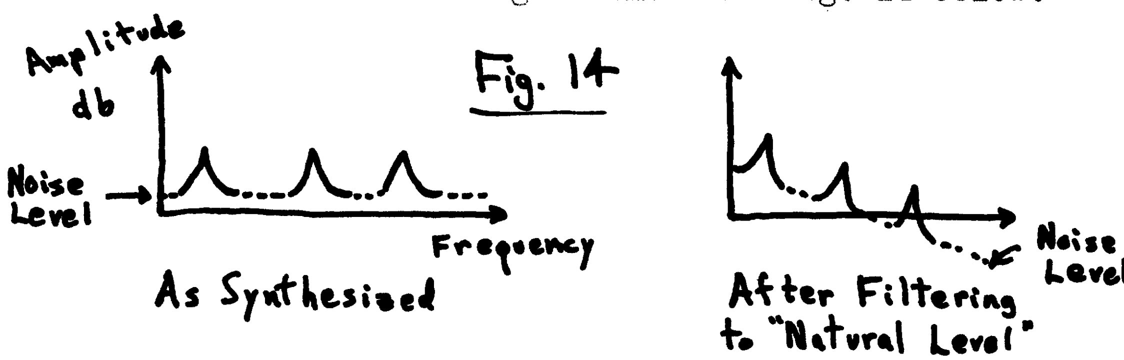


Fig. 14

Program Speed, Testing, and Future Plans

The maximum length for a single continuous sample that can be read out of the machine is 2.4 seconds at 14 kc.

In synthesizing a sample involving the first three formants the program can run as fast as twice real time, i.e., it would take the machine 1.2 seconds to synthesize a sample which would last 2.4 seconds. The slowest rate a which synthesis proceeds is half of real time. The major delay in time is preparing the sample for the output device which takes half of real time. Thus it would normally take between 6 and 10 seconds to compute the sample and ready it for read-out.

The program has been tested and debugged to a large extent. A cursory examination of the scope display of the synthesis using the instructions in Appendix F indicated that the program was functioning properly though no films have been received as yet. Further testing using scope display is in order.

The next steps in the development of this program might be the inclusion of tape routines for storing the bank samples, the piece-wise-linear program, and finally the setting up and use of the digital-to-analog equipment. One of the runs of the program should be devoted to computing the noise samples.

A reasonable arrangement for the actual operation of the program would be to have all of the programs and bank samples on tape. Then the piece-wise-linear instructions would be read in from the on-line card reader. Synthesis would then proceed, the samples finally being recorded on an audio tape recorder for listening tests.

*   *   *

ACKNOWLEDGMENT

The author would like to thank Professor Kenneth N. Stevens for his helpful advice relating to all problems of speech acoustics. Thanks are due also to Professor Dean N. Arden and Mr. Ercolino Ferretti of the RLE for stimulating discussions on various computational techniques.

BIBLIOGRAPHY

(The Journal of the Acoustical Society of America is denoted by JASA.)

1. Don Lewis, "Vocal Resonance," JASA, 8 , (1936), 91-99.
2. Ralph K. Potter and Gordon E. Peterson, "The Representation of Vowels and their Movements," JASA, 20, (1948), 528-535.
3. R. M. Fano, "The Information Theory Point of View in Speech Communication," JASA, 22, (1950), 691-696.
4. Franklin S. Cooper, "Spectrum Analysis," JASA, 22, (1950), 761-762.
5. W. H. Huggins, "System-Function Analysis of Speech Sounds," JASA, 22, (1950), 765-767.
6. Ralph K. Potter and J. C. Steinberg, "Toward the Specification of Speech," JASA, 22, (1950), 807-820.
7. J. C. R. Licklider and Irwin Pollack, "Effect of Differentiation, Integration, and Infinite Peak Clipping upon the Intelligibility of Speech," JASA, 20, (1948), 42-51.
8. Franklin S. Cooper, Pierre C. Delattre, Alvin M. Liberman, John M. Borst, and Louis J. Gerstam, "Some Experiments on Synthetic Speech Sounds," JASA, 24, (1952), 597-606.
9. Cyril M. Harris, "A Speech Synthesizer," JASA, 25, (1953), 970-975.
10. R. L. Miller, "Auditory Tests with Synthetic Vowels," JASA, 25, (1953), 114-121.

11. Kenneth N. Stevens, S. Karowski and C. Gunnar M. Fant, "Electric Analog of the Vocal Tract," JASA, 25, (1953) 734-742.

12. Kenneth N. Stevens and Arthur S. House, "Development of a Quantitative Description of Vowel Articulation," JASA, 27, (1955), 484-493.

13. Harry F. Olson and Herbert Belar, "Electronic Music Synthesizer," JASA, 27, (1955), 595-612.

14. E. S. Weibel, "Vowel Synthesis by Means of Resonant Circuits," JASA, 27, (1955), 858-865.

15. James L. Flannagan, "Note on the Design of 'Terminal--Analog' Speech Synthesizers," JASA, 29, (1957), 306-310.

16. George Rosen, "Dynamic Analog Speech Synthesizer," JASA, 30, (1958), 201-209.

17. E. E. David, Jr., "Artificial Auditory Recognition in Telephony," The IBM Journal of Research and Development, 2, (1958), 294-309.

18. R-M. S. Heffner, General Phonetics, (Madison, Wisconsin, 1952)

19. Colin Cherry, On Human Communication, (New York, 1957)

20. C. E. Shannon and W. Weaver, The Mathematical Theory of Communication, (Urbana, Illinois, 1949)

21. R. K. Potter, G. A. Kopp, and H. C. Green, Visible Speech, (New York, 1947)

22. P. M. Morse, Vibration and Sound, (New York, 1948)

23. E. A. Guillemin, Communication Networks, vol. II, (New York, 1935)

24. M. F. Gardner and J. L. Barnes, Transients in Linear Systems, (New York, 1942)

25. C. G. M. Fant, Acoustic Theory of Speech Production, (The Hague, 1959)

26. Notes on Analog to Digital Conversion Techniques, ed. A. K. Susskind, (Cambridge, Mass., 1957)

27. Coding for the MIT-IBM 704 Computer, ed. F. Helwig, (Cambridge, Mass., 1958)

28. 704 Electronic Data-Processing Machine - - Manual of Operation, IBM Corporation, (New York, 1954 to date)

Appendix A

Sub-word Arithmetic

When little accuracy is desired it is useful to divide a 36 binary digit 704 word into a number of smaller words called sub-words. Each sub-word carries a sign with it and one position must be left open for a carry so that one sub-word will not interfere with another. The sign and carry bit are indicated by S and C respectively. The negative is handled by using the two's complement. These numbers are convenient because addition, subtraction and multiplication can be performed on all of the subwords in a 704 word without ever "unpacking" them. In this program five sub-words are stored in a 704 word as follows:

1	2	3	4-8	9	10	11-15	16	17	18-22	23	24	25-29	30	31	32-36
x	C	S	...	C	S	.....	C	S	.....	C	S	.....	C	S	.....
			5			4			3			2			1

A single n-place signed sub-word is of the following form:

2^{n+1}	2^n	2^{n-1}		2^0
C	S	X	X...X...X...	X
n+2	n+1	n	n-1	1

We have assumed the binary point to be to the right of the first place but the argument below can simply be generalized to this case (normally the sub-word is surrounded by others.)

The n + 1st place designate the sign, S. A zero in S indicates a positive number, a one indicates a negative number.

The n+2nd place is a carry bit for absorbing any changes of sign -- it is erased after each computation. If a number of these sub-words in a 704 word are added to another similar 704 word, each of the n-place numbers will be added algebraically to the corresponding number (sub-word) in the other 704 word.

The negative of a number is obtained by subtracting it from 2^{n+1} (complementing it.) (and then adding 1)

First we restrict all numbers of interest so that

$$0 \leq a, b < 2^n \quad \text{and} \quad |a| + |b| < 2^n$$

We will show that the negative of a number always has a one in S. Trivially a number $< 2^n$ has a zero in S so that complementing it always produces a one in S.

It is interesting to note that the number 2^n has the properties $(-2^n) = 2^n$ and $2^n + 2^n = 0$.

Laws of Addition

$(+a)+(+b) = (a+b)$ by the normal addition process.

For $(+a) + (-b) = a-b+2^{n+1}$ we have $a > b$ or $2^n > a-b > 0$ so that $2^{n+1} + 2^n > (+a)+(-b) > 2^{n+1}$ giving a zero in S, a positive number as we had assumed.

If $a = b$, $(+a)+(-b) = 2^{n+1}$, a zero.

If $a < b$ then $0 > a-b > -2^n$ or $2^{n+1} > (+a)+(-b) > 2^{n+1} - 2^n = 2^n$, giving a one in S.

For $(-a)+(-b)$ we have $2^{n+2} > (-a)+(-b) > 2^{n+2} - 2^n$, giving a minus sign in S.

All of the sums considered here are $< 2^{n+2}$ meaning that no C ever overflows into and interferes with the sub-word on the left.

Subtraction of the sub-words "in bulk" is similar to addition but the C bits of the minuend must be loaded with 1's to prevent borrowing from the sub-word on the left.

<u>Multiplication</u>

We can multiply a number by a factor of 2^{-m}, if it is positive, by shifting it m places to the right and inserting zeros on the left. If we consider the digits shifted past position 1 to be lost we have, originally,

$$c = k_{n-1} 2^{n-1} + k_{n-2} 2^{n-2} + \ldots + k_0 2^0$$

After shifting m places we have decreased each exponent by m, giving,

$$c' = 2^{-m} c \qquad \text{to within } 2^{-0} = 1 .$$

If c is the negative of a number, $c = 2^{n+1} - a$, we insert 1's on the left after shifting.

Originally $\underset{c}{0}\,\underset{s}{1}\,x \ldots x$ is shifted to $\underset{c}{0}\,\underset{s}{0}\underbrace{\ldots 0}_{m} x \ldots x$,

and we add to this $\underset{c}{0}\,\underbrace{\underset{s}{1} \ldots 1}_{m}\,0 \ldots 0$.

The number added is $(2^{n+1} - 1) - (2^{n-m+1} - 1) = 2^{n+1} - 2^{n-m+1}$

so that $c' \cong 2^{-m}(2^{n+1} - a) + 2^{n+1} - 2^{n-m+1} \cong 2^{n+1} - 2^{-m} a$

which is the negative of the number $2^{-m} a$ as desired.

