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APPARATUS FOR PRESENTATION AND CONTINUOUS MEASUREMENT OF ERROR IN A TWO-DIMENSIONAL COMPENSATORY TRACKING TASK

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ABSTRACT

An electronic compensatory-tracking apparatus which utilizes a two-dimensional target locus is described together with its computing and recording circuits. The apparatus was designed to provide a standard task of variable difficulty for use in the study of attention. The target path used approximates the equation $\rho = \cos 2\theta$. This is a four-leafed rose curve. The stimulus spot is displayed on the face of a cathode ray oscilloscope (CRO). Control is exercised by the subject through manipulation of a joy stick of very low mass and friction. Subject error, represented by the displacement of the stimulus spot from the intersection of a pair of crosshairs on the CRO screen, corresponds to $\sqrt{x^2 + y^2}$, where x and y are the input voltages to the CRO. The quantity $\sqrt{x^2 + y^2}$ is computed continuously by the electronic analog computer and recorded both as a function of time and as an integrated error score.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

JACK BOLLERUD
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TABLE OF CONTENTS

Page

Introduction 1

Function Generator 1

Control Stick. 6

Cathode Ray Oscilloscope 7

Electronic Analog Computer 8

Bibliography 22

Appendix-Adjustment of Apparatus 23

LIST OF ILLUSTRATIONS

Figure		Page
1	Block Diagram of Two-Dimensional Electronic Compensatory Tracking Apparatus	2
2	Photograph of Function Generator	3
3	Circuit Diagram of Control Stick - Function Generator Ensemble	5
4	Photograph of Control Stick	5
5	Circuit Diagram of the Direct Current Amplifier-Cathode Follower Unit	10
6	Static Response Characteristic of Direct Current Amplifier-Cathode Follower Unit under Load Conditions	10
7	Circuit Diagram of a Square-Law Section of the Computer	12
8	Graph of Response of Square-Law Circuit	12
9	Circuit Diagram of Adding Amplifier	14
10	Graph of Static Response of Adding Amplifier	14
11	Circuit Diagram of Square Root Section of Computer	15
12	Graph of Response of Square Root Circuit	15
13	Graph of Input-Output Characteristic of Computer	16
14	Circuit Diagram of Voltage Integrator	18
15	Graph Showing Response of Voltage Integrator	20
16	Graph Showing Proportionality of Area Under the Curve to the Number of Integrator Counts	20

Introduction

In connection with work being done on the problem of attention in our laboratory, the need arose for a standardized distraction task. We wished to be able to vary the difficulty of the task and the degree of effort exerted by the subject. The experimental means proposed for the purpose consisted of a variation in the velocity of a target spot in a two-dimensional tracking task, to provide a series of difficulty levels, and a variation in the area of error-tolerance circles surrounding the aiming point, to induce differences in the degree of effort exerted by the subject. To obtain an index of the effectiveness of these two conditions it was necessary to provide a measure of the subject's performance level as each of these conditions was varied in successive trials. The principal indicant of the subject's performance used in the study was the integral of the error during a standard time interval.

Although a great deal of work utilizing single-dimensional movement of the target has been reported, relatively few investigations have been published in which two-dimensional target movement is employed. Warren, Fontaine, and Clark (8) have constructed an apparatus which is capable of generating a "scalloped circle" type of function. Their apparatus, although very flexible, is more complex than the one to be described herein, and does not yield a value corresponding to $\sqrt{x^2 + y^2}$, the displacement of the stimulus spot from a reference point in a polar display.

In an earlier attempt to obtain a measure of the relationship between target velocity and subject error, a function generator-control stick-cathode ray oscilloscope ensemble was developed (5). This ensemble, modified to suit the requirements of the computer, was used in the present work. A block diagram of the total system finally developed is shown in Figure 1. Each of the components will be discussed in some detail.

Function Generator

The function generator used in the study is shown in Figure 2. The cams in the photograph are not those used in the experiment. In Figure 2 are shown the Graham variable speed transmission and two speed reducers. The speed reducers were necessary in order to obtain a consistently reproducible speed of rotation of the cams over the range used. The Graham transmission has been calibrated in terms of radians per

