A STUDY OF DISTORTION IN A PUSH-PULL AMPLIFIER

by

Allen Moore Howery

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Preface

At the time this thesis was started there was very little material available about push-pull amplifiers. It was admitted that they worked much better than the other forms of amplification. Where there was a demand of a large output on an amplifier, the push-pull system was used.

In the past age of radio experimenting, there was little trend of thought in the theory of the apparatus until it had proved workable, then the inventor or the designer looked back and tried to find out why it worked, and then developed theory to make it work more efficiently. The development of the push-pull idea has reached the stage of theoretical explanation, and in an endeavor to determine the nearness of the theory that this approaches, this thesis was written.

General Survey of the Field

Amplifiers have made talking pictures, the trans-atlantic communication system, public address systems and first class radio performance possible. The quality of reproduction of the audio waves are directly dependent on the amplifier for faithful reproduction.

Most of the improvements have been made by experiments in a haphazard way and were later harmonized with, and transferred to, theoretical deductions.

The amplifier depends on the tubes for its ability to reproduce the signal. The amplifier depends on other parts as well, but the tubes are of major consideration.

In order to understand the complete functioning of the amplifier, it is necessary first to know what takes place in a vacuum tube while used as an amplifier. Next, it is necessary to know what the tube does in the amplifier, and how it functions while in operation.

The Purpose

The purpose of this experiment is to determine experimentally the minimum distortion that can be obtained by using the proper "C" bias, on the tubes in an audio amplifier.

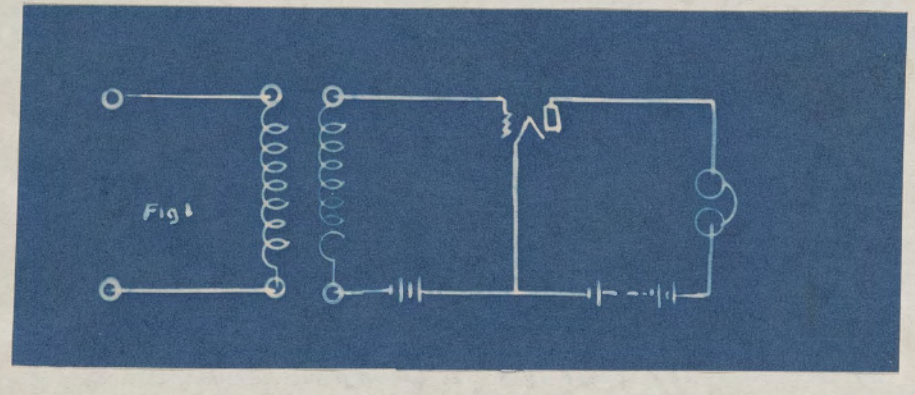
After having determined the grid voltage for minimum distortion experimentally, in an endeavor to make a more complete study of the occuring distortion, the input and output wave was photographed by means of an oscillograph.

With this in mind an amplifier was designed and built, in order that experimental data could be secured to meet the above requirements.

Theory

The tube as an amplifier:

The amplifier tube differs very little in construction from the other types of tubes. It contains a grid, a filament, and a plate. The filament, when connected to a source of current, becomes heated to a temperature high enough that it emits electrons which flow to the plate, which is of a positive potential. The grid, which is negatively charged, governs the flow of electrons. This grid voltage varies directly as the strength of the input signal, thus allowing a fluctuation of the electrons. Fig. 1 shows the arrangement of the tube as connected in a circuit.



In amplifier tubes, it is sometimes the practice to leave some few gases present. The electrons collide with the gas molecules, thus knocking off extra electrons, and thereby causing the tubes to have different characteristics. From Fig. 1, it can be seen by the circuit diagram that if electrons are taken from the neutral gas atoms, they may again return, since there is a complete circuit.

In the amplifier tube, type "45", which is used in the push-pull arrangement, the filament is supplied from a source of alternating current which is used in the same way as in the D. C. tubes. Due to the heavy filament in this tube, the alternating current does not cause a temperature change that is sufficiently great to cause an objectionable hum.

The amplifier:

To understand fully just what a push-pull amplifier is, and how it acts, it is necessary to first analyze the plain amplifier, as in Fig. 2.

