A RECEIVING-TUBE HIGH VOLTAGE AMPLIFIER

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Master of Science in Electrical Engineering

By

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Grateful thanks are due Dr. B. J. Dasher for his suggestion of this problem, and for his guidance and help throughout its completion.

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ABSTRACT

In various types of research or for demonstrational purposes, a large oscilloscope is sometimes needed. Many models are available which use magnetic deflection, but in almost all of these the frequency response is below fifty kilocycles per second. When a greater frequency response is desired, an electrostatic-deflection oscilloscope is usually used. However, obtaining the necessary deflection voltages then becomes a problem. This can be solved by using two transmitting tubes in a push-pull circuit, but the direct-current power, space requirements, and cost become excessive.

The specific problem is to build an amplifier with an output of 1000 volts, peak-to-peak, with a frequency response of five cycles per second to one hundred kilocycles per second. The approach of this thesis is to solve the problem by using receiving tubes. Many of the circuits that were tried are discussed, with reasons for their failure or partial success given. Three are presented which would not work under any conditions, and two which might be suitable for certain circumstances.

The actual solution is accomplished by connecting two tubes in series, which now act similarly to a tube with twice the voltage rating of either tube, but still operate on a small current. By connecting two such tube circuits in a push-pull arrangement, the required output is obtained. The necessary frequency response is obtained by selecting the correct value of by-pass capacitance to use with the cathode bias in the final stage and the driver stages preceding it. Thus, as the frequency increases and the gain begins to fall off because of the inter-electrode and stray

capacitances, the inverse feedback caused by the bias resistors is decreased, thus tending to keep the output constant.

The results of the thesis show that the amplifier produced the necessary output voltage, with a bandwidth of four cycles per second to 165 kilocycles per second. The dc power requirements, space requirements and cost were all less than with many other systems which might be used as deflection amplifiers of similar electrical characteristics.

CHAPTER I

INTRODUCTION

Cathode-ray tube deflection systems.--Frequently, the need arises for a large cathode-ray oscilloscope. For ordinary design or maintenance of equipment, a five-inch instrument will usually suffice. However, for demonstration experiments or in some cases where a large amount of information must be displayed at once, a larger oscilloscope must be used.

Cathode-ray tubes may be generally grouped into two classes: those using electrostatic deflection and those using magnetic deflection. Each has its own advantages and disadvantages, and each has a wide field of application. The magnetic devices, for example, have the advantage of easy deflection even for the larger tubes up to thirty inches. This deflection is accomplished by passing currents of the right wave shape through the deflection coils on the neck of the tube. At low frequencies, these currents are relatively easy to produce since the deflection of the beam is a function only of the amplitude of the current through the deflection coils and not of voltage across the coils. By making the deflection coils of low-resistance wire, small amount of actual power are required, though the reactive power may be considerable because of the inductance of the coils.

This brings up one of the major disadvantages of the magnetic deflection system. In order to obtain large deflections, the inductance of the coils must be high, since the flux they produce is proportional to the inductance and the amount of deflection is proportional to the flux. As the inductance increases, it becomes increasingly hard to raise the frequency of effective operation.

On the other hand, electrostatic deflection is used in all cases where extreme frequency response is necessary. Good oscilloscopes today may have a response of 10 megacycles per second and even inexpensive models go as high as 5 mc. In the use of a five-inch tube, then, it is possible to have good frequency response and still obtain the needed voltage for deflection. The 5BP1, a cathode-ray tube frequently used in oscilloscopes, requires a maximum of 84 volts per inch for deflection. This means a total of 420 volts, which may be obtained with ordinary tubes.

However, in the case of larger tubes using electrostatic deflection, problems arise. The origin of this thesis occurred when it was desired to construct a ten-inch oscilloscope using a 10HP4, which is an electrostatic-deflection tube. Here the deflection factors vary from 80 to 130 volts per inch, depending on the accelerating potential and on whether the vertical or horizontal plates are being considered. At any rate, this represents a minimum of 800 volts or a possible maximum of 1300 volts which may be needed for full scale deflection. Obtaining voltages of this magnitude from receiving-type vacuum tubes indeed becomes a problem. It seems that all available tubes which have been developed for television fall about 20 per cent short of the necessary requirements for using two in push-pull. On the other hand, transmitting tubes, while having the necessary voltage requirements, demand too much current for normal operation. Some of them might operate on as little as 10 milliamperes, but this would introduce excessive distortion. An 807, for instance, requires at least 40 ma for good operation. If two are used in push-pull, then a power supply of at least 700 volts would be needed. This means that it must furnish 80 ma or 56 watts. This is considered to be too much power to use for only one stage of a deflection amplifier. Transmitting tubes are therefore ruled out.

Statement of the problem.--The problem, then, is to use ordinary receiving tubes to give the desired output of approximately 1000 volts, peak-to-peak, this being the voltage necessary for maximum horizontal deflection. The frequency response between the half-power points must be from 5 cps to 100 kc.

Using ordinary receiving tubes has several advantages. Perhaps the first is that they are cheaper, which, in the case of commercial manufacturing, means lower initial cost as well as cheaper replacement. Secondly, they operate at a much reduced current (as compared with 807's), and require a comparatively low voltage for efficient operation. Because of their lower operating current, the power supplies are correspondingly lighter and less expensive.

However, one question immediately arises, and that is how to obtain such a high output voltage from receiving tubes. The solution lies in the fact that, through proper circuitry, the outputs of several tubes may be connected in series. Obviously, it is imperative that each tube be fed the proper signal in the proper phase and amplitude. Herein lies the main obstacle. Attempts at the solution of this problem and the final results are discussed in later chapters.

CHAPTER II

PUSH-PULL AMPLIFIERS

Conventional push-pull amplifiers.--The problem at hand is two-fold. First, to find a way to connect the tubes in series so that their outputs add up to give the necessary results, and second, to inject the proper signal into each tube simultaneously. These problems were eventually solved and the final working model gave the necessary output with the desired frequency response. This model will be discussed at length later, but first some of the problems that arose and the circuits which failed completely or to some extent will be presented.

Refer to Figure 1. This is a conventional push-pull amplifier, with a center-tapped transformer used to obtain the necessary phase inversion in the input circuit. Note that, due to this phase shift, the grid of V_1 is driven in a positive direction while the grid of V_2 is driven in a negative direction. Because of the inherent 180° phase reversal in vacuum tubes, the outputs of V_1 and V_2 are exactly reversed; i.e., the plate of V_1 is driven negatively while the plate of V_2 is driven positively. Suppose, now, that the tubes used in the amplifier could be made to act as any resistance from an open circuit to a short circuit by proper grid voltage. This would mean that at the peak positive grid voltage, V_1 would be a short circuit and terminal a would be at zero volts potential (if we neglect the drop across the cathode resistor), the 300 volts of the power supply being dropped across R_1. At the same moment, V_2 has been driven into absolute cut-off, so that the voltage at terminal b is 300 volts. At the peak of the next half cycle, the voltage relations are exactly reversed. Whereas previously terminal b was 300 volts positive with respect to terminal a, it is now, in effect, 300 volts negative with respect to terminal a. This is a peak-to-peak swing of 600 volts, or double the voltage of the power supply. It can be seen that actually V_1 and V_2 are in series, and the outputs of the two add to give the total output.

In one experiment, it was found that, using a circuit exactly like that of Figure 1, the maximum output was 500 volts. This was with a power supply voltage of 350 volts, and an input frequency of 100 cps. The tubes used were $\frac{1}{2}$-6SN7's. The output was measured on an oscilloscope so that the amount of distortion could also be observed. The 500 volt output mentioned was with no visible distortion. The use of 6V6's as pentodes gave slightly better results, the output being about 525 volts.

Push-pull amplifiers in series.--It then becomes obvious that if two such push-pull amplifiers could be connected in series, they would give the final results needed. Most of the time spent on the thesis was used in trying to develop this idea. Figure 2 shows a circuit which works exceedingly well. The two input transformers were connected in series, though parallel operation would have worked as well. The outputs of these transformers were fed to the various grids, and sufficient signal applied so that the grids were driven from zero bias to very near cutoff. This made each amplifier produce its maximum output, and the total was slightly over 1000 volts, this appearing between terminals a and b. Here again, 6SN7's were used, with two 350 volt power supplies.

Although this method worked, it has one main drawback--that of the transformers. The particular ones used had a frequency response of

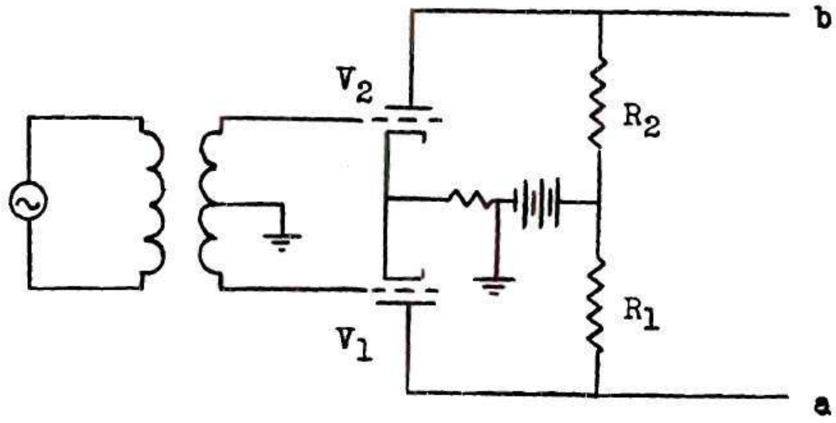

Figure 1. Conventional Push-Pull Amplifier Circuit

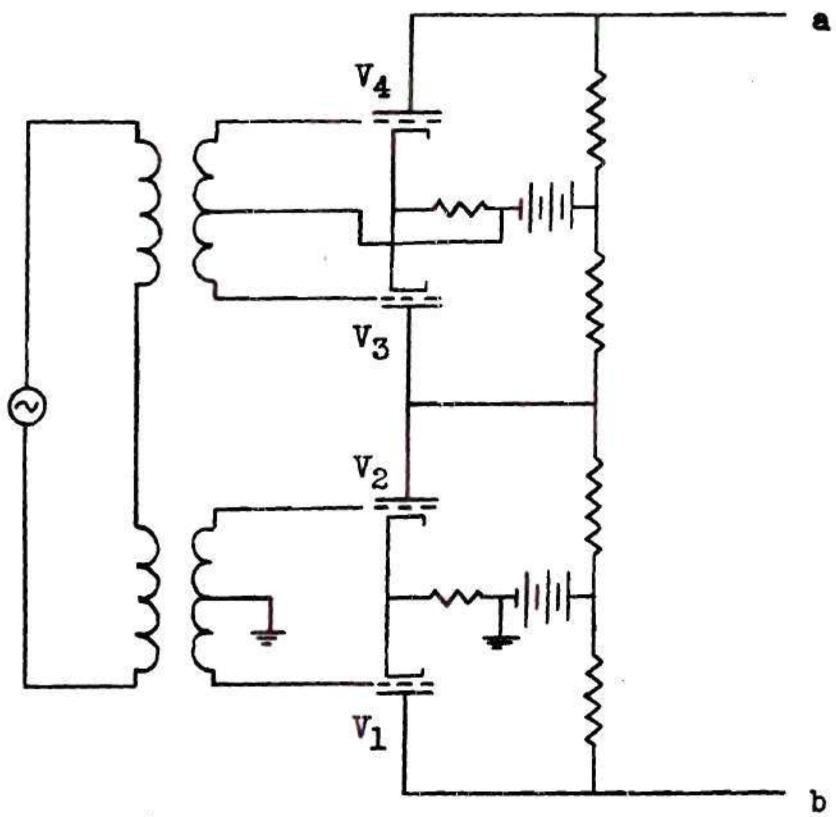

Figure 2. Push-Pull Amplifiers in Series

only about 50 kc. While transformers are available with a frequency response of well over 100 kc, they do not have the necessary low frequency response. So some other method of isolating the inputs had to be found. Another disadvantage of this system is that one of the two power supplies used was not grounded. However, this was a necessary evil of the circuit.

