6-1-1971

Design of a Tactile Vocoder

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DESIGN OF A TACTILE VOCODER

by

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A Thesis Submitted

in

Partial Fulfillment

of the

Requirements for the Degree of

MASTER OF SCIENCE

in

Electrical Engineering

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COLLEGE OF ENGINEERING

ROCHESTER INSTITUTE OF TECHNOLOGY

ROCHESTER, NEW YORK

June, 1971

Abstract

A tactile vocoder is designed for the feedback of acoustic cues for detection by the sense of touch. Design objectives based on speech signal properties are generated. An existing spectrum channel vocoder is the starting point of the design. The follow-on modulation stage after the filter channels of the spectrum channel vocoder is built up in a breadboard model and tested.

The transfer function of the modulation stage has an input dynamic range of 68 decibels, being linear over 38 decibels of this range. The complete breadboard model using one of the filter channels has an input dynamic range of 40 decibels, being able to process the maximum signal level differences between first and third formant frequencies in vowels. The circuit can process signals of durations down to 33.3 milliseconds which is the area of stop consonants.

Acknowledgments

The writer would like to express his sincere thanks to Professor Richard Aston for suggesting the topic of this thesis, and for his advice and support. The contributions of Professors Donald Johnson and George Thompson are appreciated. Financial funding, equipment, and laboratory facilities were provided by the Electrical Engineering Department, Rochester Institute of Technology. This thesis was typed by Irene Stilwell. Deepest thanks go to Helen for her encouragement and patience throughout this project.

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Chapter I

Introduction

Section 1

Statement of the Problem

The purpose of this investigation is to study and design a tactile vocoder. The tactile vocoder is a sensory aid which provides the feedback of acoustic cues through the sense of touch. The design of a tactile vocoder to accomplish this objective must simultaneously be compatible with the properties of speech signals and the sense of touch. The tactile vocoder will be designed for future study of vowels and vowel-like sounds to be carried out in other investigations. Design objectives will be developed further in Section 3.

A spectrum channel vocoder, donated by the General Dynamics Corporation, is to be studied and incorporated into the tactile vocoder design provided it satisfies the system design requirements. Wherever feasible, integrated circuit devices are to be included in originally designed circuitry. Thus, inherent integrated circuit advantages of high reliability, low cost, high performance, and small size as compared with discrete resistors, capacitors, transistors will be realized.

A breadboard model of the tactile device will be built and tested. The system transfer function will be measured experimentally. Test results will be compared with the design objectives. Conclusions and recommendations will then be discussed.

Section 2

Relevance of the Investigation to Speech Pathologists

The generation of sound waves is caused by a source initiating a mechanical disturbance which is transmitted through an elastic medium. These sources might, for example, be vibrating strings of a piano or violin or an oscillating air column in a trumpet or organ pipe. Sound waves are transmitted through gaseous, liquid, or solid mediums. The most commonly encountered elastic medium is air which presents the sound wave to the auditory system.

The sense of touch also responds to these sound generating mechanical disturbances. Thus, there is a bond between the two responses in that they both have the capability of responding to the same stimuli. This is not to conclude that the sense of touch is the optimum substitute for the hearing. However, it is a relationship which merits further study.

The energy of a vowel or vowel-like sound is concentrated at the formant frequencies in the frequency spectrum of the acoustic signal. While having similar high energy regions, a consonant's duration is a more important factor in its recognition. A tactile vocoder could be designed to process the signal components in the vowel formant frequency ranges or by the use of formant trackers, process only the signal components at the formant frequencies. A distinctive tactile display associated with a particular sound would result. Future testing involving discrimination between vowel and vowel-like sounds would then be possible for comparison with previous studies. The possibility of recognizing selected phrases may also be investigated.

A tactile vocoder might also be utilized as a rhythm indicator. Voiced sounds would generate the aforementioned distinctive tactile patterns. The lower energy unvoiced sounds would contrast sharply with the voiced sounds approaching pauses in the display. Recognizing and then controlling the durations of voiced and unvoiced sounds may lead to more natural rhythm, emphasis, and cadence of speech. Rhythm between different vowel sounds might also be developed by comparison of the distinctive tactile patterns. A preliminary evaluation was made to appraise the value of the tactile vocoder as a rhythm indicator.[1] This admittedly somewhat uncontrolled experiment seemed to indicate the device was worthy of further study.

There is a potential use of the tactile vocoder to assist in correcting vowel flatness. Vowel flatness is associated with improper tongue movement resulting in misproportioned formant frequency components. The tactile vocoder by its basic design indicates the presence and strength of the second formant frequency signal.

The above discussion is intended to illustrate some of the possible uses of the tactile vocoder. Preliminary evidence indicates positive results might be obtained in teaching programs. However, in all the areas mentioned, it is the only ultimate execution of controlled test programs which will verify these predictions.

Section 3

Design Objectives

Any device intended to present acoustic cues must extract information from the acoustic signal pressure wave. Such information reduction may be segregated into the catagories of duration, fundamental frequency, average pressure, and frequency component coefficients in the power spectrum. There are reviews of some of the instrumentation available to study specific aspects of the acoustic signal involving these catagories.[2][3] These devices utilized the senses of vision or touch for information feedback.

Within the frequency spectrum of an acoustic signal are peak pressures at what are called formant frequencies. Peterson and Barney demonstrated that the first three formant frequencies were sufficient to define a set of ten (10) conical vowels which they were investigating.[4] Thus, there is motivation to pursue the design of a vocoder which presents the formant frequencies so that investigations as to how this would assist in control of the human speech apparatus in a speech therapy program could be carried out in the future. The tactile vocoder has this potential.

Fletcher found vowels have durations ranging approximately from 211 to 251 milliseconds.[5] Stop consonants have durations of 20 to 200 milliseconds, and consonants range from 70 to 300 milliseconds. Heinz and Stevens showed that transitions have durations of less than 100 milliseconds.[6]

The response of the sense of touch as a function of signal on-time was studied by Bliss.[7] Identification tests of stimuli with on-time equal to 100 milliseconds resulted in an error rate of 10 percent. On-times of 200 milliseconds had errors of 5 percent, and 300 millisecond durations had a minimum error rate of 3 percent. The response of the sense is compatible with vowel duration and can be used in work with consonants recognizing that the identification error rate will rise into the neighborhood of 10 percent. The tactile vocoder being developed must pass signals having durations less than or equal to 100 milliseconds. This information passband is equivalent to a signal frequency of 10 hertz or less.

A maximum 40 decibel difference between first and third vowel formant levels was reported by Peterson and Barney.[8] The tactile vocoder should have at least this input dynamic range of 40 decibels. Any increase in dynamic range above this value would be of value to accommodate variations in normal speaking levels.

The frequency spectrum of the acoustic signal can be manipulated in a number of ways in a tactile vocoder. The frequency spectrum can be sampled. The signal intensities within the sampled frequency bands are then processed and presented for tactile detection.

An attractive alternative based on the previously stated findings of Peterson and Barney would be to incorporate a formant tracking device to present only the signals at the formant frequencies. In this way, unnecessary information for signal identification is eliminated. Removing these potential confusion factors would assist in minimizing error rates. A summary of these and other methods of reducing the frequency spectrum was compiled by Schroeder.[9]

The spectrum channel vocoder being incorporated into the tactile vocoder uses frequency spectrum sampling which has the effect of reducing the information in the signal. Development of formant trackers for use in tactile devices is however a worthwhile subject of future study programs.

Signal displays for the observer primarily utilize the senses of vision or touch. A discussion of visual speech devices may be found in <u>Visual Speech</u>.[10] A recent visual device reminds one of the moving news headline sign in Times Square, New York City.[11] Speech sounds are displayed in a lamp matrix of forty (40) vertical rows of twelve (12) lamps. The presence and strength of signals in specific frequency bands are denoted by the illumination of individual lamps in the vertical rows. The verticle displays move from right to left to allow a maximum display of four (4) seconds of speech.

The tactile vocoder uses the sense of touch for signal detection. The application of electrical stimuli is not feasible for tactile detection. The dynamic range between threshold and pain for electrical stimuli is very small [12] and inconsistant with the dynamic range of vowel signals. The possibility of bodily injury and pain make such a means of applying the signal unattractive.

The instrumentation used to apply stimuli in the previously mentioned study resulting in response times for the tactile sense used vibrotactile devices. Electromagnetic bone oscillators used in hearing aids fall in this class and will be used in the tactile vocoder. They are rugged, readily available, and have been used with success in previous studies.[13]

Chapter II

The Tactile Vocoder

Section 1

Historical Review

A rudimentary study of recognition of speech signals by the sense of touch was made by Gault.(14) In his experiment, subjects touched the cone of an amplifier cone. He later applied vibrations to fingertips of subjects which reflected speech signals within various frequency bands. Thus, the tactile vocoder started to evolve.

Investigation of the threshold of the tactile sense as a function of stimulus frequency was made by Knudsen.(15) He found a minimum threshold at 256 hertz. Maximum sensitivity to frequencies in the 300 hertz region was confirmed by Verrillo and other investigators.(16)

This fact was employed to improve the response to tactile vocoder stimuli. New devices used speech signals from signal frequency bands to modulate 300 hertz carriers. The modulated 300 hertz carriers were then applied to vibrators for detection. Guelke and Huyssen built such a vocoder and studied the problems of recognition and discrimination of vowels.(17) Pickett's device also operated in this manner, and he made similar studies.(18) The tactile vocoder under development in this investigation will also have 300 hertz signals at the bone oscillators.

Aston examined the effect of pattern communality in discrimination of vowel pairs.[19] Communality was defined as the percentage of channels in a display in which the signal intensity changed less than a just noticeable difference when one sound was replaced by another. Errors in signal discrimination increased above a constant level for those sound pairs having communality greater than 50 percent. Test results showed discrimination error, E_t, fit the function:

$$E_t = E_p + 0.215e^{0.0615C} \quad (1)$$

where C is the percent communality and E_p is a constant error dependent upon the ability, motivation, and experience of the observer.

A mathematical model relating signal communality to vocoder operating parameters was developed. The model showed that the number of vowel pairs with greater than 50 percent communality was significantly reduced by using 8 to 10 frequency channels at 1/3 octave spacing. Adding frequency channels below 800 hertz did not affect pattern communality. Increased dynamic range of the tactile device reduced communality, and increased noise levels operated in the opposite direction.

It is interesting to note a simple device developed by Bell Telephone Laboratores[20] for use with a telephone which utilizes tactile or visual senses. The Code-Com set includes an electromagnetic transducer for the fingers and a lamp which flashes when signal information is being transmitted. The observer can detect common telephone sounds like busy, dial tone, etc. One can communicate with the deaf subject by talking in simple patterns like yes/no answers or codes such as Morse Code. While being a consumer directed device rather than a speech therapy tool, such instrumentation has its place in presenting acoustic cues to the deaf.

Section 2

Tactile Vocoder Design

The tactile vocoder converts an audio input signal to a mechanical output for detection by the sense of touch. A block diagram of the tactile vocoder is found in Figure 1.

The frequency spectrum of the input signal is sampled within the filter stage. The filter stage is comprised of selected filter channels from the spectrum channel vocoder. Each filter channel includes a band-pass filter, amplification elements, and detection elements. These circuits act so as to make only the envelope of the signal within the pass band be the filter channel output.

Information from these selected pass bands are sent to identical multiplier, amplification, and bone oscillator stages. In the multiplier stage, the 300 hertz signal from an external oscillator is multiplied by the filter channel output using a linear four-quadrant multiplier. The multiplier stage output is amplified in the amplification stage by a power amplifier capable of being

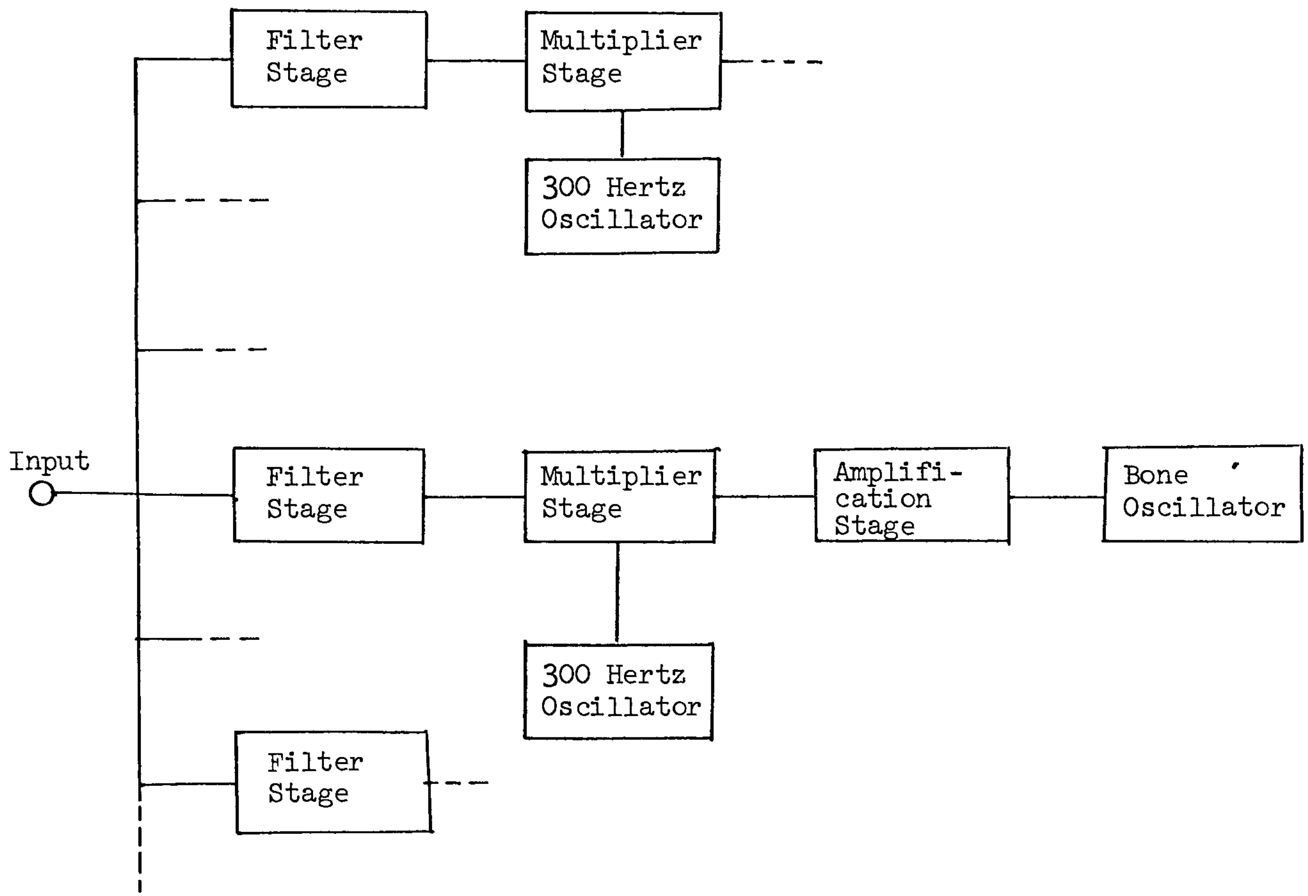

Figure 1

Tactile Vocoder Signal Flow

directly coupled to low resistance loads. The amplitude modulated 300 hertz signal is applied to the electromagnetic bone oscillators for tactile detection.

Detailed discussions of internal operation of each stage of the tactile vocoder follow. Signal flow within the spectrum channel vocoder and experimental determination of its performance characteristics are considered in Chapter III. The design and experimental verification of the multiplier, amplification, and bone oscillator stages are reviewed in Chapter IV.

Chapter III

Spectrum Channel Vocoder

Section 1

Description of Device

The tactile vocoder evolves around the incorporation of the spectrum channel vocoder donated by General Dynamics Corporation to the Electrical Department. A set of electrical schematic drawings was delivered along with the vocoder. It was necessary to perform a physical examination of the device, and experimental determination of its operating characteristics was needed before any decision could be made to determine if the vocoder could be used in this project.

The spectrum channel vocoder is a real time instrument and one of the oldest devices used for analysis and synthesis of speech signals. Basically, the frequency spectrum is sampled along the frequency axis. A voiced-unvoiced detector and pitch detector determine the fine structure of the signal. The processed signals are then recombined to recreate the original speech signal. The signal flow in such a device was illustrated by Schroeder(21) and is found in Figure 2.

