A TRANSMITTER FOR EXPERIMENTATION WITH MODULATED PULSE COMMUNICATION

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WITH MODULATED PULSE COMMUNICATION

By

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PREFACE

The advent of World War II brought about technological advances comparable to no other era. Among these advances, the development of radar and associated pulse techniques is paramount.

The migration to higher frequencies, with a consequent increase in bandwidth, made the development of pulse communication systems practical. Several systems were developed during the war and intensive commercial research and development is now under way.

However, the presently developed systems are designed for use at 1000 mcs. or higher, utilizing a system of narrow beam relay stations.

This study was begun with the idea of investigating the possibilities of modulated pulse communication at lower frequencies with transmission over existing coaxial cable systems.

With this thought in mind, the writer and Mr. C. W. Merle began a period of investigation into previous work in the field in February, 1949.

Mr. Merle left Stillwater in June, 1949, but considerable progress had been achieved on the transmitter at this time. Mr. Thomas King then joined the writer in continued development of the transmitter.

A three channel demodulator is currently under development to complete the system.

The writer wishes to acknowledge the guidance and assistance given him by those with whom he was associated while this project was underway. He thanks his wife, Katherine, for her faith and encouragement and her work on the early drafts of this thesis. He also wishes to express his gratitude to Professor A. L. Betts and Professor Harold Fristoe, both of whom have given freely of their time and able assistance throughout the progress of this work.

John A. B. Bower

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PART 1 - FAMILIARIZATION

The ever increasing congestion on the present day amplitude modulated broadcast band and existing wire facilities, together with the possibilities for technical improvements at higher frequencies, has been the principal motive in directing attention to methods of utilizing these higher frequencies to supplement communication systems now in existence. The rapid growth of frequency modulation is an indication of the advance in this direction. A continued advance in means and methods of communication is a necessity for continued world progress.

The customary method of transmitting intelligence by electrical means involves the conversion of sound pressure waves into electrical impulses. These impulses have individual identifying characteristics consisting of amplitude, frequency, or phase, in accordance with the individual sound waves. Ordinary methods of transmission utilize principles of continuous power flow typical of the individual sounds involved in the transmission process.

In recent years a new system of transmission has been proposed primarily for utilization at high frequencies. The scheme grew from a desire to take advantage of the wider bandwidths per channel available in the upper regions of the radio frequency spectrum. This system proposes that the transmission of intelligence on any particular channel be restricted to a pulse of electrical energy, which occupies but a fraction of the total time, say a microsecond, (10^{-6} second) and recurring at a suitable rate. Several methods of achieving this result have been proposed and are classified under the general heading of "Pulse Modulation."

An advantage of pulse modulation is that it is not necessary to transmit a converted sound wave in its entirety. It is sufficient to take successive samples of the wave in the channel at separate time intervals and to transmit the information gained by sampling as a series of pulses. If a wave represented by a function f(t) contains no frequencies higher than ω cycles per second, it is completely determined by giving ordinates at a series of points spaced $^{\omega}/2$ seconds apart.[1]

A mathematical proof of this fact, to prove that it is not only approximately, but exactly, true, is included in the cited reference. However, intuitive reasoning will indicate that if f(t) contains no frequencies higher than ω cycles per second, it cannot change to a new value in a time less than one-half cycle of the highest frequency.

In the geometrical representation of signals and messages, as used by Shannon, it is pointed out that the human ear is insensitive to a certain amount of phase distortion.[2] This fact, coupled with the reduction in frequency discrimination of the human ear as the frequency increases, reduces the number of necessary message dimensions. This reduction in necessary intelligence dimensions for adequate transmission is not general; in fact, it does not exist in television, but can be used to advantage in the consideration of voice transmission.

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[1] C. E. Shannon, "Communication in the Presence of Noise," Proceedings of the Institute of Radio Engineers, XXXVII (January, 1949), 10.

[2] Ibid., p. 13.

Early work in pulse modulation dates from about 1924, when a patent was assigned to one R. A. Heising. This system grew out of an attempt to increase the power efficiency of the transmission system. Recently, much attention has been given to the system as a method of multiplexing telephone channels and for multichannel microwave radio relay systems. A great advance to this method of transmission will result from the recently announced development of the electrostatically focussed radio beam tube.[3,4] In contrast to its predecessor, the magnetically focussing type, which is limited in rotational speed by losses in the magnetic structure, this tube is limited only by the capacity between tube elements. This tube provides an inertialess distributor of practically infinite speed, with definite applications in the field of time division multiplex. Tubes of this type have been developed with twelve grid leads and a single anode lead for multiplex input and a single grid and twelve plate leads for multiplex decoding. The tubes are no larger than an ordinary receiving tube. Notes in the references indicate that a thirty element tube is being developed at the National Union Radio Laboratories.

At this time there are five methods of pulse modulation under development. The different types are distinguished by the manner in which the modulation is made to vary a characteristic of the pulse. The modulating signal may be made to vary:

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[3] A. M. Skellet, "Electrostatically Focussed Radio Beam Tube," _Proceedings of the Institute of Radio Engineers_, XXXVI (November, 1948), 1354.

[4] D. D. Grieg, A. M. Levine, "Pulse Time Modulated Multiplex Radio Relay System -- Terminal Equipment," _Electrical Communication_, XXIII (June, 1946), 159.

1. The height of the pulse.
2. The duration of the pulse.
3. The repetition rate of the pulse.
4. The timing of the pulse with respect to a marker pulse.
5. A combination of (1) and (4) above.

Each type of pulse modulation listed above is classified by name and will be so referred to in this work as follows:

1. Pulse Amplitude Modulation (PAM).
2. Pulse Width Modulation (PWM).
3. Pulse Frequency Modulation (PFM).
4. Pulse Time Modulation (PTM or PPM).[5]
5. Pulse Code Modulation (PCM).[6]

In pulse amplitude modulation, the sampling pulses vary in amplitude to follow the amplitudes of the wave being sampled. This system is relatively efficient in bandwidth utilization and is receiving attention from the British.[7] If pulses which have sloping sides are used in this system, not only the height of the pulse but also the width will vary with the modulating signal. A steep pulse is therefore necessary. Of course, an infinitely steep (i.e., rectangular) pulse is also most advantageous for noise reduction. However, in this type of pulse modulation, the requirement for variations in pulse height, coupled with the random noise variations which in particular affect the leading edge and the top of the sampling pulse, caused signal-noise considerations which drew attention to other possible types of pulse modulation. The cross talk problem is modified in other types of

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[5] A. H. Reeves, French Patent 833,929, filed, 18 June, 1937 and U. S. Patent 2,266,401, filed 9 June, 1938.

[6] A. H. Reeves, French Patent 852,183, filed, 3 October, 1938 and U. S. Patent 2,272,070, filed 22 November, 1939.

[7] F. F. Roberts, J. C. Simmonds, "Multichannel Communication Systems," Wireless Engineer, XXII (November, 1945), 538.

pulse modulation by amplitude limiter circuits which would obviously have little application in pulse amplitude modulation.

One of the first methods to receive attention in the attempt to improve on pulse amplitude modulation was pulse width modulation. As the name implies, the pulse width is increased or decreased in accordance with the variations of the modulating signal. This system is more expensive in bandwidth requirement than pulse amplitude modulation. The addition to this system of a pulse of fixed amplitude causes a significant improvement in signal-noise ratio. However, the pertinent information to be transmitted may be accurately reproduced if only two dimensions, namely, the timing of the beginning and end of the individual pulses, are accurately known. The determination of these minimum requirements for adequate signal sampling was made by Shannon and others.[8] These discoveries made pulse width modulation expensive from the standpoint of power requirements and led to further investigations in pulse modulation.

Another method of pulse modulation was suggested in which the pulses would be of constant amplitude and duration, as well as time position, but would vary in carrier frequency. This system is known as pulse frequency modulation. The transmission faculties of this system became available through variation in the carrier frequency of each individual pulse which is made to change proportionally to the amplitude sample at the time. A signal-noise improvement is available in the utilization of this system due to the fixed dimensions of the pulse, but additional

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[8] Shannon, loc. cit.

bandwidth requirements are necessary. The utilization of the total bandwidth improves, however, because the number of channels is increased.[9] This is due to the fact that the additional band required for frequency modulation with a given signal-noise ratio improvement becomes a smaller fraction of the bandwidth required for the correct transmission of the pulse shape.