That isolation of the input signals is necessary can be seen by reference to Figure 3. Note that the output signal is developed across the four tubes in series, each tube contributing approximately one fourth of the signal. For an output of 1000 volts peak-to-peak, point a will at one instant be 500 volts positive with respect to point e, and at the next half cycle, will be 500 volts negative with respect to point e. Therefore the two points will never differ by more than 500 volts, although the polarity of this difference changes with each half cycle. Consider the case when point a is 500 volts positive. Thus point d is 125 volts positive, point c 250 volts positive, point b 375 volts positive and, of course point a 500 volts positive all with respect to point e. The important thing to note here is that points b and d differ by 250 volts. These same points are also the common points for their respective amplifiers. Thus, it is seen that the potential between these two points is constantly varying from 0 to 250 volts. This makes it impossible to connect the two together and then apply the signal simultaneously to the two grids of the phase inverters. It is apparent, then, that there is no way of supplying the signal to the two grids simultaneously from the same signal source, for this means connecting the grids together and the common points together, an impossible condition for proper operation.

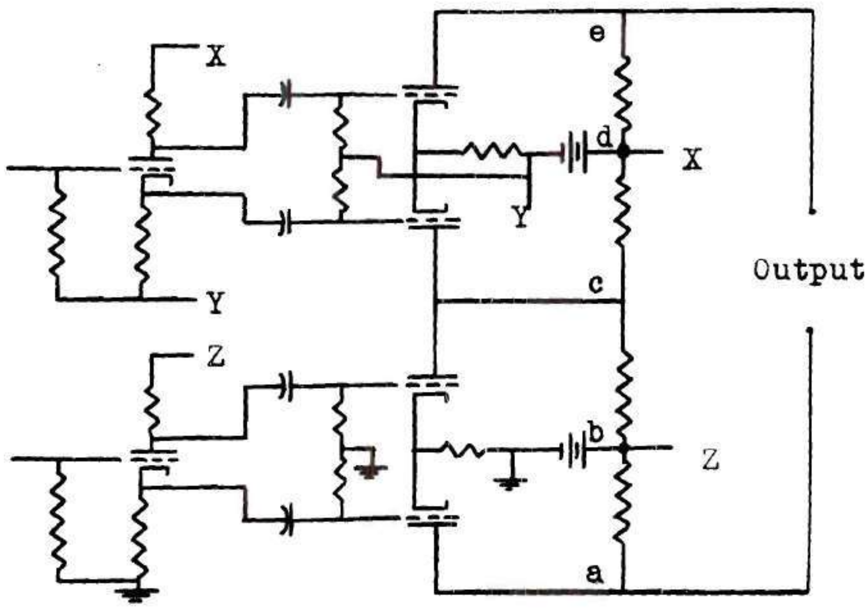

Figure 3. Circuit of Fig. 2 Without Transformers

CHAPTER III

EXPERIMENTAL CIRCUITS

<u>Unsatisfactory circuits</u>.--In order to make the two push-pull amplifiers in series work correctly, it was necessary to find some means of injecting the same signal into each amplifier simultaneously. In an attempt to do so, about 15 different circuits were tried. There is no need to give a name to each circuit, so they will be numbered consecutively. Each of them produced approximately the same results: Some small increase in amplitude over that of a single push-pull amplifier, but never double. An increase of about 10 per cent was common. Circuit No. 1, shown in Figure 4, simply has the grids connected together with no ground connection. The input signal was supplied by an audio generator. The phase inversion was accomplished by the circuit configuration. Analysis of this circuit shows reasons for its failure. The grids of V_1 and V_3 are connected together, hence they are at the same potential. The grid of V_1 is at some instantaneous potential with respect to its cathode, while the grid of V_3 is at that same potential with respect to its cathode. This means that cathodes of V_1 and V_3 should be at the same potential. However, it has been shown previously that the cathodes must not be at the same potential. Since the cathodes are at equal potentials the voltage-doubling action does not occur. Several other circuits, as mentioned, were tried, but they were simply variations of circuit No. 1. To analyze each in detail would require too much space, and add nothing to the discussion.

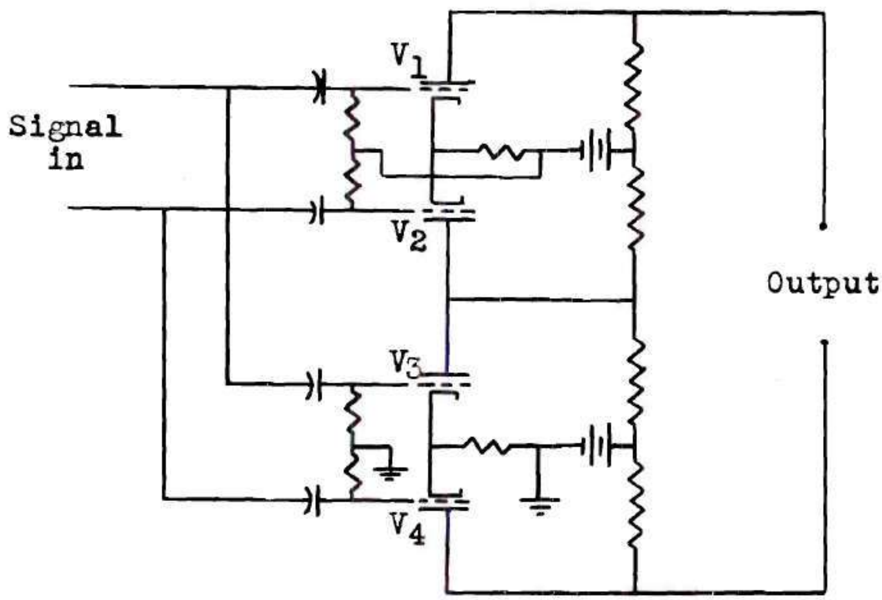

Figure 4. Circuit Number 1

It was now obvious that the two push-pull amplifiers would not work because of the lack of means to inject the same signal into both amplifiers. The next step was to inject the signal into only one, and then try to take part of the output from that amplifier as a signal for the second amplifier, and then connect the outputs in series for the required output voltage. This was tried, using circuit No. 2, shown in Figure 5. Obvious difficulties immediately occurred. The signal which is injected into the phase inverter of the upper push-pull circuit is that signal which appears between the grid of the phase inverter and point Y. This includes the entire output of one of the tubes in the upper amplifier in addition to that portion taken from the lower push-pull amplifier. Because of the phase relationships which exist between the input signal to the upper amplifier and the output signal of that amplifier, and because the output goes to make up a major part of the input, approximately 100 per cent feedback is present. This means the output of the upper amplifier is extremely low, and adds very little to the total output voltage of the entire circuit.

Partial solutions.--This experiment, and the idea of using part of the first amplifier's output as the input to the second amplifier, led to several circuits, one of which eventually met with success. The first attempt of this type which was the least bit successful is circuit No. 3, shown in Figure 6. This consists of a push-pull amplifier in series with a single-ended amplifier. This circuit was built and tested, and gave a maximum output of 750 volts. This was to be expected, since the three tubes are in series and each contributed 250 volts. The operation of this circuit may be analyzed in the following way: the phase inverter drives the grid of V_2 in a positive direction, and the grid of V_3 in a