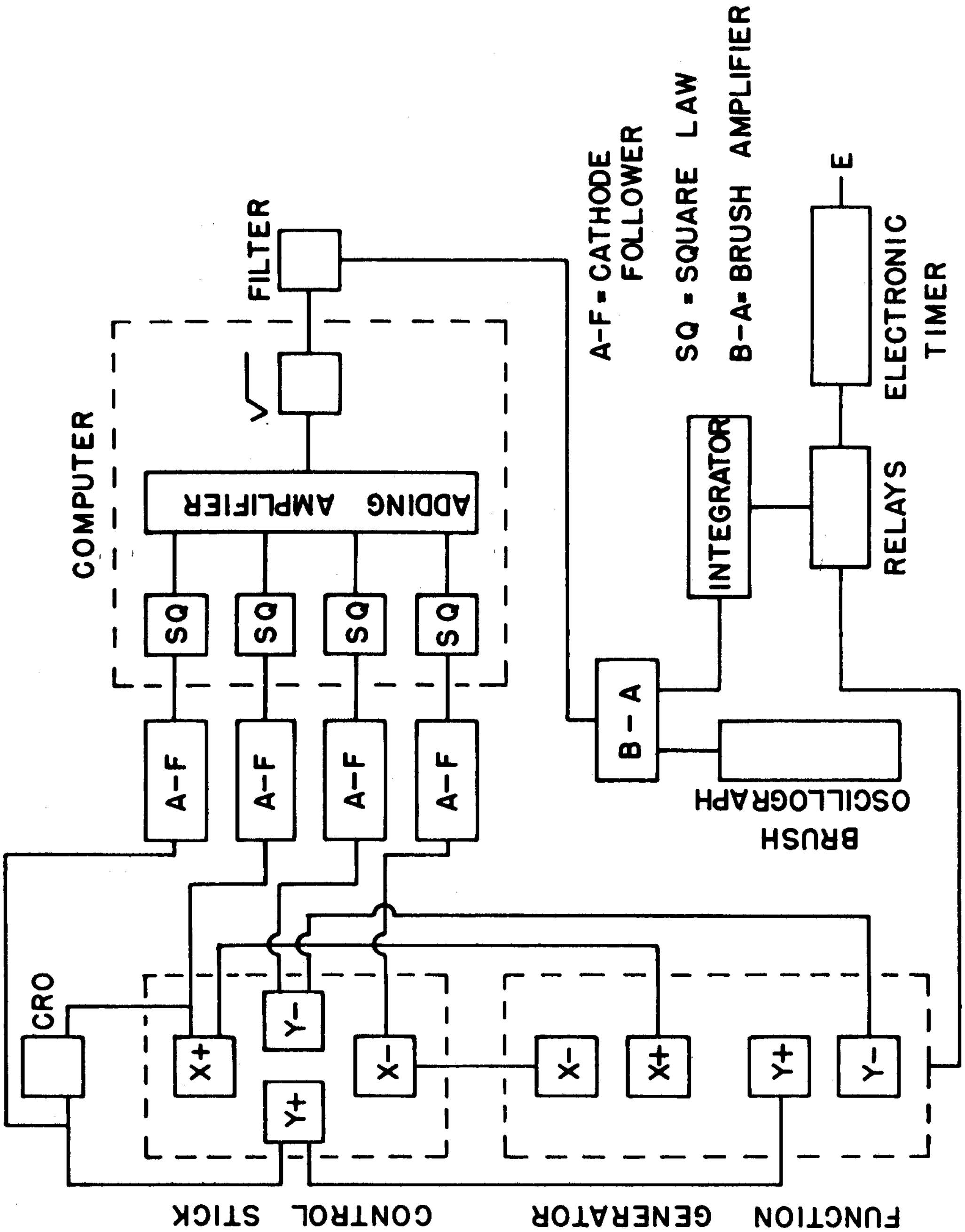

Figure 1. Block Diagram of Two-Dimensional Electronic Compensatory Tracking Apparatus.

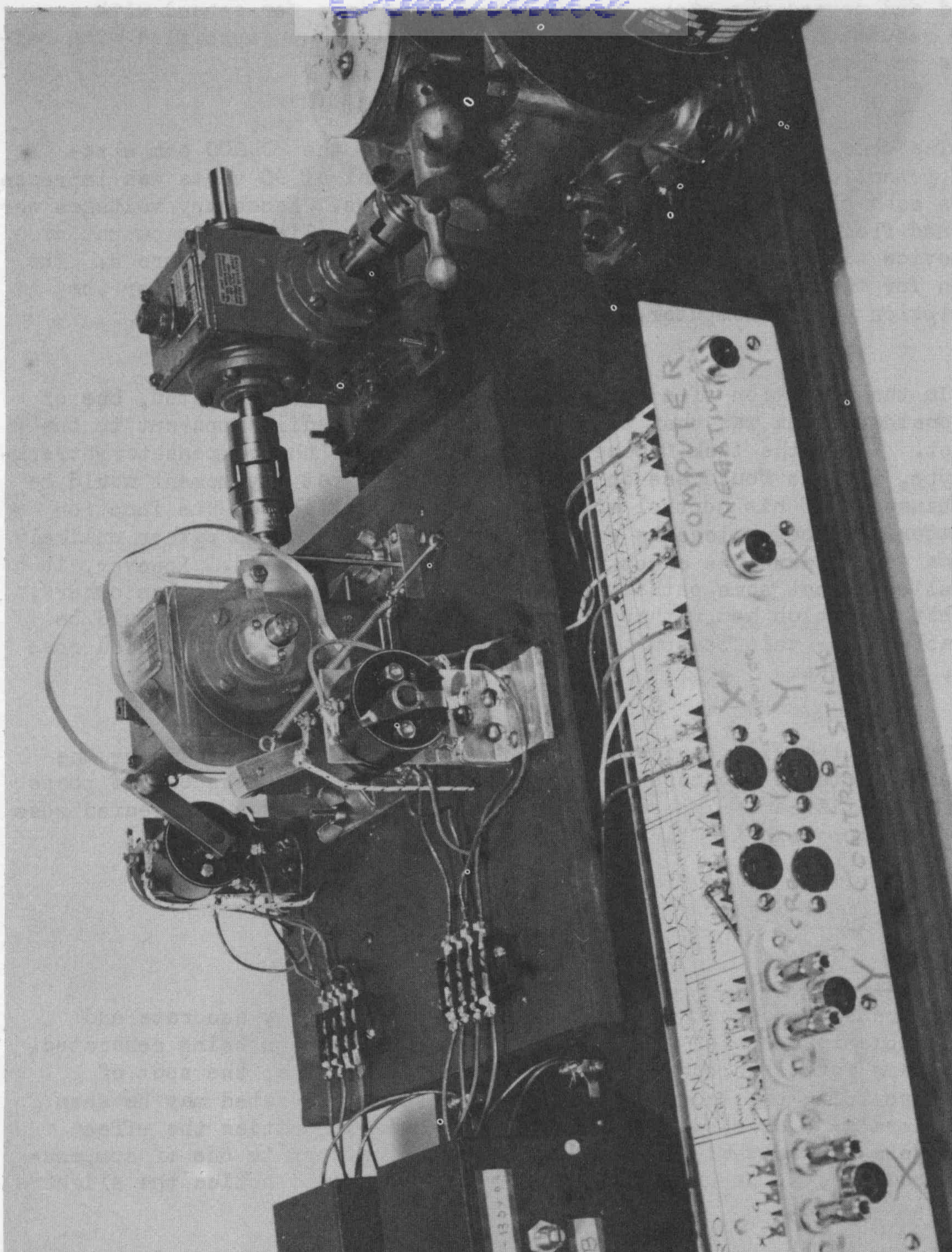

Figure 2. Function Generator.

second and covers the range from 0.2 to 1.6 radians per second with a speed reduction of 50:1. The target velocity has been specified with reference to these values[1].

The cams operate against arms which actuate the 20,000 ohm wire-wound potentiometers. A direct current potential of 90 volts was impressed across each of the four generating potentiometers. Necessary voltages were obtained from four line-regulated high voltage supplies. The output of the device was connected to the control stick as shown in Figure 3. The reason for the use of the dual potentiometers will be given under the description of the computer.

In the selection of a suitable target path to be generated, one of the considerations was that the path be one not readily apparent to the subject. Since the task facing the subject was of the compensatory tracking type, what he would see on the visual display at any moment would be a combination of his control movements plus the effect of the function generator. Hence, unless he exercised no control, it was rather unlikely that he would learn the exact target path being generated. However, it was believed that some paths were less likely to be learned than others, and that one which had rather pronounced changes of direction would be desirable. For this reason the function $\rho = \cos 2\theta$, a four-leafed rose curve, was chosen.

For the training series the same cams were used, but that for the x-axis was rotated counterclockwise until it was 90 degrees out of phase with the y-axis cam. The resulting figure approximated a two-leafed rose curve with lobes in the first and third quadrants.

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1 It is recognized that this procedure is not strictly accurate and holds precisely only for the cams, not for the function being generated. As the cams rotate through their maxima at a high rate, the spot of light describing the locus of the function being generated may be seen to accelerate or decelerate slightly. At lower velocities the effect may be detected only with difficulty. Since the task is one of compensatory tracking, it is unlikely that the subject would notice the slight change in velocity.