A further development in pulse modulation technique is known as Pulse Code Modulation. In this system the transmission of information is characterized by the presence or absence of a pulse. The absence of a pulse is transmitted as a zero; the presence of a pulse is transmitted as the figure one. A five unit binary code is most often used, giving 2^5 or 32 discrete levels or steps. For example:

Transmitted	Received as
00000	0
00001	1
00010	2
01001	9
11111	31

Systems have been devised with numerous unit codes varying from two to seven, giving four to one hundred twenty-eight discrete levels or steps. It is a characteristic of the system that the input wave is not sampled exactly in amplitude, but rather to within one-half step of its actual value at the instant the sampling is accomplished. Consequently, a quantization noise, which is a function of the number of steps used in the sampling process, is created. This quantization noise can be decreased by

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[9] E. M. Deloraine, "Pulse Modulation," Proceedings of the Institute of Radio Engineers, XXXVII (June, 1949), 702.

utilization of the proper number of sampling steps. It should be understood that an increase in the number of sampling levels as a deterrent to the creating of quantizing noise requires an increase in the number of pulses to be transmitted, and consequently increases the bandwidth required. However, a large signal-noise ratio is attainable and the signals may be compressed in transmission bandwidth to the extent of appreciable carry-over from one pulse to the next without affecting the transmission capabilities. In the case in which the communication link includes a number of relays, this type of modulation shows a striking advantage over other types when use is made of regenerative repeaters.[10]

Several novel circuits have been devised to improve the capabilities of the pulse code method. Of these, the introduction of the staircase transducer and the non-linear tapered quantizers are worthy of note. The tapered quantizers are utilized on weak signals much as a volume compressor-expander circuit.[11] Quantizers are placed on both sides of the transducer, one for compression of large signals and the other for expansion of weak signals by applying a larger number of steps to the weaker signals. The arrangement of the two non-linear quantizers provides a linear combination.

In a pulse time modulation system the channel pulses are of constant amplitude, width, and duration, varying only in time of

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[10] A. G. Clavier, P. F. Panter, W. Dite, "Signal-noise Ratio Improvement in a PCM System," Proceedings of the Institute of Radio Engineers, XXXVII (April, 1949), 355.

[11] W. R. Bennett, "Spectra of Quantized Signals," Bell System Technical Journal, XXVII (July, 1948), 446.

occurrence with respect to a common marker pulse. A marker pulse is transmitted once for each frame as illustrated in Figure 1.

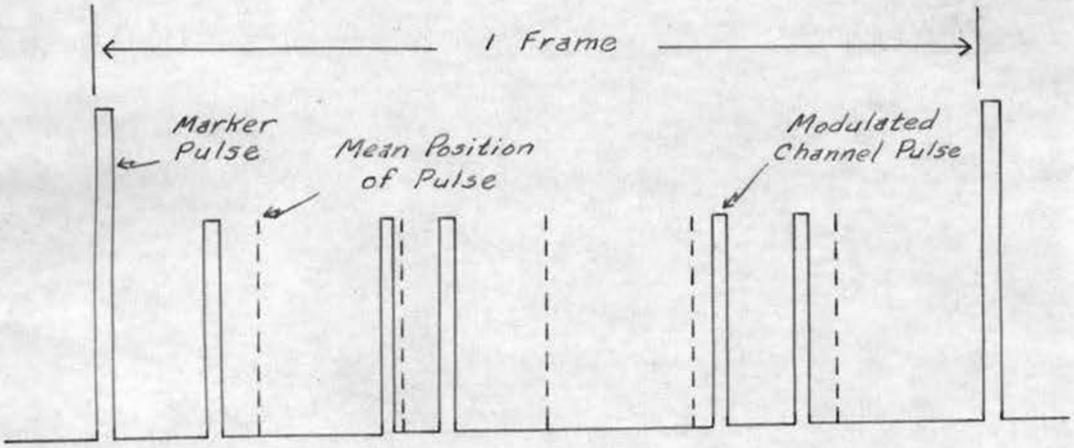

Figure 1. Pulse Time Modulation

A typical five channel system is illustrated above. Each frame contains one marker pulse which may be distinguished from the channel pulses by increased width or amplitude. The frame recurrence rate may vary; however, typical systems utilize frame recurrence rates in the vicinity of 10 KC. The modulation voltage of any one channel varies the timing of the corresponding pulse with respect to the marker. A positive modulating voltage produces an advance in pulse position with respect to the mean position of the pulse; a negative modulating voltage retards the pulse in time. The displacement of the pulse in time is proportional to the amplitude of the modulating voltage and the number of cycles of deviation per second is equal to the frequency of the modulating signal.[12] A typical system, cited from the reference, lists a marker pulse which is 4 μs. (microseconds) long, and channel pulses which are 1 μs. long. A 15 μs. space is reserved for the positive and negative variations of the pulse. This allows a variation of ± 6 μs., and a 2 μs. interval to avoid carry-over between adjacent channels. The frame recurrence rate is 8 KC., and the audible signal produced thereby is removed by filters. Therefore, in this system the modulating signal is sampled by pulses eight thousand times per second.

Another system is that utilized in the AN/TRC 6.[13] In this case, the multiplex unit generates a 4 μs. marker pulse at a recurrence rate of 8 KC., thus providing a 125 μs. frame. There are eight 1 μs. channel pulses evenly spaced in the frame with a positive modulating voltage producing a retardation of the pulse in time position and a negative modulating voltage producing an advance of the pulse from the mean position. Each channel has a 15 μs. space including 3 μs. channel separation. The duty cycle, defined as the ratio of the total time per frame to the length of time the transmitter is operating during that frame, is 125/12 or about ten. This equipment was used in the later stages of the war in the European Theater of Operations under combat conditions to provide eight channel voice communication of high quality. A particular installation operated over three hundred miles using

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[12] A. B. Bronwell, R. E. Beam, Theory and Application of Microwaves, pp. 245-246.

[13] R. E. Lacy, "Two Multichannel Microwave Relay Equipments for the United States Army Communication Network," Proceedings of the Institute of Radio Engineers, XXXV (January, 1947), 65.

two terminal and three relay stations.

A system of pulse time modulation of broadcast quality has been designed and tested by Federal Telecommunication Laboratories.[14] This unit was designed for eight channels. Twenty-four thousand pulses per second are used to sample each channel. This is approximately three times the highest audio frequency to be transmitted. The sampling pulses are one-half microsecond wide at an amplitude ten per cent above the base and have a .15 microsecond rise time. The marker pulse is composed of two adjacent channel pulses which are closer in time than any channel pulses under extreme modulation conditions and thereby identify each frame. This system, operating at 930 MCs., has proved satisfactory for AM and FM programs, teletype, facsimile, and photo transmission.

Several pulse modulation systems have been designed in foreign countries. Of those reported, the most noteworthy are the British pulse amplitude system and the French system of frequency division channel modulation with a frequency modulated carrier.[15,16] No reference was found on foreign systems utilizing pulse time modulation. However, the original experimental equipments making use of the time division theory were constructed in the Paris and London laboratories of the International Telephone

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[14] A. G. Kandaian, A. M. Levine, "Experimental Ultra-High-Frequency Multiplex Broadcasting System," Proceedings of the Institute of Radio Engineers, XXXVII (June, 1949), 694.

[15] F. F. Roberts, J. C. Simmonds, op. cit., XXII, 538.

[16] A. G. Clavier, G. Phelizon, "Paris-Montmorency 3000 Megacycle Frequency Modulation Radio Link," Electrical Communication, XXIV (June, 1947), 159.

and Telegraph Company.[17]

It has been stated that pulse modulation increases the efficiency of bandwidth utilization. In order to clarify statements and prevent ambiguity, a few definitions are presented. Effective bandwidth is defined as the total bandwidth times the fraction of time used. Obviously, with a continuous wave type of transmission the effective bandwidth is the total bandwidth. In an efficiently designed pulse time system, the fraction of time used would approach one as the efficiency of time utilization increased. Consider, for example, a series of ten conventional amplitude modulated broadcast transmitters. With an allowance of 20 KC. per transmitter, the bandwidth consumed is 200 KC. In the current amplitude modulated broadcast band this is approximately forty per cent of the lowest frequency available. With vestigial sideband transmission, the utilization of bandwidth is theoretically doubled. However, the necessary frequency space or bandwidth for present needs has not been acquired. Examine a pulse time system. Again ten channels will be used. 40,000 pulses per second will be transmitted, corresponding to an audio band of 16 KC. and a frame duration of 25 microseconds. This 25 microsecond frame is entirely sufficient, although not necessary, for the proper sampling of ten high fidelity channels, including guard time between channels. The Fourier analysis of the particular pulse shape obtained for the conditions indicated shows that the required bandwidth for the complex pulse multiplex series

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[17] E. M. Deloraine, E. Labin, "Pulse Time Modulation," Electrical Communication, XXII (March, 1944), 91.

would be approximately 2.5 megacycles.[18,19] This spectrum requirement arises from the high harmonic content of the pulses.

If this complex signal is used for conventional amplitude modulation of the carrier, a frequency spectrum of 5 megacycles width would be necessary. Vestigial sideband transmission could be used here with obvious advantages. Turning to the bandwidth comparison, it becomes evident that the 2.5 megacycle spectrum needed for pulse time modulation is 250 per cent of the lowest broadcast frequency. Re-examination of pulse time in the higher frequency region, say at 100 megacycles, where the ratio becomes 2.5 per cent, shows definite improvement. At 1000 megacycles, which is within the optimum spectrum for this system, the fraction becomes insignificant.

It is therefore obvious that pulse time modulation offers a remarkable improvement in bandwidth utilization, provided, that it is used in a region where its bandwidth requirement is relatively insignificant, compared to the bandwidth available. The fact that a specific number of channels was used in the foregoing bandwidth comparison might lead one to believe that the total bandwidth in this system is a function of the number of channels. This is not true. In a pulse modulation system, the total bandwidth is essentially independent of the number of channels.[20] The bandwidth is determined by the build-up time of the pulses,

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[18] D. D. Grieg, "Multiplex Broadcasting," Electrical Communication, XXIII (March, 1946), 19.