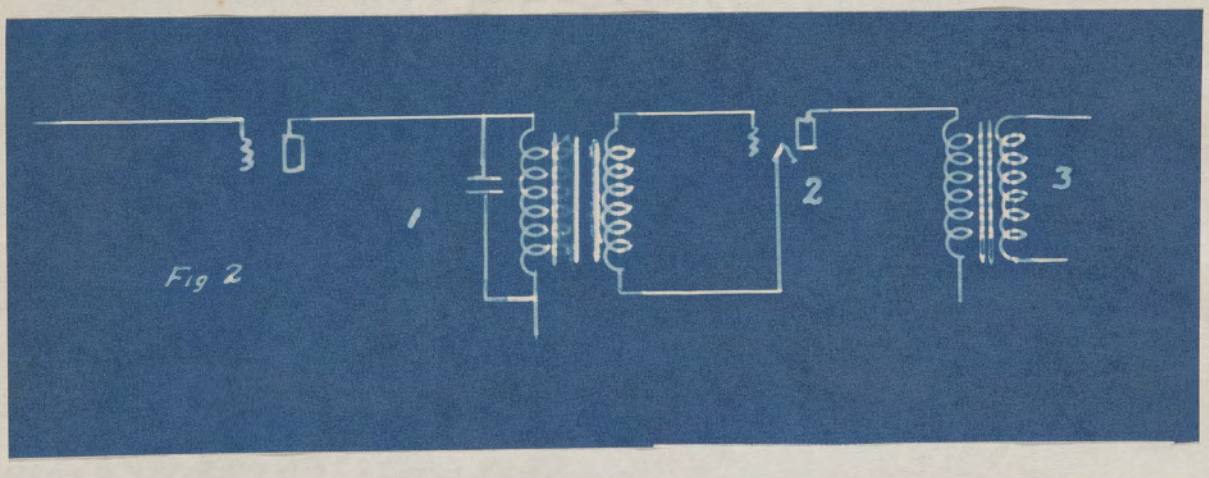


Fig 2

Here the wave is fed into the primary of the transformer, (No. 1 Fig. 2) and a corresponding wave is set up in the secondary. Due to the negative potential of the grid on tube, (No. 2) the fluctuation causes a similar change to occur in the tube. This change in the grid voltage causes the change in the plate current, thus setting up a similar wave, but of a greater magnitude, in the primary of the transformer (No.3). This process is repeated each time the wave is amplified. In order that the wave be amplified properly, it must be of limiting value, since the wave must fall on the straight portion

of the characteristic curve.

Push-pull amplifier:

In the push-pull amplifier, the grid voltage changes are applied to two tubes, so connected that increasing grid voltage on one tube is accompanied by decreasing grid voltage on the other. The result is that the plate current changes, which are opposite in direction for the two tubes, are passed through an output-coupling device in such a way that their effects are additive. One tube tends to pull the plate current through the coupler, while the other tube tends to push it through in the same direction. This action has caused the amplifier to be called the push-pull system.

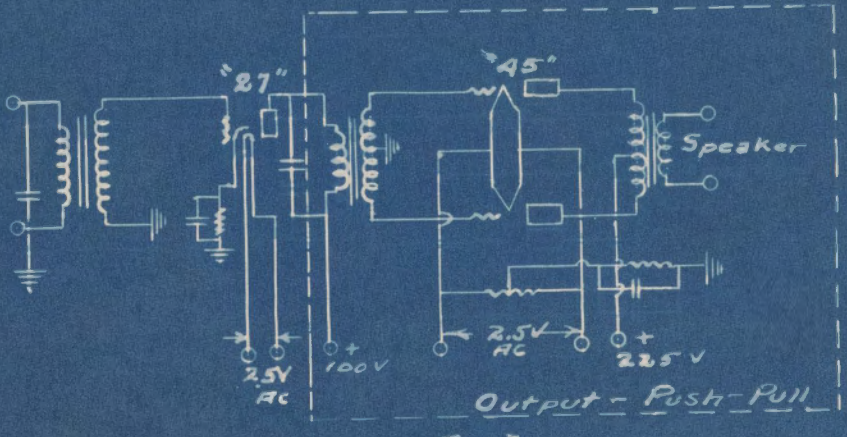


Fig. 3

The circuits of the special transformers and the tubes are shown in Fig. 3. The input transformer consists of a primary, which connects to the plate circuit of an ordinary stage of amplification, and a secondary which is center tapped, having a terminal at each end and one in the middle. The center tap

is used as a common filament at the electrical center. This is connected in conjunction with a "C" battery in the usual way. The two grid terminals are connected to each of the two respective tubes.

The output transformer also has a split winding, but this time it is the primary winding that is split. The output from the plates of the two tubes is brought to the two outside taps of the transformer, and the "B" battery terminal is brought out from the electrical center of this primary winding. This output transformer has a single winding, which is connected to the speaker.

In the double secondary of the input transformer, there is a voltage drop at one of the grid terminals, and at the same time, there is a corresponding rise in voltage at the other grid terminal. Because both parts of the secondary are coupled to the common primary in the transformer, rise and fall of plate current fed into the primary causes rise and fall of voltage in the split secondary. If either terminal of the secondary is considered, we first get a rise of voltage at the considered end, accompanied by a fall of voltage at the other end. This is a reversable process, and with a wave present, the opposite takes place.

By this action, the voltage on one grid terminal lowers and then the voltage on the other grid lowers. Thus it may be seen that the grid voltage on one tube drops during one half the signal, while during the other half of the wave, the grid

voltage of this tube rises. The grid rise and fall in the second tube is always opposite to the rise and fall of the first tube.

The outputs from the plates of the two tubes combine in the split primary of the output transformer and their combined effect passes to the output transformer's secondary.

Fig. 3 shows the connections of the push-pull amplifier and the values for all parts in the construction. The operating action of the push-pull amplifier may best be understood from Fig. 4. In Fig. 4 are shown two amplifier tubes, each connected to its own separate input and output transformer. Assumptions are made as to the flow of the plate currents in the input as indicated by the arrows. The varying plate current flows through both transformers in the same direction of the arrows through the primary sides of both input transformers. Because the plate current flows through both transformers in the same direction, the voltages in their secondary windings will be similar, both windings being positive at the top and negative at the bottom for the hypothetical case. The top of the input transformer is connected to the grid of its tube, while the bottom of the lower input transformer is connected to the grid of the lower tube. Thus the grid in the upper tube is being made more positive in voltage while the grid of the lower tube is becoming more negative.