If a digital-to-analog converter is used which only handles absolute values we add 2^n to each of the sub-words. This is a 704 word with 1's in the S bits and 0's elsewhere. We can also accomplish the same operation by simply changing the sign which can be seen to be equivalent.

Appendix B The 704 Program in Detail

The 704 program as tested in May 1959 is made of two basic sections. First is the synthesis program itself, and second the auxiliary routines -- one to initially compute the damped sines and another to display synthesized waveforms on the cathode ray tube unit attached to the computer.

Synthesis Program

The present point of time may occur at a sub-word within a 704 word so that addition, when it occurs, will involve shifting the stored samples to the right or left so that their beginning will correspond with the present point of time. On the other hand the present point of time may be at the beginning of a 704 word which means no shifting is required. Since the second operation is much simpler than the first, an optimum program could be written that would make the simple routine run much faster. Also, multiplication may or may not be required and there is quite a difference of speed when multiplication is omitted.. To take advantage of these possibilities to gain speed, routines have been designed to handle each case separately. The phase (plus or minus) is also handled separately at times. There are three working areas in the machine: the bank or sample block containing the damped sines and noise, a short work space called the multiply block, and finally the assembly block in which the entire synthesized sample is formed.

The various possible sequences of operations are shown in Fig. 15 below.

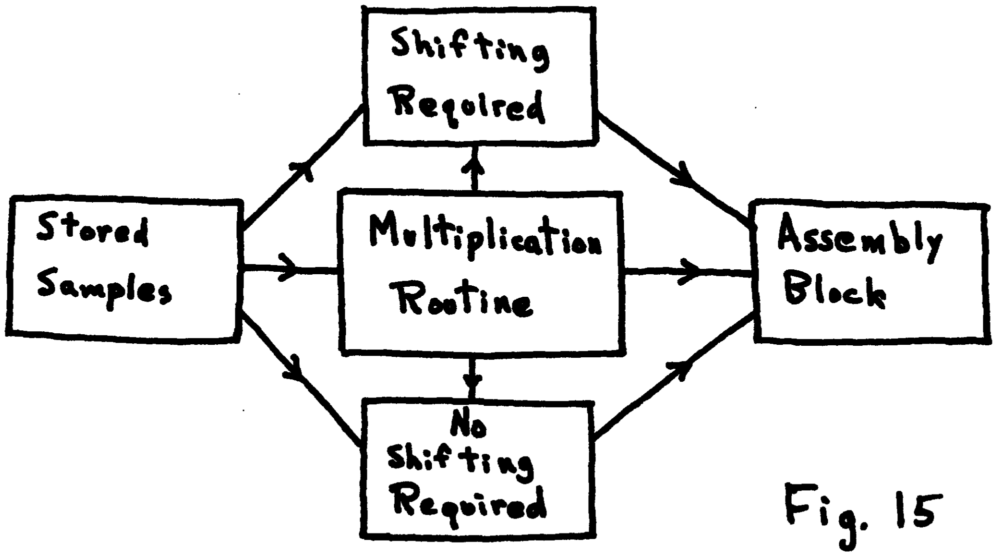


Fig. 15

The instructions are tested by the program one at a time and completely executed before the next instruction is studied. Whenever the synthesis (sometimes called "assembly") program is entered all of the markers are initialized so that it begins at the origin of the assembly block. After an instruction has been executed a return is made to obtain the next instruction, or an error count is stepped by one if an illegal instruction was given (amplitude or frequency out of range), or the assembly may terminate. Termination occurs if an all zero instruction is found (this is a T zero instruction,) or if the present point of time becomes located near the end of the assembly block.

The T instruction causes the setting of three markers: the present point of time measured in sub-words from the beginning of the assembly block, the number of 704 registers from the beginning of the assembly block, and the position of the present point of time in sub-words as measured from the beginning of the 704 word which contains it.

The D instruction sets the duration as measured in sub-words. If the duration is found to be greater than the length of the longest sample (a noise sample), then it is reduced to this value.

The F instruction first computes the phase of the sample as plus or minus and sets a marker denoting this. Since the multiplication routine can only handle shifts of multiples of 6 db in amplitude (powers of 2), and 3 db steps are desired, each sine is stored at two amplitudes separated by three db. Thus both the amplitude and the frequency enter into the calculation of the location in storage. Both the number of places to shift, for multiplication, and the sample location are then computed. Finally, advantage is taken of the fact that the sine waves damp out in shorter times for lower amplitudes. If this damping time is shorter than the duration time already specified, the routines handle the sample for the minimum time necessary and do not compute useless strings of zero's. The F routine then transfers control to the proper assembly routine for the actual synthesis.

The N instruction is quite similar to the F except that the phase is always plus and because of storage requirements the amplitude is in 6 db steps.

In this program the end of assembly is followed by the (TV) routine for scope display. In a production version the end of the assembly would cause the sample to be stored or to be read out. Then a new set of instructions would be obtained and the next sample synthesized.

Auxiliary Routines

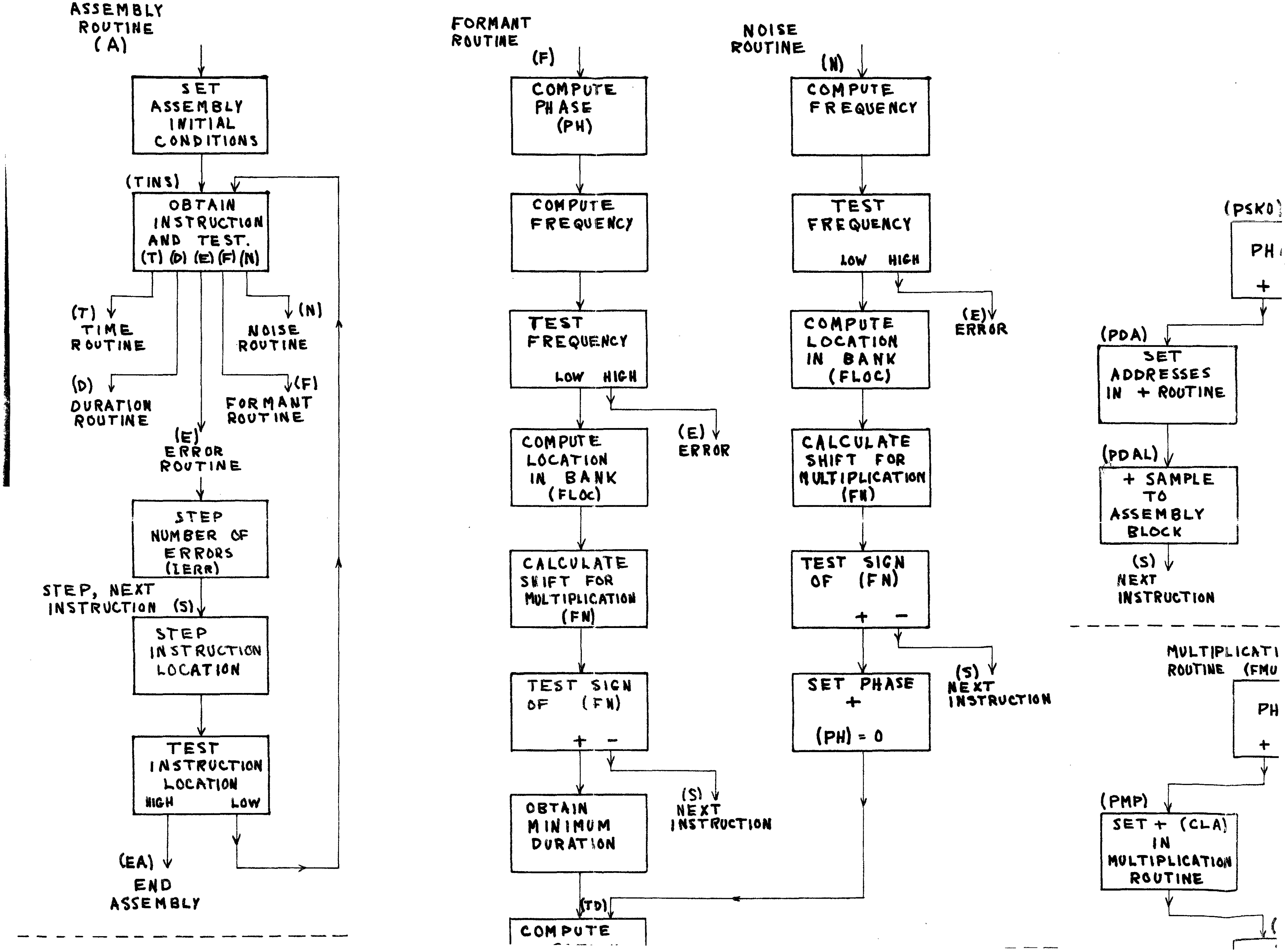
To compute the damped sine waves, one cycle of a 55 cps. tone and one exponential of somewhat longer duration are computed. The nth harmonic is then formed by indexing through the block of the sine wave, picking every nth point. The computations for the indexing are done modulo the block length (which is conveniently $256=2^8$), so that the point picked is always constrained to lie within the one cycle block. This is a very fast way to produce multiples of a waveform in time. These harmonics are multiplied by the decaying exponential, scaled to two different values and the resulting samples stored. All harmonics of 55 cps. up to a pre-set limit are computed and then every even harmonic up to a second limit. The limits in the present version of the program are 550 and 5500 cps, respectively. This routine is finished at a point called "End Computation." At this point a routine can be inserted to store the samples on tape so that they need not be computed for each run.