[19] J. C. Lozier, "Spectrum Analysis of Pulse Modulated Waves," Bell System Technical Journal, XXVI (April, 1947), 360.

[20] E. M. Deloraine, E. Labin, loc. cit.

and not by the number of channels used. Also worthy of note is the fact that pulse time modulation requires more bandwidth than does pulse amplitude modulation. The pulse time system has often been characterized as one which exchanged bandwidth for signal-noise ratio. This leads directly into another primary advantage of the system. A signal-noise improvement ratio of 20 db. over amplitude modulated transmission is easily achieved. Additional advantages of the pulse time system are size and simplicity of equipment, economy of power, high quality-low noise reception, and improved stability.

It is interesting to note that the principal efforts in utilization of this type of modulation have been directed toward the microwave relay field. The migration of the broadcast services to the higher frequency-shorter wave length portion of the Hertzian spectrum is anticipated by many engineers. In this field a complete new concept of broadcasting, utilizing pulse time modulation, is envisioned.[21] This technique of communication appears destined to take its place among the technical advances of this decade.

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[21] Grieg, loc. cit.

PART 2 - THE SYSTEM

The overwhelming advantages of this system, compared to other systems of transmission yet conceived, will force its adoption by many communication services. By this means the transmission would not be restricted to UHF point to point multiplex relay or multiplex broadcasting, but would include coaxial transmission of all types of intelligence. This concept of the possibilities of pulse modulation in general, and pulse time modulation in particular, led to the study and design of the system described here.

The system is intended to be one of many variables. This choice was dictated by a desire to allow study and testing of several forms of pulse modulation, as well as the effect of variations in each. The over-all study is to be carried out over a relatively long period. A period of research and study of the peculiarities of pulse modulation was undertaken by the writer and Mr. C. W. Merle early in February, 1949, and shortly thereafter, design and construction of the experimental system began. Early study indicated that the pulse time type of modulation was the more simple, yet most efficacious, device. Therefore, a pulse time system with numerous variables was decided upon.

A consideration of the necessary size and complexity of the equipment required for variation of basic parameters such as pulse duration, amplitude, and recurrence rate obviated the possibility of making them variable at the pulse source.[1] However,

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[1] W. R. Piggott, "Producing Rectangular R. F. Pulses of Known Amplitude," Wireless Engineer, XXII (March, 1945), 119.

the amplitude and duration (within narrow limits) could be changed by simple circuit variations in other stages of the equipment. The pulse recurrence rate was made constant. This choice was dictated by several considerations, but primarily because a stable pulse source was necessary. Several methods of producing the pulses were available. The following were considered:[2]

1. Multiplication of two recurrent square waves of slightly different time phase.
2. Limiting of a sinusoidal voltage wave of large amplitude.
3. Discharge of a capacitor through an inductance.
4. Differentiation of a square wave.
5. Blocking oscillator.
6. Non-linear inductance.

Simplicity and efficiency directed the choice of the limited sine wave oscillator. Several factors were involved in the determination of the oscillator frequency, since this frequency determines the pulse recurrence rate, which in turn affects the audio bandwidth which may be handled. Also, the pulse recurrence rate determines the length of the frame, and consequently, the number of possible channels without carry-over between pulses. Sound engineers have shown that a system capable of transmitting 2500 cycle audio band is necessary for eighty per cent speech intelligibility.[3] For adequate radio reception, a 5,000 cycle band is desirable, and improvement is noticeable up to the limits of audibility. This limit falls between 15,000 and 20,000 cycles

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[2] F. F. Roberts, J. C. Simmonds, loc. cit.

[3] H. Fletcher, Speed and Hearing, pp. 280-281.

per second, depending upon the individual. A high fidelity system was desired in this case.

Study of previous research in this field indicated that a very sharp pulse of radio frequency energy was necessary if a satisfactory signal-noise ratio improvement over existing systems was to be achieved. Also, since the system was to operate on a time base reckoned in microseconds and fractions thereof, the utilization of a common pulse signal source would simplify necessary circuitry. Therefore, a system using a common signal source with suitable variable delay networks to provide individual channel pulses separated in time was considered convenient. The combination of very sharp pulses and delay networks suggested the possible application of radar principles to the development of the system. This possibility was investigated and found satisfactory. Consequently, the system consists of a recombination of radar characteristics and principles into a pulse time system.

Since design of the pulse generator was begun with a desire for a high fidelity system and fidelity tests were to be carried out on the completed unit, the pulse generator was selected to give maximum quality, by providing an audio bandwidth of 15 kilocycles.

Numerous delay systems were available and since no difficulty with this part of the circuit was anticipated, consideration was directed to the delay circuit input. The pulse recurrence rate was fixed at a minimum of 30 KC by the requirement that it be at least twice the highest audio frequency to be transmitted. Pulse forming networks were selected to shape the limited sine wave oscillator output.

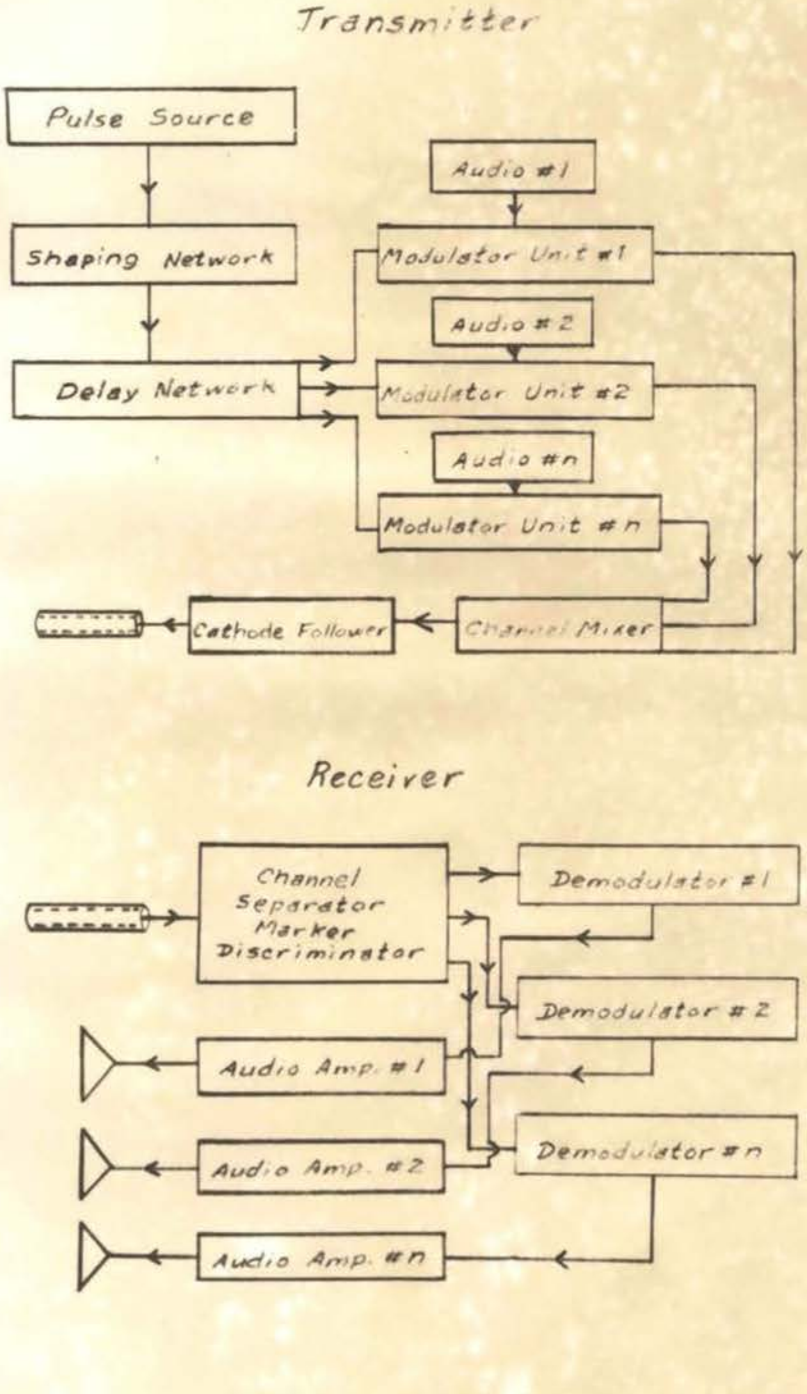

Figure 2. The System

The original system was intended to utilize a modified radar circuit for the pulse modulator. It was determined that pulse time modulation could be achieved by the insertion of a Miller effect reactance tube between grid and plate of a variable width multivibrator. The multivibrator pulse width would vary as the effective capacitance between grid and plate (the reactance tube) was changed. This change could be made to occur at an audio rate by the application of an audio signal to the grid of the reactance tube. The effective input capacitance of this type reactance tube would vary in accordance with the changes in amplitude of the incoming audio signal. This amplitude variation would be held below a specified limit by an appropriate amplitude limiter circuit in order to prevent excessive modulation deviation and consequent carry-over between pulses. The multivibrator variable-width square wave pulse output is in effect pulse width modulation. However, pulse time modulation can be achieved from this by simple differentiation of this multivibrator square wave pulse. The unmodulated portion of the differentiator output is removed by clipping. The modulated portion is retained and fed to a channel mixer. Here pulses from all channels are mixed and fed to a cathode follower in order to match the impedance of the transmission line.

