THE RICE INSTITUTE

A SERVOMECHANISM PANTAGRAPH

by

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<table>
<thead>
<tr>
<th>Acknowledgement of Help Received</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>2</td>
</tr>
<tr>
<td>Summary</td>
<td>5</td>
</tr>
<tr>
<td>Performance Data</td>
<td>6</td>
</tr>
<tr>
<td>Method of Test</td>
<td>12</td>
</tr>
<tr>
<td>Sensing Systems</td>
<td>15</td>
</tr>
<tr>
<td>Other Sensing Systems</td>
<td>20</td>
</tr>
<tr>
<td>Voltage Amplifiers</td>
<td>27</td>
</tr>
<tr>
<td>Power Amplifiers</td>
<td>29</td>
</tr>
<tr>
<td>Motor and Positioning Mechanism</td>
<td>38</td>
</tr>
<tr>
<td>Suggestions for Further Study</td>
<td>44</td>
</tr>
<tr>
<td>References</td>
<td>47</td>
</tr>
<tr>
<td>Appendix</td>
<td>48</td>
</tr>
</tbody>
</table>
ACKNOWLEDGEMENT OF HELP RECEIVED

Without the help and encouragement given by Mr. Paul Pfeiffer, my faculty advisor on this project, it would not have been completed. He was present when the idea of such a device was first mentioned and has been most helpful in offering suggestions for improvements as the project progressed. It was his suggestion to use slide-wire potentiometers as position sensing elements when the synchro system originally considered proved inadequate. He found a mechanism incorporating potentiometers which was admirably suitable for this use—a device which I did not know existed. It is not exaggerating the facts to say that this suggestion meant the difference between success and failure in this project. Other helpful suggestions were made from time to time materially facilitating the work.
INTRODUCTION

In the Spring of 1950, Messrs. Paul Pfeiffer, Earl Beck and the Author were analyzing a servomechanism whose fundamental block diagram and transfer functions were known. It was realized that the computation would be simplified and shortened greatly if the information contained in two graphs previously studied were combined onto a single set of axes. Although both graphs were normalized, they had been reproduced to different x/y proportions in the two books which made it impossible to trace one over the other. It was thus necessary to reproduce them point by point, reading the coordinates from the graph and plotting them on a sheet of standard graph paper. One of the group remarked how desirable would be a machine which would transform scales and plot the points automatically as a curve was traced. This report describes the construction and performance of such a machine.

The six-link pantograph familiar to most children and photographic enlargers both provide change of scale of
drawings. However, when these are called upon to change the proportions of a drawing such as transforming a square into a rectangle, they cannot do so. The independence of adjustment of $x$ and $y$ coordinate scales offered by this device provides for a number of possibilities. Any relationship involving the transformation

$$x' = A x$$
$$y' = B y$$

may be reproduced easily. For instance, ovals may be plotted from circles, exponential curves with different amplitude and/or time constants may be drawn from a single normalized template, sine curves with different amplitudes or time constants can be reproduced from a single drawing, etc.

The principles underlying this device are straightforward and simple. Basically, the system can be described so: The figure to be reproduced is traced manually by an operator. The pointer is connected to the input data head by a six-link pantagraph and adjusts the output voltages of the input data head proportional to the $x$ and $y$ coordinates of the pointer position. At the output, two other voltages
proportional to the coordinates of that tracing point appear and these are compared to the input data voltages. The difference between corresponding voltages is called the error; each error is amplified by its voltage amplifier whose output controls a power amplifier. The power amplifier operates a motor which in turn causes the output to move in a direction to reduce the error. The two coordinate channels are similar. Scale adjustments are provided at the output sensing devices.

The basic block diagram showing the functional arrangement of the parts is shown on the next page.
Basic Block Diagram
"A Servomechanism Pantagraph"
SUMMARY

The device described is a servomechanism pantograph driving a pen at the output. It accepts information given at the input, resolves this into cartesian coordinates of the point, and drives the pen in accordance with this information. A novel feature is the possibility of independent adjustment of the two coordinate scale factors, thus permitting transformation of curves plotted on one set of axes to another set of axes incorporating a standard pair of scales.