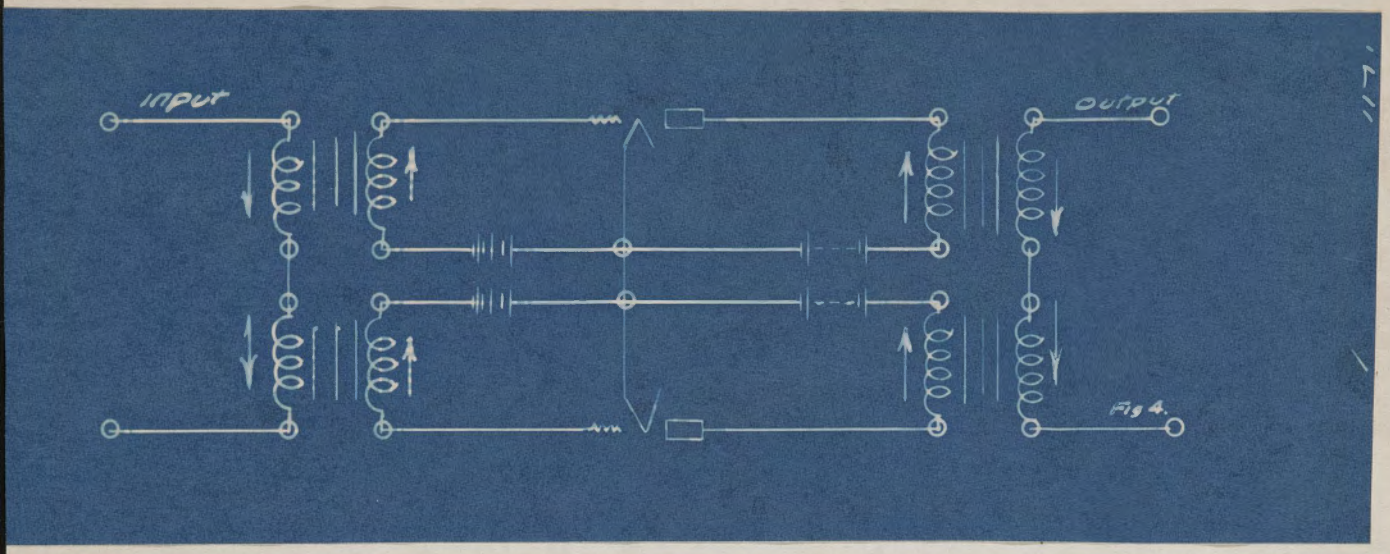


Fig 4.

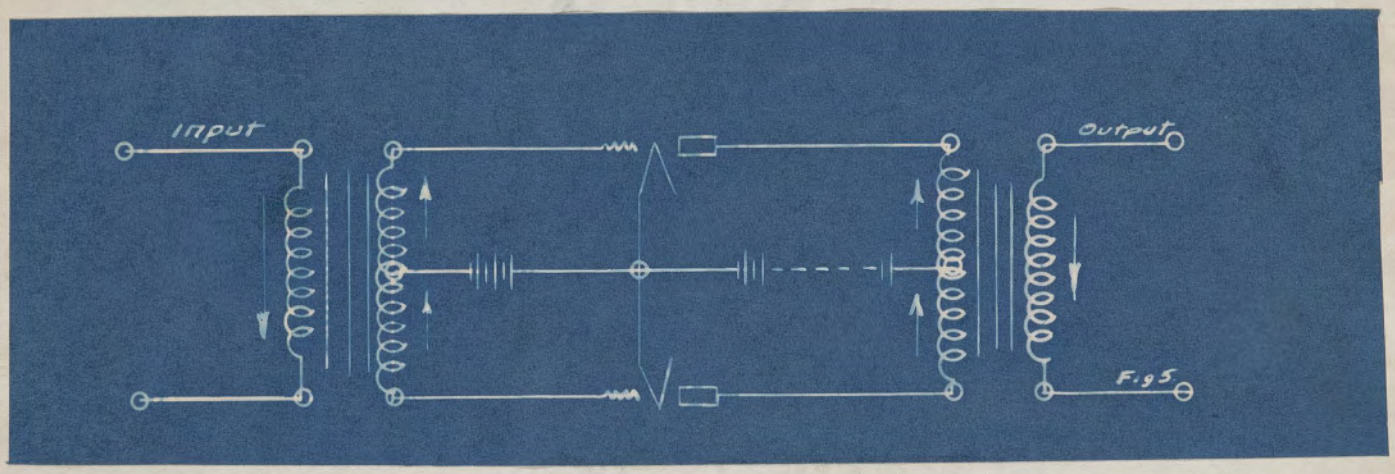


Fig 5.

The increase of the flow of the plate current will vary directly with the increase in the grid potential. It may be seen that in the upper tube the plate current is flowing toward the plate at an increasing rate as shown by the arrow. While this is taking place the plate current of the lower tube is decreasing and in effect is flowing away from the plate as indicated. Since the connections to the primary sides of the lower output transformer are reversed from those to the upper output transformer, current flow is from the bottom to the top in both transformers. This flow of current in the primary windings will cause the voltages in the output transformer secondary windings which will act together and the

two secondary windings will have an additive effect. Fig. 5 shows how the currents flow in the actual system as it is used.

It will be realized that the effect of the change in the plate current in the upper output transformer is added to the change in the plate current of the lower output transformer. Therefore the resultant current is the sum of the two.

The total voltage of the secondary of the input transformer is applied to the two tubes together, consequently each tube is acted upon by half the transformer voltage. For this reason, a push-pull is to show an advantage over a single tube in volume of output.

"Morecroft" makes the statement that when two tubes are used in push-pull, the maximum volume will be five times that of one tube used alone, the quality remaining the same.