The transmission line will consist of approximately 220 feet of RG8/U coaxial cable. This cable is made up of a seven strand copper conductor surrounded by a concentric woven copper sheath. The line is an outside diameter of .405 inches and a nominal impedance of 52 ohms. The dielectric is polyethylene. Although consideration is normally given to the attenuation characteristics of solid dielectric coax, such consideration is not warranted in this case, due to the low frequencies used. However, later investigations to be conducted on this system may well indicate that transmission losses will occur because of the bandwidth requirement of this system.[4,5]

The demodulation system is required to separate each individual channel, as well as to recover, the original modulating signal. The following demodulation systems are suggested. In a pulse time system, it is obviously necessary that the receiver be synchronized with the transmitter. This may be achieved with a multivibrator trigger circuit actuated once each frame by a marker pulse of increased amplitude. The receiver could start operation, therefore, only on the marker pulse, since that is the requisite of proper synchronization. As an alternative, it is possible to employ a negatively biassed triode and a positive marker pulse to operate as a synchronizer under the impulse of the increased amplitude marker pulse. However, the positive action of the one shot multivibrator circuit deserves consideration for this function.

After the marker pulse has served to synchronize the receiver, it may be removed by a marker discriminator. It is interesting to note that the marker pulse might also be modulated, say with frequency modulation, and thereby provide another channel.

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[4] F. A. Cowan, "Broad Band Carrier and Coaxial Cable Networks," Proceedings of National Electronics Conference, (1944), 159.

[5] J. R. Hamilton, "Systems for Wide Band Transmission Over Coaxial Lines," Bell System Technical Journal, (October, 1934).

With a pulse time system, it is possible to recover the modulating signal by means of low pass filters, providing a special separator pulse shape is employed. However, spurious frequencies will exist, to the detriment of this system, depending upon the relation between pulse repetition frequency and audio modulating frequency.[6] This phenomenon has been encountered in early tests on the equipment and is not continuous as might be expected, but rather, occurs in steps.

Another scheme is suggested which is reported as more satisfactory from the standpoint of signal-noise ratio.[7] The audio signal may be recovered by charging a capacitor which discharges through a resistor. By proper time constant adjustment the voltage across the resistor may be caused to follow the audio signal closely.

The method of separating a germane pulse chain at the receiver might be accomplished with a multivibrator for each channel.[8] The entire pulse sequence would be impressed at the circuit input terminals, but the unit would operate only on the selected pulse, once each frame, depending on the internal time constants. This system could be arranged to produce channel separation and amplitude translation as well. A low pass filter system would complete the demodulation process.

It would be possible to use a delay network for channel

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[6] F. F. Roberts, J. C. Simmonds, loc. cit.

[7] Ibid.

[8] D. D. Grieg, A. M. Levine, loc. cit.

demodulation, as was used in this unit, for producing separate channel pulses for the modulated pulse sequence. An alternative scheme would be to utilize a multivibrator to remove the marker pulse and produce a pedestal pulse delayed to the proper channel in the sequence. This pedestal pulse may serve to separate the appropriate channel pulse with the pedestal pulse slope utilized to translate the time modulated pulses into amplitude modulated pulses. Suitably timed pedestal pulses would be required for each channel in the sequence.[9]

Any commercial utilization of the pulse time system would of necessity achieve even greater than inherent simplicity and efficiency by the use of the newly developed special purpose multiplexing tubes previously mentioned. The necessity for demodulation schemes discussed here and the modulation devices discussed previously are either removed or greatly modified by the advent of these tubes.

In line with the foregoing discussion on demodulation, it should be pointed out that advantageous use can be made of limiter and differentiator circuits in the demodulator. An important measure of the protection against noise interference offered by time modulated pulses results from the high ratio of peak to average power used. In terms of the pulses, the improvement is proportional to the time modulation displacement and inversely proportional to the build-up or decay time, whichever is the smaller. The threshold of improvement is reached when the peak pulse amplitude is about twice the effective noise peaks. The

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[9] Ibid., p. 165.

greatest degree of noise suppression is obtained when successive stages of limiting and differentiation are incorporated in the receiver. Noise may enter a pulse system by any of the following:

1. Amplitude modulation of pulses.
2. Width modulation of pulses.
3. Noise between pulses.
4. Displacement in time of leading or trailing edge of pulses.

Noise arising from (1) and (3) above may be removed by proper limiting if input signal-noise is greater than 6 db. A differentiator may extract the proper pulse edge and remove noise from (2) above. This action may not be complete, due to the edge-slope variation and the process may be repeated. Noise from (4) above is of the same form as the modulating signal and although inherent in the system, it is fortunately slight. However, it may be reduced by decreasing the build-up or decay time, i.e., increasing the bandwidth. The limiter application also provides constancy of signal independent of fading and other transmission vagaries.

PART 3 - THE UNIT

The basic timing source is a 100 KC. quartz crystal controlled oscillator. The circuit with constants is illustrated in Figure 3. This circuit was removed from an A/APN-4 Loran Indicator. In its original application, this oscillator was made variable within narrow limits by means of a 5-50 $\mu\mu$f variable capacitor between grid and ground.[1] In this application of the circuit, the variable capacitor was replaced by a fixed mica capacitor of 37.5 $\mu\mu$f. This fixed capacitor provided the necessary frequency correction to 100 KC.

Since it is anticipated that additional channels will later be added to this unit, an oscillator with stable load characteristics is a necessity, because any reactance that the load couples into the circuit will affect the frequency. Also, any resistance reflected from the load into the oscillator circuit ordinarily will modify the generated frequency by affecting the phase relationship. This frequency sensitive load condition may be removed by using a buffer or isolating amplifier between the oscillator and the load. The buffer amplifier will provide a constant load on the oscillator circuit. This tube provides a slight amplification of the sine wave input, as well as isolating the oscillator. However, the primary purpose of this signal is to provide sharp, large amplitude trigger pulses to a one shot multivibrator. Wave shaping circuits are therefore necessary. The first of these is a limiter circuit to remove the positive and

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[1] Donald G. Fink, "Loran Receiver Indicator," Electronics, XVIII (December, 1945), 110.

negative sine wave peaks, and is the third function accomplished in this triode. The circuit, utilizing the second half of a 6SN7 is illustrated in Figure 3. The limiter is operated with zero fixed bias, and develops grid leak bias, due to the flow of grid current. The 330 micromicrofarad coupling capacitor is charged during the positive swing by the flow of current through the 33K resistor and through the internal resistance of the tube. During the negative swing, the accumulated charge on the coupling capacitor leaks off through the 33K resistor. The resistance of the discharge path of the coupling condenser is greater than the resistance of the charge path, with the result that a residual charge is built up on the coupling condenser. This residual charge acts as a negative bias between grid and cathode of the limiter. This results in a slight negative clamping or d.c. restoration effect. In other words, the effect of the input signal in driving the grid positive is reduced. The residual charge on the coupling capacitor provides a more negative average about which the input sinusoid wave varies. As the input wave swings negative, the plate current is reduced and ceases to flow when the combination of signal and bias reach the cutoff value.

When construction had proceeded to this point, a frequency check was made. A BC 221 secondary frequency standard was used in conjunction with a DuMont 208B oscilloscope. By means of Lissajous patterns, the frequency of the oscillator was found to remain within ± seven cycles of 100KC under various loads on the buffer amplifier limiter. This was satisfactory, and construction proceeded.

Only an approximate squaring of the wave is achieved in the limiter circuit. The sides of the wave are not vertical, as is desired for the production of sharp trigger pulses. Also, the short time constant coupling circuit charges and discharges very rapidly and the average bias produced is small. Therefore, the approximate square wave output of the limiter tube is applied to an overdriven amplifier, Figure 4, for the purpose of steepening the sides. The overdriven amplifier is a circuit wherein saturation limiting is employed in conjunction with cutoff limiting to produce a square wave.

In order to produce a sharp trigger pulse from the square wave output of the overdriven amplifier, the time constant of the coupling circuit to the next stage, a peaker and pulse amplifier, Figure 5, is made very short. In this case, the RC time constant is approximately one microsecond. The coupling capacitor charges and discharges very rapidly, producing negligible bias and the grid is therefore essentially at ground potential. The grid signal is a series of sharp positive and negative pulses from the differentiator. The tube is biased considerably beyond cutoff to remove the negative pulses as well as the broad lower portions of the positive pulses. The positive pulse peaks drive the grid very positive with respect to the cathode, causing a large plate current for the duration of the pulse. This large plate current produces a large, sharp drop in plate voltage so that the output is a high amplitude negative pulse of approximately one microsecond duration. These trigger pulses recur every ten microseconds or at a repetition frequency of 100 KC.