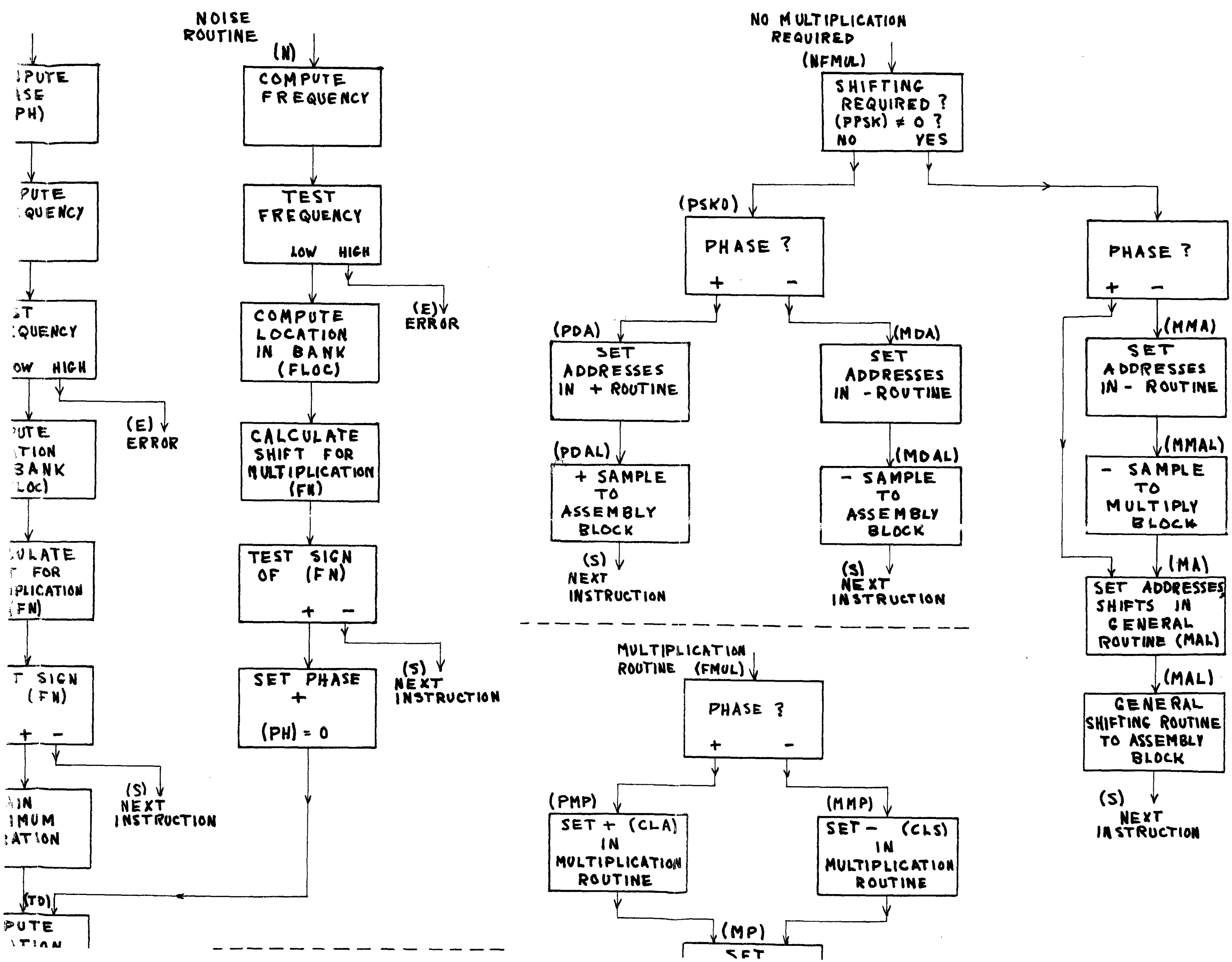
The scope routine first titles the run and then takes blocks of 100 words (500 sample points) and displays them a number of times, numbering each block sequentially from 1. The right edge, left edge and the x-axis are also displayed. The role of this routine is quite flexible, as it is only needed when there is some question of whether or not synthesis is proceeding correctly -- it is quite useful in debugging.

Appendix C

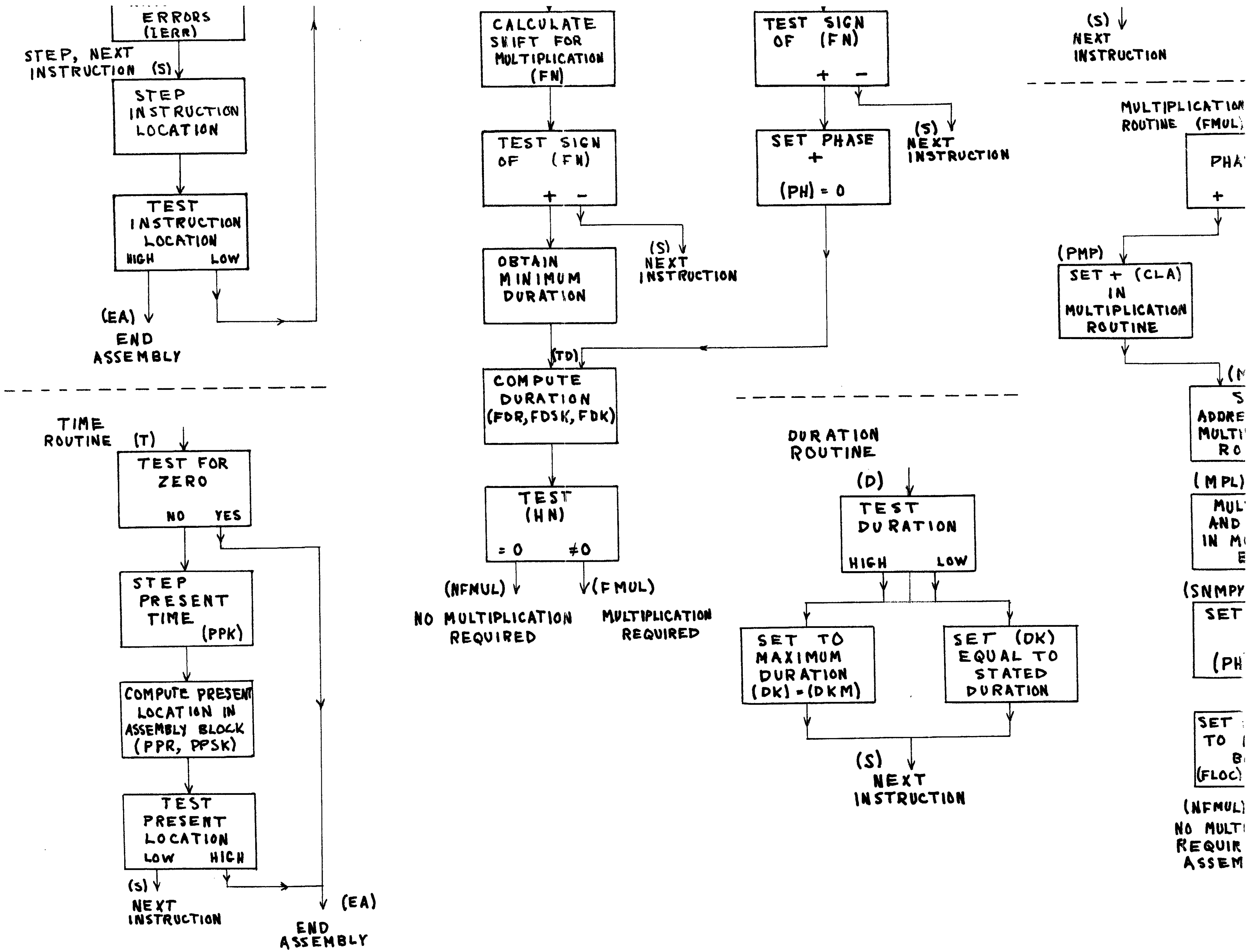
FLOW - CHARTS

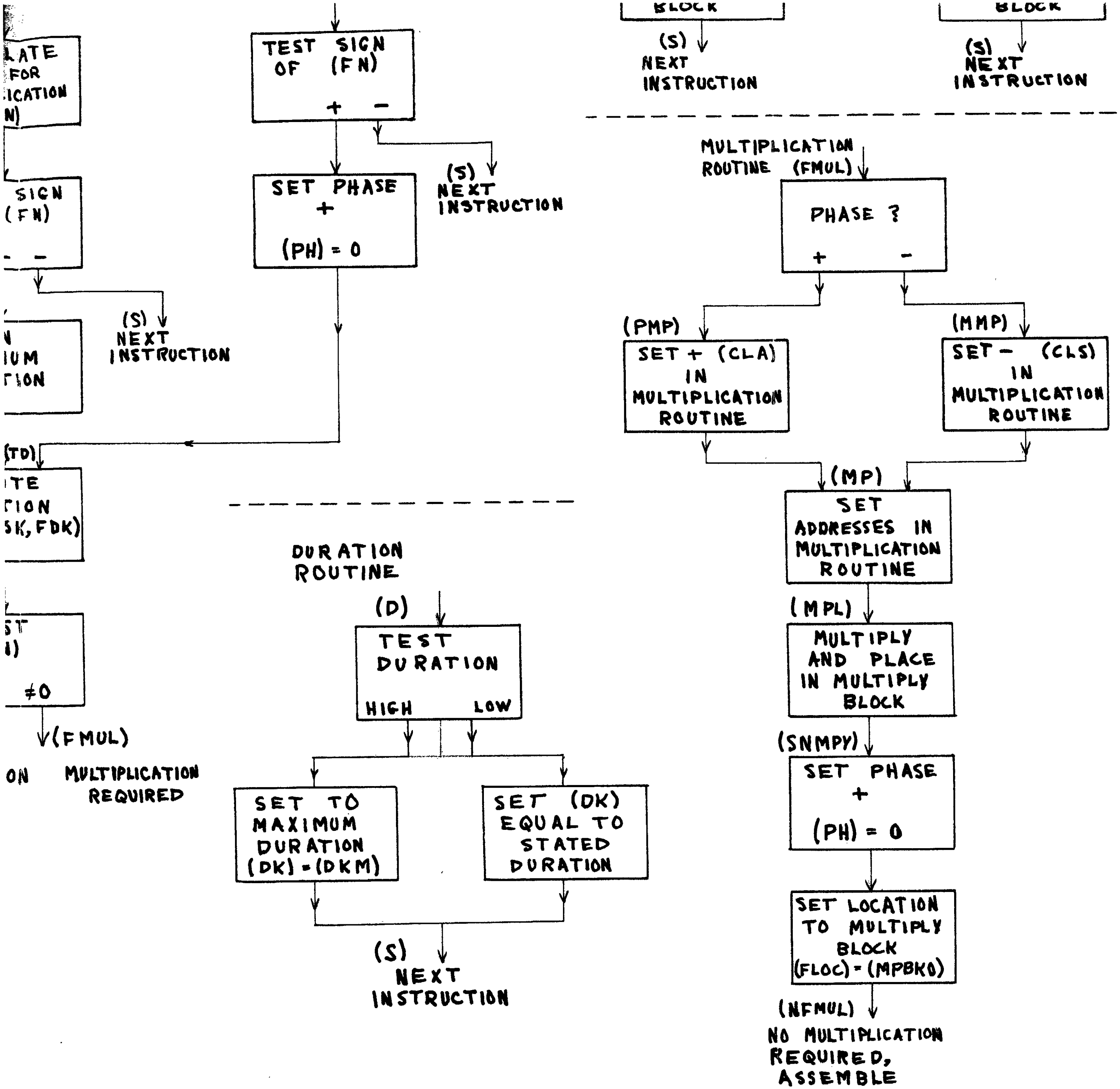
On the flow-charts the symbols in parentheses refer to points of entry and data words in the SAP program. The actual locations of the most important of these in the SAP program are indexed on page 30.