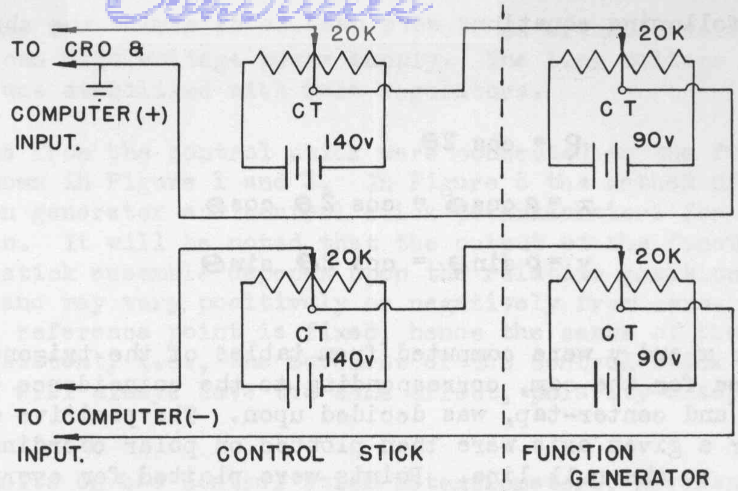

Figure 3. Circuit of Control Stick-Function Generator Ensemble.

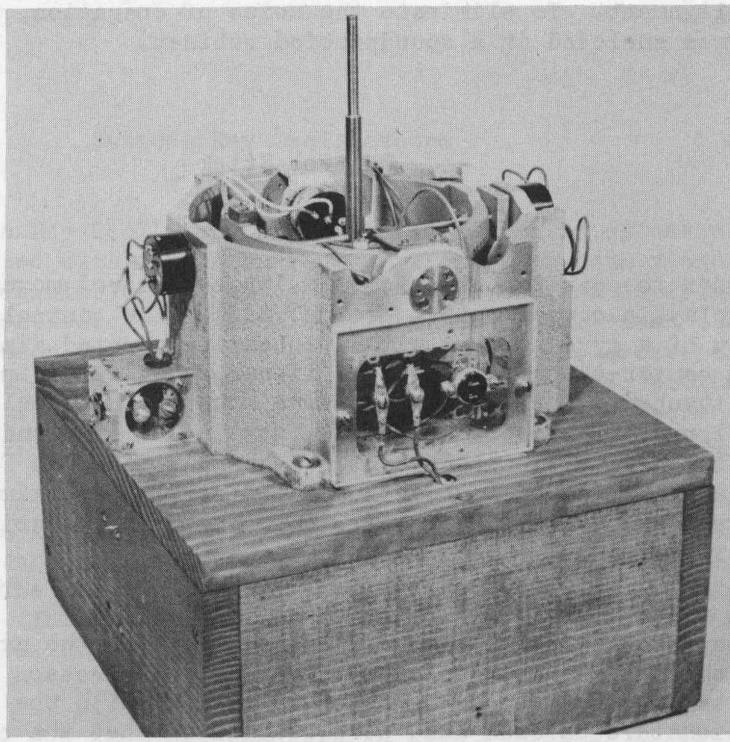

Figure 4. Control Stick. The extension rod, which increased the height of the stick to 28 inches, is not shown.

The following equations were used to determine the shape of the cams:

$$\rho = \cos 2\theta$$

$$x = \rho \cos\theta = \cos 2\theta \cos\theta$$

$$y = \rho \sin\theta = \cos 2\theta \sin\theta$$

Values for x and y were computed from tables of the trigonometric functions. A zero line for the cam, corresponding to the coincidence of the potentiometer arm and center-tap, was decided upon. The positive and negative values for a given axis were then plotted on polar coordinate paper with reference to the null line. Points were plotted for every five degrees, then connected by a smooth curve. When the plots were completed, they were cemented to 3/8 inch clear plastic, roughed out with a jigsaw, filed to a fair approximation to the curve, finished with fine emery cloth, and finally polished with steel wool to provide a smooth bearing surface for the potentiometer arm links. The zero degree, or origin, line of the curve was scribed into the surface of each cam for purposes of later alignment. To eliminate the noise of operation, the function generator was enclosed in a soundproofed cabinet.

Control Stick

In order to permit the subject to impose control movements upon the visual display, a control stick was provided. The control stick consisted essentially of a gyro housing with its bearing-mounted gimbals to which 20,000 ohm center-tapped, precision, linear, single-turn potentiometers had been attached. The gyro housing was mounted on a small stand, as shown in Figure 4. A metal stick 1/2 inch in diameter and 18 inches long was attached to the short vertical shaft visible in Figure 4. The top of this stick was 28 inches from the floor. The maximum angle, measured from the vertical position, through which the stick could be moved was 36 degrees.

Two potentiometers were mounted on each of the two axes of the control stick, as shown diagrammatically in Figure 1. The reason for the duplication will be discussed under the section dealing with the computer. The two potentiometers on each axis were aligned so that the center-tap and wiper arms were coincident when the stick was in the vertical position.

Because of the ball-bearing mounts, very little effort was required of the subject in order to move the control stick. Both friction amd mass were reduced to a very low value.

Each of the four potentiometers was provided with 140 volts direct current by its own high voltage power supply. The line voltage to the power supplies was stabilized with Sola regulators.

The outputs from the control stick were connected to the function generator as shown in Figure 1 and 3. In Figure 3 the method of connecting the function generator and control stick potentiometers for each axis may be seen. It will be noted that the output of the function generator-control stick ensemble depends upon the relative positions of the two wiper arms and may vary positively or negatively from zero. In this arrangement the reference point is fixed, hence the sense of the correction will be consistent, i.e., the movement of the control stick in a given direction will always have the same effect, polarity-wise, on the output.

With 140 volts on the control stick potentiometers, movement of the control stick to the limit of its travel produced an output between the center-tap and wiper arm of 18 volts, which could be positive or negative, depending upon the direction of movement of the stick.

Voltages available from the function generator for each axis were about 16 volts, maximum, giving a small advantage to the subject operating the control stick.

Cathode Ray Oscilloscope

The Cathode Ray Oscilloscope (CRO) used in the study was a Dumont type 304, equipped with direct current amplifiers on both x and y axes. The lucite rectangular coordinate grid was removed from in front of the CRO screen and replaced by a piece of 1/8th inch thick clear plastic upon which had been scribed a set of cross-hairs. The cross-hairs intersected at the center of the screen. With this intersection as center, circles 1/4, 1/2, 1 inch and 2 inches in diameter were scribed into the plastic, forming an aiming reticle.

Two 6 volt dial lamps were enclosed in sleeves which allowed light to escape from a slit 1 inch long by 1/16 inch in width. By means of these two lamps the aiming reticle was edge-lighted from the top and right side, at the point where the cross-hairs reached the periphery of the reticle. This method of illumination caused the cross-hairs and concentric circles to appear bright compared to the rest of the CRO screen.

The cathode ray beam was focussed so that it formed a circle of light 2 millimeters in diameter. The intensity used was one which was just low enough so that no corona was visible under the conditions of lighting which prevailed. This setting was maintained for all subjects.

The 115 volt alternating current line source for the CRO was stabilized with a Sola voltage regulator.

Inputs to the x and y amplifiers of the CRO were as shown in Figure 3. The gain of the x and y amplifiers was adjusted so that 10 volts input produced a beam deflection of 1 inch.