In this unit a common oscillator-limiter circuit provides the driving voltage for the pulse forming networks. From the oscillator-limiter to the output mixer, a duplicate circuit is required for each channel. It was decided that the assigned functions of the unit could be carried out with a three channel transmitter. Therefore, each circuit from the oscillator-limiter to the output mixer exclusive, when satisfactorily designed, was executed in triplicate. A separate pulse forming network, identical with that described except for addition of an amplitude controlling potentiometer, was used for the marker pulse.

This marker pulse is fed directly from the pulse forming network into the output mixer. The three channel pulses, identical in time and shape, are fed to a pulse delay network. Many delay systems have been devised, and the artificial transmission line, often called a "delay line", is probably the most common. This device utilizes inductances with capacitances in shunt and must be terminated in its characteristic impedance. The delay available from this device is equal to the square root of the product of L and C per section. Therefore, if sizable delay (above a few microseconds) is to be realized, many identical sections must be utilized. Failure to recognize this fact will result in excessive attenuation and pulse shape deterioration. The difficulty in obtaining precise values of inductance required use of another system in this unit.

Recourse was had to a system of delay, using vacuum tubes as delay elements. Since this is an experimental unit, this delay, as it determines the relative occurrences of the channel pulses, must be manually variable. It must also be continuous throughout its range and great enough to allow complete separation of channels plus guard time between channels under 100 per cent modulation. The circuit is illustrated in Figure 6.

The cathode of the triode delay tube is connected directly to ground, and the tube is therefore normally conducting. The high amplitude negative pulse from the peaker-amplifier circuit drives the delay tube into cutoff instantaneously, since there is no resistance in the charge path of the capacitor between grid and ground. The discharge time of the parallel RC network between grid and ground determines the amount of the delay by fixing the time the tube is held cut off. The output is a positive going square wave with variable trailing edge as determined by the setting of the potentiometer in the RC network.

In the original contemplation of the unit, this delayed pulse was to control directly the action time of the modulator fed one shot multivibrators. However, experimentation proved that this resulted in loading back from the multivibrator into the delay circuit and interaction between circuit time constants which seriously modified the delay output wave form. The delay tube output was therefore coupled out through a cathode follower, Figure 6, into the one shot multivibrators, Figure 7.

The first 6AC7(T_1) is normally conducting since its cathode is tied directly to ground. T_2 is normally below cutoff. The necessary bias for this condition is provided by the voltage divider made up of the 150 K and 12 K resistors. The grid of T_1, since it is connected to the plate of the reactance tube, tends to be positive. Grid current flow charges the effective capacitance presented by the reactance tube, holding the grid of T_1 at ground potential. A positive pulse is applied from the delay cathode follower through the coupling condenser to the grid of T_2. The multivibrator action causes T_2 to conduct and drives the grid of T_1 below cutoff. The charge accumulated in the reactance tube capacitance begins to leak off through the resistor R_1. Due to this leakage, the potential at the grid of T_1 approaches that at the plate of T_2 at an exponential rate determined by the discharge path time constant. This time constant is a complex parameter, variable with the reactance tube audio input and will therefore be discussed in conjunction with the reactance tube.

When the potential at the grid of T_1 raises this tube above cutoff, T_2 is cut off, the reactance tube effective capacitance is again charged by grid current flow and the action repeats. The positive pulse output, taken from the grid of T_1, is differentiated, the leading edge pulse is clipped, and the pulse from the trailing edge is fed to a mixer tube where the individual channel outputs are multiplexed.

The variable time output is achieved by the multivibrator. The multivibrator is an adaptation of a radar circuit for producing a movable range marker. In its original application, the delay was manually controlled by means of a variable 320 $\mu\mu$f capacitor in shunt with a 630 K fixed resistance which determined the time constant of the discharge path between the grid of T_1 and the plate of T_2. This time constant controls the width of the multivibrator output pulse by controlling the time required for the grid of T_1 to rise above cutoff. In the present application, this time constant is caused to vary electronically at an audio rate by means of a reactance tube. The circuit is illustrated in Figure 7 in conjunction with the variable width multivibrator. It may be classified as a Miller Effect reactance tube.[2,3]

In this application, the alternating plate voltage appears across both C_1 and R_1. The alternating grid voltage appears across R_1. Since the voltage across R_1 leads that across the series combination of C_1 and R_1 and the grid voltage has more effect upon the plate current than does the plate voltage, the plate current leads the plate voltage. The tube, therefore, acts as an impedance with capacitive reactance effect. Between the input terminals, cathode and plate, the circuit appears as a shunt combination of capacitive reactance and resistance. This circuit, or a variation thereof, may therefore be substituted in place of the manually controlled reactance in the original application of the circuit to produce the same result electronically.

Reich shows that the maximum effective capacitance is directly proportional to the transconductance and inversely proportional to twice the angular frequency.[4] This relationship brings several considerations to mind. Primarily, since the transconductance is dependent upon the grid bias, the effective capacitance, and hence the time constant of the discharge path between grid and plate of the multivibrator, can be varied by the grid bias. The grid bias is varied at an audio rate by the audio

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[2] H. J. Reich, Theory and Applications of Electron Tubes.

[3] F. L. Smith, The Radiotron Designer's Handbook.

[4] H. J. Reich, loc. cit.

input to the reactance tube. Also, the inverse dependency of the effective capacitance on the angular frequency will cause the time constant of the discharge path to vary with the frequency of the audio signal. Since both amplitude and frequency of the audio signal produce effective capacitance variations in the reactance tube and thereby vary the width of the multivibrator output pulse, this method may be used to produce modulation by an audio signal on a pulse of radio frequency energy.

Also, the relationship indicates that in order to provide a large effective capacitance, it is necessary to use a tube with high transconductance. However, the effective shunting resistance varies inversely with the transconductance. This causes an opposing effect in the time constant since an increase in transconductance increases the effective capacitance and decreases the shunt resistance. The net result is a smaller change in time constant than would otherwise be available. This may be construed as an advantage or a disadvantage, depending upon the sensitivity of the detection system.

Another consideration based on this relationship is the allowable audio frequency variation. It is, of course, necessary to provide an amplitude limiter between the audio source and the reactance tube to remove the peaks which would cause objectionable carry-over and possible cross talk between pulses.

However, the fidelity requirement must be compromised if true unit efficiency is to be achieved. Transmission of a 50 cycle audio signal will cause twice as much effective capacitance to be presented to the time constant circuit as a 100 cycle signal or four times as much as a 200 cycle signal. Obviously, a limit must be set on the low frequency reproduction if the best use is to be made of the available time space. This limit, of course, would be variable dependent on the type of intelligence to be transmitted. A 50 cycle tone is of no advantage in speech transmission, yet is highly desirable if music is to be reproduced.

The multivibrator pulse width, controlled by the electronically varied time constant, will change at an audio rate. At this point, pulse width modulation has been achieved. This pulse width modulated output may be converted to pulse time modulation by differentiation and clipping. Actually, the trailing edge of the multivibrator output carries the majority of the modulation, since the leading edge is constant in time. However, some modulation is apparent on the top of the output pulse. The width modulated output is differentiated and the pulse from the trailing edge, a negative pulse, is used as a time modulated pulse. A double-diode clipper circuit removes the positive pulse as well as the objectionable modulation on the top of the negative pulse. This system therefore provides a pulse variable directly in time in accordance with an audio modulating voltage applied to the reactance tube input terminals.

The time modulated pulses from each channel are multiplexed in a mixing stage and then fed to a cathode follower for proper matching to RG8/U coaxial transmission line. These circuits are illustrated in Figure 8.

PART 4 - UTILIZATION

The purpose of this investigation is to conduct a preliminary study of the advantages of pulse technique applied to wire communication. The immediate aim of the project, subsequent to necessary preliminary research, has been the construction of a working model. The working model is to consist of the transmitter, herein described, interconnecting coaxial cable, and a decoder or receiver for each channel. One of the basic requirements of the unit is that it lends itself readily to testing for fidelity, required bandwidth, cross talk, signal-noise ratio, and other pertinent transmission characteristics. Each of the characteristics is to be considered from the viewpoint of obtaining the maximum possible transfer of intelligence in a given frequency spectrum.

A unit designed for a comprehensive testing procedure must necessarily contain many variable parameters. This unit has been designed to provide a workable pulse time multiplex system wherein all practicable parameters are variable within limits. The delay, or guard time, between channels is independently variable. Both the amplitude and the shape of the modulated pulse are variable. The repetition rate of this pulse is also easily made variable. The unit will therefore readily lend itself to a comprehensive testing program to determine the optimum pulse shape, repetition rate, and number of channels for a specific transmission requirement utilizing the pulse time scheme. Also, if the output of the modulated multivibrator is not differentiated and clipped before mixing, a similar study might be conducted into the possibilities of pulse width multiplex, since the pulse is originally width modulated and then converted to a time modulated pulse. Other types of pulse multiplex may be tested with slight modification of the present unit.

The transmitter has been tested on one channel. 220 feet of RG8/U coaxial cable has been laid between test benches in rooms 406 and 401 of the Engineering Building. A field phone system was installed along with the coaxial cable to permit rapid communication during tests. This test was not comprehensive and was intended only to prove the workability of the system. Both audio generator input and one voice channel were impressed and a satisfactory reproduction was obtained. Effort has therefore been directed to the construction of a satisfactory three channel decoder.