ASSEMBLY ROUTINE (A)
SET ASSEMBLY INITIAL CONDITIONS
(TINS)
OBTAIN INSTRUCTION AND TEST. (T) (D) (E) (F) (N)
(T) TIME ROUTINE
(D) DURATION ROUTINE
(E) ERROR ROUTINE
(N) NOISE ROUTINE
(F) FORMANT ROUTINE
STEP NUMBER OF ERRORS (IERR)
STEP, NEXT INSTRUCTION (S)
STEP INSTRUCTION LOCATION
TEST INSTRUCTION LOCATION HIGH LOW
(EA) END ASSEMBLY
FORMANT ROUTINE
(F)
COMPUTE PHASE (PH)
COMPUTE FREQUENCY
TEST FREQUENCY LOW HIGH
(E) ERROR
COMPUTE LOCATION IN BANK (FLOC)
CALCULATE SHIFT FOR MULTIPLICATION (FN)
TEST SIGN OF (FN) + −
(S) NEXT INSTRUCTION
OBTAIN MINIMUM DURATION
(TD)
COMPUTE
NOISE ROUTINE
(N)
COMPUTE FREQUENCY
TEST FREQUENCY LOW HIGH
(E) ERROR
COMPUTE LOCATION IN BANK (FLOC)
CALCULATE SHIFT FOR MULTIPLICATION (FN)
TEST SIGN OF (FN) + −
(S) NEXT INSTRUCTION
SET PHASE + (PH) = 0
(PSKO)
PH
+
(PDA)
SET ADDRESSES IN + ROUTINE
(PDAL)
+ SAMPLE TO ASSEMBLY BLOCK
(S) NEXT INSTRUCTION
MULTIPLICATI
ROUTINE (FMU
PH
+
(PMP)
SET + (CLA) IN MULTIPLICATION ROUTINE



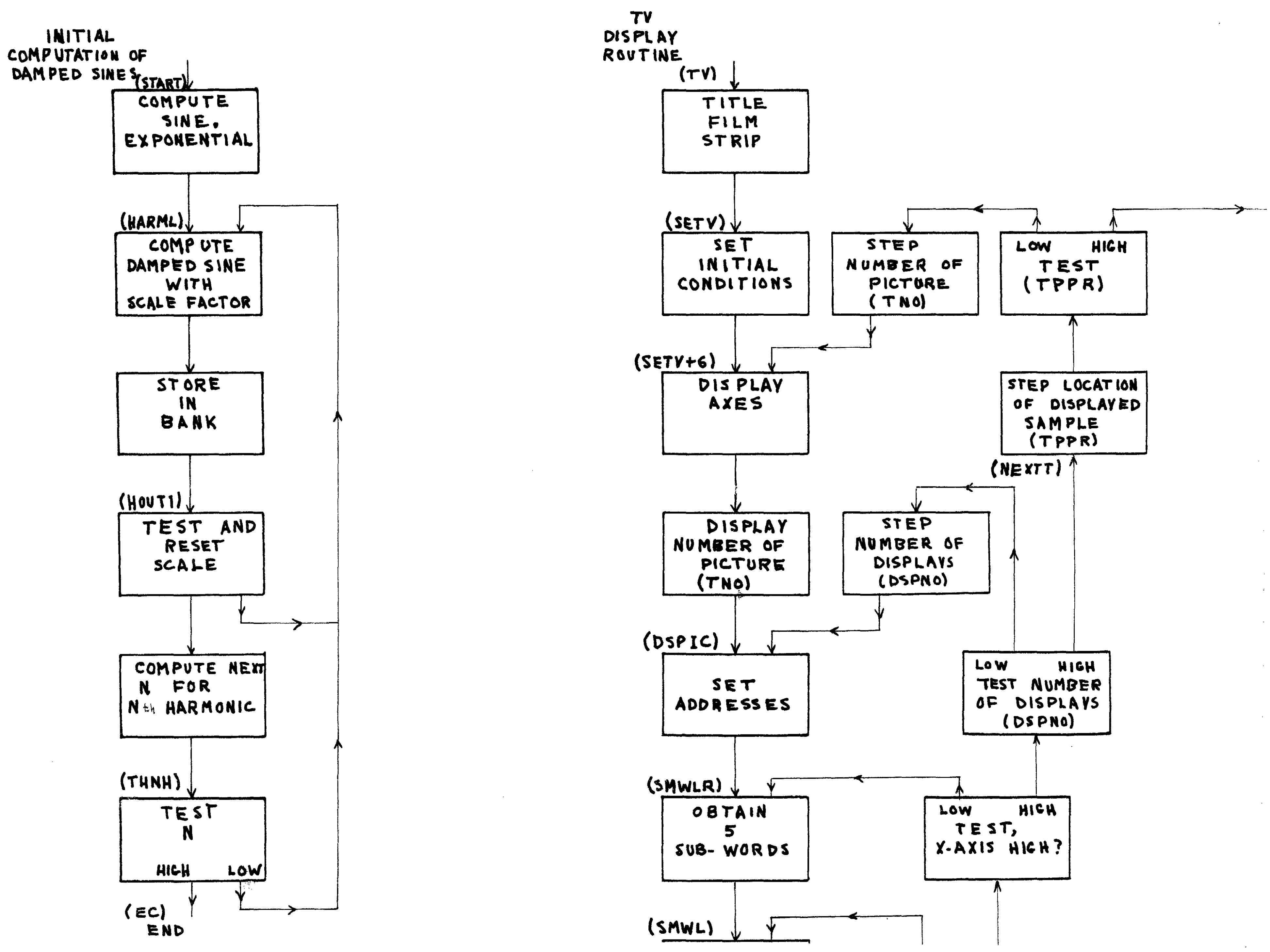
NOISE ROUTINE
(N)
COMPUTE FREQUENCY
TEST FREQUENCY
LOW HIGH
(E) ERROR
COMPUTE LOCATION IN BANK (FLOC)
CALCULATE SHIFT FOR MULTIPLICATION (FN)
TEST SIGN OF (FN)
+ -
(S) NEXT INSTRUCTION
SET PHASE + (PH) = 0
(E) ERROR
(S) NEXT INSTRUCTION
(TD)
NO MULTIPLICATION REQUIRED
(NFMUL)
SHIFTING REQUIRED ? (PPSK) ≠ 0 ?
NO YES
(PSKO)
PHASE ?
+ -
(PDA)
SET ADDRESSES IN + ROUTINE
(PDAL)
+ SAMPLE TO ASSEMBLY BLOCK
(S) NEXT INSTRUCTION
(MDA)
SET ADDRESSES IN - ROUTINE
(MDAL)
- SAMPLE TO ASSEMBLY BLOCK
(S) NEXT INSTRUCTION
PHASE ?
+ -
(MMA)
SET ADDRESSES IN - ROUTINE
(MMAL)
- SAMPLE TO MULTIPLY BLOCK
(MA)
SET ADDRESSES, SHIFTS IN GENERAL ROUTINE (MAL)
(MAL)
GENERAL SHIFTING ROUTINE TO ASSEMBLY BLOCK
(S) NEXT INSTRUCTION
MULTIPLICATION ROUTINE (FMUL)
PHASE ?
+ -
(PMP)
SET + (CLA) IN MULTIPLICATION ROUTINE
(MMP)
SET - (CLS) IN MULTIPLICATION ROUTINE
(MP)