Electronic Analog Computer[2]

An undesirable aspect of the recording method used in an earlier study (5) was the necessity for assuming that the area enclosed by the maximum contour of the photographic trace of the subject's response during a trial was a good measure of his error. In addition, a target path which followed a closed contour was required.

In developing the apparatus for the present study it was decided that the method of measuring the subject's error should permit the use of any function which could be produced by the function generator. It was further decided that the apparatus should not require any assumptions which could not be tested readily.

Since the display on the CRO was in polar coordinates and the subject's error was represented by the distance of the spot from the intersection of the cross-hairs, what was required was a device which could compute the electrical analog of this distance. The quantity desired could be obtained by squaring the x and y voltages applied to the CRO, adding these squared quantities, and taking the square root of their sum. Because the system utilized direct current throughout, resolver systems such as those used in triangle solvers or coordinate transformers (1, 2, 3) could not readily be applied. After some consideration, the idea of using choppers to convert the direct current output of the function generator-control stick ensemble to a form which could be used to actuate a resolver servo system was also discarded. It was decided at length to

[2] The square-law, adding, and square root circuits used in the computer were suggested by Dr. Robert W. Benson of the Central Institute for the Deaf, St. Louis, Missouri. Dr. Benson also gave valuable assistance in the adjustment of these circuits.

perform the required operations by means of vacuum tubes.

Soon after work was begun on the square-law circuits it was found that negative voltages could not be handled by these circuits directly. Full wave rectification was tried, but losses were severe because of loading effects. One solution was to duplicate the function generator-control stick system and to reverse the output leads from the parallel system so that a movement which normally would produce a negative voltage would, so far as the computer was concerned, produce a proportionate positive voltage. There were thus two parallel systems in the function generator-control stick ensemble, only the normal one of which was connected to the CRO inputs, but both of which contributed to the computation of subject error (see Figure 1).

Amplifier-Cathode Follower Units

The amplifier-cathode follower units were developed in order to isolate the function generator-control stick circuits from the square-law circuits. In the initial apparatus tests it was found that the input circuits of the square-law units so loaded the output circuits of the function generator-control stick ensemble that a non-linear relationship obtained between the error shown on the CRO screen and that measured at the output of the computer. It was therefore necessary to insert an impedance transformer between the two units to insure linearity of transfer over the range of voltages used. Additional requirements were first, that no loss be introduced by the insertion of the impedance transformer, and second, that no potential difference appear at the output unless a potential difference existed across the input. A search of available publications on direct current amplifiers yielded two circuits (4, 7) which were combined and modified with respect to circuit constants to fit the requirements of our system (see Figure 5).

The cathode follower section of the circuit gave a gain of 0.65 under load. To compensate for this, the input stage, which was originally designed for a vacuum tube voltmeter, was introduced. Both the amplifier and the cathode follower were of the balanced type. Four such units were required, one for each of the inputs to the square-law circuits.

The input-output characteristic of the amplifier-cathode follower circuit under load conditions is shown graphically in Figure 6. The gain control of the amplifier section permitted the over-all gain of the unit to be adjusted to unity under load.

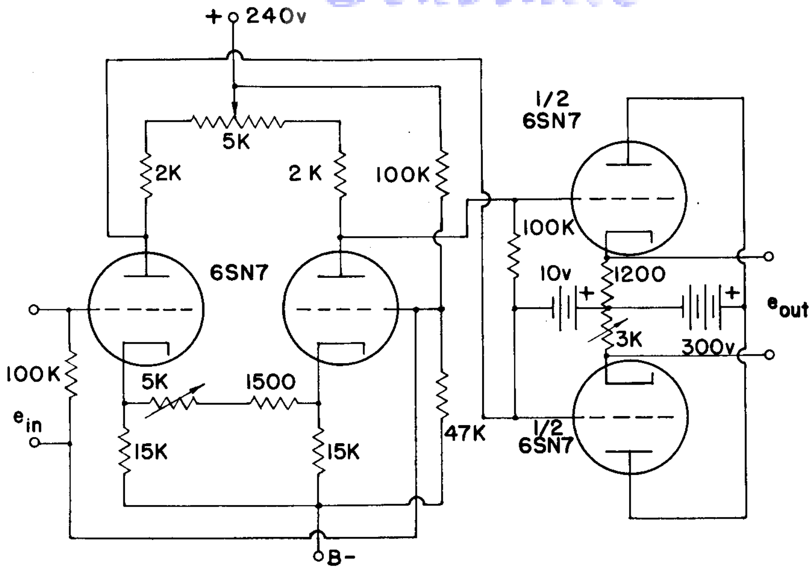

Figure 5. Circuit Diagram of the Direct Current Amplifier-Cathode Follower Unit.

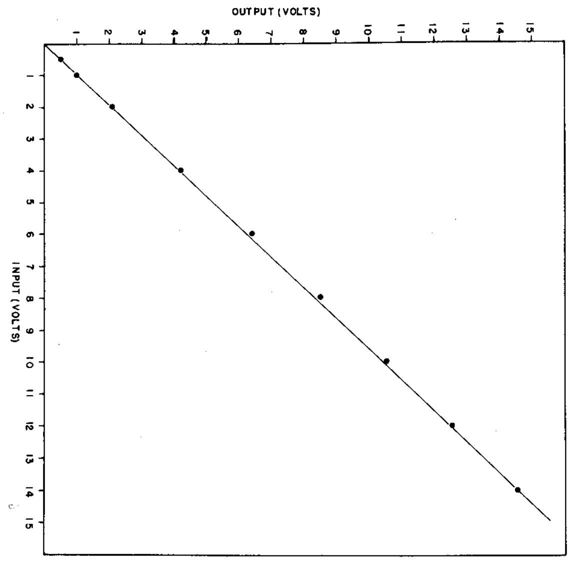

Figure 6. Static Response Characteristic of Direct Current Amplifier-Cathode Follower Unit under Load Conditions.

Square-Law Circuits

In Figure 7 is shown the circuit employed in the construction of the square-law units. The approximation of the output of the units to the mathematical curve is shown in Figure 8.

Essentially, the squaring circuit consists of a series of diodes, the output curves of which are added segmentally to give a composite curve which approximates the square of the input, but differs from it by a constant multiplier. The 6H6's used in this study were operated so as to give the relationship $e_{out} = .01\ (e_{in})^2$.

The procedure involved in arriving at the proper values for circuit constants was as follows:

1. Using a single diode section, try some value of resistance in the output circuit and obtain e_{out} as a function of e_{in} over the range of voltages which will be encountered in practice.

2. Plot the values from 1., and plot the mathematical curve, using some likely scale value which has been chosen, say 0.1 or 0.01.

3. Compare the two curves. If the slope of the empirical curve is not coincident with that of the mathematical curve, change the output resistor until a segment is obtained at the low end of the curve which coincides with the mathematical curve for some distance. The slope is reduced by reducing the value of the output resistor.