As a result of information gained through the design of this unit, a more simple transmitter is considered practical. The present system operates with a required transmitter complement of eight tubes per channel including the marker generator. In the more recently conceived system, this requirement would be reduced to approximately three and one-half tubes per channel, including the marker generator. This figure compares favorably with information available on current models utilizing special purpose multiplexing tubes, developed for commercial exploitation.[1] The existing system has proved that it will lend itself to many and varied studies in the field of pulse communication.

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[1] D. D. Grieg, A. M. Levine, loc. cit.

BIBLIOGRAPHY

Bennett, W. R. "Spectra of Quantized Signals." *Bell System Technical Journal*, XXVII (July, 1948), 446.

Bronwell, A. B., Beam, R. E. *Theory and Application of Microwaves*. New York: McGraw-Hill Book Company, Inc., 1947.

Clavier, A. G., Panter, P. F., Dite, W. "Signal-Noise Ratio Improvement in a PCM System." *Proceedings of the Institute of Radio Engineers*, XXXVII (April, 1949), 355.

Clavier, A. G., Phelizon, G. "Paris-Montmorency 3,000 Megacycle Frequency Modulation Radio Link." *Electrical Communication*, XXIV (June, 1947), 159.

Cowan, F. A. "Broad Band Carrier and Coaxial Cable Networks." *Proceedings of National Electronics Conference*, (1944), 159.

Deloraine, E. M., Labin, E. "Pulse Time Modulation." *Electrical Communication*, XXII (March, 1944), 91.

Deloraine, E. M. "Pulse Modulation." *Proceedings of the Institute of Radio Engineers*, XXXVII (June, 1949), 702.

Earp, C. W. "Relationship Between Rate of Transmission of Information, Frequency Bandwidth, and Signal-to-Noise Ratio." *Electrical Communication*, XXV (June, 1948), 178.

Fink, Donald G. "Loran Receiver Indicator." *Electronics*, XVIII (December, 1945), 110.

Fletcher, H. *Speech and Hearing*. New York: D. Van Nostrand Company, Inc., 1929.

Goldberg, H., Bath, C. C. "Multiplex Employing Pulse-time and Pulsed-Frequency Modulation." *Proceedings of the Institute* of Radio Engineers, XXXVII (January, 1949), 22.

Grieg, D. D. "Multiplex Broadcasting." *Electrical Communication*, XXIII (March, 1946), 19.

Grieg, D. D., Gallay, H. "Pulse-Time-Modulated Multiplex Radio Relay System -- Radio-Frequency Equipment." *Electrical Communication*, XXIV (June, 1947), 141.

Grieg, D. D., Levine, A. M. "Pulse Time Modulated Multiplex Radio Relay System -- Terminal Equipment." *Electrical Communication*, XXIII (June, 1946), 159.

Hamilton, J. R. "Systems for Wide Band Transmission Over Coaxial Lines." *Bell System Technical Journal*, XIII (October, 1934).

Kandoian, A. G., Levine, A. M. "Experimental Ultra-High Frequency Multiplex Broadcasting System." *Proceedings of the Institute of Radio Engineers*, XXXVII (June, 1949), 694.

Labin, E. "Microwave Radio Relay Systems." *Electrical Communication*, XXIV (June, 1947), 131.

Lacy, R. E. "Two Multichannel Microwave Relay Equipments for the United States Army Communication Network." *Proceedings of the Institute of Radio Engineers*, XXXV (January, 1947), 65.

Levine, D. "Response of RC Circuits to Multiple Pulses." *Proceedings of the Institute of Radio Engineers*, XXXVII (October, 1949), 1207.

Lozier, J. C. "Spectrum Analysis of Pulse Modulated Waves." *Bell System Technical Journal*, XXVI (April, 1947), 360.

Macfarlane, G. G. "On the Energy-Spectrum of an Almost Periodic Succession of Pulses." *Proceedings of the Institute of Radio Engineers*, XXXVII (October, 1949), 1139.

Moskowitz, S., Grieg, D. D. "Noise-Suppression Characteristics of Pulse Time Modulation." *Electrical Communication*, XXVI (March, 1949), 46.

Piggott, W. R. "Producing Rectangular R. F. Pulses of Known Amplitude." *Wireless Engineer*, XXII (March, 1945), 119.

Reich, H. J. *Theory and Applications of Electron Tubes*. New York: McGraw-Hill Book Company, Inc., 1944.

Roberts, F. F., Simmonds, J. C. "Multichannel Communication Systems." *Wireless Engineer*, XXII (November, 1945), 538.

Shannon, C. E. "Communication in the Presence of Noise." *Proceedings of the Institute of Radio Engineers*, XXXVII (January, 1949), 10.

Skellett, A. M. "Electrostatically Focussed Radial Beam Tube." *Proceedings of the Institute of Radio Engineers*, XXXVI (November, 1948), 1354.

Smith, F. L. *The Radiotron Designer's Handbook*. Sydney, Australia: Radio Printing Press Pty. Ltd., 1945.

Tuller, W. G. "Theoretical Limitations on the Rate of Transmission of Information." *Proceedings of the Institute of Radio Engineers*, XXXVII (May, 1949), 468.

War Department Technical Manual. TM 11-467. "Radar System Fundamentals." (April, 1944).