Study of the electrical schematic drawings supplied with the General Dynamics vocoder showed that its signal flow paralleled such a general device. A block diagram of the General Dynamics device is found in Figure 3. Nomenclature from the schematic drawings is

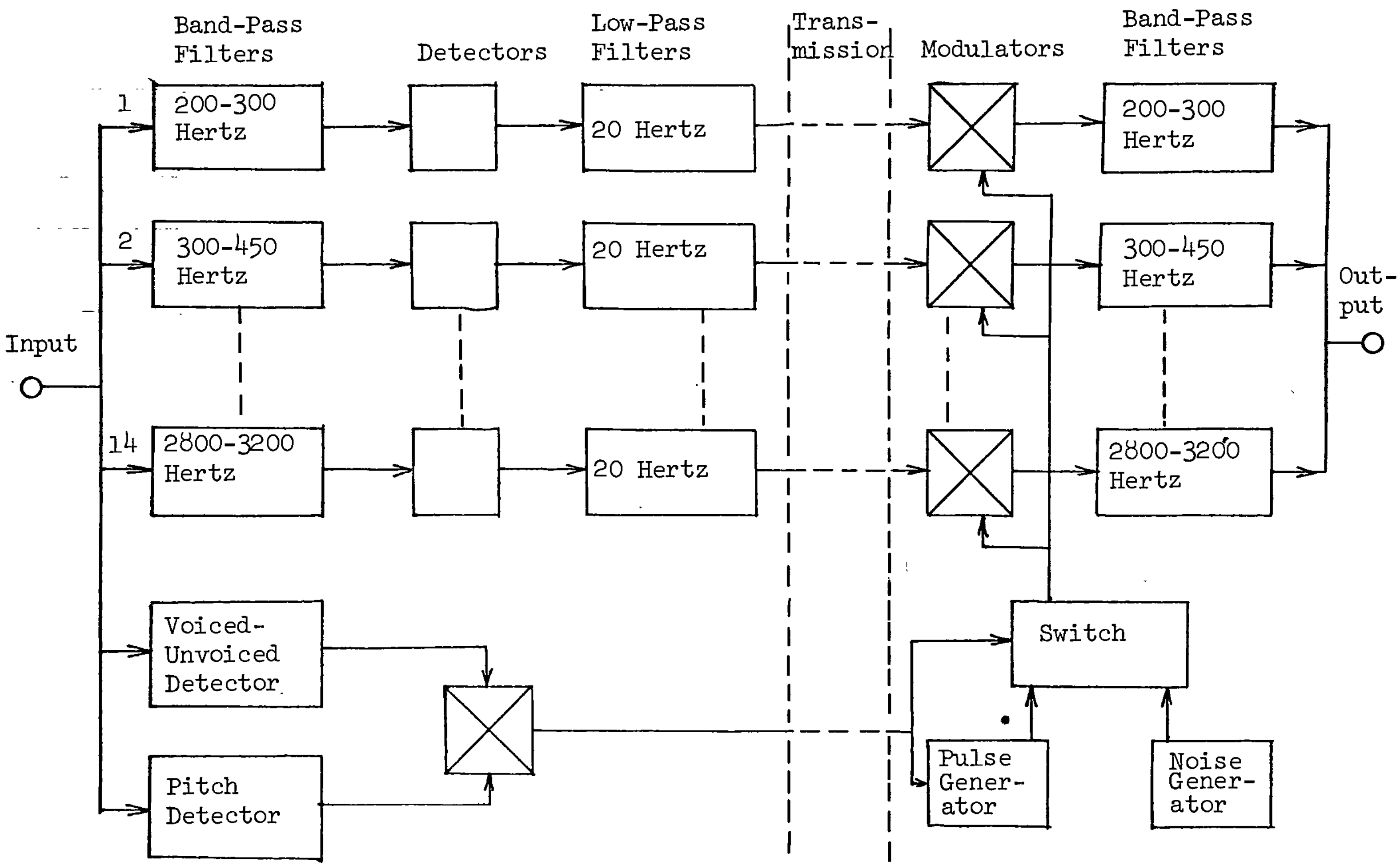

Figure 2

Generalized Spectrum Channel Vocoder Signal Flow

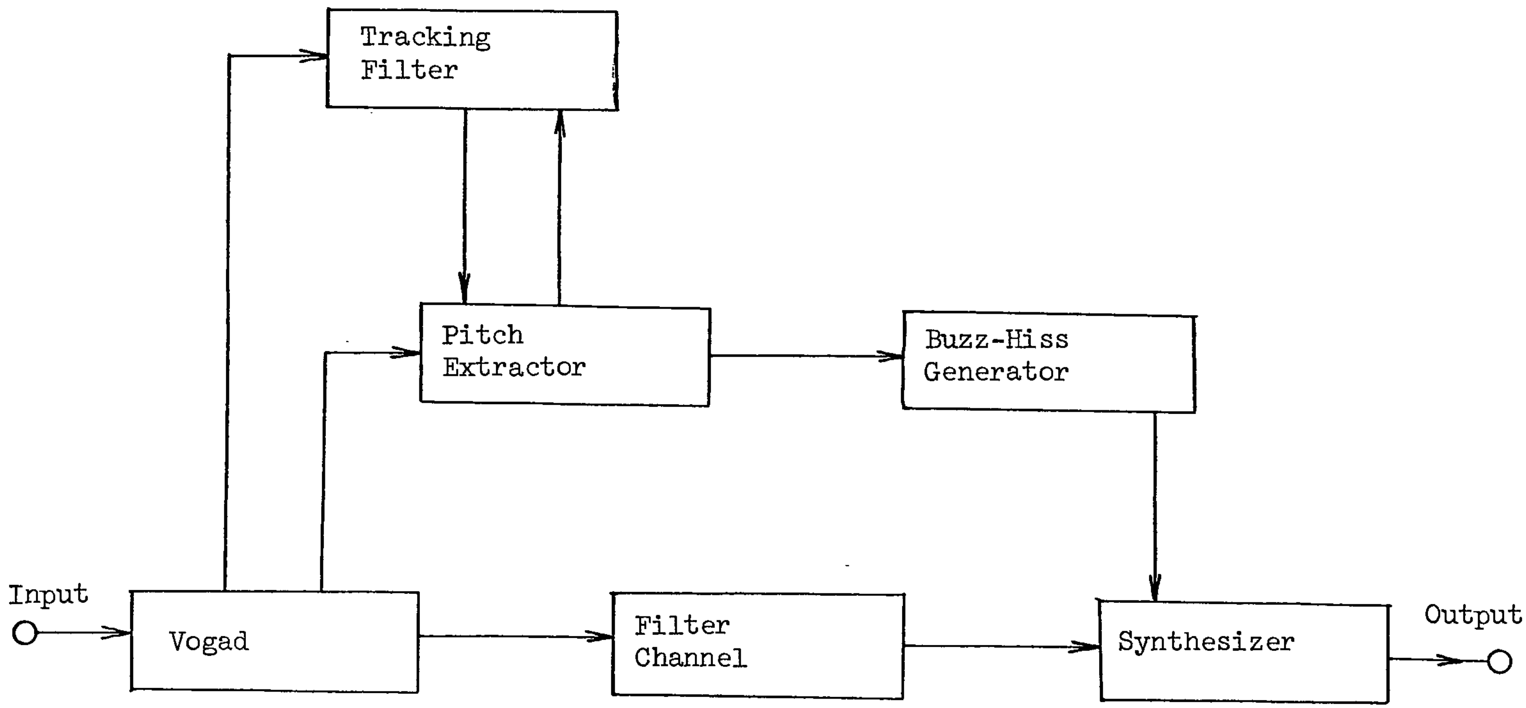

Figure 3

General Dynamics Spectrum
Channel Vocoder Signal Flow

used wherever possible to identify basic stages.

The spectrum channel vocoder is mounted in one (1) wheel caster mounted cabinet. There are eight (8) chassis racks containing the electrical circuitry within the cabinet. The electrical circuitry is basically built up of discrete passive elements, vacuum tube devices, and packaged filtering modules. Circuit elements are hard wired together.

Input and output connections are made in a control panel located at the top of the cabinet. Operating controls are also found in this panel. The main power ON-OFF switch with a pilot indicating light is in a second control panel at the bottom of the cabinet. A voltmeter and selection switch to measure bias voltages in the vocoder are in the second panel. A power cord for connection to a convenience electrical power outlet for 110 volt AC, 60 hertz, single phase power to operate the device is provided. There are two (2) convenience power receptacles at the bottom rear of the cabinet for connecting any auxiliary equipment being used with the vocoder.

Connections from the top control panel and various input and output signal conditioning subcircuits are located in the top chassis rack. The Vogad, pitch extractor, and buzz-hiss generator are located in the next two (2) racks. The Vogad is a processing stage sending signals to the tracking filter, pitch extractor, and filter channels. The filter channels are in the following two (2) chassis racks, and the synthesizer makes up two (2) racks. The bottom chassis rack contains regulated power supplies for biasing active elements and providing cathode heater power.

An audio input signal is introduced into the spectrum channel vocoder from a microphone or tape recorder via input jacks in the top control panel. There is a switch in this panel which connects the input jack being used to a shielded cable going to the Vogad stage.

There are several output signals from the Vogad. The signal flow in the Vogad is illustrated in Figure 4. One subsystem starts the operations necessary to determine the fine structure of the audio signal. The input is amplified and passed through a parallel RLC circuit tuned to a center frequency of 650 hertz with a bandwidth of 204 hertz. The bandpass output is processed by an envelope detector to remove the higher frequencies and amplified. This signal is then sent to the tracking filter and to the pitch extractor as an enable signal.

The signal is further amplified in a tuned push-pull amplifier stage and sent to the pitch extractor as a disable signal. The amplified input signal is also sent to the filter channels. There are fifteen (15) parallel independent filter channel systems.

The filter channels sample the frequency spectrum of the audio signal along the frequency axis. The basic structure of each filter channel is shown in Figure 5. Each filter channel has a band-pass filter with a different center frequency from the other channels. Except for the band-pass filters, the remaining elements are common between all filter channels.

The band-pass output is amplified in the 6BA6 pentode. The

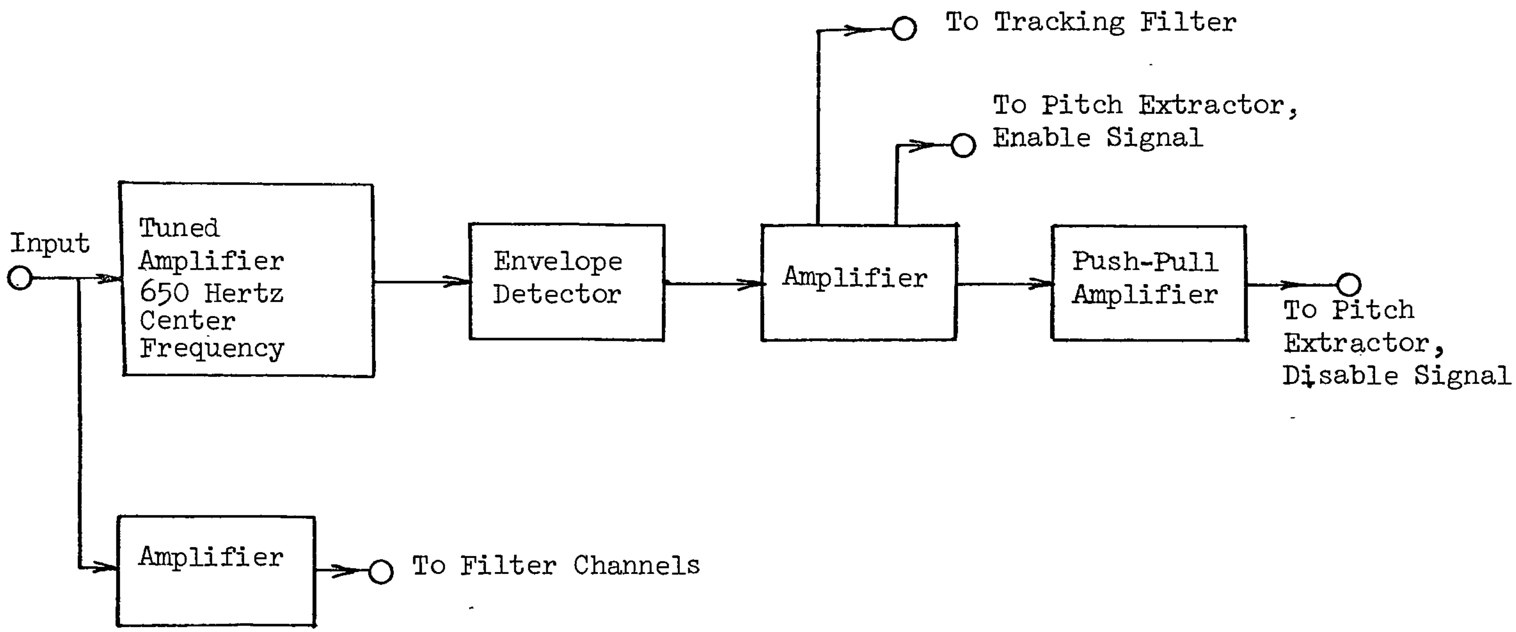

Figure 4

Spectrum Channel Vocoder
Vogad Stage

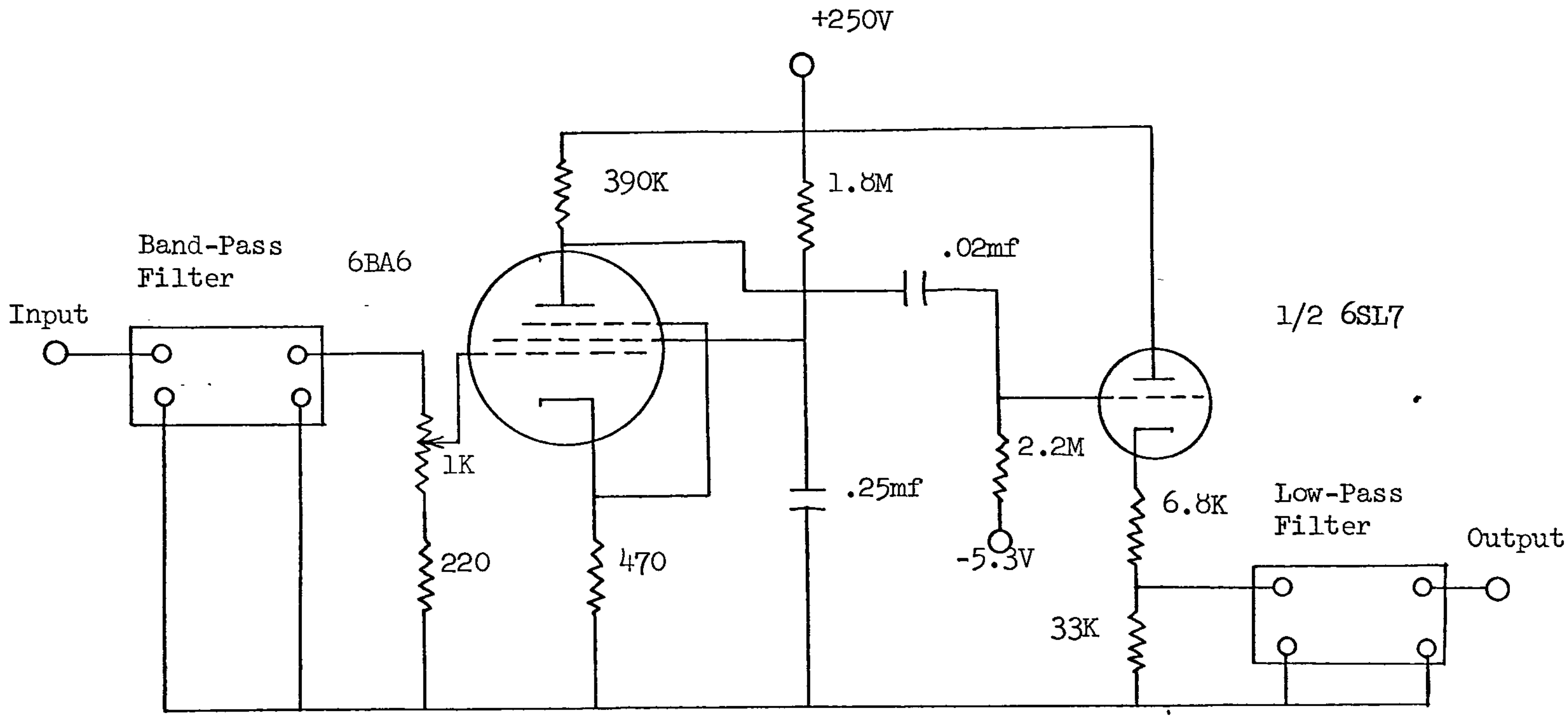

Figure 5

Spectrum Channel Vocoder
Filter Channel

6SL7 triode is biased at cut-off to function as a detector. The higher frequencies of the pass-band are partially removed leaving the envelope of the filter output. The low-pass filter removes the traces of the higher frequencies which were passed by the detector. This envelope output corresponds to the rhythm or voiced sound timing of the audio input within the pass-band.