4. From $e_{out} = k\ (e_{in})^2$, determine k by substituting values actually found.

5. From the plot of curves for various values of output resistor, determine from comparison to the mathematical curve which segments of the empirical curves to use to approximate the calculated curve. Since the slopes of the empirical curves have been fixed by the values of resistance used, the appropriate resistor size for a given segment may be obtained from the plot and used as the output resistor for a subsequent diode section, so that the desired curve may be approximated by addition of these segments.

6. In order that the segments chosen may be added at the appropriate points along the composite curve, it will be necessary to use a biasing arrangement such as that shown in Figure 7. Before a given diode section will start to conduct, the input voltage must reach a certain value. The exact values of the bias voltages must be determined by test, adjustment, and retest, plotting e_{out} as a function of e_{in} each time and comparing it to the desired curve.

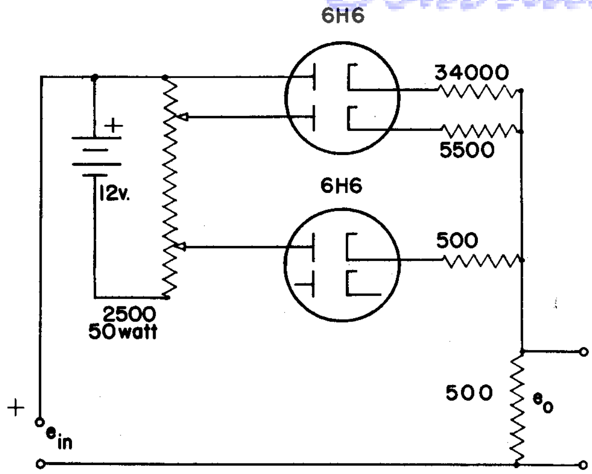

Figure 7. Circuit Diagram of a Square Law Section of the Computer.

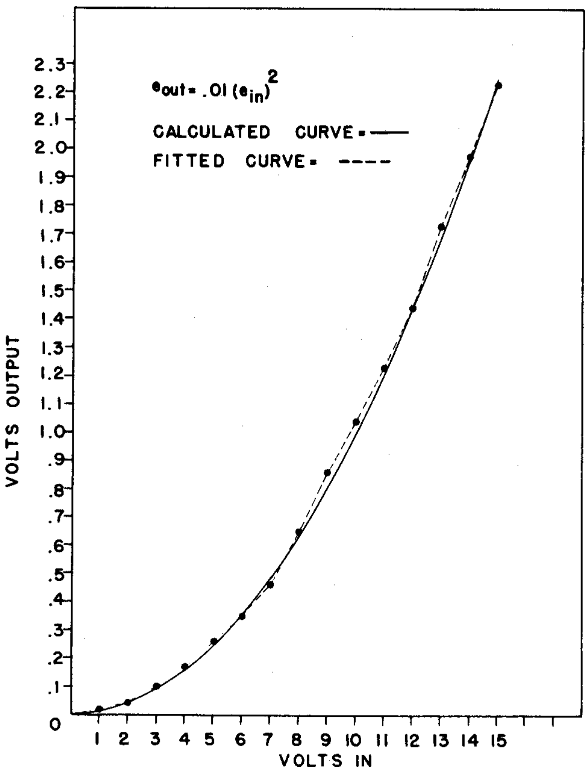

Figure 8. Graph of Response of Square Law Circuit.

This is a somewhat tedious and time-consuming, but necessary process. In the present study it was found that three diode sections gave a fair approximation to the curve $e_{out} = .01(e_{in})^2$ over the range of inputs used. (see Figure 8).

Adding Amplifier

After the positive and negative components had been squared as explained in the preceding section, they were summed as shown in Figure 9. The 500 ohm resistors across the input to the amplifier are the output resistors of the square-law circuits. Since the output of the square-law circuits was small, a gain of about seven was built into the amplifier. Again, the balanced type of amplifier was used so that an output would appear only when a potential difference existed across the input.

The static response characteristic of the adding amplifier is shown in Figure 10.

Square Root Circuit

When the squaring and adding circuits were functioning properly, work was begun on the square root circuit. The circuit shown in Figure 11 is the result of combining the square-law circuit and a cathode follower so that the characteristic of the square-law was subtracted, in effect, from the straight line response of the cathode follower. The approximation of the response of the circuit to the calculated curve is shown in Figure 12. It will be noted that the curve represents the function

$$e_{out} = 1/2\sqrt{e_{in}}$$

It was felt that a good test of the operation of the computer was one which would relate the output to the input for the whole system, over the range of voltages to be encountered in actual practice. If the computer were operating properly, the output should be a straight line. Because of the losses inherent in the system, which were not compensated for by amplification, one would not expect the output to correspond to the input exactly, but to differ from the input by some constant scale factor. In Figure 13 is shown the over-all response of the computer and its approximation to a straight line.

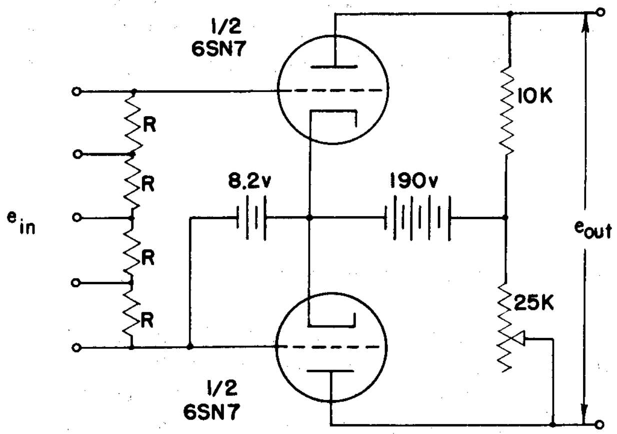

Figure 9. Circuit Diagram of Adding Amplifier.

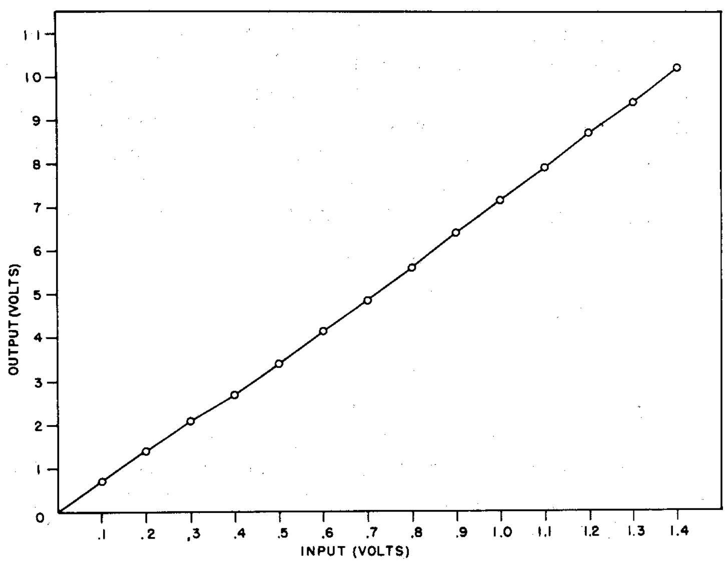

Figure 10. Graph of Static Response of Adding Amplifier.