APPENDIX

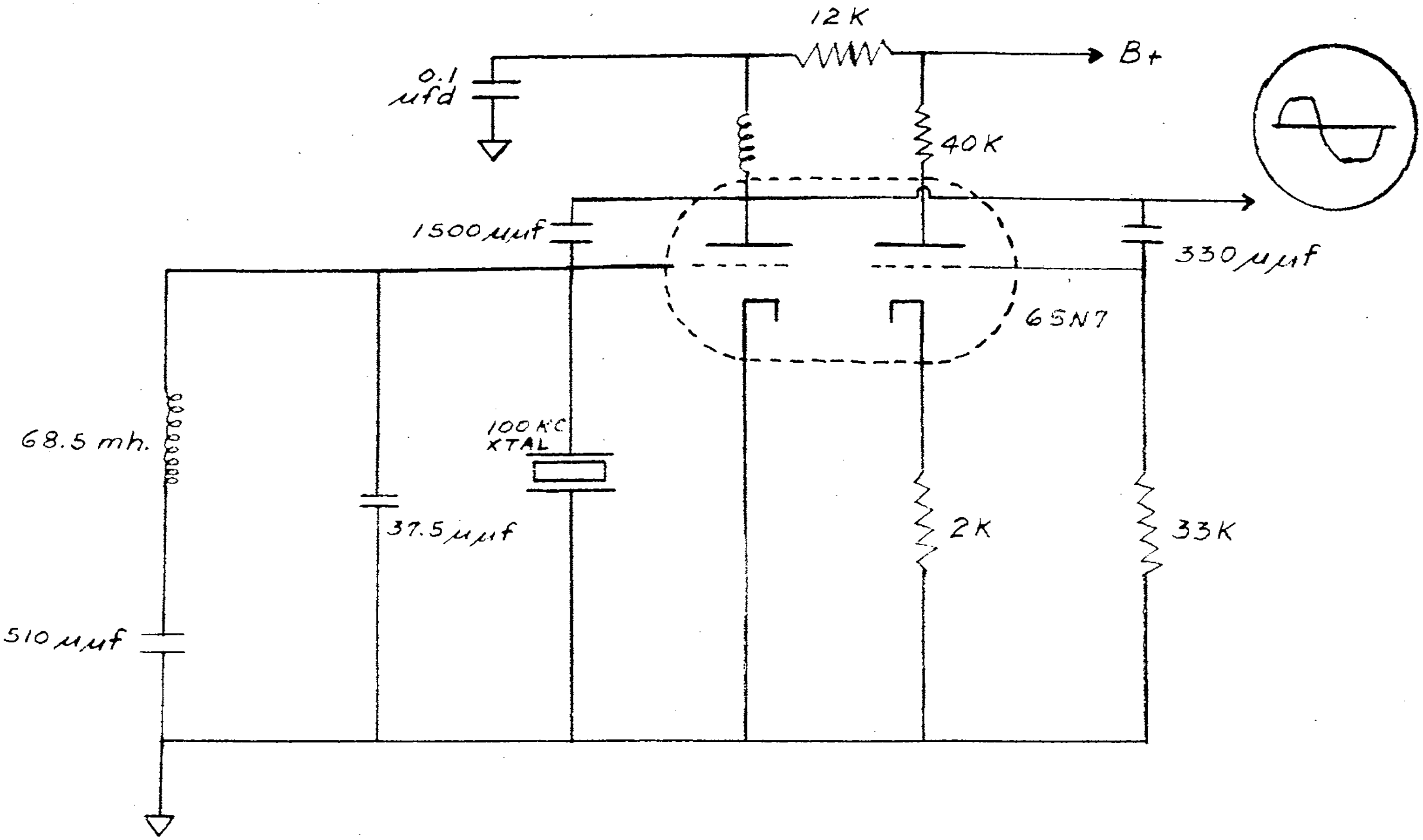

Figure 3. Oscillator - Buffer Amplifier

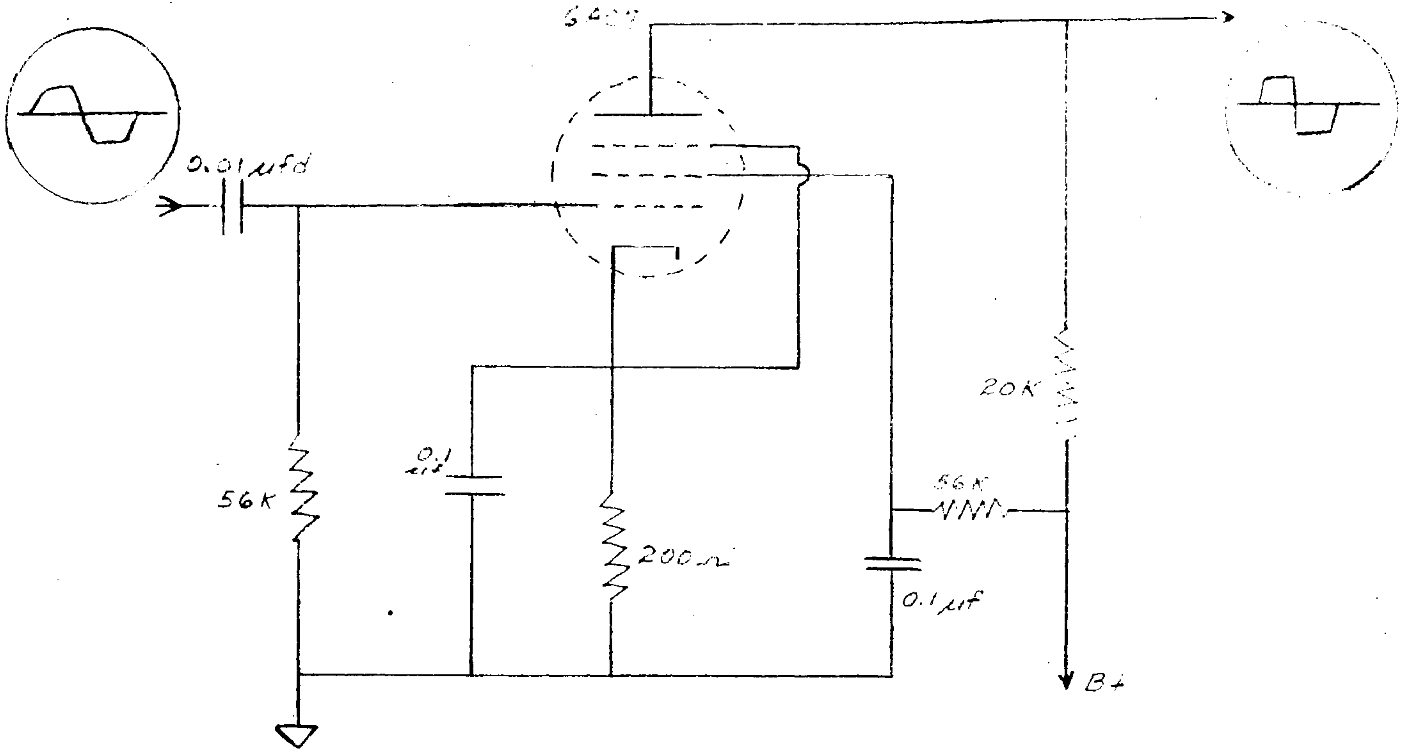

Figure 4. Overdriven Amplifier

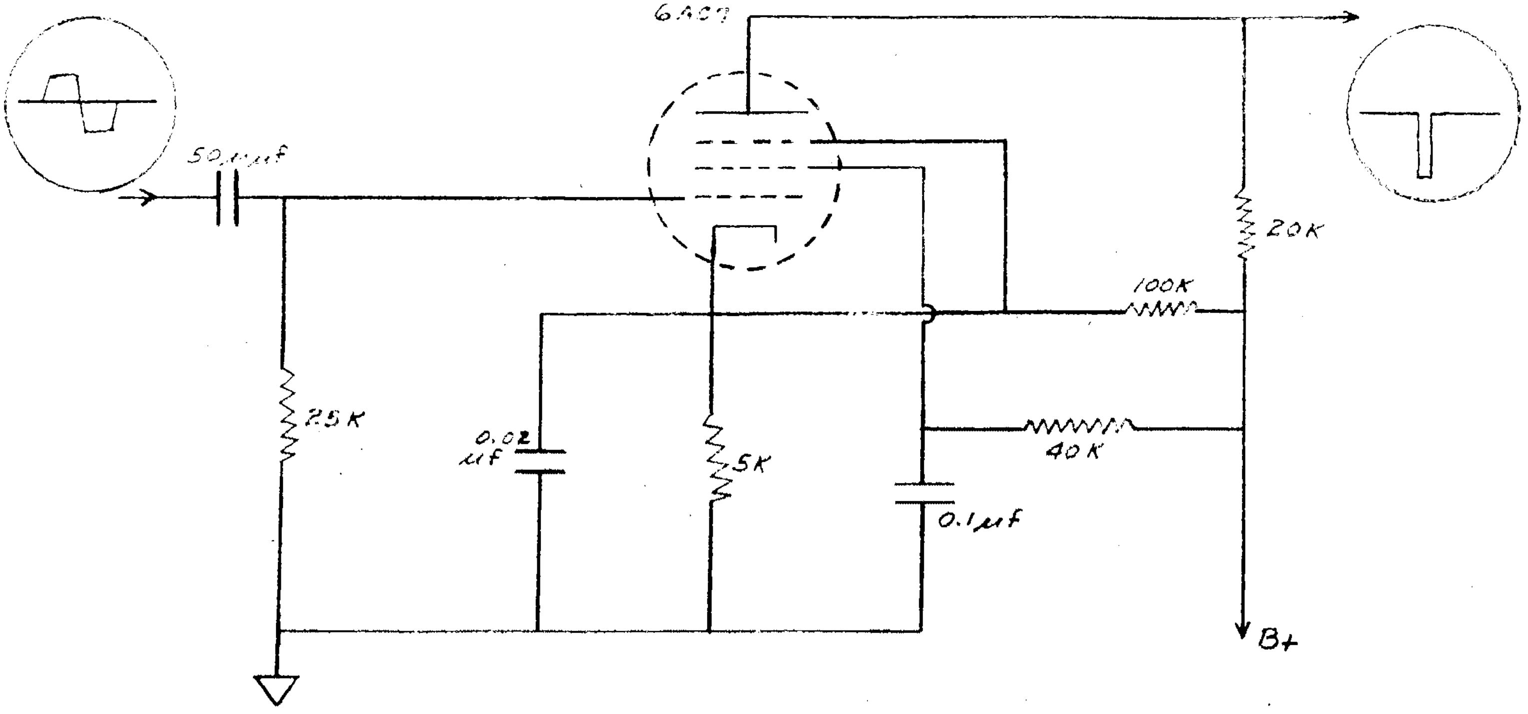

Figure 5. R-C Peaker-Pulse Amplifier