The output of two tubes when operated in a push-pull fashion is: $$P = \frac{M^2 E_g^2}{2R_p}$$

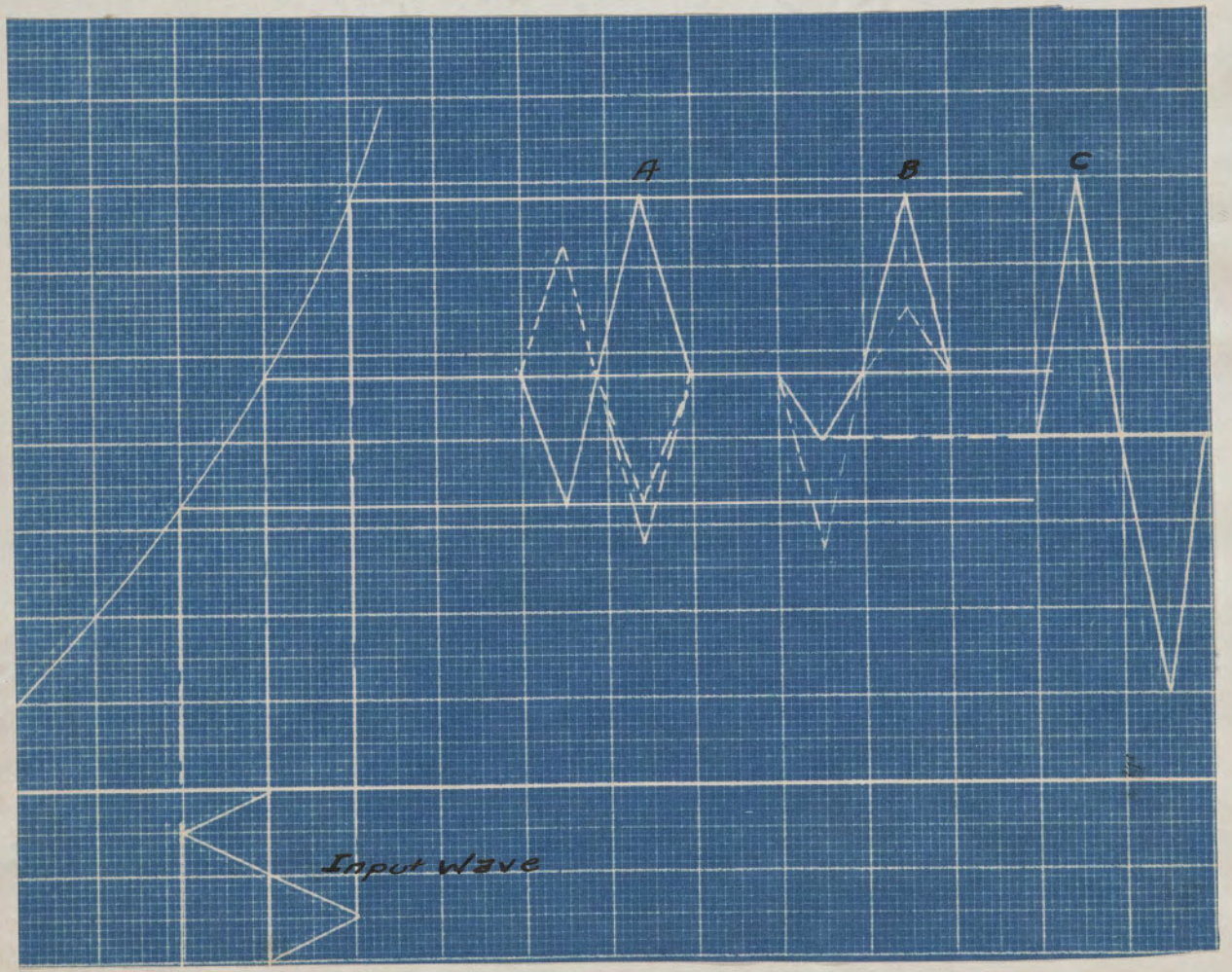
E_g = Grid Voltage
R_p = Tube Impedance
M = Amplification factor of tube

When a single stage of amplification is used the output is:

$$P = \frac{(M E_g)^2}{8 R_p}$$

From the above equations it is obvious that the output of the two tubes in push-pull is more than four times as great as that obtained from an amplifier of the later type.

In Fig. 6 is shown the effect of applying the grid voltages on a part of the grid plate current curve that causes each tube to distort. For an equal applied grid voltage, the decrease in plate current is somewhat less than the corresponding increase as shown at "A". The output transformer connection causes the current changes to assist each other which in reality consists of reversing one of them at "B". These combined effects cause the change at "C". It is found that here the large change of the broken line curve at "B" is combined with the smaller portion of the full line curve to produce the first half of the curve "C", while the large change of the full line curve combines with the smaller one of the broken line curve to produce the second half of curve "C".



One of the best features of the push-pull amplifiers is that the second harmonic currents are eliminated. This is because the second harmonic currents are 180 degrees out of phase, thus they neutralize themselves. The voltage in the transformer is 90 degrees out of phase with the current.

To obtain the value of the grid voltage for best performance, it is essential that either one of two things be done. The practical solution is to adjust the grid voltage by means of a variable resistance for the best performance. The second method is to determine by the use of the characteristics of the tube, the voltage that should be used on the tubes. The characteristic curves of the type "45" amplifying tube give lead to the probable grid voltage that gives minimum distortion. By practical experience it is found to be much easier to put a variable resistor in the grid circuit and proceed by hunting the best grid value for least distortion as decided upon by a group of individuals assembled for this specific task.