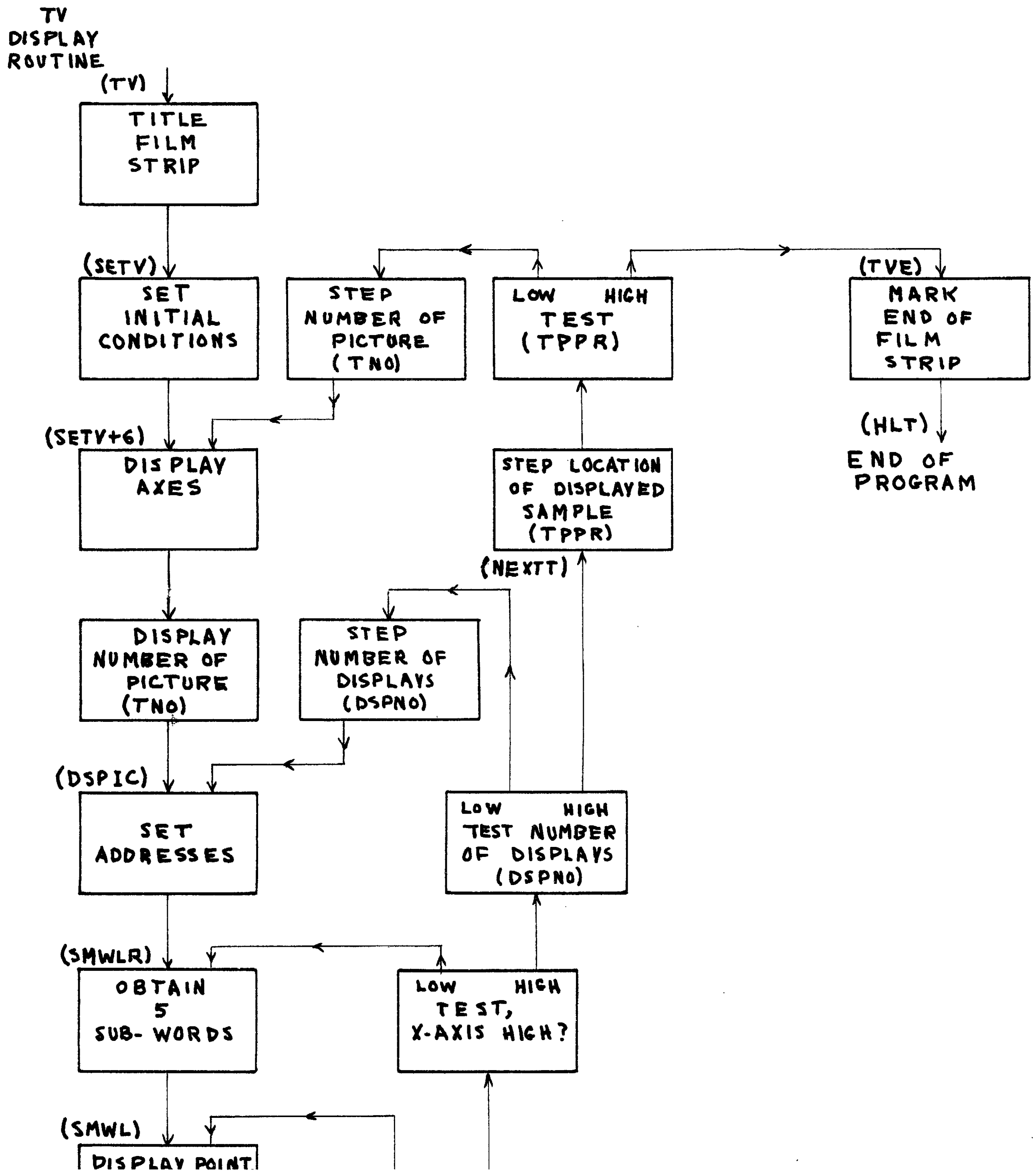

ERRORS (IERR)
STEP, NEXT INSTRUCTION (S)
STEP INSTRUCTION LOCATION
TEST INSTRUCTION LOCATION
HIGH
LOW
(EA) END ASSEMBLY
TIME ROUTINE (T)
TEST FOR ZERO
NO
YES
STEP PRESENT TIME (PPK)
COMPUTE PRESENT LOCATION IN ASSEMBLY BLOCK (PPR, PPSK)
TEST PRESENT LOCATION
LOW
HIGH
(S) NEXT INSTRUCTION
(EA) END ASSEMBLY
CALCULATE SHIFT FOR MULTIPLICATION (FN)
TEST SIGN OF (FN)
+
-
(S) NEXT INSTRUCTION
OBTAIN MINIMUM DURATION
(TD)
COMPUTE DURATION (FDR, FDSK, FDK)
TEST (HN)
= 0
≠ 0
(NFMUL) NO MULTIPLICATION REQUIRED
(FMUL) MULTIPLICATION REQUIRED
TEST SIGN OF (FN)
+
-
(S) NEXT INSTRUCTION
SET PHASE + (PH) = 0
DURATION ROUTINE (D)
TEST DURATION
HIGH
LOW
SET TO MAXIMUM DURATION (DK) = (DKM)
SET (DK) EQUAL TO STATED DURATION
(S) NEXT INSTRUCTION
(S) NEXT INSTRUCTION
MULTIPLICATION ROUTINE (FMUL)
+
(PMP)
SET + (CLA) IN MULTIPLICATION ROUTINE
(MPL)
(SNMPY
SET
(FLOC)
(NFMUL)



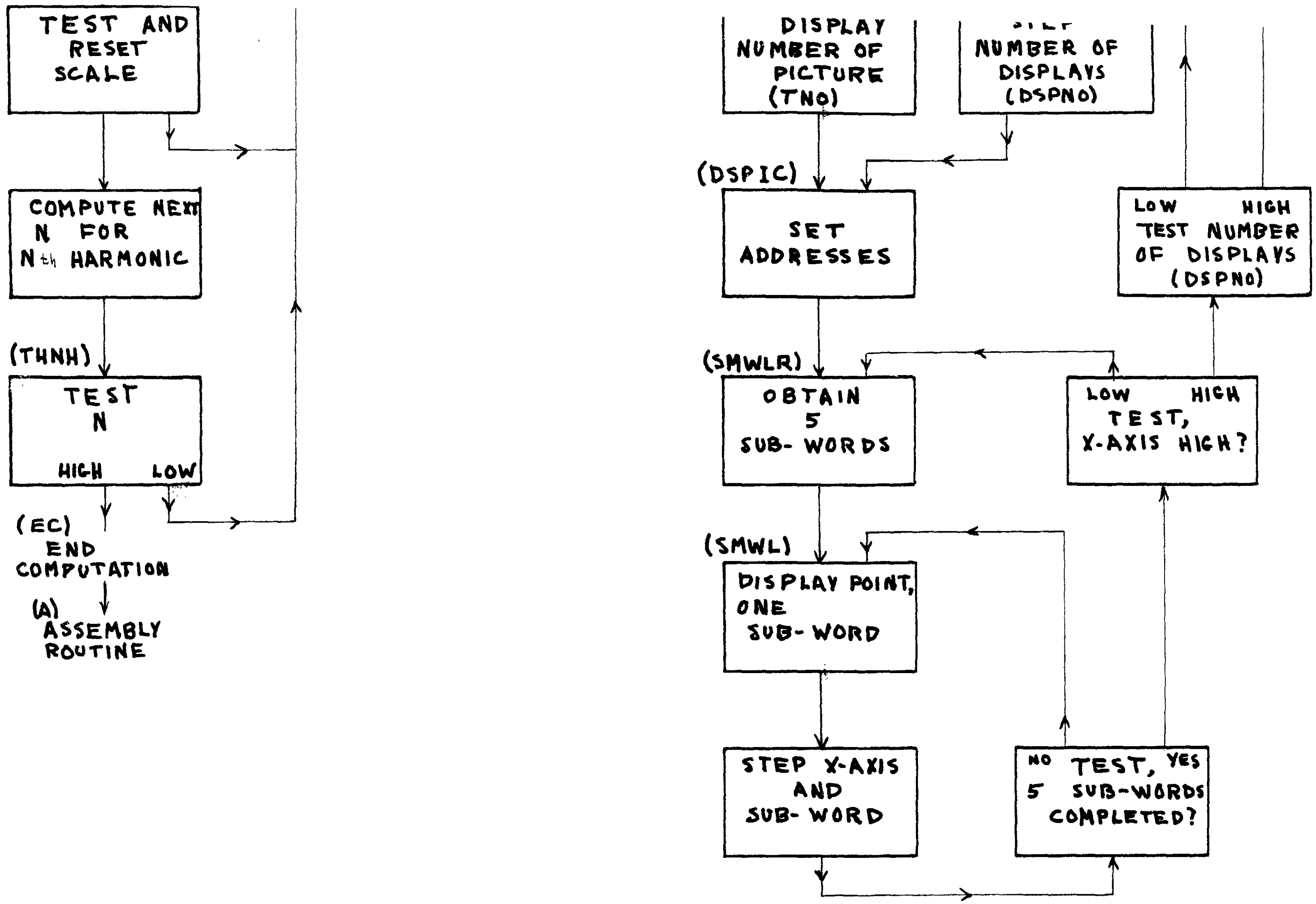
GENERAL SYNTHESIS PROGRAM

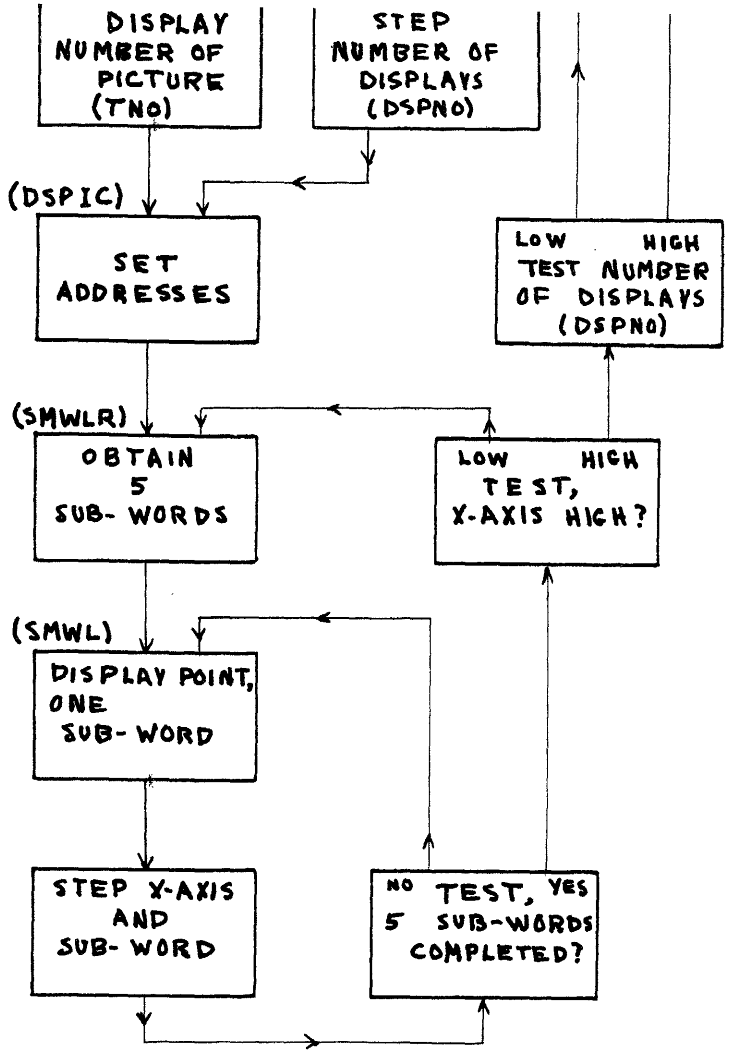
SYMBOLS IN PARENTHESES REFER TO LOCATIONS IN THE SAP PROGRAM


INITIAL COMPUTATION OF DAMPED SINES
(START)
COMPUTE SINE, EXPONENTIAL
(HARML)
COMPUTE DAMPED SINE WITH SCALE FACTOR
STORE IN BANK
(HOUT1)
TEST AND RESET SCALE
COMPUTE NEXT N FOR Nth HARMONIC
(THNH)
TEST N
HIGH
LOW
(EC)
END
TV DISPLAY ROUTINE
(TV)
TITLE FILM STRIP
(SETV)
SET INITIAL CONDITIONS
STEP NUMBER OF PICTURE (TNO)
LOW HIGH
TEST (TPPR)
(SETV+6)
DISPLAY AXES
STEP LOCATION OF DISPLAYED SAMPLE (TPPR)
(NEXTT)
DISPLAY NUMBER OF PICTURE (TNO)
STEP NUMBER OF DISPLAYS (DSPNO)
(DSPIC)
SET ADDRESSES
LOW HIGH
TEST NUMBER OF DISPLAYS (DSPNO)
(SMWLR)
OBTAIN 5 SUB-WORDS
LOW HIGH
TEST, X-AXIS HIGH?
(SMWL)