The tracking filter output and enable, disable signals from the Vogad operate in the pitch extractor to determine the frequency of the voiced sound signal generator (buzz). The pitch extractor sends control signals to the tracking filter to form a feedback loop. The pitch extractor output is directed to the buzz-hiss generator.

The presence of a pitch extractor output actuates a relay in the buzz-hiss generator. When a signal is present, the buzz generator, whose signal frequency is set by the pitch extractor, is connected to the buzz-hiss generator output. When no pitch extractor signal is present, the relay is not actuated, and a random noise generator (hiss) is connected to the buzz-hiss generator output. This buzz-hiss nomenclature was first used by Dudley[22] when he built the first spectrum channel vocoder. The buzz-hiss generator output is connected to the synthesizer. Bias signals for the synthesizer are also sent from the buzz-hiss generator. Figure 6 illustrates the signal flow through the pitch extractor and buzz-hiss generator stages.

The buzz-hiss generator output and filter channel outputs are modulated in the synthesizer to reconstruct the signal within each of fifteen (15) frequency bands. Modulation is accomplished using

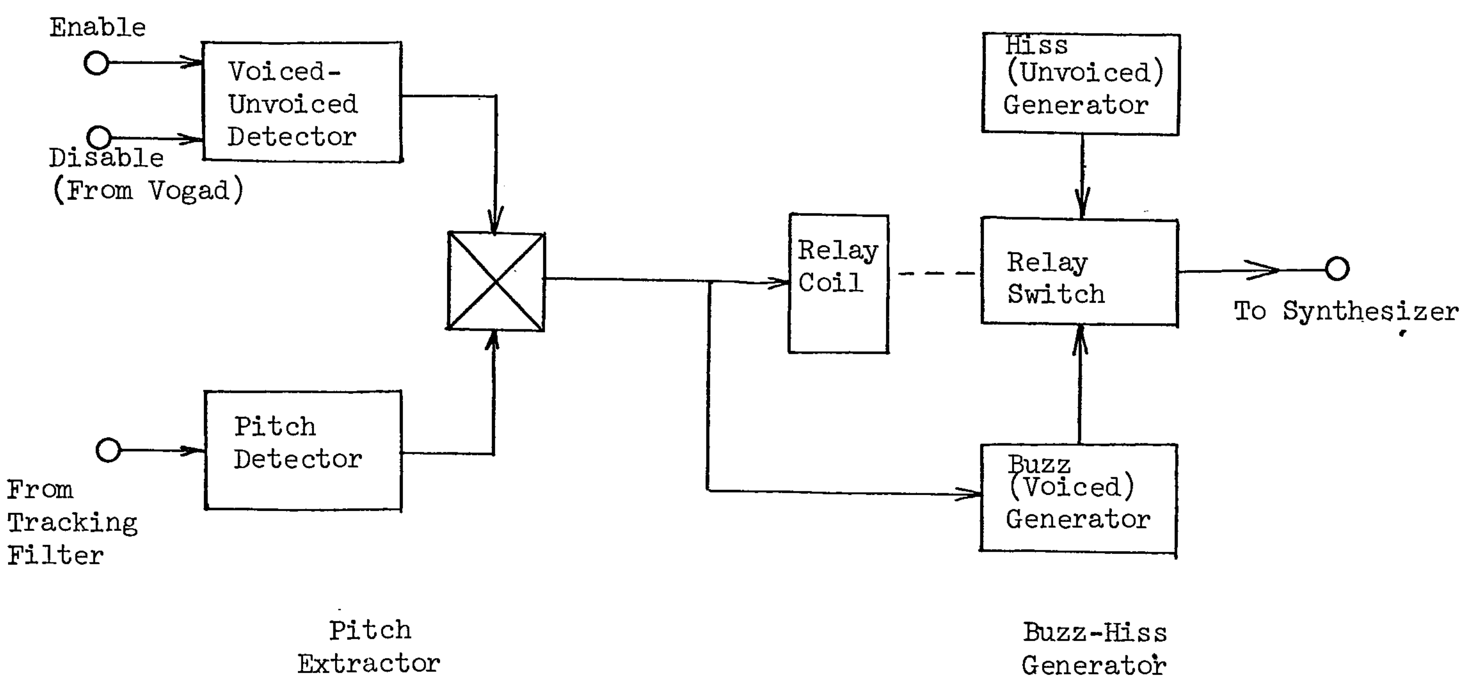

Figure 6

Spectrum Channel Vocoder
Pitch Extractor and Buzz-Hiss Generator

full wave rectification bridges. The modulated signals are connected in parallel to recreate the audio signal.

The synthesizer output is sent to an output jack in the top control panel. There is also a control in this panel to vary the pitch of the reconstructed signal. The enable signal from the Vogad is also available in the control panel after passing through a 200-3800 hertz band-pass filter.

Reconstruction of the audio signal is not necessary in the tactile vocoder. The vibratory displays of the bone oscillators indicating signal energy in the individual frequency bands are the device outputs. The filter channels from the spectrum channel vocoder will be utilized to sample the frequency spectrum of the input signal and reduce it to the envelopes of the components in each pass band. The remaining circuitry of the spectrum channel vocoder will not be used.

Section 2

Investigation of Filter Channel Performance

Only the filter channels and regulated power supplies from the spectrum channel vocoder will be used in the tactile vocoder. The audio signal will go directly into selected filter channels followed by modulation stages as shown in Figure 1. The remaining circuitry in the spectrum channel vocoder will be disabled and disconnected.

Therefore, study of filter channel performance was needed to determine their suitability for the tactile vocoder. Experimental investigation of the filter channels followed. Each filter channel was tested in an identical manner.

The first test determined the bandwidth and roll-off of the band-pass filters. The filter channel was disconnected from the Vogad and synthesizer. A 30,000 ohm resistive load to duplicate the input impedance of the synthesizer was connected to the filter channel output. A General Radio Company Unit R-C Oscillator was connected to the filter channel input.

The input signal was set at a constant 0.5 volts (RMS). The input signal frequency was varied, and the D.C. output was measured at each frequency setting. The filter channel output data were converted to decibels and plotted as a function of input signal frequency. The results for filter channel #3 are shown in Figure 7. This graph is typical for the results obtained for the remaining filter channels, and the remaining plots will not be included. The important data from these graphs are summarized for each filter channel in Appendix A, Tables A1 and A2.

Using the same test set-up, the second test was conducted to determine the linear dynamic range of the filter channel. The input signal frequency was set to the band-pass filter center frequency. The filter channel noise output was measured for no input. The input signal was raised from zero to the point where the filter channel output just rose (.001 volt DC) above the output noise level. The input signal amplitude was then increased and output measurements were

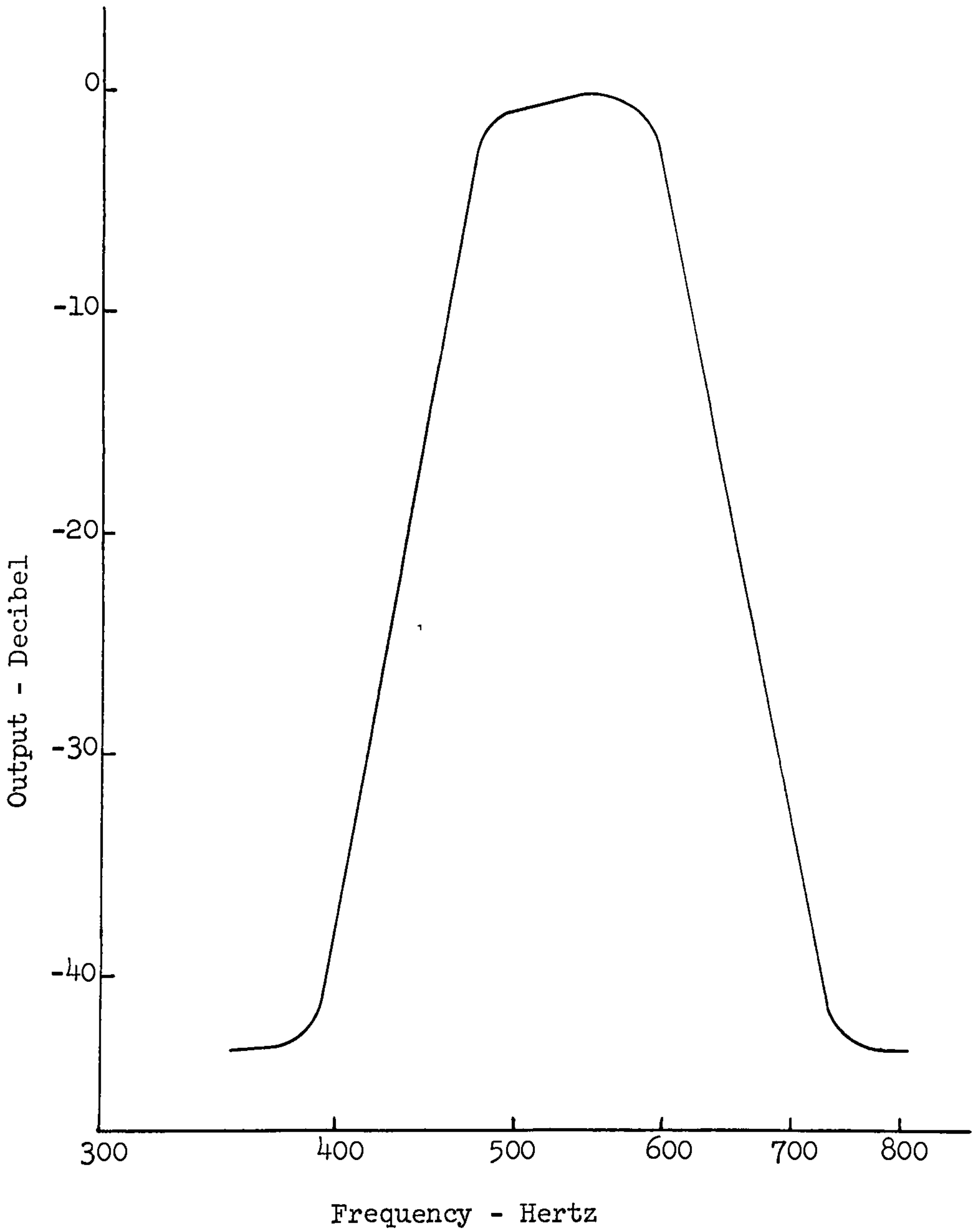

Figure 7

Band-Pass Filter Frequency Response - Filter Channel #3 made until it became obvious that linearity was not being maintained. The data were plotted after conversion to decibels. The graph for filter channel #3 is found in Figure 8. Again, this graph is typical. The test results for each filter channel are summarized in Appendix A, Table A3.

A third test procedure was used to determine the minimum signal duration which the filter channel could process in order to determine whether vowel signal durations were compatible with the hardware capability. This information pass-band could be determined by using half cycles of a modulating signal in the input signal to duplicate signal on-time. Filter response as the on-time was decreased via increased modulating frequency could then be measured.

In this test, a carrier signal set at the center frequency of the band-pass filter of the filter channel was 100% modulated using an analog computer in the Control Laboratory of the Electrical Department. The modulated output of the analog computer, set at a constant 1.5 volts peak-to-peak, was the input to the filter channel.

The modulating signal frequency was varied from 0.1 hertz to a frequency at which the filter channel output was nil. The output signal amplitude was measured for each modulating signal frequency setting. The output data were converted to decibels and plotted as a function of modulating signal frequency. The results for filter channel #3, typical for the filter channel system, are found in Figure 9. The output is seen to fall off as frequency is increased and the circuit cannot follow the input. The results for all filter