Apparatus

The apparatus consists of an audio amplifier which is composed of the following parts:

1 - 227 tube socket

2 - 245 tube sockets

1 - 3:1 audio transformers

2 - push-pull transformers, General Radio "441"

1 - 750 ohm resistor

1 - variable resistor

2 - .006 mf. condensers

2 - .5 mf. condensers

Source of power supply

Electric Victrola with magnetic pick-up and volume control

Two loud speakers:

Philco magnetic cone speaker

Magnavox Dynamic cone speaker

Tubes:

1 - "227" (amplifier)

2 - "245" (power amplifier)

Supreme "400" B test instrument

Weston Voltmeter 0-7.5-300

Weston Milliampmeter 0-25-50

Weston Ohm-meter

Weston A. C. voltmeter

G. E. oscillograph

Construction of the Amplifier

Because of durability and neatness, aluminum was chosen for the metal part which was arranged in the most suitable manner for the location of the parts and the neatness of construction. Since it was necessary that a power source be arranged for in connection with the amplifier, it was decided to build this unit in with the amplifier. For this reason it was necessary that the unit be made much larger than it otherwise would.

The transformers, condensers, chokes and tube sockets were mounted on the panel, and the parts wired up as indicated in the drawing previously referred to.

After having wired the apparatus and getting it in functioning order, the amplifier was tried out. Complying with the data offered by the manufacturer of the amplifier tubes, the grid voltage was adjusted to the nearest possible value for the corresponding plate voltage. To see how near this would come to being true, it was necessary to plot the tube characteristic curves. To plot these curves it was necessary to secure the suitable data by means of electrical instruments. With a fixed voltage, the plate current was read for arbitrarily assumed plate voltages. This gave ample data to plot the tube characteristic curves mentioned.

By means of the voltmeter the plate voltage was read and the grid voltage adjusted to the manufacturer's rated data. With

this condition existing and the amplifier reproducing music, several people were asked to judge the fidelity of the reproduction. While they were not conscious of the fact, the grid voltage was varied 10 volts below the original value, and later 10 volts above the original value. In both instances, the tone qualities changed.

Fechner, who is one of the world's most outstanding psychologists, says that the sound wave must be changed from 1/3 to 1/4 in intensity to cause a noticeable change in volume heard by the ear. This being the case, the dependability of the human ear as a judge would be very inaccurate. However the fact that the intensity and the tone qualities bear a very distant relationship to each other is to an advantage, for with persons who are trained in musical lines, the variation in tone qualities, if such were measurable, would be less than a ten percent variation, according to Mr. Fechner.

Following is a tabulated result of the test conducted. This shows very clearly that in actual practice the tone qualities change slightly.

Special care was used in conducting the test. Two loud speakers were used, one a magnetic speaker and the other one a dynamic speaker. By means of a switch, the two were interchanged at will.

In an attempt to analyze the amplification and the distortion to a further extent than theory, the use of the oscillograph was made. The amplifier was fed by means of an audio

oscillator which had the frequency calibration made. By using the various frequencies, it was found that the amplification was undistorted over the three chosen frequency bands.

The prints shown were made of the input and the output wave of the three chosen frequencies which were 860, 1050 and 1185 cycles respectively. In the input wave there are present harmonics which do not show up in the resultant wave. In the amplifier the input wave was of a voltage nature; thus in the push-pull arrangement the second harmonic currents being 180 degrees out of phase, they are eliminated.

This type of wave was particularily desirable since it would in actual practice represent a probable wave from a one stage amplifier, having present a second harmonic it would then pass through the push-pull system and again be an undistorted wave.

Whether or not the amplifier would respond to all frequencies to the same degree, is dependent to a large extent on the design of the transformers. If the transformers do not respond accurately to the audio range, no matter what conditions may otherwise exist, the only remedy will be to choose suitable, and adequately designed transformers for this purpose.

In order to limit the distortion to the amplifier it is necessary to have a suitable source for amplification and to have reproducers which faithfully reproduce the signals delivered them. It was found by using a radio as a source of input to the amplifier that the output of the radio varied to

such an extent in signal strength that an analysis was made. The chief source which causes distortion is not in the amplifier in this case, but in many cases the signal that feeds the input of the amplifier is distorted before ever reaching the amplifier stage to such an extent that the resultant wave is a much more exaggerated form than the one shown as taken from the test.

Conclusions

1 The push-pull amplifier eliminates the second harmonic currents; thus producing an undistorted wave.

2 The output of a push-pull amplifier is much greater than can be obtained using the tubes in any other arrangement.

3 The amplifier is not directly independent of the grid voltage but it will not distort the wave to any great extent if higher than rated value is used.

4 The chief source of distortion occurs before the amplifier stage in the radio set.

5 The transformers to reproduce faithfully, must be exactly center tapped, and thus respond over the entire range of audio frequency ranges.