When run at slow speed (about 0.03 cps. for a three-inch circle at output), the maximum deviation from a true circle was 0.07 inches. Accuracy is better than five percent to a frequency of about 0.5 cps. The error increases rapidly for higher speeds.

The construction of this device is described. Reasons for the particular choice of the various parts are given, and discussion of some difficulties encountered is included. The major parts considered are the sensing members, the comparison device, error amplifiers, the power amplifiers, and the motor-and-table assembly.

Suggestions for further study are given.
PERFORMANCE DATA

The two quantities of major interest in describing the performance of a positional device are the accuracy of positioning and its rate of positioning. The stability of the device is important also, but this quantity is related to the other two. It is customary to measure the response of the system to a sinusoidal variation at the input as a function of the frequency. This was done for this mechanism, and the results shown on the OUTPUT vs. FREQUENCY curves included in this report. Since there are two separate channels (X and Y) which are not identical, two curves are shown.

These curves indicate that the overall response (peak to peak deflection) of the X-channel is essentially constant to a frequency of about 0.8 cps, while that of the Y-channel has a slight peak at 0.53 cps and a dropping response thereafter. The Y response is down about 50% at a frequency of one cps. These curves were drawn from measurements on the actual output traces of the machine. Peak to peak amplitude was recorded for both the X-displacement and the Y-displacement. These displacements are shown on the traces included here.
A study of these traces indicates peculiarities in the behavior of the device. For higher frequencies, both X and Y channels appear to move at a constant velocity for a major part of their paths. This results in a rather lop-sided skewed figure. This effect increased as the frequency was raised. The X-channel, as might be expected from the OUTPUT vs. FREQUENCY curve, was a worse offender in this respect than the X-channel. The combined effect of the two channels is to produce a curve which differs from a true circle.

For the purposes of this report, the deviation of the trace from a circle with diameter equal to that of the lowest frequency response is defined as distortion. The maximum deviation is used wherever it is noted; thus a RMS error would be less than the amount shown on the DISTORTION vs FREQUENCY graph. Since the distortion as defined here cannot be attributed to either channel alone but is characteristic of the entire system, only one distortion curve is drawn.

The DISTORTION vs. FREQUENCY graph indicates a slightly increasing distortion as frequency is raised to
about 0.5 cps. At 0.079 cps, the distortion is 0.07 inches and the deviation is generally well under this figure. A sharp break occurs slightly below 0.5 cps, after which the distortion rises quickly to intolerable limits.

Several remarks concerning the response should be made. Reducing the thyratron bias permits the mechanism to oscillate rapidly. This is shown on two traces (0.079 cps and 0.23 cps.). This apparently does not change the response of the device except that the high-frequency variations are superimposed on the desired low-frequency response. The definition of distortion used above would give about the same distortion figure whether the oscillation were present or not. However, it is apparent that this oscillatory response is undesirable. All curves and traces other than the two mentioned were taken for the non-oscillatory case.

On the trace for 0.079 cps., normal bias (non-oscillatory case), a small nick in the "circle" is noted about halfway up on the right-hand side. Other such artifacts are visible (bottom of 0.30 cps. curve, etc.). These are systematic. The response at 0.079 cps. was watched for about twenty cycles and this nick occurred as shown every time. It is believed that an imperfect gear tooth or other such mechanical imperfection
is the cause. Most of the other wiggles in the traces are believed due to random variations such as backlash, belt slippage, striction, etc.