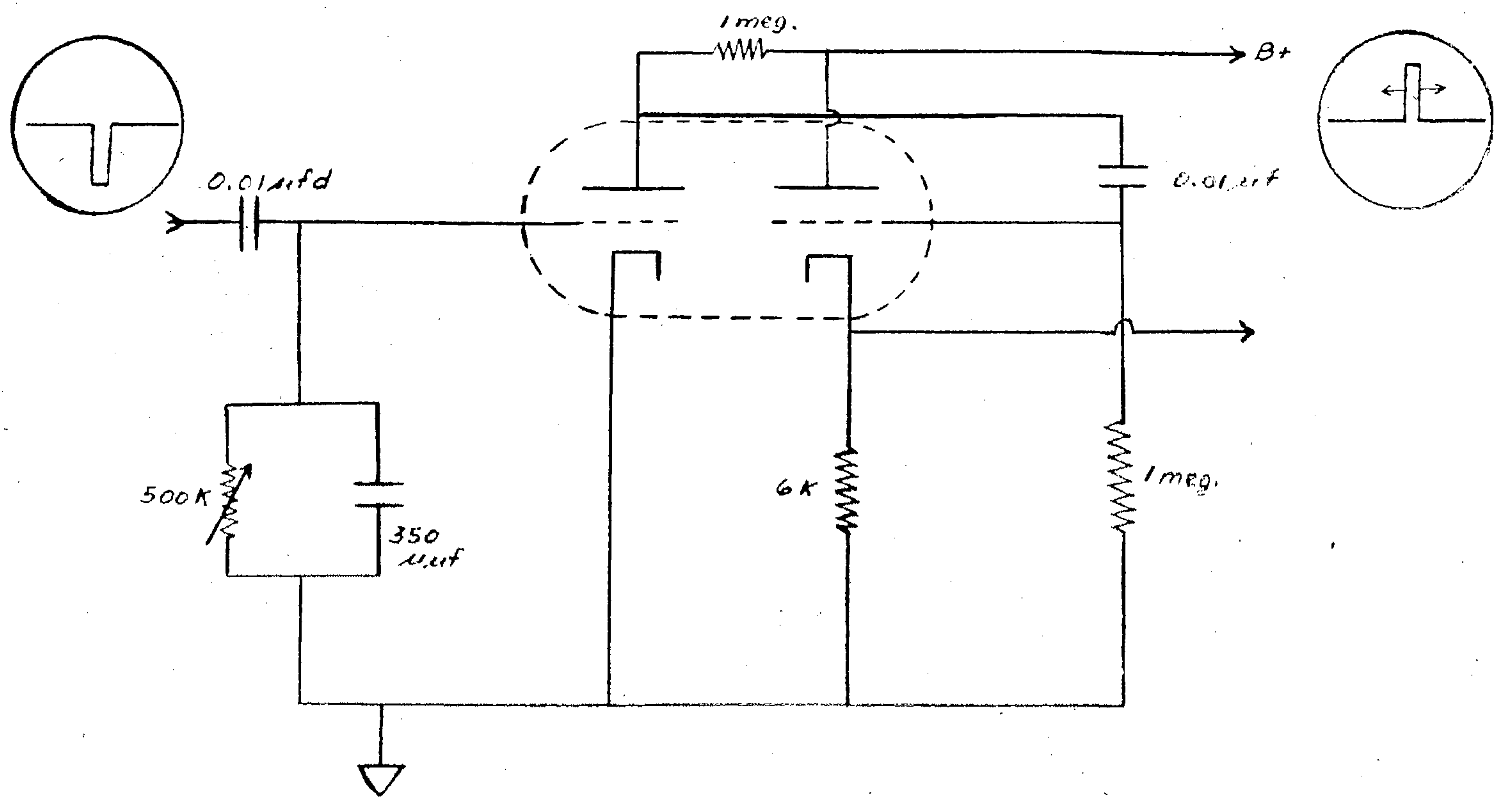

Figure 6. Delay-Cathode Follower

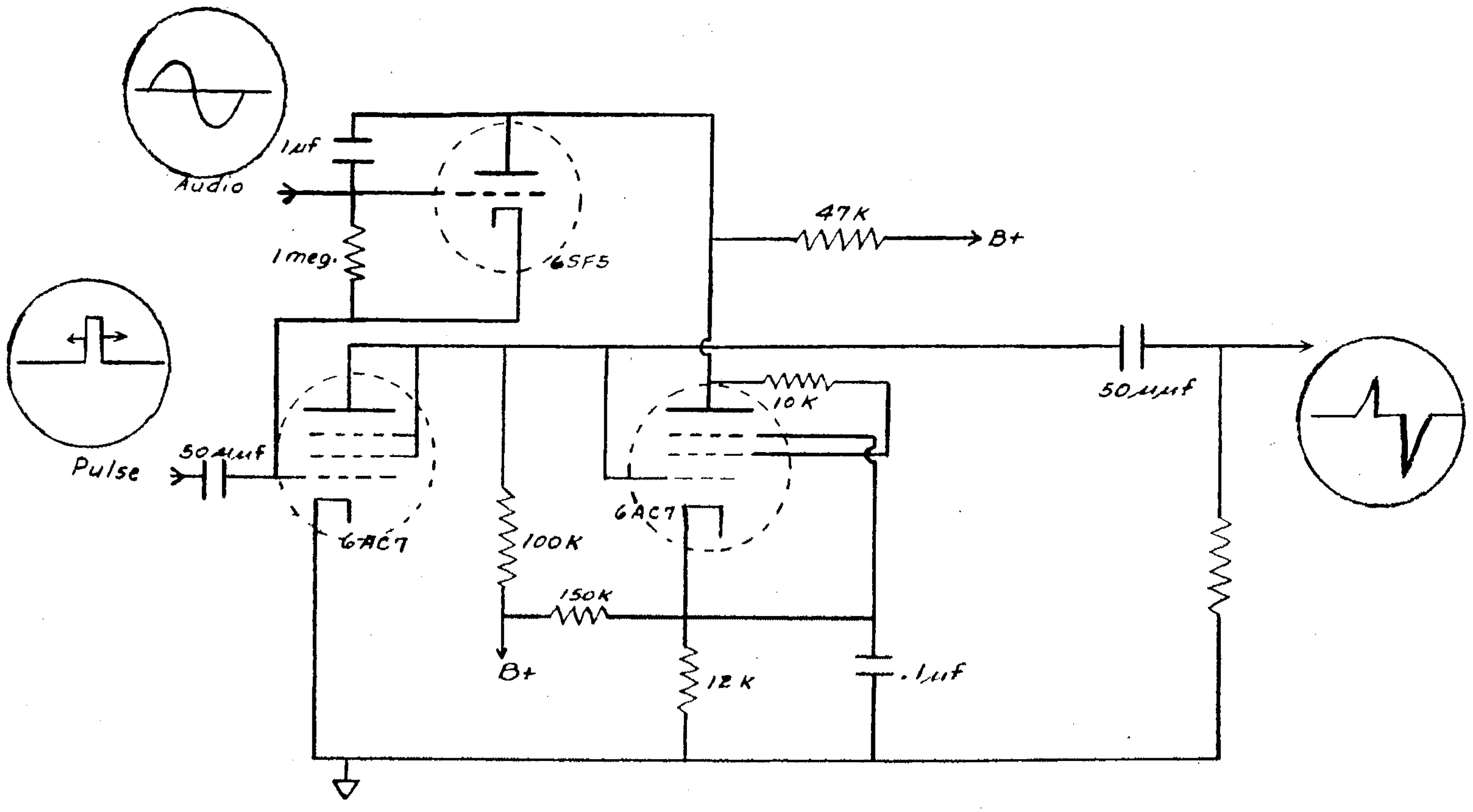

Figure 7. Modulated Multivibrator

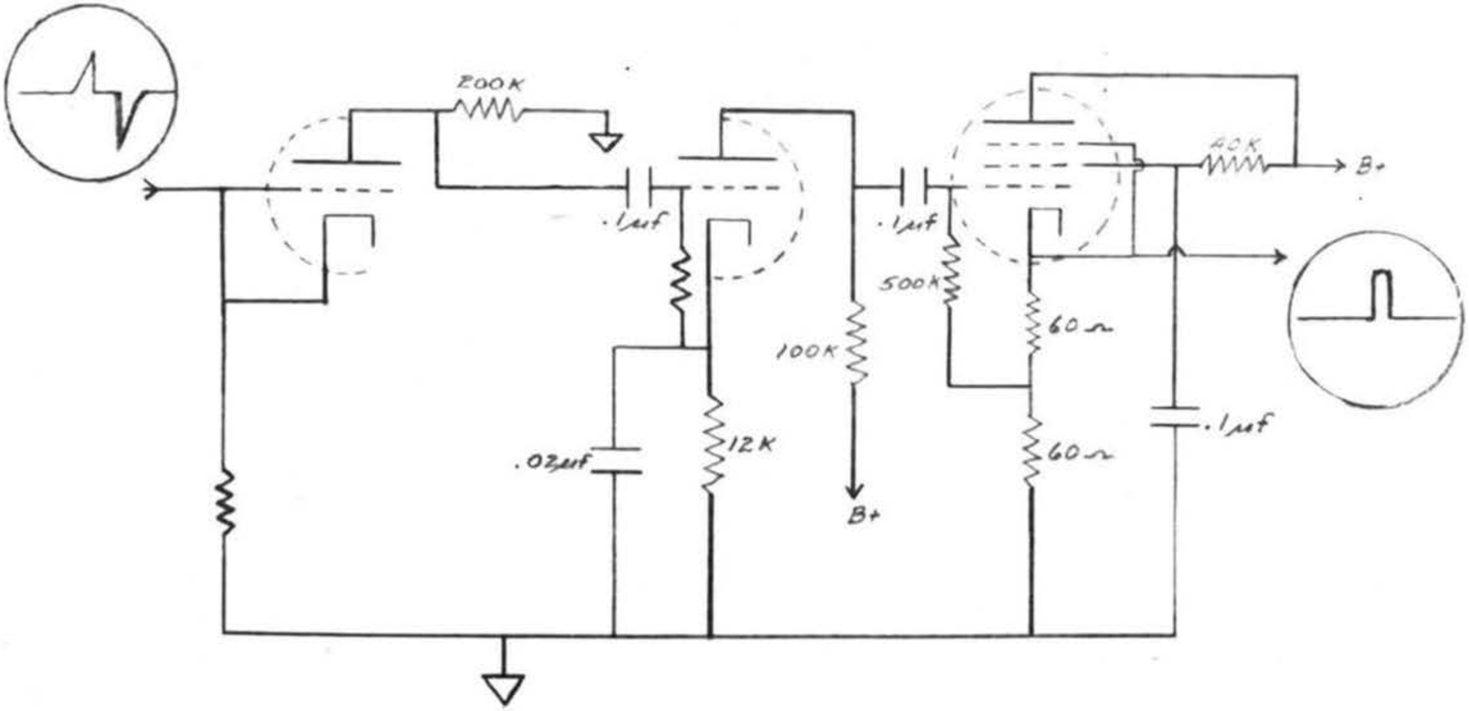

Figure 8. Clipper-Cathode Follower

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