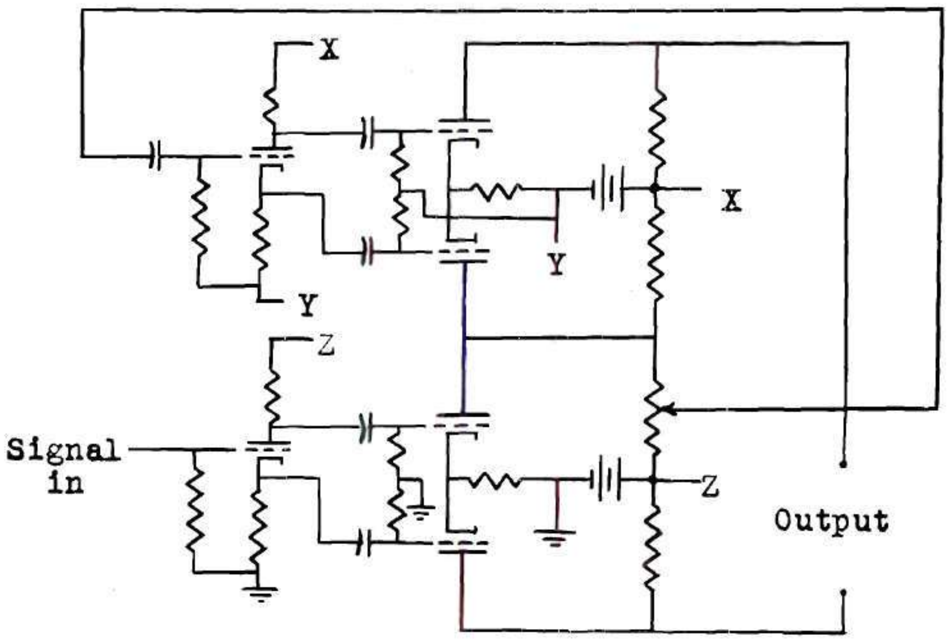

Figure 5. Circuit Number 2

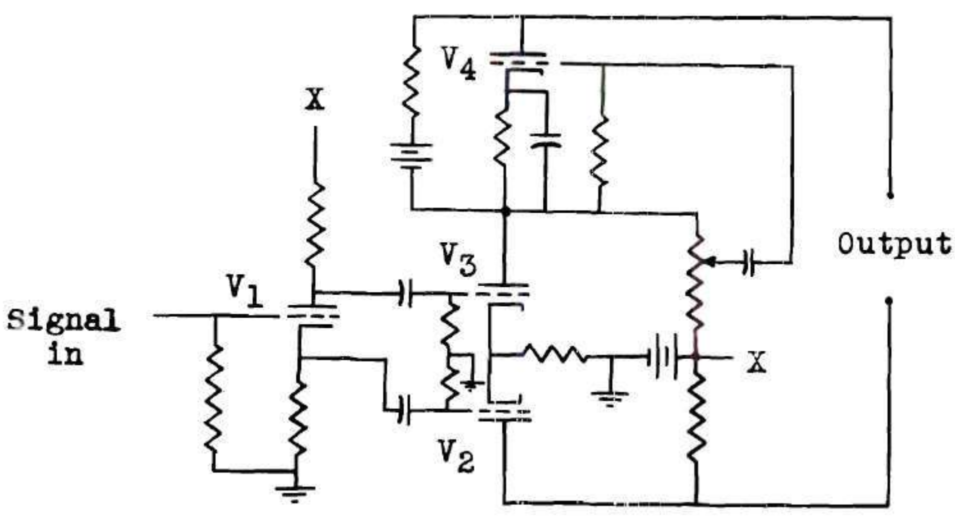

Figure 6. Circuit Number 3

negative direction. The outputs of these tubes are reversed in phase, of course, making the plate of V_3 positive, that of V_2 negative. The cathode of V_4 is connected directly to the plate of V_3, which now means all three tubes are in series. Part of the signal across R_4 is tapped to provide an input for V_4. This provides a signal which drives the grid of V_4 negative, so that the plate goes positive. Note that, starting with the plate of V_2 as a reference, there is a positive voltage from the plate to cathode of V_2, a positive voltage from the cathode to plate of V_3, and a positive voltage from the cathode to plate of V_4. In other words all of these outputs are additive, which was borne out by the experimental results.

The obvious step from there was to add another single-ended stage on the remaining side of the push-pull amplifier. The major disadvantage in this was that still another power supply would be required. Still, the possibilities of this circuit showed such promise that an attempt was made to use a common power supply for the two additional single-ended stages, while a second was used to supply the push-pull stages. Figure 7 shows the circuit used. The four tubes are connected in series so that their outputs add. Each single-ended stage gets its signal from the load resistors of the push-pull amplifier. The output of the entire amplifier appears between terminals a and b.

The dc path for V_4 is from the negative side of its power supply, through the diode V_5, through V_4, and return by way of diode V_7. The dc path for V_3 is from the negative side of the power supply, through diode V_6, through V_3, and return by way of diode V_8. V_3 and V_4 can easily draw whatever direct current is needed for operation, but the cathodes of these two tubes are isolated to ac because the diodes V_5 and V_6 are connected back-to-back, so that whenever one diode is in a conducting condition, the other is not. The same condition exists for the diodes V_7 and V_8. While this circuit showed considerable promise, it failed for the following reason: consider the condition when the plate of V_2 is driven maximum negative. At that time, the plate of V_4 is also maximum negative, and each will have an absolute voltage drop of about 50 volts. Under these conditions, V_1 and V_3 are both cut off. R_2 and R_4 have a voltage drop of 250 volts each while the drop across R_1 and R_3 is zero. With the ground as reference, 350 volts appears on the plate of V_1. There is an additional 350 volts across V_3, making a total of 700 volts on the plate of V_3. A total voltage of 200 volts appears on the plate of V_4, supposedly making a difference of potential between the two of 500 volts. However, adding the drop across R_4 to that on the plate of V_4 gives a voltage of 450 volts. This is the potential applied to the cathode of the diode V_7, and since it is positive, tends to prevent the conduction of the diode. However, applied to the plate of the diode is the 350 volts of the power supply plus the 350 volt signal on the plate of V_1 which makes a total of 700 volts positive on the plate with 450 volts positive on the cathode, or a net potential of 250 volts positive on the plate. The diode then conducts and the signal is shorted out. No arrangement of the diodes would allow the direct current to flow without short-circuiting the signal.

Of all the circuits mentioned so far, none worked satisfactorily. One which does work is circuit No. 5, shown in Figure 8. This circuit consists of a push-pull amplifier with two additional stages added. A small portion of the output of one side of the push-pull amplifier is

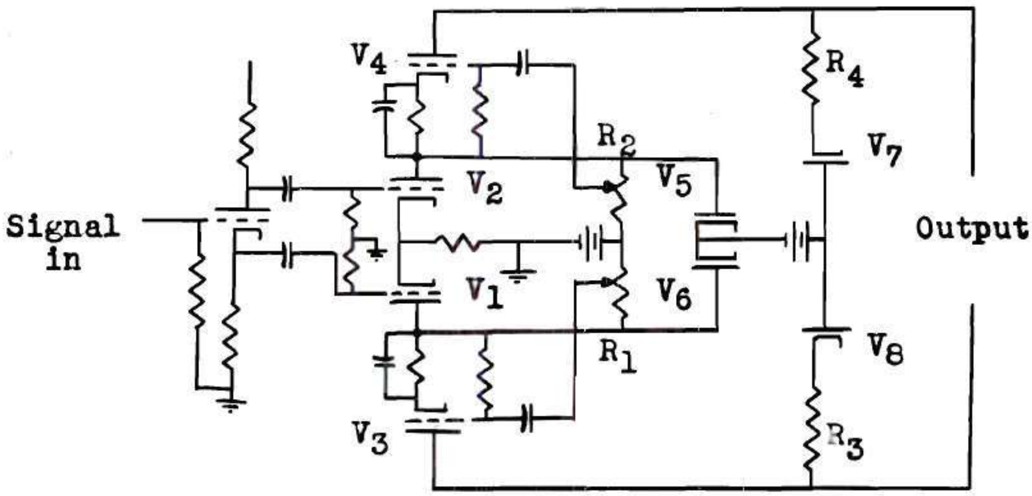

Figure 7. Circuit Number 4

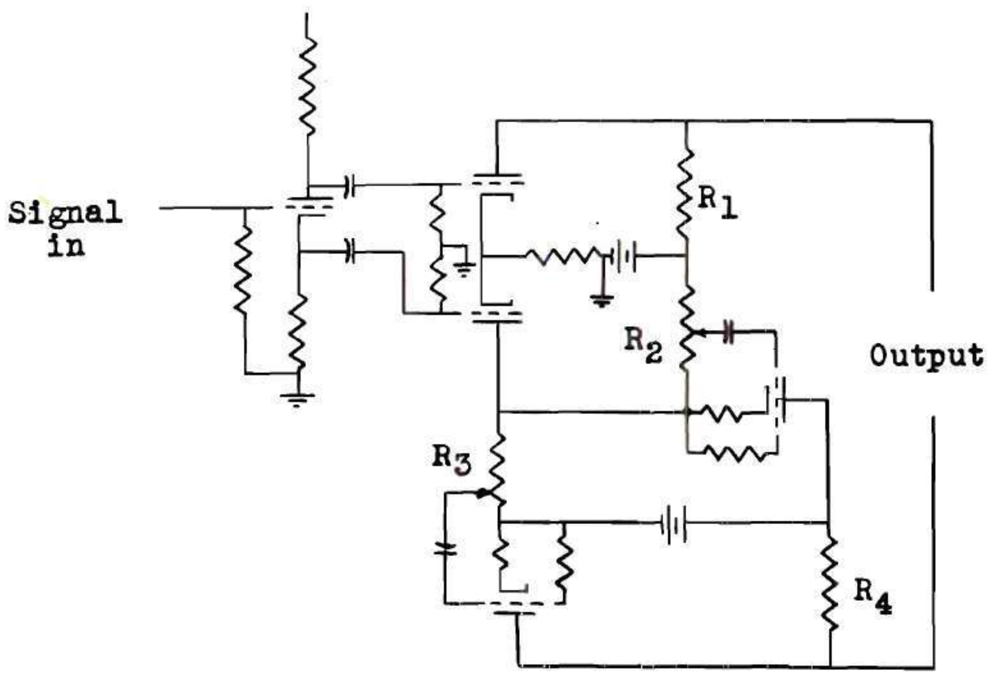

Figure 8. Circuit Number 5

fed to a cathode loaded amplifier. It should be noted here that it makes no difference how a tube, power supply, and load resistor are placed in a series circuit, so long as the signal is still applied between the grid and the cathode. Such is the case here. Part of the signal which appears across the load resistor R_3 is now applied to a plate-loaded amplifier, and the output taken across the four tubes. This scheme, as most of the others, has the disadvantage of requiring two power supplies. Still, at low frequencies this amplifier worked very well, giving the desired 1000 volts output.

The primary disadvantage of this amplifier is its inadequate frequency response. There is an inherent capacity between the power supplies which is hard to avoid. This means that at high frequencies the two power supplies are connected by a low reactance path which seriously reduces the output signal. One thing which helped considerably was to connect one power supply--both positive and negative leads--to its amplifier through inductances.

One more disadvantage is that the amplifier is unbalanced. The push-pull section would be run from a power supply common to the pre-amplifiers, and the second power supply would float above ground at some level, depending on the input signal. The net result of all this is that, for a signal output of 1000 volts, one output terminal would be 250 volts positive with respect to ground, while the remaining terminal would be 750 volts negative with respect to ground. On the next half cycle, the polarities would reverse, but the absolute voltage magnitudes would not. Naturally, the preferred case would be one where each was 500 volts from ground (with opposite polarities, of course).

Nothing mentioned yet disqualifies the amplifier for use with low frequencies (up to 10 kc), and certainly it will work under such conditions. At any frequency, however, there is one major obstacle. As mentioned previously, the secondary or additional power supply floats above ground, and the voltage by which it differs from ground depends on the signal. This is to say that the positive or negative terminal of the secondary power supply actually has some part of the output signal on it (which is not true of the primary power supply). In essence, this means that the secondary power supply cannot be used by any other amplifier. In an oscilloscope, then, three power supplies would be required: one primary and two secondary supplies, one each for the vertical and horizontal amplifiers. This is too many power supplies, and almost any system conceivable would cost less, take up less room, and require less maintenance than this one.

CHAPTER IV

THE FINAL SOLUTION

Satisfactory amplifier.--Most of the previous attempts have been a variation of connecting two push-pull amplifiers in series. The next step was to connect two tubes in series, and then connect two such circuits in push-pull. Figure 9 shows such a circuit. Immediately, several advantages are apparent. First, only one power supply is used even though it must be approximately 800 volts. This means that there are no floating power supplies, which are a potential source of trouble. Second, the amplifier is balanced, and both halves are identical. This means that the dc difference of potential at the output terminals is approximately zero, so that no off-centering of the electron beam occurs when the amplifier is used as a deflection amplifier. By suitable bias arrangements, however, the dc potential between the two output terminals may be varied to produce off-centering, if desired. The third advantage is that frequency response falls within the stated limits. Also, injection of the signal into the tubes in the proper phase is easily accomplished.