AUXILIARY ROUTINES


TEST AND RESET SCALE
COMPUTE NEXT N FOR Nth HARMONIC
(THNH)
TEST N
HIGH
LOW
(EC) END COMPUTATION
(A) ASSEMBLY ROUTINE
DISPLAY NUMBER OF PICTURE (TNO)
NUMBER OF DISPLAYS (DSPNO)
(DSPIC)
SET ADDRESSES
LOW HIGH TEST NUMBER OF DISPLAYS (DSPNO)
(SMWLR)
OBTAIN 5 SUB-WORDS
LOW HIGH TEST, X-AXIS HIGH?
(SMWL)
DISPLAY POINT, ONE SUB-WORD
STEP X-AXIS AND SUB-WORD
NO TEST, YES 5 SUB-WORDS COMPLETED?



AUXILIARY ROUTINES

SYMBOLS IN PARENTHESES REFER TO LOCATIONS IN THE SAP PROGRAM

Appendix D

SAP - PROGRAM

Index of the more important entry points.

*

General Synthesis Program

Symbol	Instruction Number
A	80
D	148
E	103
EA	106+1
F	155
FMUL	210
N	385
NFMUL	202
MA	297
MAL	324
MDA	244
MDAL	263
MMA	279
MMAL	289
MMP	346
MP	352
MPL	368
PDA	213
PDAL	232

Program Index (continued)

Symbol	Instruction Number
PMP	349
PSKO	207
S	107
SNMPY	381
T	133
TD	193

Auxiliary Routines

A	80
DSPIC	427
EC	79
HARML	27
HOUT1	54
NEXTT	458
SETV	413
SMWL	434
SMWLR	430A
START	1
THNH	75
TV	405
TVE	468

THE SYNTHESIS PROGRAM

AS RUN, MAY, 1959

```
START  CAL  SINOL                                   1
       PAX  0,1                                     2
       PXD                                          3
       TRA  *+4                                     4
DSINO  CAL  BETA          LOOP                      5
       ADM  DBETA                                   6
       SLW  BETA                                    7
       TSX  SIN2,4                                  8
       STO  SINO+256,1                              9
       TIX  DSINO,1,1                               10
       CLA  EXPOL        EXPONENTIALCOMPUTATION     11
       PAX  0,1                                     12
       PXD                                          13
       TRA  *+4                                     14
DEXPO  CLA  EXPF           LOOP
       FAD  DEXP
       STO  FXPF
       TSX  S816EX,4
       NOP
       UFA  FIX
       ROL  9
       LGL  8
       STO  EXPO+320,1                              20
       TIX  DEXPO,1,1                               21
HNCOM  CAL  HN                                      22
       COM                                          23
       ADD  I1                                      24
```

```
        ALS 18
        STD HIN
HARML   LXA HIR10,1
        LXA HIR20,2
        LXA HIR40,4
HAR1    LDQ SIN0+255,1    COMPUTE SINE TIMES EXPONENTIAL
        MPY FXP0+320,2
        LRS 35
SCALE   MPR HSCAL+2            SCALE TO DESIRED AMPLITUDE
        ADM 1CRT
        ANA 1CMSK
        STO 5WRD+5,4
        TNX H5WRD,4,1
HIN     TXI *+1,1,-1      STEP N, MODULO SINE LENGTH
        TXI *+1,2,-1
        PXD 0,1
        ARS 18
        ANA MDMSK
        PAX 0,1
        TRA HAR1
H5WRD   CAL 5WRD+5,4
        LRS 7
        TXI *+1,4,1
        TXL *-3,4,5
        CAL SQ5WD
        ADM I1
        STA SQ5WD
SQ5WD   STQ FBLK-1             FORM DAMPED SINES IN STORAGE
        TXL HOUT1,2,1
        TRA HAR1
HOUT1   CLA TSC
        TMI SHN
        SSM
        STO TSC
        CLA HSCAL+1
        STA SCALF              RESET, SCALE 2
        TRA HARML
```