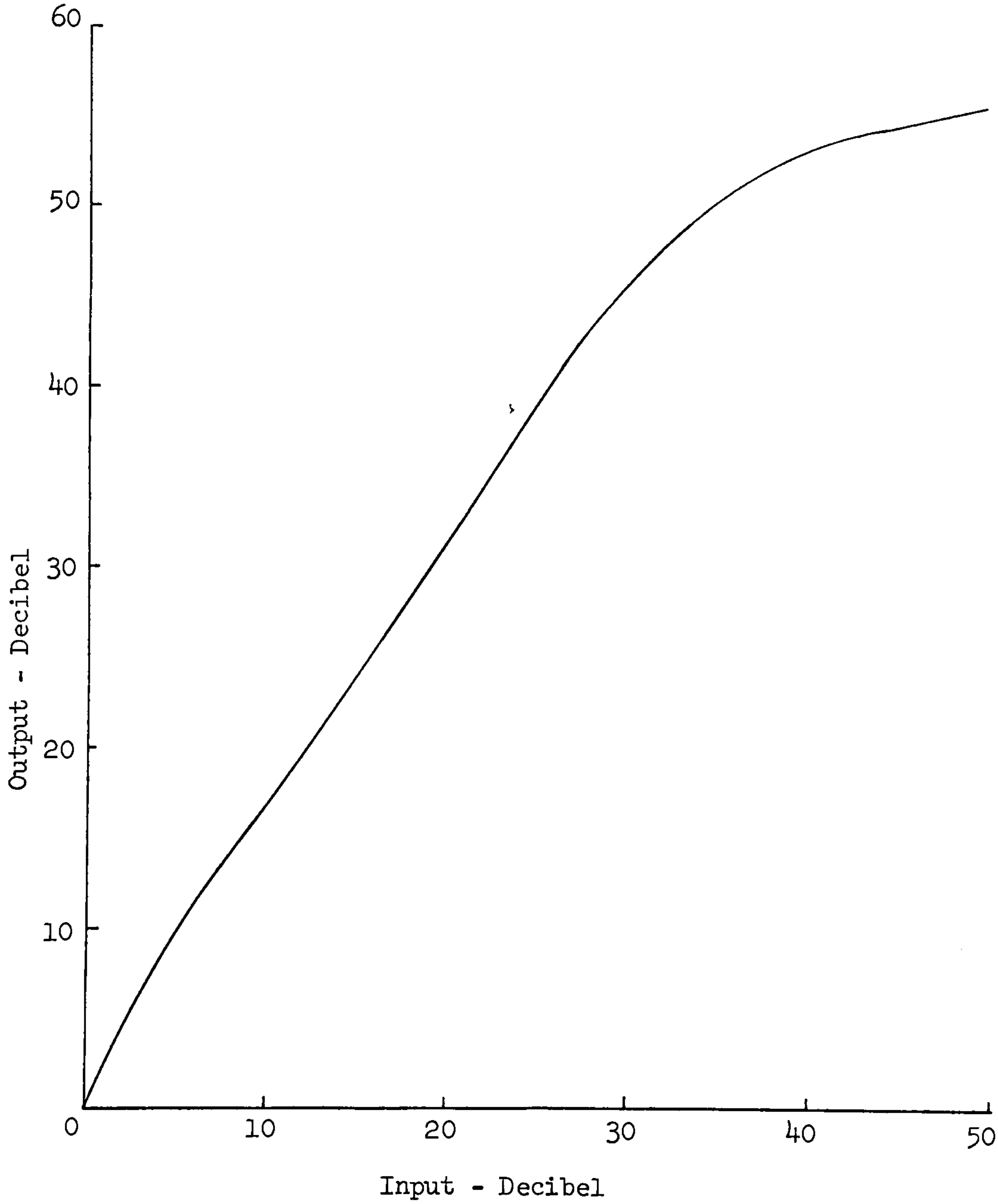

Figure 8

Filter Channel Dynamic Range -
Filter Channel #3

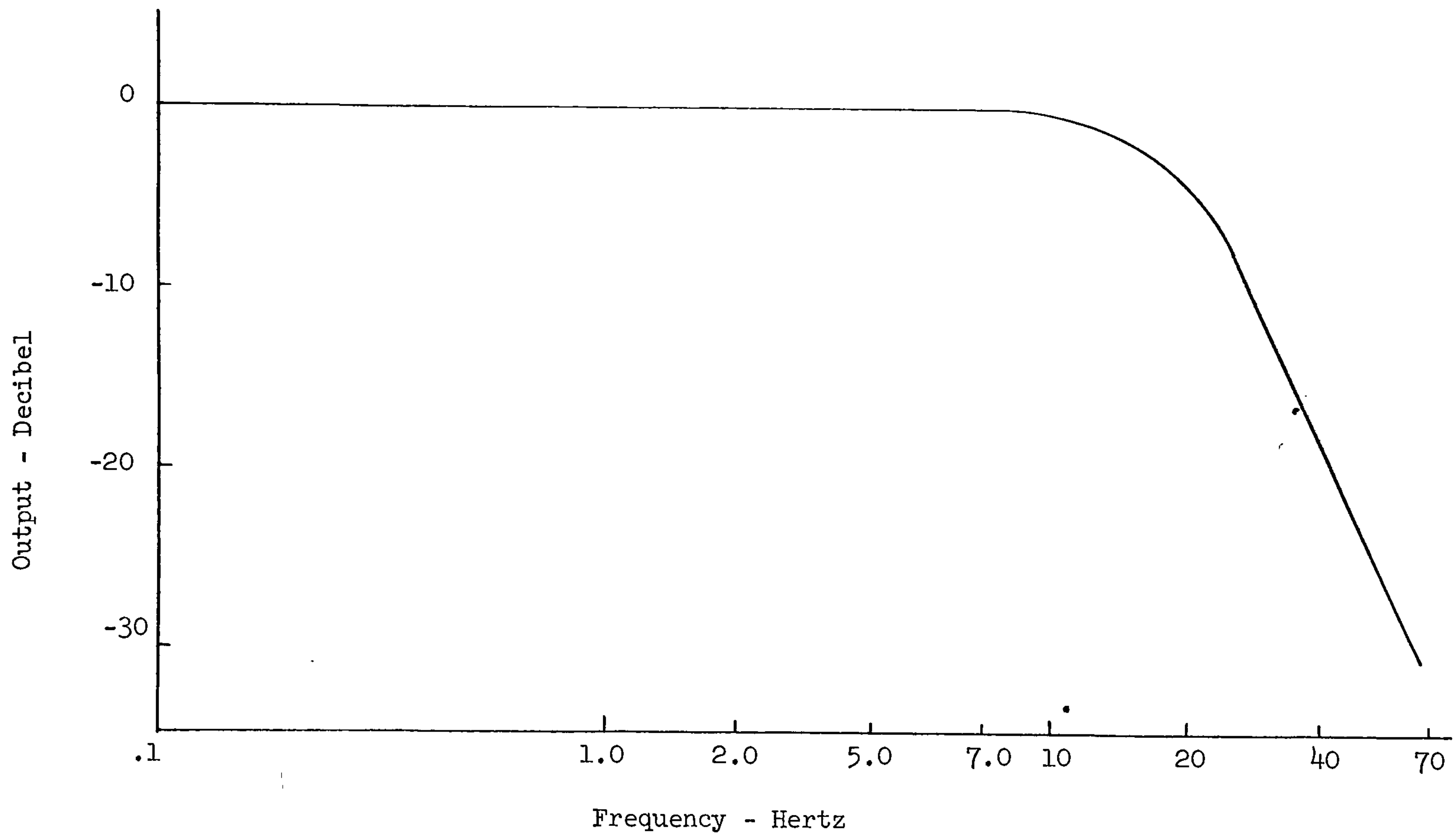

Figure 9

Filter Channel Passband -
Filter Channel #3

channels are summarized in Appendix A, Table A4. The passband in milliseconds is obtained by multiplying the cut-off modulating signal frequency by 2, and taking the reciprocal of the product.

Section 3

Discussion of Test Results

Referring to Appendix A, Table A1, it is seen that pass-band bandwidth varied from 2/3 octave to 1/7 octave. The filter channels with center frequencies above 670 hertz had bandwidths of 1/5 to 1/7. Center frequency spacing is not uniform, varying from 5/8 to 1/6 octave. Again, the filter channels above 670 hertz center frequency exhibited more similar results. Here, spacing is more uniform, varying from 1/4 to 1/6 octave.

It is necessary to insure that roll-off at the edges of the pass-bands is sufficient to prevent one formant frequency signal from masking the true level of another formant frequency signal in another filter channel. Using the band-pass filter graphs, the first three (3) formant frequencies of twenty-two (22) vowel and vowel-like sounds are located along the frequency axis. These formant frequencies are found in Table 1.[23][24]

The signal levels are assumed to be at 0 decibels for all formant frequency. In actuality, this is not the case, but this is a more conservative approach. The pass-band for a formant frequency is noted. The signal level of the other two (2) formant frequencies in

Table 1

Formant Frequencies for Vowels and

Vowel-Like Sounds

Sound	F_1	F_2	F_3
/i/	270	2290	3010
/ɪ/	390	1990	2550
/ɛ/	530	1840	2480
/æ/	660	1720	2410
/ɑ/	730	1090	2440
/ɔ/	570	840	2410
/ʊ/	440	1020	2240
/u/	300	870	2240
/ʌ/	640	1190	2390
/ɜ/	490	1350	1690
/m/	250	800	2200
/n/	250	800	2000
/ŋ/	300	900	2200
/w/	200	600	-
/j/	300	1800	2500
/l/	250	800	2500
/r/	250	1200	-
/e/	400	1800	2500
/a/	500	1200	2400
/ɒ/	600	900	2800
/o/	250	700	2200
/ə/	500	1200	2500

this pass-band is measured using the test graphs. The minimum signal level difference between the formant frequency being checked and an adjacent formant frequency was found to be 36 decibels. This is satisfactory and will prevent masking of true signal levels.

Using Appendix A, Table A3, the linear dynamic ranges were not greater than 40 decibels for all filter channels. The linear range varied from about 35 to 50 decibels. There were seven (7) filter channels with linear dynamic ranges less than 40 decibels. If the 40 decibel input dynamic range design objective is to be satisfied, any of the filter channels could certainly be used, but nonlinearity would introduce possible discrimination errors.

The information passband was found to vary from 13.5 to 19 hertz which were equivalent to 37 and 26.3 milliseconds respectfully. This means a signal of 37 milliseconds duration, minimum, could be processed in the filter channel system with no sacrifice in signal level. This signal on-time is well within the requirements dictated by vowel sound durations. In fact, there are essentially no restrictions on sounds which can be processed in a tactile vocoder using these filters with the possible exception of the very short duration stop consonants.

A study was made to determine communality between the vowel and vowel-like sounds using the filter channels. Communality was defined as the percentage of filter channels where signal levels did not change more than just noticeable difference when one sound was replaced by another.

Using previously computed spectrum envelopes from another study[26] for ten (10) vowels, a graphical solution was obtained. The individual spectrum channel vocoder filter channel bandwidths were superimposed on each of these spectrum envelopes. The average signal level within each pass-band was calculated. The calculations are summarized in Table 2.

All possible vowel pairs were then compared using all fifteen (15) filter channels to calculate communality as previously defined. It was found that 15.% of the possible pairs had communality greater than or equal to 50% using all fifteen (15) filter channels. A previous study indicated that low frequency channels do not significantly affect communality.[27] Filter Channels #5 thru 12, 14, and 15 were checked to verify these results. The same percentage of 15.5% was calculated. This is also consistant with that same study's findings that increasing the number of channels above 8-10 does not significantly affect results.

Based on these findings, the filter channels in the spectrum channel vocoder can be used in the tactile vocoder. It is recognized that the filter channels are not all linear within the 40 decibel input dynamic range. The ten (10) filter channels which would be used have center frequencies at 800, 930, 1075, 1200, 1400, 1580, 1810, 2090, 2755 and 3130 hertz. The spacing is fairly uniform ranging from 1/4 to 1/6 octave. There will be a built-in communality factor of 15.5% based on the graphical comparison of forty five (45) possible

Table 2

Average Signal Level (Decibels) in Each Spectrum Channel Vocoder Filter Channel

Filter Channel Passband in Hertz

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Sound	210-335	345-460	480-600	610-730	740-860	870-980	1010-1130	1150-1300	1330-1470	1490-1680	1700-1930	1950-2230	2250-2550	2580-2930	2930-3350
/i/	51	36	25	18	14	11	9	8	6	7	10	21	26	24	26
/I/	47	53	36	28	23	20	18	16	16	18	27	32	28	23	14
/ε/	44	45	53	38	31	27	24	23	24	27	38	30	30	19	10
/æ/	43	41	46	51	40	34	31	29	30	36	38	29	30	18	11
/ɑ/	43	41	44	53	53	46	51	38	27	21	16	16	22	11	4
/ɔ/	45	46	56	52	52	42	27	19	14	10	7	10	16	7	4
/ʊ/	46	54	44	35	33	36	36	22	14	10	8	13	7	-6	-10
/u/	54	42	32	29	34	31	16	8	3	-1	-2	5	2	-8	-9
/ʌ/	44	42	48	54	42	38	42	42	30	22	18	21	26	16	14
/ɜ/	45	50	50	37	32	30	32	37	42	38	28	14	-2.5	-8	-10

vowel pairs. It is about this level that discrimination errors start to rise above a common level as previously stated.

Chapter IV

The Multiplier, Amplification, and Bone Oscillator Stages

Section 1

Description of Design

The output of each of the filter channels from the spectrum channel vocoder being used in the tactile vocoder is directed to its respective multiplier, amplification, and bone oscillator stages. This signal flow was illustrated in the tactile vocoder block diagram, Figure 1. The complete electrical schematic diagram of these follow-on stages is found in Figure 10.

Multiplier Stage

The filter channel output and a 300 hertz signal from an external oscillator are the inputs to the Motorola MC 1495 Linear Four-Quadrant Multiplier. The output of the multiplier is a voltage which equals the product of a scale factor, the 300 hertz signal, and the filter channel output. A common mode quiescent output voltage of 10 to 15 volts DC which is blocked by the 1.0 microfarad coupling capacitor is also present at the multiplier output, pin 2 in Figure 10.

The multiplier has the capability of operating with input signals varying up to 5 volts peak-to-peak. The external 300 hertz oscillator is set to have a 5 volt peak-to-peak output at all times. By modifying the external circuitry connected to the multiplier and

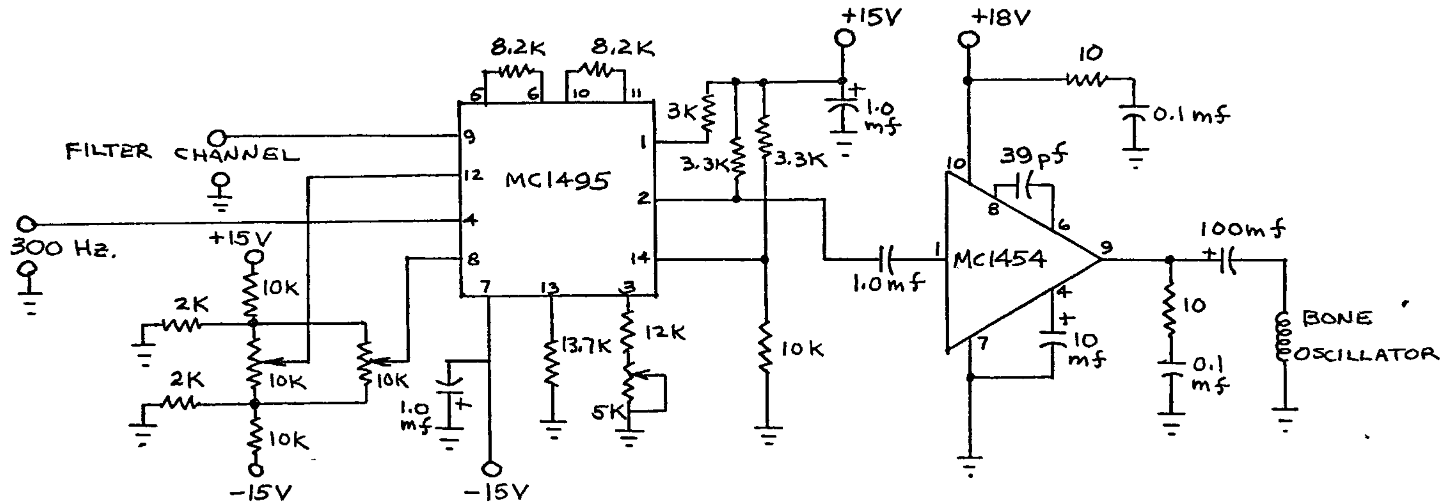

Figure 10

Multiplier, Amplification, and Bone Oscillator Stages increasing the positive bias power supply to 32 volts DC, the input voltage range could be extended to a maximum of 10 volts peak-to-peak.

The Motorola MC 1495 Linear Four-Quadrant Multiplier is a monolithic silicon epitaxial passivated integrated circuit device. Analog multiplication is accomplished using the variable transconductance principle. This principle of operation is based upon the theory that the output of a transistor amplifier is proportional to the input signal times a function of the emitter current. The 300 hertz signal is the input to the amplifier, and the emitter current is a function of the filter channel output. The balanced differential mode of amplification is used throughout the device.

The electrical schematic diagram of the multiplier stage is shown in Figure 11. A functionally oriented model of the MC 1495 device denoting the major systems within the part is shown in Figure 12. The purposes of the external components connected to the MC 1495 multiplier will be explained after internal multiplier operation is examined.

The inputs to the multiplier device are preconditioned to eliminate nonlinear processing distortion. Neglecting the voltage drop across the base, the Ebers-Moll equation for emitter current is:

$$i_e = I_{EBS} \left(e^{qV_{BE}/kT} - 1\right) - \alpha_I I_{CBS} \left(e^{qV_{CB}/kT} - 1\right) \qquad (2)$$

Assuming that the transistor is in the forward active region, the collector saturation, I_{CBS}, can be neglected along with the minus one in