Data

Rated output of a 245 tube as given by the manufacturers:

A. C. voltage 2.5

D. C. Plate 180

D. C. Grid -33

Plate current 26 Millamps

Max. undistorted output 780 mill watts

Grid voltage 0

I	E
70	140
57	120
45	100
35	80
24	60
15	40
0	0

Grid voltage -10

74.5	180
61	160
48	140
37	120
27.5	100
16.5	80
7.5	60
8.5	

Grid voltage -20

51	180
40	160
30	140
20	120
10.5	100
4	80

Grid voltage -30

Grid voltage -30

I	E
31.5	180
21.5	160
12.00	140
5.0	120
1.5	100

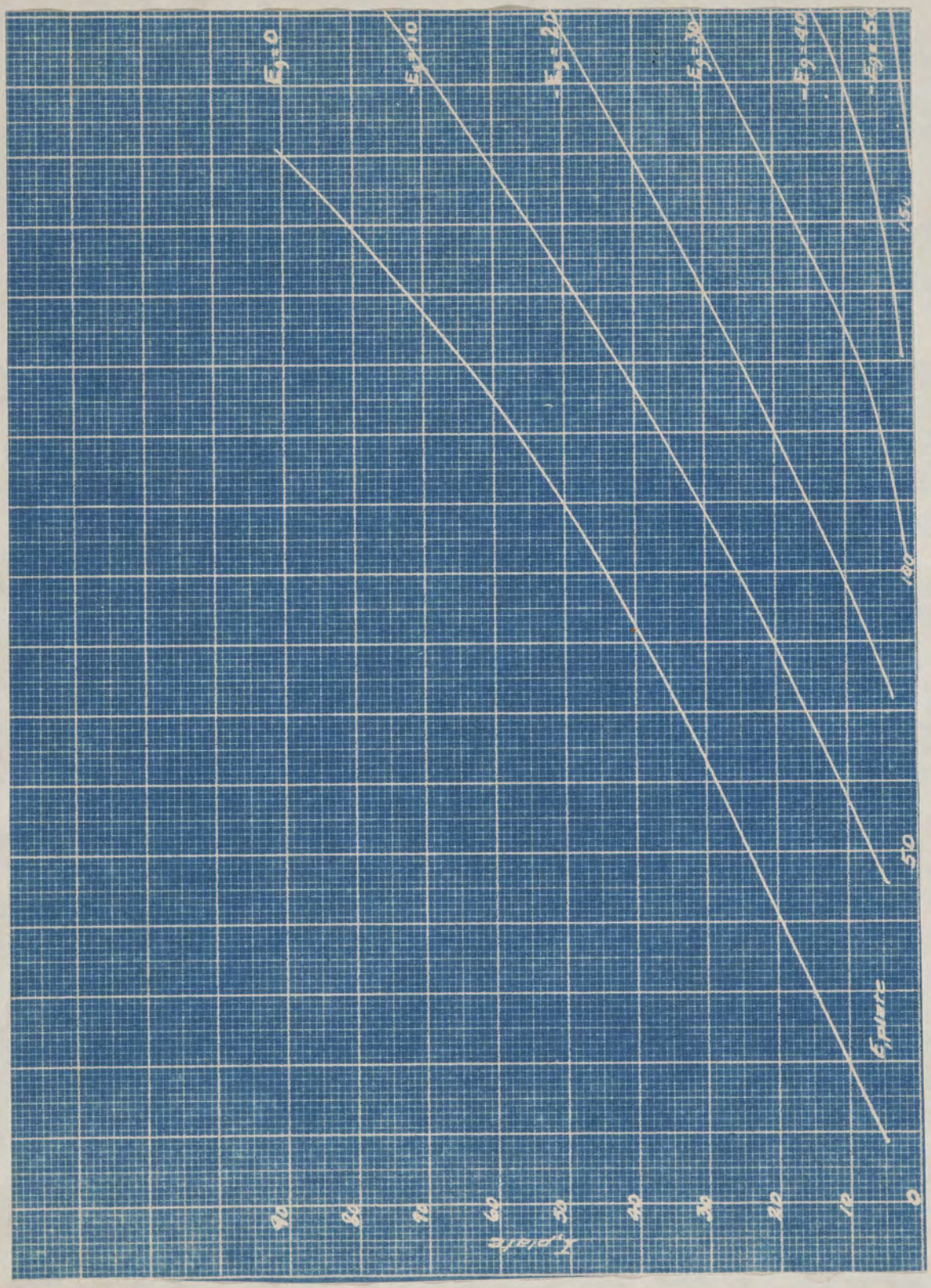