33

```
SHN    SSP                                                          61
       STO TSC                                                      62
       CLA HSCAL                                                    63
       STA SCALE        RFSET, SCALF 1                              64
       CLA HN                                                       66
       CAS HN1                                                      67
       NOP                                                          68
       TRA SHN2         HN GRTR THAN HN1                            69
SHN1   ADD I1           HN LESS THAN HN1                            70
       STO HN                                                       71
       TRA THNH                                                     72
SHN2   ADD I10          INITIAL TEST VALUE                          73
       STO HN                                                       74
THNH   CAS HN2                                                      75
       TRA EC                                                       76
       NOP                                                          77
       TRA HNCOM                                                    78
EC     TRA A            FND COMPUTATION OF SINE, EXP.               79
A      LDQ PPRO         SET PPR, ASSEMBLY INITIAL CONDITIONS        80
       STQ PPR                                                      81
       MPY I5           5*PPR                                       82
       STQ PPK                                                      83
       STZ PPSK                                                     84
       STZ ILT                                                      85
       CLA INS00        INITIALIZES INS BLOCK                       86
       STA S                                                        87
       TRA S                                                        88
TINS   LDQ INS                                                      89
       PXD                                                          90
       LGL 3                                                        91
       ADD TINSO                                                    92
       STA *+1                                                      93
       TRA *            TRANSFER TO PROPER INSTRUCTION ROUTINE      94
TRINS  TRA T                                                        95
       TRA D                                                        96
       TRA F                                                        97
       TRA N                                                        98
```

```
        TRA  E                                         99
        TRA  E                                        100
        TRA  E                                        101
        TRA  E                                        102
E       CLA  IFRR          INS ERROR                  103
        ADD  I1                                       104
        STO  IFRR                                     105
        TRA  S                                        106
EA      TRA  TV            END ASSEMBLY, TRA TO TV
S       CLA  INSO          OBTAIN INSTRUCTION  (INS)  107
        STO  INS                                      108
        CLA  ILT                                      109
        TMI  INSM                                     110
        SSM                                           111
        STO  ILT                                      112
        CAL  INS           LEFT HALF INS              113
        LRS  18                                       114
        LDQ  IO                                       115
        LRS  18                                       116
        LGL  1                                        117
        STQ  INS                                      118
        TRA  IMLT                                     119
INSM    SSP                                           120
        STO  ILT                                      121
        LDQ  INS           RIGHT HALF INS             122
        LGL  18                                       123
        STQ  INS                                      124
        CAL  S                                        125
        ANA  MSKA                                     126
        ADD  I1                                       126A
        STA  S                                        126B
IMLT    CAL  S                                        127
        ANA  MSKA                                     128
        CAS  INSOM         TEST MAX INS LOC           129
        NOP                                           130
        TRA  EA            END ASSEMBLY               131
        TRA  TINS                                     132
```

```
T       PXD                     PRESENT TIME ROUTINE
        LGL 15
        TZF FA                  T=0, END ASSEMBLY
        ADD PPK
        STO PPK                 RESET PPK
        LRS 35
        DVP I5
        STO PPR                 FORM PPR
        STO PPSK                FORM PPSK
        PXD
        LLS 35
        CAS PPRM                TEST FOR END OF ASSEMBLY BLOCK
        NOP
        TRA FA                  END ASSEMBLY
        TRA S
D       PXD                     DURATION ROUTINE
        LGL 15
        CAS DKM                 TEST FOR D MAXIMUM
        NOP
        CLA DKM
        STA DK                  SET DK
        TRA S
F       LGL 2                   FORMANT ROUTINE
        PXD
        LLS 0
        STO PH                  SET PHASE
        LGL 1
        PXD
        LGL 6
        CAS FM
        NOP
        TRA E                   FREQ. HIGH
        ALS 1
        STO COMMON
        PXD
        LGL 6
        STO COMMON+1            STORE AMPLITUDE
```

```
         LRS 1
         PXD
         LLS 1                     COMPUTE FLOC
         ADD COMMON
         LRS 35
         MPY FWDL
         LLS 35
         ADD FO
         STA FLOC
         CLA COMMON+1
         ARS 1
         ANA I7
         ADD FNO
         STA *+1
         CLA *                     OBTAIN N FOR MPY
         STO FN
         TMI S
         CLA FDKMA
         ADD FN
         STA *+1
         CLA *                     OBTAIN DURATION
         CAS DK
         NOP
TD       CLA DK
         STO FDK                   SET MAXIMUM DURATION
         LRS 35
         DVP I5
         STQ FDR                   SET FDR
         STO FDSK                  SET FDSK
         CLA FN
         TZE NFMUL                 NO MULTIPLY
         TRA FMUL                  MULTIPLY
NFMUL    CLA PPSK                  NO MULTIPLY
         TZE PSKO                  PPSK=0
         CLA PH
         TPL MA                    PLUS TO ASSEMBLY
         TRA MMA                   MINUS TO MPBLK
```

```
PSKO   CLA PH
       TPL PDA                  PLUS DIRECT ASSEMBLY
       TRA MDA                  MINUS DIRECT ASSEMBLY
FMUL   CLA PH
       TMI MMP                  MINUS MULTIPLY
       TRA PMP                  PLUS MULTIPLY
PDA    CLA FDR         PPSK=0,  PLUS DIRECT ASSEMBLY, SET-UP
       PAX 0,1
       ADM FLOC
       STA PDAL                 SET B
       STA PDAL+5
       CLA FDR
       ADM PPR
       STA PDAL+1               SET A
       STA PDAL+2
       STA PDAL+9
       STA PDAL+10
       CLA I5                   COMPUTE (5-FDSK)*7
       SUB FDSK
       LRS 35
       MPY I7
       LLS 35
       STA PDAL+6
       STA PDAL+8
       TRA PDAL
PDAL   CLA *,1                  B, PLUS DIRECT ASSEMBLY LOOP
       ADM *,1                  A
       STO *,1                  A
       TIX PDAL,1,1
       TXI *+1,1,-1
       CLA *,1                  B
       LRS 0                    (5-DSK)*7
       LDQ I0
       LLS 0                    (5-DSK)*7
       ADM *,1                  A
       STO *,1                  A
       TRA S
```

```
MDA     CLA FDR        PPSK=0, MINUS DIRECT ASSEMBLY, SET-UP
        PAX 0,1
        ADM FLOC
        STA MDAL                 SET B
        STA MDAL+7
        CLA FDR
        ADM PPR
        STA MDAL+3               SET A
        STA MDAL+4
        STA MDAL+13
        STA MDAL+14
        CLA I5                   COMPUTE (5-FDSK)*7
        SUB FDSK
        LRS 35
        MPY I7
        LLS 35
        STA MDAL+8
        STA MDAL+10
        TRA MDAL
MDAL    CLS *,1                  B, MINUS DIRECT ASSEMBLY LOOP
        ADD CBITS
        ANA CBITO
        ADM *,1                  A
        STO *,1                  A
        TIX MDAL,1,1
        TXI *+1,1,-1
        CLA *,1                  B
        LRS 0                    (5-DSK)*7
        LDQ MIO
        LLS 0                    (5-DSK)*7
        ADD CBITS
        ANA CBITO
        ADM *,1                  A
        STO *,1                  A
        TRA S
MMA     CLA FDR                  MINUS TO MPBK, SET-UP
        ADM I1
```

```
        PAX 0,1                                          281
        ADM FLOC                                         282
        STA MMAL              SET B                      283
        CLA FDR                                          284
        ADM MPBKO                                        286
        STA MMAL+3            SET C                      287
        TRA MMAL                                         288
MMAL    CLS *,1        B, OBTAIN F, MINUS TO MPBK        289
        ADD CBITS             FORM NEGATIVE              290
        ANA CBITO                                        291
        STO *,1               C                          292
        TIX MMAL,1,1                                     293
        CLA MPBKO             RESET FLOC                 294
        STA FLOC                                         295
        TRA MA                                           296
MA      CLA FDR               SET-UP FOR MAL             297
        PAX 0,1                                          298
        ADM FLOC                                         299
        STA MAL               SET B                      300
        STA MAL+9                                        301
        CLA FDR                                          302
        ADM PPR                                          303
        STA MAL+2             SET A                      304
        STA MAL+3                                        305
        STA MAL+15                                       306
        STA MAL+16                                       307
        STA MAL+19                                       308
        STA MAL+20                                       309
        LDQ PPSK                                         310
        MPY I7                                           311
        LLS 35                                           312
        STA MAL+4             SET PPSK*7                 313
        SUB I35                                          314
        STA MAL+1             -(5-PPSK)*7                315
        STA MAL+14                                       316
        LDQ FDSK                                         317
        MPY I7                                           318
```

```
        LLS 35
        STA MAL+10                   SET FDSK*7
        STA MAL+12
        TRA MAL-1                    END MAL SET-UP
        PXD
MAL     LDQ *,1         B, GENERAL   ASSEMBLY SHIFTING LOOP
        LLS 0                        (5-PPSK)*7
        ADM *,1                      A
        STO *,1                      A
        LLS 0                        PPSK*7
        TIX MAL,1,1
        STO COMMON
        PXD
        TXI *+1,1,-1
        LDQ *,1                      B
        LLS 0                        DSK*7
        LDQ I0
        LRS 0                        DSK*7
        CLA COMMON
        LLS 0                        (5-PPSK)*7
        ADM *,1                      A
        STO *,1                      A
        LLS 35
        TXI *+1,1,-1
        ADM *,1                      A
        STO *,1                      A
        TRA S                        END MAL
MMP     CLA CLS                      SET MINUS MULTIPLY
        STO MPL
        TRA MP
PMP     CLA CLA                      SET PLUS MULTIPLY
        STO MPL
        TRA MP
MP      CLA FDR                      MULTIPLY ROUTINE, SET-UP
        ADD I1
        PAX 0,1
        ADD FLOC
```

```
        STA MPL           SET FOR FLOC
        SUB FLOC
        ADD MPBKO
        STA MPL+10        SET FOR MPB LOCATION
        CLA FN            SET SHIFT, N
        STA MPL+2
        ADD JNKNO
        STA MPL+3         SET JUNK MASK (N)
        CLA FN
        ADD MSKNO         SET SIGN MASK (N)
        STA MPL+5
        TRA MPL
MPL     CLS *,1           MULTIPLY ROUTINE
        ADD CBITS
        ARS 0             N
        ANA *             JUNKN
        STO COMMON
        ANA *             MASK SIGNS
        ALS 1
        SUB CBITS
        SUB COMMON
        ANA CBITO
        SLW *,1           MPBK
        TIX MPL,1,1
        TRA SNMPY
SNMPY   STZ PH            SET FOR NO MULTIPLY, SET PHASE +
        CLA MPBKO
        STO FLOC          SET FLOC
        TRA NFMUL
N       PXD 0             NOISE ROUTINE
        LGL 6
        CAS NM
        NOP
        TRA E             FREQUENCY HIGH, ERROR
        STO COMMON
        PXD 0
        LGL 3
```

```
        ADD NNO
        STA *+1
        CLA *
        TMI S
        STO FN                 SET FN
        LDQ COMMON             COMPUTE ADDRESS
        MPY NWDL
        LLS 35
        ADD NO
        STA FLOC               SET ADDRESS
        STZ PH
        TRA TD
TV      WTV                    TV DISPLAY ROUTINE
        CFF
        TSX WRIMG,4            TITLE TV RUN
        PZE 500,7,100
        PZE BCDT,0,5
        STZ BCDTE              ERROR
        CFF
        TRA SETV
SETV    CLA PPRO
        ADD I100
        STA SMWL-2
        STA TPPR               INITIALIZE BLOCK ADDRESS
        CLA I1
        STO TNO                SET TNO=1
        CPY XAXIS              X-AXIS
        CPY YAXIS              Y-AXIS
        CPY XMARK              RIGHT EDGE MARK
        LDQ TNO
        TSX WRINT,4            NUMBER PHOTO
        PZE 770,7,770
        STZ TVERR              ERROR
        STZ DSPNO              SET DIPLAY NO. = 0
DSPIC   CLA I100              DISPLAY, INITIAL CONDITIONS
        PAX 0,1                LARGE WORDS
        PXD 0
```

```
        PAX 0,6             SMALL WORDS AND X-AXIS                  430
SMWLR   PXD 0                                                       430A
        PAX 0,2                                                     430B
        TRA SMWL-2                                                  431
        LDQ ABLK+100,1     OBTAIN LARGE WORD                        432
        LGL 1                                                       433
SMWL    LGL 1               SMALL WORD LOOP                         434
        LLS 0                                                       435
        CHS                                                         436
        LRS 0                                                       437
        PXD 0                                                       438
        LGL 6               SMALL WORD IN AC                        439
        ALS 4               SCALE                                   440
        STA TVPT                                                    441
        SXD TVPT,4                                                  442
        STQ COMMON          SAVE MQ FROM CPY DISTURBANCE            443
        CPY TVPT            DISPLAY POINT                           444
        NOP                DISPLAY DELAY (TEMPORARY)
        NOP
        NOP
        NOP
        NOP
        NOP
        NOP
        LDQ COMMON                                                  445
        TXI *+1,4,2         STEP X-AXIS                             446
        TXI *+1,2,1         STEP SMALL WORD                         447
        TXH *+2,2,4                                                 448
        TRA SMWL                                                    448A
        TIX SMWLR,1,1      NEXT LARGE WORD                          449
        CLA DSPNO                                                   450
        CAS DSPNM                                                   451
        NOP                                                         452
        TRA NEXTT           NO. OF DISPLAYS HIGH, NEW PICTURE       454
        ADD I1                                                      455
        STO DSPNO           STEP DISPLAY NO.                        456
        TRA DSPIC           NEXT DISPLAY                            457
```

```
NEXTT  CLA TPPR              NEW PICTURE                                 458
       ADD I100                                                          459
       STA SMWL-2                                                        460
       STA TPPR                                                          461
       CAS PPRM                                                          462
       NOP                                                               463
       TRA TVE1             END TV RUN                                   464
       CLA TNO                                                           465
       ADD I1                                                            466
       STO TNO                                                           466A
TVCAM  NOP                                                               466B
       TRA SETV+6                                                        467
TVE1   HPR 77               TEST FOR FILM RECORDING                      467A
       SWT 1                                                                B
       TRA TVE              NO, END                                         C
       CAL CFF              YES, INSERT CFF                                 D
       SLW TVCAM                                                            E
       TRA TV                                                               F
TVE    CFF                   TITLE END OF TV RUN                         468
       TSX WRIMG,4                                                       469
       PZE 500,7,100                                                     470
       PZE BCDTF,0,4                                                     471
       STZ BCTFE                                                         472
       CFF                                                               473
       HLT          PANIC * *  * * STOP * *  END OF PROGRAM              474
       REM               DATA  FOLLOWS                                   D1
DSPNM  DEC 10                                                            D1A
DSPNO  DEC 0
TNO    DEC 0
TPPR   DEC 0
FDSK   DEC 0
FLOC   DEC 0
PPSK   DEC 0
I0     DEC 0                                                             D2
I1     DEC 1                                                             D3
I2     DEC 2                                                             D4
I3     DEC 3                                                             D5
```

```
I4     DEC 4                                                       D6
I5     DEC 5                                                       D7
I6     DEC 6                                                       D8
I7     DEC 7                                                       D9
I10    DEC 10                                                      D10
I35    DEC 35                                                      D11
I100   DEC 100                                                     D11A
I200   DEC 200                                                     D12
MIO    DEC -0                                                      D13
IFRR   DEC 0                 ERRORS                                D14
TVERR  PZE -1                                                      D15
BCDTE  PZE -1                                                      D16
BCTFE  PZE -1                                                      D18
       REM            SINE AND EXP. COMPUTATION                    D19
BETA   DEC 0                                                       D20
EXPF   DEC 0                                                       D21
DBETA  DEC 1B8                                                     D22
DEXP   DEC -1.08E-2                                                D23
SINOL  DEC 256                                                     D24
EXPOL  DEC 320                                                     D25
FIX    OCT 201000000000                                            D26
 HN    DEC 2                                                       D27
1CBT   OCT 100                                                     D28
1CMSK  OCT 77                                                      D29
MDMSK  OCT 377                                                     D30
HIR10  DEC 255                                                     D31
HIR20  DEC 320                                                     D32
HIR40  DEC 5                                                       D33
HSCAL  PZE *+2                                                     D34
       PZE *+2                                                     D35
       DEC 40                                                      D36
       DEC 60                                                      D37
TSC    DEC 0                                                       D38
HN1    DEC 10                                                      D39
HN2    DEC 105               INITIAL TEST VALUE                    D40
       REM            ASSEMBLY                                     D41
TINSO  PZE TRINS                                                   D42
```