The unusual biasing of the thyatrons and consequent motor current results in very strong viscous damping. This prevents the device from following rapidly but also effectively, transient overshoot. The damping is reduced near the null, however, and so velocities of about three inches per second are attainable. This is considered adequate for the task the machine is to perform because the operator at the input tracing point is not likely to trace a figure more rapidly than this. The human servo characteristics must be considered as a limiting factor.
DISTORTION vs FREQUENCY

"A SERVOMECHANISM PANTOGRAPH"
Input Varied 1.00 in. (P to P)
Thyratron Bias: X: -34V, Y: -45V
Ampl. B+: 250V, Field: 200V
EE 510 The Rice Institute
May 8, 1952
W.J. Lee,
METHOD OF TEST

Since a mechanism for translating a point along a line with sinusoidal velocity is more involved than that for driving the point around a circle at constant velocity, the latter was chosen for this test. The particular potentiometer mechanism has a construction which automatically resolves the position of the input point into X and Y coordinates which vary sinusoidally with time for circular motion of the input. Thus, circular drive produces sinusoidal excitation of the two channels simultaneously.

To obtain this condition, a small motor with a cone-and-disc mechanism was arranged to slew the input potentiometer tracing point. A small disc was keyed to the disc shaft, and a hole 0.50 inches from the center was slipped over this tracing point. The device was then turned on, the disc position adjusted for the desired speed, and a trace taken at the output of the servo. (These traces are included in the Appendix.) Responses at other speeds were obtained similarly after adjusting the disc to a new position. Frequency was measured by counting the number of cycles per minute and dividing by 60. Response was measured by scaling from the output traces, using a regular
engineer's scale.

Distortion was measured by superimposing a 3.30 inch diameter circle over the trace, and measuring the maximum deviation.
Test Set-Up, Variable Frequency Drive
SENSING SYSTEMS

Four position sensing devices are used in this servo: one input and one output for each of the two channels. All are wire-wound potentiometers. The two channels differ only in minor details. However, within a channel, a decided difference exists between the input and output potentiometers.

The input system is a commercially manufactured device (General Electric Catalogue Number 8252905 G2). It consists of four separate wire-wound potentiometers so mounted that motion of the input tracing point moves the wiper-arms along the resistance elements. Two of these resistors are mounted on the main frame parallel to one another. The wiper-arms associated with these are mounted on another link above the resistors and arranged by a four-link parallel-motion mechanism to move parallel to the resistors when the tracing point is moved appropriately. The other two resistors are mounted above this wiper-arm link and are free to move in a direction perpendicular to the motion of the wiper-arm link. Thus, any particular motion of the tracing point results in changes in the position
INPUT SENSING DEVICE
of the wiper-arms proportional to the proper components of input motion.

In this device, a voltage of about 15 volts (rms) at 60 cps. is impressed across the two ends of a resistor. The wiper-arm is grounded so that the voltage swings at the ends of the resistor are proportional to the displacement of the wiper-arm. This is done in both channels, using separate transformer windings to excite the two resistors.

Potentiometers are used also to sense the position of the output. These are geared to the output shafts so that positive motion results. These potentiometers are connected electrically in parallel with the appropriate input potentiometers so that the ends of the resistors swing in voltage in step with the corresponding ends of the input potentiometers. The output wiper-arms are connected to the grids of the appropriate voltage amplifiers. At these grids, the voltage to ground is the difference between the voltages of the two wiper-arms and thus is proportional to the difference in positions of the two wiper-arms, that is, to the error.
The input resistor is shunted by distributed capacitance to ground which tends to destroy the linear relationship between voltage and displacement of the wiper-arm. This resistor has a resistance of only 120 ohms, however, which is very small compared to the shunting impedances. The higher resistance output potentiometers work into high impedance grid circuits. Thus, loading effects result in negligible error.

The use of this particular input data mechanism greatly simplified the construction of this device. It is improbable that an equally satisfactory potentiometer resolver could have been constructed using the modest machining facilities available.
Scale changes can be accomplished easily by connecting an adjustable resistance in series with the potentiometer corresponding to the scale increase. Adjustment of this resistor determines the amount of scale magnification in proportion to the increased resistance. This occurs because the mechanism attempts to equalize the voltage output to the voltage at the input potentiometer. Addition of a series resistance lowers the voltage output for any particular displacement, thus the displacement must be increased to provide sufficient voltage for a null.
OTHER SENSING SYSTEMS

The original plan was to use synchro control transformers to resolve the information into voltages proportional to the cartesian coordinates of a point. This plan was abandoned after much effort because of poor wave form of the synchro output voltages. However, it is considered worth while to include a description of this system because the experience obtained in the efforts to make it work may be helpful to others.