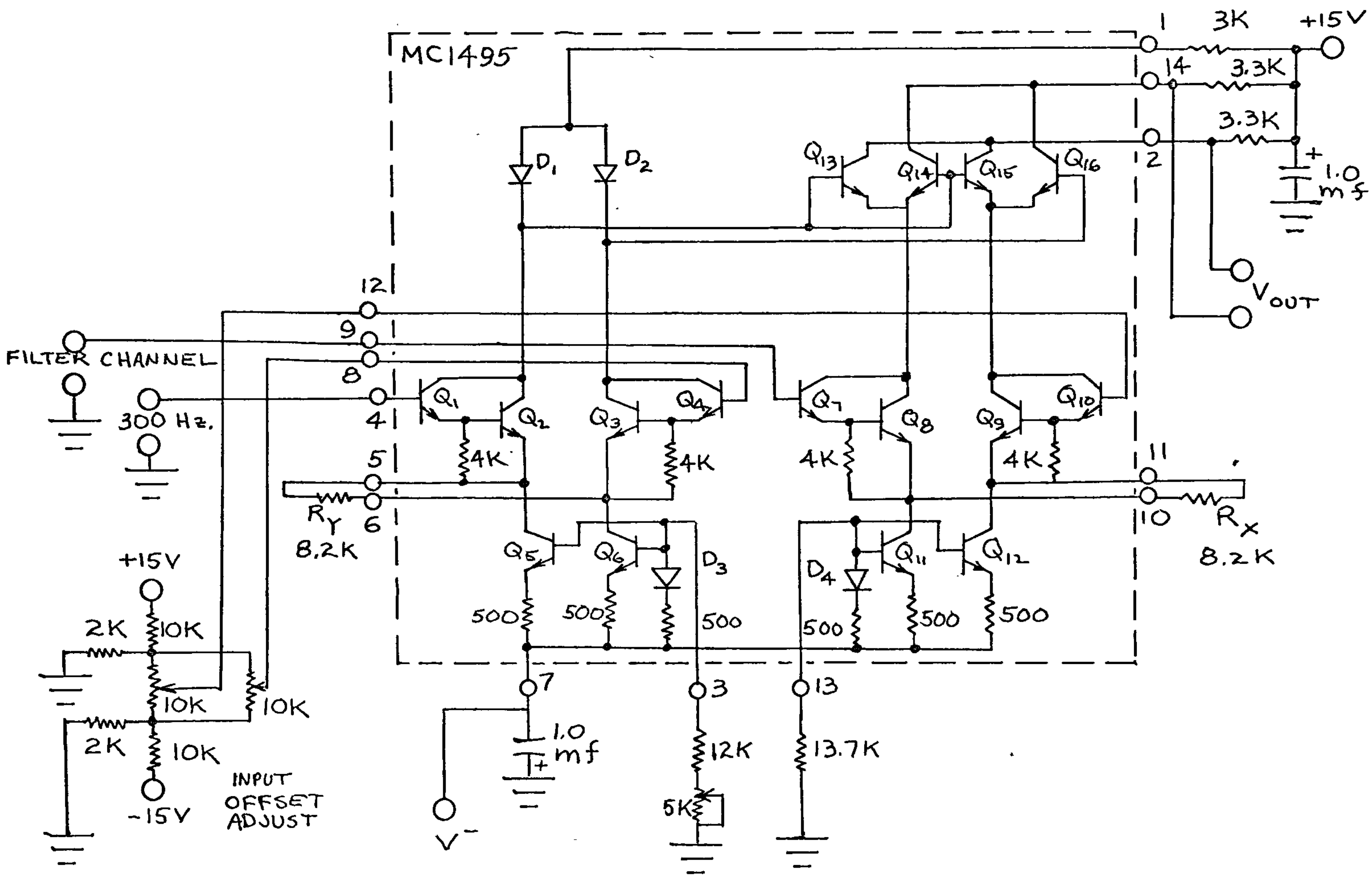

Figure 11

Multiplier Stage

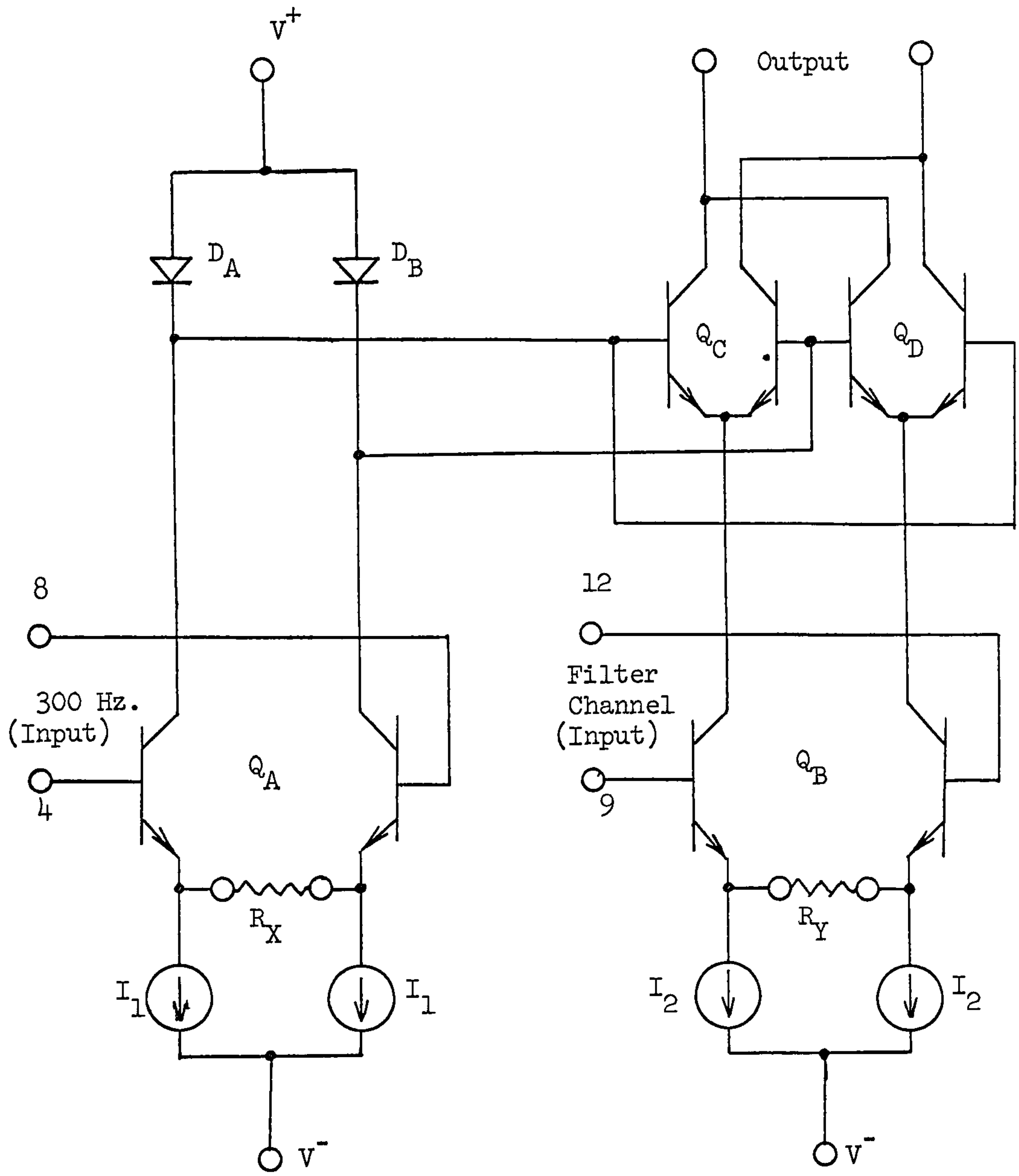

Figure 12

MC1495 Multiplier - Functional Model

the I_{EBS} expression. If base currents are neglected, emitter current equals collector current and

$$I_c = I_{EBS} e^{qV_{BE}/kT} \quad (3)$$

$$V_{BE} = (kT/q) \ \ln(I_c / I_{EBS}) \quad (4)$$

Thus, there is logarithmic amplification. However, transistors can be cascaded to have the relationships shown in (3) and (4) operate in series. The logarithmic amplification cancels the exponential amplification, and the output of the cascaded stages is a linear function of the input. This principle is used in the MC 1495 multiplier to insure linear amplification.

Referring to Figure 12, the constant current generators I_1 maintain constant emitter current in the input differential amplifier Q_A. The constant current generators I_1 are represented by Q_5, Q_6, D_3 and the 500 ohm resistors in the actual device in Figure 11. The input differential amplifier Q_A is comprised of Q_1, Q_2, Q_3, and Q_4 in Figure 11. The combination of the differential amplifier Q_A and D_A, D_B in Figure 12 ,process the 300 hertz signal input at pins 4 and 8 so as to present input voltages to the differential amplifiers Q_C and Q_D which are logarithmic functions of the 300 hertz input signal. Q_C and Q_D are made up of Q_{13}, Q_{14}, Q_{15}, and Q_{16}, and D_A and D_B are D_1 and D_2 in Figure 11.

The constant current generators I_2 maintain constant emitter current in the input differential amplifier Q_B in Figure 12. The constant current generators I_2 are Q_{11}, Q_{12}, D_4 and the 500 ohm resistors in Figure 11. The input differential amplifier Q_B is comprised of Q_7, Q_8, Q_9, Q_{10} in Figure 11. The differential amplifier Q_B regulates the emitter currents of the differential amplifiers Q_C and Q_D as functions of the filter channel output signals which are introduced at pins 9 and 12.

The actual multiplication of the two (2) input signals is accomplished in the differential amplifiers Q_C and Q_D. By preconditioning of the 300 hertz signal in a nonlinear operation, the final output is a linear product of the 300 hertz signal and the filter channel output. A mathematical derivation of the output voltage expression is found in Appendix B.

Referring to Figure 11, emitter resistors R_x and R_y (8.2K ohm) are large with respect to the bulk emitter resistances of the input differential amplifiers so that the emitter resistances can be neglected in determining the output voltage expression. The resistances at pins 3 and 13 set the outputs of the constant current generators at 1.0 milliamperes. The 1.0 microfarad capacitors at the bias power supply connections assist in maintaining constant bias levels. The 3.3K ohm resistors at pins 2 and 14 are output loads. The 3.0K ohm resistor at pin 1 establishes the collector bias voltage.

The input offset adjust circuit is intended to null the multiplier output when the filter channel output is zero. Voltage offsets and ohmic base resistances in the output differential amplifiers and the constant current generator diodes are potential sources for finite multiplier outputs with one input at zero. The nulling is accomplished by introducing a D.C. voltage of such a polarity at the input so as to cancel out these sources of error. The adjustment is made by setting the 300 hertz signal at 5 volt peak-to-peak and monitoring the multiplier output. With no filter channel output, the 10K ohm potentiometer slide connected to pin 8 is rotated until the multiplier output is zero.

Amplification Stage

The multiplier output signal is fed to the Motorola MC 1454 1-Watt Power Amplifier. The power amplifier is a monolithic silicon epitaxial passivated integrated circuit device. It has the capability of being direct coupled or capacitively coupled to low resistance loads (down to at least one (1) ohm). This means that transformer coupling of the amplifier load to shift its effective load impedance level is not required.

A complete electrical schematic diagram of the amplification stage is found in Figure 13. The bias power supply is set at 18 volts. The MC 1454 amplifier can be operated with bias levels down to 8 volts. However, the maximum deliverable power is reduced as the bias is decreased.

The external connections at pins 2, 4, and 5 determine the overall voltage gain of the amplifier. Connecting pin 4 to AC ground as shown in Figure 13 will result in an 18 volt per volt gain. If pin 5 is connected to AC ground instead of pin 4, the voltage gain is

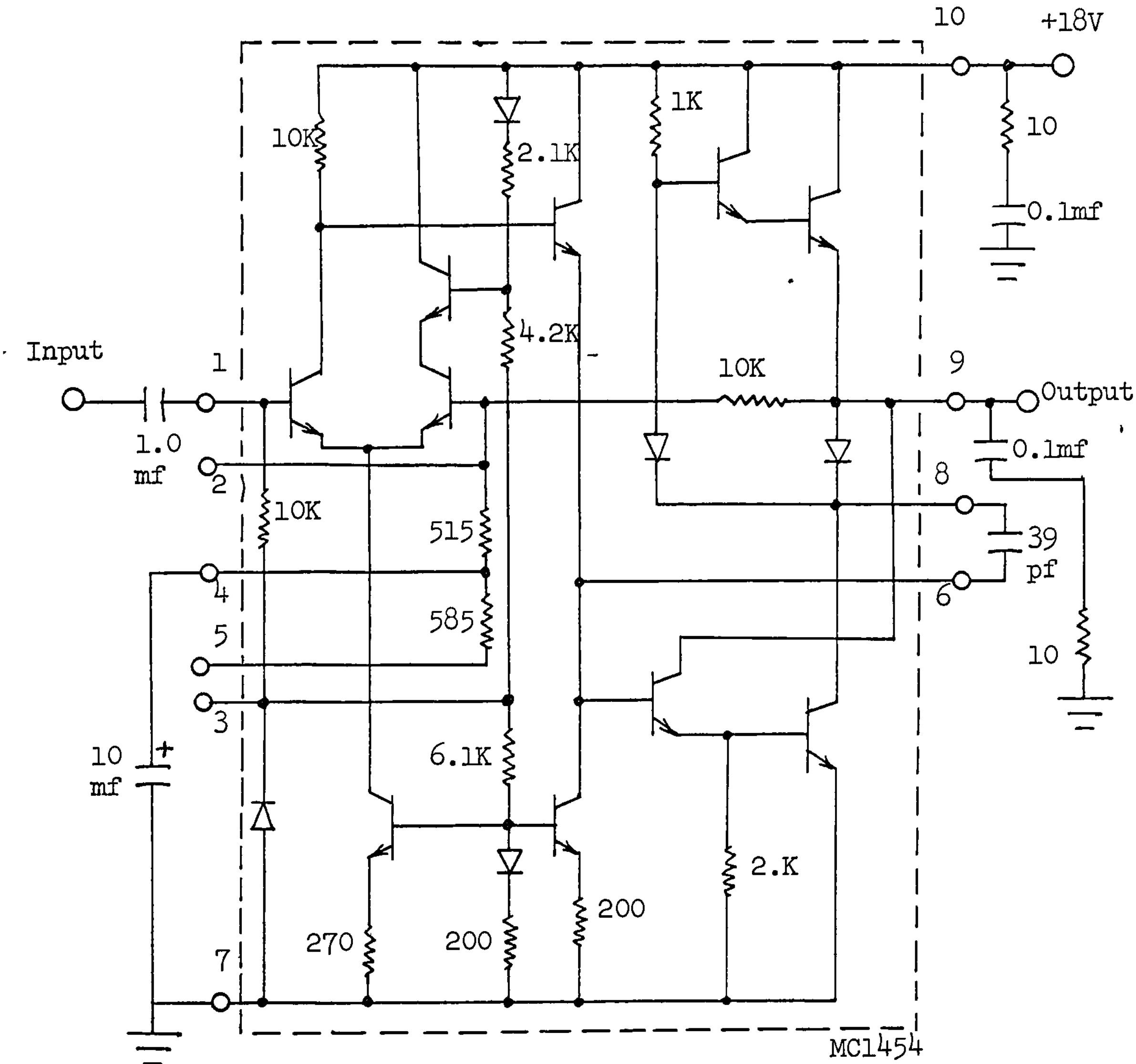

Figure 13

Amplification Stage

10 volt per volt. When pins 2 and 5 are connected together and pin 4 is connected to AC ground, a voltage gain of 36 volt per volt is obtained. If an external potentiometer is connected between pin 2 and AC ground, the voltage gain is a function of potentiometer setting. This fine adjustment feature might be desirable in the complete tactile vocoder to balance amplifications between individual channels.

The 0.1 microfarad capacitor in series with the 10 ohm resistor at pin 9 is an R-C stabilizing network. It prevents local VHF instability by compensating for lead inductance of the load. The same R-C configuration at pin 10 performs the same function to compensate for lead inductance of the 18 volt power supply.

The flexibility of readily changing output signal levels and coupling to very low resistance loads led to the selection of the MC 1454 amplifier. It was compared to configurations utilizing discrete components and possibly necessitating a transformer to couple the load. This design is not tied down to the selection of one bone oscillator with its particular impedance level. Oscillators from various sources can be considered in any follow-on research programs.

Bone Oscillator Stage

The output of the power amplifier is applied through a 100 microfarad capacitor for DC isolation to an electromagnetic bone oscillator. In breadboard testing of the design, a Radio Ear, Model B-70 bone oscillator was used. The input impedance of the bone oscillator was measured and found to be 400 ohms. This is a fairly high impedance load and the specialized MC 1454 power amplifier might not have been necessary. However, its flexibility for further studies and low device cost were important enough to justify its use.

Section 2

Investigation of Breadboard Model Performance

A breadboard model of the design was constructed for one channel. Initial testing revealed that internally generated noise and noise pickup at the multiplier input from the filter channel were problems. As a result, internal connections and lead lengths were minimized. Ground loops were avoided, and the multiplier input from the filter channel utilized shielded wire.

The breadboard model was set up to determine the transfer function of the multiplier, amplification, and bone oscillator stages. Lambda Regulated Power Supplies were used for multiplier bias and a Sorenson Q Nobatron Power Supply was used for power amplifier bias. A General Radio Company Unit R-C Oscillator was the 300 hertz source, and one phase of a General Radio Company Low Frequency Three Phase Oscillator simulated the filter channel output. The simulated filter channel output was varied from the lowest obtainable value (.002 volts) to 5.0 volts peak-to-peak at a frequency of 10 hertz. The voltage at the bone oscillator was measured. The test results are plotted in terms of voltage in Figure 14 and in decibels in Figure 15.