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```
ILT    DEC 0                                                  D44
INS    DEC 0                                                  D45
MSKA   PZE -1                                                 D46
INSOM  PZE INSO+2000                                          D47
INSOO  PZE INSO                                               D48
PPK    DEC 0                                                  D49
PPR    DEC 0                                                  D50
PPRO   PZE ABLK                                               D51
PPRM   PZE ABLK+2000         INITIAL TEST VALUE               D52
DK     DEC 0                                                  D53
DKM    DEC 1280                                               D54
PH     DEC 0                                                  D55
FM     DEC 22          INITIAL TEST VALUE                     D56
FWDL   DEC 64                                                 D57
FO     PZE FBLK                                               D58
FN     DEC 0                                                  D59
FDKM   DEC 320                                                D60
       DEC 255                                                D61
       DEC 190                                                D62
       DEC 125                                                D63
       DEC 65                                                 D64
FDKMA  PZE FDKM                                               D65
FNO    PZE *+1                                                D67
       DEC -0                                                 D68
       DEC 4                                                  D69
       DEC 3                                                  D70
       DEC 2                                                  D71
       DEC 1                                                  D72
       DEC 0                                                  D73
       DEC 0                                                  D74
       DEC 0                                                  D75
FDK    DEC 0                                                  D76
FDR    DEC 0                                                  D77
CBITS  OCT 201004020100                                       D78
CBITO  OCT 176773757677                                       D79
MPBKO  PZE MPBK                                               D80
NNO    PZE*+1                                                 D81
```

```
         DEC -0                                                  D82
         DEC 5                                                   D83
         DEC 4                                                   D84
         DEC 3                                                   D85
         DEC 2                                                   D86
         DEC 1                                                   D87
         DEC 0                                                   D88
         DEC 0                                                   D89
NM       DEC 30          INITIAL TEST VALUE                      D90
NO       PZE NBLK                                                D91
NWDL     DEC 256                                                 D92
NKL      DEC 1280                                                D93
CLA      CLA *,1                                                 D94
CLS      CLS *,1                                                 D95
CFF      CFF                                                     D95A
         REM                            TV                       D96
BCDT     BCD 5SSI 1 R.P. FUTRELLE M630-2-1                       D97
BCDTF    BCD 4SSI 1 M630-2-1  END                                D98
XAXIS    MTW 512                                                 D99
YAXIS    MON 0                                                   D100
TVPT     DEC 0                                                   D100A
XMARK    MON 0,0,1000                                            D101
         REM                 MASKS                               D102
JNKNO    PZE *                                                   D103
         OCT 376371747637                                        D104
         OCT 076371747637                                        D105
         OCT 036170743617                                        D106
         OCT 016070341607                                        D107
         OCT 006030140603                                        D108
         OCT 002010040201                                        D109
MSKNO    PZE *                                                   D110
         OCT 040201004020                                        D111
         OCT 020100402010                                        D112
         OCT 010040201004                                        D113
         OCT 004020100402                                        D114
         OCT 002010040201                                        D115
         REM                     LIBRARY ROUTINES                D116
```

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```
NA.110 LIB                                                         D117
NA.117 LIB                                                         D118
LAS816 LIB                                                         D119
       REM MU SIN 2  0039 CARDS  FIXED POINT SINE                  MUSIN201
 SIN2  SXD COMMON,1        SAVE IR1                                SIN20002
       ALS 1               THETA/PI                                SIN20003
       PBT 1               TEST FOR THETA/2PI GREATER OR =1/2      SIN20004
       TRA SIN2+5                                                  SIN20005
       CHS                                                         SIN20006
       ALS 1                                                       SIN20007
       PBT 1               TEST FOR THETA/PI GREATER OR =1/2       SIN20008
       TRA SIN2+9                                                  SIN20009
       COM                                                         SIN20010
       LRS 1                                                       SIN20011
       RND                                                         SIN20012
       STO COMMON+1                                                SIN20013
       LDQ COMMON+1        THETA/PI                                SIN20014
       MPY COMMON+1        (THETA/PI)EXP2                          SIN20015
       LLS 2               (2THETA/PI)EXP2                         SIN20016
       RND                                                         SIN20017
       PBT 1               TEST FOR OVERFLOW                       SIN20018
       TRA SIN2+19                                                 SIN20019
       COM                                                         SIN20020
       STO COMMON+2                                                SIN20021
       LXA SIN2+18,1       SET IR1=6                               SIN20022
       LDQ SIN2+31         A SUB 13                                SIN20023
       MPR COMMON+2        (2 THETA/PI)EXP2                        SIN20024
       ADD SIN2+38,1                                               SIN20025
       LRS 35                                                      SIN20026
       TIX SIN2+22,1,1     LOOP TRANSFER, OUT AFTER 6 PASSES       SIN20027
       MPY COMMON+1        THETA/PI                                SIN20028
       LLS 1                                                       SIN20029
       RND                                                         SIN20030
       LXD COMMON,1        RESTORE IR1                             SIN20031
       TRA 1,4             OUT                                     SIN20032
       OCT 000000001650    A SUB 13                                SIN20033
       OCT 400000170505    A SUB 11                                SIN20034
```

```
        OCT 000012407327    A SUB 9                              SIN20035
        OCT 400462645440    A SUB 7                              SIN20036
        OCT 012146570632    A SUB 5                              SIN20037
        OCT 522535716304    A SUB 3                              SIN20038
        OCT 311037552421    A SUB 1                              SIN20039
        REM                   BLOCKS OF STORAGE                   D119A
COMMON  BSS 20                                                    D120
 5WRD   BSS 20                                                    D121
 MPBK   BSS 400                                                   D122
 SINO   BSS 300                                                   D123
 FXPO   BSS 350                                                   D124
 FBLK   BSS 7000                                                  D124A
 ABLK   BSS 7000                                                  D125
 NBLK   SYN FBLK              ONLY INITIALLY                      D127
        END START
```

Appendix E

The Format of the Instructions

Octal numbers are based on the numbers 0 through 7 as our decimal system is based on 0 through 9. Octal numbers are especially useful in computer work as there is a one-to-one correspondence between an octal digit and a group of three binary digits. The instructions will be composed of six octal digits so that two will occupy each 704 word. The positions are numbered from the left.

T will have a 0 in position 1. Positions 2-6 contain the value of the shift in units of one sub-word, from 0 to $77,777_8$ (0 to $32,767_{10}$.) A 0 will terminate assembly.

D will have a 1 in position 1. Positions 2-6 contain the duration in units of one sub-word.

F will have a 2 in position 1. Position 2 is even for a starting phase of 0^o (plus) and odd for a starting phase of 180^o (minus.) Positions 3 and 4 contain the number of the sample and thus determines the frequency. Positions 5 and 6 contain the amplitude.

N will have a 3 in position 1. Positions 2 and 3 specify the nature of the noise desired. The samples would be numbered and their characteristics listed for the programmer's convenience. Position 4 specifies the amplitude. Positions 5 and 6 are disregarded.

Appendix F - Instructions

THE INSTRUCTIONS USED TO TEST

THE SYNTHESIS PROGRAM

```
INSO   OCT 000062100062   T50, D50
       OCT 201212000144   F+550, 30DB, T100
       OCT 211212000144   F-550, 30DB, T100
       OCT 201210000144   F+550, 24DB, T100
       OCT 211210000310   F-550, 24DB, T200
       OCT 100024201212   D20, F+550, 30DB
       OCT 000050100027   T40, D23
       OCT 201212000050   F+550, 30DB, T40
       OCT 211212000050   F-550, 30DB, T40
       OCT 000001100024   T1, D20
       OCT 201212000050   F+550, 30DB, T40
       OCT 211212000050   F-550, 30DB, T40
       OCT 100027201212   D23, F+550, 30DB
       OCT 000050211212   T40, F-550, 30DB
       OCT 000403110000   T259, DMAX
       OCT 304600001440   N4(550,1100) 36DB, T800
       OCT 100226306500   D150, N6(2750,3600) 30DB
       OCT 000062100702   T50, D450
       OCT 200212201212   F+110, 30DB, F+550, 30DB
       OCT 000764200210   T500, F+110, 24DB
       OCT 201210000764   F+550, 24DB, T500
       OCT 211212200212   F-550, 30DB, F+110, 30DB
       OCT 000764211212   T500, F-550, 30DB
       OCT 210212201312   F-110, 30DB, F+1100, 30DB
       OCT 000764100024   T500, D20
       OCT 201312201512   F1100, 30DB, F2200, 30DB
       OCT 100024000036   D20, T30
```

```
OCT 201312201512   F1100, 30DB, F2200, 30DB
OCT 100024000036   D20, T30
OCT 201312201512   F1100, 30DB, F2200, 30DB
OCT 100024000036   D20, T30
OCT 201312201512   F1100, 30DB, F2200, 30DB
OCT 100024000036   D20, T30
OCT 201312201512   F1100, 30DB, F2200, 30DB
OCT 100024000036   D20, T30
OCT 201312201512   F1100, 30DB, F2200, 30DB
OCT 100024000036   D20, T30
OCT 201312201512   F1100, 30DB, F2200, 30DB
OCT 100024000036   D20, T30
OCT 201312201512   F1100, 30DB, F2200, 30DB
OCT 0                                   THE VERY END
```

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