Grid voltage -40

14.5	180
10.5	170
6.5	160
3.5	150
2.25	140
2.00	125

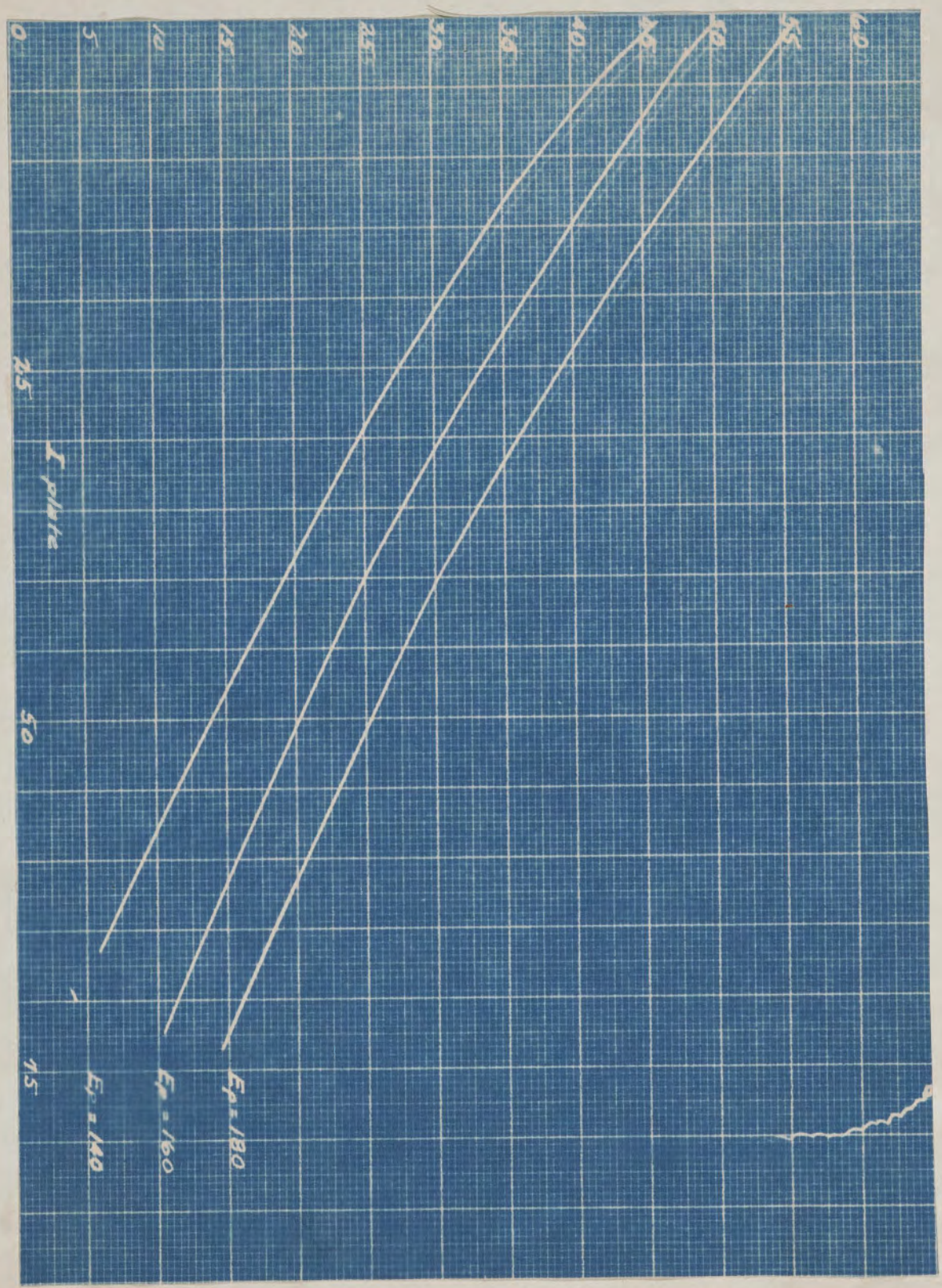
Grid voltage -50

3.75	180
1.00	160

The Curve sheet shows the relation between Ip and Ep for constant grid voltage

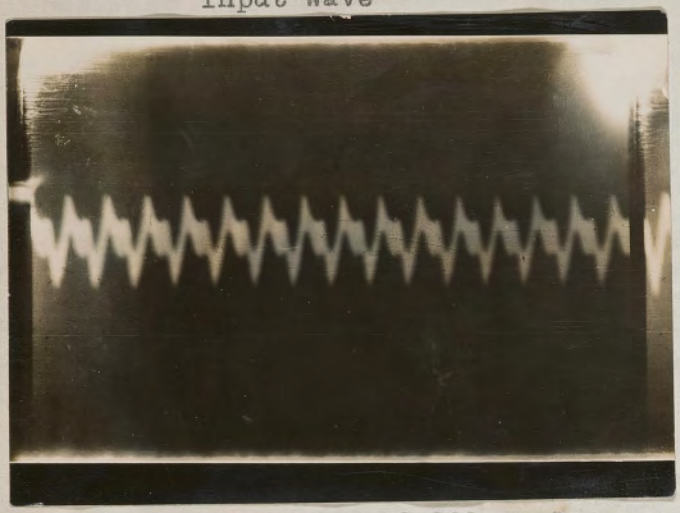


The Curve sheet shows the relation between Eg and Ip for constant plate voltages

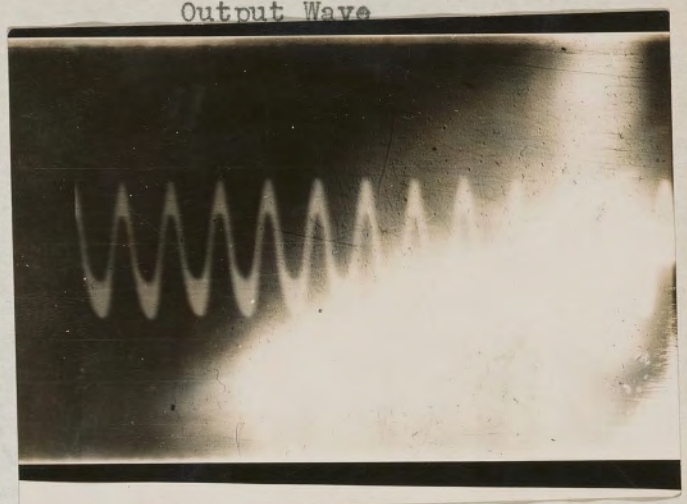


Below are photographs of the input and output waves as taken by the Oscillograph .