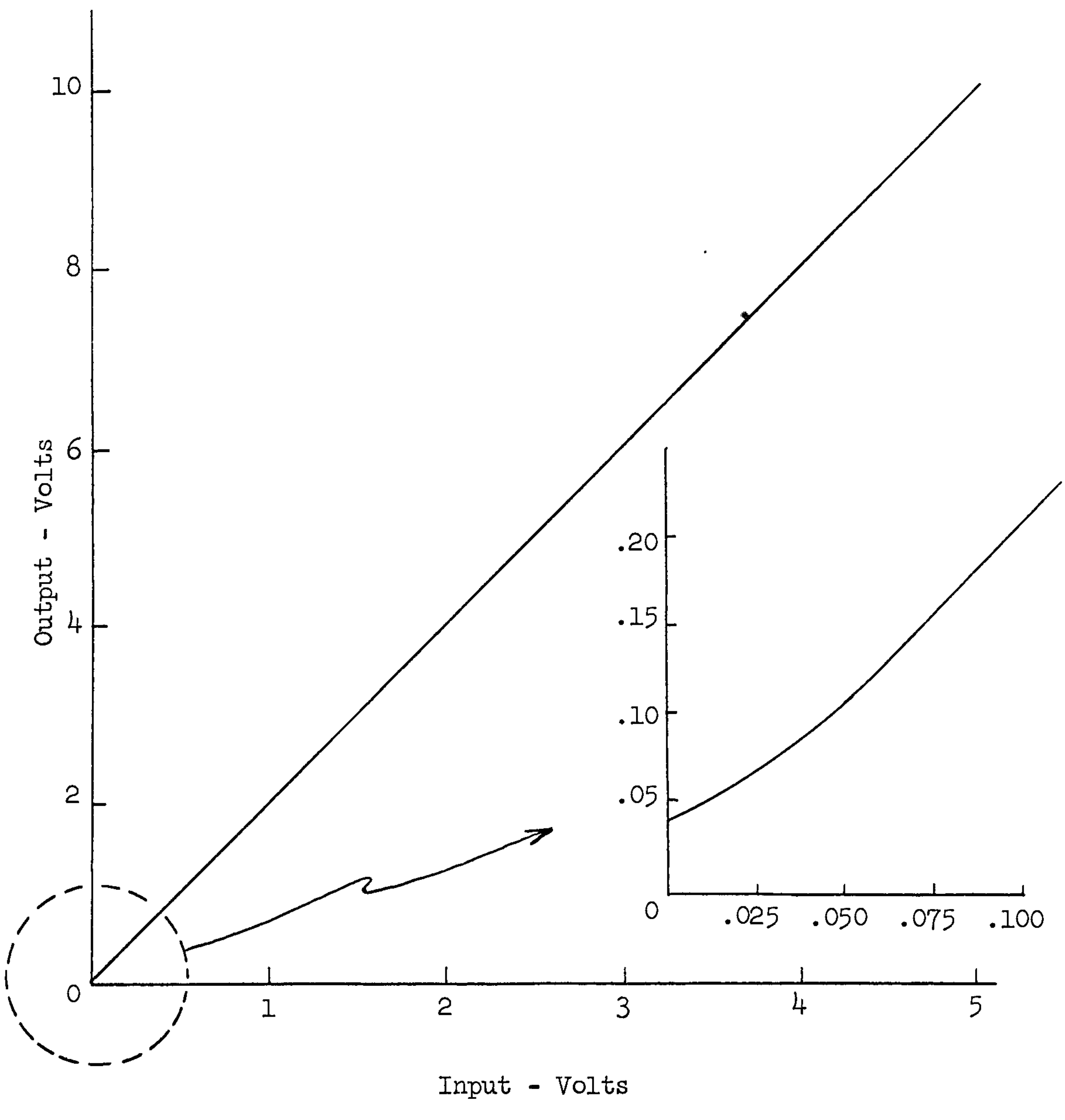

Figure 14

Multiplier, Amplification, and Bone

Oscillator Stages Transfer Function

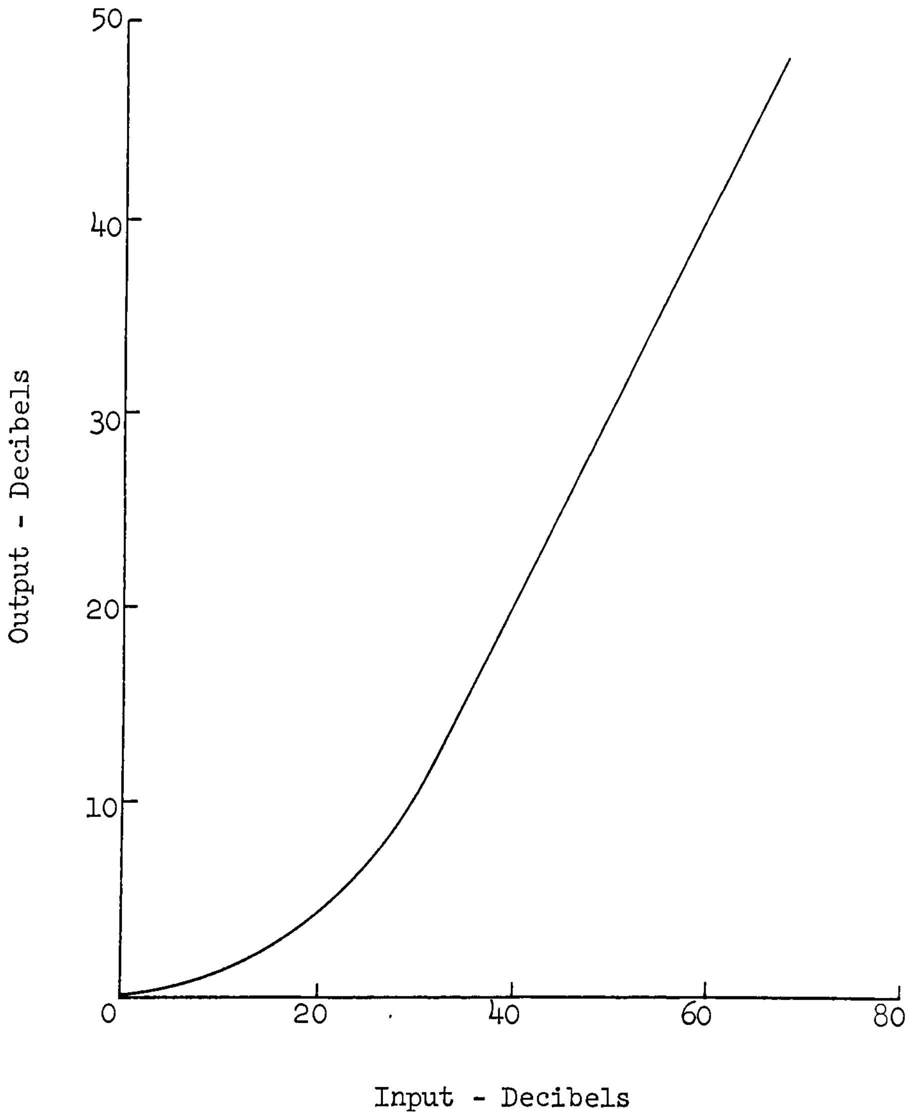

Figure 15

Multiplier, Amplification, and Bone

Oscillator Stages Transfer Function

A second test was run using the spectrum channel vocoder to obtain a typical complete system transfer function. Filter Channel #8, center freqeuncy of 1200 hertz, was disconnected from the vocoder synthesizer. The filter channel output was connected to the multiplier input. The Low Frequency Three Phase Oscillator was connected directly to the filter channel input and set at 1200 hertz. The filter channel input was varied from zero to a value 4.0 volts peak-to-peak. At this value input, the voltage at the bone oscillator was greater than 13.5 volts peak-to-peak and the test was discontinued. The test results are plotted in terms of voltage in Figure 16 and in decibels in Figure 17.

It was desired to determine the information passband for a complete channel. The test set-up as outlined in Chapter III for determining the filter channel information pass-bands which employed the use of the analog computer was duplicated. Filter Channel #8 was selected for the test. The input carrier signal to the computer was set to 1200 hertz. The test procedure used in Chapter III was followed. The test results are plotted in Figure 18. The test results from Chapter III for channel #8 are included in dashed lines for comparison.

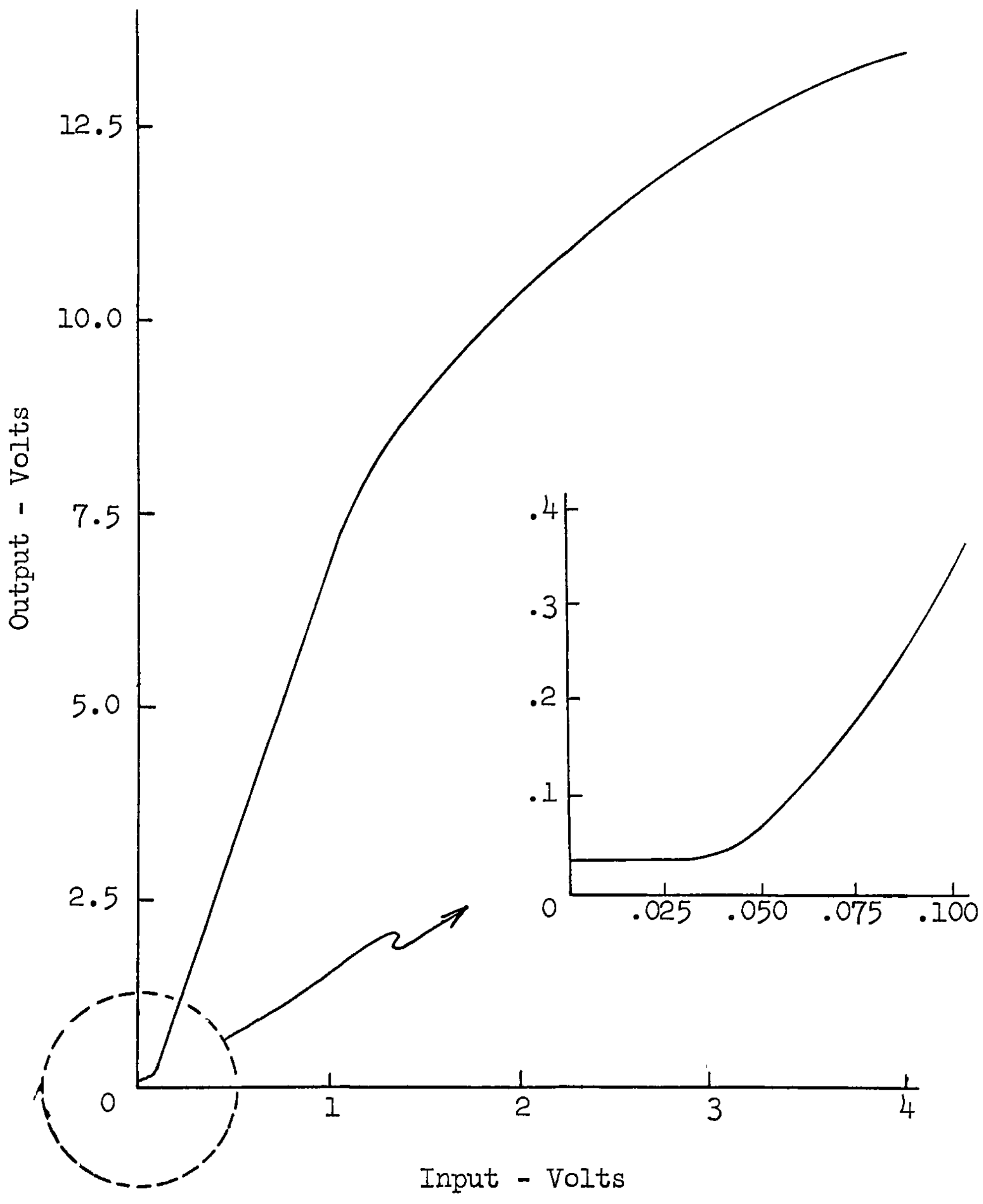

Figure 16

Complete System Transfer

Function, Filter Channel #8

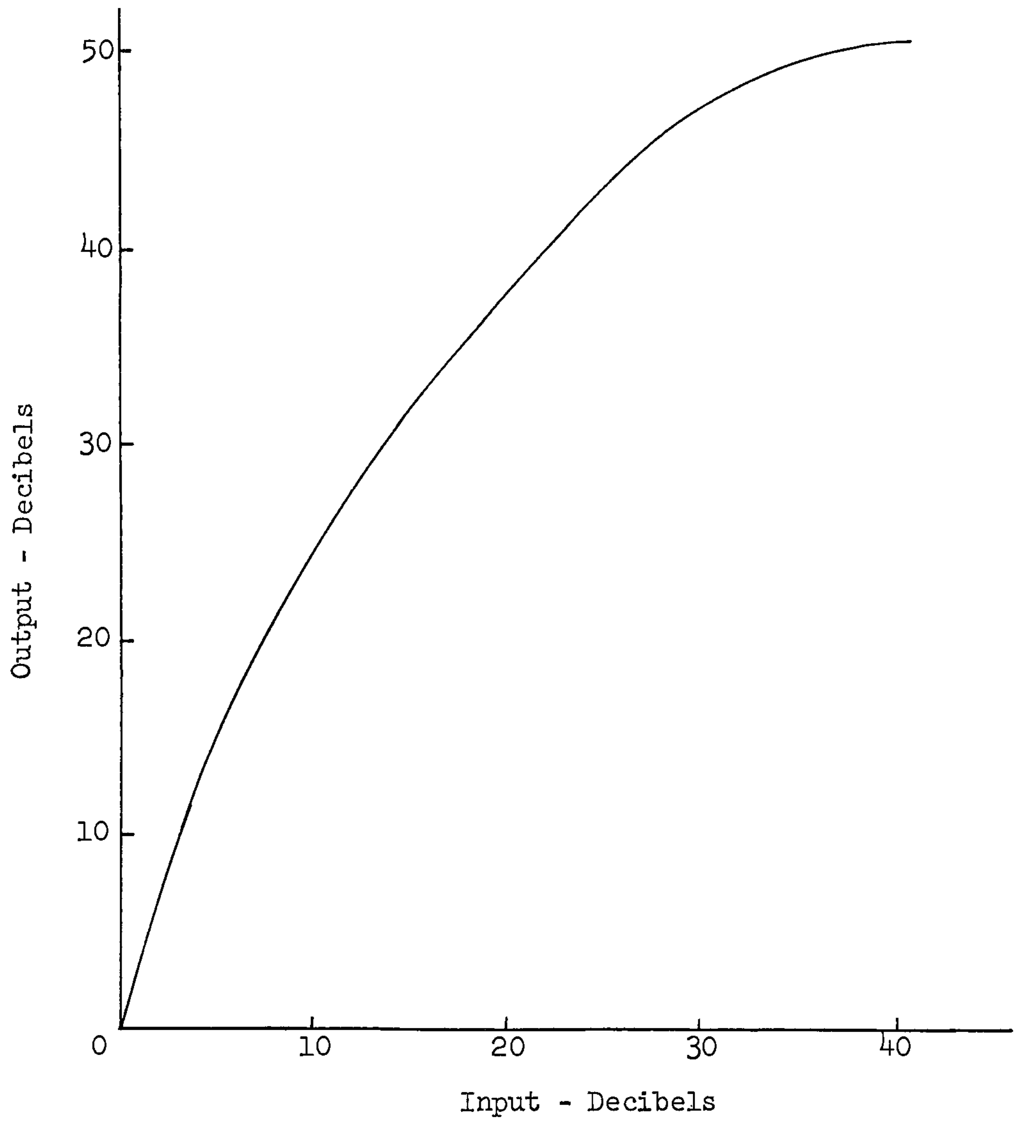

Figure 17

Complete System Transfer

Function, Filter Channel #8

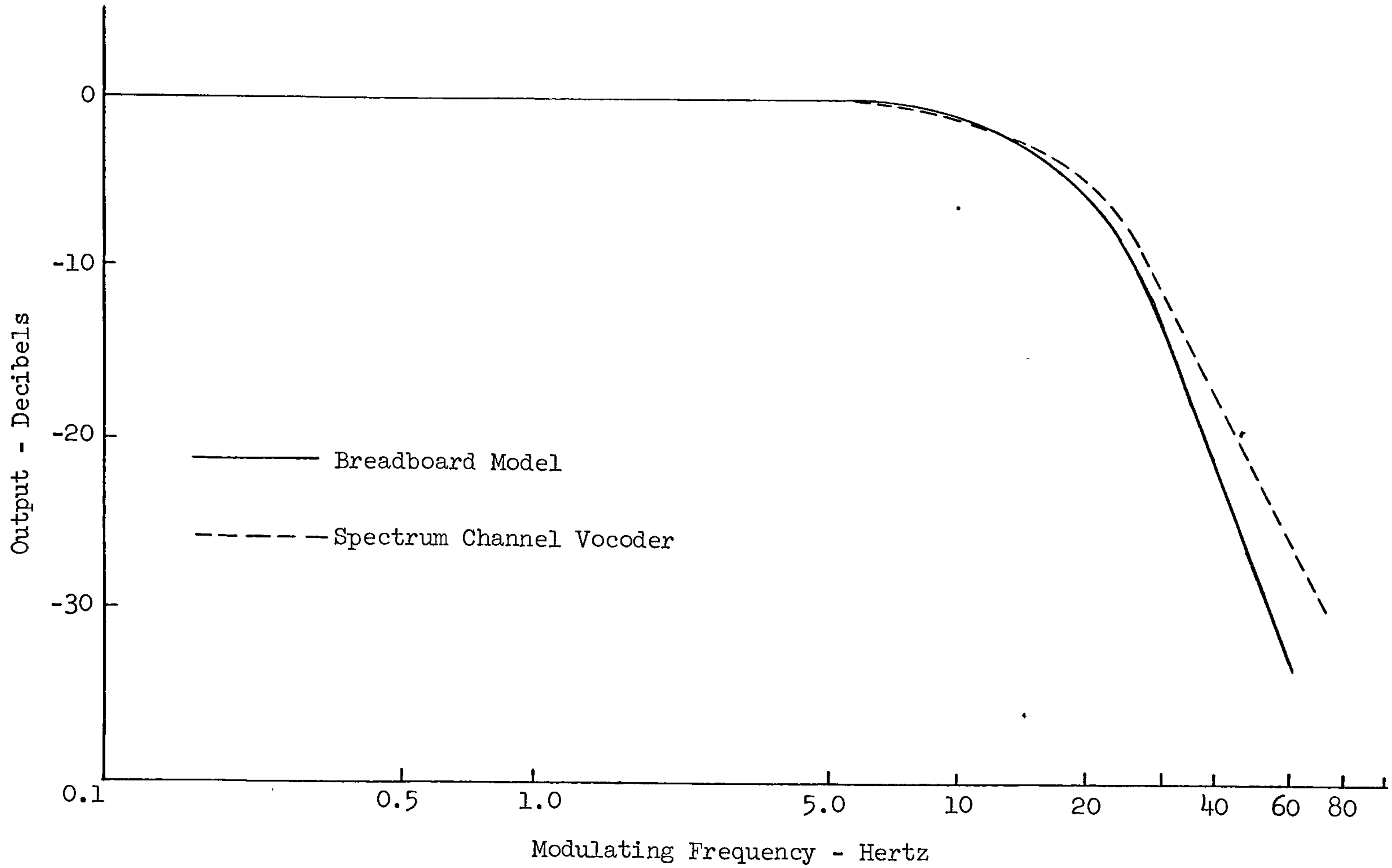

Figure 18

Information Pass-band, Filter Channel #8

Section 3

Discussion of Test Results

The transfer function of the multiplier, amplification, and bone oscillator stages is linear for inputs of 0.060 volts and greater as shown in Figure 14. This corresponds to a linear dynamic range between 30 and 68 decibels, input from Figure 15. The output dynamic range over this input span is 38 decibels. For 5.0 volts peak-to-peak input, the output at the bone oscillator was 10.1 volt peak-to-peak. The complete input dynamic range is 68 decibels. These test results are consistent with the design objective of an input dynamic range of 40 decibels.