The underlying idea was to use angular position to represent input and output information. A number of devices are in common use which yield voltages dependent upon angular position (synchros, telegons, microysns, etc.), and so would permit transmitting and comparing these signals.

A rhombus with one corner fixed in location can be used to convert cartesian coordinate positions into related angular positions:
\[ x = L (\cos \alpha + \cos \theta) \]
\[ y = L (\sin \alpha + \sin \theta) \]

A synchro control transformer with two stator windings 90 electrical degrees apart presents output voltages whose magnitudes are proportional to the sine and cosine of the angular position of the rotor. If such units are connected to the two pivoted arms of the rhombus and corresponding coils then connected in series, the output voltages from the combinations would then be proportional to the \( X \) and \( Y \) coordinates of the point \( P(x, y) \).

In the units constructed, a three-fold step-up in synchro rotation was provided by gearing. This was
Synchro Error Sensing System
expected to provide increased accuracy in the region of a null. The output voltages then would correspond to a fictitious point \( P' \) related to the actual point \( P(x, y) \). Comparison of these two points \( (P' \) at input and output) electrically would correspond to comparison of the actual points \( P(x, y) \). Scale adjustment could be provided by use of simple voltage dividers.

As has been mentioned, difficulties were encountered. First, the resolvers ("two phase" synchro control transformers) commercially available were much too expensive to serve the needs of this project. Consequently, the common "three phase", 400 cycle units available on the surplus market were used. This made opening the stator wye necessary, and the bringing out the new lead detached from the common junction of the other two coils. Two windings, presumably 90 degrees apart electrically, resulted, one set having a transformation ratio considerably larger than the other. The task of opening this wye was difficult because of the very small wire used in winding the units and by the solid impregnation techniques used in manufacture.

When the units were completely assembled, considerable time was spent in aligning the two units. The two pivot arms
were bolted together and clamped in the extreme clockwise position. An oscilloscope was connected across the "alpha" coil of one unit and another oscilloscope across the two "alpha" coils in series. The first synchro unit was rotated in its mounting until minimum signal was seen on the screen; then, the other unit was rotated until minimum output was obtained from the combination. Unfortunately, this minimum had high harmonic content (about 0.05 volts, rms) entirely sufficient to cause firing of the thyatrons and to render the system useless in that form.

Also, it was noted that the "best" alignment of the "alpha" coils was not best for the "beta" coils. It is suspected that capacitive coupling between the windings of the amended control transformers resulted in considerable disturbance in this respect.

The harmonic difficulty was reduced somewhat by use of interstage coupling transformers across the output terminals. The poorest quality transformers available were sought in hopes that the high frequency (harmonic) terms would be unfairly treated. The outputs of these transformers were shunted by sizable (2 mfd) condensers
for the same reason. This unorthodox procedure resulted in considerable but not sufficient improvement.

Another solution considered for this harmonic problem was to use a peaking amplifier tuned to the desired fundamental frequency. Briefly, this is an amplifier with extreme negative feedback. In the feedback loop, a single frequency rejection filter of the bridged-T type (perhaps) is used so that all frequencies except that rejected by the filter will be attenuated strongly. This results in an output wave of very low harmonic content.

This plan was not used because of the very rapid change of phase and loss of sensitivity with small changes of the carrier (400 cps) frequency. For this particular application, this was not deemed a practical solution because the carrier frequency was not sufficiently stable. For stabilized sixty-cycle applications, however, it should be useful.

The voltage amplifier was designed to have poor upper frequency response to reduce harmonic influences, by shunting the plate to ground capacitively. The amplifiers are described more fully elsewhere.
All of the systems described so far use a-c error signals. When the violent hunting described in the power amplifier section of this report was experienced and a suitable corrective network remained undiscovered, serious consideration was given to the design of a system using a d-c error signal. The particular amplifier intended for this use required two d-c signals of opposite polarity for each channel. These signals were to be proportional to the error. This was to be obtained by doubling the system finally adopted. Two potentiometers were to be connected to each output shaft and their outputs compared to the outputs of two input potentiometers. By grounding the wiper-arm on one input potentiometer and on the other output potentiometer, the desired reversed polarities were obtained.