Figure 9 shows the entire amplifier, including the phase inverter and preamplifiers. The final stage is a push-pull amplifier, composed of two identical sections. In each section, the input signal is fed to the lower or grounded tube. Connected across this tube is a potentiometer which allows any part of the voltage developed across the tube to be fed to the upper tube. It is necessary that each tube develop the same voltage, lest one of them be overloaded, so that adjustment of the

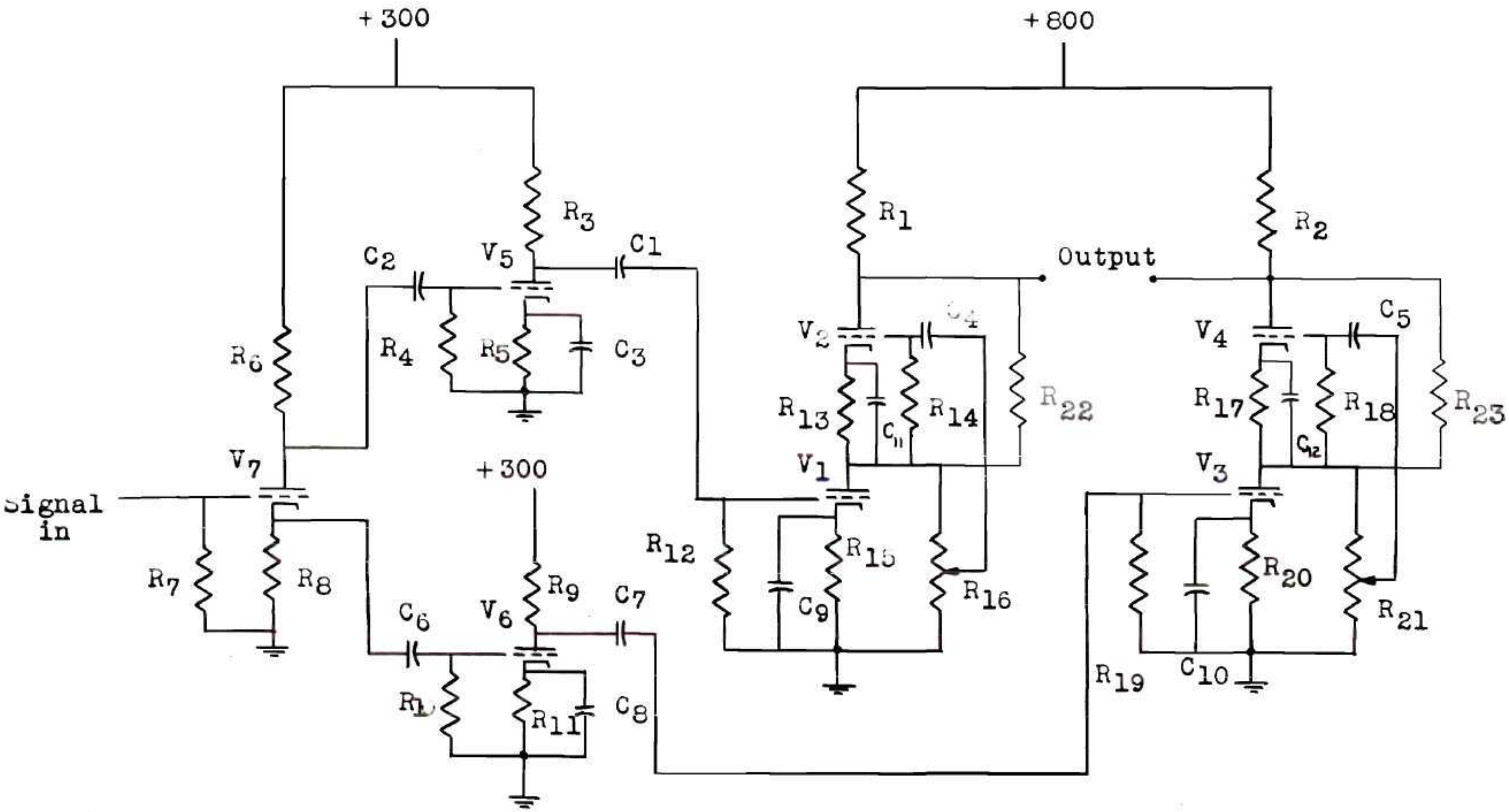

Figure 9. The Final, Successful Amplifier

potentiometers is rather critical. The method of adjustment is simple. The ac voltage from the ground to the plate of V_1 is measured, and then the ac voltage from ground to the plate of V_2 is measured. The potentiometer is adjusted until the voltage on the plate of V_2 is twice that of the voltage on V_1. While this adjustment is made in reference to the ac voltage, the dc voltages are also in the ratio of 2 to 1.

Naturally, it is essential that V_1 and V_2 operate in phase. As the grid of V_1 goes positive, its plate goes negative. However, because of the way the grid of V_2 is connected, it goes positive, causing the plate of V_2 to go negative. Thus, both tubes go negative at the same time, and operate in phase.

The desired result, briefly, is to make two tubes in series act like a single tube with twice the output voltage rating and twice the gain of either one. From the general gain equation, $A = \frac{uR_L}{R_L + r_P}$, it appears that doubling all the factors would double the gain (the amplification factor is doubled, not squared, because only a portion of the output signal of the lower tube is applied to the upper tube). While a single tube using a power supply voltage of 300 volts produced an output of 200 volts, the two tubes in series required about an 800-volt power supply for an output of 550 volts. In the case of the single tube, the ac to dc ratio is .667, while the two tubes in series have a ratio of .687.

Figure 10 is an equivalent circuit for one side of the final, push-pull stage. The conductance of the potentiometer in parallel with the lower tube and the conductance of the .5 megohm resistor in parallel with the upper tube will be neglected, since they are small compared to that of r_P. The loop equation is

$$i(R_L + 2r_P + 2R_K) = u(Eg_1 + Eg_2)$$

This is for low frequencies where the cathode bias resistors are unbypassed. Now, let $D = \frac{R_1}{R_1 + R_2}$ where $R_1 + R_2$ is the total resistance of the potentiometer, and D is the portion of the signal developed across the lower tube which is applied to the upper tube.

$$Eg_2 = -iR_K + D\left[(r_P + R_K)i - uEg_1\right]$$

Inserting this value of Eg_2 into the first loop equation gives:

$$i(R_L + 2r_P + 2R_K) = u\left\{Eg_1 - iR_K - D\left[(r_P + R_K)i - uEg_1\right]\right\}$$

$$Eg_1 = Es_1 - iR_K$$

$$i\left[R_L + r_P(2 + uD) + R_K(2 + 2u + uD + u^2D)\right] = uEs_1(1 + uD)$$

$$A = \text{Gain} = \frac{iR_L}{Es} = \frac{u(1 + uD)R_L}{R_L + r_P(2 + uD) + R_K(2 + 2u + uD + u^2D)}$$

Inserting the circuit parameters gives:

$$A = \frac{(20 \times 82 + 400 \times 82D)10^3}{(82 + 14 + 140D + 105 + 1050D)10^3}$$

$$A = \frac{1640 + 32800D}{201 + 1190D} = \frac{1.378 + 27.6D}{.169 + D}$$

Thus, it is apparent that the gain is dependent upon D. Note that when D = 0 (no signal applied to the upper tube from the lower one), the gain is 8.2. Now refer to Figure 11. This is the equivalent circuit of one half the amplifier, in which the load resistance is one half that used in the series arrangement, or 41 Kilohms. The gain is

$$A = \frac{\frac{uR_L}{2}}{\frac{R_L}{2} + r_P + R_K(u + 1)} = 8.2$$

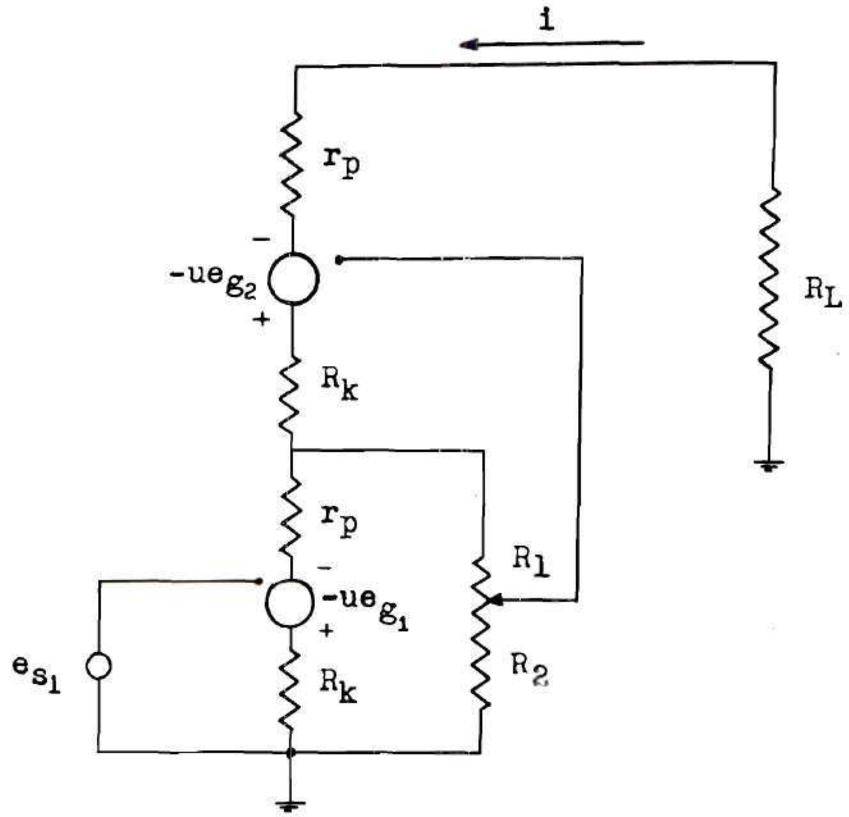

Figure 10. Equivalent Circuit of One Side of Final Amplifier

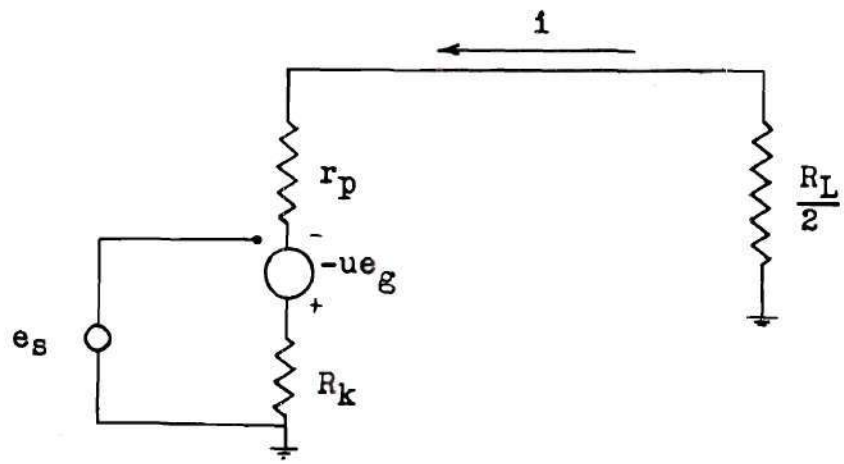

Figure 11. Equivalent Circuit of Lower Tube of Figure 10

It might appear at first that this could not be true. However, the upper tube is actually being driven by the signal iR_K in its cathode, which is out of phase with the signal developed by the lower tube. This decreases the gain of the series arrangement, causing it to equal that of the single tube.