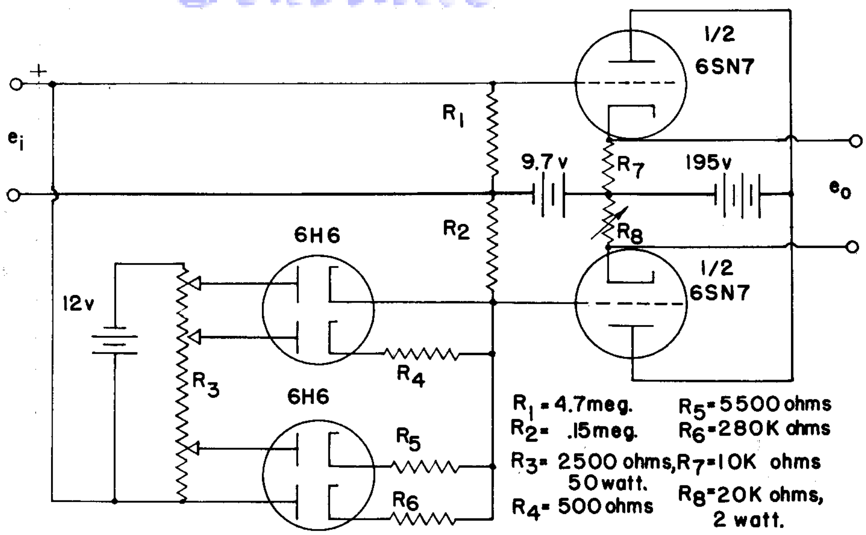

Figure 11. Circuit Diagram of Square Root Section of Computer.

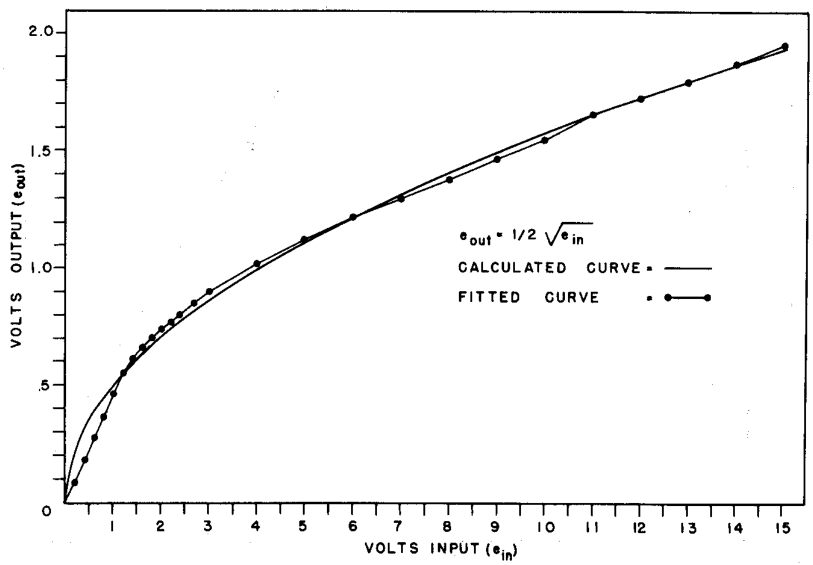

Figure 12. Graph of Response of Square Root Circuit.

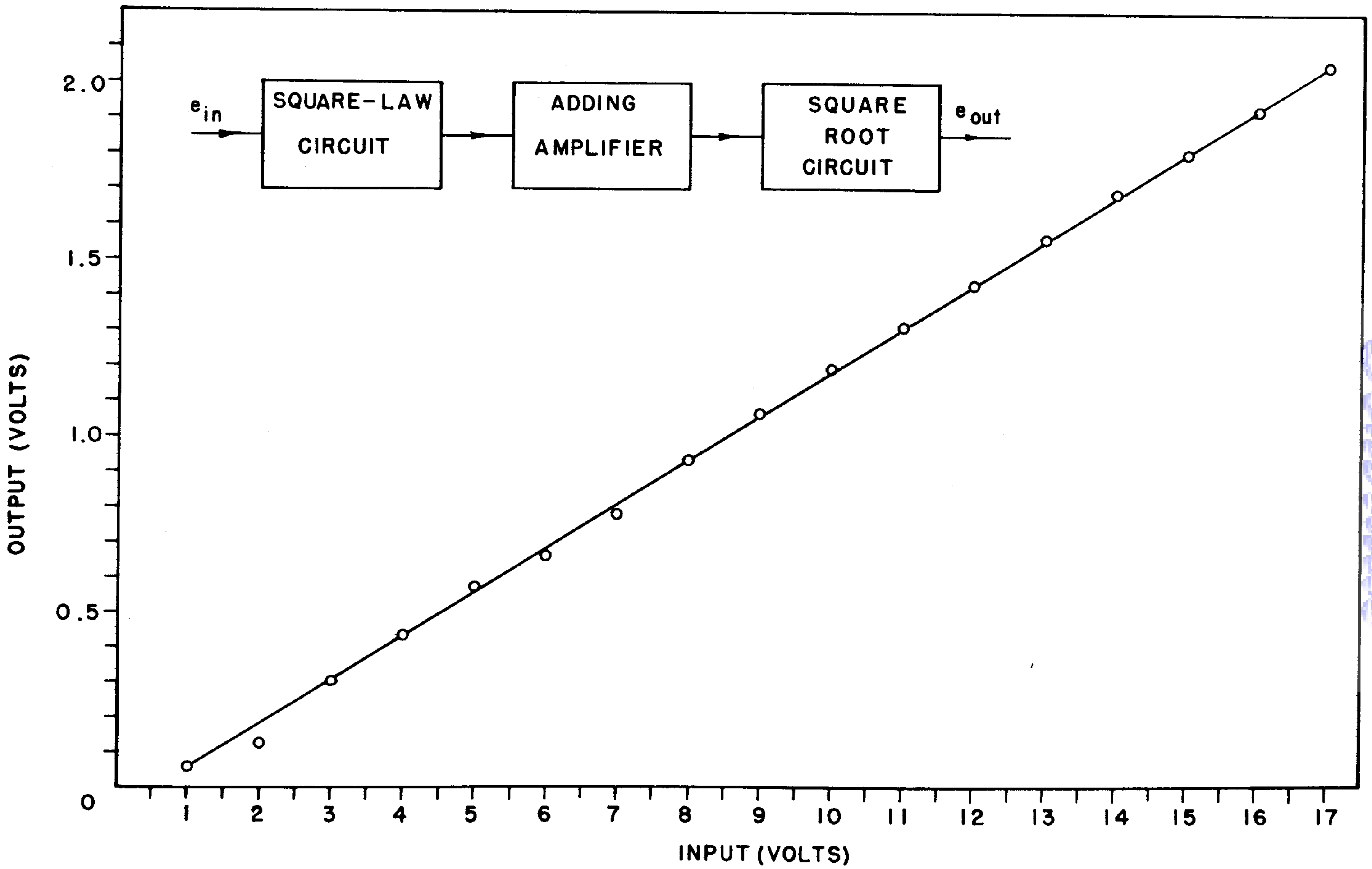

Figure 13. Input-Output Characteristic of Computer Showing Approximation to a Straight Line.