It was not possible to obtain a zero output when the filter channel output was zero. The minimum nulled output voltage at the bone oscillator was 0.04 volts. This corresponds to just a little over 0.002 volts at the multiplier output.

The aforementioned problem of noise in the multiplier was one reason why this nonzero output was obtained. Also, the procedure recommended by Motorola uses a 1.0 volt signal at one input while the other input is grounded. In this design, the 300 hertz signal is always set at 5.0 volt peak-to-peak. This increased signal level contributed to the magnitude of the residual output. Also, the filter channel output is never grounded. These deviations from the recommended procedure were another reason for not obtaining zero output.

The entire situation is magnified by the fact that the residual output is immediately processed in an 18 volt per volt smplification stage. However, the minimum output which was obtained can be tolerated. The dynamic range design objective was satisfied.

The transfer function of the complete Filter Channel #8 breadboard model was linear between about .050 and 1.0 volts input as seen in Figure 16. For 4.0 volts input to the filter channel, an output of 13.5 volts was obtained at the bone oscillator. An input dynamic range of 40 decibels which corresponded to 51 decibels, output, was obtained in Figure 17. The residual output at the bone oscillator was 0.035 volts when the filter channel output was zero. The objective of 40 decibels, input, was satisfied.

The information pass-band of the complete model was not appreciably different from that of the filter channel as loaded in the spectrum channel vocoder as demonstrated in Figure 18. The pass-band for the complete model was 15 hertz compared to 16.0 hertz for the first test. Roll-off increased from 14.5 decibels per octave to 19 decibels per octave. The results indicate that there were no appreciable coupling or loading problems when the filter channel is connected to the input of the multiplier stage.

Section 4

Alternate Multiplier Stage Utilizing a Motorola MC 1596 Balanced Modulator-DeModulator

In arriving at the decision to include the MC 1495 multiplier in the multiplier stage, the use of a Motorola MC 1596 Balanced Modulator-DeModulator was considered. The modulator is a monolithic silicon epitaxial passivated integrated circuit device. The complete electrical schematic diagram is found in Figure 19. A functional model for use in discussing modulator operation is found in Figure 20.

The modulating signal, labeled V_s in Figure 20, is the input to the differential amplifier Q_A. The constant current generators, I_1, maintain a constant emitter current in the amplifier. The differential amplifier Q_A is made up of Q_1 and Q_2 in Figure 19. The constant current generators are Q_3, Q_4, D_1, and the 500 ohm resistors in Figure 19.

The carrier signal V_c in Figure 20 is the input to transistor current-mode gates S_1 and S_2. These gates form a pair of synchronized, single-pole, double-throw switches. The differential amplifier drives the switches, and the normally open, normally closed poles of the switches (collectors of the transistors making up the switches) are cross-coupled to obtain full-wave balanced modulation.

If the current mode gates are assumed to be ideal switches, the carrier signal is reduced to a square wave having the frequency of the original carrier signal. The modulator output is then the

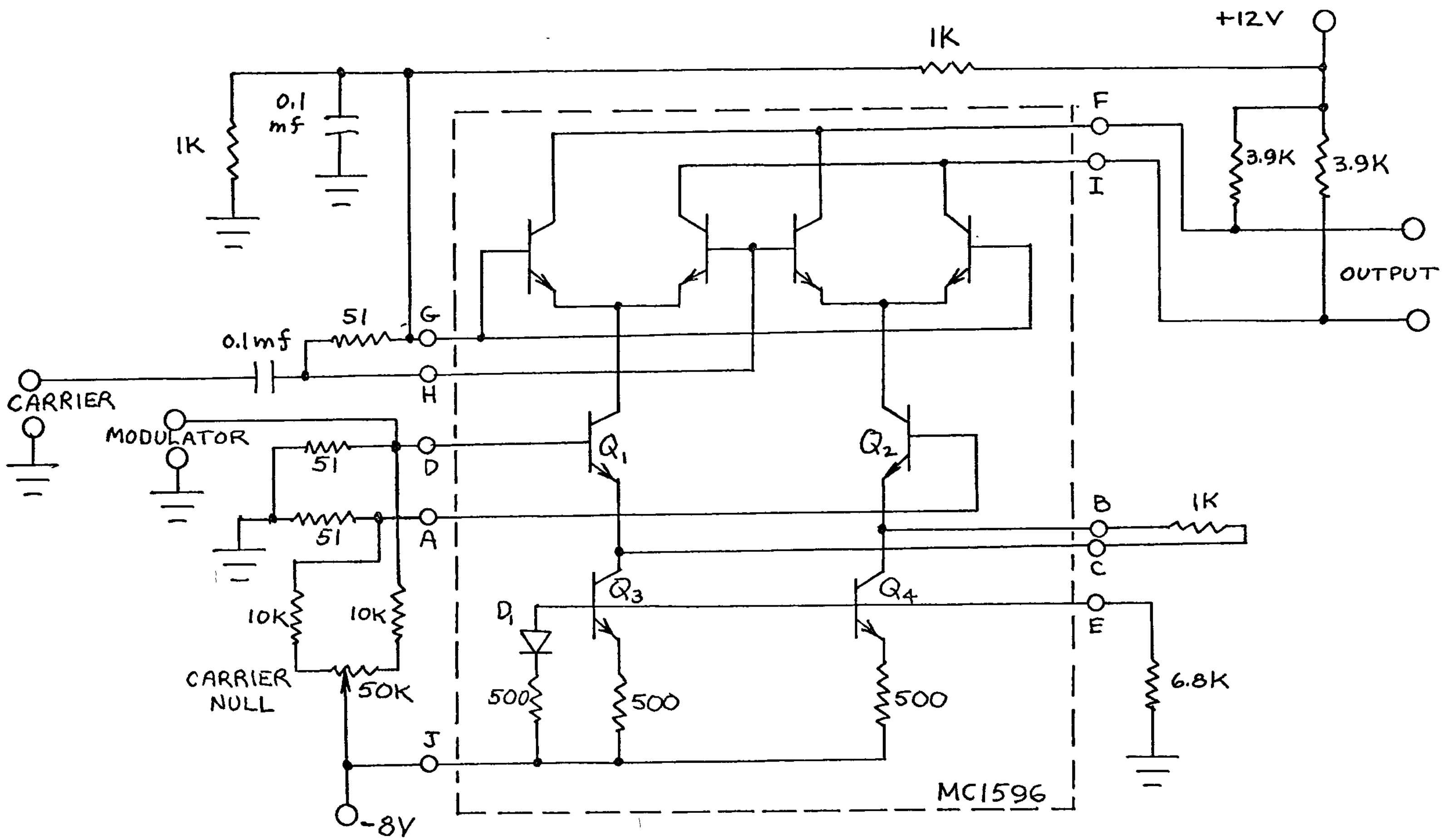

Figure 19

MC1596 Balanced Modulator - Demodulator Multiplier Stage

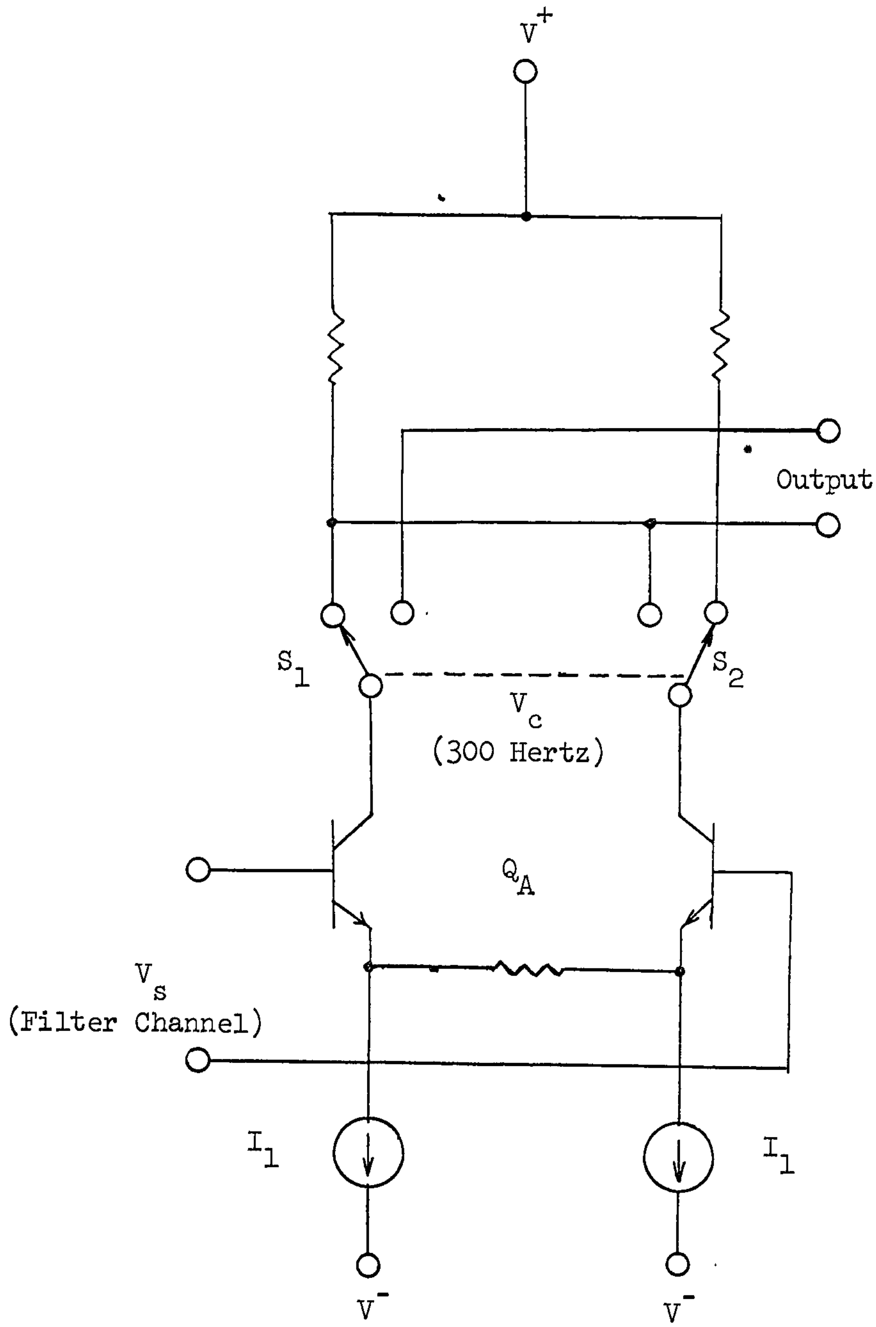

Figure 20

Functional Model of MC1596 Modulator - Demodulator product of the modulating signal and a square wave. Since the original sinesoidal carrier signal has been replaced by a square wave, odd harmonics of the original carrier are now present in the output.

This is evident when considering the Fourier Series for a square wave.

$$V(t) = 2 \sum_{n=1} A_n \text{ Cos } nwt \tag{5}$$

where

$$A_n = (\text{Sin } n\pi/2)/(n\pi/2) \tag{6}$$

The modulator has an input signal range of 5 volt peak-to-peak maximum as compared to 10 volt peak-to-peak for the MC 1495 multiplier. The presence of harmonics in the output signal prevents testing with the tactile vocoder in which responses to only pure tones can be studied. It would be necessary to add bandpass filters to remove these harmonics. It was for these reasons that the modulator was not used.

Chapter V

Conclusions and Recommendations

Section 1

Conclusions

The tactile vocoder was designed with objectives based on speech signal properties. The filter channels of the spectrum channel vocoder were found to be satisfactory for use in the tactile device. While not having a linear transfer function over the entire region, each filter channel had a minimum input dynamic range of 40 decibels, the tactile vocoder design objective. A minimum signal level difference of 36 decibels between two (2) adjacent formant frequencies in the same filter channel pass-band was determined. This is sufficient to prevent masking of true signal levels.

The information pass-bands of the filter channels varied from 13.5 to 19 hertz. This frequency range as previously explained can be converted to signal on-times ranging from 26.3 to 37 milliseconds. The filter channels can then be used to process signals down to stop consonent durations which vary to 20 milliseconds minimum without loss of signal level. The design objective of 100 milliseconds was therefore very easily satisfied. It is then the basic time response of the tactile sense which limits the use of the tactile vocoder.

The transfer function of the multiplier, amplification, and bone oscillator stages was linear for inputs between 0.06 and 5.00

volts. This range was equivalent to 38 decibels of linear input dynamic range. The complete input range was 68 decibels compared to a design objective of 40 decibels.

The transfer function for the complete breadboard model using Filter Channel #8 exhibited the nonlinear influence of the basic filter channel signal response. However, an input dynamic range of 40 decibels was still obtained, being reasonably linear over a 20 decibel region and satisfying the design objective. The information passband for the complete model was 15 hertz compared to 16 hertz for only the filter channel as loaded in the spectrum channel vocoder. Thus, the complete breadboard model can also process signals of duration down to stop consonant values of 33.3 milliseconds with no loss in signal level.

The study of signal communality in the spectrum channel vocoder showed that a combination of the filter channels #5 through 12, 14, and 15 was worthy of further study. It was calculated that 15.5 percent of the possible vowel pairs in the study had communality greater than or equal to 50 percent. As previously mentioned, this agrees with findings of a previous study.

Section 2

Recommendations

The pitch extraction circuitry of the spectrum channel vocoder has potential for use in future speech therapy programs where control of the fundamental frequency component of speech would be studied.

This system will be left intact when the filter channels of the spectrum channel vocoder are used in the tactile vocoder. Therefore, future study of the pitch extraction system's transfer characteristics could be made.

The breadboard model of the tactile vocoder was built with the goal of verifying the basic design. However, using the components from the model, a compact possibly totally enclosed package could be assembled. Spectrum channel vocoder power supplies could be used to bias this module package. Adding a mounting bracket to the spectrum channel vocoder to hold the module would result in a self-contained unit.