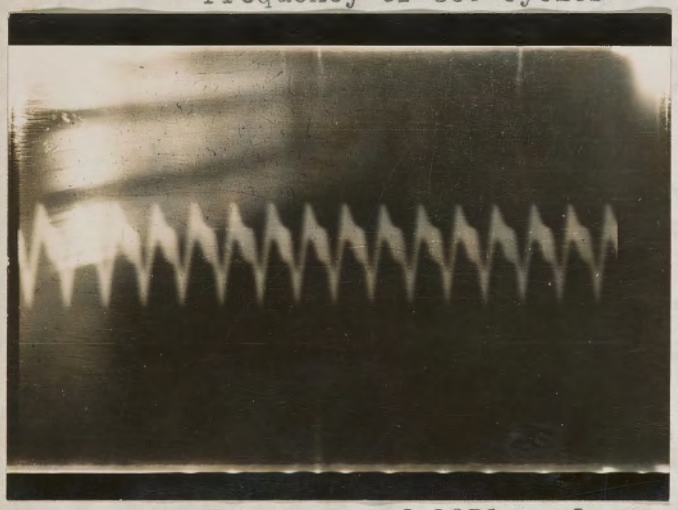
Input Wave

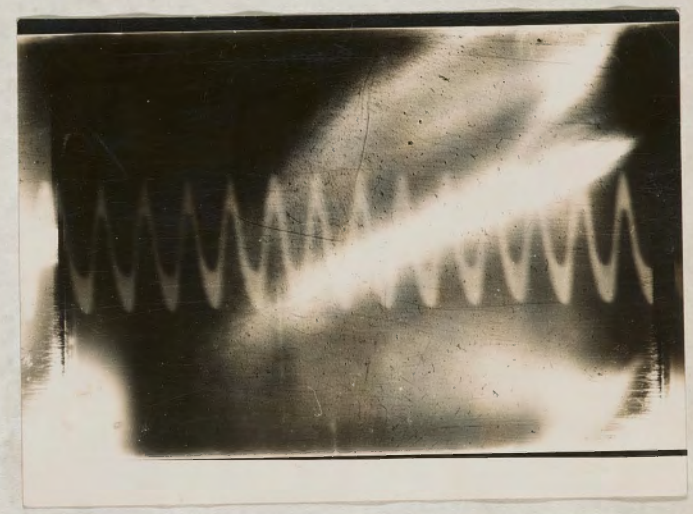


Output Wave

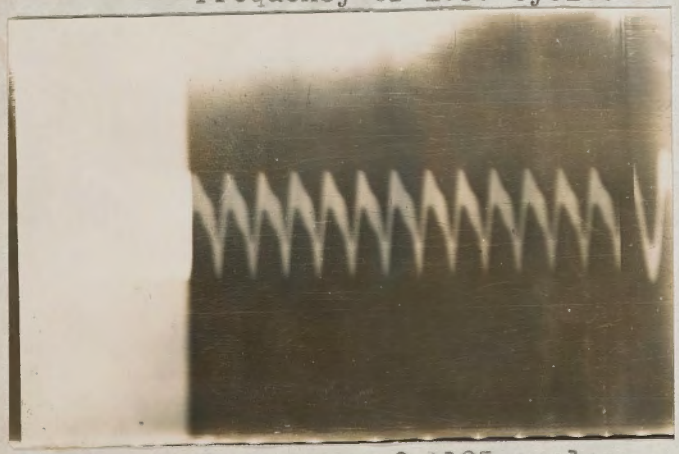


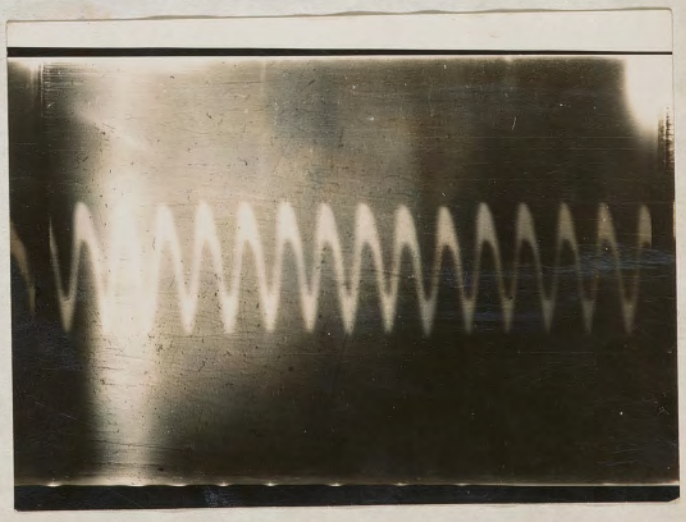
Frequency of 860 cycles





Frequency of 1050 cycles





Frequency of 1185 cycles

Below is the tabulated result as rendered by the listener.

Persons listening	Grid voltage	Quality
Person A	-20	Poor
	-10	Poor
	-40	Good
Person B	-40	Good
	-50	Fair
Person C	-30	Good
Person D	-35	Good
	-25	Poor
	-45	Poor
Person E	-35	Good
Person F	-35	Good

Bibliography

Principals of Radio Communication

J. H. Morecroft

Elements of Radio Communication

J. H. Morecroft

Radio Handbook

Moyer & Wastrel

Miscellaneous Sources Including:

Radio News

Electronics

Radio Engineering

APPROVAL

The foregoing thesis is hereby approved as a creditable study of an engineering subject, carried out and presented in a manner sufficiently satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is to be understood that by this approval that the undersigned does not necessarily endorse or approve any statement made, opinions expressed, or conclusions drawn therein, but approves the thesis only for the purpose for which it is submitted.

Name- J. G. Tarboux

Title- Prof. of Elec. Eng.