It is desired that the two tubes have identical outputs so that one will not be overdriven before the other. The original loop equation for the equivalent circuit is

$$i(R_L + 2r_P + 2R_K) = u(Eg_1 + Eg_2)$$

If the voltages across the two tubes are equal, then

$$ir_P - uEg_1 = ir_P - uEg_2$$

$$Eg_1 = Eg_2$$

Therefore

$$i(R_L + 2r_P + 2R_K) = 2uEg_1$$

$$i(R_L + 2r_P + 2R_K) = 2u(E_s - iR_K)$$

$$A = \frac{iR_L}{E_s} = \frac{2u(R_L)}{R_L + 2r_P + 2R_K(u + 1)}$$

This may also be written

$$A = 2\left[\frac{uR_{L/2}}{R_{L/2} + r_P + R_K\,(u + 1)}\right]$$

from which it can be seen that the gain is exactly twice that of the single-tube amplifier mentioned earlier. The actual gain is 2 x 8.2 = 16.4

The value of D for equal outputs may now be obtained.

$$16.4 = \frac{1.378 + 27.6\,D}{.169 + D}$$

from which

$$D = \frac{1}{8.2}$$

Under the condition that the two tubes have equal outputs, it would be expected that the gains of the tubes would also be equal. This is shown by obtaining the gain of the lower tube.

$$A\ \text{lower} = \frac{E_{out}}{E_{in}} = \frac{i(r_P + R_K) - uEg_1}{Es_1}$$

$$= \frac{i\left[r_P + R_K(u + 1)\right] - uEs_1}{Es_1}$$

$$\frac{i}{E_s} = \frac{A\ \text{total}}{R_L}$$

$$A\ \text{lower} = A\ \text{total}\left[\frac{r_P + R_K\,(u + 1)}{R_L}\right] - u$$

$$= 16.4\frac{(7 + 52.5)}{82} - 20$$

$$= 8.2$$

$$A\ \text{upper} = A\ \text{total} - A\ \text{lower}$$

$$= 16.4 - 8.2$$

$$= 8.2$$

As expected

$$Eg_2 = (Es_2 - iR_K)$$

$$Es_2 = D\left[\text{Voltage Across Lower Tube}\right]$$

$$Es_2 = D\left(8.2\ Es_1\right)$$

$$Es_2 = \frac{1}{8.2}\left(8.2\ Es_1\right)$$

$$Es_2 = Es_1$$

The actual gain of the final stage (entire push-pull circuit) was measured and found to be 15.4. This was with an output of 100 volts. At an output of 1000 volts, the gain was 12.5. At such high amplitudes, some non-linearity occurs, which decreases the gain. At the lower signals, where the linear equivalent circuits apply, the measured and calculated results agree closely.

The values of the components used are not critical, and 10% tolerances may be used. The potentiometers provide an excellent means for compensating for these differences. While theoretically D should equal .122, the variations in component values will probably necessitate some other value which differs only slightly from .122.

Frequency considerations.--In this thesis, amplitude of the output voltage was the major problem. However, this amplifier is eventually intended for use in an oscilloscope, and the reason for using this amplifier and an electrostatic deflection tube was to obtain frequency response not possible with a magnetic-deflection oscilloscope. Therefore, having devised the method for giving the necessary output, the next step was to insure the required frequency response. With no high frequency compensation of any type, the upper half-power point (70.7 per cent of maximum voltage) occurred at approximately 35 kc, well short of the intended 100 kc. Originally, un-bypassed cathode bias was used, in hopes that the effect of the inverse feedback would extend the frequency range. This obviously was not sufficient.

In most ordinary amplifiers, the cathode resistor is by-passed sufficiently with a large capacitor so that no inverse feedback occurs. Since this feedback tends to decrease the total output, the gain is increased by the addition of the by-pass capacitor. However, sufficient gain was already present at the frequencies below 10 kc, so by-passing at these frequencies was not necessary. By connecting the appropriate amount of capacitance across the cathode resistor, the upper frequencies were by-passed to ground, but no effect was made on the lower frequencies. This is exactly what was needed. By actually using a decade capacitor for by-pass, the value of capacitance could be adjusted for maximum frequency response. While the value of this capacitance is not extremely critical; nonetheless, it had to be chosen with some care. The range of capacitance in question was never enough to affect the 1 kc response, so the gain at that frequency was essentially constant. Now, if too little capacitance were added, the response at 100 kc would be more than 3 decibels down. On the other hand, if enough capacitance were added so that the response at 100 kc was the same as that at 1 kc, then the response at 35 kc was increased too much and a hump occurred in the response curve near this frequency. As a compromise, the response was adjusted so that at no frequency was it greater than at 1 kc, and an effort made to keep the response flat for as far as possible. The frequency response curve and a discussion of the frequency characteristics are contained in the following chapter.

The entire amplifier.--In the final version of the amplifier, a phase inverter and preamplifiers were naturally required. Because the phase inverter does not work well at large amplitudes, it was made the first stage of the amplifier. The output of this, of course, was two signals 180°

out of phase. However, they were of insufficient amplitude to drive the final stage, so they were amplified separately. In all, then, this meant the use of 7 tubes: one as a phase inverter, two as preamplifiers or drivers, and four in the final push-pull stage. Since 6SN7GTA's were used throughout, this required four complete envelopes. This meant that one triode was unused, and this could easily be used as an amplifier preceding the phase inverter, which would increase the sensitivity by a factor of about ten.

The tubes used throughout were 6SN7GTA's. This tube is similar in every way to the 6SN7GT except for its voltage rating. Its maximum plate supply voltage is 450 volts dc (as opposed to 300 for the 6SN7GT). This means that by operating two in series, a maximum supply voltage of 900 volts could be used.

CHAPTER V

DISCUSSION OF RESULTS

Output amplitude.--In designing this amplifier, the foremost consideration was that of output amplitude. To build an amplifier with a given frequency response presents no particular problem, but to obtain 1000 volts output from receiving tubes is an obstacle. So before any circuit was tested for frequency characteristics, the amplitude was tested at 1 kc. The circuit by means of which the problem was solved has been discussed in detail in the preceding chapter. There is little more to say in regard to the output amplitude, except that it is well in excess of the required 1000 volts. With an input of 5 volts rms (14.2 volts, peak-to-peak), the peak-to-peak output was 1100 volts. This was with no visible distortion on the oscilloscope.

Frequency response.--The operating characteristics of the amplifier are shown in the frequency response curve, Figure 12, the linearity curve, Figure 21, and the wave-shape oscillograms, Figures 13 through 20. The data from which the two curves were drawn are contained in tables 1 and 2 of the appendix.

The frequency response curve and the wave shapes were all taken at 1000 volts output or greater. The frequency response was slightly improved at lesser amplitudes, but the interest with this amplifier is at large outputs. Therefore 1000 volts was used everywhere, except, of course, in taking the linearity data.

The frequency response curve perhaps tells more than anything else.

In taking this data, a sine-wave input was used, and this was kept constant at 11.7 volts, peak-to-peak, this being the amount necessary for 1000 volts output at 1 kc. The output voltage was measured on an oscilloscope since a vacuum-tube voltmeter put too much load on the amplifier. Because the oscilloscope was used, the voltages could not be read with great accuracy. The main effect of this was that small variations along the flat portion of the curve were missed, but the larger variations at the high frequency end were easily read, so that a good indication of the frequency response was obtained. The exact procedure used in measuring the output voltage is presented in Chapter VII.

The frequency response curve is a plot of all frequencies from 10 cps to 170 kc. The output voltage is plotted on the ordinate in volts instead of decibels. The reason for doing this is that the maximum voltage is 1000 volts, and everything is easily referred to this number. For example, to find the upper half-power point, it is necessary only to find at what frequency the output was down to 707 volts. The low frequency end never dropped down, as is indicated on the curve. In trying to determine the lower half-power point, the frequency was run as low as five cps (the lower limit of the signal generator) and still no decrease in amplitude was noted. In the amplifier, .05 microfarad capacitors were used for coupling throughout, and 1.5 megohm resistors were used for grid resistors. There are two stages of coupling (if the coupling within the final stage is neglected) and each stage has a lower half-power point at $f = \frac{1}{2\pi RC}$ or 2.12 cps. For the two stages in cascade, however, the half-power point occurs when the response is $\frac{1}{\sqrt{2}}$ times the value at $\omega=\infty$; i.e., where the series coupling capacitor has negligible reactance. For a single RC coupling net-