Construction of the breadboard model demonstrated that the circuit was sensitive to noise pick-up. Therefore, when building this enclosed module or the complete tactile vocoder, particular attention should be given to noise suppression techniques. Care should be taken to maintain high component densities in the printed circuit board, short connections, and no ground loops. These precautions should lead to greater noise immunity. It is then anticipated that the linear region of the transfer function might extend down farther into the lower signal level region where noise is a more significant portion of the signal being processed.

Building such an enclosed module would provide instrumentation to start clinical studies of the feasibility of the tactile vocoder in a learning situation using only one filter channel. This might be desirable prior to constructing a complete tactile vocoder. One possible test would be to establish threshold levels for the Radio Ear bone oscillator. Interaction between the speech therapist and the Engineering Department would ensure that any desired additions or modifications would be incorporated in the final device. The construction of a complete tactile vocoder would then allow testing to verify operation of the previously recommended combination of ten (10) filter channels from the spectrum channel vocoder.

APPENDIX A

Test Data for Spectrum Channel Vocoder Filter Channels

Table A1

Band-Pass Filter Frequency Response

Filter Channel	Center Frequency Hertz	Bandwith (-3DB) Octave	Center Frequency Spacing Between Filter Channels Octave
1	270	.688	-
2	408	.477	.593
3	538	.333	.407
4	670	.250	.313
5	800	.228	.250
6	930	.187	.229
7	1075	.167	.208
8	1200	.187	.157
9	1400	.144	.218
10	1580	.177	.177
11	1810	.177	.187
12	2090	.198	.197
13	2400	.187	.197
14	2755	.177	.187
15	3130	.198	.187

Table A2

Band-Pass Filter Roll-Off

Filter Channel	Rise DB per Octave	Duration of Rise Octave	Fall DB per Octave	Duration of Fall Octave
1	57	.709	60	.969
2	90	.281	84	.229
3	132	.297	135	.297
4	132	.203	151	.208
5	186	.187	156	.229
6	192	.229	192	.240
7	192	.187	168	.208
8	204	.197	192	.208
9	264	.125	294	.117
10	336	.117	264	.139
11	228	.167	186	.229
12	234	.150	240	.167
13	264	.146	240	.156
14	252	.114	264	.167
15	210	.135	240	.156

Table A3

Linear Dynamic Range

Filter Channel	Filter Noise DC Volts	Input to Raise Output Above Noise AC Volts (RMS)	Linear Range Input-DB	Linear Range Output-DB
1	.005	.0022	35	43
2	.023	.0020	50	40
3	.003	.0075	35	50
4	.019	.0025	40	38
5	.009	.0030	45	42
6	.003	.0015	50	52
7	.011	.0035	45	44
8	.007	.0032	38	41
9	.002	.0080	35	53
10	.002	.0100	35	54
11	.002	.0048	40	55
12	.002	.0050	40	55
13	.002	.0068	35	54
14	.002	.0065	37	54
15	.007	.0020	50	47

Table A4

Information Passband

Filter Channel	Bandwidth (-3DB) Hertz	Passband Milliseconds	Roll-off DB per Octave
1	16.0	31.3	13.0
2	13.5	37.0	17.5
3	18.5	27.0	14.5
4	16.0	31.3	17.5
5	15.0	33.3	15.0
6	16.0	31.3	19.0
7	16.5	30.3	29.0
8	16.0	31.3	14.5
9	18.0	27.8	14.0
10	17.5	28.6	15.0
11	17.0	29.4	14.5
12	18.0	27.8	15.5
13	16.0	31.3	17.0
14	19.0	26.3	14.5
15	15.5	32.3	14.5

Appendix B

Motorola MC 1495 Linear Four-Quadiant Multiplier - Derivation of Output Voltage Expression

The equivalent circuit used to derive the output voltage expression of the MC 1495 multiplier is shown in Figure B1. Conventional assumptions that components of similar construction within the monolithic chip are matched, and that transistor collector and emitter currents are equal are made in the analysis which follows.

From Figure B1, the following equations are obtained:

$$I_3 + I_y = I_6 + I_8 \qquad \text{(B1)}$$

$$I_4 - I_y = I_5 + I_7 \qquad \text{(B2)}$$

$$I_A = I_6 + I_7 \qquad \text{(B3)}$$

$$I_B = I_8 + I_5 \qquad \text{(B4)}$$

Utilizing the Ebers-Moll Transistor Model, namely that collector current is an exponential function in input voltage as shown in Chapter IV, page 36, the following relationships are derived from the above equations:

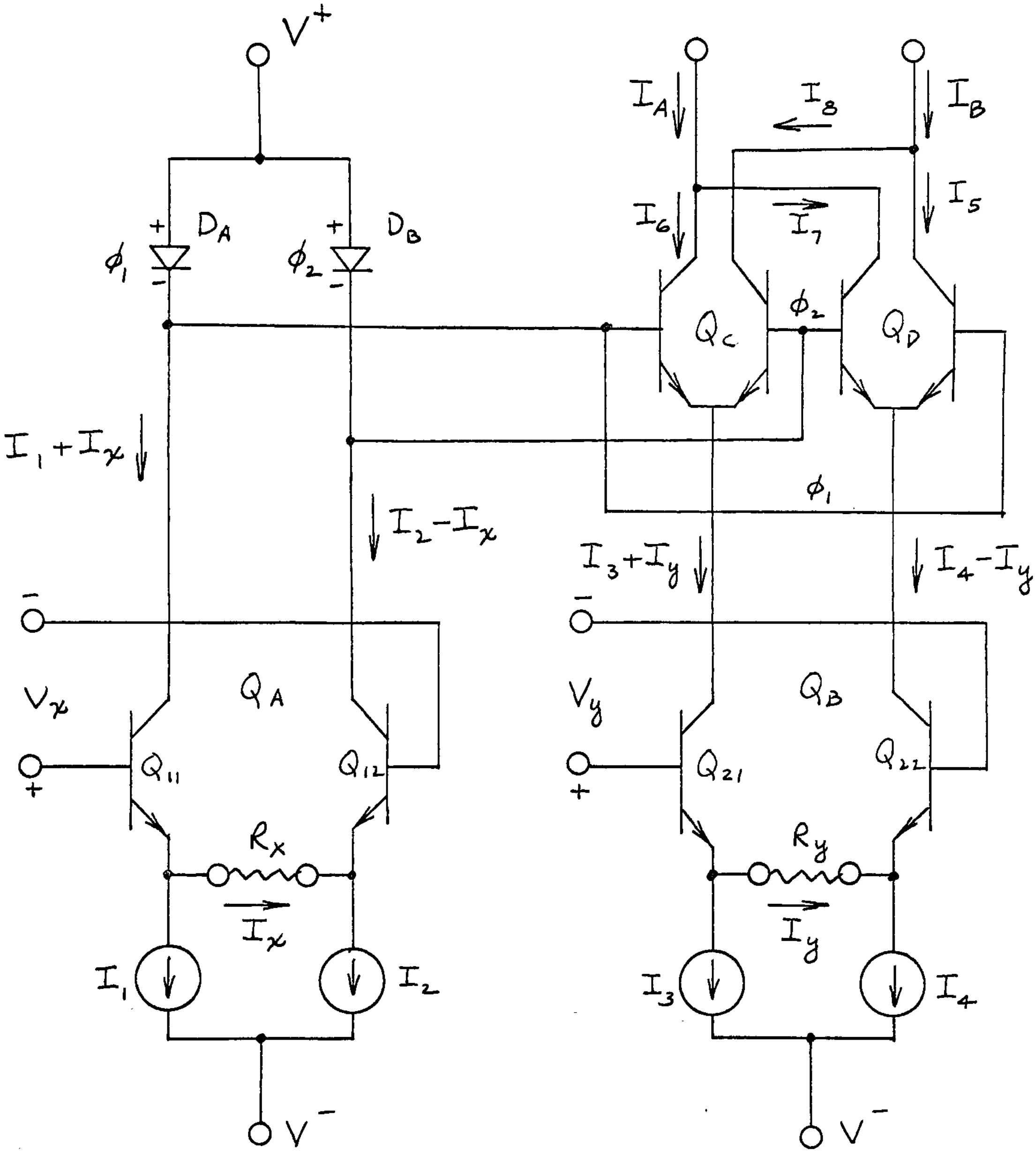

Figure B1

Equivalent Circuit for MC1495 Multiplier

$$I_8 = \frac{I_3 + I_y}{1 + e^{\frac{q(\phi_1 - \phi_2)}{kT}}} \quad \text{(B5)}$$

$$I_5 = \frac{I_4 - I_y}{1 + e^{\frac{q(\phi_2 - \phi_1)}{kT}}} \quad \text{(B6)}$$

$$I_6 = \frac{I_3 + I_y}{1 + e^{\frac{q(\phi_2 - \phi_1)}{kT}}} \quad \text{(B7)}$$

$$I_7 = \frac{I_4 - I_y}{1 + e^{\frac{q(\phi_1 - \phi_2)}{kT}}} \quad \text{(B8)}$$

Substituting (B5) and (B6) into (B4), and (B7) and (B8) into (B3), and using the following identity

$$\Delta I = I_A - I_B \quad \text{(B9)}$$

the differential output current ΔI is expressed as

$$\Delta I = \frac{\left(e^{\frac{q(\phi_1 - \phi_2)}{kT}} - e^{\frac{q(\phi_2 - \phi_1)}{kT}}\right)(I_3 - I_4 + 2I_y)}{\left(1 + e^{\frac{q(\phi_1 - \phi_2)}{kT}}\right)\left(1 + e^{\frac{q(\phi_2 - \phi_1)}{kT}}\right)} \tag{B10}$$

Referring to Figure B1, the following equations are obtained,

$$I_1 + I_x = a_{11}\left(e^{\frac{q\phi_1}{kT}} - 1\right) \approx a_{11} e^{\frac{q\phi_1}{kT}} \tag{B11}$$

$$I_2 - I_x = a_{11}\left(e^{\frac{q\phi_2}{kT}} - 1\right) \approx a_{11}\, e^{\frac{q\phi_2}{kT}} \tag{B12}$$

where the approximation is justified by assuming that the diodes are sufficiently forward biased.[28] Combining (B11) and (B12),

$$\frac{I_1 + I_x}{I_2 - I_x} = e^{\frac{q(\phi_1 - \phi_2)}{kT}} \tag{B13}$$

Substituting (B13) into (B10) and applying one of the initial assumptions that similar components are matched (resulting in $I_1 = I_2$ and $I_3 = I_4$),

$$\Delta I = \frac{2I_x I_y}{I_1} \tag{B14}$$

Since the assumption was made that base current can be neglected, the currents I_x and I_y are given by

$$I_x = \frac{V_x}{R_x + r_{e_{11}} + r_{e_{12}}} \tag{B15}$$

$$I_y = \frac{V_y}{R_y + r_{e_{21}} + r_{e_{22}}} \tag{B16}$$

where $r_{e_{mn}}$ are bulk emitter resistances of the model transistors Q_{mn}. Substituting (B15) and (B16) into (B14),

$$\Delta I = \frac{2V_x V_y}{I_1 (R_x + r_{e_{11}} + r_{e_{12}})(R_y + r_{e_{21}} + r_{e_{22}})} \tag{B17}$$

The bulk emitter resistance is given by[29]

$$r_e = \frac{kT}{qI_E} \qquad \text{(B18)}$$

The maximum values of the bulk emitter resistance can be limited by control of emitter current I_E. If emitter currents are never allowed to be less than one-third the value fixed in the current sources I_1 (= I_2) and I_3 (=I_4), the bulk emitter resistances are small enough (less than 1% of R_x and R_y) to ignored in (B17).[30] Then,

$$\Delta I \approx \frac{2V_xV_y}{I_1R_xR_y} \qquad \text{(B19)}$$

If the differential output current Δ I is dropped across a load resistor R_L, the differential output voltage would be

$$\Delta V_o = \Delta IR_L \qquad \text{(B20)}$$

$$\Delta V_o \approx \frac{2R_LV_xV_y}{I_1R_xR_y} = KV_xV_y \qquad \text{(B21)}$$

References

1. R. Aston and H. Reynolds, "A Subjective Evaluation of the Tactile Vocoder as an Aid to Oral Teaching of the Deaf", Unpublished progress report (December 1969).

2. American Annals of the Deaf, Vol. 13, No. 2 (March 1968).

3. J. M. Pickett, "Some Applications of Speech Analysis to Communication Aids for the Deaf", The Volta Review, Vol. 73, No. 3 (March 1971), pp 147-156, 185.

4. G. E. Peterson and H. L. Barney, "Control Methods Used in a Study of the Vowels", J. Acoustical Soc. of America, Vol. 24, No. 2 (March 1952), pp 175-184.

5. H. Fletcher, Speech and Hearing in Communication (New York: D. Van Nostrand Co., 1953), pp 62-67.

6. J. M. Heinz and K. N. Stevens, "On the Properties of Voiceless Fricative Consonants", J. Acoustical Soc. of America, Vol. 33, No. 5 (May 1961), pp 589-596.

7. J. C. Bliss, H. D. Crane, S. W. Link, and J. T. Townsend, "Tactile Perception of Sequentially Presented Spatial Patterns", Perception and Psychophysics, Vol. 1, No. 5 (May 1966), pp 125-130.

8. Peterson and Barney, op. cit., pp 175-184.

9. M. R. Schroeder, "Vocoders: Analysis and Synthesis of Speech", Proceedings of the IEEE, Vol. 54, No. 5 (May 1966), pp 720-734.

10. R. K. Potter, G. A. Kopp, and H. C. Green, Visible Speech, (New York: D. VanNostrand Co., 1947).

11. J. L. Kisner, "The Visual Vocoder: A Speech Teaching Aid for the Deaf", (Master of Science Degree Thesis, Ohio State University, 1970).

12. J. B. Wiesner and L. Levine, "Felix (Sensory Replacement)", Quarterly Progress Reports, Research Laboratory of Electronics, MIT, (Cambridge, Mass., January, 1949 to April 1951).

13. D. Johnson and D. Frisina, "A Nonverbal Hearing Test for Children with Deafness", (Research Project, U. S. Department of Health, Education, and Welfare, Office of Education, Division of Handicapped Children and Youth, Research Grant #OE 5-0962-4-11-3), p. 105.

14. R. H. Gault and G. W. Crane, "Tactile Patterns from Certain Vowel Qualities Instrumentally Communicated from a Speaker to a Subject's Fingers", J. Gen Psychology, Vol. 1, (1928), pp 353-359.

15. V. O. Knudsen, "Hearing with the Sense of Touch", J. Gen Psychology, Vol. 1, (1928), pp 320-352.

16. R. T. Verrillo, "Investigation of Some Parameters of the Cutaneous Threshold for Vibration", J. Acoustical Soc. of America, Vol. 33, No. 11 (November 1962), pp 1768-1773.

17. R. W. Guelke and R. M. J. Huyssen, "Development of Apparatus for the Analysis of Sound by the Sense of Touch", J. Acoustical Soc. of America, Vol. 31, No. 6 (June 1959), pp 799-809.

18. J. M. Pickett and B. H. Pickett, "Communication of Speech Sounds by a Tactile Vocoder", J. Speech and Hearing Research, Vol. 6, (1963), pp 207-222.

19. R. Aston, "An Investigation of Pattern Communality in the Instrumentation of Tactile Displays of Vowel Spectra", (Ph. D. Dissertation, Ohio State University, 1969).

20. R. H. Nichols, Jr., "Technical Notes and Research Briefs", J. Acoustical Soc. of America, Vol. 46, No. 6 (December 1969), pp 1409-1410.

21. M. R. Schroeder, op. cit., pp 720-734.

22. H. Dudley, "Remaking Speech", J. Acoustical Soc. of America, Vol. 11, No. 2 (October 1939), pp 169-177.

23. R. K. Potter, G. A. Kopp, and H. C. Green, op. cit. pp 54-55.

24. H. K. Dunn, "Methods of Measuring Vowel Formant Bandwidths", J. Acoustical Soc. of America, Vol. 33, No. 12 (December 1961) p. 1737.

25. R. Aston, "An Investigation of Pattern Communality in the Instrumentation of Tactile Displays of Vowel Spectra", (Ph. D. Dissertation, Ohio State University, 1969).

26. R. Aston, op. cit., pp 44-53.

27. R. Aston, op. cit., p 103.

28. L. B. Valdes, The Physical Theory of Transistors, (New York, McGraw-Hill Book Company, 1961), p 4.

29. L. B. Valdes, op. cit., p. 315.

30. E. Renschler, "Analysis and Basic Operation of the MC1595" (Application Note AN-489 Motorola Seniconductor Products, Inc., 1970).