This plan was abandoned because of voltage drifts in the d-c amplifiers.
VOLTAGE AMPLIFIERS

The voltage amplifiers used are two-stage pentode units. The gain is about 5000 at the operating level. When saturated, the output is about 90 volts rms.

Almost complete electrostatic shielding was found necessary to reduce feedback from the steep wave-front voltages present in the thyratron circuits. This shielding is provided by the aluminum shields surrounding the individual stages and by use of shielded leads for grid and filament conductors.

Conventional RC coupling is used. However, plate load resistors, grid resistors, and coupling capacitors are smaller than usual in order to reduce high-frequency response and avoid harmonic difficulties.

Proper phasing of the thyratron signal for the X-channel was obtained by shifting the phase of the input signal to this channel. A 100,000 ohm resistor in series with a 1.0 mfd capacitor in shunt across the input to this channel have been added to provide this shift.

Circuit details are shown on the accompanying diagram.
POWER AMPLIFIERS

This servo has two channels and so uses two power amplifiers. These two amplifiers are similar in design. Each consists of two grid-controlled thyatron rectifier circuits operating in opposition. The grids are driven by the output signals from the voltage amplifier and so are controlled by the error signal. The output currents of the rectifiers pass through the armature of the d-c drive motor providing a torque tending to reduce the error.

The basic power amplifier is described in Reference 1. It is not operated as indicated there, however, for unorthodox bias and grid signals were found necessary to avoid a peculiar type of hunting described in Reference 2 and quoted here:

One consequence of the finite grid circuit impedance of thyatrons is that when two tubes are driven from a single source of moderately high impedance and appreciable reactance, such as a coupling condenser, it is possible for grid current of one tube to cause a bias to build up that tends to prevent the other tube from firing at its normal control point. This effect (or similar effects caused by feedback from the fired tube to the amplifier input) gives rise to a peculiar servo performance in which the apparent balance point is different for the two directions of rotation. As the error signal is reduced, the servo approaches a balance point that turns
out to correspond to an overshoot and gives a reverse error. In driving back in the opposite direction a similar effect is present. Under these conditions, a control circuit and motor may hunt with an amplitude that cannot be controlled by varying the amplifier gain.

Except for the grid signal, (which is discussed more fully later), operation of the circuit is straightforward. When tubes T1 and T2 conduct, current flows downward through the armature. When T3 and T4 conduct, armature current flows in the opposite sense. Thus, the direction of the torque is dependent upon which pair of tubes fires.

The grids of the two rectifiers are driven in phase, but the plate supplies are reversed in phase. Consequently, a reversal of the phase of grid voltage results in reversal of direction of armature current.

In conventional circuits, thyratrons are biased off and require definite grid signals to fire them. The size of grid signal needed to do this is, of course, dependent on the bias on the thyratron. When this particular device was operated, effects similar to those described in the reference quoted above were painfully evident. The grid bias of any extinguished tube was held well negative until that tube was fired, whereupon the other tube became biased.
similarly. The consequence of this was the definite absence of any true null.

These effects were discovered before the above reference was found. They were identified when attempts were made to bring the system to a null manually. As the output was moved slowly in the direction it was seeking, a very abrupt reversal of torque was felt. As the output was moved back in the new direction, a similar effect was noted but at a considerable distance from the first reversal. The system sought a null, but could not stop until it had passed it. This effect was similar to action of a shuttle-cock: it could not be reversed until it had overshot the net.

The width of this null overlap in this servo was noted to be independent of the speed at which the output shuttled back and forth, so no normal phase-lead corrective networks were suitable. This non-linearity was not recognized, however, until many attempts had been made to stabilize the system by use of bridged-T, twin-T, and other stabilizing networks.