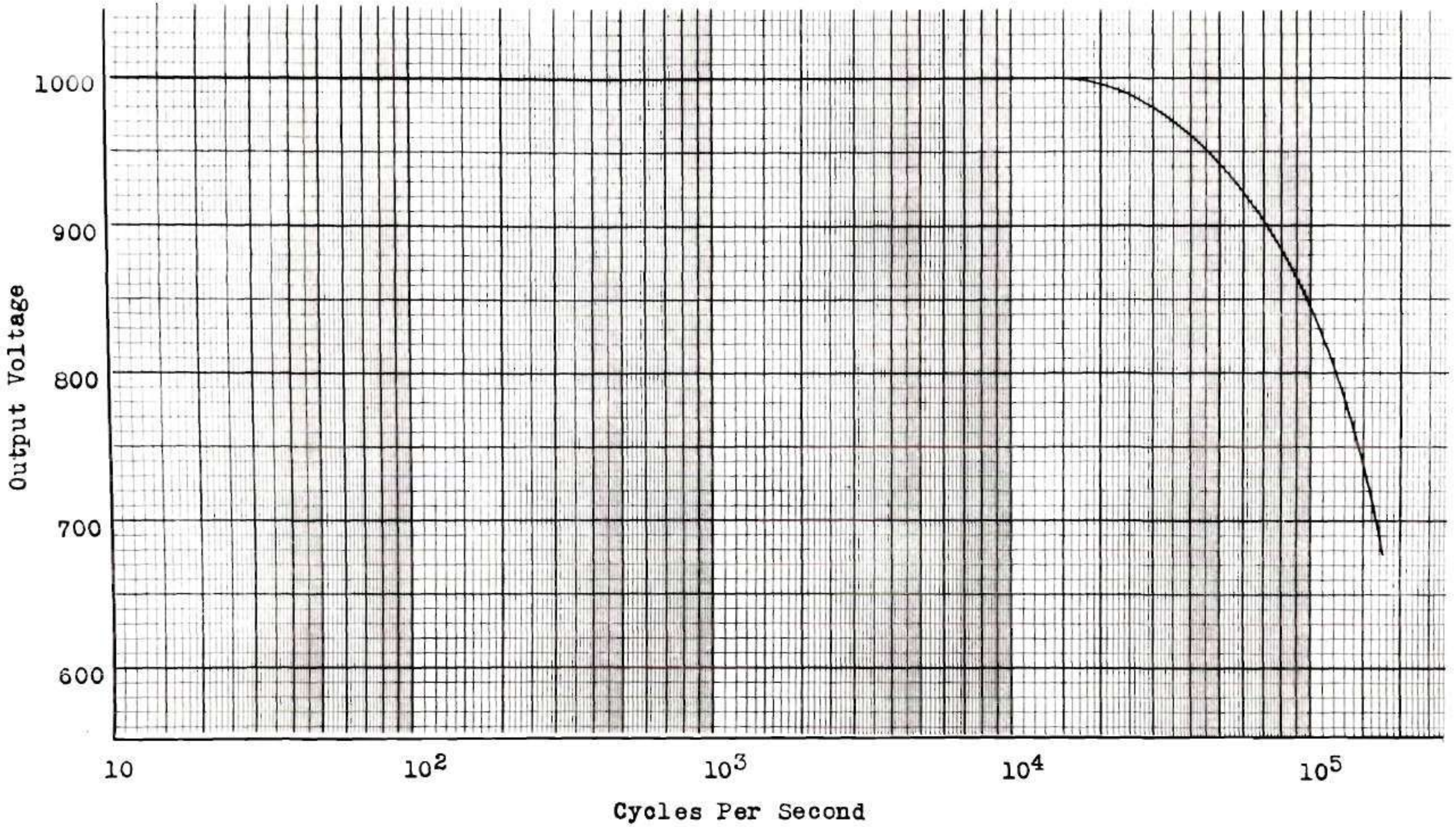

Figure 12. Frequency Response of Final Amplifier

work $\frac{E_{out}}{E_{in}} = \frac{R}{R + \frac{1}{j\omega C}}$, where E_{in} is the voltage across the RC series combination, and E_{out} is the voltage across the resistor only. For two identical RC networks isolated by a tube

$$\left|\frac{E_{out}}{E_{in}} \times \frac{E_{out}}{E_{in}}\right| = \frac{1}{\sqrt{2}} = \left|\frac{E_{out}}{E_{in}}\right|^2$$

$$\frac{E_{out}}{E_{in}} = \frac{1}{\sqrt[4]{2}} = \frac{R}{R + \frac{1}{j\omega C}} = \frac{1}{1 + \frac{1}{j\omega RC}} = \frac{1}{\sqrt{1 + \frac{1}{\omega^2 R^2 C^2}}}$$

$$1 + \frac{1}{\omega^2 R^2 C^2} = 1.414$$

$$\omega RC = 1.55$$

However, the RC time constant used throughout the amplifier is $.05 \times 10^{-6} \times 1.5 \times 10^6 = 75$ milliseconds. Therefore

$$\omega = \frac{1.55}{RC} = \frac{1.55}{.075} = 20.7 \text{ radians per second}$$

$$f_1 = \frac{\omega}{2\pi} = \frac{20.7}{2\pi} = 3.3 \text{ cps}$$

This is the lower half-power point.

Now, refer to Figure 17, an oscillogram of a 250 cps square wave. The amplitude of the wave is 1 7/8 inches, which represents an output of 1000 volts. The period of one cycle is $\frac{1}{250}$ seconds or 4 ms. The time for one-half cycle is 2 ms. The decrease in amplitude during one-half cycle is 3/32 inch. Since the maximum amplitude itself is 60/32 inches, this is a decrease of 3/60 or 5 per cent. In other words, in one-half cycle, the