Measurement and Recording of Subject Error

Two types of recording of subject error were desired. One was a type which would yield a record of the time course of the subject's error on a moving paper tape, in this instance, a Brush Oscillograph. The second was one which would provide an easily read result which could be subjected readily to statistical procedures. For the latter purpose a voltage integrator was used in conjunction with a zero-reset Veeder-Root counter.

Since the over-all gain of the computer discussed above was only about 0.12 and produced outputs which rarely exceeded 2 volts, it was necessary to introduce amplification in order to obtain good records on the oscillograph. The additional gain was obtained from the Brush d.c. amplifier, Model BL 932, which is a companion unit to the oscillograph. A gain of 10 was chosen as the most appropriate value for the purpose. Since the gain of the computer without the Brush amplifier was about 0.12, the addition of the Brush meant that the over-all system would have an output approximately 1.2 times the input. Because this factor was a constant, however, it did not affect the usefulness of the apparatus for our purposes.

The output of the Brush d.c. amplifier fed both the oscillograph and the voltage integrator.

Voltage Integrator

One of the requirements of the voltage integrator was that it cycle as often as possible over the voltage range to be encountered in the experiment, within the limits of the components. The requirement was imposed by the fact that each trial lasted for only 30 seconds, and that, at the low target velocities, only a small error voltage was to be expected.

If a large capacitor were to be used in the integrating circuit, it might not reach the critical charge necessary to cause the unit to operate before the end of the trial. Also, the more often the unit cycled, the more samples of the error would be obtained, and the greater would be the accuracy of the measure.

The original circuit for the integrator is due to S. S. Stevens (6), and is reproduced in Figure 14 by permission of the author and publisher. Certain of the constants have been changed to meet the requirements of the present work. We were able to obtain counting rates of 14 per second, which is near the upper limit of the Veeder-Root counter used in the system. Because of its noise, the counter was placed in a sound-proofed

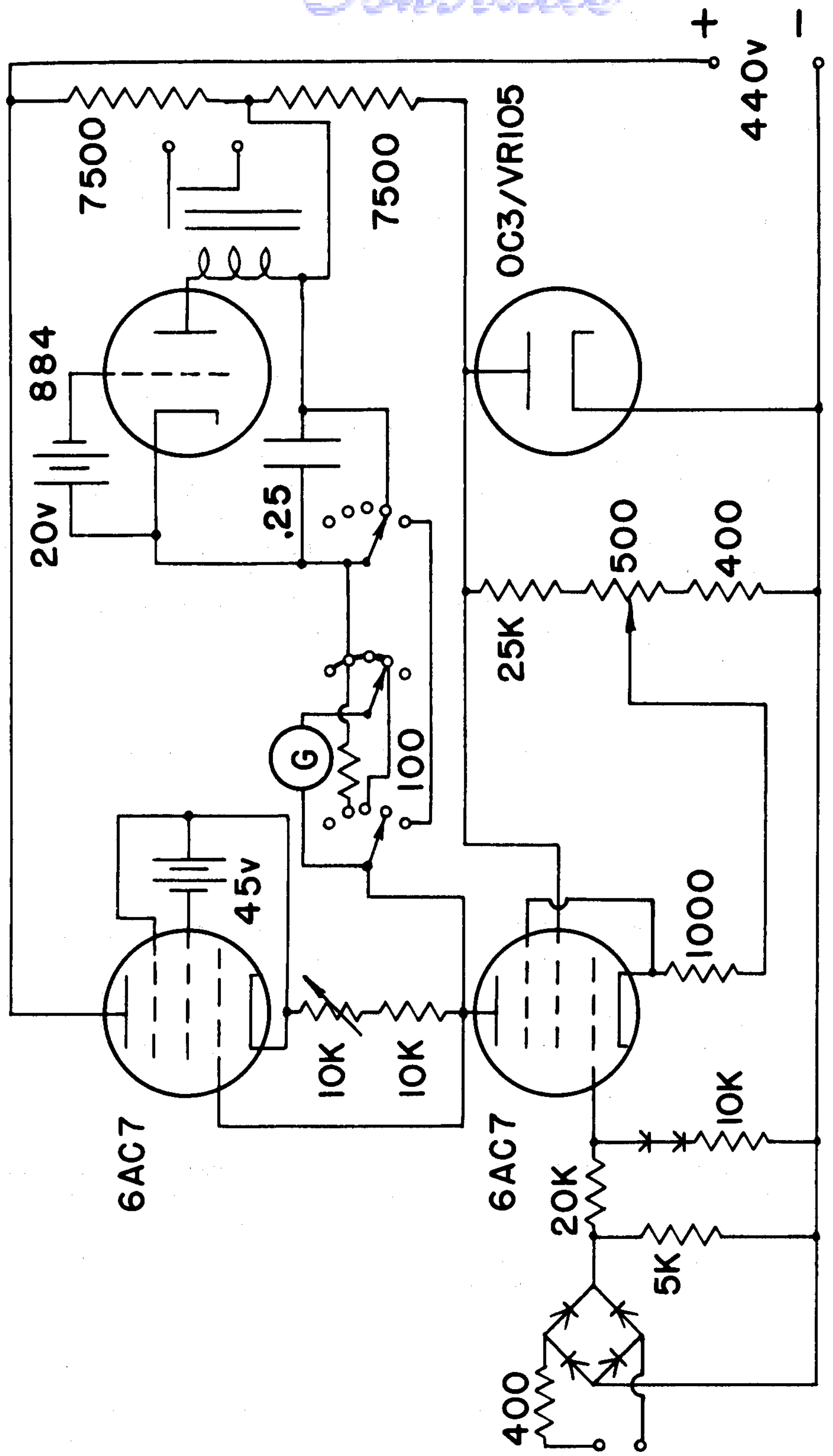

Figure 14. Circuit of Voltage Integrator (Modified from Stevens, 6)

box. Figure 15 shows the response of the integrator.

As a check on the proportionality of the integrator to the input signal, simultaneous integrator and oscillograph records at various input voltages were obtained and compared. The results are shown graphically in Figure 16.

Brush Oscillograph

A tape speed of 5 millimeters per second was used.