The remedies suggested in Reference 2 did not work. According to this reference, grid current in the conducting
tube is the origin of the bias. Such was not the case in this system, for the bias was still present when all but the non-conducting tube were pulled from their sockets. Thus, grid current in the non-conducting tube provided a self-bias at the place most difficult to shield from its effects.

A vacuum-tube voltmeter was used to measure voltages around the circuits of the two amplifiers. The results are indicated on the circuit diagram included here. Readings indicated a positive grid current of about 50 to 90 micro-amperes from ground through the grid-leak and the grid-protective resistors to the grid. These grid currents apparently resulted from electron bombardment of the grid. If so, increasing the grid-leak resistor as recommended in the reference would serve to make the grid even more negative.

One possible cause of interaction between the rectifier circuits was the common circuit element: the motor armature. Normally, the cathode of the off-tube goes negative by a voltage equal to that by which the on-tube cathode goes positive. This should reduce the grid bias and relieve the shuttlecock effect. To check this, rectifier cells
D-C POTENTIALS MEASURED AROUND THYRATRON CIRCUIT (ONE TUBE ON, ONE OFF)

"A SERVOMECHANISM PANTAGRAPH"
EE 510, THE RICE INSTITUTE
(type 1N21 Germanium diodes) were connected cathode-to-ground with such polarity that the off-tube cathode would be clamped to ground. This should have resulted in a change of bias on the off-tube if such bias were due to the conducting tube. Some such effect was noted, but it was slight. Without clamping, the grid potential (off-tube) was about $-18.5$ volts and the cathode about $-12.7$ volts, a negative bias of $5.8$ volts. With clamping, the cathode potential was raised to plus $1.1$ volts but the grid came up only to $-7.2$ volts, a negative bias of $-8.3$ volts. The grid protective resistor was reduced tenfold but its voltage drop appeared essentially unchanged. These effects indicate that this grid bias was spontaneous.

When a tube was fired at some time during the cycle, its grid bias dropped to about one-half volt negative and its firing was much more reliable. One solution for this spontaneous grid poisoning was to fire the tube late in its period as it approached the null position from the "off" side. It would then be ready to fire vigorously as the error signal reached zero rather than after the error signal had badly overshot the null. This was attempted, but could
not be accomplished using a fixed-phase grid signal. The off-tube can be fired this way when the error signal is sizeable but not when the error signal becomes small. This is evident from the grid-signal, control characteristic relationships.

As the possible control relationships were studied, it became evident that one arrangement would permit the oncoming tube to be fired more vigorously as the null was approached. This condition would permit deceleration as the error was reduced and might provide the desired stability. This can be done (for fixed-phase signal) only when the error signal is used to hold the proper tubes off rather than to turn others on. This was done for this servo. These relationships are shown on the accompanying diagram.

This method is inefficient. At a null, full output of both rectifiers is passed through the motor armature. The correction torque is provided by a reduction in the restraint offered by one rectifier or the other. However, the system remains "alive" and no evidence of reluctance to move has been noted, even for the smallest changes of input position.
III. 

Illustration showing how reducing error signal results in reduction of the correcting direct current.
AMPLIFIER ASSEMBLY
MOTOR AND POSITIONING MECHANISM

A fractional-horsepower direct current motor is used in each channel for positioning the tracing point. The armatures of these motors are supplied with current from the power amplifiers and the fields are supplied from a source of constant direct current. An electronic power supply with output voltage adjusted to 200 volts was used during the tests reported here.

The rotation of the motor is transformed into translation of the tracing point by a system of shafts, pulleys and wires. The general arrangement of these parts is shown on the accompanying photograph.

The shafts along the edges of the table are supported by ball bearings to reduce friction. Cylindrical pulleys are attached firmly to these shafts at each end. Between the fixed pulleys on each shaft, a movable pulley is placed. These movable pulleys are supported by ball bearing rollers so that they may roll along the shafts but are constrained by a spline to turn with the shaft. The movable pulleys position the tracing point; the fixed pulleys position the movable ones. This positioning is done by a wire attached to the object to
be moved and then wrapped securely around the appropriate fixed pulleys.