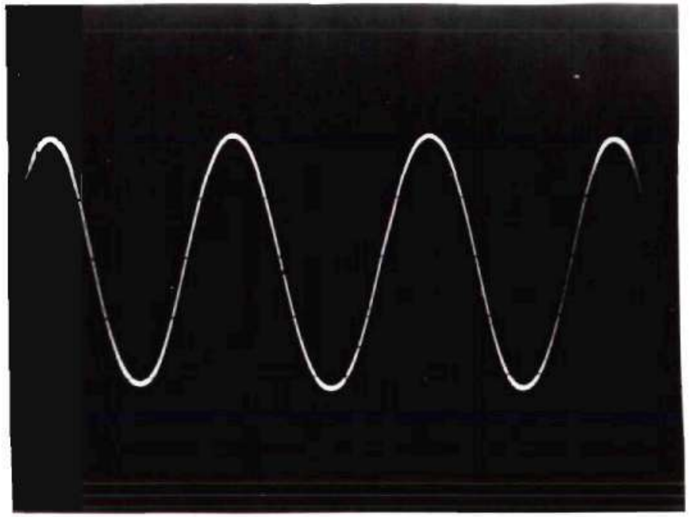

Figure 13. 1 KC Sine Wave

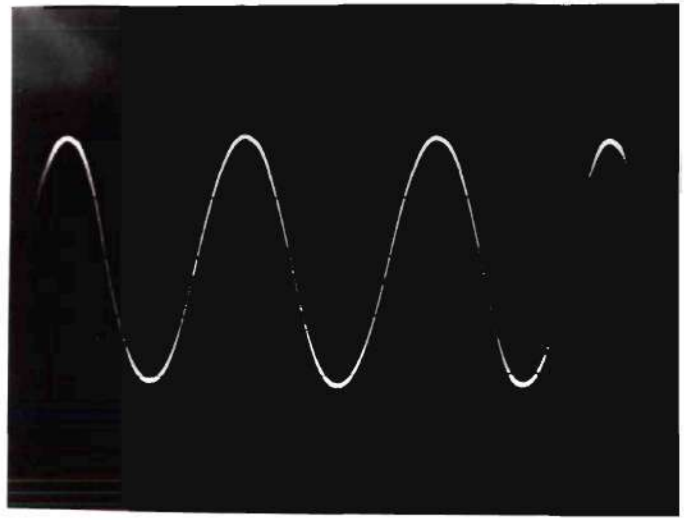

Figure 14. 10 KC Sine Wave

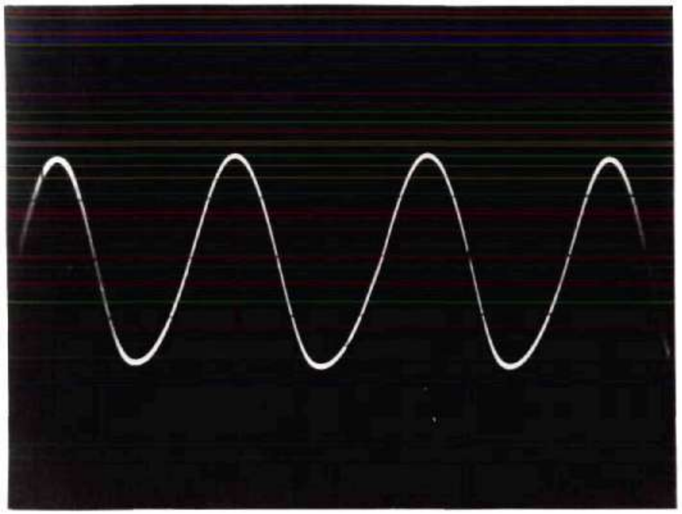

Figure 15. 100 KC Sine Wave

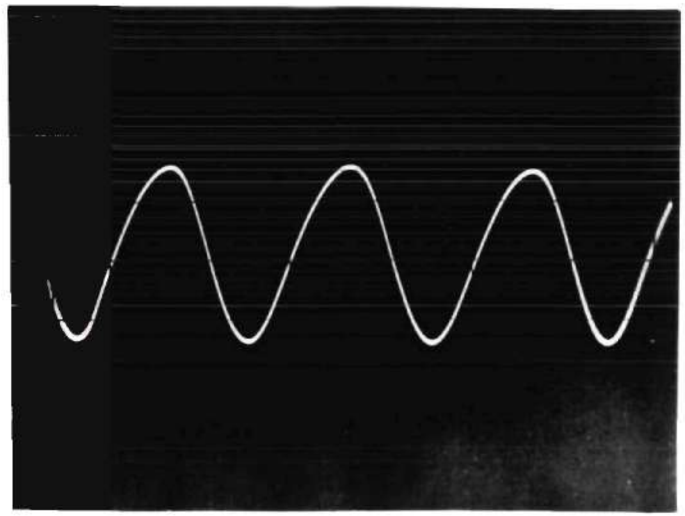

Figure 16. 150 KC Sine Wave

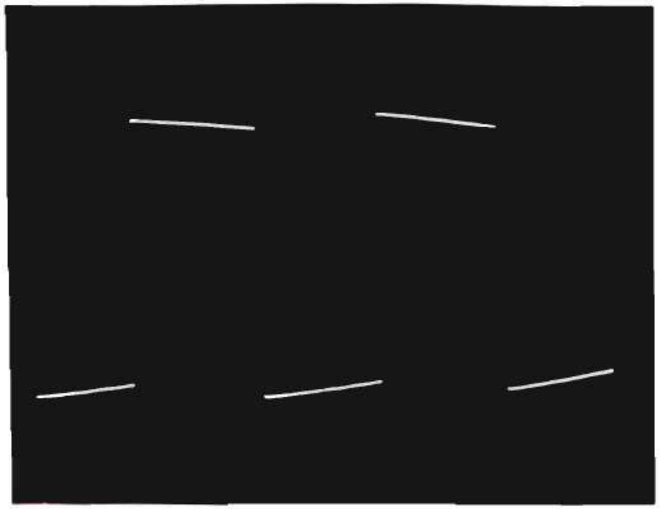

Figure 17. 250 CPS Square Wave

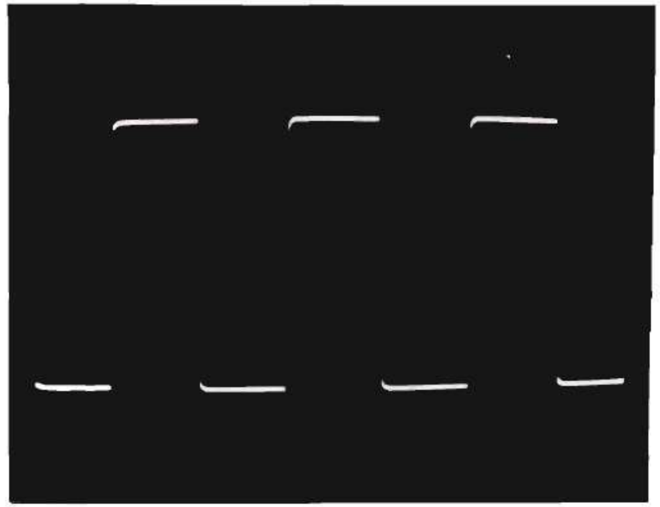

Figure 18. 1 KC Square Wave

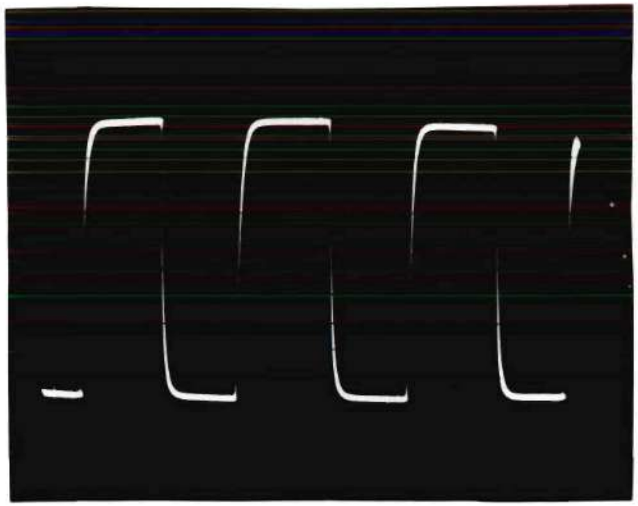

Figure 19. 10 KC Square Wave

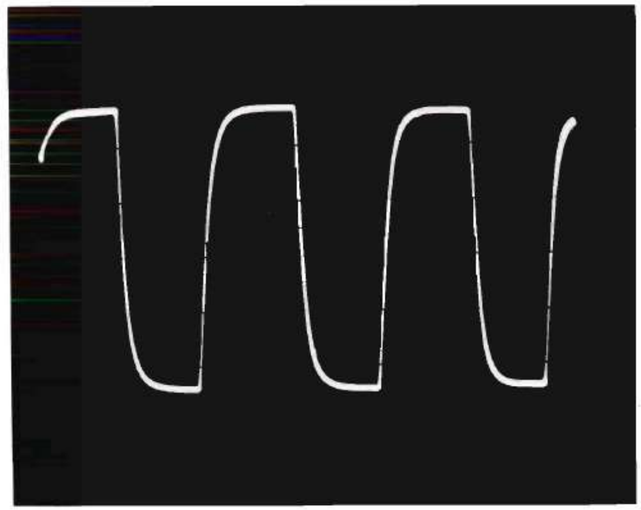

Figure 20. 25 KC Square Wave

output voltage decays to 95 per cent of its initial value.

Analytically, the output voltage is given by the equation

$$\frac{E_{out}}{E\ initial} \cong 1 - \frac{2t}{RC}$$ [1]

This is for two stages of coupling, where the RC time constants of each stage are identical. For this case, t = 2 ms and RC = 75 ms. So

$$\frac{E_{out}}{E\ initial} \cong 1 - \frac{2(2)}{75} = 1 - .053 = .947$$

Thus we see that the experimental and analytical results agree very well. Some error was introduced by neglecting the coupling between the two tubes of the final stage. However, if the final stage were fed by a constant alternating voltage, the upper tube would have to decrease its output by 58.6 per cent before the entire stage was down to 70.7 per cent. This is because the lower tube would never decrease its output, so all decrease in output is a result of the upper tube.

As shown in Figure 12, the response is flat up to approximately 20 kc, where it begins to fall off gradually. At 100 kc, which was originally supposed to be the upper half-power point, the response is down only 1.4 db. According to the response curve, the half-power point actually occurs slightly beyond 150 kc. Figure 16 shows an oscillogram of this frequency. While some distortion is present, for most purposes it would not be objectionable.

Figures 17 through 20 are oscillograms of 250 cps, 1 kc, 10 kc, and 25 kc square waves, respectively. The upper half-power point can theo-

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[1] Lawrence B. Arguimbau, Vacuum Tube Circuits, John Wiley and Sons, New York, 1948, p. 170.

retically be computed from these oscillograms, but this assumes no phase shift. There undoubtedly is some shift in phase, and this causes the square wave results to differ from the sine wave results. For instance, the 10-90 per cent rise time (as measured on the 25 kc oscillogram) is 3.5 microseconds. Since bandwidth $= \frac{.45}{\text{rise time}} \Big|_{10\text{-}90\%} = \frac{.45}{3.5 \times 10^{-6}}$, the bandwidth in 129 kc. The lower end of the band is essentially zero, so the upper end is 129 kc. The number .45 is used where there is no overshoot. As previously mentioned, these results differ slightly from the results obtained with the use of sine waves, but phase shift and inaccuracy in graphical measurements account for the variation.

Linearity.--Figure 21 is a plot of gain versus input voltage. As can be seen, the gain varies from about 105 at small inputs to 85 at an output of 1000 volts. The effect of this variation in gain is that some amplitude distortion will occur. When the input is a sine wave, for instance, the small instantaneous values of voltage will be amplified more than the peaks. This should result in some slight flattening of the peaks, but in Figures 13 and 14, which are oscillograms of 1 kc and 10 kc, respectively, no distortion is apparent to the eye. This non-linearity might introduce some trouble with calibration when the amplifier is used as a deflection amplifier in an oscilloscope. For example, if one-half volt input to the amplifier produced one inch of deflection, then an 8 inch deflection would not mean the input was four volts. It would, instead, mean some higher voltage.

In taking the data for the linearity curve, a 1-kc sine wave was used. At 5 volts rms input, the gain was 80, which means the peak-to-peak output voltage was $5 \times 80 \times 2\sqrt{2}$ or 1140 volts, and still no distortion was evident. At an input of 5.5 volts, a small amount of distortion was present, and at 6.0 volts, severe clipping was apparent. The data from which the linearity curve was drawn are contained in table 2 of the appendix.

Table 3 contains the parts list for the entire amplifier. The part-numbers refer to those in Figure 9.

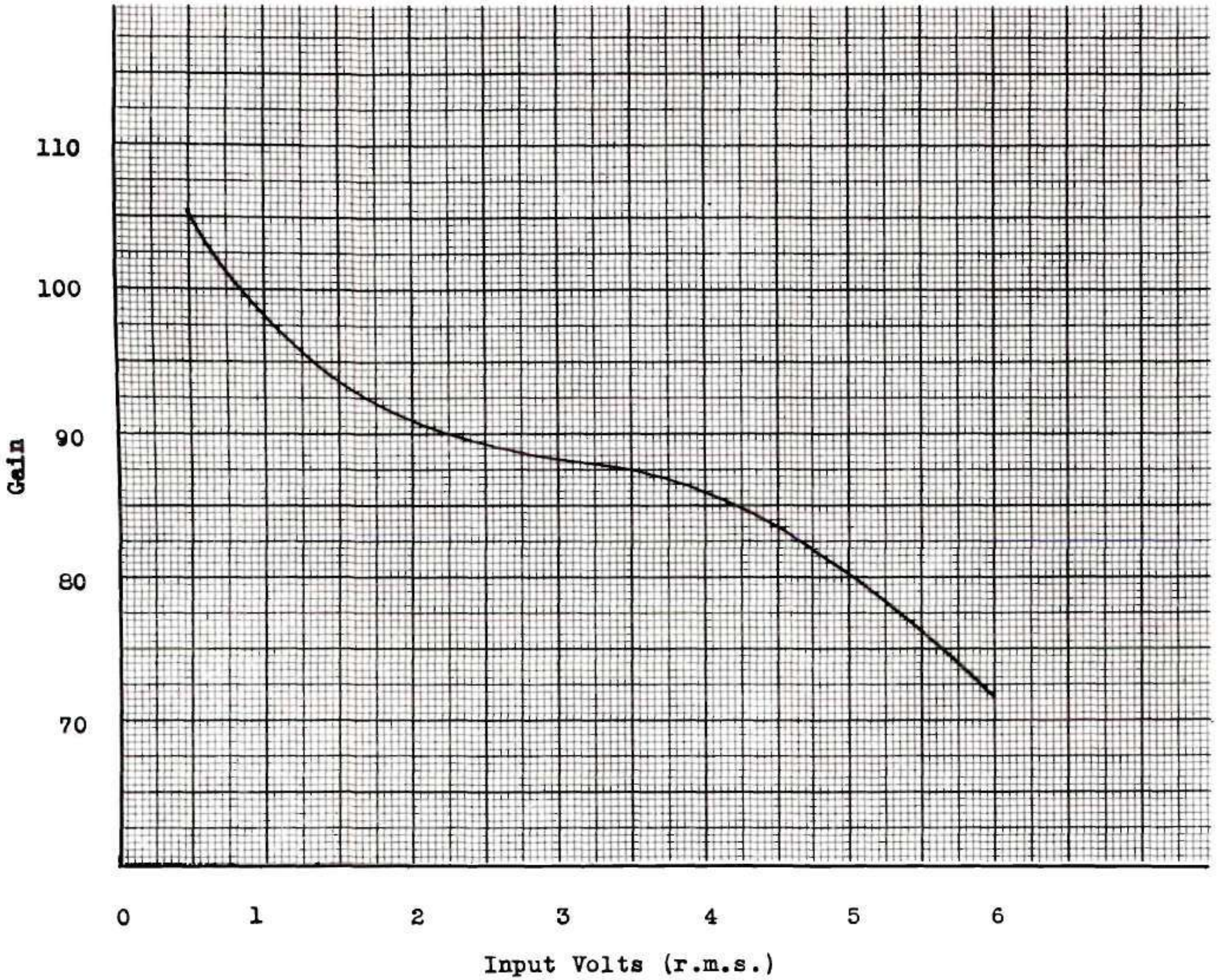

Figure 21. Linearity Curve of Final Amplifier

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

The conclusions arrived at as a result of the research conducted in connection with this thesis are as follows:

1. It is possible to connect receiving tubes in series, so that their outputs are additive. This gives an output voltage much higher than is usually associated with receiving tubes. In the case of this thesis, over 1000 volts output was produced by four such tubes.

2. The use of receiving tubes is not only possible, as pointed out above, but actually preferable to many methods. The final stage, while requiring four tubes, made use of only two tube envelopes, since the 6SN7GTA contains two tubes per envelope. This means that less space is actually taken by this method than by using two 807's or equivalent.