Filter

A small amount of a.c. pickup was noticed at the output of the computer proper. All usual means were tried in an attempt to eliminate the unwanted pickup, but met with only partial success. Finally, a simple single section resistance-capacitance filter, designed to provide 20 decibels of attenuation at 60 cycles per second, was placed between the output of the computer and the input to the Brush amplifier, as shown in Figure 1. This completely eliminated the pickup from the oscillograph recordings. A check of the total system with the filter in place failed to yield any measureable change in the amplitude of the signal when corrective movements through the same distance were made at slow and very fast rates.

Timing and Control Circuits

Photoswitch

A trial length of 30 seconds was chosen for the reason that at 0.2 radians per second, the lowest target velocity we intended to use, 30 seconds were required in order for the generating cams to make one complete revolution, that is, for the function to be generated once.

To standardize the length of the trial, a Photoswitch model 1000, type 30 HLI electronic timer was employed. The timer was calibrated against a Standard Electric Time Company timer, which measured intervals as low as 1/100th second.

Relays

In addition to the Photoswitch, two relays were used in control circuits. One was used to close the circuit from the 440 volt d.c. power supply to the integrator. The other was used to close a local

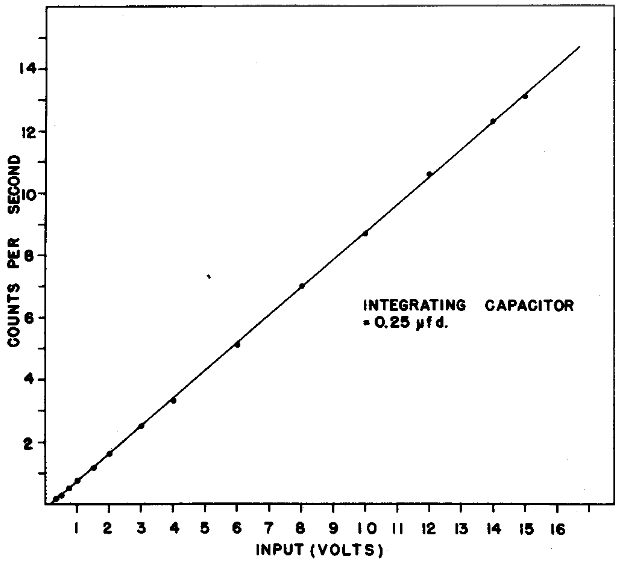

Figure 15. Response of Voltage Integrator.

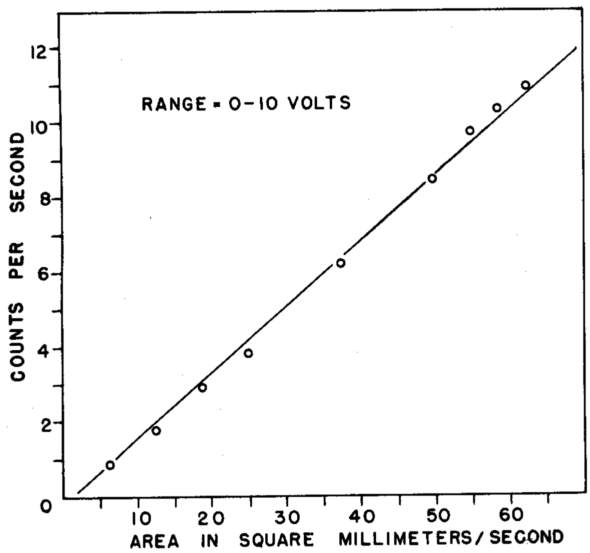

Figure 16. Proportionality of Area under the Curve to the Number of Integrator Counts, Showing Approximation to a Straight Line.

circuit which connected 110 volts, a.c., regulated, to the motor of the Graham variable speed transmission of the function generator.

Operation of the Photoswitch caused the two control relays to close, starting a trial. When 30 seconds had elapsed, the integrator and the function generator were rendered inoperative by the opening of these relays. It was necessary for the integrator to become inoperative at the end of a trial in order for an accurate count to be obtained from the counter.

Adjustment of Apparatus

For the procedure involved in the adjustment of the voltage integrator and the amplifier-cathode follower units, as well as for a listing of the critical voltages, see the Appendix.

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ADJUSTMENT OF APPARATUS

1. Amplifier-Cathode Follower Units

   a. Bias
   The bias on the 6SN7 of the cathode follower section of the circuit should be set at 10 volts without load or input.

   b. Balancing
   Balancing should be done with the load connected, but the input disconnected. The amplifier section should be balanced first, using the 0-10 volt scale of a meter such as the Simpson (20,000 ohms per volt). By adjustment of the 5,000 ohm balancing potentiometer the output of the amplifier section should be reduced to zero. The cathode follower section should then be balanced so that the output of the entire unit is zero. In the adjustment of the cathode follower section the 2.5 volt scale of the meter is used.

   c. Gain Control
   After the unit has been balanced as in b., above, the over-all gain of the amplifier-cathode follower circuit must be adjusted to unity under load. This is best done by using an input from the function generator. Set the output of the function generator to to 18 volts, without load. Next, connect the output of the function generator to the input of the amplifier section. Using the 50 volt scale, connect the meter across the input of the cathode follower section. The meter should read 18 volts with the load connected, i.e., with the output of the amplifier-cathode follower circuit connected to the computer and with all voltages applied to the computer. If this is not the case, adjust the gain control of the amplifier section until the meter reads 18 volts output. The above adjustments should be made with the control stick out of the circuit. The open circuit left by the removal of the control stick connectors should be closed with a shunt.

2. Voltage Integrator Circuit

   a. Bias
   6AC7 - 45 volts, d.c.

884 - 20 volts, d. c.

b. High voltage
440 volts, d. c.

c. Steps in Adjustment
Remove input to integrator

Rotate switch to position 4. In this position the microammeter is placed in the circuit with the integrating capacitor. Use the 100 microampere scale of the meter.

Adjust the 10,000 ohm and 500 ohm potentiometers until the microammeter reads zero current (see Figure 14). Any combination of settings of these two controls which will give zero current flow is acceptable.

Turn the rotary switch to position 5, the operate position.

Re-connect the input to the integrator.

3. Critical Direct Current Voltages

a. Control Stick Power Supplies
Set control stick potentials to 140 volts as measured across the Helipots.

b. Function Generator Power Supplies
Set the function generator potentials to 90 volts with load connected.

c. Amplifier-Cathode Follower Units
The amplifier section requires 240 volts. The cathode follower section requires 300 volts. The "no load" bias of the cathode follower is 10 volts.

d. Computer
Bias:
Adding amplifier (6SN7) - 8.2 volts.

Square root circuit (6SN7) - 9.7 volts.

Square root circuit (6H6) - 11.0 volts.

Square law circuit (6H6) - 12.0 volts.

High Voltage:

Adding amplifier (6SN7) - 190.0 volts.

Square root circuit (6SN7) - 195.0 volts.

e. Integrator

Bias:

884 - 20 volts

6AC7 - 45 volts

High Voltage:

440 volts.