The construction of this output drive mechanism involved many details. The actual fitting together of the parts was quite tedious as well. The movable pulleys are supported by five ball bearings which must hold the pulleys concentric with the shaft with rigidity, and yet permit very free motion along the shaft. The spline in the shaft required hand lapping and nicks in the surface of the shaft called for considerable attention before sufficient freedom was obtained.

The pulleys were all made from two-inch lengths of three-inch diameter aluminum tubing. Ends were squared in a lathe after cutting. End plates for the fixed pulleys were made from hard, free-cutting aluminum. The stock was cut into squares, drilled for the through-bolts, fastened securely to the face plate of a lathe, and the hole and the shoulder flange turned.

Details of the motor drives and the potentiometer mountings are shown in photographs. These mountings are not similar because the X-output shafts were placed 3.5 inches higher than the Y-output shafts.
Belts for the drives were made from No. 8 cotton sewing thread. The thread was wound around the sheaves about ten times and then the ends tied. No effort was made to lay these turns as in a grommet, for the flat belt offered better friction because of its increased surface compared to a single larger-diameter cord. Use of thread in this way resulted in a smaller knot than could be obtained had a larger cord been used: a consideration of importance in this application.

The positioning wires were made of 30 gage (B&S) bare chromel thermocouple wire. Springs are placed in each loop to maintain proper tension.
General View, Output Tracing Mechanism
Detail: X-Drive and Output Potentiometer
Detail: Y-Drive and Output Potentiometer
SUGGESTIONS FOR FURTHER STUDY

Study of this system indicates that a more efficient power amplifier is needed. Because of the relationships inherent in a system using variable-amplitude, fixed-phase signals to drive the thyratron grids, another type of signal should be used. Only by doing so can the on-tube be fired later and the oncoming tube earlier in the cycle as the error signal approaches a null.

One way of doing this is to use a d-c error signal and a comparison amplifier. If the error is compared to a triangular wave having equal rise and fall rates, a shift in the error level will advance the time of one cross-over (condition of equal voltages) and will retard the next cross-over. If the positive-going cross-over causes one thyratron to fire and the negative-going cross-over causes the other to fire, very smooth control should be experienced. Since the time of cross-over and not the actual voltage at that time is the quantity desired, pulses may be generated and used for triggering the thyratrons. This should provide relief from the bias problems encountered in this project.
A practical system of this sort was planned but lack of time prevented its construction. This was to include a triangular wave generator, a comparison amplifier and a pulse generator. The triangular wave generator was to be composed of a strongly overdriven amplifier feeding an RC "integrating" circuit with a buffer amplifier to amplify the "integrated" wave. The comparison amplifier was to be an ordinary difference amplifier with a saturating transformer connected plate-to-plate. This would provide a voltage pulse corresponding closely in time to the moment of equality. Such transformers were not immediately available although many magnetic amplifiers of suitable characteristics have been mentioned in the literature.

Another comparison circuit and pulse generator that offers promise is described in Reference 3 under the name of Multiar. Here, a diode is placed in the feedback circuit of an oscillator and the signals to be compared are impressed
across the diode. When the difference in signals reaches the diode conducting characteristic — a very constant quantity — the oscillator breaks into high-frequency, high-voltage oscillation entirely suitable for triggering the thyratrons. Another such circuit with reversed diode polarity could be used to provide signal for the opposing thyratron. Several other circuits can be found that might serve equally well or better.
REFERENCES


2. Ibid., except for page number. Page 411.

APPENDIX

TRACES DRAWN BY THE PANTOGRAPH
WITH ONE-INCH DIAMETER CIRCULAR INPUT

(INPUT FREQUENCY SHOWN BELOW EACH TRACE)
0.079 cps.
ZERO BIAS

3.30 in.

3.32 in.

0.079 cps.
NORMAL BIAS

3.35 in.

3.32 in.
0.23 CSPS
ZERO BIAS

3.35 in

3.30 in

3.25 in

0.23 CSPS
NORMAL BIAS
V • 0.53 cps

3.50

3.22

1.75

1.16

1.00 cps

2.44

2.73

2.14

1.145