3. The use of receiving tubes decreases the amount of dc power used. The final stage drew only 9 ma at 800 volts or 7.2 watts. Of this, 3.0 watts is dissipated in the load resistors, which means each tube dissipates only about 1 watt. Maximum allowable dissipation of each tube of a 6SN7GTA is 2.5 watts. Also, because such a small amount of current is needed, filtering in the power supply is no problem.

4. The amplifier exceeds all the characteristics specified in the statement of the problem. The frequency response (within the half-power points) is from 5 cps to 165 kc. The maximum output voltage is 1140 volts peak-to-peak undistorted at 1 kc.

CHAPTER VII

INSTRUMENTATION AND EQUIPMENT

Equipment.--All the equipment used in work on this thesis was conventional laboratory equipment. An 800-volt power supply was necessary, but this was easily obtained by connecting in series two 400-volt power supplies. For wave-shape analysis and measurement, a Tektronix 511-AD cathode-ray oscilloscope was used. The sine-wave generator was a Hewlett-Packard 200-CD, and the square wave generator was a Tektronix Type 105. Figure 22 is a photograph of the amplifier and some of the equipment used in conjunction with it. On the extreme left is a vacuum-tube voltmeter, then the square wave generator, a power supply, and finally the oscilloscope. In front of the power supply is the second power supply, these two being connected in series to obtain the necessary 800 volt supply voltage. The amplifier itself is in the foreground. Note the two potentiometers on the end for adjusting the balance between the tubes of the final stage.

Instrumentation.--In the measurement of the output voltages one major problem arose. In push-pull amplifiers the output must be taken from the two plates. This means that the ground lead of the oscilloscope must be connected to one plate, with the probe connected to the remaining plate. This arrangement worked nicely below 10 kilocycles but at frequencies above this, and especially at 100 kc, it was completely unsatisfactory. The unsatisfactory operation was caused by the unavoidable capacitance between the power supply of the amplifier and the power supply of the oscilloscope. In effect, the ground lead of the oscilloscope is shorted to the negative

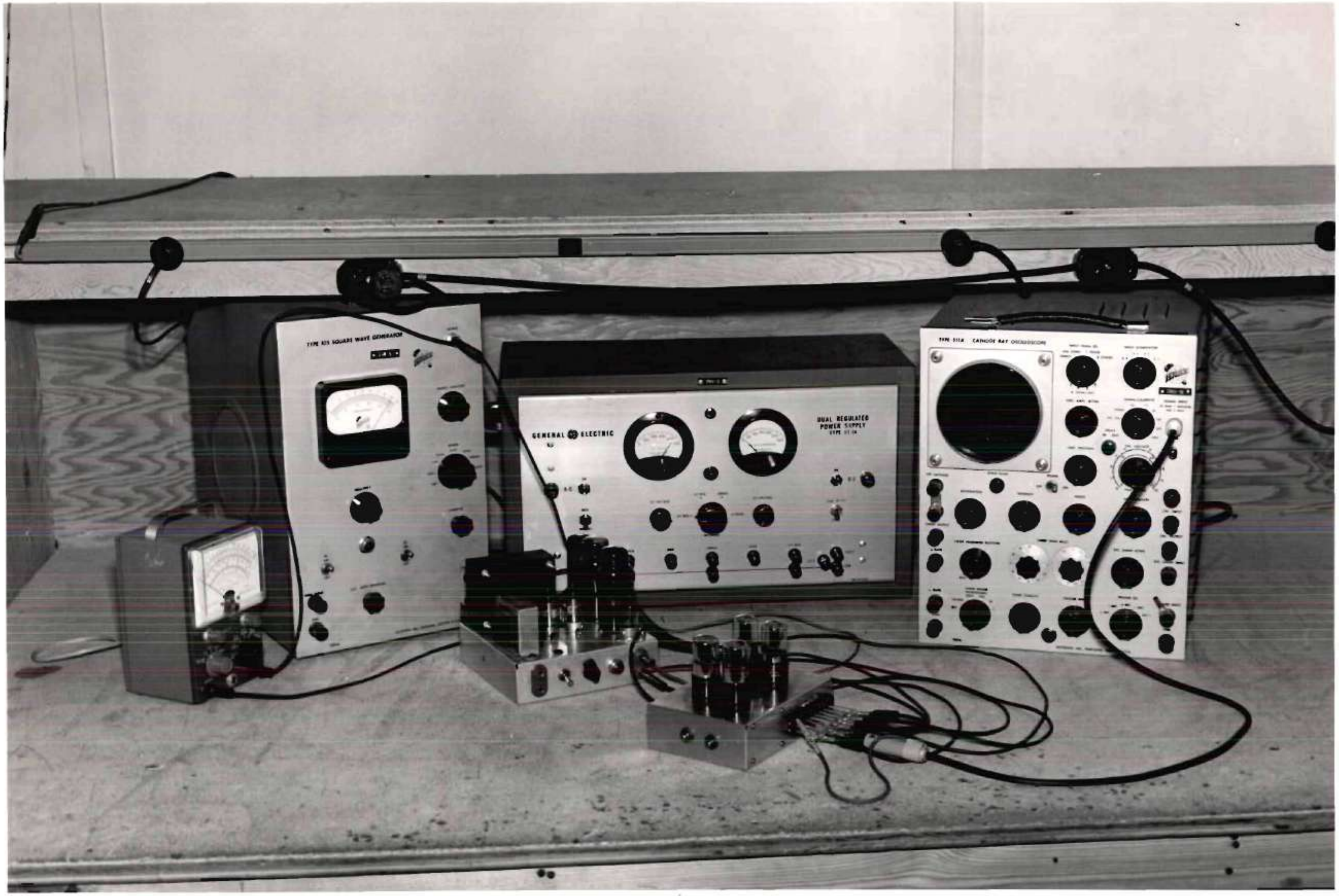

Figure 22. Photograph of Final Amplifier and Test Equipment

terminal of the amplifier power supply. This means that the plate to which the ground lead is connected is at ground potential; hence it produces nothing. That this is so was easily demonstrated. At 1 kc, the oscilloscope measured a certain voltage from either plate to ground. From plate to plate, however, twice the voltage was measured as was expected. At 100 kc, though, the voltage from one plate to ground was equal to the voltage of the other plate to ground. The voltage from plate to plate, however, did not double, but was equal to that previously measured from one plate to ground. This indicated that one plate--the one to which the ground lead was connected--was effectively shorted. This, of course, was at high frequencies only where the reactance of the capacity previously mentioned was small.

In a push-pull amplifier, the outputs of each side should be equal, so that ordinarily one side can be measured, and that amount doubled taken as the total plate to plate output. The principal requirement that this be true is that the outputs of the tubes be 180° out of phase. While this may be true at frequencies around 1 kc, it is not true at frequencies of 100 kc and higher. So while this method might give some indication of the total output voltage, it is not as accurate as that described below.

A still better method, and the one used in taking all the data and oscillograms, is to use two resistors in series for each load resistor. One of the resistors--6.8 kilohms--is connected to the power supply, with the remaining end connected to the other resistor--75 kilohms. The other end of the 75-kilohm resistor is connected to the plate of the tube. This gives a voltage division of 81.8:6.8 or approximately 12:1. The voltage which now appears between the two 6.8 kilohm resistors is applied directly to the deflection plates, and a true indication of the wave shape and amplitude obtained.

In order to measure the amplitude in this way, a 1000 cps sine wave was amplified until the output was 1000 volts. This meant that approximately 83 volts was applied to the vertical deflection plates. The amount of deflection which this produced was noted, and the oscilloscope was calibrated. All amplitude measurements, at whatever frequency, were then made on the oscilloscope.

A P P E N D I X

Table 1. Frequency Test Results

Item	Frequency in kilocycles per second	Input voltage in peak-to-peak volts	Output voltage in peak-to-peak volts
1	.010	11.7	990
2	.020	11.7	1000
3	.050	11.7	1000
4	.100	11.7	1010
5	.200	11.7	1000
6	.500	11.7	1000
7	1.0	11.7	1000
8	2.0	11.7	1000
9	5.0	11.7	1000
10	10.0	11.7	1000
11	20.0	11.7	980
12	50.0	11.7	950
13	75.0	11.7	900
14	100.0	11.7	850
15	125.0	11.7	800
16	150.0	11.7	750
17	165.0	11.7	700

Table 2. Linearity Test Results

Item	Input voltage in rms volts	Output voltage in rms volts	Output voltage in peak-to-peak volts	Gain
1	.5	53	149	105.2
2	1.0	99	281	99.0
3	1.5	140	396	93.4
4	2.0	183	518	91.4
5	2.5	224	634	89.6
6	3.0	264	748	88.0
7	3.5	306	866	87.4
8	4.0	340	963	85.0
9	4.15	354	1000	85.2
10	4.5	374	1060	83.2
11	5.0	404	1140	80.8
12	5.5	420	1190	76.4
13	6.0	430	1220	71.6

Table 3. Parts List of Final Amplifier

Item	Part-number	Value
1	R_1	82K-2W
2	R_2	82K-2W
3	R_3	27K-1W
4	R_4	1.5M-$\frac{1}{2}$W
5	R_5	3.3K-1W
6	R_6	27K-1W
7	R_7	1.5M-$\frac{1}{2}$W
8	R_8	27K-1W
9	R_9	27K-1W
10	R_{10}	1.5M-$\frac{1}{2}$W
11	R_{11}	3.3K-1W
12	R_{12}	1.5M-$\frac{1}{2}$W
13	R_{13}	2.4K-1W
14	R_{14}	1.5M-$\frac{1}{2}$W
15	R_{15}	2.4K-1W
16	R_{16}	0.5M-$\frac{1}{2}$W
17	R_{17}	2.4K-1W
18	R_{18}	1.5M-$\frac{1}{2}$W
19	R_{19}	1.5M-$\frac{1}{2}$W
20	R_{20}	2.4K-1W
21	R_{21}	0.5M-$\frac{1}{2}$W
22	R_{22}	0.5M-$\frac{1}{2}$W
23	R_{23}	0.5M-$\frac{1}{2}$W
24	C_1	.05uf-600V
25	C_2	.05uf-600V
26	C_3	500uuf
27	C_4	.05uf-600V
28	C_5	.05uf-600V
29	C_6	.05uf-600V
30	C_7	.05uf-600V
31	C_8	500uuf
32	C_9	500uuf
33	C_{10}	500uuf
34	C_{11}	500uuf
35	C_{12}	500uuf
36	V_1	$\frac{1}{2}$6SN7GTA
37	V_2	$\frac{1}{2}$6SN7GTA
38	V_3	$\frac{1}{2}$6SN7GTA
39	V_4	$\frac{1}{2}$6SN7GTA
40	V_5	$\frac{1}{2}$6SN7GTA
41	V_6	$\frac{1}{2}$6SN7GTA
42	V_7	$\frac{1}{2}$6SN7GTA

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